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ATLAS Higgs CP analyses

Hongtao Yang (LBNL)

on behalf the ATLAS Collaboration

LHC Higgs WG2 Meeting

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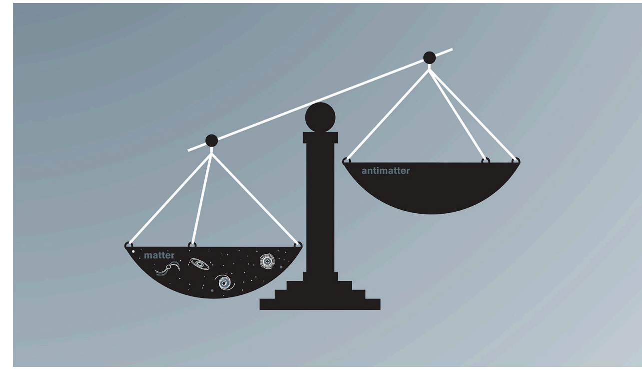
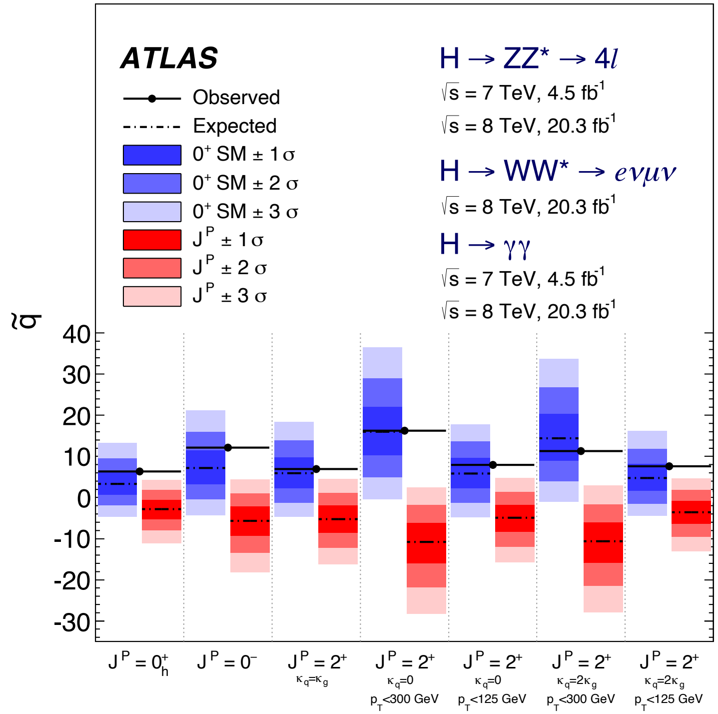
Introduction

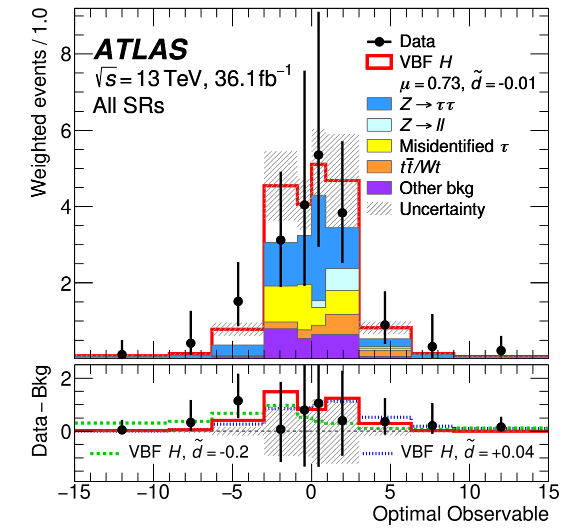
- Known CP violation sources in SM are not enough to explain observed matter-antimatter asymmetry
- Higgs boson productions and decays at LHC offer an novel opportunity for probing new CP violation sources in Higgs boson interaction with SM particles





Recent ATLAS results: H→ττ and H→WW

- H→ττ: probe CP of V-H interaction in VBF
  - Use EFT model with only CP odd dim-6 operators considered
  - Build optimal observable as ratio between SM-CP odd interference and SM²
  - CP violation strength constrained $\tilde{d} \in [-0.090, 0.035]$ @68% CL
- H→WW: probe CP mixing in effective g-H interaction using ggF+2-jet events
  - Use Higgs Characterization model
  - Using both shape and rate: $\kappa_{Agg}/\kappa_{Hgg} = 0 \pm 0.5$



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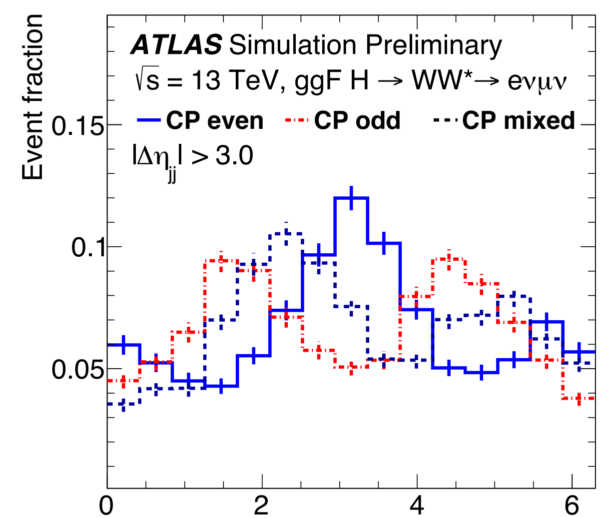
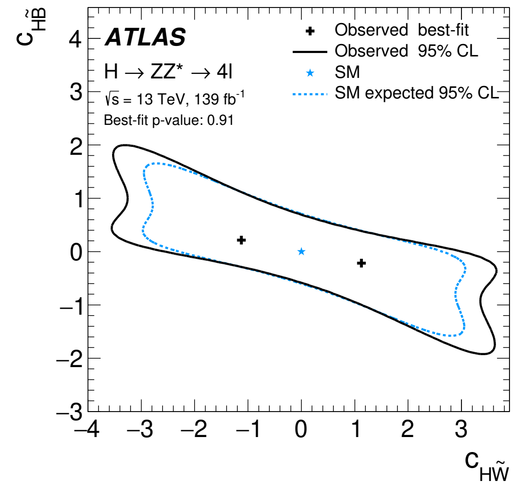
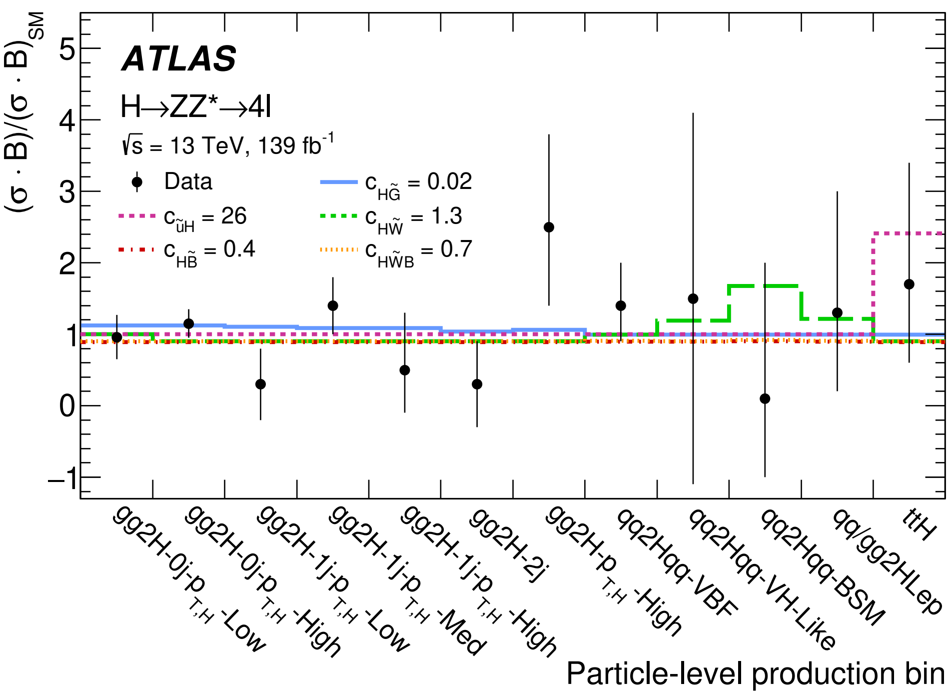


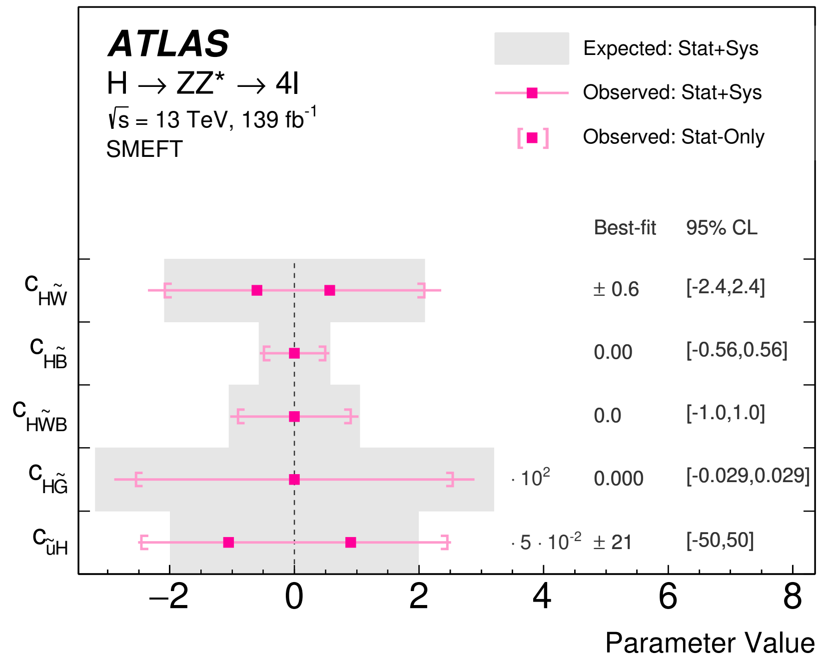
ATLAS-CONF-2020-055

Recent ATLAS results: H→ZZ

- Reinterpret simplified template x-section (STXS) measurements in SMEFT framework: fitting CP-odd Wilson coefficients to data
  - Viable in other channels & combination as STXS framework is widely implemented
  - Need to be careful with modification of acceptance

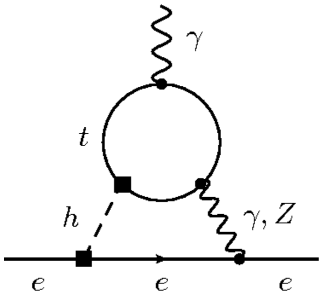






Today's focus: ttH/tH, H→γγ CP analysis

- Only indirect constraints on CP mixing in **t-H** interaction existed before Run 2 ttH observation
  - Stringent limits from **EDMs (e, n, …)**: $\kappa_t \sin(\alpha) < 10^{-3}$
  - Also from loop-induced **H→γγ** and **ggF** rates: $\kappa_t \sin(\alpha) < \sim 0.5$



- **The ttH/tH production mode** opens a new possibility to **probe CP mixing** **directly in the top Yukawa coupling at tree-level**
  - The Lagrangian for t-H interaction including CP mixing is

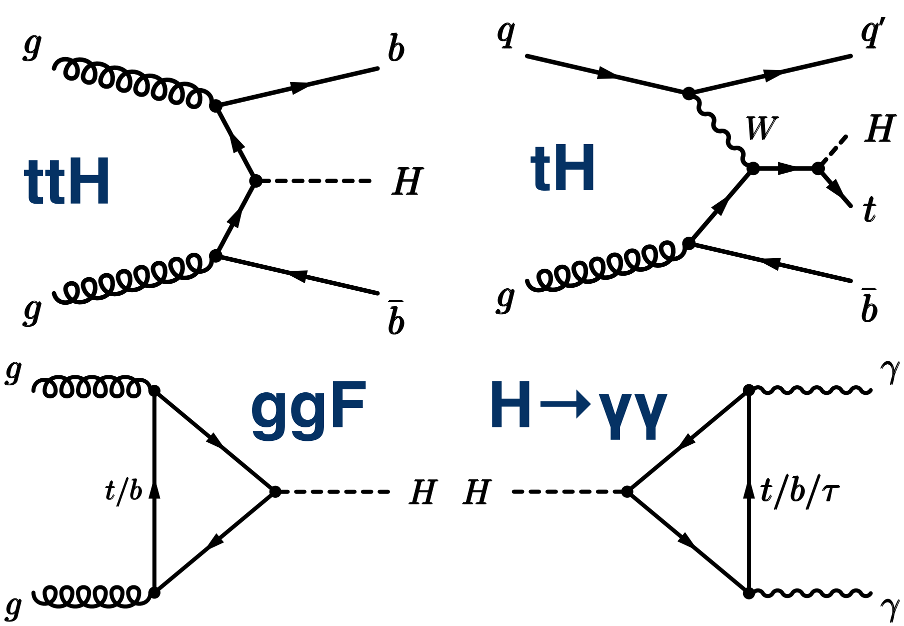
$$\mathscr{L}_t = -\frac{m}{v}\kappa_t(\cos(\alpha)\bar{t}t + i\sin(\alpha)\bar{t}\gamma_5 t)H,\ \kappa_t > 0,\ \alpha \in [-\pi, \pi]$$

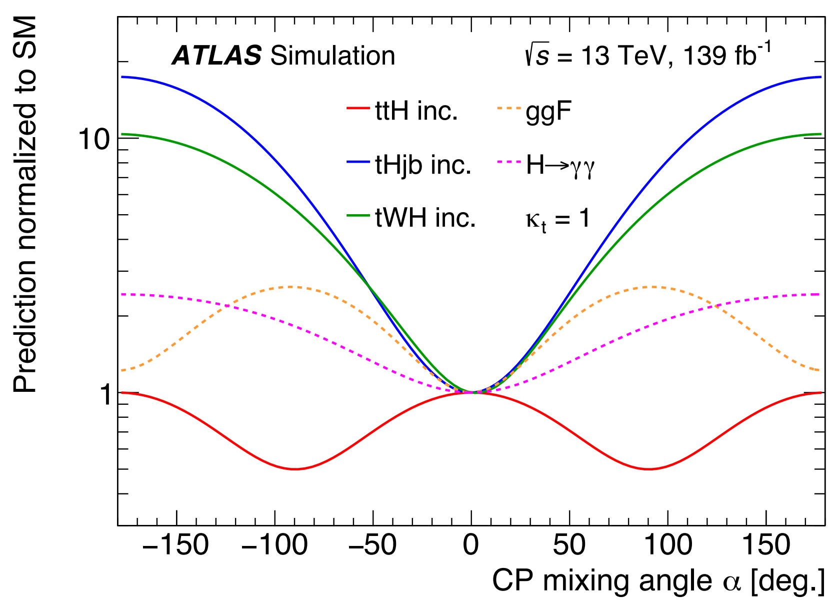
SM corresponds to **$\alpha = 0$, $\kappa_t = 1$**, full CP odd is **$\alpha = 90°$**

- **The H→γγ channel** is ideal for this study due to excellent sensitivity and clean signature

What if there is CP mixing?

- The presence of a CP odd component in t-H coupling alters:
  - **Cross sections as well as kinematics of ttH & tH processes**: can provide direct constraint to top Yukawa coupling (focus of this analysis)
  - H→γγ BR and ggF cross-sections: indirect constraint, can have different interpretation scenarios



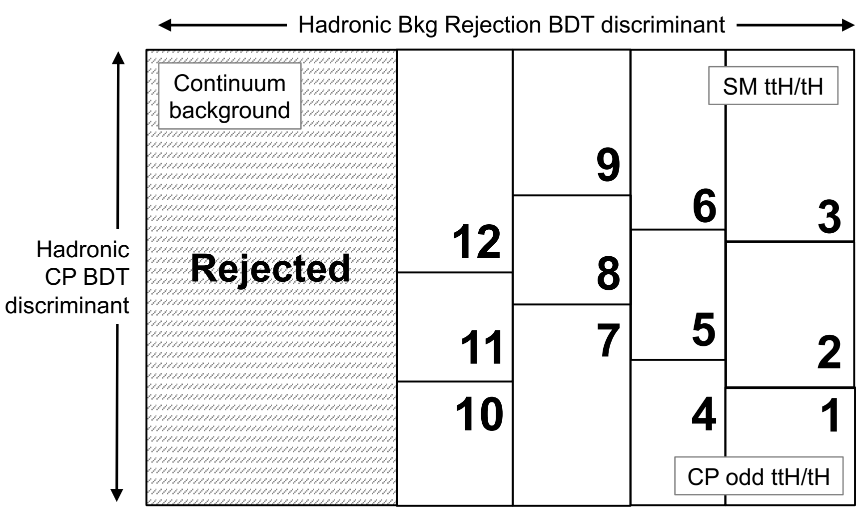


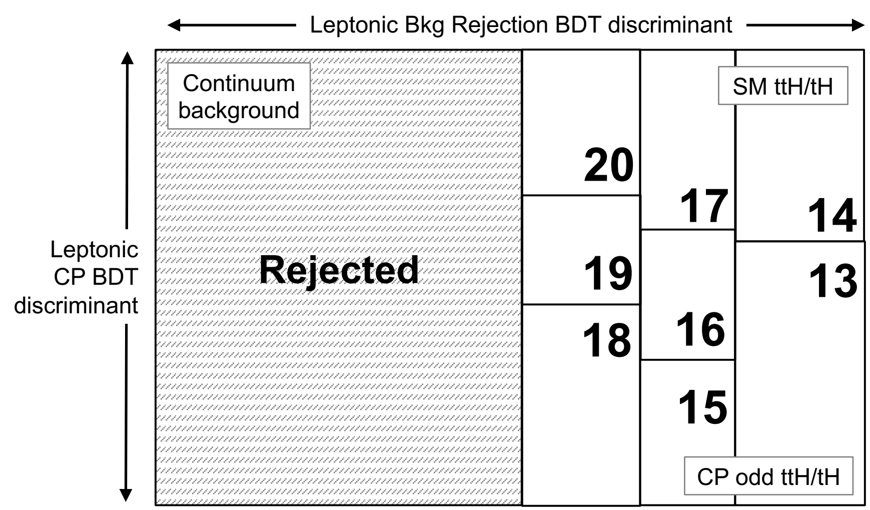
Data & signal MC samples

- **Data**: full Run 2 dataset of 139 fb^{-1}
- **ttH/tH signal**: **NLO MG5_aMC+Pythia8** using **Higgs Characterization (HC) model**
  - ttH: $\boldsymbol{\kappa_t = 1}$, α = 0°, 15°, 30°, …, 90°
  - tHjb/tWH: sample generated with both $\boldsymbol{\kappa_t = 1}$ **and ≠ 1** at different mixing angles. $\kappa_W = 1$
- **ggF signal**: PowHeg NNLOPS
  - Kinematic dependence on CP mixing checked to be well-covered by syst. using **MG_aMC HC model ggF+2j** samples
- **Other Higgs production modes**: same as typical ATLAS Run 2 Higgs analyses

Analysis strategy

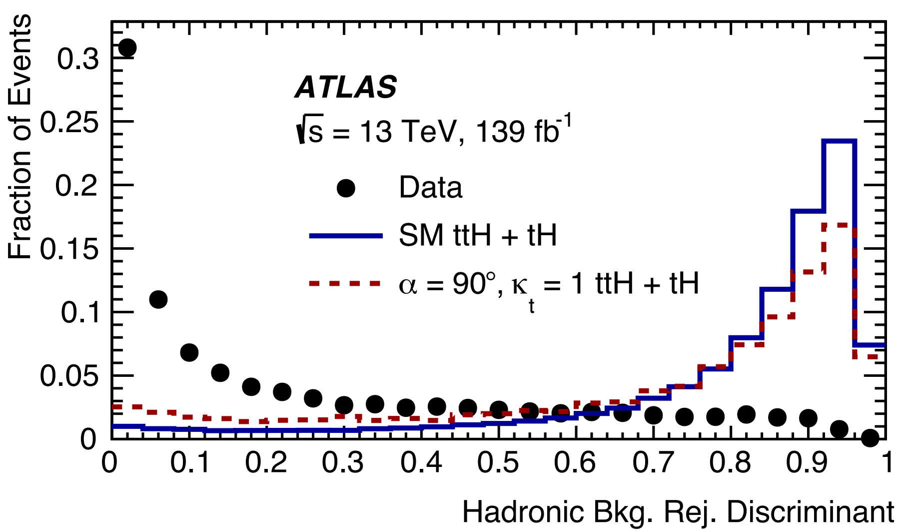
- Divide diphoton event sample into **hadronic (≥3 jets, ≥1 b-jet, 0 lep)** and **leptonic (≥1 b-jet, ≥1 lep)** regions
- In each region, train following two BDTs (using XGBoost)
  - **Bkg. rejection BDT**: separate ttH-like events from continuum background
  - **CP BDT**: separate CP-even-like ttH/tH events from CP-odd-like
- Divide categories on 2D plane of bkg. rejection vs. CP BDTs
- Fit the $m_{\gamma\gamma}$ spectrum in all categories simultaneously to extract signal

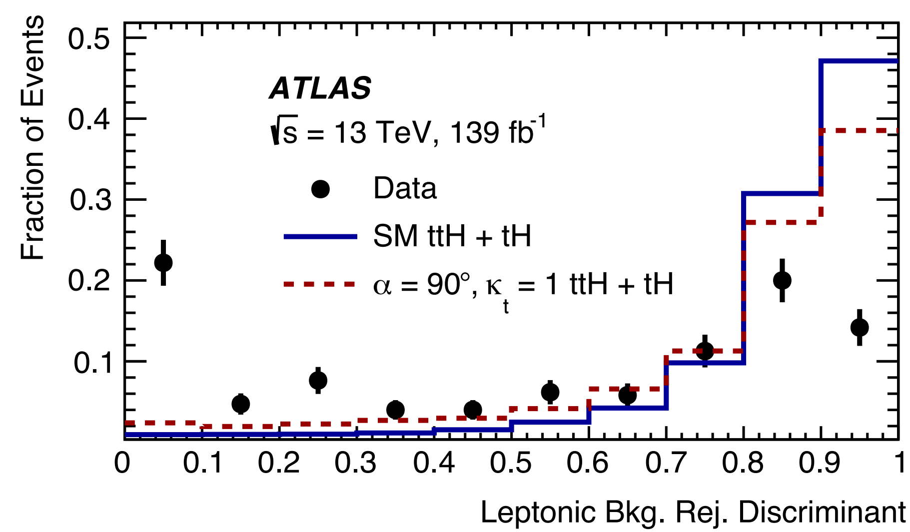




Background rejection BDT

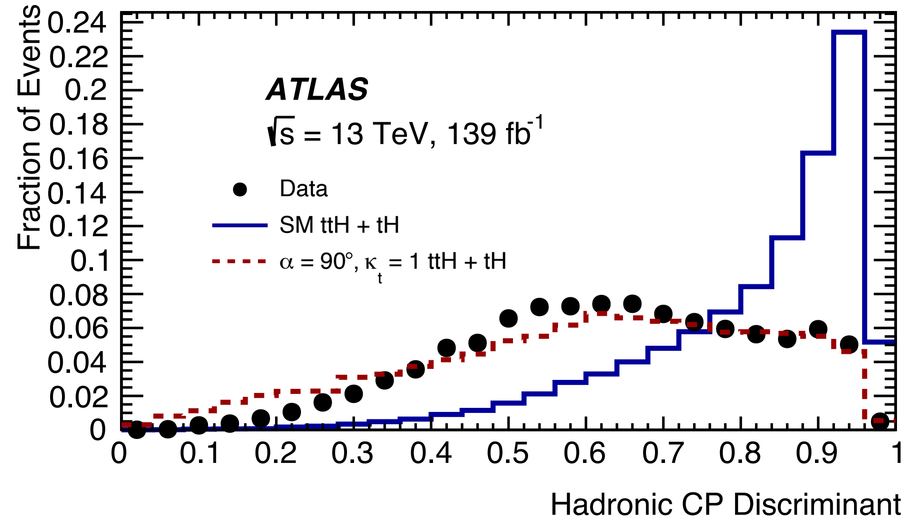
- Use the same BDT discriminant (but not categories!) from Moriond 2019 CONF note
  - Trained on PowHeg ttH sample using 4-vec. of γ, j, l, and MET
- Serves the purpose of CP analysis very well
  - Good rejection of background; good acceptance of ttH/tH signal
  - Weak dependence on CP mixing angle

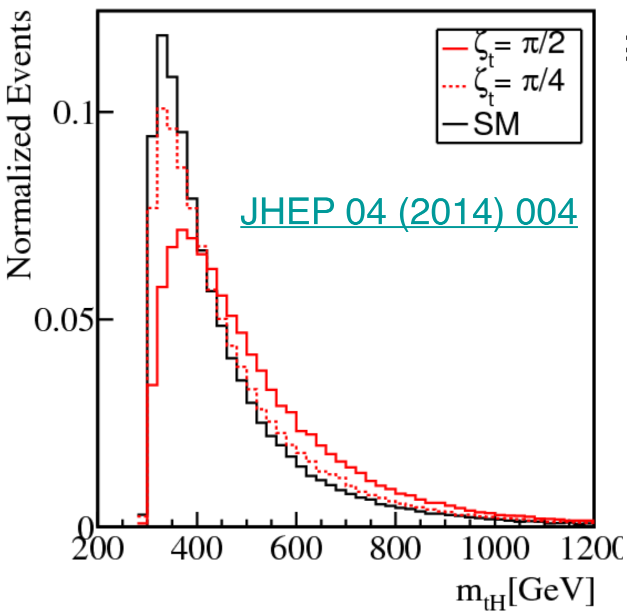


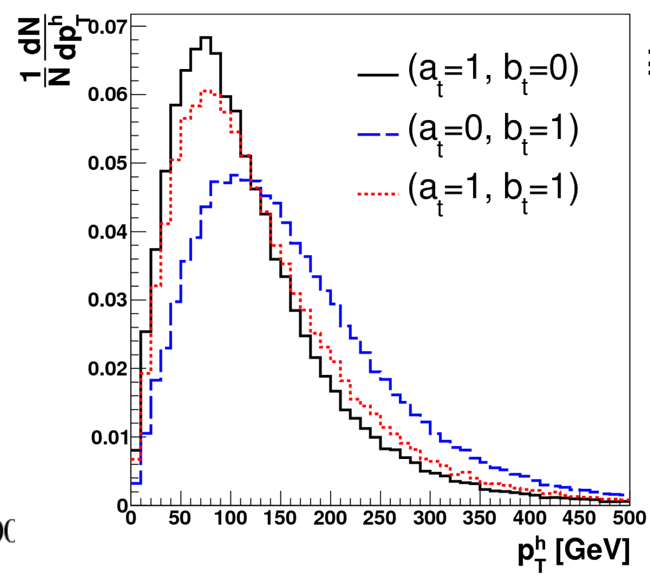


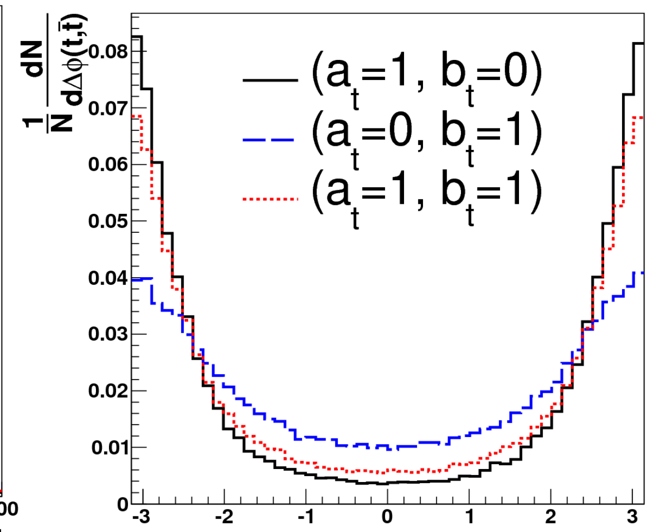
CP BDT

- Train BDT to separate between **CP even** and **CP odd** ttH+tH signal using
  - p_T / η of diphoton system;
  - p_T / η / ϕ / **top reco. BDT** score of 1st and 2nd reco. top, $\Delta\eta(t_1, t_2)$, $\Delta\phi(t_1, t_2)$, m_{tt}, m_{t1H};
  - H_T, n_{jets}, n_{bjets}, 1st and 2d min ΔR(γ, j)





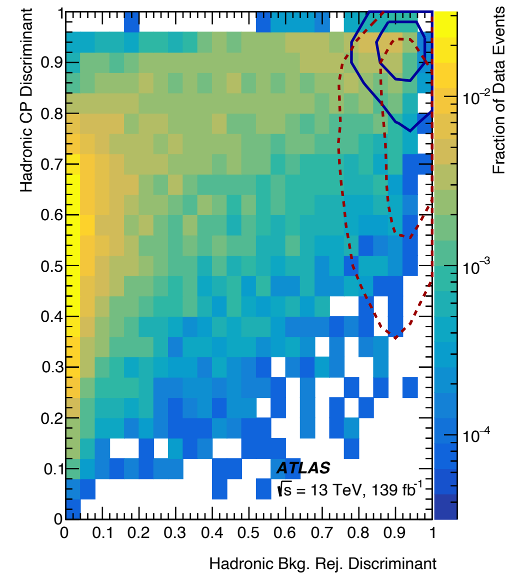


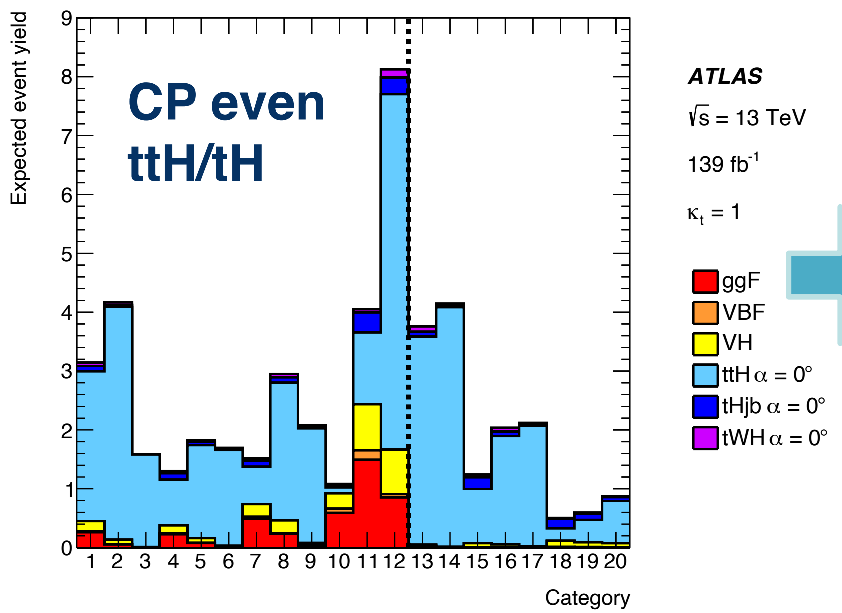


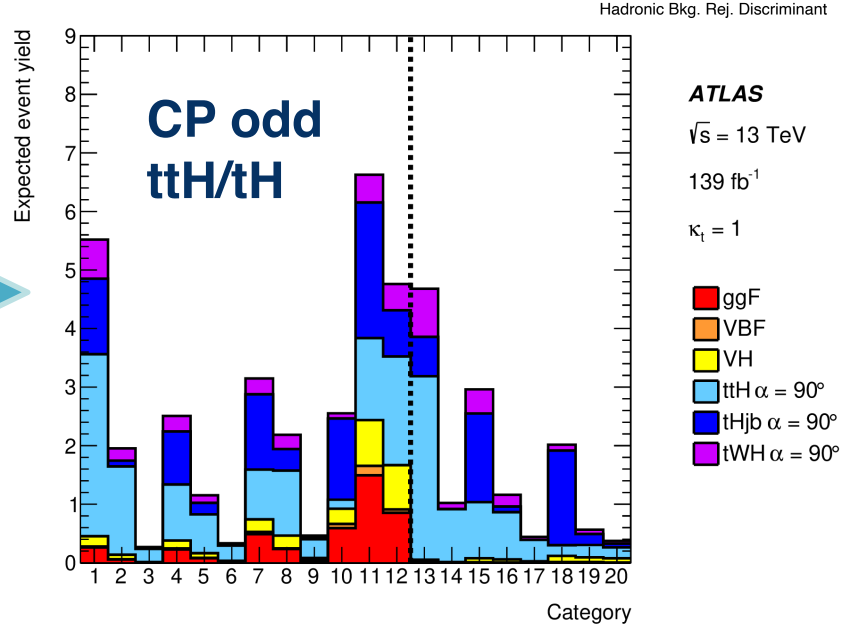
PRD 92, 015019 (2015)

Categorization

- Scan category boundaries on 2D bkg. rejection BDT vs. CP BDT plane to optimize both SM ttH significance and CP separation
- **20 analysis categories** defined in total
  - 12 categories in hadronic region, 8 in leptonic



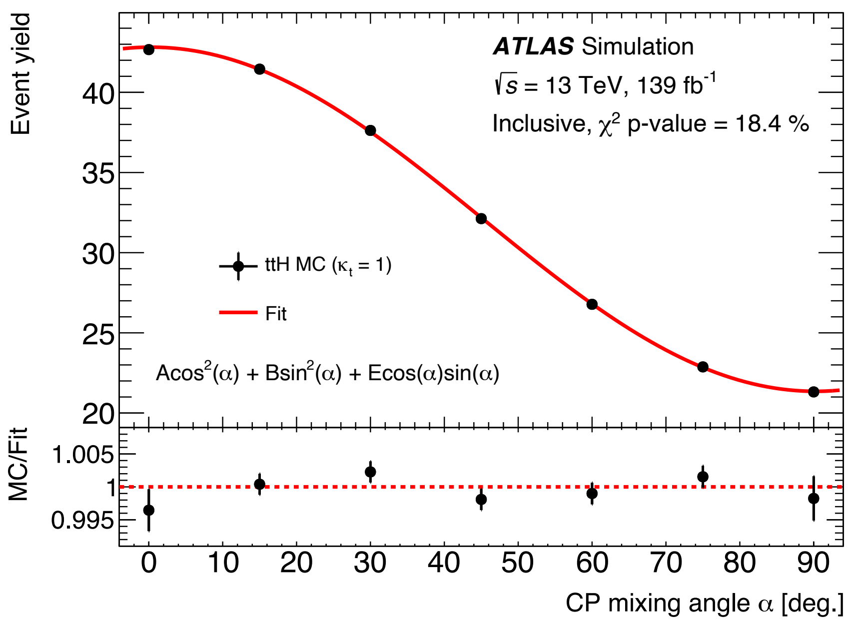




ttH signal yield parameterization

- To fit **mixing angle α** and **top Yukawa coupling strength κ_t** as free parameters, need to parameterize **ttH** and **tH** signal yields in each category as function of these two parameters
- For ttH process, use

$$A\kappa_t^2\cos^2(\alpha) + B\kappa_t^2\sin^2(\alpha) + E\kappa_t^2\sin(\alpha)\cos(\alpha)$$



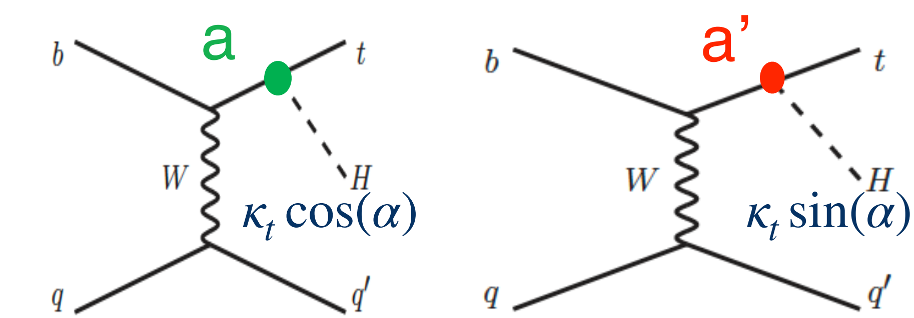
- Parameterization describe MC predictions well in all categories
- Coefficient E for interference term found to be negligible as expected

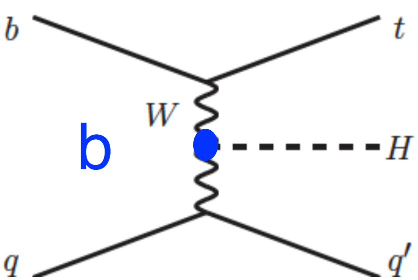
tH signal yield parameterization

- For tHW and tHjb processes, need to use more complicated parameterizations considering interference between t-H and W-H

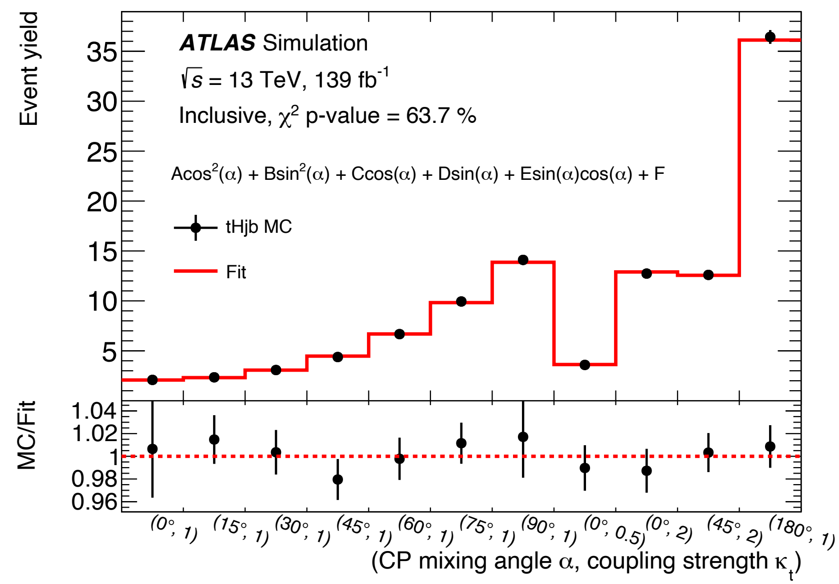
$$A\kappa_t^2\cos^2(\alpha) + B\kappa_t^2\sin^2(\alpha) + C\kappa_t\cos(\alpha) + D\kappa_t\sin(\alpha) + E\kappa_t^2\sin(\alpha)\cos(\alpha) + F$$

a² | **a'²** | **2 Re(a b)** | **2 Re(a' b)** | **2Re(a a')** | **b²**



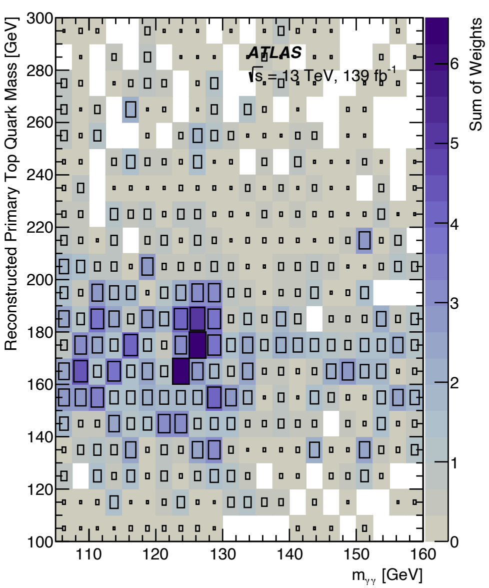


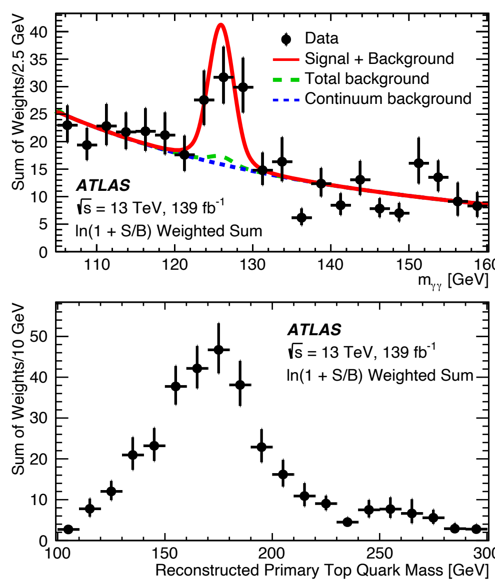
Interference terms between CP even and odd found negligible

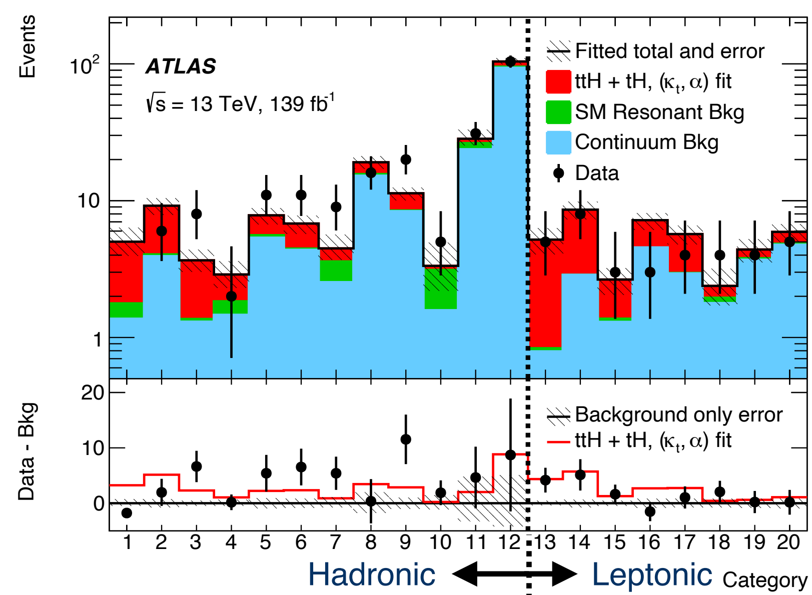


ttH and tH cross-section measurements

- Single-channel ttH observation at **5.2σ**, assuming SM for other prod. modes
- $\sigma(ttH, H\rightarrow\gamma\gamma) = 1.64^{+0.38}_{-0.36}(\text{stat.})^{+0.17}_{-0.16}(\text{syst.})$ fb
- tH cross-section < 12×SM @95% CL
- **Statistical uncertainty dominates**

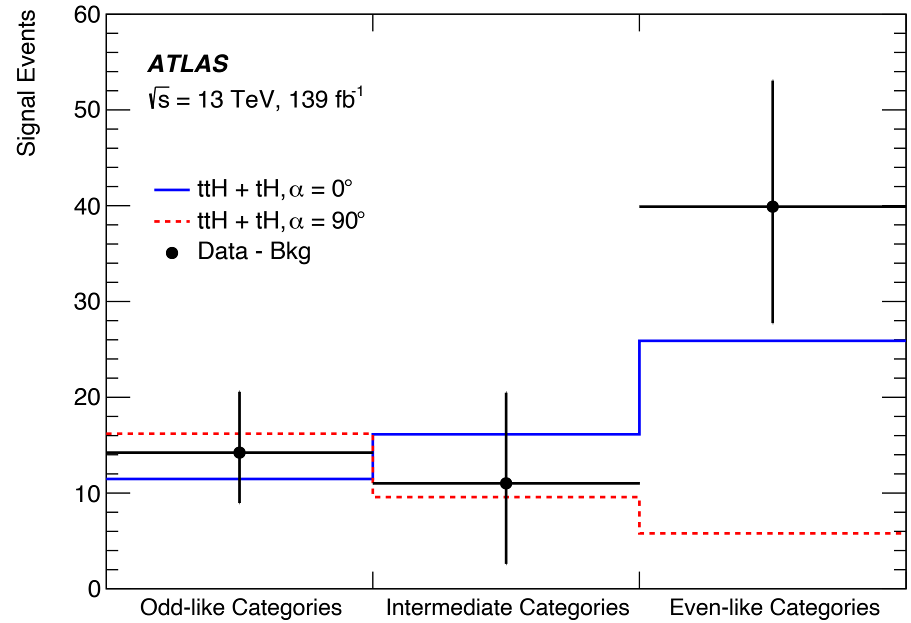


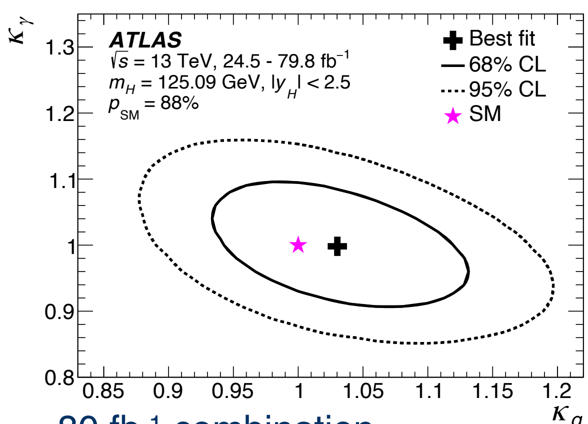




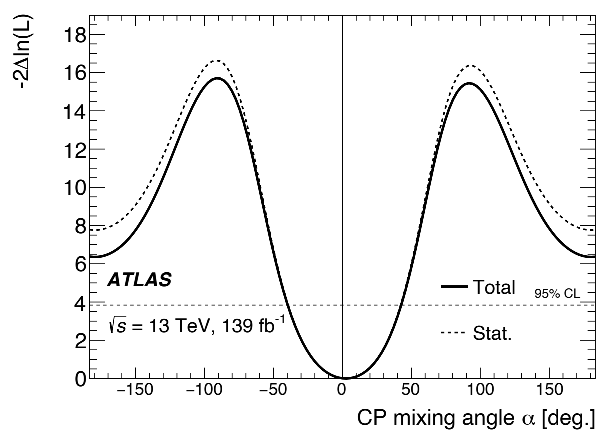
CP constraint: not resolve H→γγ/ggF loops

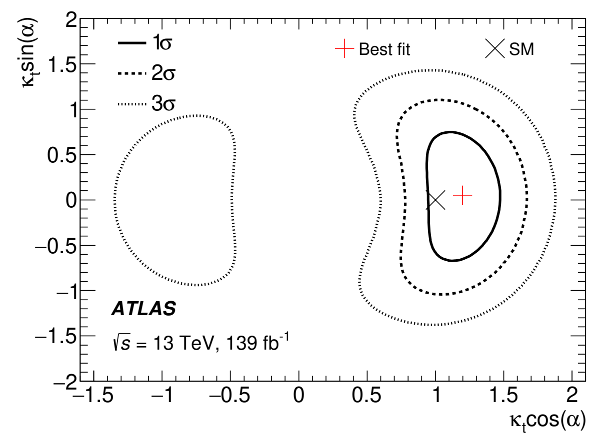
- Constrain mixing angle α **using only info from ttH and tH**
  - Use κ_γ vs κ_g results from 80 fb^{-1} Higgs coupling combination ⊖ ttH(γγ) to constrain H→γγ and ggF rates
- **|α| > 43° excluded @95% CL** with no prior constraint on κ_t. Pure CP odd excluded at 3.9σ





80 fb^{-1} combination





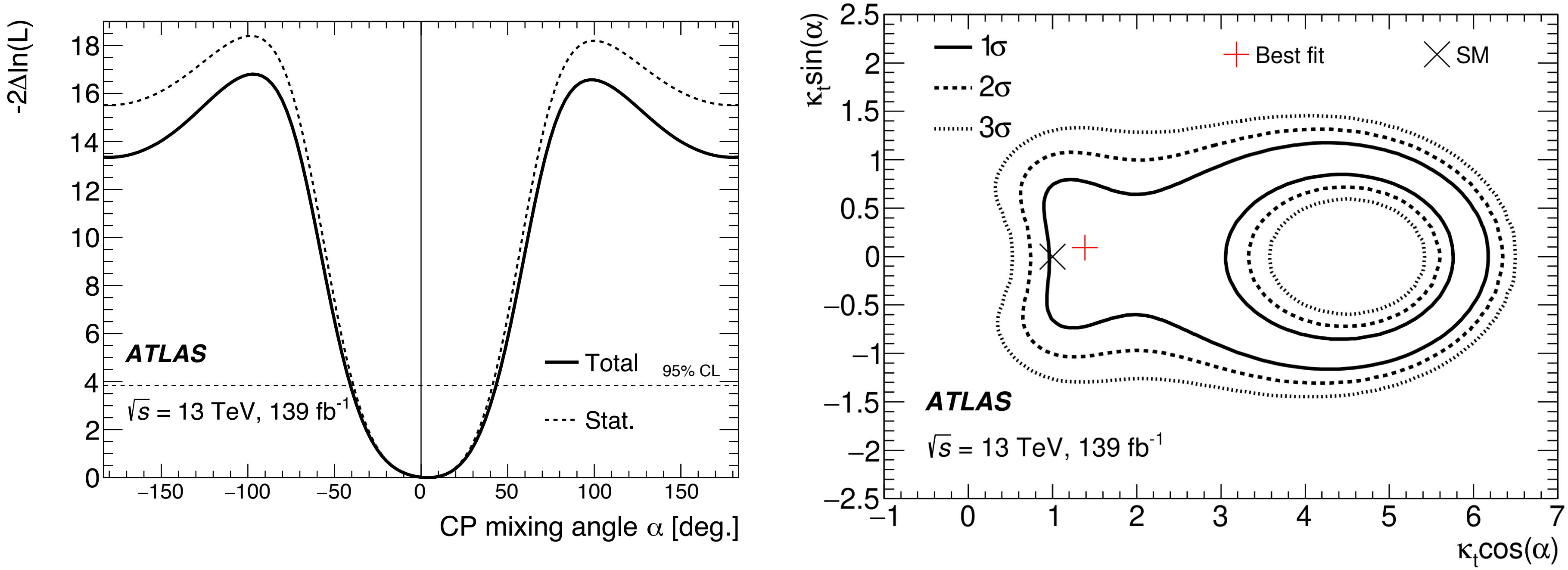
CP constraint: resolve H→γγ/ggF loops

- Assume potential new physics in H→γγ/ggF is only in t-H coupling, and can be parameterized as function of **α** and **κ_t** (Ellis et. al. JHEP 04 (2014) 004)

$$\kappa_g^2 = \kappa_t^2 \cos^2(\alpha) + 2.6\kappa_t^2 \sin^2(\alpha) + 0.11\kappa_t \cos(\alpha)(\kappa_t \cos(\alpha) - 1)$$
$$\kappa_\gamma^2 = (1.28 - 0.28\kappa_t \cos(\alpha))^2 + (0.43\kappa_t \sin(\alpha))^2$$

such that H→γγ/ggF rates could be used to constrain α together with ttH and tH

- Exclude **|α| > 43° @95% CL with no prior constraint on κ_t**



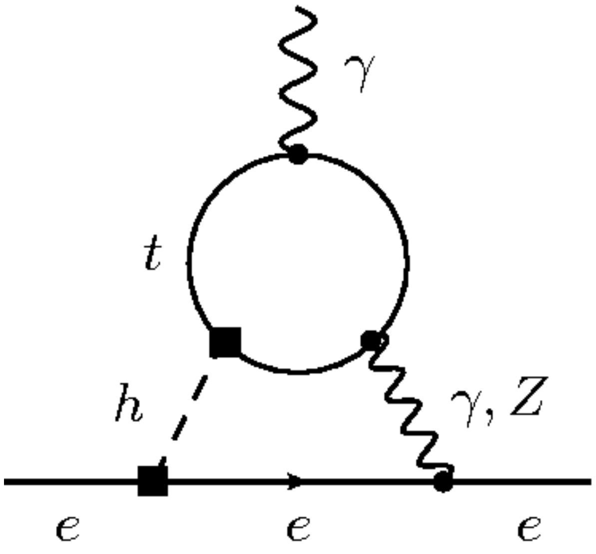
Conclusions

- Probing CP mixing in Higgs interactions remains interesting for Run 3+
  - CP mixing could be small, and thus would require high precision measurements based on large dataset to expose
  - Measurements limited by stat. uncertainty
- CP analyses still largely in exploratory domain so far, with many interesting ideas tested
  - V-H: harmonize analysis strategies to facilitate combination: STXS bin sensitive to CP mixing; optimal observable
  - t-H: explore multiple decay channels of ttH/tH; interpret ggF and $H\to\gamma\gamma$ rates and ggF event topologies
  - Look into $H\to\tau\tau$

Backup

EDM constraint of CP mixing

- From Eq. 2.4 of JHEP 1311, 180 (2013),
  $d_e/e = 9.0 \times 10^{-27}\text{cm}\ \kappa_e \tilde{\kappa}_t$
- From ACME experiment
  $d_e/e = 1.1 \times 10^{-29}\text{cm} \rightarrow$
  $\tilde{\kappa}_t < 10^{-3}$
- Also could to constrain CP odd $\tilde{\kappa}_t$ using neutron and mercury EDMs with no assumption on coupling to 1st generation fermions



JHEP 1311, 180 (2013)