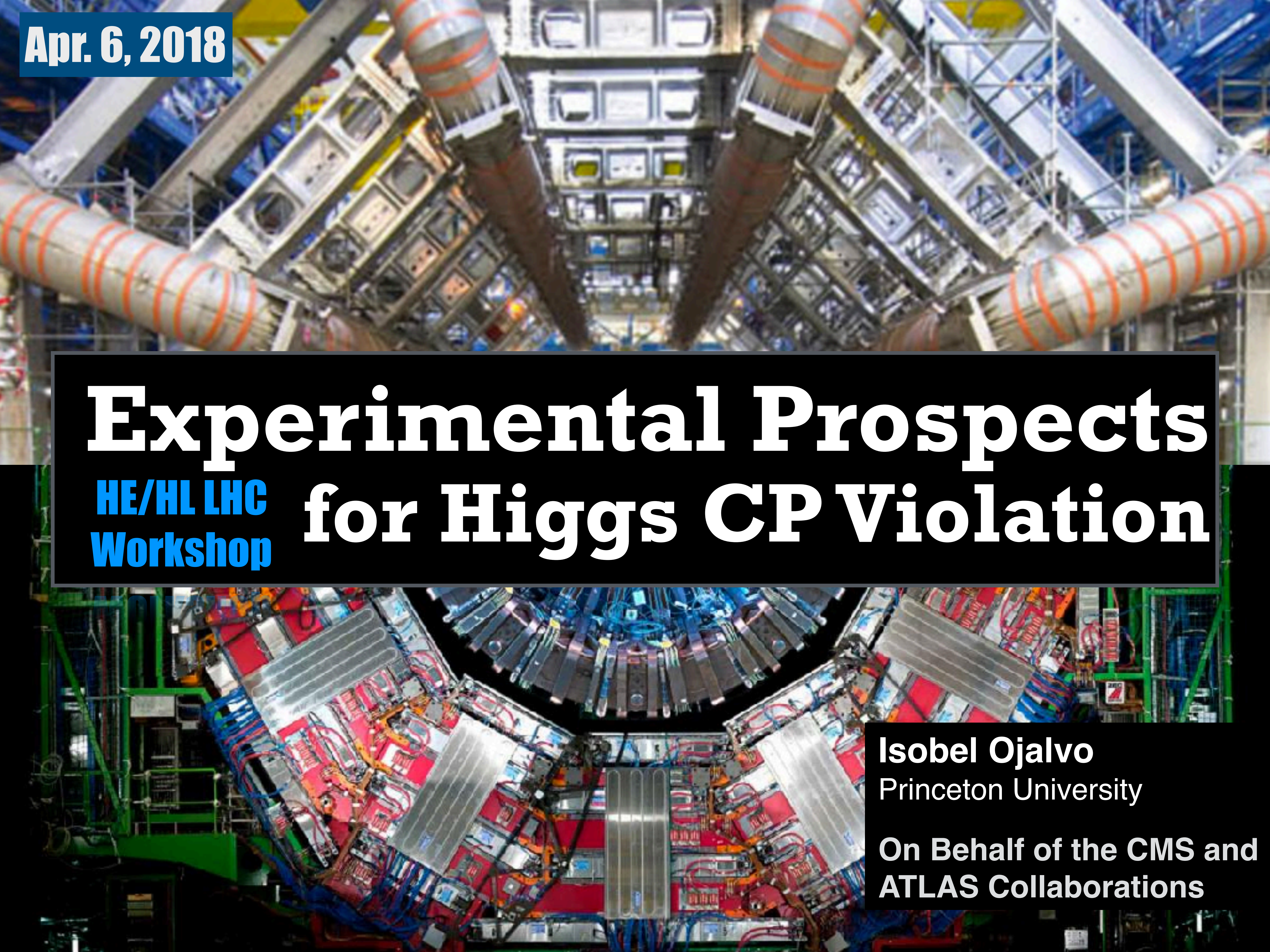
Apr. 6, 2018



Experimental Prospects for Higgs CP Violation

HE/HL LHC Workshop

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On Behalf of the CMS and ATLAS Collaborations

Why Probe SM Charge Parity Violation

- Very early in the universe one might expect equal numbers of baryons and anti-baryons
- Today the universe is matter dominated (no evidence for anti-galaxies, etc.)
- From Big Bang Nucleosynthesis obtain the matter/anti-matter asymmetry

To generate this initial asymmetry three conditions must be met (Sakharov, 1967):

- **Baryon number violation**

- **C and CP violation**, if CP is conserved for a reaction which generates a net number of baryons over anti-baryons there would be a CP conjugate reaction generating a net number of anti-baryons

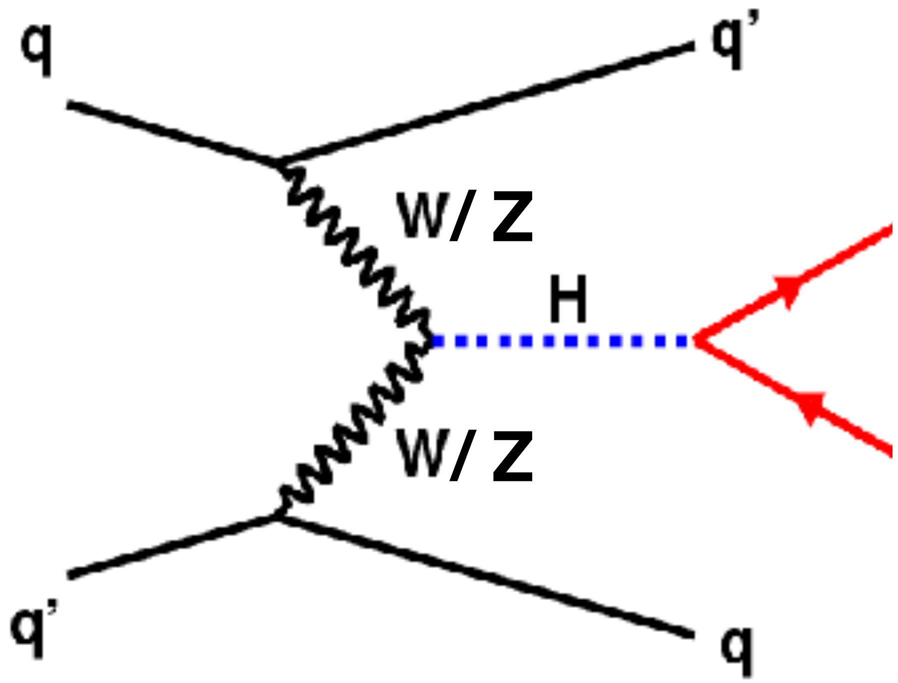
- **Departure from thermal equilibrium** in thermal equilibrium any baryon number violating process will be balanced by the inverse reaction

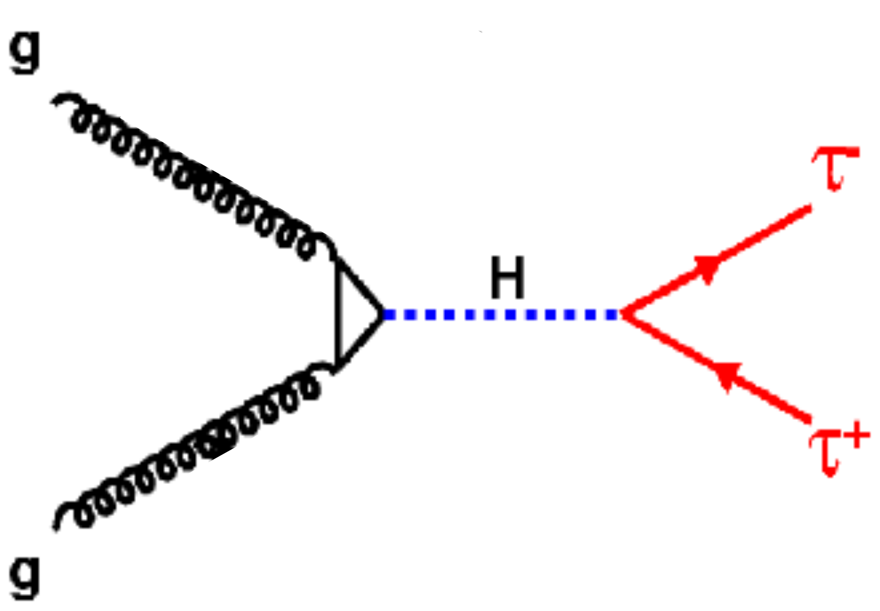
- CP Violation is an essential aspect of our understanding of the universe
- Can the SM provide the necessary CP violation?
- To date CP violation has been observed only in the quark sector

Why use the Higgs to Study CP/Anomalous Couplings?

Higgs couples to SM particles (and potentially couples anomalously) on the **production** and the **decay side**

- Opportunity to look for Anomalous Couplings by classifying production/decay kinematics





Anomalous Couplings

Scattering amplitude describing the interaction between a spin-zero H boson and two spin-one gauge bosons VV (ZZ, Zγ, γγ, WW, gg):

$$A(\mathrm{HVV}) \sim \left[a_1^{\mathrm{VV}} + \frac{\kappa_1^{\mathrm{VV}} q_1^2 + \kappa_2^{\mathrm{VV}} q_2^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\kappa_3^{\mathrm{VV}} (q_1 + q_2)^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2} \right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^* + a_2^{\mathrm{VV}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + a_3^{\mathrm{VV}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

Only tree-level contribution,
$a_1^{ZZ} = a_1^{WW}$ (custodial symmetry)

Anomalous Couplings (example on formalism)

It is convenient to measure the **effective cross-section ratios rather** than the **anomalous couplings**:

- Cancellation of systematic uncertainties in the ratio [Bounded between 0 and 1]
- Does not depend on coupling convention

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right),$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right),$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda 1}/\left(\Lambda_1\right)^4 + \ldots}, \qquad \phi_{\Lambda 1},$$

$$f_{\Lambda 1}^{Z\gamma} = \frac{\tilde{\sigma}_{\Lambda 1}^{Z\gamma}/\left(\Lambda_1^{Z\gamma}\right)^4}{|a_1|^2\sigma_1' + \tilde{\sigma}_{\Lambda 1}^{Z\gamma}/\left(\Lambda_1^{Z\gamma}\right)^4 + \ldots}, \qquad \phi_{ai}^{Z\gamma},$$

Higgs Spin, Anomalous Couplings, CP: Run 1

CMS

Study of the mass and spin-parity of the Higgs boson candidate via its decays to Z boson pairs CMS-HIG-12-041, CMS arXiv:1212.6639 - **fa3 in H→4ℓ & hypothesis testing**

Measurement of the properties of a Higgs boson in the four-lepton final state CMS arXiv:1312.5353, CMS-HIG-13-002 - **fa3 in H→4ℓ & more hypothesis testing**

Constraints on the spin-parity and anomalous HVV couplings of the Higgs boson in proton collisions at 7 and 8 TeV CMS arXiv:1411.3441, CMS-HIG-14-018 - **fa3,fa2,fΛ1 in H→WW,ZZ,Zγ*,γ*γ* & testing**

Limits on the Higgs boson lifetime and width from its decay to four charged leptons CMS arXiv:1507.06656, CMS-HIG-14-036 - **fΛQ in H*→4ℓ offshell**

Combined search for anomalous pseudoscalar HVV couplings in VH production and H to VV decay CMS arXiv:1602.04305, CMS-HIG-14-035 - **fa3 in VH(→bb) & combination**

ATLAS

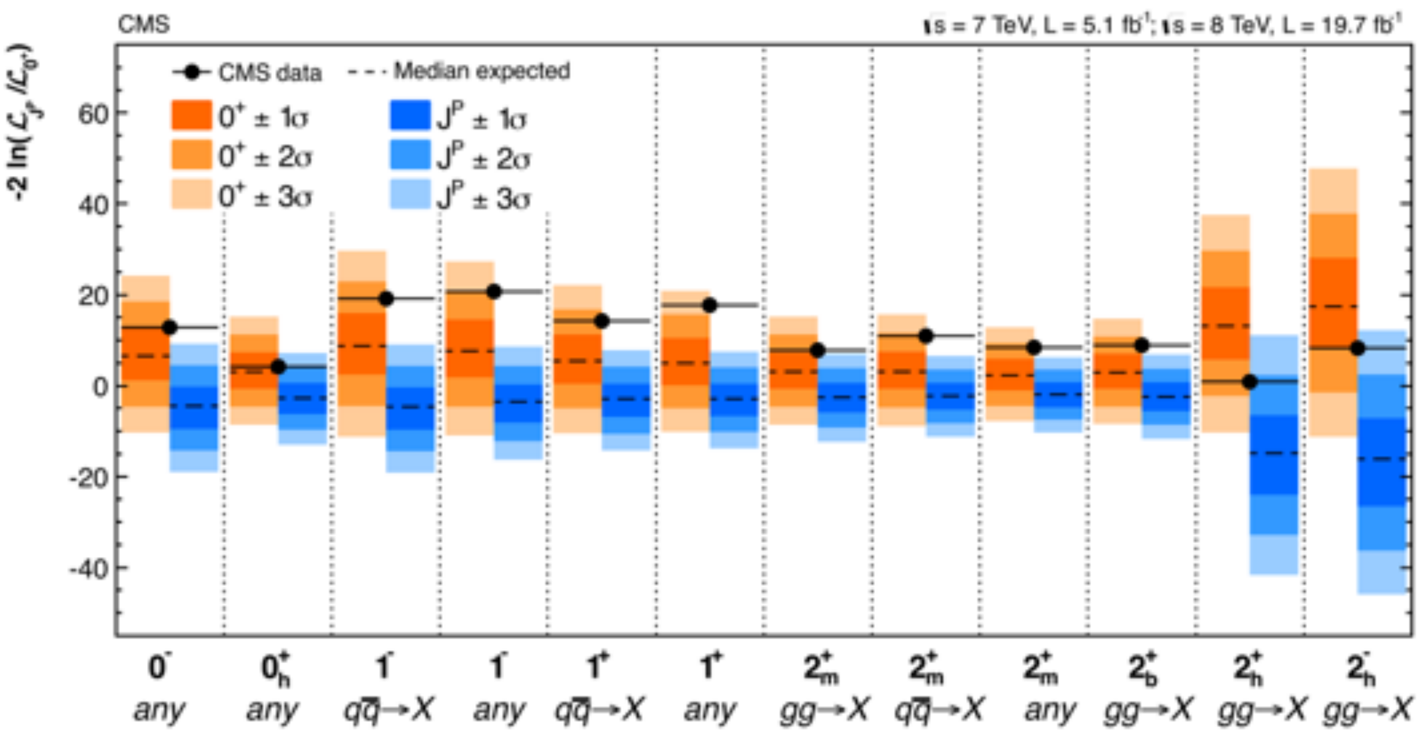
Evidence for the spin-0 nature of the Higgs boson using ATLAS data ATLAS arXiv:1307.1432 - hypothesis testing - **{fa3},{fa2} in H→ZZ,WW & hypothesis testing**

Study of the spin and parity of the Higgs boson in diboson decays with the ATLAS detector ATLAS arXiv:1506.05669

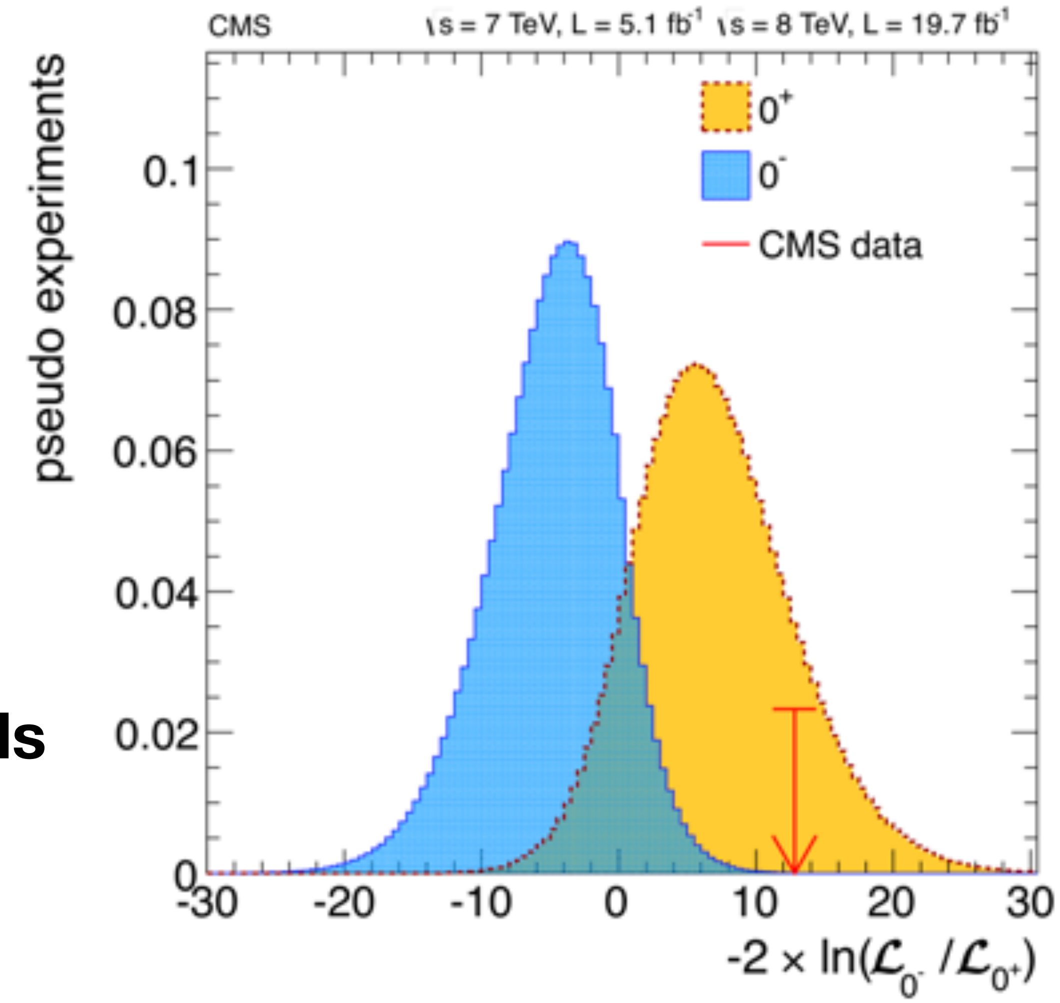
Test of CP Invariance in vector-boson fusion production of the Higgs boson using the Optimal Observable method in the ditau decay channel with the ATLAS detector ATLAS arXiv:1602.04516 - **{fa3} in VBF(H→ττ)**

Current constraints

CP properties of H(125) have been studied in bosonic decays



Limits set using information on the event yields



Constraints on anomalous HVV couplings → additional information on Higgs CP

Although **hypothesis of pure pseudoscalar state is ruled out**, the H(125) state **could be a mixture of CP-even and CP-odd** states (with small pseudoscalar component)

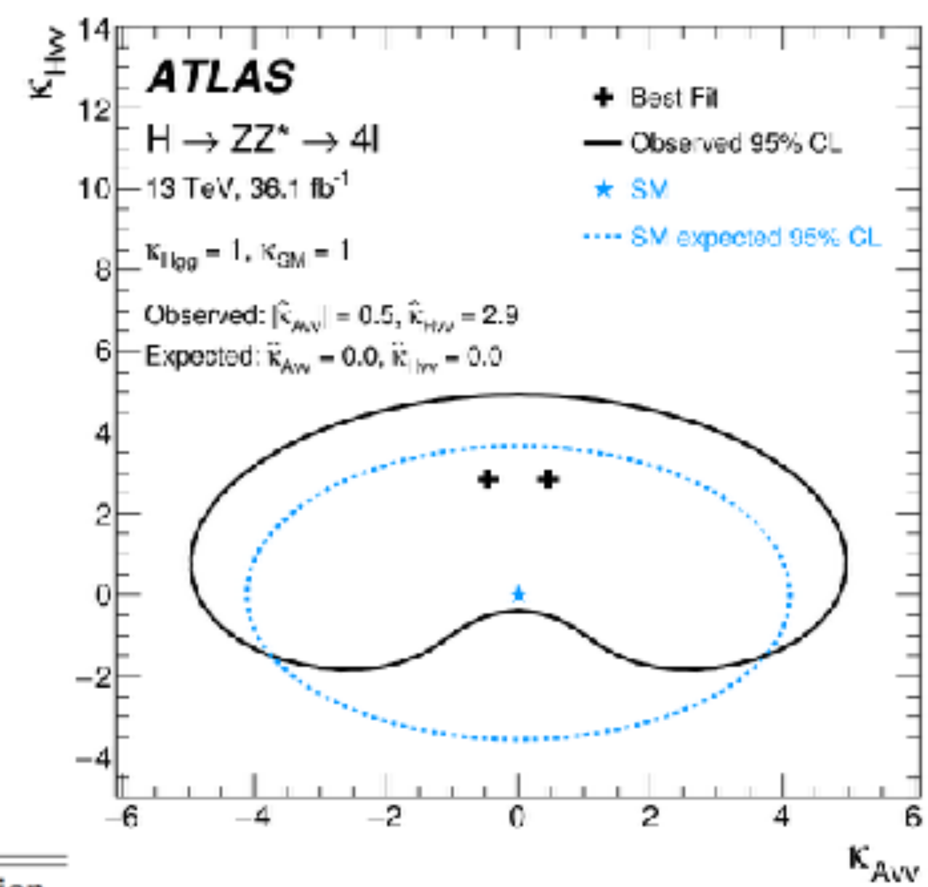
Run 2 HVV ATLAS

[arXiv: 1712.02304](https://arxiv.org/abs/1712.02304)

ATLAS Study of the tensor structure of the Higgs through **additional BSM terms** added to the effective Lagrangian

$$\mathcal{L}_0^V = \Bigg\{ \kappa_{\rm SM}\left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W^+_\mu W^{-\mu}\right] - \frac{1}{4}\left[\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tan\alpha\, \kappa_{Agg} g_{Agg} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right] - \frac{1}{4}\frac{1}{\Lambda}\left[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha\, \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \frac{1}{2}\frac{1}{\Lambda}\left[\kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + \tan\alpha\, \kappa_{AWW} W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\Bigg\} X_0$$

$\mathcal{X}_0$ defines a new bosonic state
Coupling terms describe CP-even and CP-odd interactions



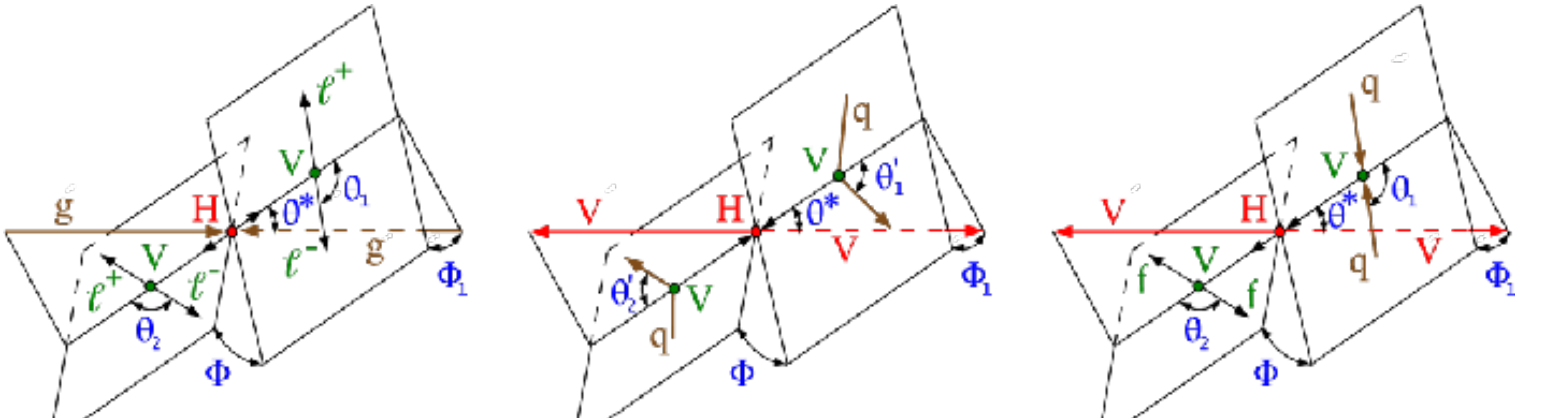
BSM coupling $\kappa_{\rm BSM}$	Fit configuration	Expected conf. inter.	Observed conf. inter.	Best-fit $\hat{\kappa}_{\rm BSM}$	Best-fit $\hat{\kappa}_{\rm SM}$	Deviation from SM
κ_{Agg}	($\kappa_{Hgg} = 1, \kappa_{\rm SM} = 1$)	[−0.47, 0.47]	[−0.68, 0.68]	±0.43	-	1.8σ
κ_{HVV}	($\kappa_{Hgg} = 1, \kappa_{\rm SM} = 1$)	[−2.9, 3.2]	[0.8, 4.5]	2.9	-	2.3σ
κ_{HVV}	($\kappa_{Hgg} = 1, \kappa_{\rm SM}$ free)	[−3.1, 4.0]	[−0.6, 4.2]	2.2	1.2	1.7σ
κ_{AVV}	($\kappa_{Hgg} = 1, \kappa_{\rm SM} = 1$)	[−3.5, 3.5]	[−5.2, 5.2]	±2.9	-	1.4σ
κ_{AVV}	($\kappa_{Hgg} = 1, \kappa_{\rm SM}$ free)	[−4.0, 4.0]	[−4.4, 4.4]	±1.5	1.2	0.5σ

Mostly sensitive to anomalous couplings in production

Event categories are defined to target regions where a given anomalous coupling would have a large yield

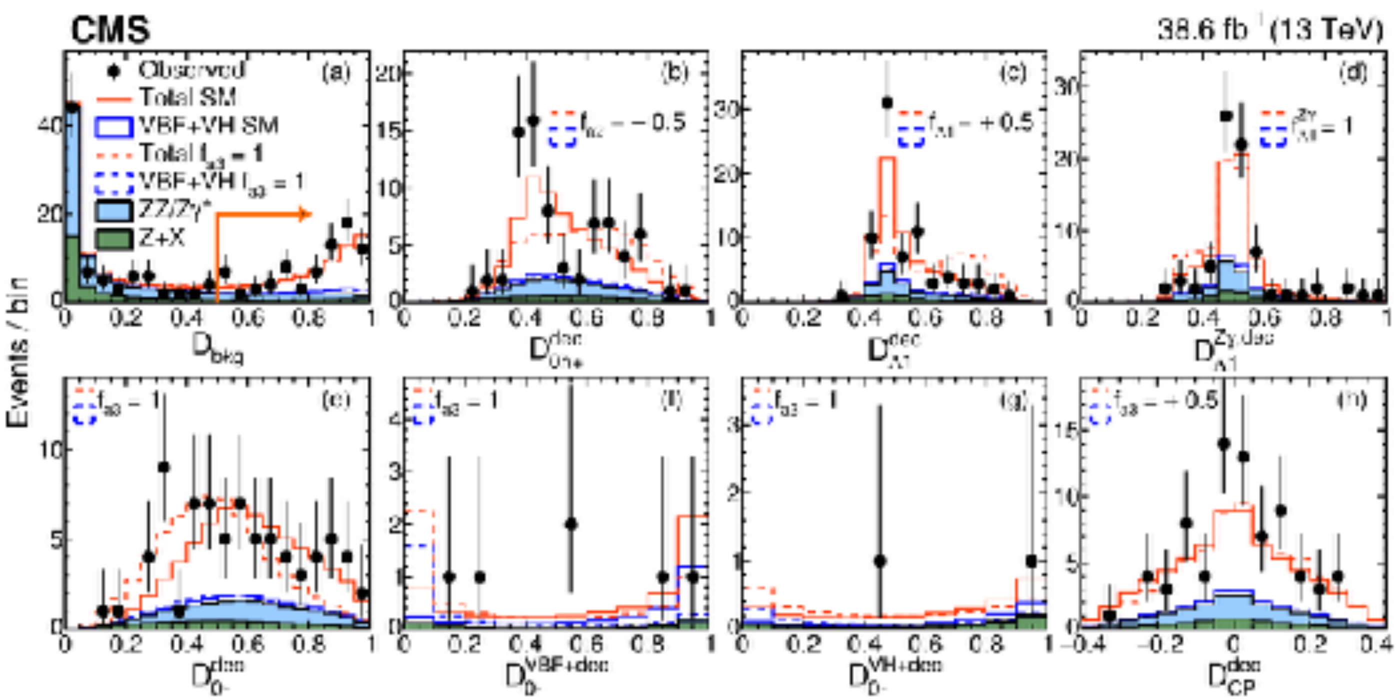
Limits are set using using only the event yield per category

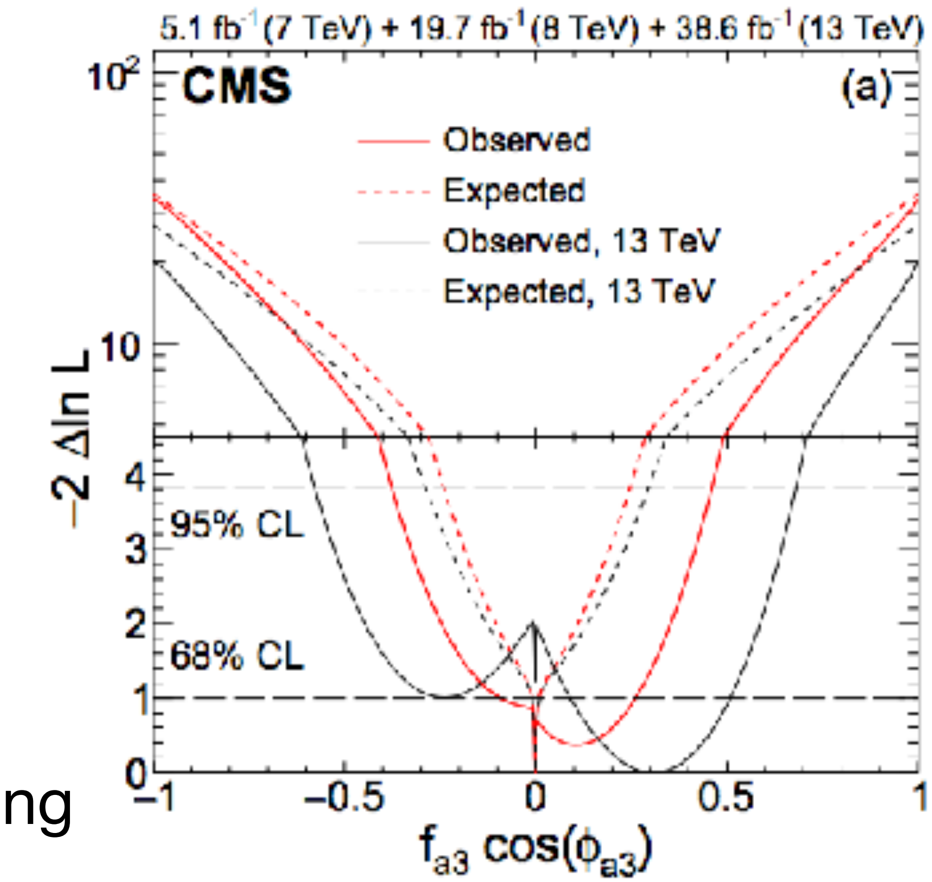
Run 2 HVV CMS



gg→H→VV→4l **VBF→VV** **qq→V→VH→VV**

Sensitive to anomalous couplings in production, decay





Parameter	Observed	Expected
$f_{a3}\cos(\phi_{a3})$	$0.00^{+0.26}_{-0.09}$ $[-0.38, 0.46]$	$0.000^{+0.010}_{-0.010}$ $[-0.25, 0.25]$
$f_{a2}\cos(\phi_{a2})$	$0.01^{+0.12}_{-0.02}$ $[-0.04, 0.43]$	$0.000^{+0.009}_{-0.008}$ $[-0.06, 0.19]$
$f_{\Lambda1}\cos(\phi_{\Lambda1})$	$0.02^{+0.08}_{-0.06}$ $[-0.49, 0.18]$	$0.000^{+0.003}_{-0.002}$ $[-0.60, 0.12]$
$f^{Z\gamma}_{\Lambda1}\cos(\phi^{Z\gamma}_{\Lambda1})$	$0.26^{+0.30}_{-0.35}$ $[-0.40, 0.79]$	$0.000^{+0.019}_{-0.022}$ $[-0.37, 0.71]$

4 Parameters probed including CP violation parameter f_{a3}

arXiv: 1707.00541

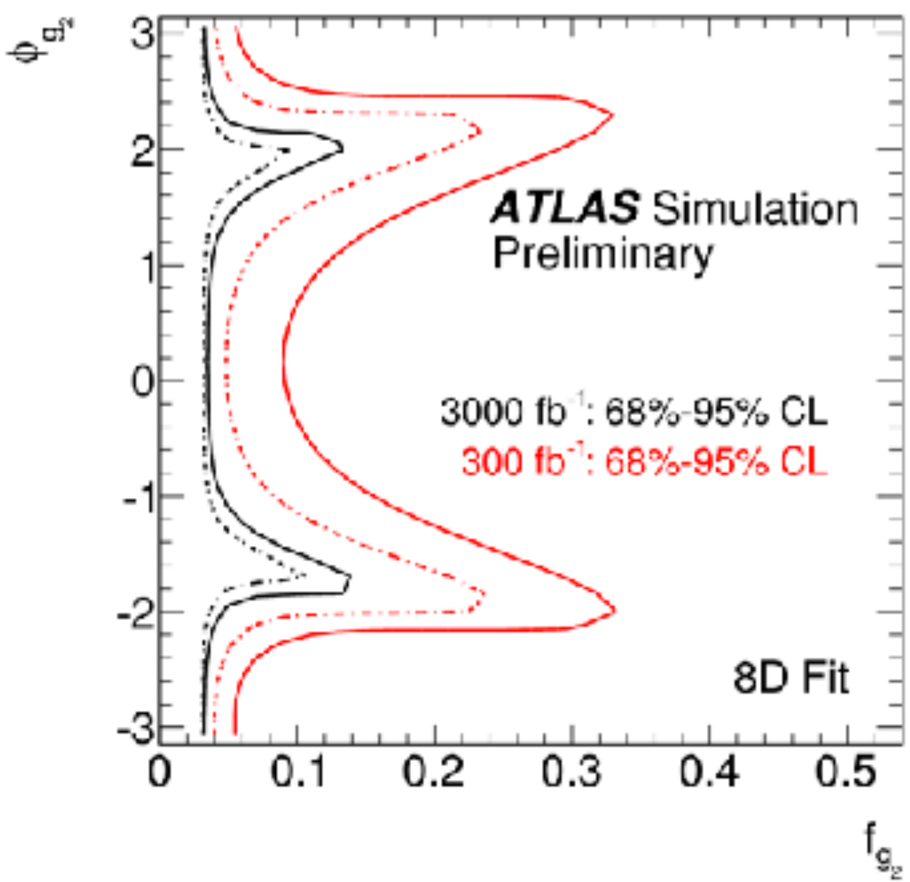
HL-LHC Projections ATLAS

$$a_1 = g_1 \frac{m_V^2}{m_H^2} + \frac{s}{m_H^2}\left(2g_2 + g_3 \frac{s}{\Lambda^2}\right);$$

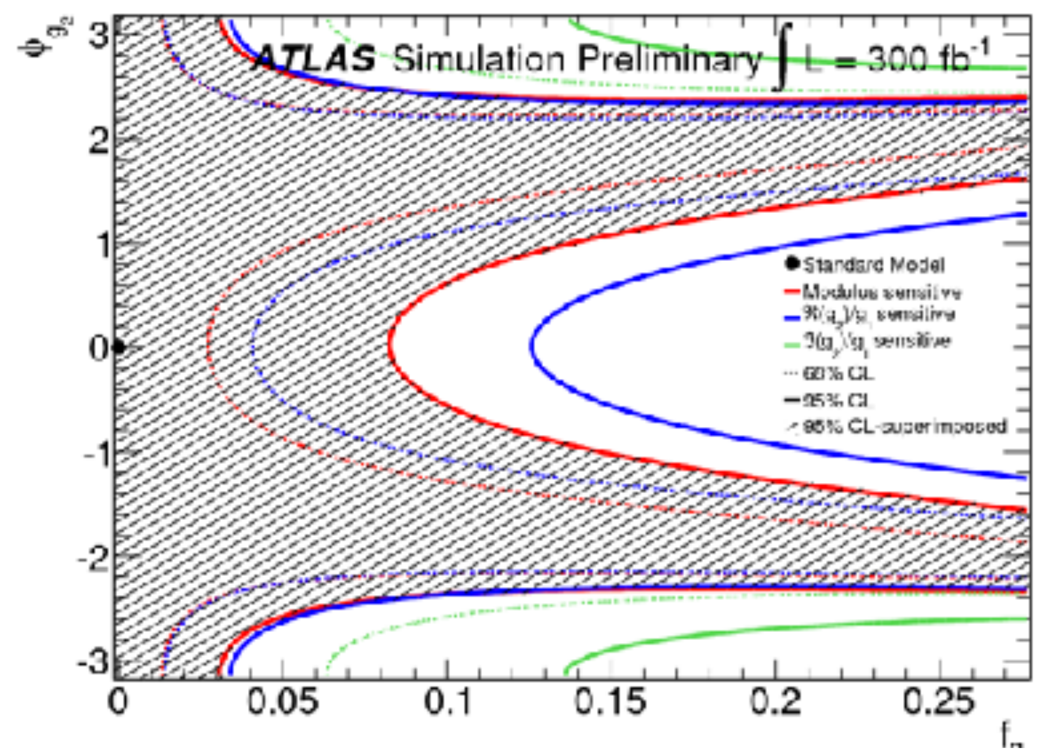
$$a_2 = -\left(2g_2 + g_3 \frac{s}{\Lambda^2}\right); \quad a_3 = -2g_4,$$

$$f_{g_i} = \frac{|g_i|^2 \sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}; \quad \phi_{g_i} = \arg\left(\frac{g_i}{g_1}\right)$$

Projection performed 2 dimensional fit using BDT trained to separate signal from ZZ background

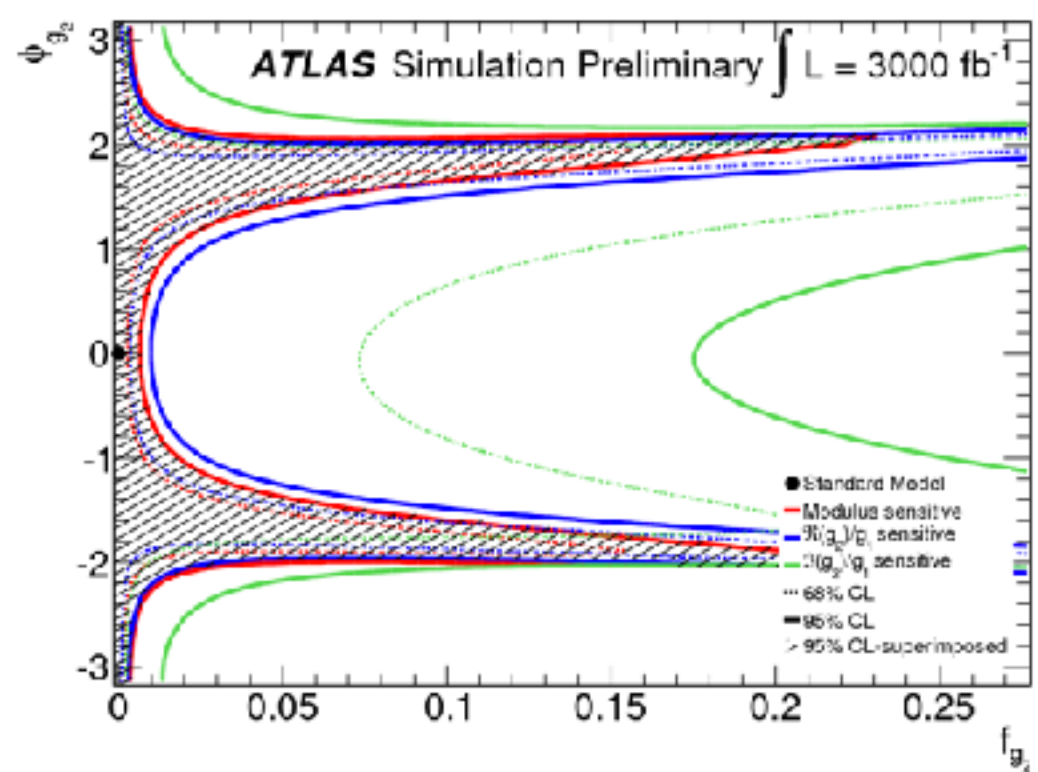


ATLAS-PHYS-PUB-2013-013



Statistically limited. 1% reach @ 3000 fb^{-1}

(based on Run1 methods)

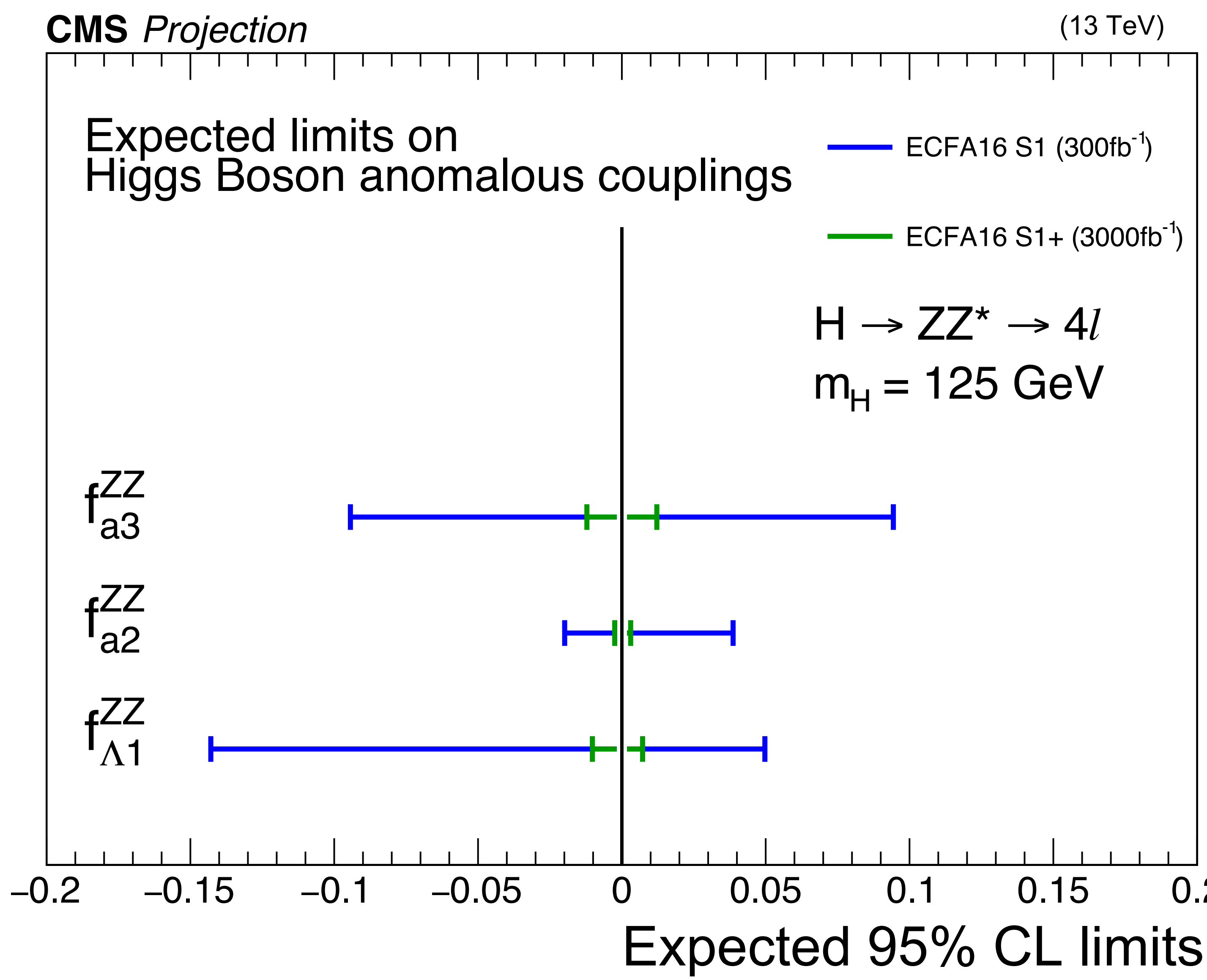


FTR-16-002

ECFA 16 projections

- Statistically limited therefore showing projections for Scenario 1*

*All systematic uncertainties are kept constant with integrated luminosity, assumes unchanged CMS detector



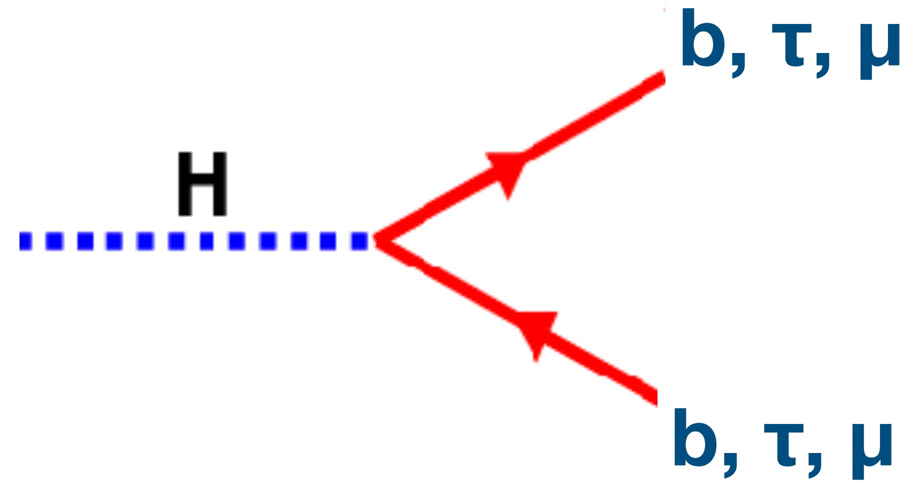
Parameters defined on previous slides

Accessing CP Information: Hff couplings

Only two contributions to Hff

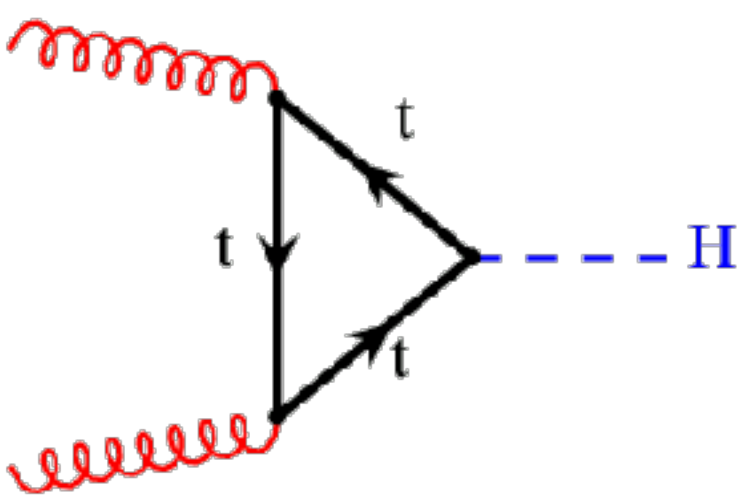
$$\mathcal{A}(\mathrm{H}ff) = -\frac{m_f}{v}\bar{\psi}_f\left(\kappa_f + \mathrm{i}\,\tilde{\kappa}_f\gamma_5\right)\psi_f$$

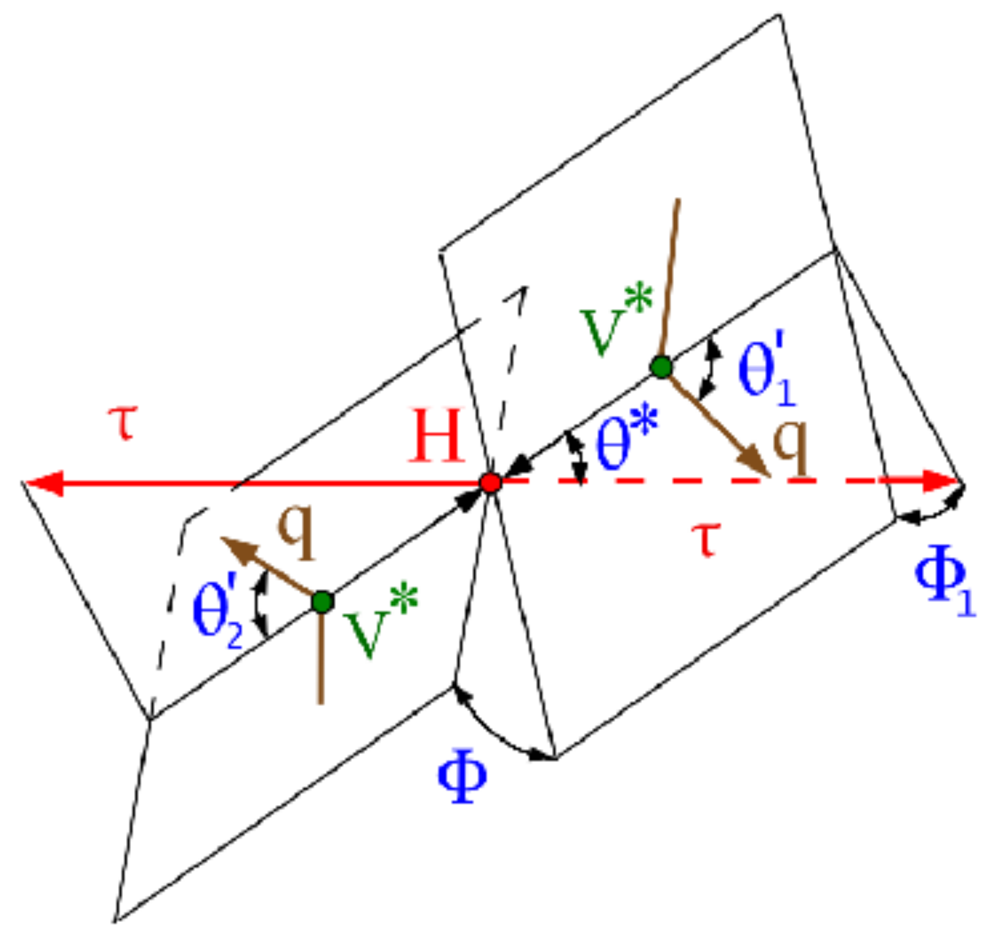
CP Even (κ_f) **CP Odd** ($\tilde{\kappa}_f$)



Possible to study in ttH, tH and H→ττ

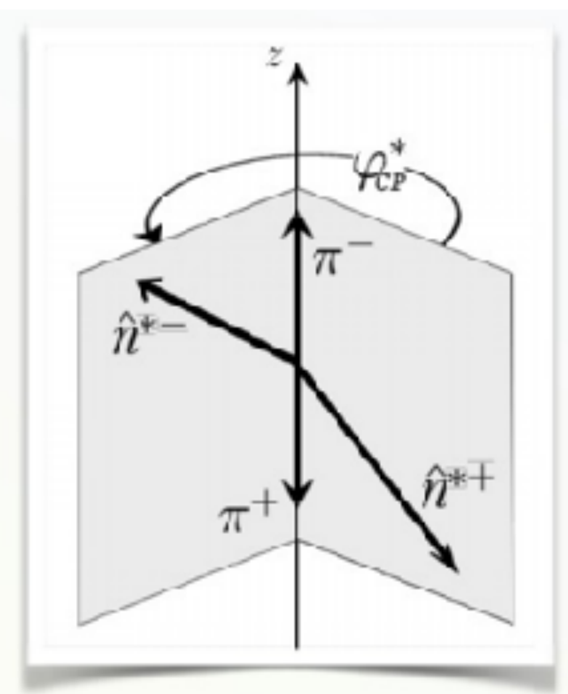
Note: Hff appears in (for example) Hgg couplings through the fermion loop but difficult to discern/affects tails of p_T distribution

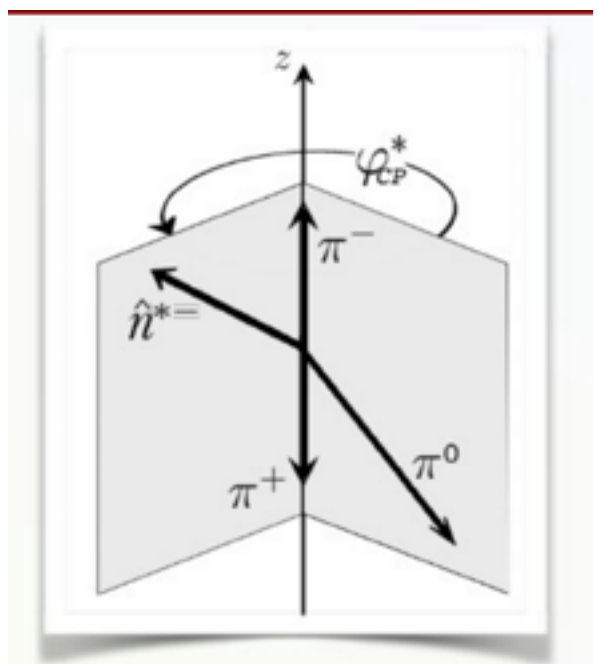


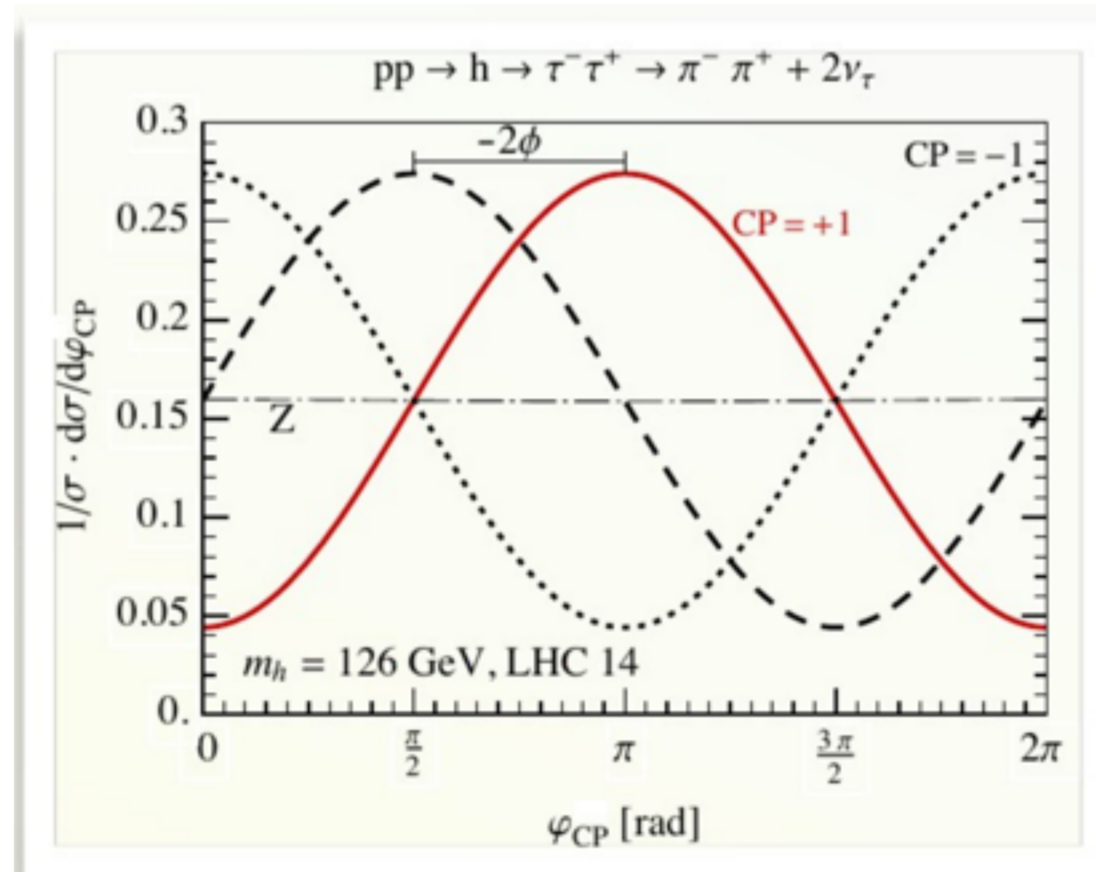


Accessing CP Information : Impact Parameters

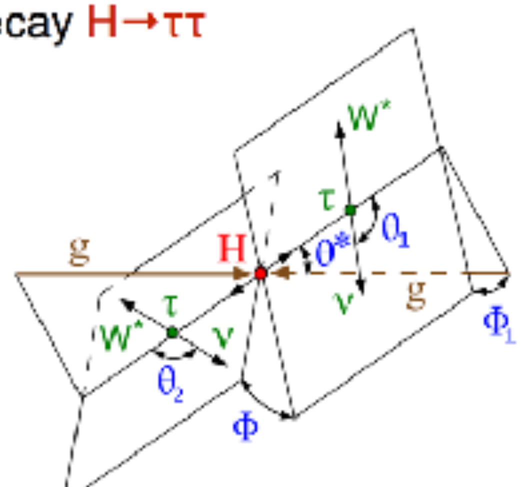
Possible to measure CP using rho decay plane as well as Impact parameters and MELA:



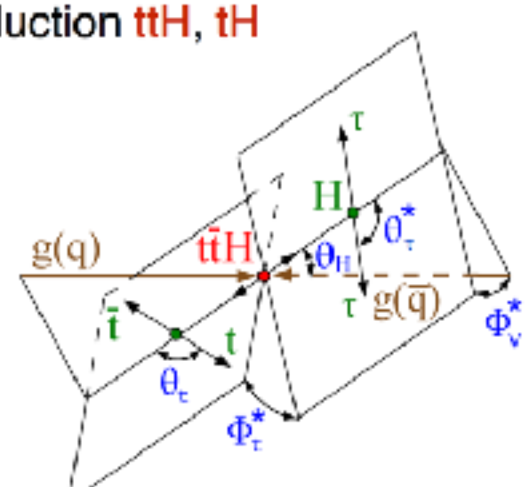




- Decay H→ττ



- Production ttH, tH



Low Branching Fraction

- **11% BR τ±→h±** [Dell'Aquia, Nelson (1989)]
- **Similar possibilities with other τ DM**
- **Requires quite a lot of data (HL-LHC)**

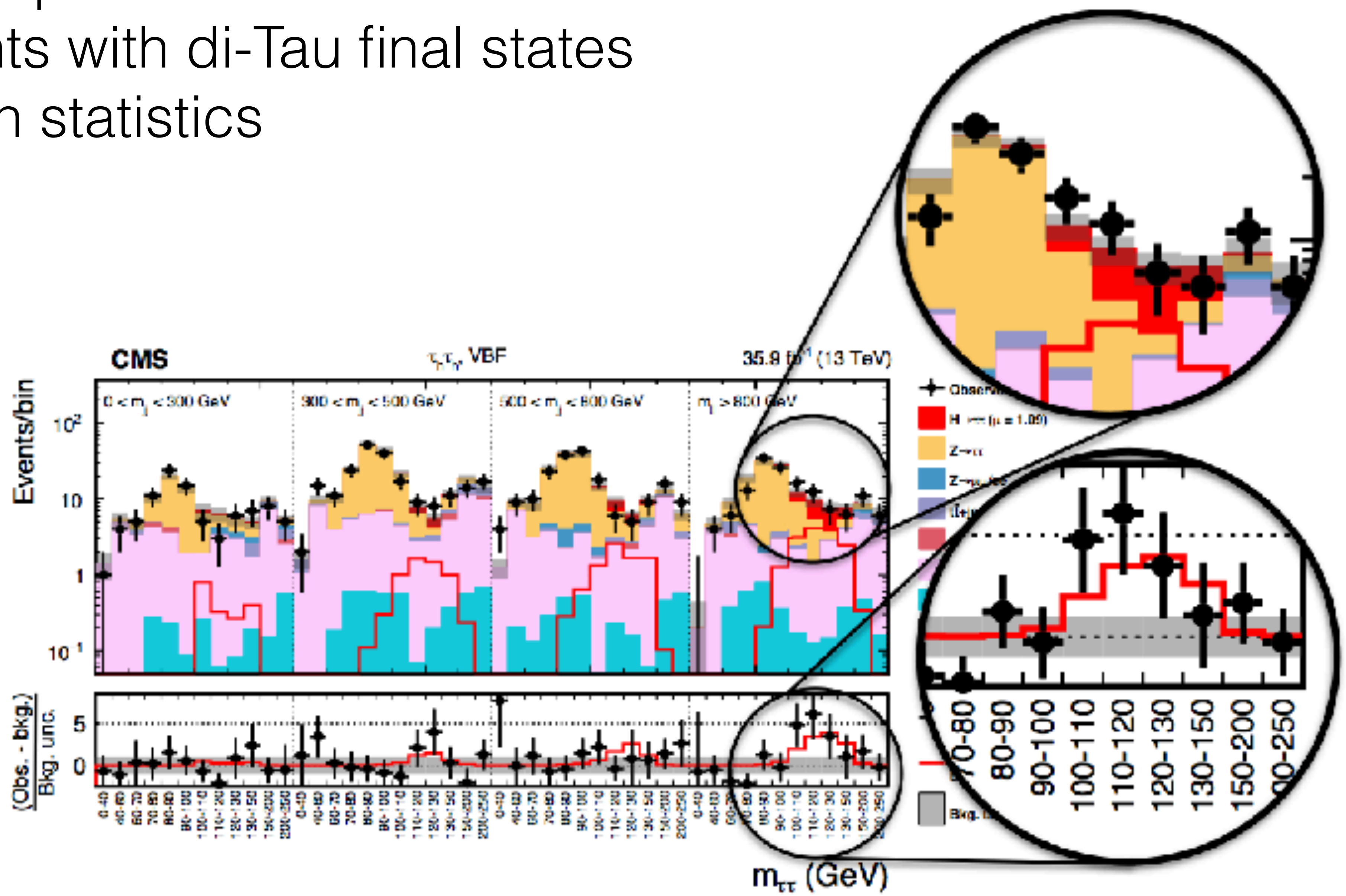
Hff using MELA explored, ttH perhaps more promising than Hττ [arXiv 1606.03107]

Considering the HL-LHC Environment

Run 2 Tau Analyses are already complex due to nature of Tau Decays

- Possibility to perform CP Violation measurements with di-Tau final states given enough statistics

$\tau_h\tau_h$, VBF

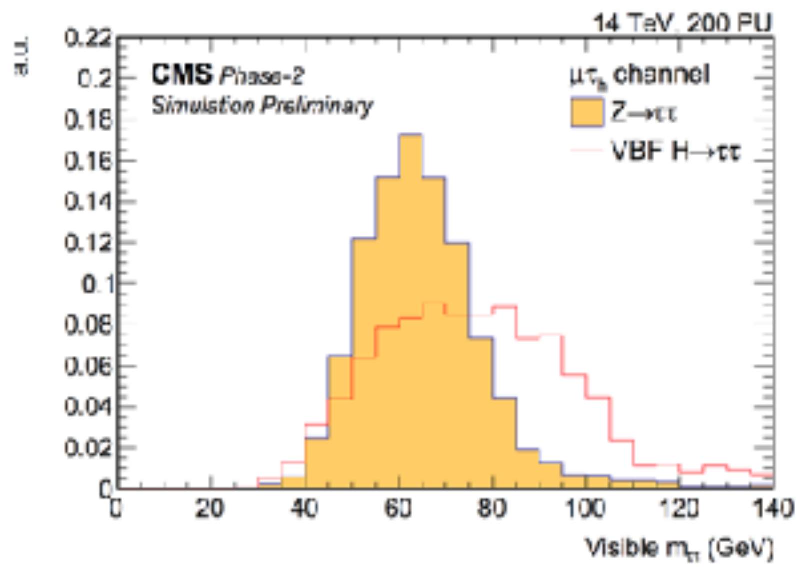


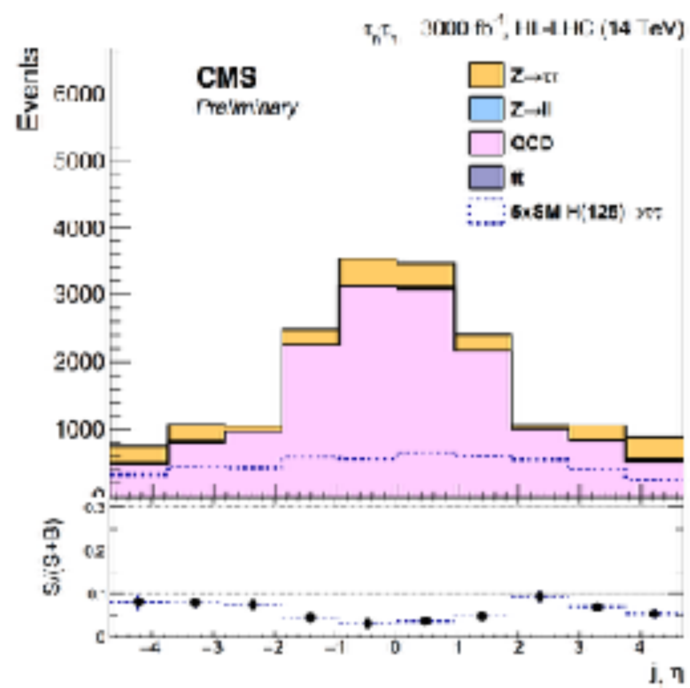
I.Ojalvo

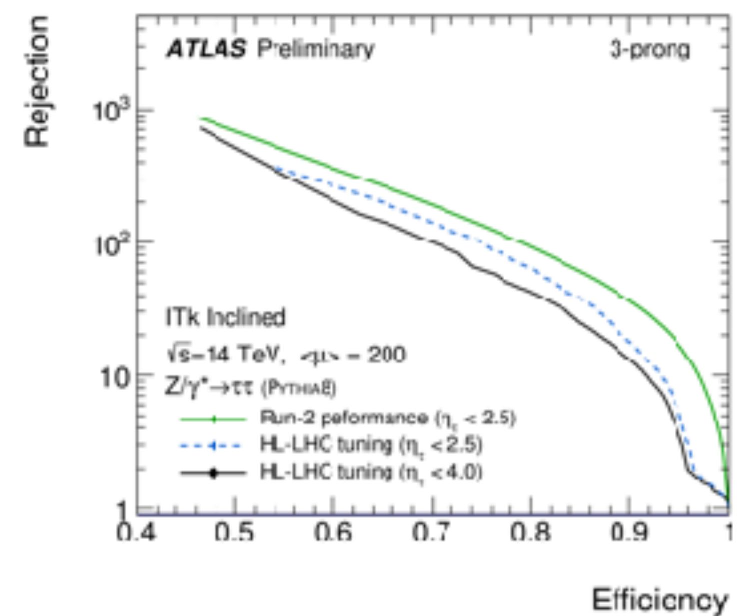
Considering the HL-LHC Environment

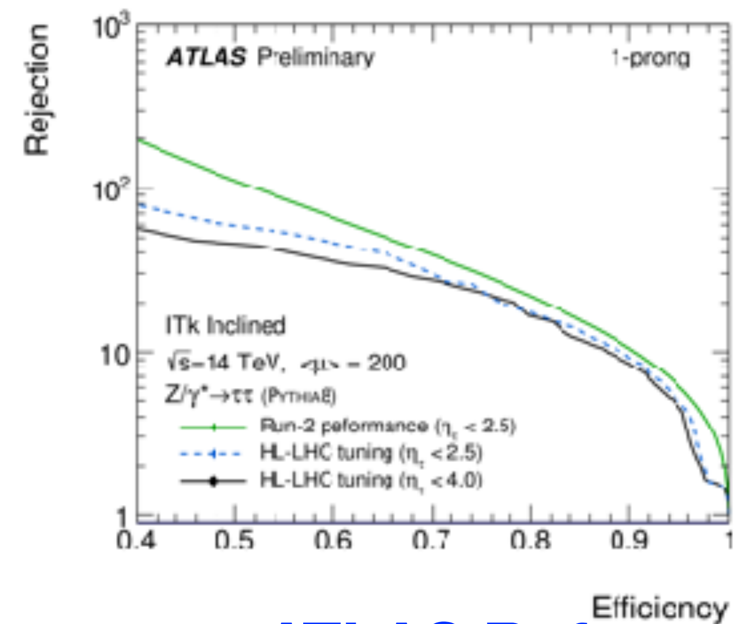
Run 2 Tau Analyses are already complex due to nature of Tau Decays
- Large Background Contributions

Higher Pile Up environment present a **significant challenge** for Taus, Jets,and Missing Energy









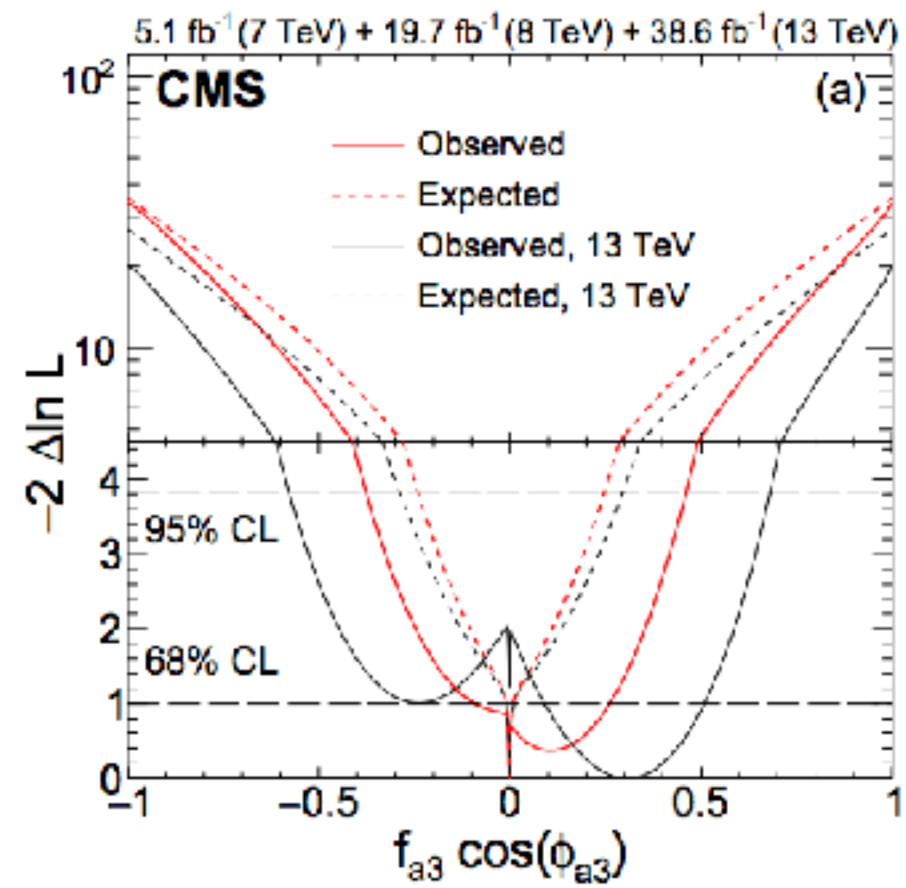
CMS Ref. **ATLAS Ref.**

Plans for YR

HIG-17-011 will be extrapolated to 3000 fb-1
Expect to have significant improvement in expected limits w.r.t ECFA'16 public results

Some points to be considered:

- Most sensitivity is from angles between jets - need to understand detector upgrade effects (jets acceptance)
- Should CMS/ATLAS express results in a common language (e.g. POs as discussed within HXSWG)?
- Possibility to separately perform analysis witn fermionic decays to probe for anomalous **HVV** or **Hff couplings**



Summary

A Final Note: collaborations are also using differential cross section measurement to place constraints on CP violating interaction in Higgs sector (see https://arxiv.org/pdf/1802.04146.pdf

New CP phases are motivated from general baryogenesis arguments

Each measured Higgs coupling can be a test bed for CPV
- $h \to \tau\tau$ is a promising first channel to study at HL-LHC and HE-LHC

For the Yellow Report:
Several scenario assumptions made on how systematic and theoretical uncertainties will evolve and how detector upgrades will perform to compensate degradations due to high pileup

Possibility to either use projections of current and future Run 2 analyses or to attempt to run the analysis from scratch

- Likely a mix will be needed

Back Up

ATLAS VBF Hττ

Run I Results

- Contributions from CP violating interactions between the Higgs boson and EWK bosons are described using a model independent EFT

-The strength of CP violation is governed by a parameter $\tilde{d}$

$$\mathcal{M} = \mathcal{M}_{\rm SM} + \tilde{d} \cdot \mathcal{M}_{\rm CP\text{-}odd}$$

Matrix Element is then a mixture of CP even and CP Odd

In the absence of CP violation the curve is expected to have a minimum at $\tilde{d}$ = 0