Deciphering the CP nature of the 95 GeV Higgs boson

Prasenjit Sanyal

1, October 2025

CQUeST, Sogang University, Korea

Outline and Reference

- 95 GeV excesses reported at LHC and LEP ($\gamma\gamma$, $\tau\tau$ and $b\bar{b}$ channels).

- Test the CP nature of a possible new scalar (CP-even, CP-odd, or mixed) in a model independent way

- Construction of observables sensitive to CP-mixing in the $\tau\tau$ decay mode.

- HL-LHC can probe the scalar, pseudoscalar, and mixed cases with good precision.

On the CP Nature of the '95 GeV' Anomalies

Tanmoy Mondal,[a] **Stefano Moretti**[b,c] **and Prasenjit Sanyal**[d,e]

[a] *Birla Institute of Technology and Science, Pilani, 333031, Rajasthan, India*
[b] *School of Physics and Astronomy, University of Southampton, Southampton SO17 1BJ, United Kingdom*
[c] *Department of Physics and Astronomy, Uppsala University, Box 516, SE-751 20 Uppsala, Sweden*
[d] *Department of Physics, Konkuk University, Seoul 05029, Republic of Korea*
[e] *Center for Quantum Spacetime, Sogang University, 35 Baekbeom-ro, Seoul 121-742, Republic of Korea*

E-mail: tanmoy.mondal@pilani.bits-pilani.ac.in, s.moretti@soton.ac.uk, stefano.moretti@physics.uu.se, psanyal@sogang.ac.kr

95 GeV Anomalies

S: 95 GeV spin-0 resonance H: SM Higgs of mass 95 GeV

(1) **CMS $\tau\tau$ excess:**

$$\mu^{\text{exp}}_{\tau^+\tau^-} = \frac{\sigma^{\text{exp}}(gg \to S \to \tau^+\tau^-)}{\sigma^{\text{SM}}(gg \to H \to \tau^+\tau^-)} = 1.2 \pm 0.5$$

with local (global) significance 2.6σ (2.3σ) at $m_{\tau\tau} = 95$ GeV.

JHEP 07 (2023) 073

(2) **CMS $\gamma\gamma$ excess:**

$$\mu^{\text{exp}}_{\gamma\gamma} = \frac{\sigma^{\text{exp}}(gg \to S \to \gamma\gamma)}{\sigma^{\text{SM}}(gg \to H \to \gamma\gamma)} = 0.6 \pm 0.2$$

with local (global) significance 2.8σ (1.3σ) at $m_{\gamma\gamma} = 95.3$ GeV.

Phys. Lett. B 793 (2019) 320

(3) **LEP $b\bar{b}$ excess:**

$$\mu^{\text{exp}}_{bb} = \frac{\sigma^{\text{exp}}(e^+e^- \to ZS \to Zb\bar{b})}{\sigma^{\text{SM}}(e^+e^- \to ZH \to Zb\bar{b})} = 0.117 \pm 0.057$$

with local significance 2.3σ at $m_{bb} = 98$ GeV.

Eur.Phys.J.C47:547-587,2006

Literature Review

(1) **Mounting Evidence for a 95 GeV Higgs Boson** – **Heinemeyer *et al.***

- Studied a two-Higgs-doublet model extended by a real singlet (**N2HDM**).
- The lightest CP-even Higgs in Type-II and Type-IV N2HDM can explain $\gamma\gamma$ and $b\bar{b}$ excesses.
- Type-IV N2HDM can simultaneously explain all the excesses.

(2) **Explaining 95 (or so)GeV Anomalies in the 2-Higgs Doublet Model Type-I** – **Moretti *et al.***

- Studied Type-I 2HDM with two solutions:
  - (A) h **solution:** lightest CP even Higgs as the 95 GeV resonance.
  - (B) $h + A$ **solution:** Superposition of the h and A such that $\mu(h + A)_{\gamma\gamma,\tau\tau} = \mu(h)_{\gamma\gamma,\tau\tau} + \mu(A)_{\gamma\gamma,\tau\tau}$ and $\mu(h)_{b\bar{b}}$

(3) **Superposition of CP-Even and CP-Odd Higgs Resonances: Explaining the 95 GeV Excesses within a Two-Higgs Doublet Model** – **Moretti *et al.***

- Studied the general 2HDM (Type-III) with two solutions:
  - (A) A **solution:** explains the CMS $\gamma\gamma$ and $\tau\tau$ excesses.
  - (B) $h + A$ **solution:** explains the CMS $\gamma\gamma$, $\tau\tau$ and LEP $b\bar{b}$ excesses.

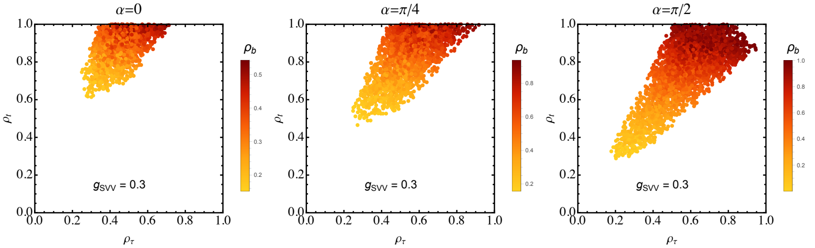
Minimal Framework for the 95 GeV Anomalies

- **Yukawa Interaction:** $\mathcal{L}_{Sf\bar{f}} = -\rho_f^S \frac{m_f}{v} \left(\cos\alpha \bar{f} f + i \sin\alpha \bar{f} \gamma_5 f \right) S, \quad f = t, b, \tau$
  ρ_f^S are the Yukawa coupling modifiers; $\alpha = 0$ (pure scalar), $\pi/2$ (pseudoscalar) and intermediate α CP states.

- **Gauge Coupling:** to accommodate LEP $e^+e^- \to ZS$, a small effective SVV coupling $g_{SVV} \approx 0.3$ is considered.

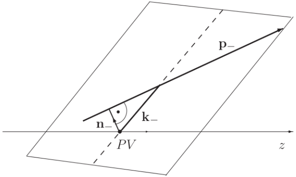
- **Production (LHC):** ggF production at NNLO in the large top mass limit is $\sigma(gg \to S) = \rho_t^{S2} \left(76.35 \cos^2\alpha + 176.32 \sin^2\alpha \right)$ pb.

- **Decays:** $S \to b\bar{b},\ \tau\tau,\ VV^*,\ gg,\ \gamma\gamma$ and $Z\gamma$.



Moretti, Mondal and Sanyal 2412.00474

Probing the CP nature of the 95 GeV resonance



- The differential decay width of S into a pair of τ leptons

$$d\Gamma_{S\to\tau^+\tau^-} \propto 1 - \frac{\pi^2}{16} b(E_+) b(E_-) \cos(\phi_{\rm CP} - 2\alpha)$$

$\phi_{\rm CP}$ = signed acoplanarity angle and $b(E_\pm)$ = spin analyzing power.

Hadronic decay mode:

(1) $\tau^-\tau^+ \to (\pi^-\nu_\tau)(\pi^+\bar{\nu}_\tau)$ IP method

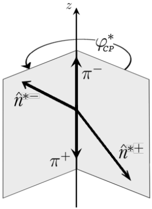
(2) $\tau^-\tau^+ \to (\rho^-\nu_\tau \to \pi^-\pi^0\nu_\tau)(\rho^+\bar{\nu}_\tau \to \pi^+\pi^0\bar{\nu}_\tau)$ ρ method

(3) $\tau^-\tau^+ \to (\pi^-\nu_\tau)(\rho^+\bar{\nu}_\tau \to \pi^+\pi^0\bar{\nu}_\tau)$ IP–ρ method

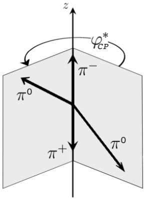
Semi-leptonic decay mode:

(1) $\tau^-\tau^+ \to (\ell^-\bar{\nu}_\ell\nu_\tau)(\pi^+\bar{\nu}_\tau)$ IP method

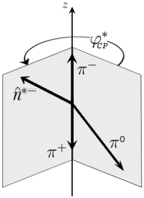
(2) $\tau^-\tau^+ \to (\ell^-\bar{\nu}_\ell\nu_\tau)(\rho^+\bar{\nu}_\tau \to \pi^+\pi^0\bar{\nu}_\tau)$ IP–ρ method



IP method

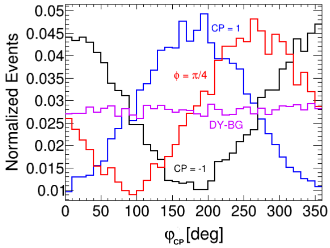


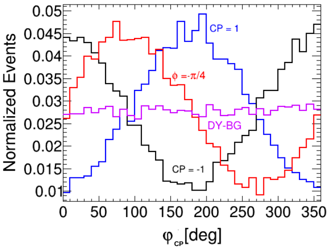
ρ method



IP-ρ method

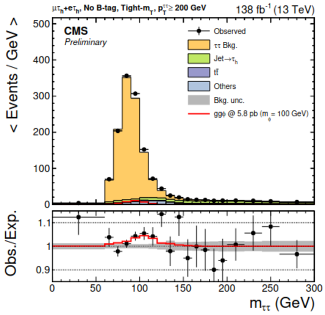
- ϕ_{CP} distributions for CP-even, CP-odd and maximal CP mixed states $\alpha = \pm\pi/4$.

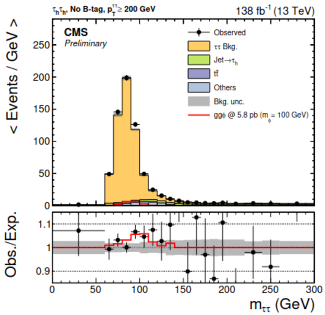




- Decay modes of the τ leptons, with the associated method to construct the ϕ_{CP} observable and the fraction of events to all di-τ decays.

Decay channel	Method	Fraction in all τ-pair decays
$\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$	IP	8.1%
	IP–ρ	18.3%
$\tau_{\mathrm{had}}\tau_{\mathrm{had}}$	IP	1.3%
	ρ	6.7%
	IP–ρ	6.0%



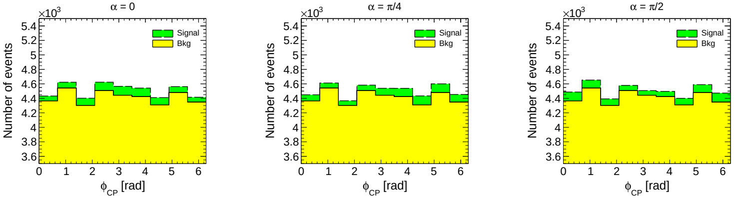


JHEP 07 (2023) 073

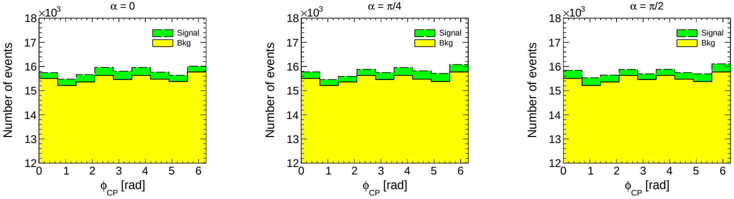
- CMS paper on the $\tau\tau$ excess at $\sim$ 95 GeV.
- Upper panel: semi-leptonic mode.

  Lower panel: hadronic mode.
- No b-tagged jets and $p_T^{\tau\tau} > 200$ GeV at 13 TeV LHC with 138 fb^{-1} luminosity.
- Data provided by the CMS collaboration through **HEPDATA**.

- Event selection: $p_T^{\tau\tau} > 200$ GeV, $60 < m_{\tau\tau} < 120$ GeV at 13 TeV LHC with 3000 fb^{-1} luminosity.

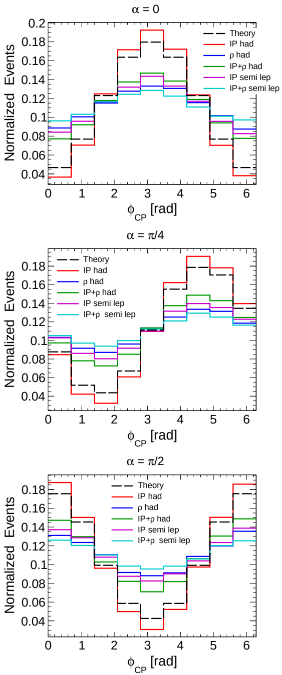


- Signal (green) and background (yellow) $\phi_{\rm CP}$ distributions considering all the hadronic modes.

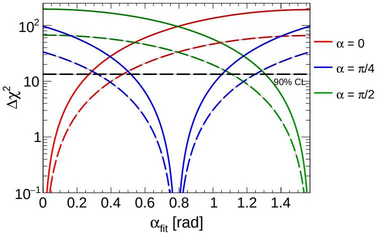


- Signal (green) and background (yellow) $\phi_{\rm CP}$ distributions considering all the semi-leptonic modes.

Moretti, Mondal and Sanyal 2412.00474



- $\chi^2(\alpha) = \sum_{\text{Modes}} \sum_{i \in \text{Bins}} \frac{\left(S_i^{\alpha H} - \frac{n_S}{\Gamma} \frac{d\Gamma}{d\phi_{\text{CP}}}(\alpha) \right)^2}{(\delta S_i)^2 + (\delta^2_{sys})}$
- $\delta S_i = \sqrt{S_i}; \quad \delta S_{sys} = \epsilon \frac{N_{Bkg}}{N_{\text{Bins}}}, \quad \epsilon = 0.5\%, \ 1\%.$
- HL-LHC: best-fit $\alpha \pm 0.27$ rad (0.5%) or ± 0.47 rad (1%) at 90% CL.



Moretti, Mondal and Sanyal 2412.00474

Conclusions

- Assuming a spin-0 resonance explains the LHC ($\tau\tau$, $\gamma\gamma$) and LEP ($b\bar{b}$) excesses, **characterizing its CP nature** becomes essential.

- The $\tau\tau$ channel of a 95 GeV Higgs-like state provides a **direct CP probe**, allowing us to distinguish **CP-even**, **CP-odd**, or **CP-mixed** scenarios.

- Using hadronic and semi-leptonic τ decays, we employ the **IP method**, the ρ **method**, and their combined **IP-ρ method** to build CP sensitive observable.

- At the High-Luminosity LHC, the CP-mixing angle can be determined with a precision of $\pm$(0.27-0.47) radian at 90% CL with a background systematic uncertainties of 0.5% and 1%.

Conclusions

- Assuming a spin-0 resonance explains the LHC ($\tau\tau$, $\gamma\gamma$) and LEP ($b\bar{b}$) excesses, **characterizing its CP nature** becomes essential.

- The $\tau\tau$ channel of a 95 GeV Higgs-like state provides a **direct CP probe**, allowing us to distinguish **CP-even**, **CP-odd**, or **CP-mixed** scenarios.

- Using hadronic and semi-leptonic τ decays, we employ the **IP method**, the ρ **method**, and their combined **IP-ρ method** to build CP sensitive observable.

- At the High-Luminosity LHC, the CP-mixing angle can be determined with a precision of $\pm$(0.27**-**0.47) radian at 90% CL with a background systematic uncertainties of 0.5% and 1%.

THANK YOU!

Backup

A. Impact parameter method

The method described in [8, 9, 13, 15] can be used for all $\tau^{\mp}$ decay modes (3) - (7) if the charged prongs prongs a^-, a'^+ have a non-vanishing impact parameter. This method requires the measurement of the 4-momenta of a^- and a'^+ and their impact parameters vectors $\mathbf{n}_{\mp}$ in the laboratory frame. The vectors $\mathbf{n}_{\mp}$ begin at the Higgs-boson production vertex (which should be known with some precision also along the beam direction, which we take to be the z direction) and end perpendicular on the a^- and a'^+ tracks. The corresponding unit vectors are denoted by $\hat{\mathbf{n}}_{\mp}$. The 4-momenta q_-^μ, q_+^μ of a^-, a'^+ and the impact parameter 4-vectors defined by $n_{\mp}^\mu = (0, \hat{\mathbf{n}}_{\mp})$ are boosted into the $a^- a'^+$ ZMF. The variables in the $a^- a'^+$ ZMF are denoted by an asterisk, for instance, $q_{\mp}^{*\mu}$, $n_{\mp}^{*\mu}$. An observable that is sensitive to the CP nature of the Higgs boson is obtained as follows: We decompose $\mathbf{n}_{\mp}^*$ into their normalized components $\hat{\mathbf{n}}_{||}^{*\mp}$ and $\hat{\mathbf{n}}_{\perp}^{*\mp}$ which are parallel and perpendicular to the respective 3-momentum $\mathbf{q}_-^*$ and $\mathbf{q}_+^*$. An unsigned angle φ^* $(0 \leq \varphi^* \leq \pi)$ and a CP-odd and T-odd triple correlation $\mathcal{O}_{CP}^*$ $(-1 \leq \mathcal{O}_{CP}^* \leq 1)$ can be defined by

$$\varphi^* = \arccos(\hat{\mathbf{n}}_\perp^{*+} \cdot \hat{\mathbf{n}}_\perp^{*-}) , \qquad \mathcal{O}_{CP}^* = \hat{\mathbf{q}}_-^* \cdot (\hat{\mathbf{n}}_\perp^{*+} \times \hat{\mathbf{n}}_\perp^{*-}) , \tag{10}$$

where $\hat{\mathbf{q}}_-^*$ is the normalized a^- momentum in the $a^- a'^+$ ZMF. Using these two quantities one can define a signed angle φ_{CP}^* [13] between the $\tau^- \to a^-$ and $\tau \to a'^+$ decay planes by

$$\varphi_{CP}^* = \begin{cases} \varphi^* & \text{if } \mathcal{O}_{CP}^* \geq 0 , \\ 2\pi - \varphi^* & \text{if } \mathcal{O}_{CP}^* < 0 , \end{cases} \tag{11}$$

Stefan Berge *et al.* Phys.Rev.D 92 (2015) 096012

B. ρ decay method

Rather than choosing the $\rho^-\rho^+$ ZMF we use in the following, as for the impact parameter method, the $a^-a'^+$ ZMF of the charged pions from $\rho^\mp$ decay. This allows us to standardize the definition of the discriminating variable for both methods. In the remainder of this section we define this variable for the $h \to \tau^-\tau^+ \to \rho^-\rho^+$ decay channel. One boosts the π^-, π^0 and π^+, π^0 4-momenta, measured in the laboratory frame, into the $\pi^-\pi^+$ ZMF. In this frame, we denote the π^-, π^0 (π^+, π^0) 3-momenta by $\mathbf{q}^{*-}, \mathbf{q}^{*0-}$ $(\mathbf{q}^{*+}, \mathbf{q}^{*0+})$. In the $\pi^-\pi^+$ ZMF we compute, for each neutral pion, the normalized vector $\hat{\mathbf{q}}_\perp^{*0-}$ and $\hat{\mathbf{q}}_\perp^{*0+}$ which is transverse to the direction of the associated charged pion. The angle between these two vectors is given by[6]

$$\varphi^* = \arccos\left(\hat{\mathbf{q}}_\perp^{*0+} \cdot \hat{\mathbf{q}}_\perp^{*0-}\right), \qquad 0 \le \varphi^* \le \pi. \tag{13}$$

In order to define a signed angle we use the CP-odd triple correlation $\mathcal{O}^*$

$$\mathcal{O}^* = \hat{\mathbf{q}}^{*-} \cdot \left(\hat{\mathbf{q}}_\perp^{*0+} \times \hat{\mathbf{q}}_\perp^{*0-}\right), \qquad -1 \le \mathcal{O}^* \le +1.$$

The discriminating variable that is sensitive to the mixing angle ϕ_τ is defined by

$$\varphi_{CP}^* = \begin{cases} \varphi^* & \text{if } \mathcal{O}^* \ge 0 \\ 2\pi - \varphi^* & \text{if } \mathcal{O}^* < 0 \end{cases}, \qquad \text{with} \quad 0 \le \varphi_{CP}^* \le 2\pi. \tag{14}$$

Stefan Berge *et al.* Phys.Rev.D 92 (2015) 096012