# State-of-the-art of Higgs-CP measurements at the LHC

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*SEMINAR AT LLR (Virtual)*
*7-12/2020*

CMS

CERN

ATLAS EXPERIMENT

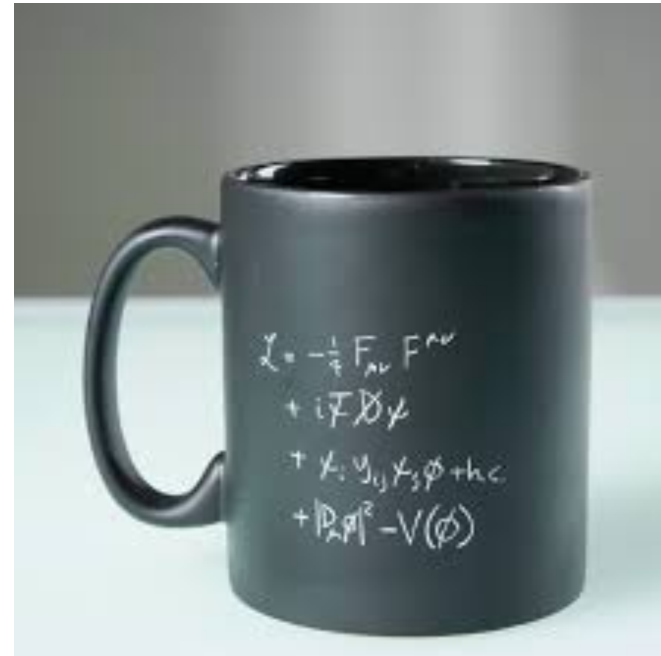
# Content

- **Introduction Higgs physics**
- **In-depth discussion analysis CP structure Higgs-tau Yukawa coupling**
- **Birds eye view state-of-the-art CP structure Higgs gauge boson and Higgs-fermion (Yukawa) couplings**
  - CP structure $t\bar{t}H$ coupling
  - CP structure ggH coupling in H->4$l$ and H->WW$^*$
  - Anomalous couplings in VBF H->$\tau\tau$ events
- **Future and prospects**

Links to refereces in purple throughout

Full Run-2 analyses indicated Run-II

# Higgs boson: the pivotal constituent of the Standard Model of particle physics




- Most Gauge bosons and fermions have a mass
  - Direct mass assignments for gauge bosons and fermions forbidden in SM!
- Higgs field: 4 scalar bosons

⇒ Via electroweak symmetry breaking, obtain gauge-invariant and renormalizable massive bosons and charged fermions!

  - 3 goldstone bosons transferred into massive gauge bsosons
  - Charged fermion masses result of coupling fermions to non-zero vacuum expectation value (vev)
- Remaining Higgs field provides experimental signature

⇒ Pivotal particle, postulated in 1964, that couples to all massive particles!

# Centuries of Higgs hunting

**Tevatron set limits in proton collisions at $\sqrt{s} = 2\ TeV$**

**CERN build underground circular tunnel. 27 km accomodating 2 colliders**

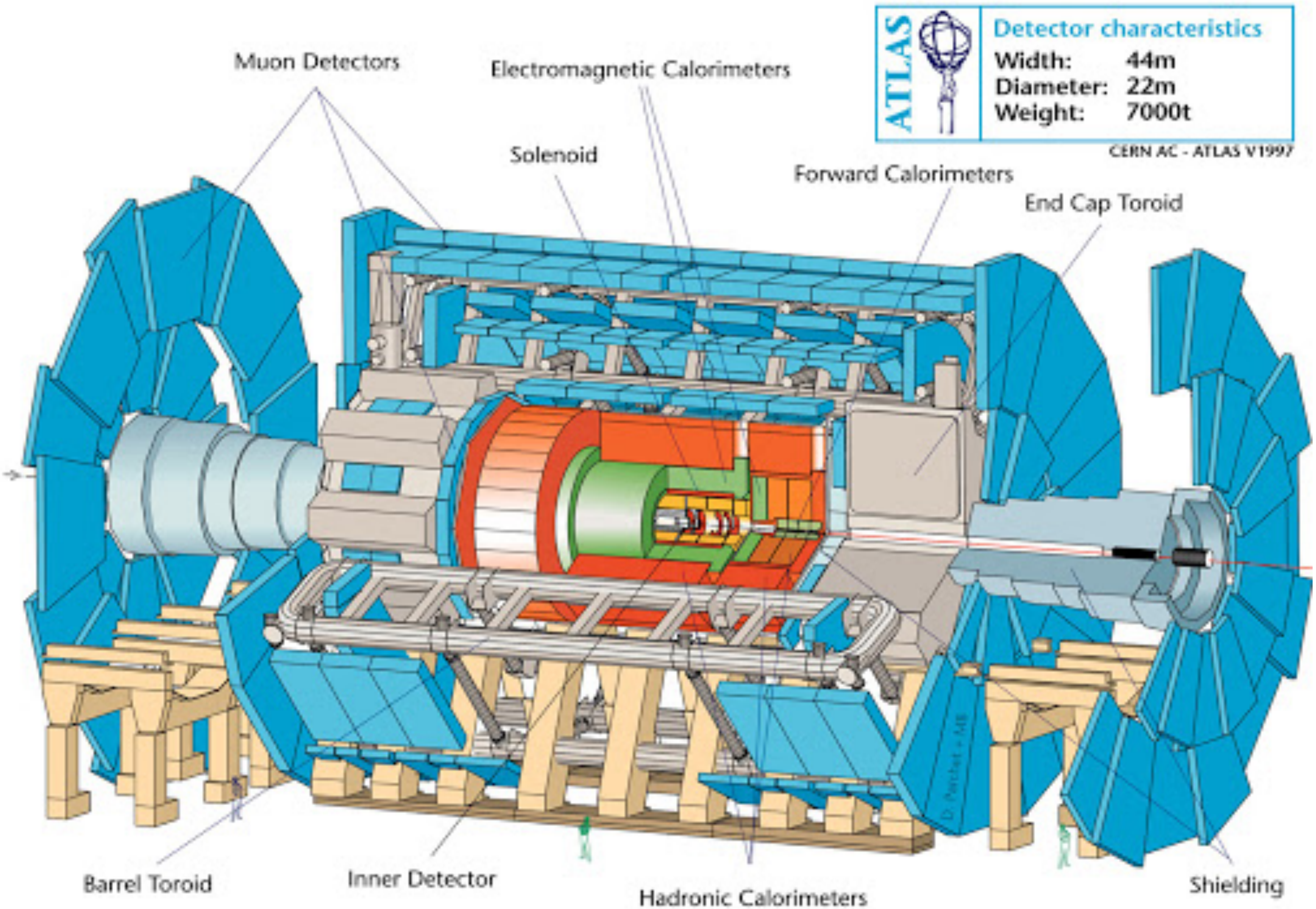
- LEP (Large Electron Positron Collider). **1989-2000.** $\sqrt{s} = 209\ GeV$
  - Main target precision measurement Z-mass
  - Observed hints of Higgs boson decay


- LHC (Large Hadron Collider; recycle tunnel!). **2008~2035.** $\sqrt{s} = 13\ TeV$
  - Dedicated hadron collider targeting Higgs discovery
  - protons and lead ions, and mixture
  - Four experiments:
    - ALICE (heavy ions)
    - LHC-b (b-quark physics)
    - ATLAS and CMS. Multi-purpose detectors for searches Higgs boson and beyond

**Many decades of successful project management at CERN!**

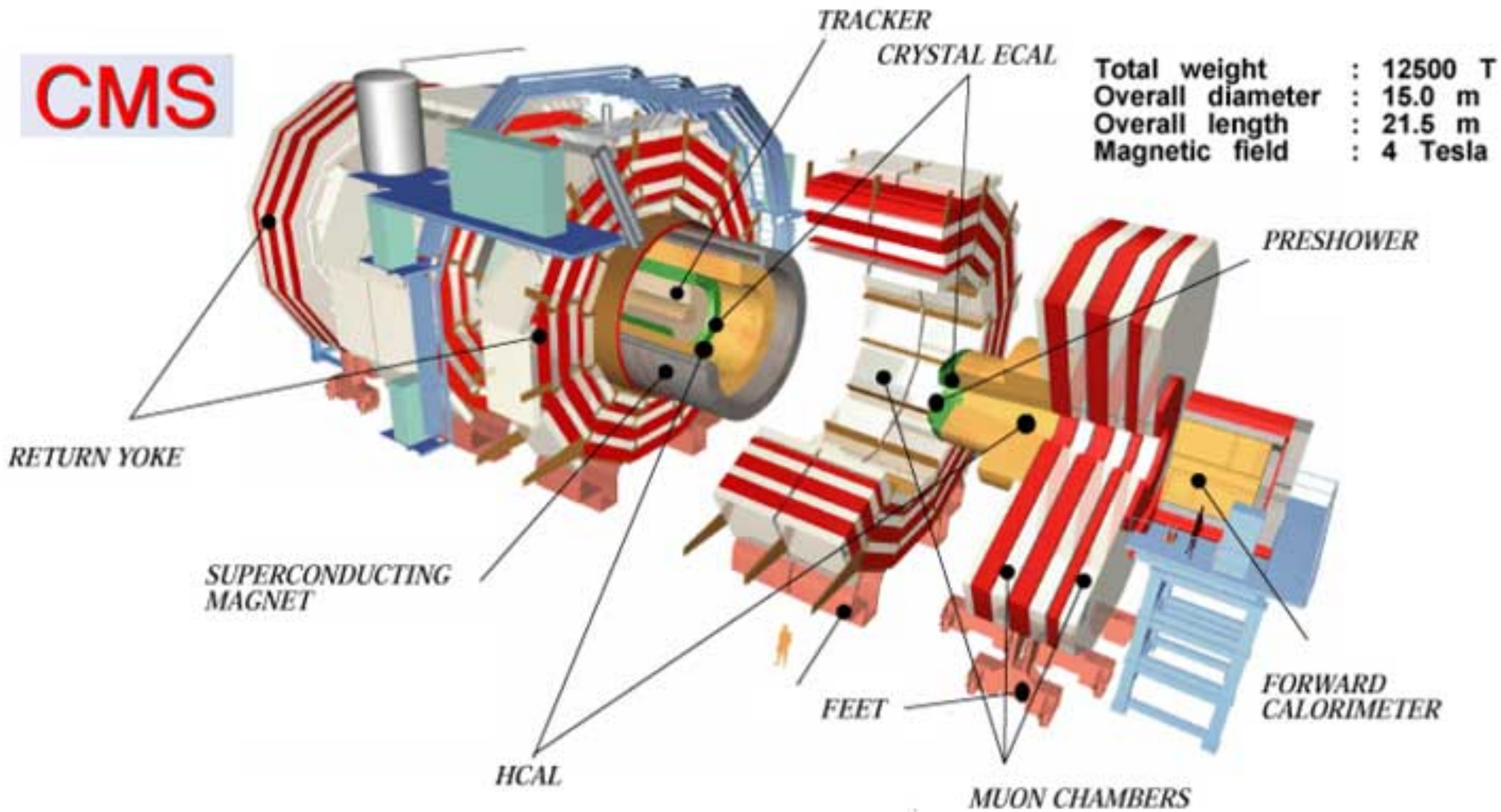
# The ATLAS experiment at LHC

## Collaborations with >3000 authors



# The CMS experiments at LHC

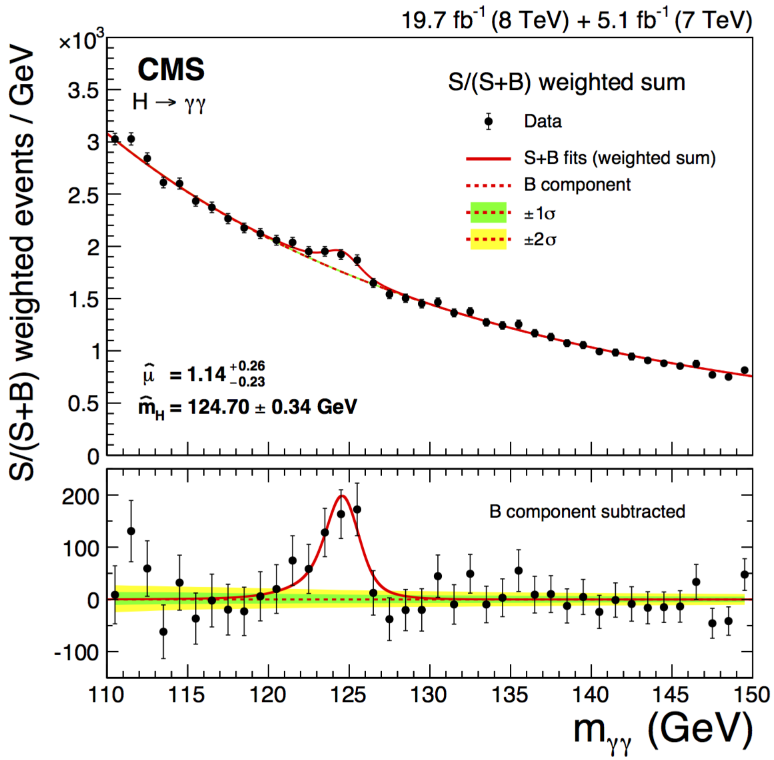
## Collaborations with >4000 members



# 2012: discovery!!

## 46 years after its prediction!

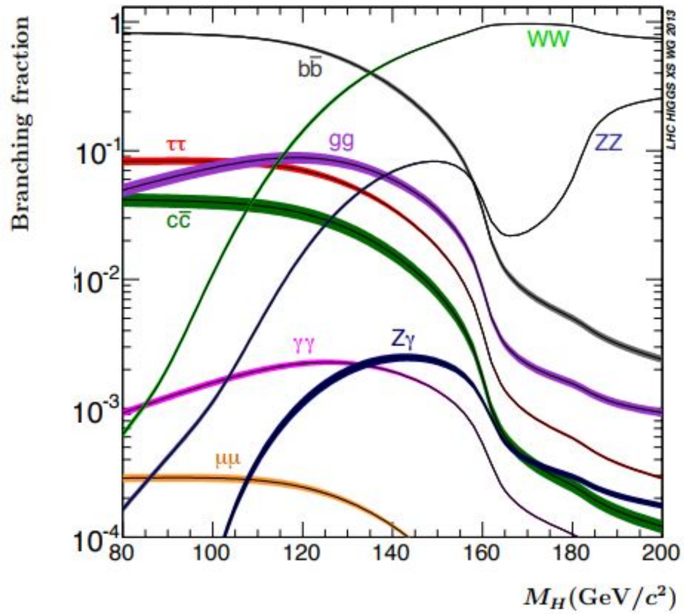
- New boson discovered in 2012 simultaneous by ATLAS and CMS experiment!
  - Using collision data of 7 a 8 TeV proton collisions
  - Using decay to photons and Z bosons
- 4 decades after its prediction, Nobel awarded
- Since then properties analysed by ATLAS and CMS experiment




# Beyond the discovery

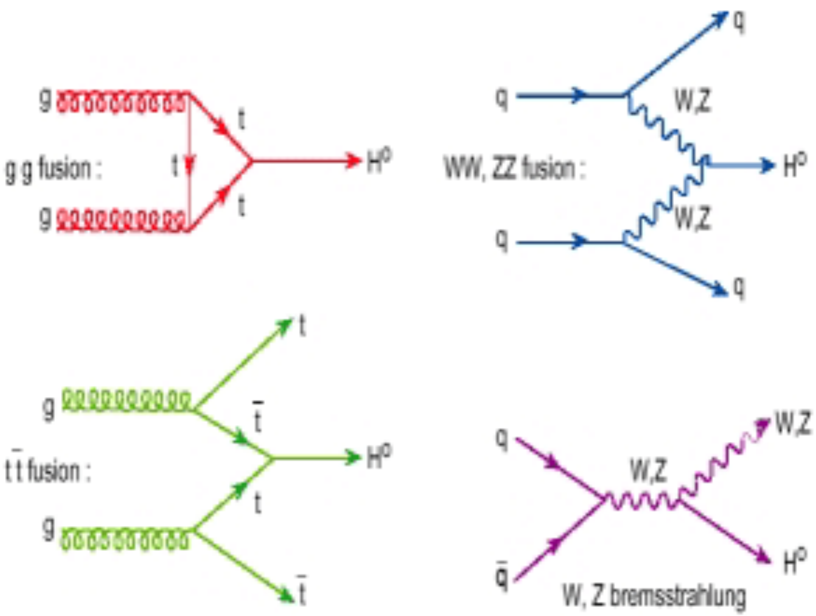
## Production and decay modes

- Higgs decay modes




  - Hadron collider: photon, Z and W boson optimal discovery modes
  - Top quark too heavy (SM Higgs)
  - b-quarks hard (QCD background)
  - Di-leptons: substantial Z-decay background, light mass

- Higgs production modes
  - Gluon fusion (87%)
  - Vector-boson fusion (7%)
    - Two forward jets
  - Associated top-quark production (2%)
    - Decay products top quarks
  - Associated V-boson production (4%)
    - Decay products vector boson

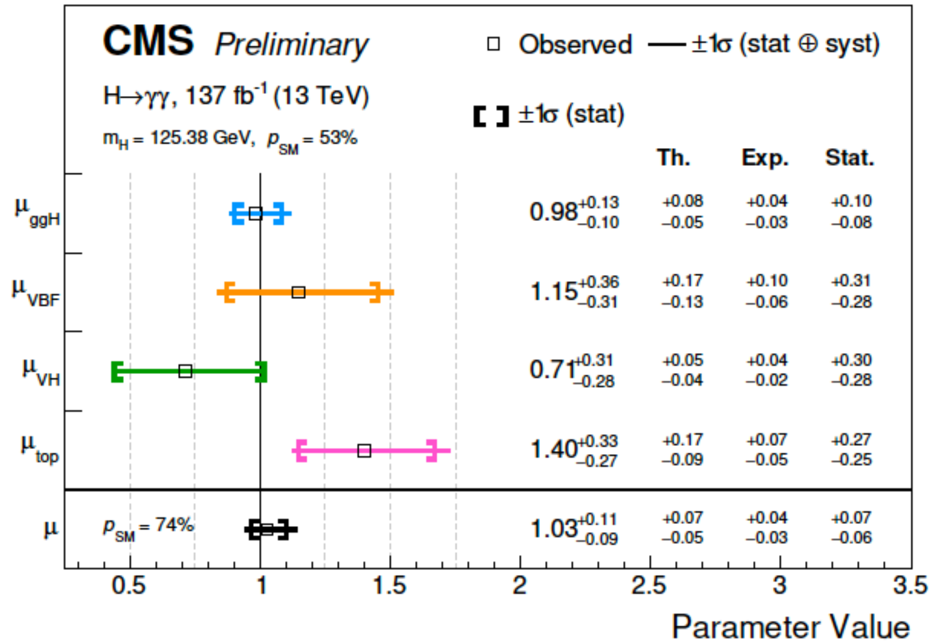


# Beyond the discovery

## Precision era has started

- Higgs boson mass fixes all couplings
- All couplings sensitive to physics beyond Standard Model
  - Total Higgs decay width
  - Higgs couplings
    - W, Z, top, gamma, b-quark, tau established
    - Coupling 2nd generation (hot topic)
    - Once coupling established, refine granularity in dedicated kinematic bins (STXS) or Higgs-pt spectra
- Higgs potential via self-coupling
- **CP-structure couplings**

  ⇒ **Standard model: all couplings are CP-even!**



# CP-structure Higgs-fermion coupling

## Fermionic couplings

- Couplings of (speudo) scalar boson to fermions can be:
  - CP-even (scalar), $J^{CP}=0^{++}$ $\frac{1}{\sqrt{2}}[|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle]$
  - CP-odd (speudoscalar), $J^{CP}=0^{+-}$ $\frac{1}{\sqrt{2}}[|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle]$
  - Mixture of even and odd couplings
- Even and odd coupling at leading order (but different tensor structure):

$$A(\mathrm{Hff}) = -\frac{m_\mathrm{f}}{v}\bar{\psi}_\mathrm{f}\left(\kappa_\mathrm{f} + \mathrm{i}\,\tilde{\kappa}_\mathrm{f}\gamma_5\right)\psi_\mathrm{f}$$

- Define mixing angle in terms of even and odd coupling:

$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}}{\kappa}$$

- LHC: probe CP-structure Higgs-top and Higgs-tau couplings

**First review recent analysis CP-structure Higgs-tau Yukawa coupling CMS!**

# CP-structure Higgs-tau Yukawa coupling (CMS)

HIG-20-006

Run-II

- Parameterise CP even and odd couplings via mixing angle $\phi_{\tau\tau}$:

$$\mathcal{L}_Y = -\frac{m_\tau \mathrm{H}}{\mathrm{v}}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau) \quad \tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau},$$

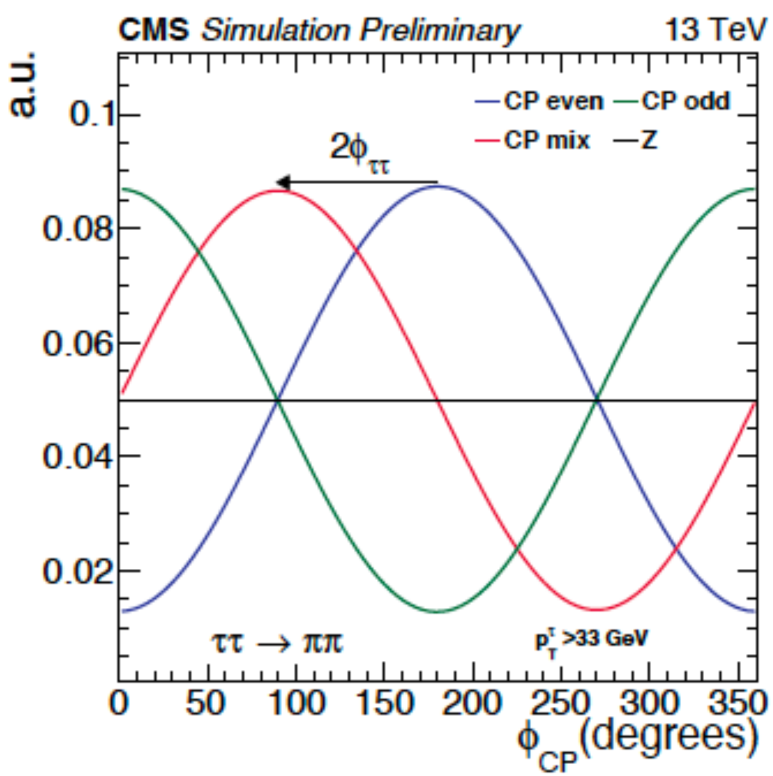
- The CP information is transferred to correlations between transversal components tau spin

$$d\Gamma_{h\to\tau^+\tau^-} \sim 1 - s_z^- s_z^+ + |s_T^-||s_T^+| \cos(\varphi_s - 2\phi_\tau)$$

- This correlation can be probed via the angle $\phi_{cp}$ between the **tau decay planes**

$$d\Gamma_{h\to\tau^+\tau^-} \approx 1 - b(E_+)\,b(E_-)\,\frac{\pi^2}{16}\cos(\varphi^*_{CP} - 2\phi_\tau)$$

- Gen level distribution $\phi_{cp}$ for scalar, pseudoscalar and Z boson
  $\Rightarrow$ $\phi_{cp}$ discriminating variable for this analysis!



# Analysis strategy

## In a nuthsell

- Utilise full Run 2 data set (137 $fb^{-1}$)
- For PAS HIG-20-006 analyse most important decay modes (~50%)
  - Muon plus hadronic
  - Fully hadronic

| Mode | $\mu^{\pm}$ | $\pi^{\pm}$ | $\rho^{\pm} \to \pi^{\pm}\pi^{0}$ | $a_1^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ | $a_1^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}$ |
|---|---|---|---|---|---|
| $\mathcal{B}(\%)$ | 17.4 | 11.5 | 25.9 | 9.5 | 9.8 |
| Symbol | $\mu$ | $\pi$ | $\rho$ | $a_1^{1pr}$ | $a_1^{3pr}$ |

- Extract ~90% of background events in data-driven manner
- Categorise events in one signal and 2 background categories using Multivariate Discriminants (MVA)
- Extract mixing angle $\phi_{\tau\tau}$ via combined template fit to signal and background distributions
- **First** review parts analysis not specific to CP-analysis
  => Analysis indebted to work STXS analysis **HIG-19-010** (full Run 2) and **HIG-18-032** (‘16/’17 with embedding and Machine learning techniques)
- **Next** focus on dedicated methods developed to optimise CP signal strength

# Modelling background processes

## 90% of backgrounds obtained in data-driven way

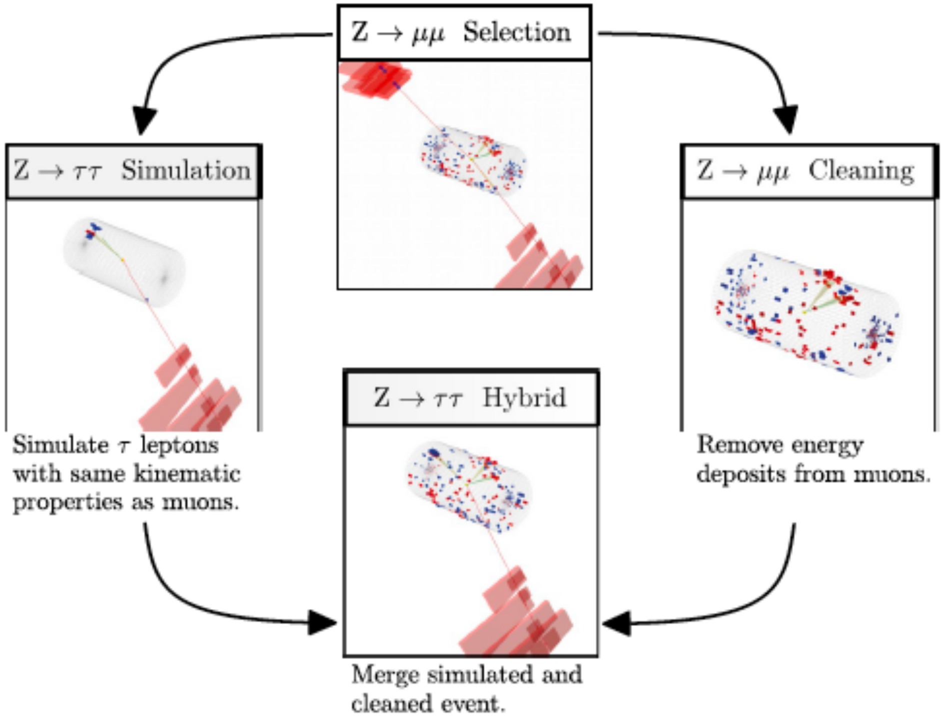
- Background processes:
    - Drell-Yan (leading semileptonic BG), QCD (leading hadronic BG), W+jets, ttbar, single top, diboson
- May also categorise backgrounds instead in genuine tau, jet-fakes, lepton-fakes, and prompt leptons
    - Backgrounds with 2 genuine taus obtained from tau embedding technique
    - Bg with QCD jet faking hadronic tau via fake-factor method
    - Remaining backgrounds via simulation

$\Rightarrow$ Overall, 90% of backgrounds obtained in data-driven manner!

# Modelling background processes

## Tau embedding, Link

- Tau embedding relies on principle **lepton universality EWK processes**
- Exploit principle to model **genuine di-tau background:**
  - Select di-muon events in real data
  - Remove hits associated to muons
  - Simulate decaying Z-boson to **di-tau** with **identical kinematics as di-muon pair** (pt, invariant mass, eta-phi). **In empty detector**
  - Add the hits of tau decay products to the data event
- Obtain rate genuine tau background events, with fully data-driven rates and underlying event!



# Modelling background processes

## Fake factor method, link

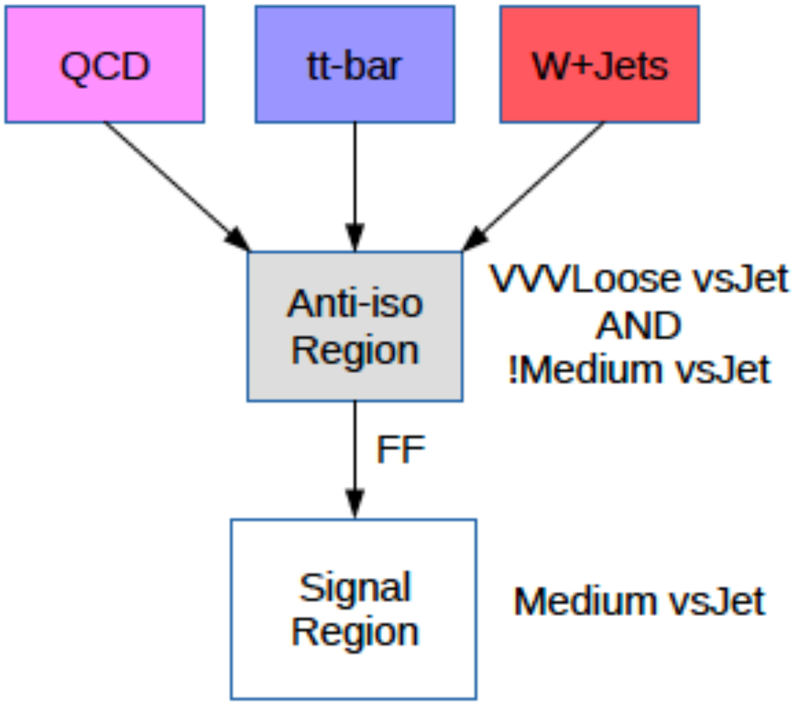
- Fake factor: data-driven approach to obtain contribution in signal region of **quark or gluon jet faking a tau lepton**

  - Define jet-enriched determination region, orthogonal to signal region
  - Determine rate of jets faking a hadronic tau lepton using tight and loose tau isolation criteria

  ⇒ Apply the fake factors to loose tau candidates in application region to obtain jet-fake rate!

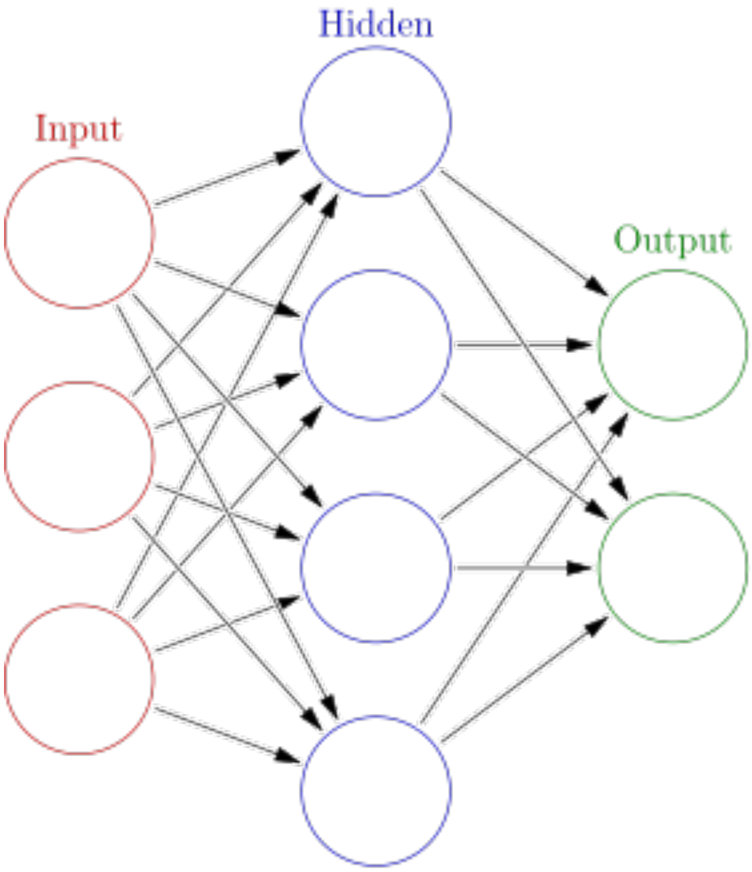
  - Hadronic channel: QCD background only. Semileptonic: weighted average for QCD, ttbar and W+jets

- Obtain rate of jet faking tau, with fully data-driven underlying event



# Using multivariate techniques for signal-background separation

- Multivariate discriminant MVA to discriminate signal from background events
- Defines probability for event to be background or signal
- Key advantage: includes correlations between input observables
    - pt Higgs boson (boost)
    - Presence VBF jets and kinematics
    - Mass estimate di-tau pair




- Virtually all modern Higgs analyses use MVA techniques (direct or indirect)

# Event categorisation Higgs-tau analysis

## Separating signal from background events

- Mu+tau channel: use neural net
- Hadronic channel: use Boosted Decision tree
- Input variables as in PAS-18-032
- Categorise events in 3 mutually exclusive cats:
  - Signal (ggH, VBF, VH)
  - Genuine tau pair
  - Jet fake (inc. prompt leptons and leptons faking hadronic tau)

| Observable | $\tau_\mu\tau_h$ | $\tau_h\tau_h$ |
|---|---|---|
| $p_T$ of leading $\tau_h$ or $\tau_\mu$ | ✓ | ✓ |
| $p_T$ of (trailing) $\tau_h$ for $\tau_\mu\tau_h$ ($\tau_h\tau_h$) channel | ✓ | × |
| $p_T$ of visible di-$\tau$ | ✓ | ✓ |
| $p_T$ of di-$\tau_h$ + $p_T^{miss}$ | × | ✓ |
| $p_T$ of $\mu + \tau_h + p_T^{miss}$ | ✓ | × |
| Visible di-$\tau$ mass | ✓ | ✓ |
| $\tau_\mu\tau_h$ or $\tau_h\tau_h$ mass (using SVFIT) | ✓ | ✓ |
| Leading jet $p_T$ | ✓ | ✓ |
| Trailing jet $p_T$ | ✓ | × |
| Jet multiplicity | ✓ | ✓ |
| Dijet invariant mass | ✓ | ✓ |
| Dijet $p_T$ | ✓ | × |
| Dijet $\lvert\Delta\eta\rvert$ | ✓ | × |
| $p_T^{miss}$ | ✓ | ✓ |

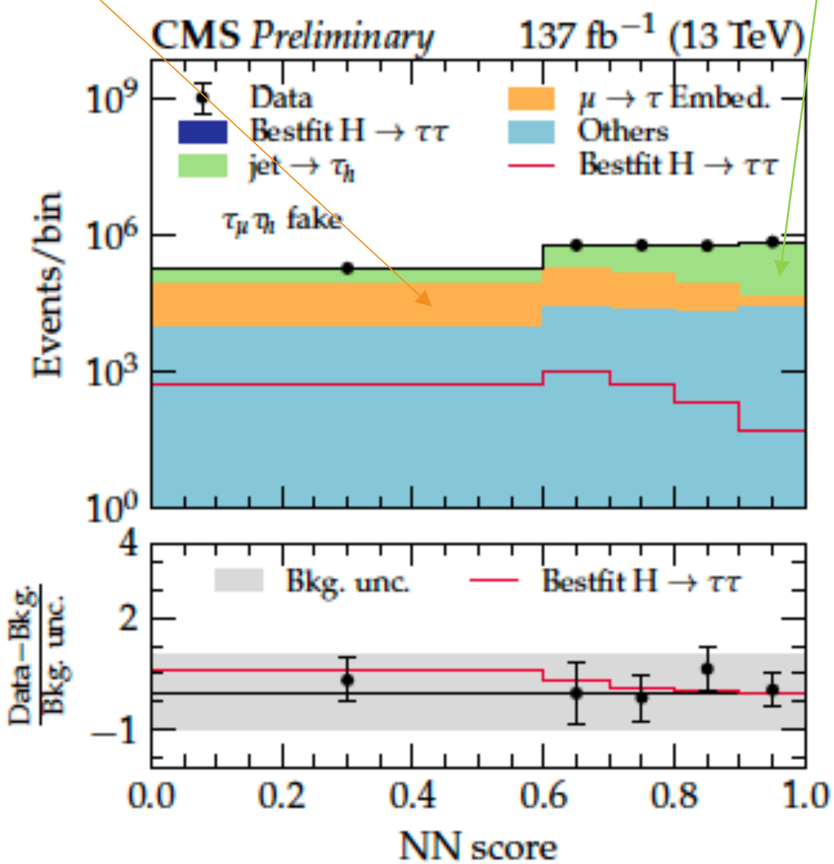
# MVA scores in background categories

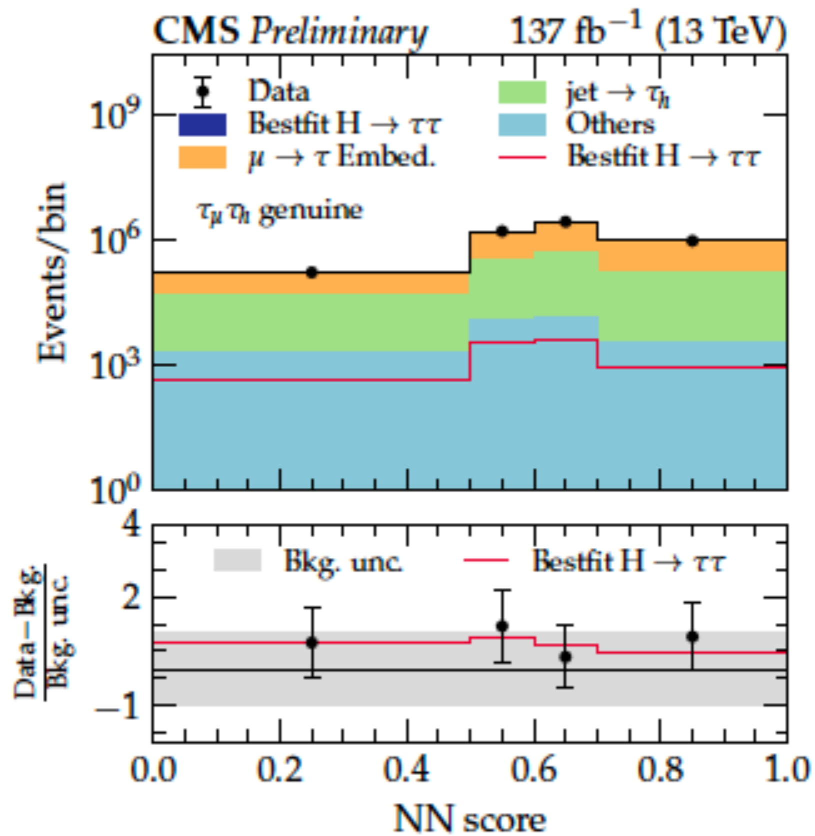
## Left: jet fake category

## Right: genuine tau category

Genuine taus

Jet fakes

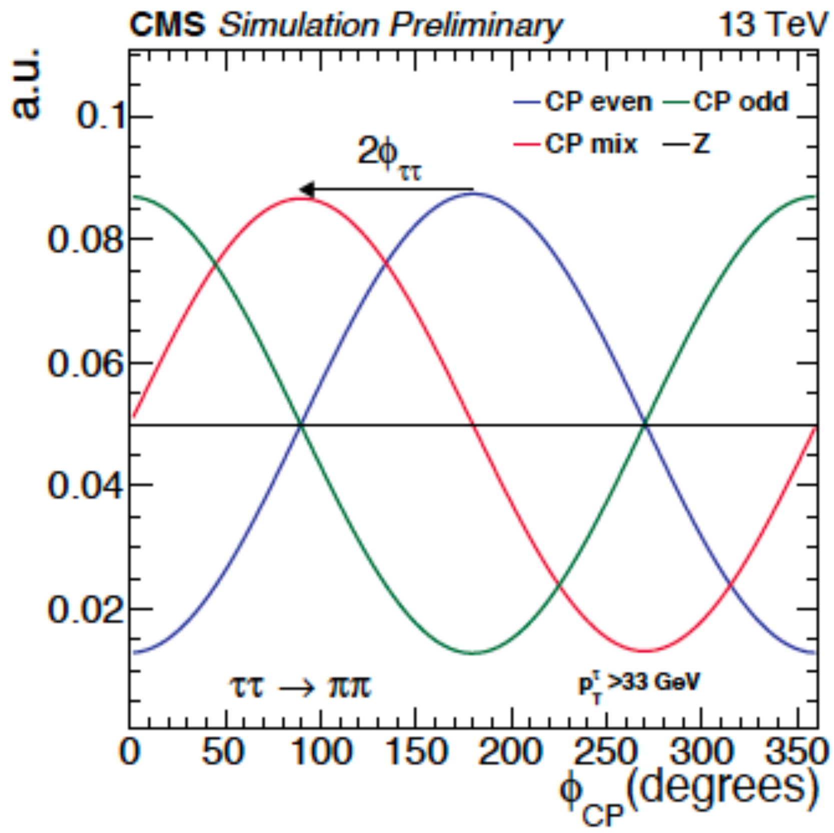


# Extracting and optimising sensitivity

⇒ Next: review how **experimentally** assess $\phi_{CP}$

⇒ Methods dedicatedly developped for analysis to **optimise analysis sensitivity**



# Experimentally extracting $\phi_{\tau\tau}$

## Extracting tau decay planes

| Mode | $\mu^{\pm}$ | $\pi^{\pm}$ | $\rho^{\pm} \to \pi^{\pm}\pi^{0}$ | $a_1^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}$ | $a_1^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}$ |
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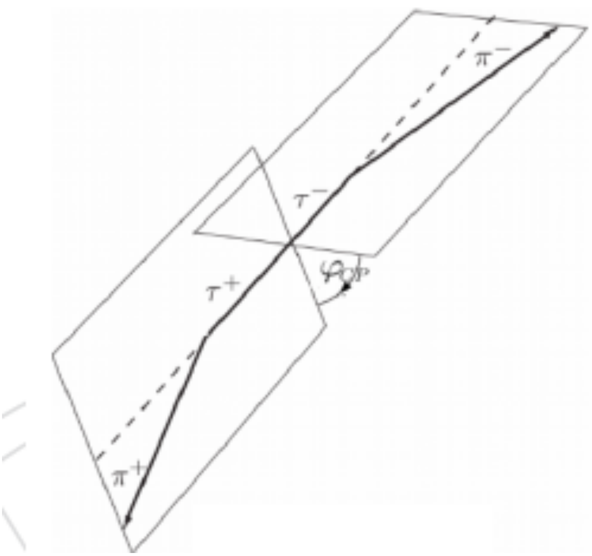
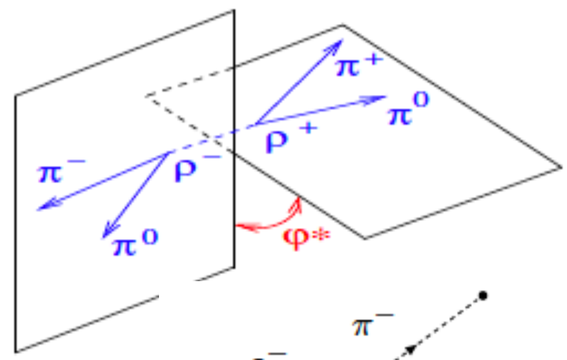
| $\mathcal{B}(\%)$ | 17.4 | 11.5 | 25.9 | 9.5 | 9.8 |
| Symbol | $\mu$ | $\pi$ | $\rho$ | $a_1^{1pr}$ | $a_1^{3pr}$ |

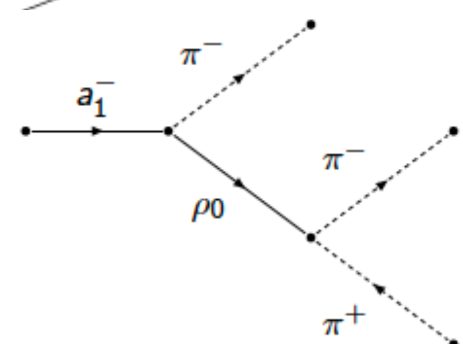
- Decay to muon or single charged pion
  - Use Impact parameter method




- IP method: arXiv:1108.0670

- Decay to rho, $a_1^{1p}$, $a_1^{3p}$
  - Use neutral pion method



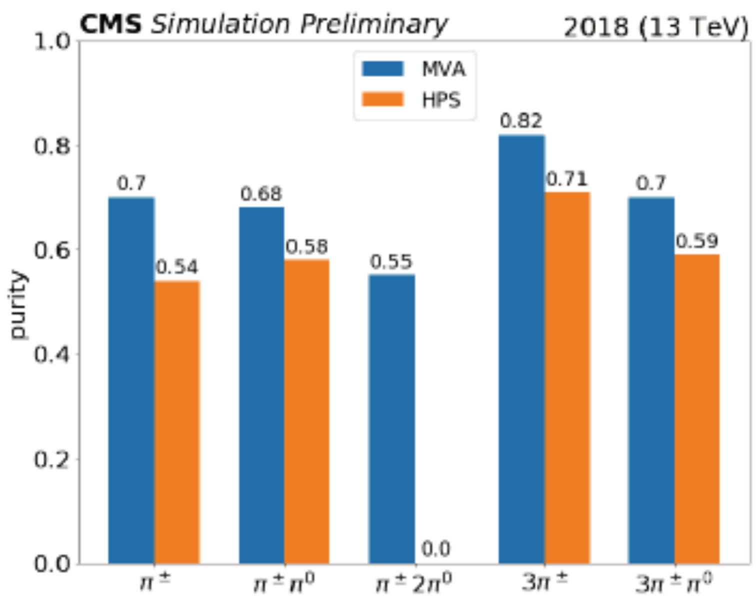



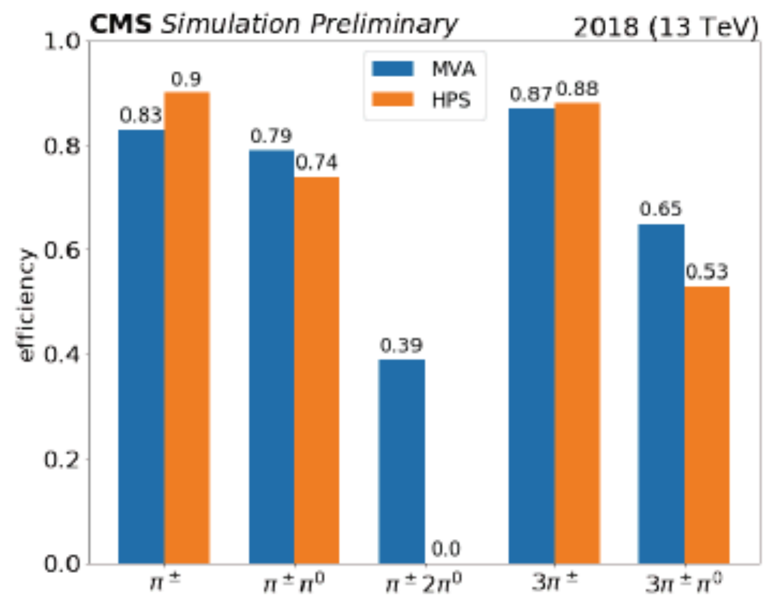

- DP Method: arXiv:0307.331

# Optimisation analysis sensitivity

## Focus on additional corrections applied to optimise signal strength

- Decay mode identification important, migrations will lead to incorrect $\phi_{cp}$ estimates
- Per default, decay mode given by HPS (hadron-plus-strip) algorithm
- Dedicated MVA developpd for enhanced decay mode distinction (on top of deeptau discriminant, CMS-DP-2019-033)
  - Inputs: kinematics tau decay products and HPS decay mode
- Improves signal sensitivity by O(15%)



# Improvements related to IP method

## Improvements in Primary Vertex (PV) estimates

- Two improvements in determination PV location:
  - Remove tracks associated to tau decay products. If boosted Higgs, non-zero impact parameters may pull PV
  - Add beam spot information in fit of PV
- Resolution in transversal plane increases by factor 3 to 4 (!)

| Production mode | Vertex type | $\sigma_x^{PV}$ | $\sigma_y^{PV}$ | $\sigma_z^{PV}$ |
|---|---|---|---|---|
| $H \to \tau_\mu \tau_h$ | Nominal | 17 | 17 | 26 |
| | Refitted Beamspot-Corrected | 5 | 5 | 29 |
| $Z \to \tau_\mu \tau_h$ | Nominal | 20 | 20 | 30 |
| | Refitted Beamspot-Corrected | 5 | 5 | 34 |

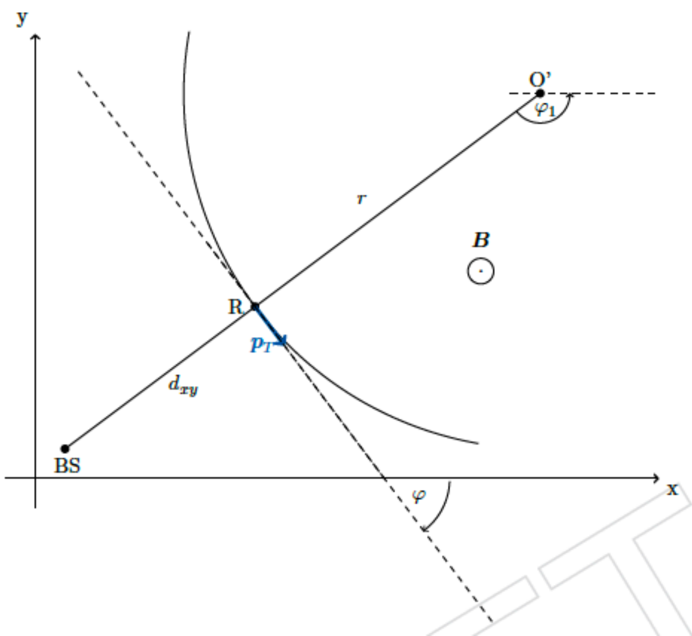
# Helical extrapolation

## 3-d vs 2-d extrapolation tracks

- Per default, track extrapolation to find PCA (point closest approach) performed in trasnversal plane
- Using helical, 3-dimensional approach has 2 profound advantages:
  - IP estimate better for tracks with high eta values
  - Can propagate uncertainties in track and PV in consistent manner

  ⇒ Define an impact-parameters significance as |IP|/sigma(IP)

  ⇒ throughout analysis require |IP|/sigma IP> 1.5
- Combined, lead to improvement sensitivity O(15%)

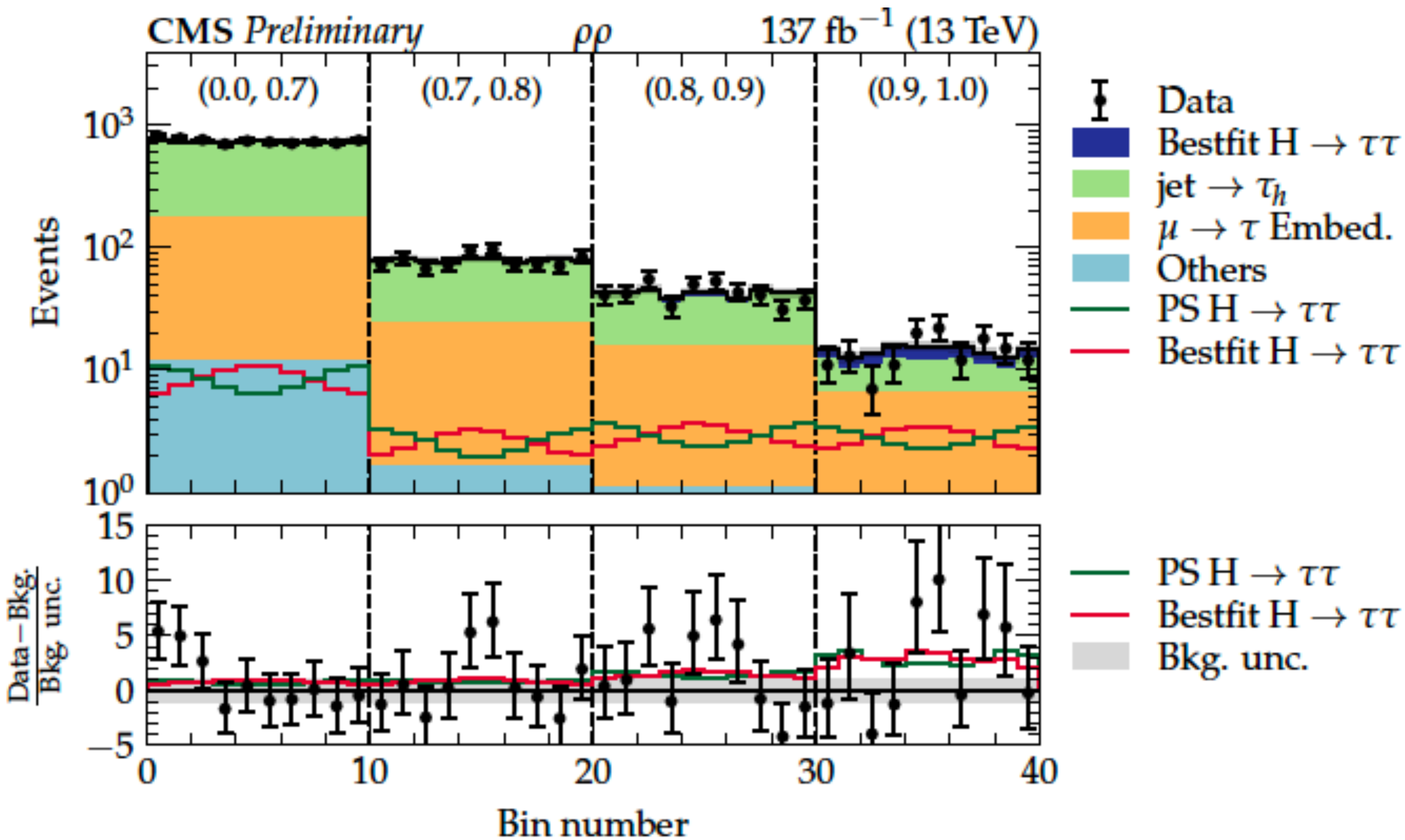



More details in PAS

# Unrolled phi-CP distributions

## rho+rho channel. Resolution ~ 1.1 sigma

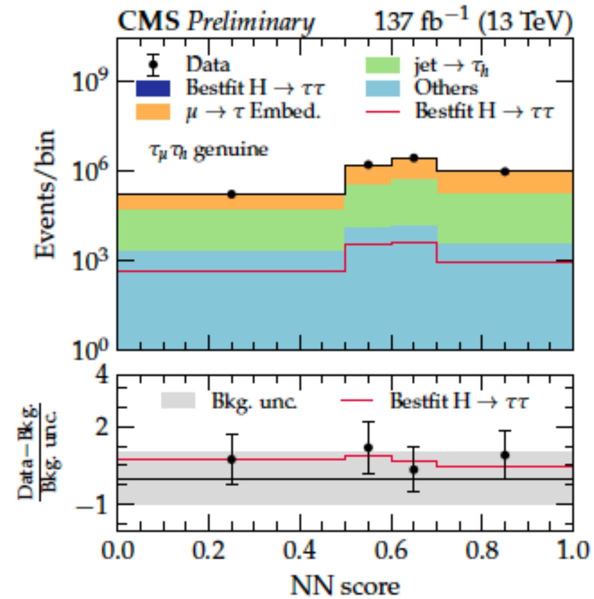
- Observe s/b improvement owing to BDT
- Observe resolution to distinguish CP-even and odd

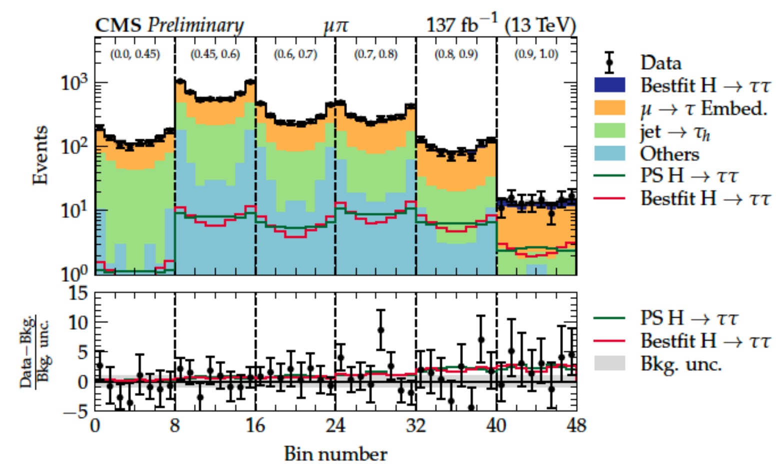


# Extracting mixing angle $\phi_{\tau\tau}$

## Perform log-likelihood scan of $\phi_{\tau\tau}$

- Fit data in background and signal categories simultaneously with templates of different $\phi_{\tau\tau}$ hypotheses
    - Background templates insensitive to $\phi_{\tau\tau}$, but help constraining background contributions
    - Unrolled distributions contain sensitivity to $\phi_{\tau\tau}$
    - Note: different signal templates obtained from linear combinations 0, 45, and 90°



# First result direct measurement $\phi_{\tau\tau}$!!

## Combined Negative log-likelihood fit

- Reject CP-odd hypothesis with observed (expected) 3.2 (2.3) sigma

$$\phi_{\tau\tau} = (4 \pm 17\,(\text{stat}) \pm 2(\text{bin-by-bin}) \pm 1\,(\text{syst}) \pm 1(\text{theory}))^\circ$$

⇒ Statistical uncertainty leading, followed by hadronic tau trigger and E scale, theory, …

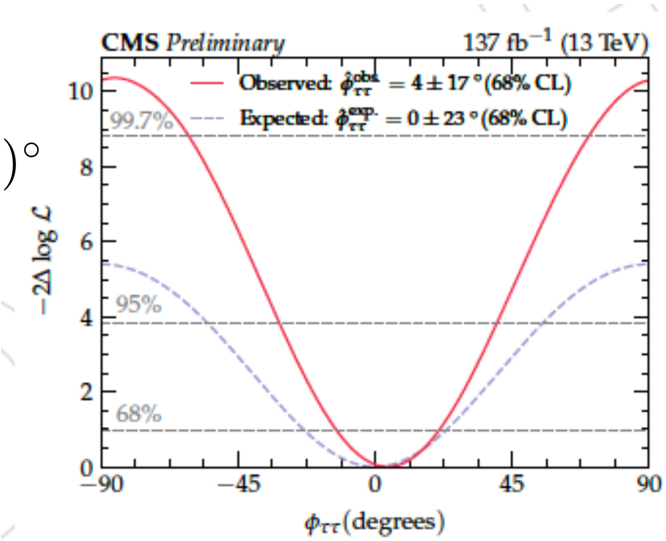
- Mixing angle observed (expected) 68% CL:

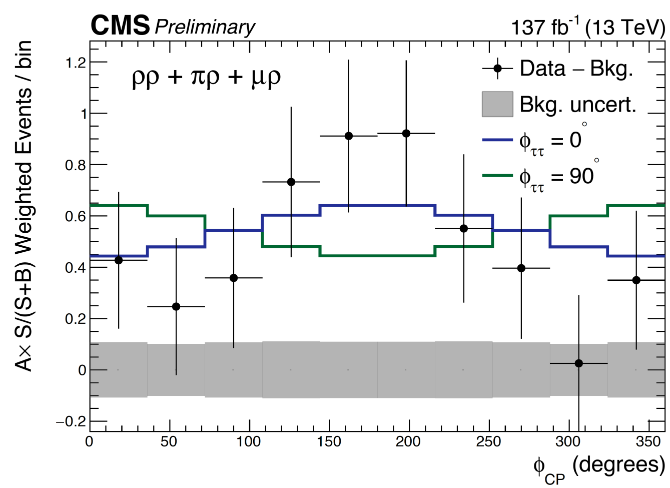
$$4 \pm 17^\circ \;\; (0 \pm 23^\circ)$$

⇒ nMSSM: $|\phi_{\tau\tau}|<27^o$ Nuclear Physics B 901 526

⇒ Part nMSSM phase space outside observed 68% CL!

- LHC Run-III and beyond: combine analysis with regressive ML algorithms for $\phi_{cp}$ determination



# CP-structure Higgs to Vector-boson coupling

## Bosonic couplings

- Couplings of (speudo) scalar boson to gauge bosons
  - CP-even (scalar), $J^{CP}=0^{++}$
  - CP-odd (pseudocalar) coupling does not occur at leading order
  - We can introduce non-renormalisable CP-odd effective-field-theory operators

- An example: Standard model plus EFT dim-6 operators:

$$\mathcal{L}_{\mathrm{H}VV} = g \cdot \mathrm{H} V_\mu V^\mu + \tilde{g} \cdot \mathrm{H} \tilde{V}_{\mu\nu} V^{\mu\nu}$$

$$V^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu$$

$\Rightarrow$ CP-even and (effective) CP-odd couplings have different tensor structure

  - Also applies, for example, to effective gluon Higgs coupling

- Note: CP-odd couplings to W and Z bosons already excluded

  arXiv:1903.06973, arXiv:1712.02304

# CP properties of Higgs-top interactions in $t\bar{t}H$ and tH using $H \rightarrow \gamma\gamma$ (ATLAS)

CERN-EP-2020-046

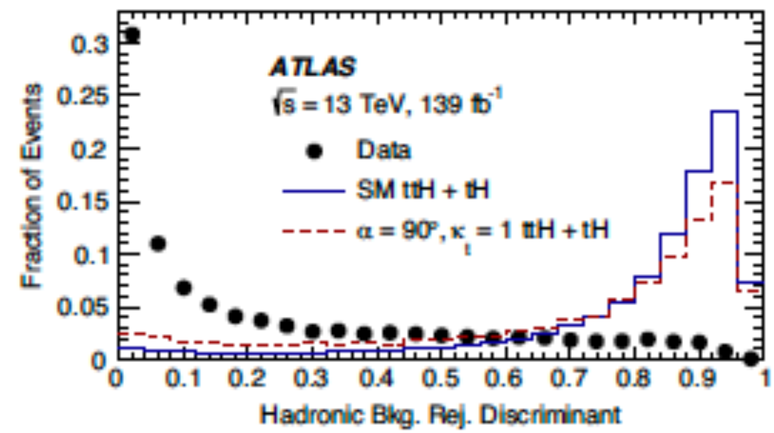
- Analysis targets mixing angle and reduced coupling $k_t$:

$$\mathcal{L} = -\frac{m_t}{v}\{\bar{\psi}_t\kappa_t[\cos(\alpha) + i\sin(\alpha)\gamma_5]\psi_t\}H$$

- Classify $t\bar{t}H$ and tH events in hadronic and leptonic channel (one or two W decay leptonically)

- Dedicated signal-background BDT, and $BDT_{CP}$ to extract $\alpha$:
  - $BDT_{CP}$: use top and diphoton system kinematics
- Extract signal strength in 20 categories via fit $m_{\gamma\gamma}$

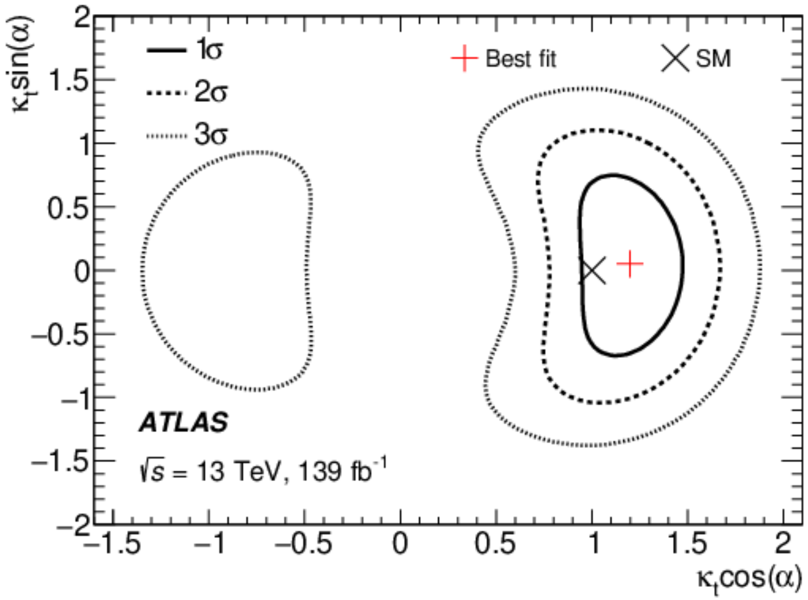
$\Rightarrow$ Obtain signal strength and mixing angle $\alpha$




Run-II

# CP structure of Higgs-top Yukawa coupling in $t\bar{t}H$ production using $H\rightarrow\gamma\gamma$ (ATLAS)

## Results




- Obtain 2-dimensional likelihood contour CP-even vs CP-odd
  - Pure CP-odd excluded at 3.9 sigma
    - $|\alpha|>43^{o}$ excluded at 95% CL

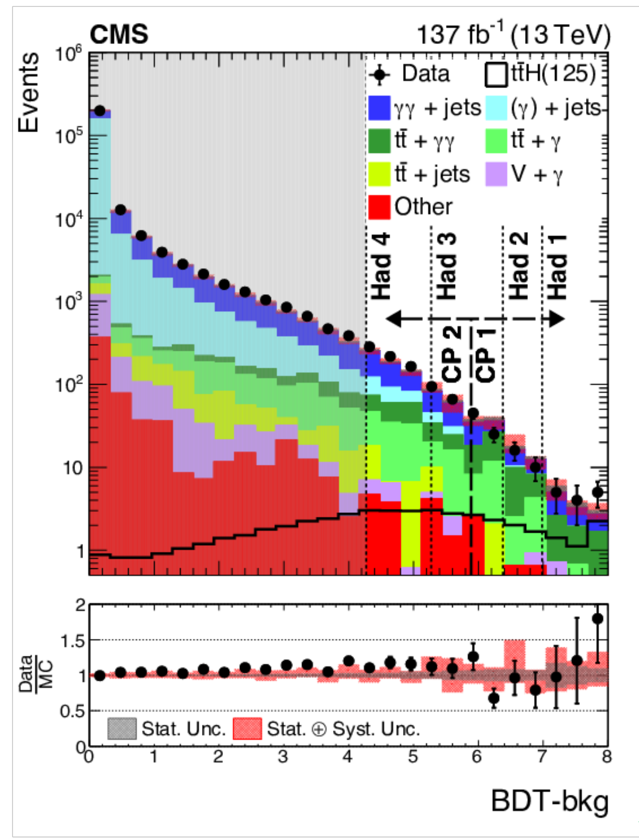
# CP structure of Higgs-top Yukawa coupling in $t\bar{t}H$ production using $H\to\gamma\gamma$ (CMS)

HIG-19-013

- Parameterise couplings via $f_{CP}^{Htt} = \frac{|\tilde{\kappa}_t|^2}{|\kappa_t|^2 + |\tilde{\kappa}_t|^2}\,\mathrm{sign}(\tilde{\kappa}_t/\kappa_t)$
- Use two optimal observables $D_{0-}$ and $D_{cp}$
  - $D_{0-}$ : distinguish CP-even vs CP-odd (neglects interference term!)
  - $D_{cp}$ : includes interference term

  $\Rightarrow$ This analysis focusses on $D_{0-}$ (thus: $|f_{CP}|$ only!)
- Classify events as hadronic or leptonic
- Signal background separation via hadronic and leptonic BDT's

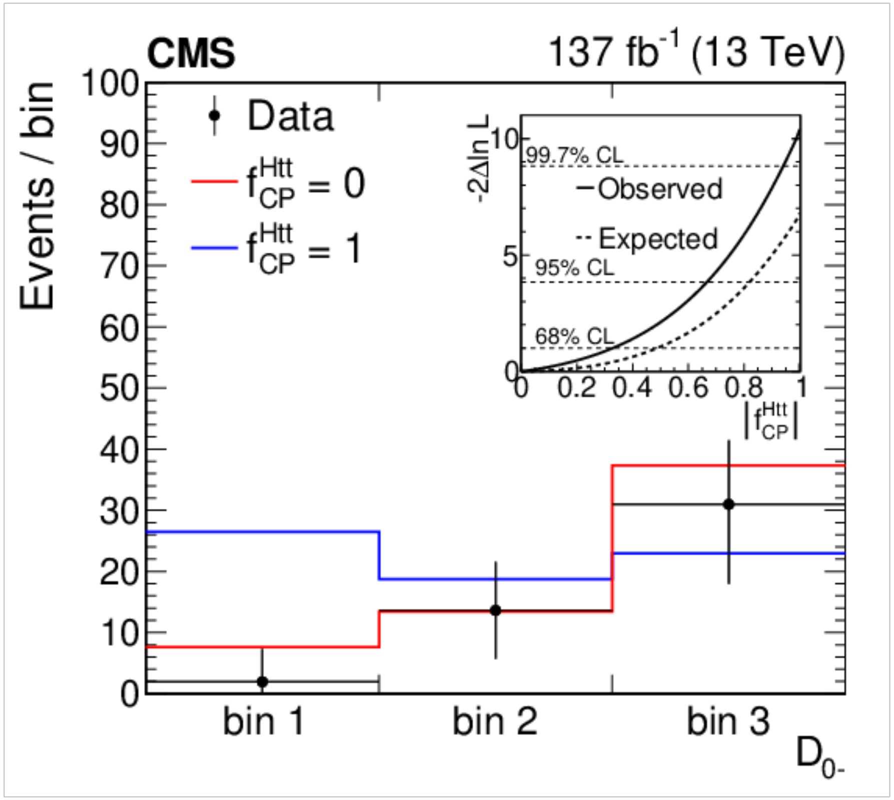
  $\Rightarrow$ **CP-analysis deploys 2 signal regions per class**




Run-II

# CP structure of Higgs-top Yukawa coupling in $t\bar{t}H$ production using $H\to\gamma\gamma$ (CMS)

- Dedicated BDT deployed to estimate $D_{0-}$
  - Uses jet kinematics and b-tags, diphoton kinematics, lepton kinematics and multiplicity
- Simultaneously fit signal strength via $m_{\gamma\gamma}$ in 12 bins
  - Note: tH measurement included in fit!
- Results:
  - Observed: $f_{CP}^{Htt} = 0.00 \pm 0.33$ at 68% CL
  - Expected: $f_{CP}^{Htt} = 0.00 \pm 0.49$
- Exclude CP-odd:
  - 3.2 sigma (observed)
  - 2.6 sigma (expected)

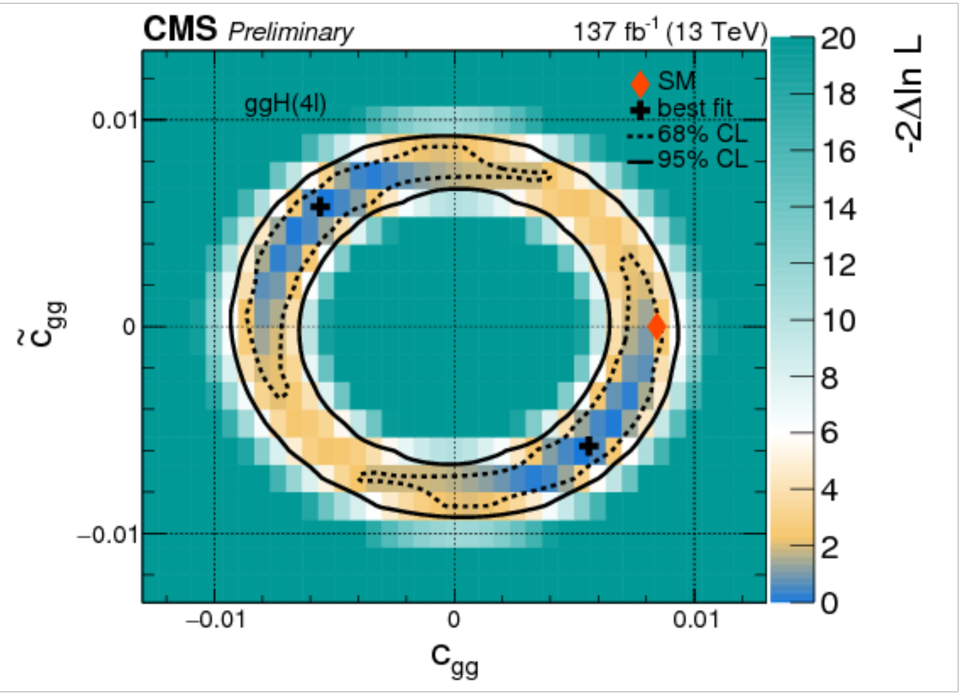


# Anomalous couplings in H->4l decays (CMS)

HIG-19-009

**First direct measurement CP structure ggH coupling!**

- All production modes of H->4l assessed
- Analyse ggH events using matrix element techniques
- Determine $D_{0-}$ and $D_{CP}$ via likelihood fit
- Note: sign couplings determined via interference term




| Parameter | Observed | Expecte |
|---|---|---|
| $f_{a3}^{ggH}$ | $-0.53^{+0.51}_{-0.47}$ $[-1,1]$ | $0 \pm 1$ $[-1,1]$ |

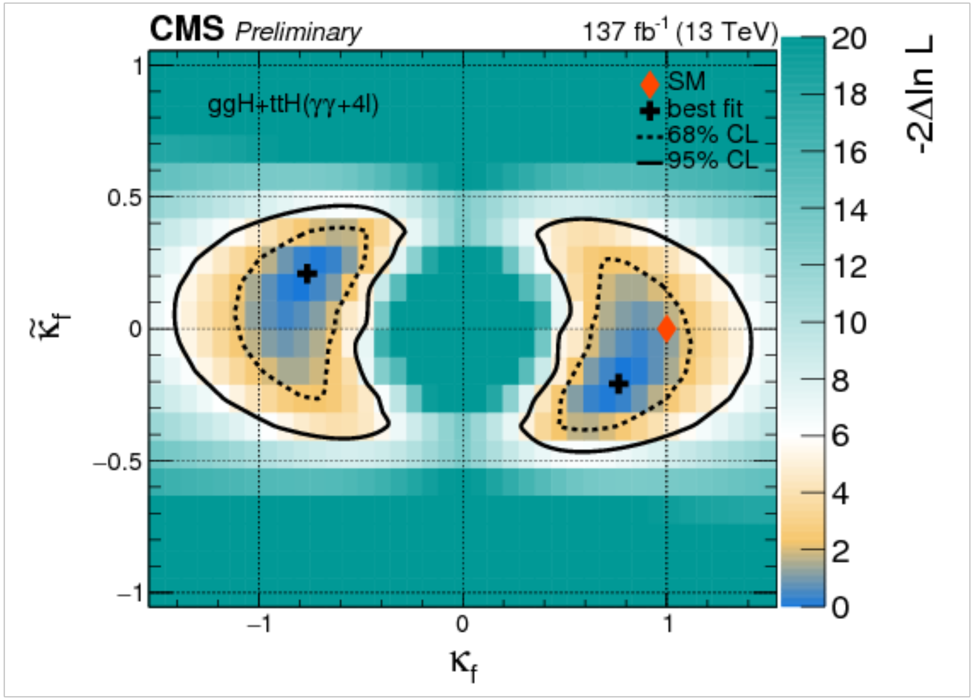
Run-II

# Anomalous couplings in H->4l decays (CMS)

## CP structure $t\bar{t}H$ coupling

- CP structure analysed using $D_{0-}$ observable (analogue to H->γγ analysis)
- Combine ggH with $t\bar{t}H$ with $H\to ZZ^*\to 4l$, assuming only top and b in fermion loop and $k_t = b_t$ $\tilde{k}_t = \tilde{b}_t$

$$\left|f_{CP}^{Hff}\right| = \left(1 + 2.38\left[\frac{1}{\left|f_{a3}^{ggH}\right|} - 1\right]\right)^{-1} = \sin^2\alpha^{Hff}$$




- Combine H->4l with $t\bar{t}H$ analysis in H->γγ
- Results consistent with SM

# Constraints on Higgs couplings in H->WW*->eνμν+jj (ATLAS)

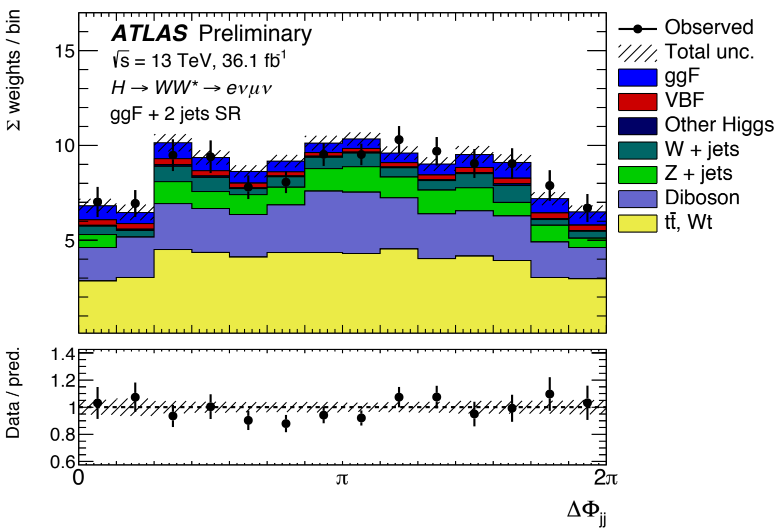
ATLAS public Higgs results

## CP structure ggH coupling

- Kinematics of top coupling may differ from on-shell associated production
- Deviation w.r.t. SM would point to CP-violation or new particles in loop:

$$\mathcal{L}_0^{\text{loop}} = -\frac{1}{4}\left(\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \kappa_{Agg} g_{Agg} G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}\right) X_0$$

- Apply cuts plus BDT to define signal region
- Exploit $\Delta\phi_{jj}$ (signed angle between outgoing jets) and rate of process
- 2015+2016 data used



# Constraints on Higgs couplings in H->WW*->eνμν+jj (ATLAS)

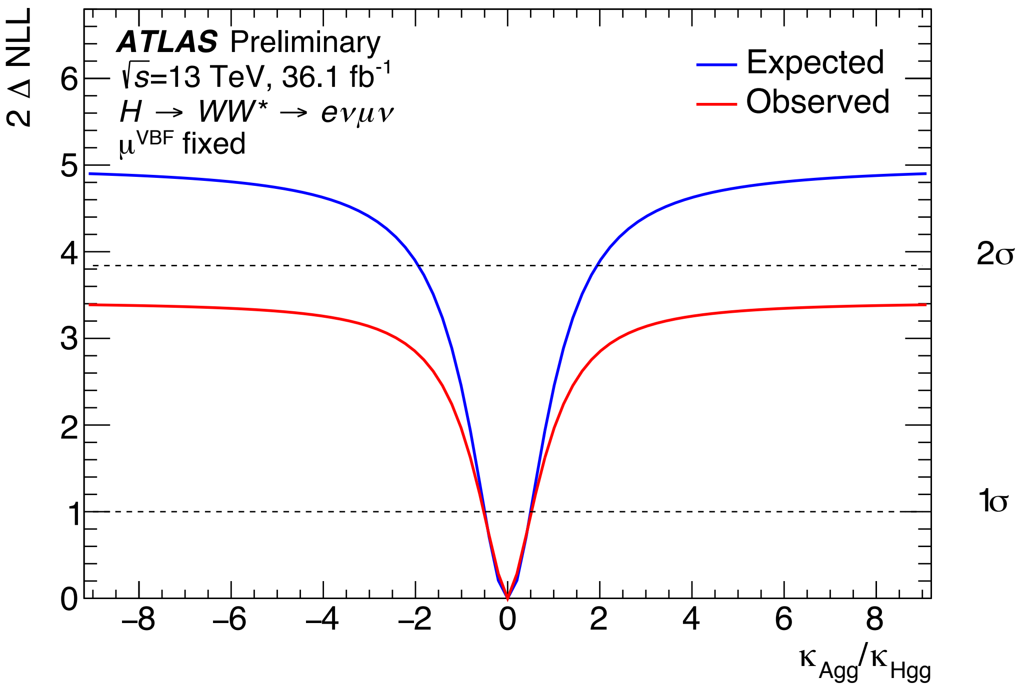
## CP in ggH production

- Scan $\kappa_{Agg}/\kappa_{Hgg}$ with rate fixed to BSM scenario (i.e. non-floating)

⇒ Consistent with SM!

- Stat uncertainty leading, theory leading sys.

$$\kappa_{Agg}/\kappa_{Hgg} = 0.0 \pm 0.4(\text{stat.}) \pm 0.31(\text{syst.})$$



# Test of CP invariance in VBF in H->$\tau\tau$ (ATLAS)

**Analysis of 2015-2016 data** CERN-EP-2020-009 **Run-1:** CERN-EP-2016-002

- Reminder: CP-odd HVV couplings in SM **do not occur at tree level**
- Introduce (non-renormalisable) dimension 6

  CP-odd operators of effective field theory (EFT):
- Assuming U(1) and SU(2) symmetry with additional assumption:

$$\tilde{g}_{HAA} = \tilde{g}_{HZZ} = \frac{1}{2}\tilde{g}_{HWW} = \frac{g}{2m_W}\tilde{d} \quad \text{and} \quad \tilde{g}_{HAZ} = 0$$

$\Rightarrow$ We have expressed new CP-odd operators in terms of single coupling $\tilde{d}$

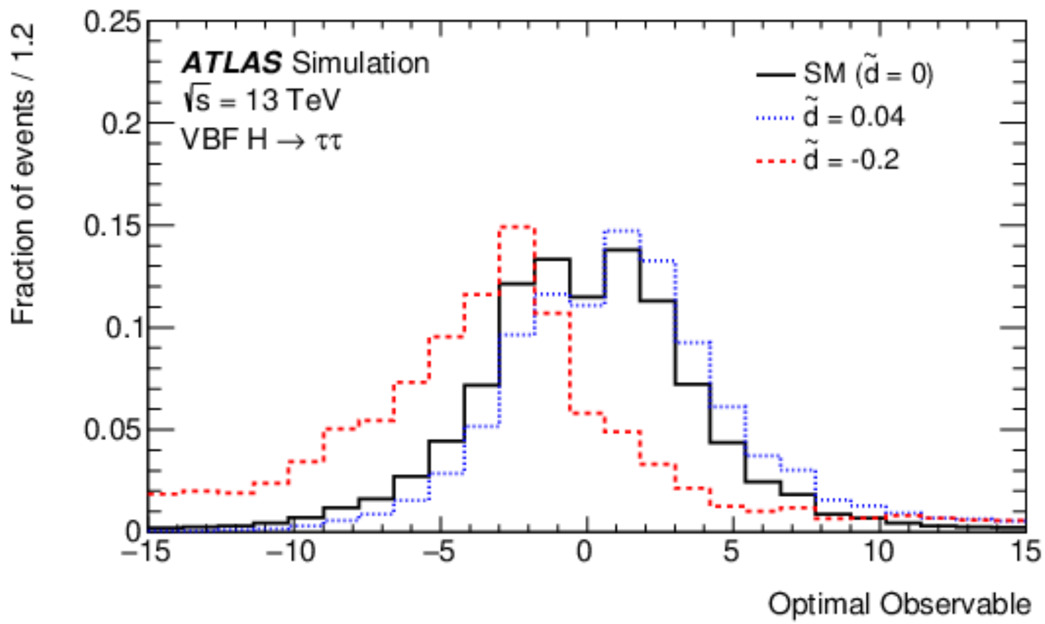
- Obtain two CP-even and CP-odd interference term:

$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + \tilde{d} \cdot 2\,\mathrm{Re}(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\text{CP-odd}}) + \tilde{d}^2 \cdot |\mathcal{M}_{\text{CP-odd}}|^2$$

# Test of CP invariance in VBF in H->$\tau\tau$ (ATLAS)

## Optimal observable

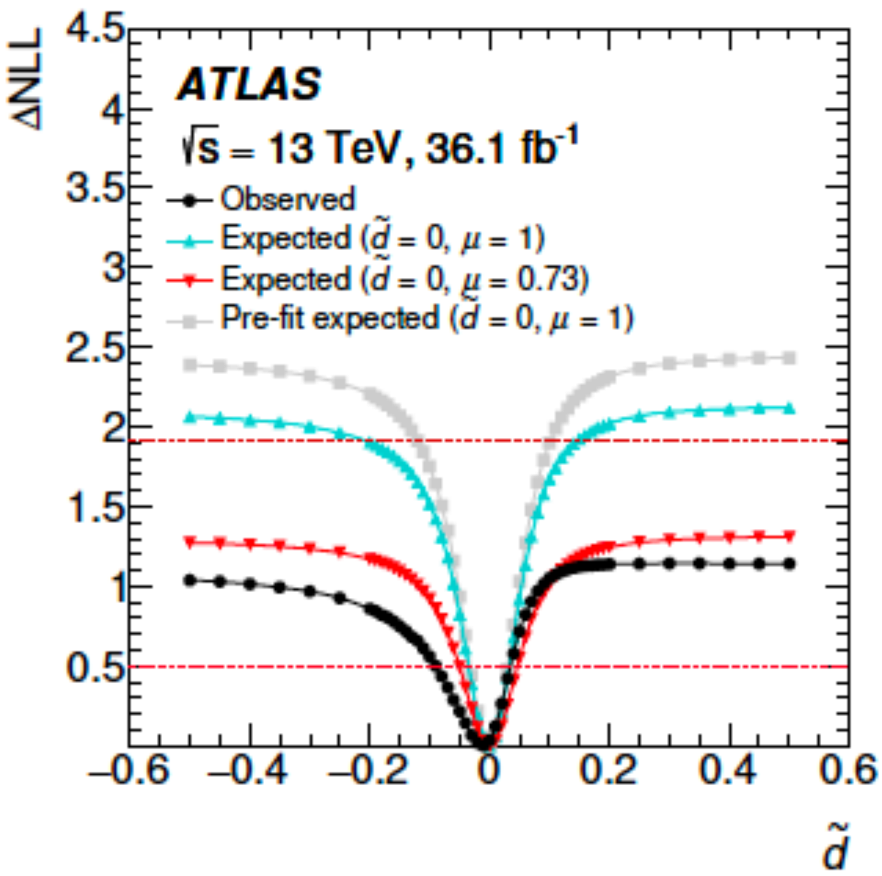
- Optimal observable $\boldsymbol{O}_{opt}$ (CP-odd): $\mathcal{O}_{\text{opt}} = \frac{2\,\text{Re}(\mathcal{M}^*_{\text{SM}}\mathcal{M}_{\text{CP-odd}})}{|\mathcal{M}_{\text{SM}}|^2}$
  - $\boldsymbol{O}_{opt}$ proven more sensitive than $\Delta\phi_{jj}$ between VBF jets
- Expectation value $\langle \boldsymbol{O}_{opt} \rangle$:
  - Zero for SM (CP-even couplings)
  - Non-zero: CP-odd operator (or BSM particles in loops..)



# Test of CP invariance in VBF in H->$\tau\tau$ (ATLAS)

## Results using 2015-2016 data

- Profile likelihood as function of $\tilde{d}$
- Results consistent with SM:
- 68% CL **observed**: [-0.09, 0.035]
- **Expected** (SM): [-0.035, 0.033]
  - Jet systematics leading uncertainty
- Improved previous Run-1 result : [-0.11, 0.05]



# Outlook Higgs in near and far future…

**LHC schedule here**

- **Run-2 data (~140 $fb^{-1}$)**
  - Many coupling analyses still expected
    - Higgs-tau final coupling result
    - VH(H->bb)
    - Grand combination Run-2 STXS and pT spectra
    - final Run-2 mass and width measurement combinations
    - di-Higgs production studies and their combination
    - Searches for Beyond Standard Model Higgs bosons (many!)
    - … and many more!

- **Run-3, start 2022. Combination with Run-2 data:(~300 $fb^{-1}$):**
  - CP-structure Higgs-Yukawa couplings: exclusion pure-odd couplings perhaps feasible
  - Possibly observation Higgs-muon coupling

  $\Rightarrow$ Observations expected for combinations ATLAS and CMS experiments

  - Bosonic couplings:
    - precision will increase. Not for all measurements as $\sqrt{L}$ though!
- Combined CP-analyses Yukawa and vector coupling

- **High-Lumi LHC, start 2027 (~3000 $fb^{-1}$):**
  - A pivotal motivation is observation Higgs boson self-coupling

# Beyond LHC

## Higgs factories

- Recent European strategy update particle physics: next collider project should be Higgs factory
- Various options on the table:
  - ILC (Japan)
  - FCC-ee or FCC-pp (CERN)
  - CLIC (muon collider, CERN)
  - CEPC (Chinese electron-positron)

$\Rightarrow$ **All these colliders could explore certain Higgs parameters ~order magnitude better than LHC**

$\Rightarrow$ **EXCITING TIME TO BE A PARTICLE PHYCISIST!!**

# Summary

## 13 TeV proton collisions provided wealth of Higgs-CP asnalyses

- **CMS first H->$\tau\tau$ CP-mixing angle measurement (Full Run-II)**
  - **Constrained to $\phi_{\tau\tau}$=(4 +/- 17)° (68% CL)**
- **ATLAS and CMS presented first measured $\phi_{tt}$ (Full Run-II)**
  - **ATLAS: $|\phi_{tt}|$<43° (95% CL)**
  - **CMS:** $f_{CP}^{Htt} = 0.00 \pm 0.33$ at 68% CL
- **CMS anomalous couplings in H->4l (Run-II): first ggH CP analysis!**
- **ATLAS CP in ggH in H->WW*->eνμν**
- **ATLAS: more tight constraints anomalous couplings from VBF H->$\tau\tau$ measurement (2015-2016 data)**

***….No clear sign of BSM physics (yet)***
***Many more Run-II results expected***
***Precision will be ever-increasing with data***
***Hoping for the unexpected!***

**THANKS FOR YOUR ATTENTION!**

# Higgs-CP: state-of-the-art

## Latest ATLAS and CMS Higgs-CP analyses in a nutshell

- ATLAS and CMS observed $t\bar{t}H$ coupling in H->γγ full Run-II analyses and analysed CP-structure
  - ATLAS: CERN-EP-2020-046
  - CMS: HIG-19-013
- CMS analysis anomalous couplings in H->4l decays HIG-19-009
- ATLAS analysis CP structure Higgs-gluon effective vertex ATLAS-CONF-2020-055
- ATLAS analysis CP invariance in vector boson fusion with Higgs to tau decays: CERN-EP-2020-009

$\Rightarrow$ Reminder: this presentation focusses exclusively on CP parts of analyses

# CP structure of Higgs-$\tau$ Yukawa coupling (CMS)

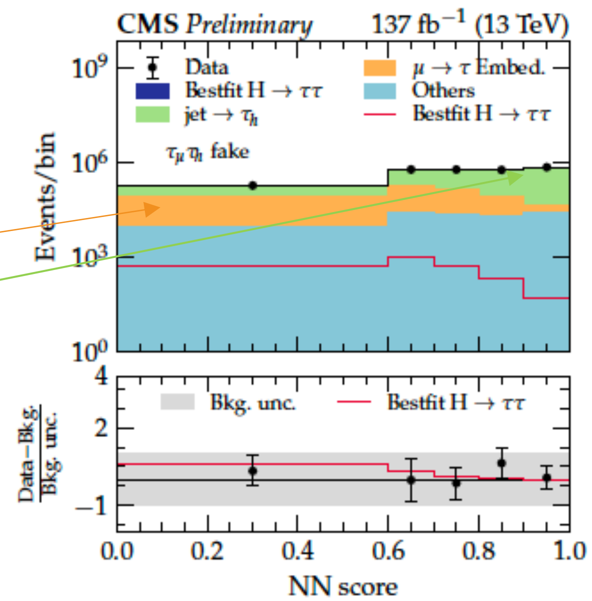
**Begin backup slides**

Run-II

# CP structure of Higgs-$\tau$ Yukawa coupling (CMS)

**~90% of backgrounds data-driven manner!**

- Genuine di-tau background: exploit lepton universality
  - use event-embedding (replace di-muon pair from data event) ref
- Jets faking hadronic tau: use fake-faktor method ref
  - Deduce jet misidentification rate in control region
  - Apply rate to jets in application region to get rate in signal region
- Apply MVA to separate signal, genuine background, jet-fake background
- Event selection, reconstruction, background methodology, event categorisation: mostly analogous to STXS analysis
  - One important difference: use one category for signal events instead
- Distribution: $\phi_{cp}$ unrolled in NN windows

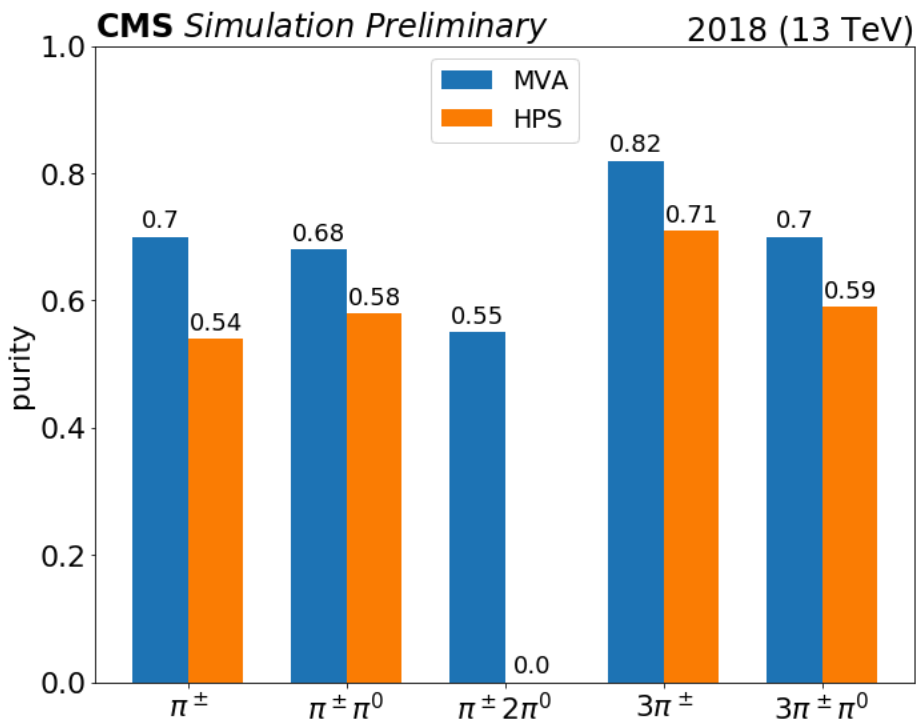


# CP structure of Higgs-$\tau$ Yukawa coupling (CMS)

## Additional corrections applied to optimise signal strength

- Decay mode identification important, migrations will lead to incorrect $\phi_{cp}$ estimates
- Per default, decay mode given by HPS (hadron-plus-strip) algorithm
- Dedicated MVA developpd for enhanced decay mode distinction (on top of deeptau discriminant)
  - Inputs: kinematics tau decay products and HPS decay mode
- Substantial gain in purity and efficiency
- Improves signal sensitivity by O(15%)
- Reference

- Purity



# CP structure of Higgs-$\tau$ Yukawa coupling (CMS)

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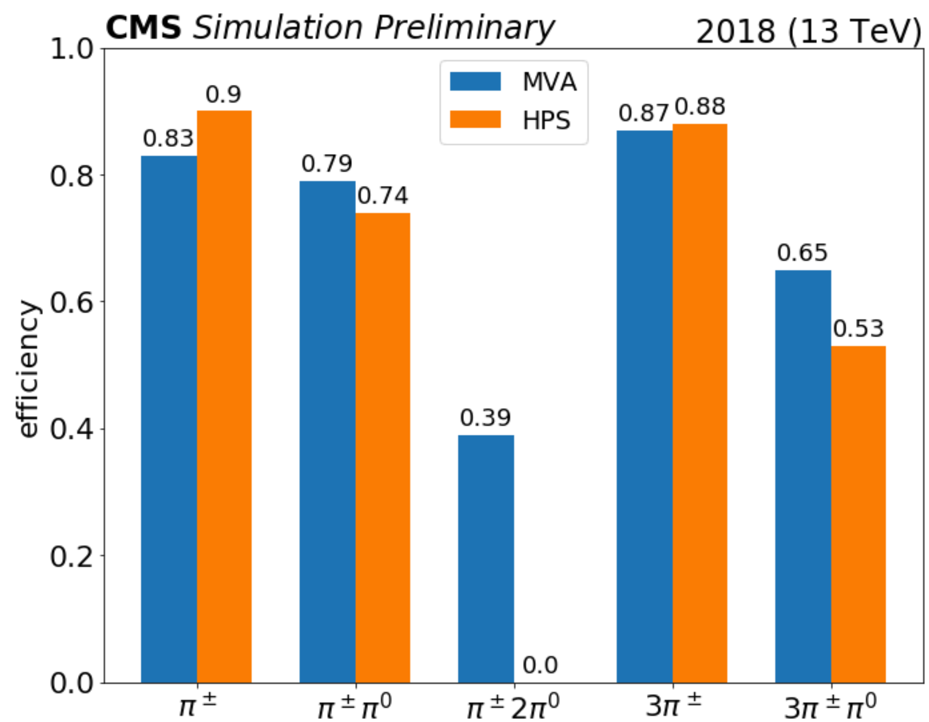
- Efficiency



# CP structure of Higgs-$\tau$ Yukawa coupling (CMS)

HIG-20-006

## 3-d vs 2-d extrapolation tracks

- Per default, track extrapolation to find PCA (point closest approach) performed in trasnversal plane
- Using helical, 3-dimensional approach has 2 profound advantages:
  - IP estimate better for tracks with high eta values
  - Can propagate uncertainties in track and PV in consistent manner

  ⇒ Define an impact-parameters significance as |IP|/sigma IP

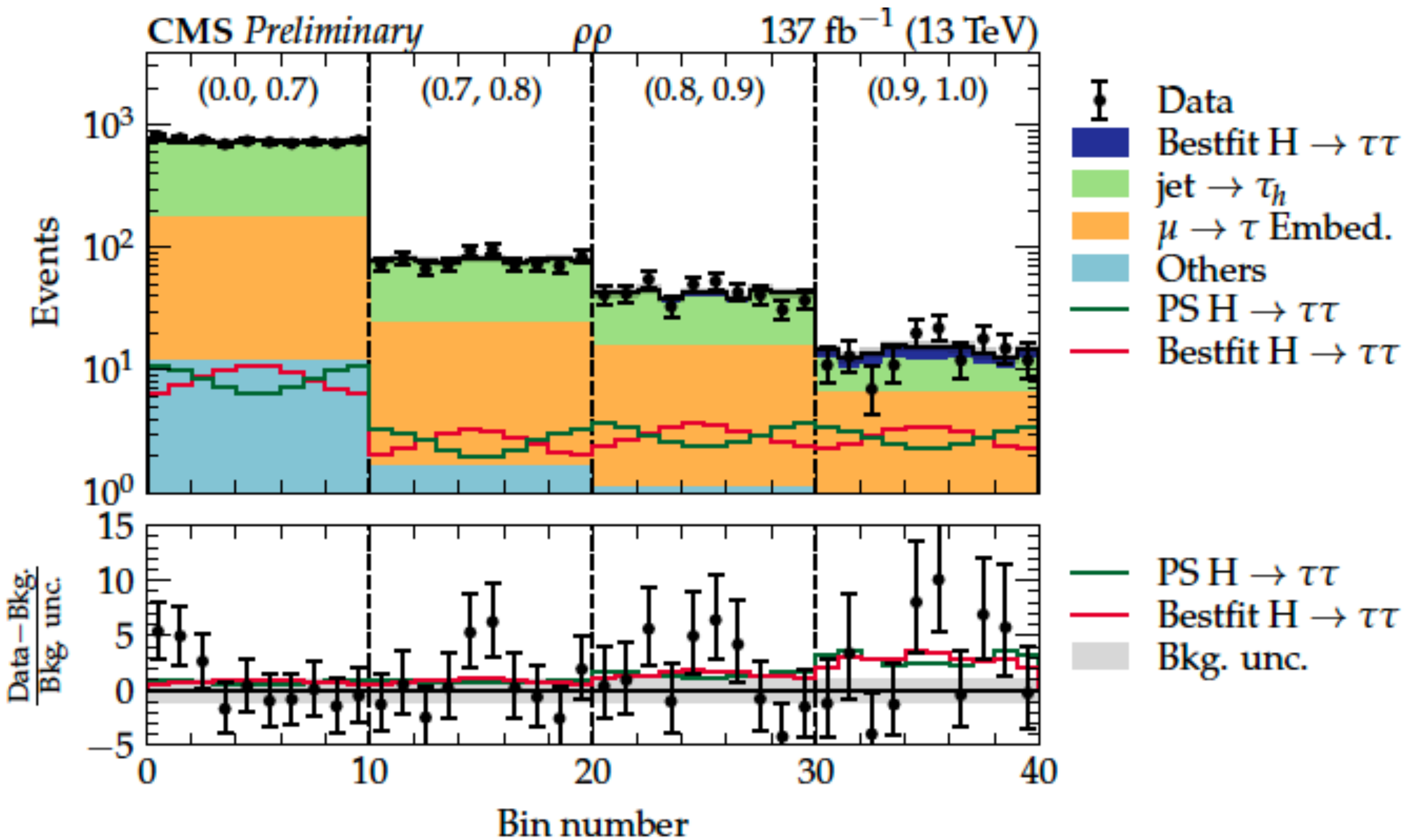
  ⇒ throughout analysis require
  |IP|/sigma IP> 1.5
- Lead to improvement sensitivity O(15%)

# CP structure of Higgs-$\tau$ Yukawa coupling (CMS)

## rho+rho channel. Resolution:

- Observe s/b improvement owing to BDT
- Backgrounds with genuine $\tau$ expected to be flat in $\phi_{cp}$

$\Rightarrow$ Enhance sensitivity by merging bins. Jet fakes: symmetrise around $\phi_{cp}=\pi$

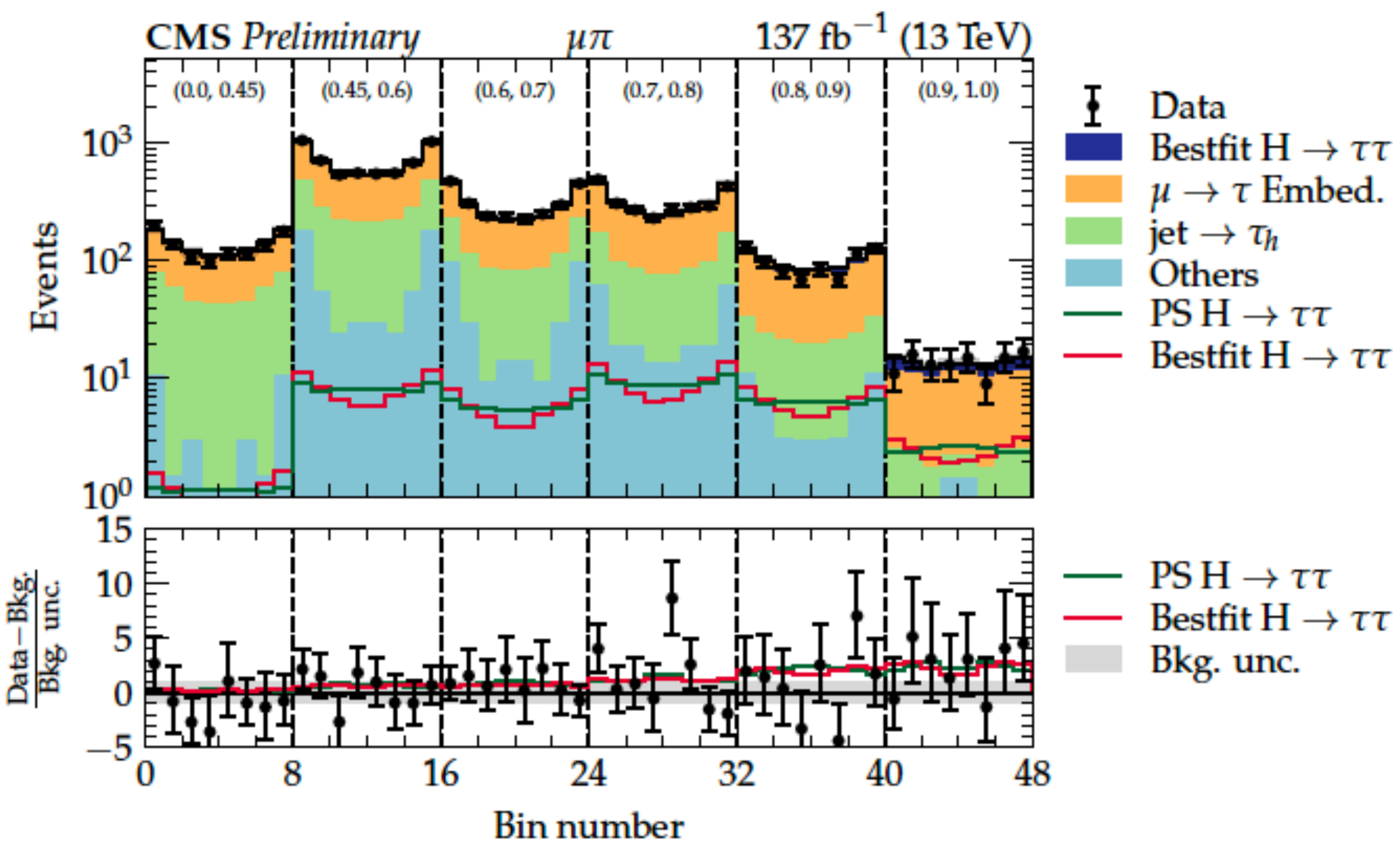


# Unrolled phi-CP distributions

## mu+pi channel. Resolution: ~1.0 sigma

- Using IP method twice results in correlated PV smearing effects

  $\Rightarrow$ Only symmetrise bins in $\phi_{cp}=\pi$



# CP structure of Higgs-$\tau$ Yukawa coupling (CMS)

## Explanation observed vs expected significance

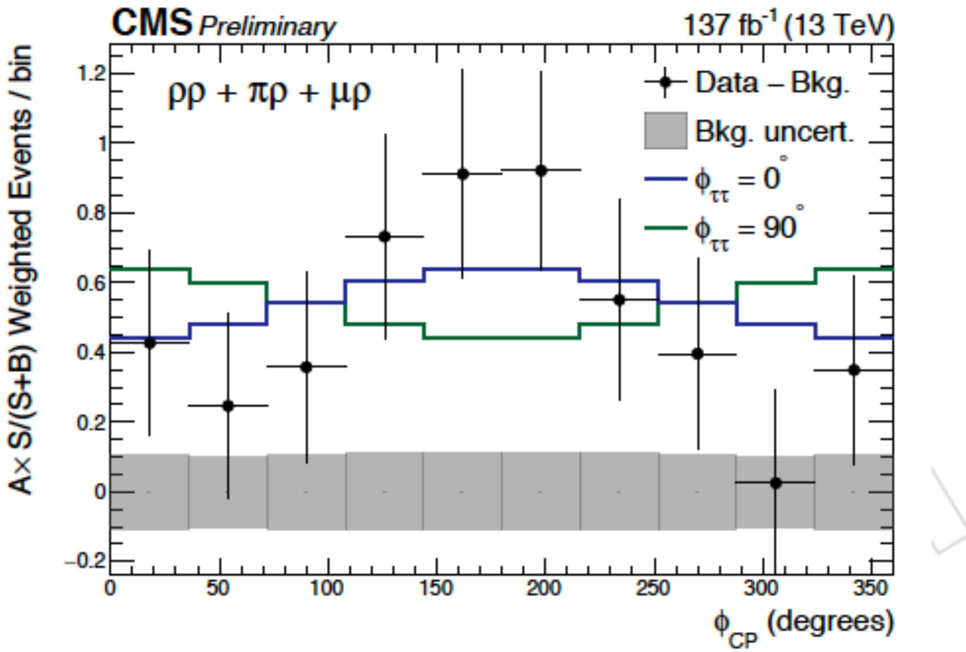



Figure 10: The $\phi_{CP}$ distribution for the three most sensitive channels combined. Events were collected from all years and NN/BDT bins in the three signal categories. The background is subtracted from the data. The events are reweighed via $A\, S/(S+B)$, in which $S$ and $B$ are the signal and background rates, respectively, and $A$ is a measure for the average asymmetry between the scalar and pseudoscalar distributions. The definition of the value of $A$ per bin is $|\mathrm{CP}^{\mathrm{even}} - \mathrm{CP}^{\mathrm{odd}}|/(\mathrm{CP}^{\mathrm{even}} + \mathrm{CP}^{\mathrm{odd}})$, and $A$ is normalised to the total number of bins. In this equation $\mathrm{CP}^{\mathrm{even}}$ and $\mathrm{CP}^{\mathrm{odd}}$ are the scalar and pseudoscalar contributions per bin. The scalar distribution is depicted in blue, while the pseudoscalar is displayed in green. In the predictions, the rate parameters are taken from their best-fit values. The grey uncertainty band indicates the uncertainty on the subtracted background component. In combining the channels, a phase-shift of 180° was applied to the channel involving a muon since this channel has a phase difference of 180° with respect to the two hadronic channels due to a sign-flip in the muon spectral function.

# CP structure of Higgs-$\tau$ Yukawa coupling (CMS)

## 2-dimensional scan of reduced couplings

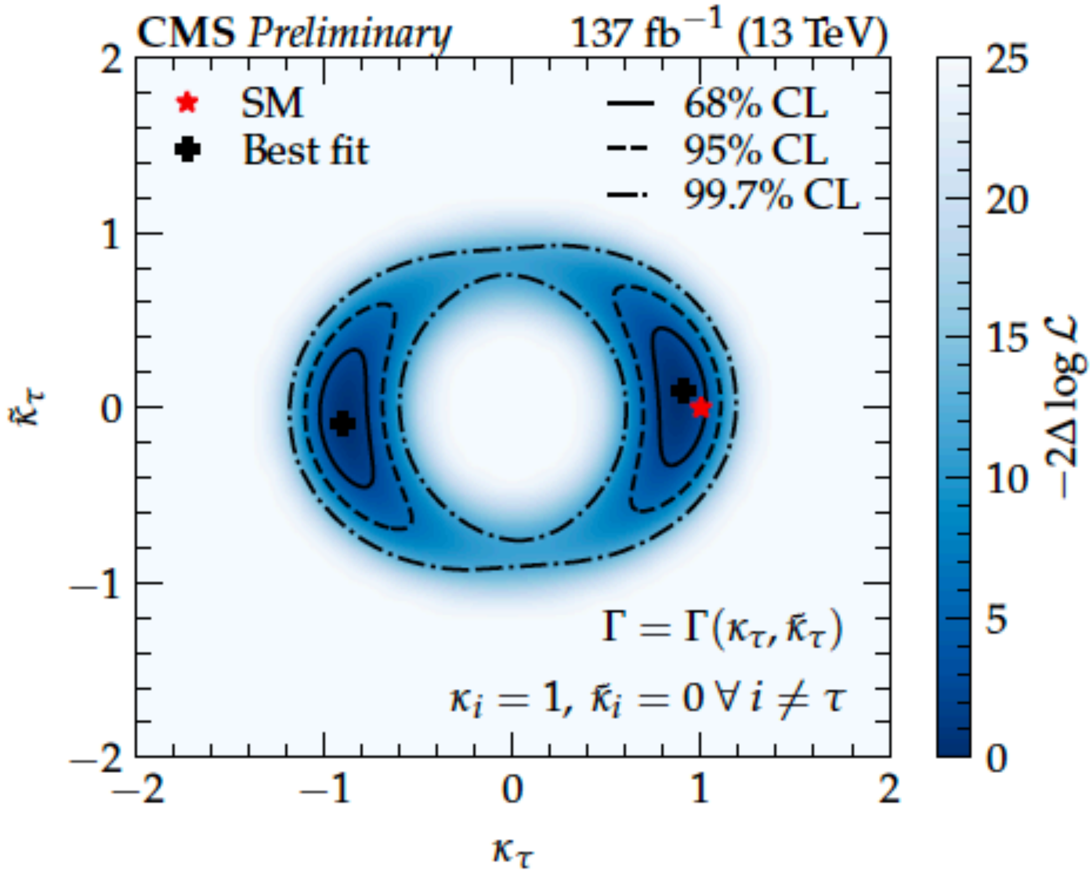


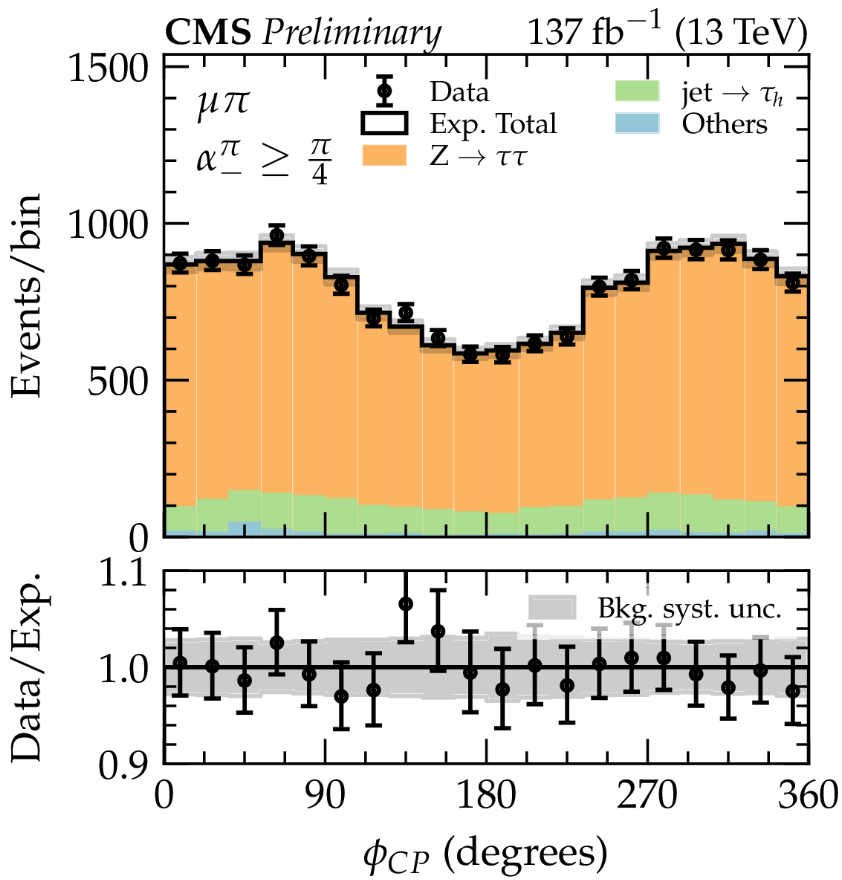

Figure 9: Two-dimensional scan of the (reduced) CP-even ($\kappa$) and CP-odd ($\tilde{\kappa}$) $\tau$ Yukawa couplings.

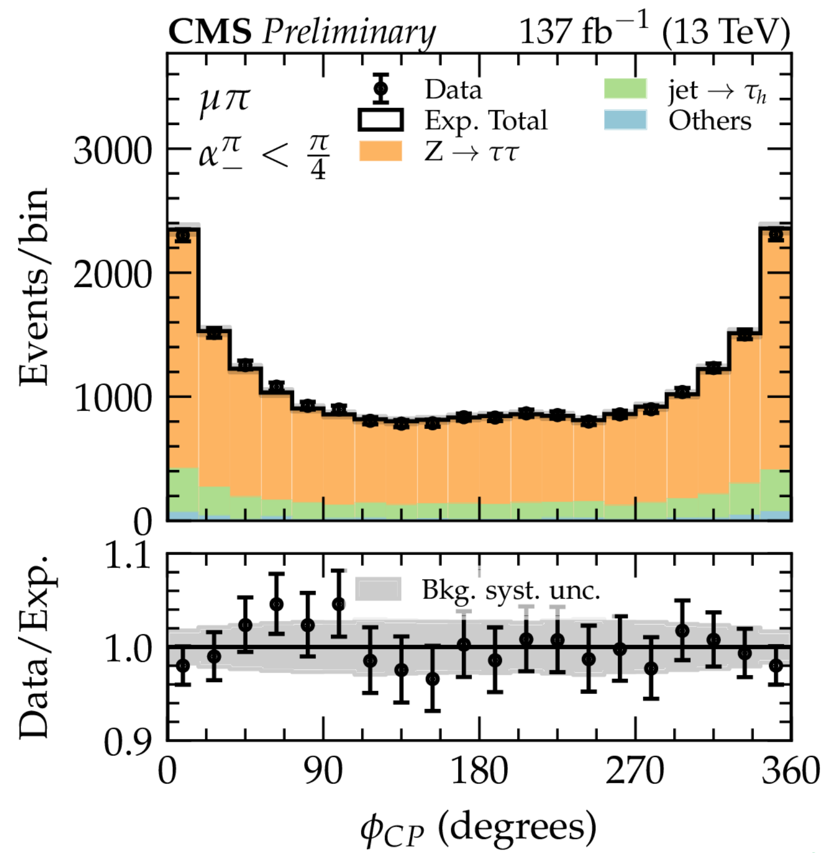
# CP structure of Higgs-$\tau$ Yukawa coupling (CMS)

**Decomposed $\phi_{cp}$ distribution for Drell-Yan events**

**Observable $\alpha$ explained in this reference**

More auxiliary results here




Run-II

# CP structure of Higgs-$\tau$ Yukawa coupling (CMS)

**Correlated effects of smearing primary vertex reviewed in this reference**

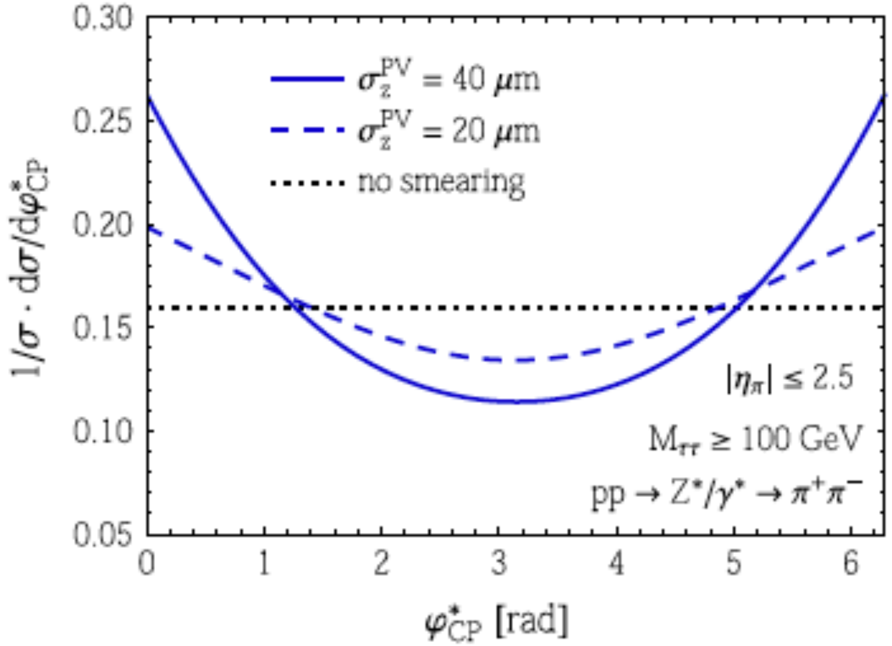
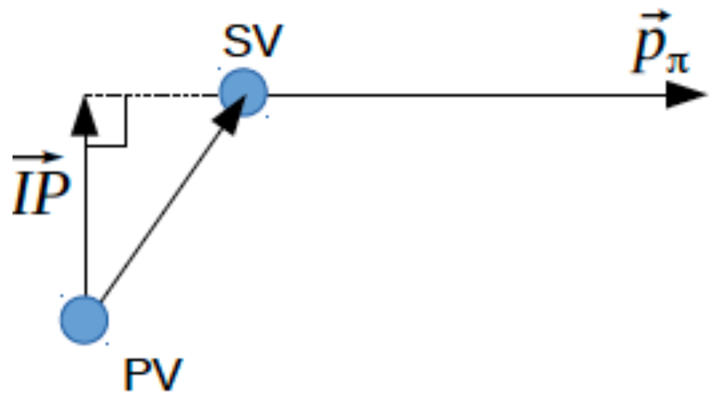



**Fig. 9** Left: $pp \to Z^*/\gamma^* \to \tau^-\tau^+ \to \pi^+\pi^-$ with $p_T^\pi \geq 20$ GeV and $n_\pm \geq 20\,\mu m$. Normalized smeared $\varphi^*_{CP}$ distribution for two different values of $\sigma_z^{PV}$. The *dotted black line* is the prediction with-




Run-II

# CP properties of Higgs-top interactions in $t\bar{t}H$ and tH using $H\rightarrow\gamma\gamma$ (ATLAS)

**Begin backup**

# CP properties of Higgs-top interactions in $t\bar{t}H$ and tH using $H \rightarrow \gamma\gamma$ (ATLAS)

## Signal-background BDT

- Uses as input top quark reconstruction BDT
- Input
  - Pt, eta, phi and E of W boson and b-jets
  - Angular distance between W boson and b-jet

- Signal-background BDT explained in ref
- One for leptonic events
  - Uses $p_T$, $\eta$, $\phi$, E of up to 4 (2) leading jets (leptons)
  - Missing energy and its angle
  - Photon $p_T$ divided by invariant mass of the pair, and photon $\eta$, $\phi$
- Hadronic events:
  - 6 leading jets, inc b-jet scores
  - Further same observables as for leptonic BDT

# CP structure of Higgs-top Yukawa coupling in $t\bar{t}H$ production using $H\rightarrow\gamma\gamma$ (CMS)

**Begin backup**

# CP structure of Higgs-top Yukawa coupling in $t\bar{t}H$ production using $H\rightarrow\gamma\gamma$ (CMS)

## Signal-background BDT

- Kinematic properties of jets, leptons, photons, and di-photons (but not the di-photon mass)
- Jet and lepton multiplicities
- B-tagging scores of jets
- Missing transverse momentum
- Generally, jets and leptons of signal events higher pt and more central pseudorapidity than background
- Validated in sidebands

- Further inputs
  - Top-tagger BDT
  - DNN to separate $t\bar{t}H$ from dominant background in signal enriched phase space
    - Exploits low-level information, four vectors
    - Score is input to signal-background BDT. If used standalone, suffers from overfitting

# CP structure of Higgs-top Yukawa coupling in $t\bar{t}H$ production using $H\rightarrow\gamma\gamma$ (CMS)

## Invariant mass

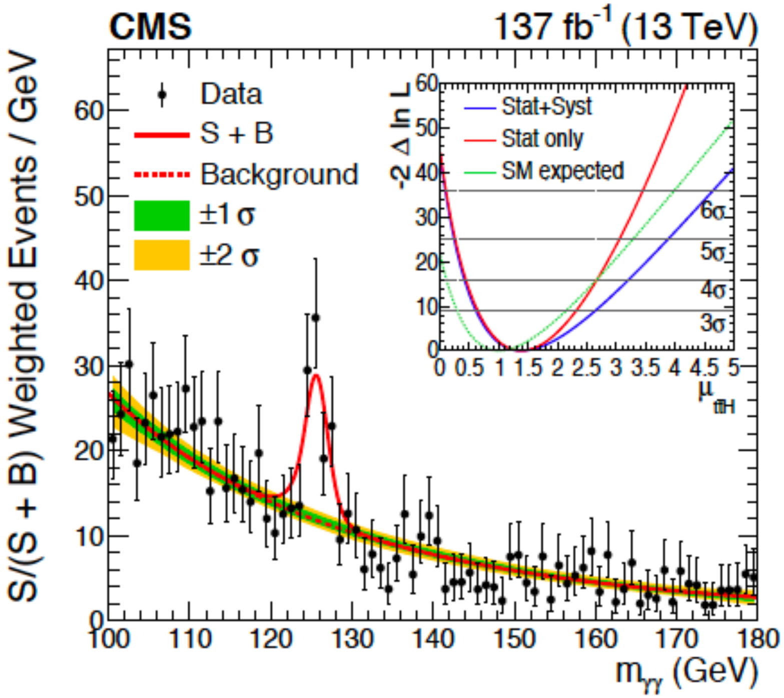



Figure 2: Invariant mass distribution for the selected events (black points) weighted by S/(S + B), where S (B) is the numbers of expected signal (background) events in a $\pm 1\sigma_{\text{eff}}$ mass window centered on $m_{\text{H}}$. The $\sigma_{\text{eff}}$ is defined as the smallest interval containing 68.3% of the $m_{\gamma\gamma}$ distribution, and ranges from 1.2 to 1.6% for different categories. We show curves for fitted signal + background (solid red) and for background only (dashed red), with bands covering the $\pm 1\sigma$ and $\pm 2\sigma$ uncertainties in the fitted background. The inner panel shows the likelihood scan for $\mu_{t\bar{t}H}$ with $m_{\text{H}}$ profiled.

# Anomalous couplings in H->ZZ$^*$->4l decays (CMS)

**Begin backup**

# Anomalous couplings in H->ZZ*->4l decays (CMS)

## $D_{0-}$ and $D_{CP}$

$$\mathcal{D}_{\text{alt}}(\Omega) = \frac{\mathcal{P}_{\text{sig}}(\Omega)}{\mathcal{P}_{\text{sig}}(\Omega) + \mathcal{P}_{\text{alt}}(\Omega)},$$

$$\mathcal{D}_{\text{int}}(\Omega) = \frac{\mathcal{P}_{\text{int}}(\Omega)}{2\sqrt{\mathcal{P}_{\text{sig}}(\Omega)\ \mathcal{P}_{\text{alt}}(\Omega)}},$$

- $D_{0-}$ is given by $P_{odd}/(P_{even}+P_{odd})$

# Anomalous couplings in H->ZZ*->4l decays (CMS)

$D_{0-}$ and $D_{CP}$ Link

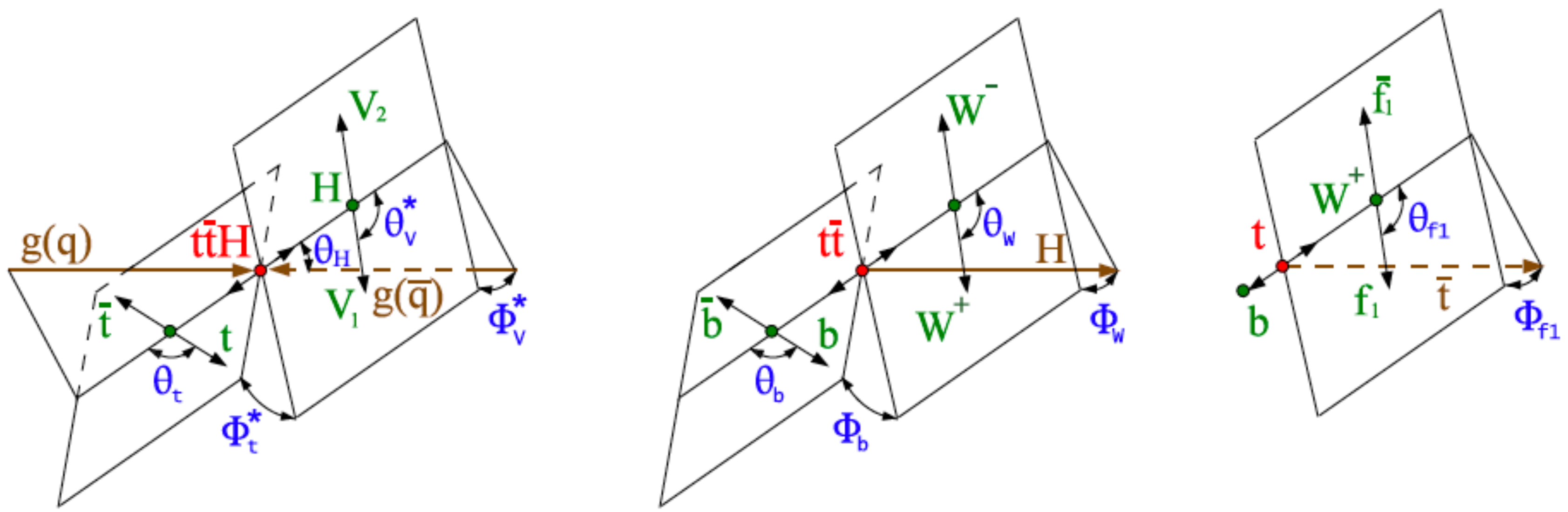



FIG. 4: The definition of observable in the sequential process of production and decay of $t\bar{t}H$, see text for details. Each angle is defined in the respective reference frame of the decaying system.

# Anomalous couplings in H->ZZ*->4l decays (CMS)

## $D_{0-}$ and $D_{CP}$ Link

- $m_{t\bar{t}H}$: invariant mass of the $t\bar{t}H$ system;
- $\theta_H$: angle between the $H$ boson direction and the incoming partons in the $t\bar{t}H$ frame;
- $\theta^*_V$: angle of the $H \to VV(f\bar{f})$ decay with respect to the opposite $t\bar{t}$ direction in the $H$ frame;
- $\Phi^*_V$: angle between the production plane, defined by incoming partons and $H$, and $H \to VV(f\bar{f})$ decay plane;
- $\theta_t$: angle between the top quark direction and the opposite Higgs direction in the $t\bar{t}$ frame;
- $\Phi^*_t$: angle between the decay planes of the $t\bar{t}$ system and $H \to VV(f\bar{f})$ in the $t\bar{t}H$ frame;
- $m_{tt}$: invariant mass of the $t\bar{t}$ system;
- $\theta_W$: angle between $W^+$ and opposite of the $b\bar{b}$ system in the $W^+W^-$ frame;
- $\Phi_W$: angle between the production $(b\bar{b})(W^+W^-)H$ plane and the plane of the $W^+W^-$ system in the $t\bar{t}$ frame;
- $\theta_b$: angle between the $b$ quark and opposite of the $W^+W^-$ system in the $b\bar{b}$ frame;
- $\Phi_b$: angle between the planes of the $b\bar{b}$ and $W^+W^-$ systems in the $t\bar{t}$ frame;
- $m_{Wb1}$ or $m_{Wb2}$: invariant mass of the $W^+b$ or $W^-\bar{b}$ system;
- $\theta_{f1}$ or $\theta_{f2}$: angles between fermion direction and opposite of the $b$ or $\bar{b}$ quark in the $W^+$ or $W^-$ frame;
- $\Phi_{f1}$ or $\Phi_{f2}$: angle between the $W^+$ or $W^-$ decay plane and the $\bar{t}W^+b$ or $tW^-\bar{b}$ plane in the $t$ or $\bar{t}$ quark frame;
- $m_{f1\bar{f}1}$ or $m_{f2\bar{f}2}$: invariant mass of the $f_1\bar{f}_1$ or $f_2\bar{f}_2$ system.

# Anomalous couplings in H->ZZ*->4l decays (CMS)

## D0- and DCP

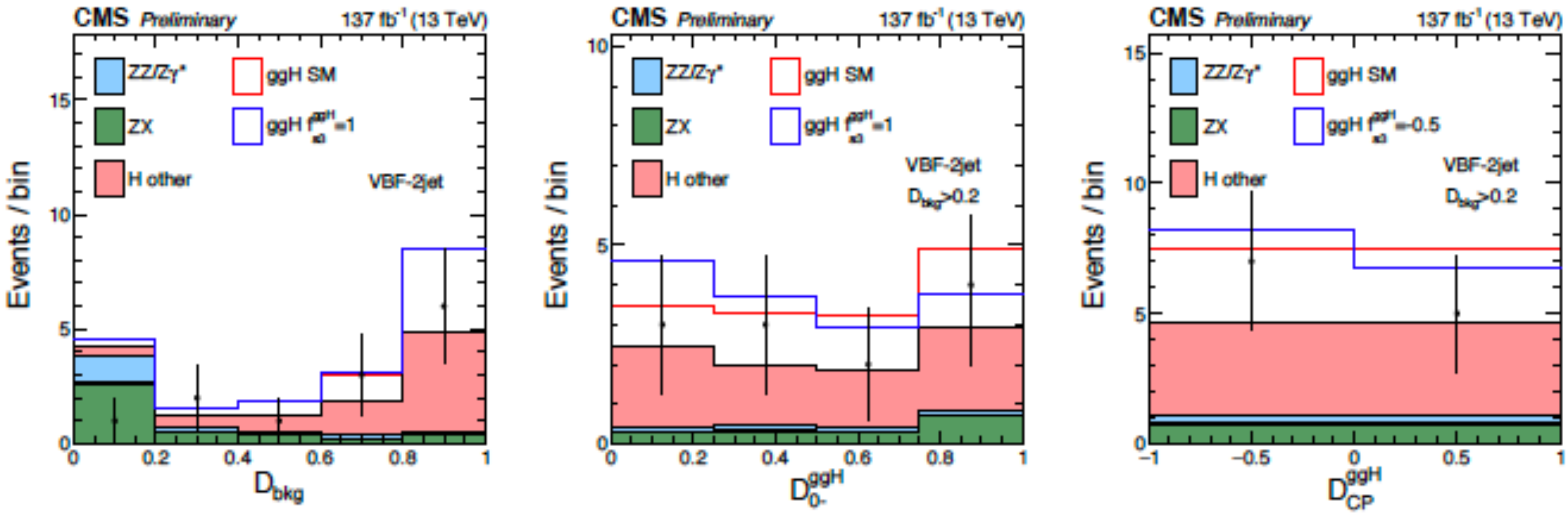



Figure 4: Distribution of the $\mathcal{D}_{\rm bkg}$ (left), $\mathcal{D}_{0-}^{\rm ggH}$ (middle), and $\mathcal{D}_{\rm CP}^{\rm ggH}$ (right) discriminants in the VBF-2jet category in Scheme 1. The latter two distributions are shown with the requirement $\mathcal{D}_{\rm bkg} > 0.2$ in order to enhance signal over the background contribution.

# Anomalous couplings in H->ZZ*->4l decays (CMS)

## Schemes for observables

| Category | Selection | Observables $\vec{x}$ for fitting |
|---|---|---|
| **Scheme 1** | | |
| Untagged | none below | $\mathcal{D}_{\text{bkg}}$ |
| VBF-1jet | $\mathcal{D}_{\text{1jet}}^{\text{VBF}} > 0.7$ | $\mathcal{D}_{\text{bkg}}$ |
| VBF-2jet | $\mathcal{D}_{\text{2jet}}^{\text{VBF}} > 0.5$ | $\mathcal{D}_{\text{bkg}}, \mathcal{D}_{\text{2jet}}^{\text{VBF}}, \mathcal{D}_{0-}^{\text{ggH}}, \mathcal{D}_{\text{CP}}^{\text{ggH}}$ |
| VH-leptonic | see Sec. 3 | $\mathcal{D}_{\text{bkg}}$ |
| VH-hadronic | $\mathcal{D}_{\text{2jet}}^{\text{VH}} > 0.5$ | $\mathcal{D}_{\text{bkg}}$ |
| $\text{t}\bar{\text{t}}\text{H}$-leptonic | see Sec. 3 | $\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0-}^{\text{t}\bar{\text{t}}\text{H}}$ |
| $\text{t}\bar{\text{t}}\text{H}$-hadronic | see Sec. 3 | $\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0-}^{\text{t}\bar{\text{t}}\text{H}}$ |
| **Scheme 2** | | |
| Untagged | none below | $\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0-}^{\text{dec}}, \mathcal{D}_{0\text{h}+}^{\text{dec}}, \mathcal{D}_{\Lambda1}^{\text{dec}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\text{dec}}, \mathcal{D}_{\text{CP}}^{\text{dec}}, \mathcal{D}_{\text{int}}^{\text{dec}}$ |
| Boosted | $p_{\text{T}}^{4\ell} > 120$ GeV | $\mathcal{D}_{\text{bkg}}, p_{\text{T}}^{4\ell}$ |
| VBF-1jet | $\mathcal{D}_{\text{1jet}}^{\text{VBF}} > 0.7$ | $\mathcal{D}_{\text{bkg}}, p_{\text{T}}^{4\ell}$ |
| VBF-2jet | $\mathcal{D}_{\text{2jet}}^{\text{VBF}} > 0.5$ | $\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0-}^{\text{VBF+dec}}, \mathcal{D}_{0\text{h}+}^{\text{VBF+dec}}, \mathcal{D}_{\Lambda1}^{\text{VBF+dec}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\text{VBF+dec}}, \mathcal{D}_{\text{CP}}^{\text{VBF}}, \mathcal{D}_{\text{int}}^{\text{VBF}}$ |
| VH-leptonic | see Sec. 3 | $\mathcal{D}_{\text{bkg}}, p_{\text{T}}^{4\ell}$ |
| VH-hadronic | $\mathcal{D}_{\text{2jet}}^{\text{VH}} > 0.5$ | $\mathcal{D}_{\text{bkg}}, \mathcal{D}_{0-}^{\text{VH+dec}}, \mathcal{D}_{0\text{h}+}^{\text{VH+dec}}, \mathcal{D}_{\Lambda1}^{\text{VH+dec}}, \mathcal{D}_{\Lambda1}^{Z\gamma,\text{VH+dec}}, \mathcal{D}_{\text{CP}}^{\text{VH}}, \mathcal{D}_{\text{int}}^{\text{VH}}$ |

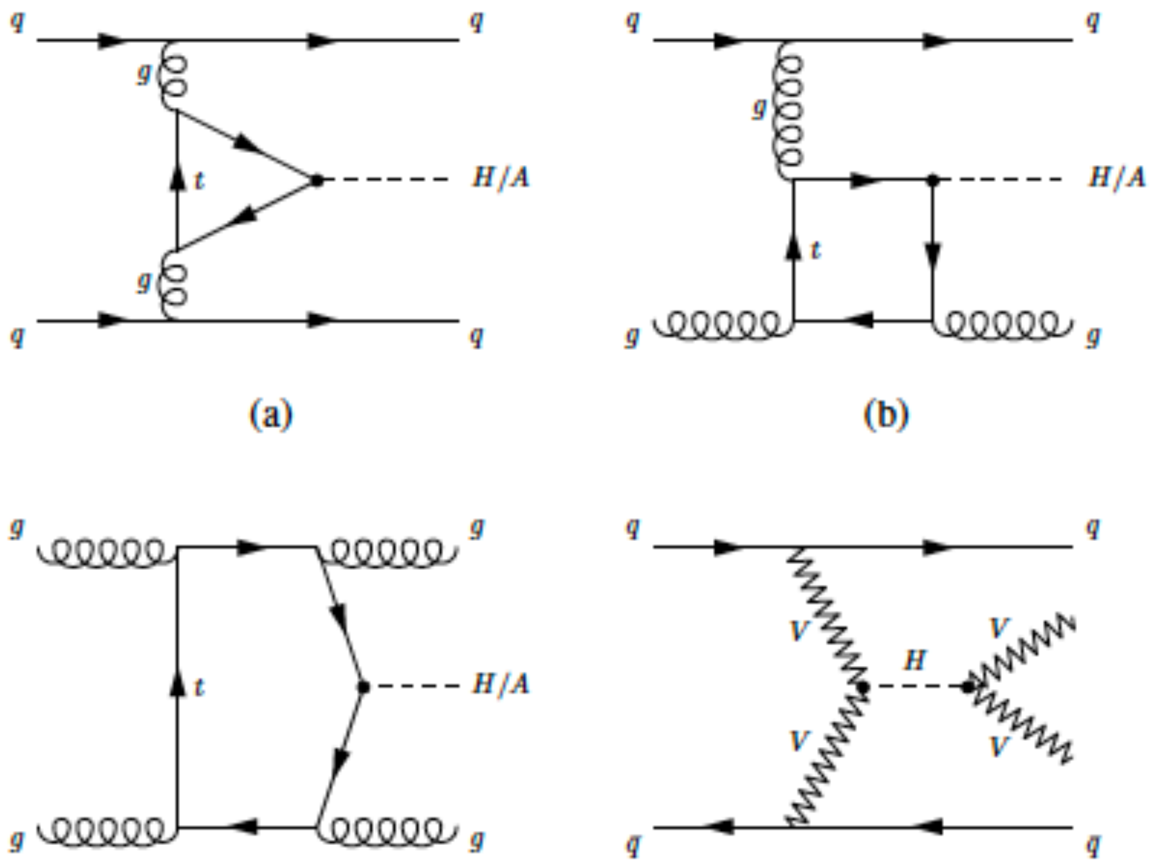
# Constraints on Higgs couplings in $H \rightarrow WW^* \rightarrow e\nu\mu\nu + JJ$ (ATLAS)

**Begin backup slides**

New!

# Constraints on Higgs couplings in H->WW*->eνμν+JJ (ATLAS)

## Leading diagrams contributing to ggH anf VBF production with 2 jets




New!

# Constraints on Higgs couplings in $H \to WW^* \to e\nu\mu\nu$+JJ (ATLAS)

## Selection criteria and BDT input variables

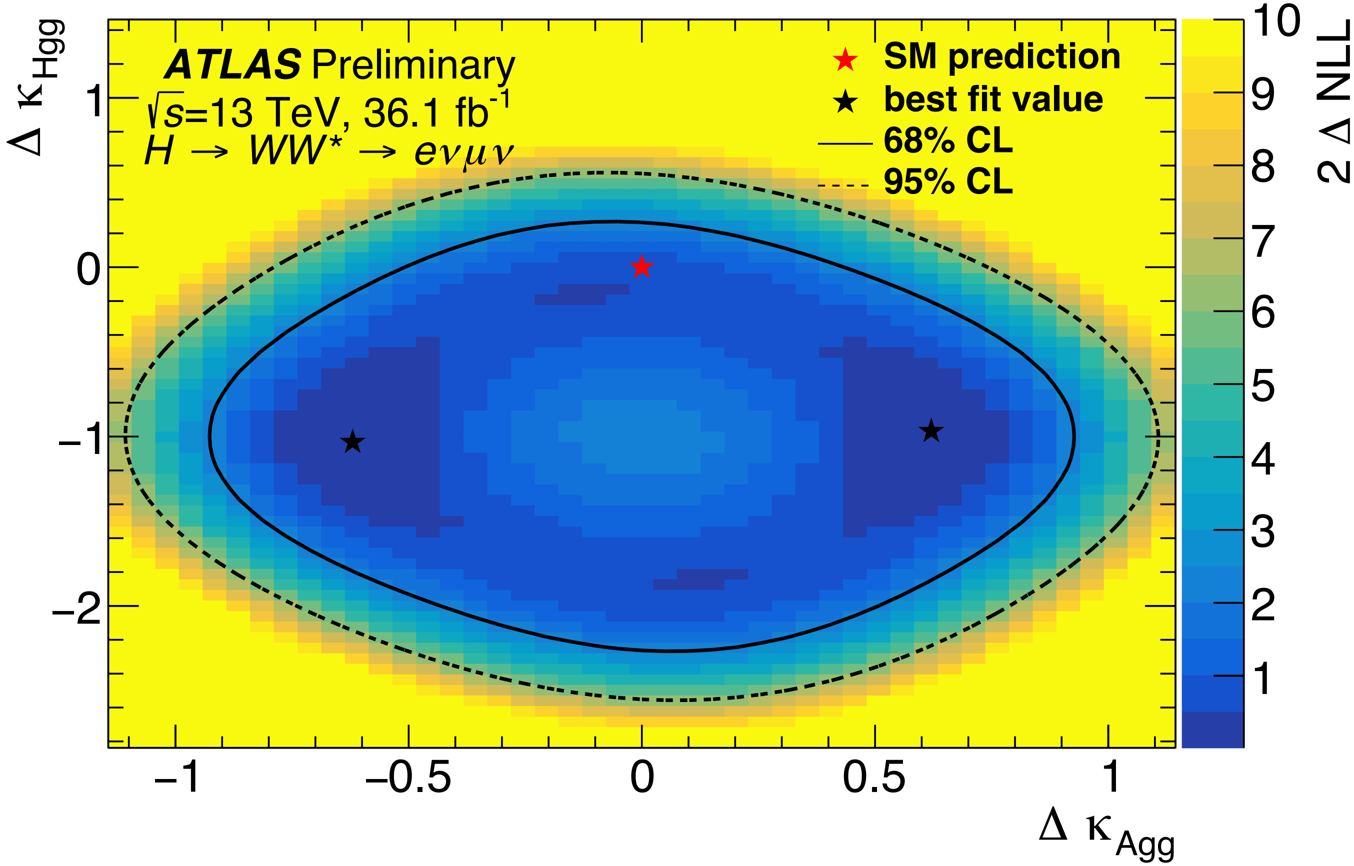
Table 3: Event selection criteria used to define the signal regions for the ggF + 2 jets and VBF event categories.

| | ggF + 2 jets | VBF |
|---|---|---|
| Preselection | Two isolated, different-flavour leptons ($\ell = e, \mu$) with opposite charge | |
| | $p_T^{\text{lead}} > 22$ GeV, $p_T^{\text{sublead}} > 15$ GeV | |
| | $m_{\ell\ell} > 10$ GeV | |
| | $N_{\text{jet}} \geq 2$ | |
| Background rejection | $N_{b-\text{jet},(p_T>20\text{ GeV})} = 0$ | |
| | $m_{\tau\tau} < 66$ GeV | |
| | $\Delta R_{jj} > 1.0$ | central jet veto |
| | $p_{T,\ell\ell} > 20$ GeV | outside lepton veto |
| | $m_{\ell\ell} < 90$ GeV | |
| | $m_T < 150$ GeV | |
| BDT input variables | $m_{\ell\ell}$, $m_T$, $p_{T,\ell\ell}$, $\Delta\phi_{\ell\ell}$ | $m_{jj}$, $\Delta Y_{jj}$, $m_{\ell\ell}$, $m_T$, $\Delta\phi_{\ell\ell}$ |
| | $\min \Delta R(\ell_1, j_i)$, $\min \Delta R(\ell_2, j_i)$ | $\sum_\ell C_\ell$, $\sum_{\ell,j} m_{\ell,j}$, $p_T^{\text{tot}}$ |

New

# Constraints on Higgs couplings in H->WW*->eνμν+JJ (ATLAS)

## 2 dimensional scan of $\kappa_{Agg}$ vs $\kappa_{Hgg}$




New!

# Test of CP invariance in VBF in H->$\tau\tau$ (ATLAS)

## Begin backup slides

# Test of CP invariance in VBF in H->$\tau\tau$ (ATLAS)

## Strategy

- Generally, signal/background strategy follows observation analysis
- Study four event classes
  - Hadronic, semileptonic, same-flavour (SF) and different-flavour (DF) leptonic

$\Rightarrow$ Improvement w.r.t. Run-I analysis (only leptonic and semi-leptonic)

# Test of CP invariance in VBF in H->$\tau\tau$ (ATLAS)

## Signal-background separation

- Separate BDT per class
- Split in High BDT-score region (signal) and control region (bg normalisation)
- Few other cats for better control background normalisation

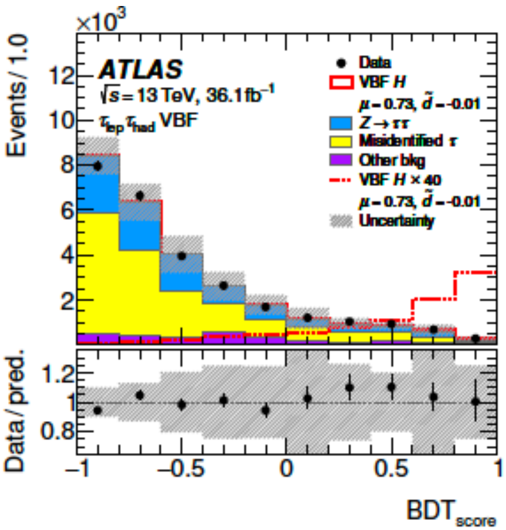
Table 2: Summary of the event selection requirements for the four analysis channels. In the case of the $p_T$ requirements on the $\tau$-lepton decay candidates, the asterisk marks the lowest $p_T$ threshold, which varies depending on the trigger used. Details of this are given in Ref. [41]. The transverse momentum of the visible decay products of the $\tau$-lepton candidate with the higher (lower) transverse momentum is denoted by $p_T^{\tau_1}$ ($p_T^{\tau_2}$). The input variables used for the BDT training and the $\text{BDT}_{\text{score}}$ threshold used to define the signal regions are also reported.

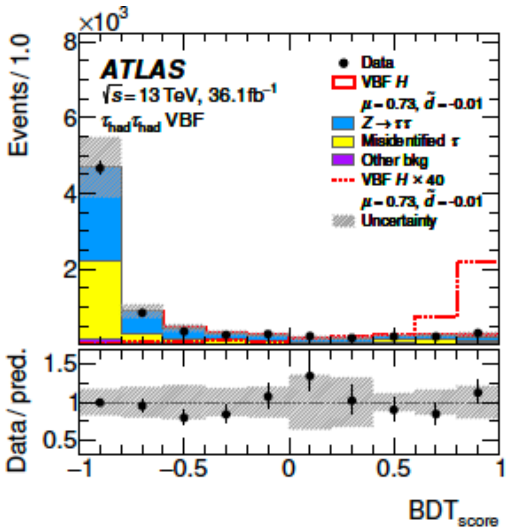
| Channel | $\tau_{\text{lep}}\tau_{\text{lep}}$ SF | $\tau_{\text{lep}}\tau_{\text{lep}}$ DF | $\tau_{\text{lep}}\tau_{\text{had}}$ | $\tau_{\text{had}}\tau_{\text{had}}$ |
|---|---|---|---|---|
| Preselection | Two isolated $\tau$-lepton decay candidates with opposite electric charge | | | |
| | $p_T^{\tau_1} > 19^*/15^*$ GeV $(\mu/e)$ | $p_T^{e} > 18$ GeV | $p_T^{\tau_{\text{had}}} > 30$ GeV | $p_T^{\tau_1} > 40$ GeV |
| | $p_T^{\tau_2} > 10/15^*$ GeV $(\mu/e)$ | $p_T^{\mu} > 14$ GeV | $p_T^{\tau_{\text{lep}}} > 21^*$ GeV | $p_T^{\tau_2} > 30$ GeV |
| | $m_{\tau\tau}^{\text{coll}} > m_Z - 25$ GeV | | $m_T < 70$ GeV | $0.8 < \Delta R_{\tau\tau} < 2.5$ |
| | $30 < m_{\ell\ell} < 75$ GeV | $30 < m_{\ell\ell} < 100$ GeV | | $\lvert\Delta\eta_{\tau\tau}\rvert < 1.5$ |
| | $E_T^{\text{miss}} > 55$ GeV | $E_T^{\text{miss}} > 20$ GeV | | $E_T^{\text{miss}} > 20$ GeV |
| | $E_T^{\text{miss, hard}} > 55$ GeV | | | |
| | $N_{b\text{-jets}} = 0$ | | | |
| VBF topology | $N_{\text{jets}} \geq 2$, $p_T^{j_2} > 30$ GeV, $m_{jj} > 300$ GeV, $\lvert\Delta\eta_{jj}\rvert > 3$ | | | |
| | $p_T^{j_1} > 40$ GeV | | | $p_T^{j_1} > 70$ GeV, $\lvert\eta_{j_1}\rvert < 3.2$ |
| BDT input variables | $m_{\tau\tau}^{\text{MMC}}$, $m_{jj}$, $\Delta R_{\tau\tau}$, $C_{jj}(\tau_1)$, $C_{jj}(\tau_2)$, $p_T^{\text{tot}}$ | | | |
| | $m_{\tau\tau}^{\text{vis}}$, $m_T^{\tau_1,E_T^{\text{miss}}}$, $p_T^{j_3}$ | | $C(\phi^{\text{miss}})/\sqrt{2}$ | |
| | $\Delta\phi_{\tau\tau}$ | $E_T^{\text{miss}}/p_T^{\tau_1}$, $E_T^{\text{miss}}/p_T^{\tau_2}$ | $m_{\tau\tau}^{\text{vis}}$, $\lvert\Delta\eta_{\tau\tau}\rvert$ | $p_T^{\tau\tau E_T^{\text{miss}}}$, $\lvert\Delta\eta_{\tau\tau}\rvert$ |
| Signal region | $\text{BDT}_{\text{score}} > 0.78$ | | $\text{BDT}_{\text{score}} > 0.86$ | $\text{BDT}_{\text{score}} > 0.87$ |

# Test of CP invariance in VBF in H->$\tau\tau$ (ATLAS)

## Strategy

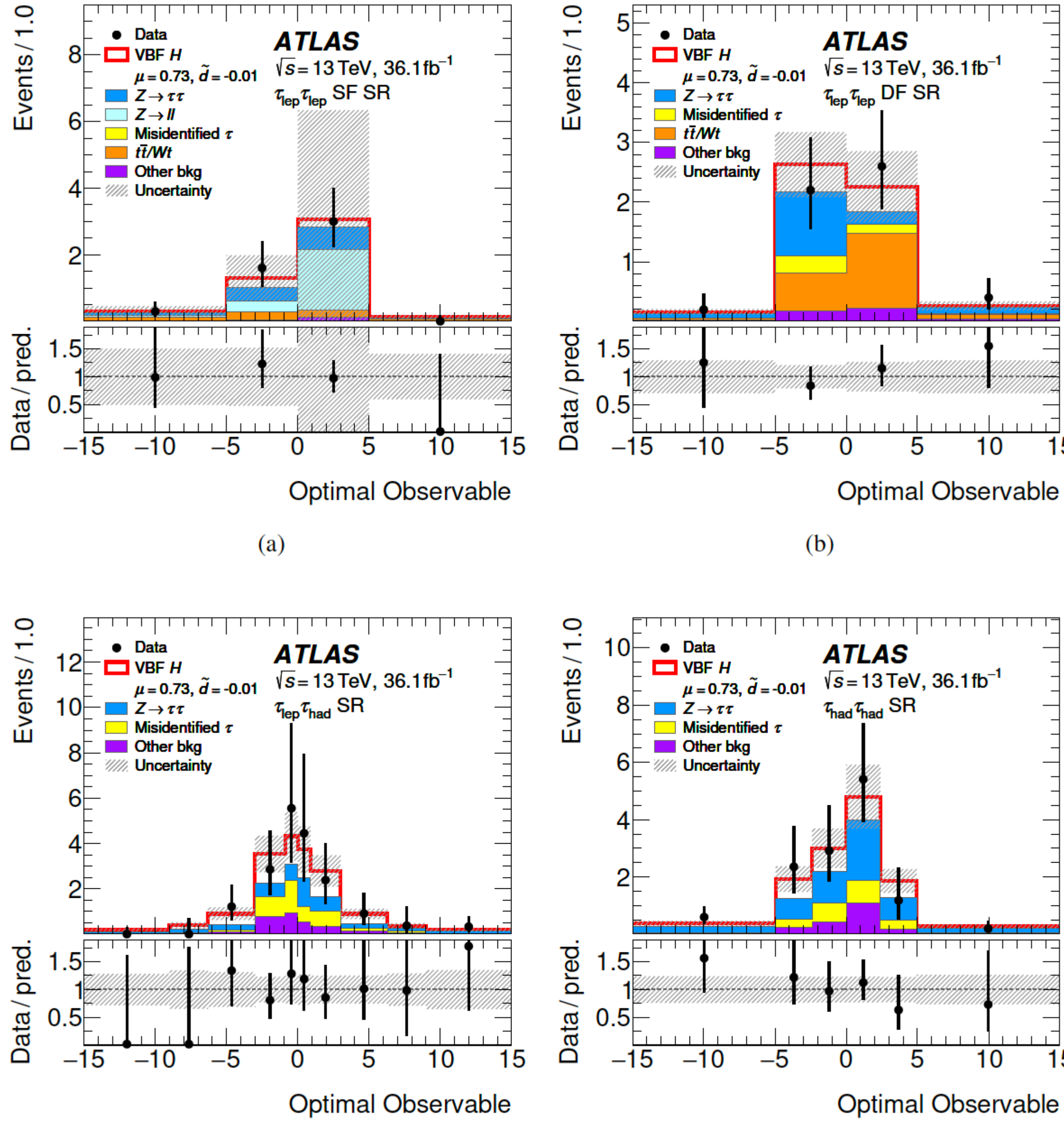
- Generally, signal/background strategy follows observation analysis
- Study four event classes
  - Hadronic, semileptonic, same-flavour (SF) and different-flavour (DF) leptonic
  - $\Rightarrow$ Improvement w.r.t. Run-I analysis (only leptonic and semi-leptonic)
- Signal-background separation
  - Separate BDT per class
  - Split in High BDT-score region (signal) and control region (bg norm)
  - Few other cats for better control background normalisation
- Fit:
  - Simultaneous to Signal and Control region
  - Signal strength floating parameter
  - Signal templates by reweighing SM signal events



# Test of CP invariance in VBF in H->ττ (ATLAS)

- Optimal observable postfit
- Leptonic channel most sensitive



(a) (b) (c) (d)

| Channel | ⟨Optimal Observable⟩ |
|---|---|
| $\tau_{\text{lep}}\tau_{\text{lep}}$ SF | $-0.54 \pm 0.72$ |
| $\tau_{\text{lep}}\tau_{\text{lep}}$ DF | $0.71 \pm 0.81$ |
| $\tau_{\text{lep}}\tau_{\text{had}}$ | $0.74 \pm 0.78$ |
| $\tau_{\text{had}}\tau_{\text{had}}$ | $-1.13 \pm 0.65$ |
| Combined | $-0.19 \pm 0.37$ |

# myosotis

- Perhaps ratio higgs cross sectioon in pp vs total cross section
- Backup: plots with phi_cp in DY. Explain the correlated vertex smearing effect
- What is established for Higgs-gamma vertex?