Deciphering the CP nature of the 95 GeV Higgs boson

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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

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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.

(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.

(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.

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.

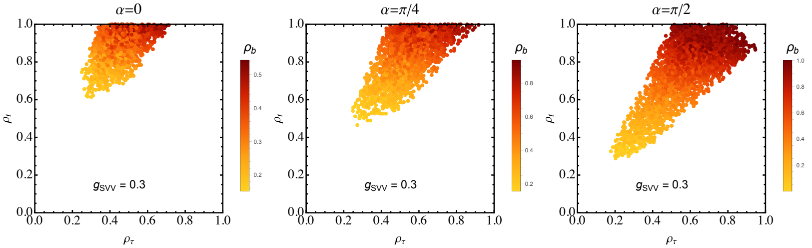
Minimal Framework for the 95 GeV Anomalies

- **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 $Z\gamma$.



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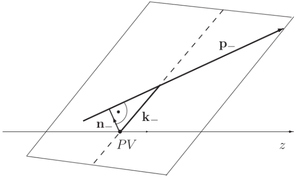
Probing the CP nature of the 95 GeV resonance

- 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

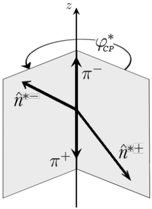
(2) $\tau^-\tau^+ \to (\rho^-\nu_\tau \to \pi^-\pi^0\nu_\tau)(\rho^+\bar{\nu}_\tau \to \pi^+\pi^0\bar{\nu}_\tau)$ ρ method

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

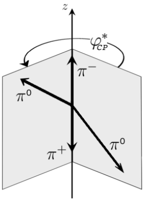
Semi-leptonic decay mode:

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

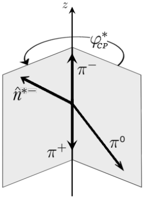
(2) $\tau^-\tau^+ \to (\ell^-\bar{\nu}_\ell\nu_\tau)(\rho^+\bar{\nu}_\tau \to \pi^+\pi^0\bar{\nu}_\tau)$ IP–ρ method



IP method

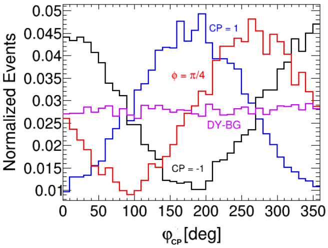


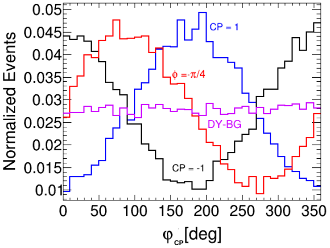
ρ method



IP-ρ method

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

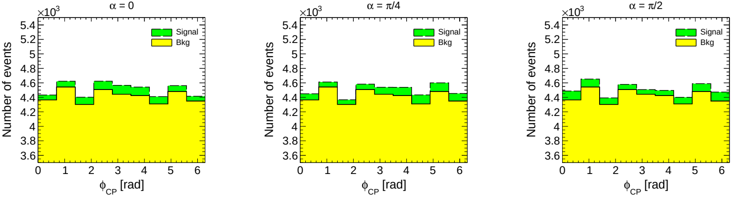




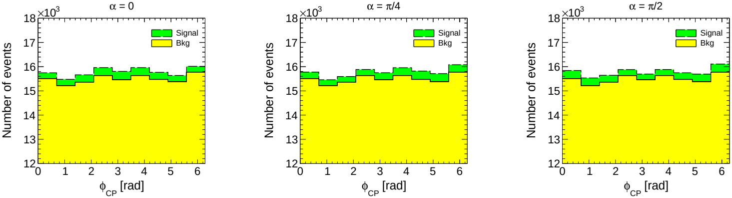
- Decay modes of the τ leptons, with the associated method to construct the ϕ_{CP} observable and the fraction of events to all di-τ decays.

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%

- 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.

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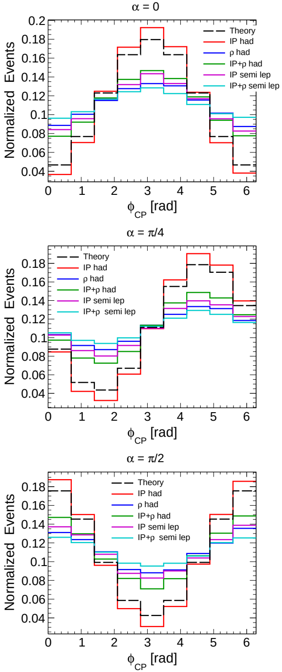
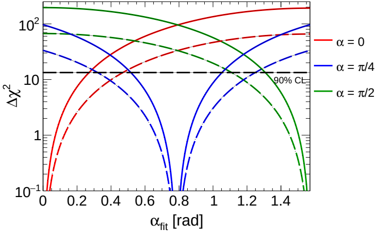


- $$\chi^2(\alpha) = \sum_{\text{Modes}} \sum_{i \in \text{Bins}} \frac{\left(S_i^{\alpha H} - \frac{n_S}{\Gamma} \frac{d\Gamma}{d\phi_{CP}}(\alpha) \right)^2}{(\delta S_i)^2 + (\delta^2_{sys})}$$

- $\delta S_i = \sqrt{S_i}; \quad \delta S_{sys} = \epsilon \frac{N_{Bkg}}{N_{\text{Bins}}}, \quad \epsilon = 0.5\%, \ 1\%.$

- HL-LHC: best-fit $\alpha \pm 0.27$ rad (0.5%) or ± 0.47 rad (1%) at 90% CL.



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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%.

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