CP VIOLATION TESTS IN HIGGS MEASUREMENTS AT FUTURE COLLIDERS

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Motivating CPV tests

• Sakharov’s three conditions for baryogenesis motivate searches for new sources of CP violation
  – Need B violation
  – Need C and CP violation
  – Need interactions to happen out of thermal equilibrium

• Our picture of baryogenesis is currently incomplete
  – SM EW baryogenesis is insufficient
  – Should probe for new sources of CPV
CP and the Higgs

• A natural place to test for CP violating phases is with Higgs physics
  – scalar-pseudoscalar admixture (*e.g.* scalar potential)
    • naively tested via rate suppression
  – couplings to gauge bosons (*e.g.* bosonic CPV)
    • for example, tested via acoplanarity measurement in 
      \( h \rightarrow ZZ^* \rightarrow 4l \)
  – couplings to fermions (*e.g.* fermionic CPV)
    • our work: test via \( h \rightarrow \tau^+ \tau^- \rightarrow (\rho^+\nu) (\rho^-\nu) \rightarrow (\pi^+\pi^0)\nu (\pi^-\pi^0)\nu \)

• [Full UV models to connect any given CP phase to a baryogenesis mechanism is BTSOTW]
Outline

• Brief review of current status of Higgs CP properties
• Motivate new measurement in $\tau^+\tau^-$ decay channel
• Sensitivity studies at colliders
  – Lepton collider prospects
  – First proposal for an LHC measurement
• Summary
Admixture constraints from signal strengths

**ATLAS Prelim.**

<table>
<thead>
<tr>
<th>H → γγ</th>
<th>μ = 1.17^{+0.27}<em>{-0.27}^{+0.16}</em>{-0.11}</th>
</tr>
</thead>
<tbody>
<tr>
<td>H → ZZ* → 4l</td>
<td>μ = 1.44^{+0.40}<em>{-0.33}^{+0.21}</em>{-0.11}</td>
</tr>
<tr>
<td>H → WW* → lvlv</td>
<td>μ = 1.09^{+0.23}<em>{-0.21}^{+0.17}</em>{-0.14}</td>
</tr>
<tr>
<td>W,Z H → b¯b</td>
<td>μ = 0.5^{+0.4}<em>{-0.4}^{+0.2}</em>{-0.2}</td>
</tr>
<tr>
<td>H → ττ</td>
<td>μ = 1.4^{+0.4}<em>{-0.4}^{+0.3}</em>{-0.3}</td>
</tr>
</tbody>
</table>

- "atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/"; CMS [1412.8662]
- Separate channels cannot be combined without assumptions!
Testing CPV in Higgs decays to (electroweak) gauge bosons

- Using Higgs EFT, assuming spin-0, write dimension-6 operators for scalar coupling to dibosons
- Perform simultaneous fit to coefficients of non-SM coupling structures based on differential distribution

\[
L(HVV) \sim a_1 \frac{m_Z^2}{2} H Z^\mu Z_\mu + \frac{1}{(\Lambda_1)^2} m_Z^2 H Z_\mu \square Z^\mu - \frac{1}{2} a_2 H Z^{\mu \nu} Z_{\mu \nu} - \frac{1}{2} a_3 H Z^{\mu \nu} \tilde{Z}_{\mu \nu} \\
+ a_1^{WW} \frac{m_W^2}{2} H W^\mu W_\mu + \frac{1}{(\Lambda_1^{WW})^2} m_W^2 H W_\mu \square W^\mu - \frac{1}{2} a_2^{WW} H W^{\mu \nu} W_{\mu \nu} - \frac{1}{2} a_3^{WW} H W^{\mu \nu} \tilde{W}_{\mu \nu} \\
+ \frac{1}{(\Lambda_1^{Z \gamma})^2} m_Z^2 H Z_\mu \partial_\nu F^{\mu \nu} - a_2^{Z \gamma} H F^{\mu \nu} Z_{\mu \nu} - a_3^{Z \gamma} H F^{\mu \nu} \tilde{Z}_{\mu \nu} - \frac{1}{2} a_2^{\gamma \gamma} H F^{\mu \nu} F_{\mu \nu} - \frac{1}{2} a_3^{\gamma \gamma} H F^{\mu \nu} \tilde{F}_{\mu \nu},
\]

- Can also test spin-2
Testing CPV in Higgs decays to (electroweak) gauge bosons

- For ZZ*, measure acoplanarity angle $\Phi$ (angle between $Z_1$ and $Z_2$ decay planes)
- Golden channel
  - everything measureable, can reconstruct the Higgs rest frame and appropriate decay planes
Testing CPV in $h \rightarrow ZZ^*$ — ATLAS

• ATLAS performs likelihood test between pure scalar and pure pseudoscalar hypotheses

$0^-$ excluded in favor of $0^+$ hypothesis at 97.8% C.L.
Testing CPV in $h \rightarrow ZZ^*$ – CMS

\[ f(J^P) = \frac{\sigma_J}{\sigma_0 + \sigma_J} \]

\[ D_{JP} = \frac{P_{J-}}{P_{J-} + P_{JP}} = \left[ 1 + \frac{P_{J-}(m_{Z_1}, m_{Z_2}, \bar{\Omega}(m_{4\ell}))}{P_{J-}(m_{Z_1}, m_{Z_2}, \bar{\Omega}(m_{4\ell}))} \right] \]
Electroweak diboson results

• Thus far, measurements consistent with SM

• $f_{a_3} = 1$ excluded at 99.98% CL

$f_{a_3} < 0.43 (0.40)$ at a 95% CL for the positive (negative) phase
Testing “fermionic” CPV

- The BSM source of a CPV phase in SM Yukawa couplings is distinct from possible phases in the scalar potential or pseudoscalar couplings to gauge bosons
  - Motivates CPV tests in fermionic couplings even if bosonic CPV coupling tests give null results
  - For example, new fermions which mix with SM fermions could introduce explicit phases in the Yukawa sector
Testing “fermionic” CPV with Higgs

• The tau decay channel for the Higgs is the most promising system for direct measurement of fermionic CPV couplings
  – Top coupling only probed via loops or ttH (tH) production
  – Bottom quark polarizations generally washed out by QCD
  – Tau channel suffer from lost information via neutrinos (at hadron colliders), but still have an appreciable rate

<table>
<thead>
<tr>
<th>$M_H = 126$ GeV</th>
<th>SM Br</th>
</tr>
</thead>
<tbody>
<tr>
<td>bb</td>
<td>56.1%</td>
</tr>
<tr>
<td>WW*</td>
<td>23.1%</td>
</tr>
<tr>
<td>gg</td>
<td>8.48%</td>
</tr>
<tr>
<td>$\tau\tau$</td>
<td>6.16%</td>
</tr>
<tr>
<td>ZZ*</td>
<td>2.89%</td>
</tr>
<tr>
<td>cc</td>
<td>2.83%</td>
</tr>
<tr>
<td>$\gamma\gamma$</td>
<td>0.228%</td>
</tr>
<tr>
<td>$Z\gamma$</td>
<td>0.162%</td>
</tr>
<tr>
<td>$\mu\mu$</td>
<td>0.0214%</td>
</tr>
</tbody>
</table>
The $h \rightarrow \tau^+ \tau^-$ experimental status

- Both experiments have evidence and are actively searching in all $\tau$ decay modes

CMS [1401.5041], ATLAS-CONF-2014-061
A Tau Yukawa CPV phase

- From an effective field theory perspective, can readily generate a tau Yukawa phase via the addition of a dimension 6 operator

\[
\mathcal{L}_{\text{eff}} \supset - \left( \alpha + \beta \frac{H^\dagger H}{\Lambda^2} \right) H\ell^\dagger_{3L} \tau_R + \text{c.c.}
\]

- $\alpha$ and $\beta$ are generally complex
- After inserting Higgs vevs, use the $\tau_R$ redefinition to get

\[
\alpha + \beta \frac{v^2}{\Lambda^2} = y_{\tau}^{\text{SM}} > 0,
\]

- Then, the Higgs coupling to taus is

\[
y_{\tau}^{\text{SM}} + 2\beta \frac{v^2}{\Lambda^2}
\]

Also see, e.g. Kearney, Pierce, Weiner [1207.7062]
A Tau Yukawa CPV phase

- The new phase can thus be captured by considering the Lagrangian

\[
L_{\text{pheno}} \supset -m_\tau \bar{\tau} \tau - \frac{y_\tau}{\sqrt{2}} h \bar{\tau}(\cos \Delta + i\gamma_5 \sin \Delta)\tau
\]

\[
= -m_\tau \bar{\tau} \tau - \frac{y_\tau}{\sqrt{2}} h (\tau^\dagger_L (\cos \Delta + i \sin \Delta) \tau_R
\]

\[
+ \text{c.c.},
\]

- $\Delta = 0$ is SM (CP-even)
- $\Delta = \pi/2$ is pure CP-odd (and CP conserving)
- $\Delta = \pm\pi/4$ is maximally CP-violating
- $\Delta$ is currently unconstrained

- We will assume the $y_\tau$ magnitude is SM strength
A CPV Observable

- We already lose information from missing neutrinos
  - Leptonic decays, though clean, lose even more information
- Need an intermediate vector (not scalar) in the tau decay: focus on the $\rho$ vector meson
  - $\text{Br}(\tau^+ \rightarrow \rho^+ \nu) \approx 26\%$
  - $\text{Br}(\rho^+ \rightarrow \pi^+ \pi^0) \approx 100\%$

PDG
Extracting the phase in Higgs decays

• Tau Yukawa CPV is imprinted on the tau polarizations relative to each other
  – Tau polarizations then get imprinted on the $\nu$ and $\rho$, $\rho$ polarization is imparted to the $\pi$s

• Simplest observable (appropriate for LHC) is $\rho^+\rho^-$ acoplanarity angle

• New, better observable (appropriate for $e^+e^-$ collider) is $\Theta$

\[
\begin{align*}
h & \longrightarrow \tau^-\tau^+ \\
& \quad \longrightarrow \rho^-\nu_\tau \rho^+\bar{\nu}_\tau \\
& \quad \longrightarrow \pi^-\pi^0 \nu_\tau \pi^+\pi^0 \bar{\nu}_\tau.
\end{align*}
\]
Matrix element calculation

• Will trace how the CP phase $\Delta$ appears in the squared matrix element by treating the Higgs decay as a sequence of on-shell 2-body decays

$$\mathcal{M}_{h\rightarrow \tau\tau} \propto \sum_{s,s'} \chi_{s,s'} \bar{u}_\tau^s \left( \cos \Delta + i \gamma_5 \sin \Delta \right) v_{\tau'}^{s'}$$

$$\mathcal{M}_{\tau\rightarrow \rho \nu} \propto (\varepsilon^*_\rho^-)_\mu \bar{u}_\nu \gamma^\mu P_L u_\tau^-$$

$$\mathcal{M}_{\rho\rightarrow \pi\pi} \propto \varepsilon_\rho^- \cdot (p_{\pi^-} - p_{\pi^0})$$

• Together, gives

$$\mathcal{M}_{\text{full}} \propto \bar{u}_\nu \left( p_{\pi^-} - p_{\pi^0^-} \right) P_L \left( p_{\tau^-} + m_\tau \right) \times \left( \cos \Delta + i \gamma_5 \sin \Delta \right) \times \left( -p_{\tau^+} + m_\tau \right) \left( p_{\pi^+} - p_{\pi^0^+} \right) P_L v_\nu^+$$
The Theta Variable*

\[ \Theta = \text{sgn} \left[ \vec{\nu}_{\tau^+} \cdot (\vec{E}_- \times \vec{E}_+) \right] \arccos \left[ \frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+||\vec{E}_-|} \right] \]

\[ P_\Delta, s = -2e^{i(2\Delta - \Theta)} \left| \vec{E}_+ \right| \left| \vec{E}_- \right| \]

- In the Higgs rest frame, the “electric” components are

\[ \vec{E}_\pm = \frac{m_h}{2} \left[ (y_\pm - r) \vec{p}_\pi^\pm|_0 - (y_\pm + r) \vec{p}_{\pi^0\pm}|_0 \right]^\perp \]

- If neutrinos were measured, we would have complete information to reconstruct tau momentum, tau and Higgs rest frames

\[ |_0 = \text{tau rest frame} \]

*See backup or [1308.1094] for details
Ideal situation

Note MC Z background is flat
Ideal – compare to $\rho^+\rho^- \text{ acoplanarity}$*

Truth level $\Theta$ and truth level $\phi^*$ for $\Delta = 0$

$\Theta$ amplitude is larger than $\phi^*$ amplitude by 50%

*Bower, Pierzchala, Was, Worek [hep-ph/0204292]
Worek [hep-ph/0305082]
Lepton collider possibilities

• We obviously cannot directly measure neutrino momenta

• At a lepton collider, have enough constraints to solve algebraically for neutrino momenta
  – Have two neutrino momenta solution sets
    • Both solutions give correct Higgs mass
    • Weight each solution by half an event
    • Necessarily require visible Z decay
Lepton collider – reconstructed

Truth level $\Theta$ and reconstructed $\Theta$ at the ILC for $\Delta = 0$

Normalized yield

Reconstructed amplitude degraded by 30%
Lepton collider – reconstructed

Reconstructed $\Theta$ at the ILC

- $\Delta = 0$
- $\Delta = \pi/4$
- $\Delta = \pi/2$
Lepton collider possibilities

• For $\sqrt{s} = 250$ GeV ILC, polarized beams, $Zh$ production is about 0.30 pb

• With unpolarized beams (FCC-ee or CEPC), cross section is about 30% less

• ILC signal yield (using SM $\text{Br}(h \rightarrow \tau^+\tau^-)$ and restricting to visible $Z$ decays) is 990 events with 1 ab$^{-1}$ luminosity

<table>
<thead>
<tr>
<th>$\sigma_{e^+e^-\rightarrow hZ}$</th>
<th>0.30 pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Br}(h \rightarrow \tau^+\tau^-)$</td>
<td>6.1%</td>
</tr>
<tr>
<td>$\text{Br}(\tau^- \rightarrow \pi^-\pi^0\nu)$</td>
<td>26%</td>
</tr>
<tr>
<td>$\text{Br}(Z \rightarrow \text{visibles})$</td>
<td>80%</td>
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<tr>
<td>$N_{\text{events}}$</td>
<td>990</td>
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Lepton collider possibilities

• For $\sqrt{s} = 250$ GeV ILC, polarized beams, Zh production is about 0.30 pb
  
  – ILC signal yield (using SM $\text{Br}(h \rightarrow \tau\tau)$ and restricting to visible Z decays) is 990 events with 1 ab$^{-1}$
  
  – Construct binned likelihood using a sinusoidal fit to signal, determine sensitivity by variation of test $\Delta$

With 1 ab$^{-1}$ of ILC $\sqrt{s}=250$ GeV, expect 1$\sigma$ discrimination of 4.4° (compared* to 6° using $\phi^*$ [albeit included backgrounds and detector effects])

*Desch, Imhof, Was, Worek [hep-ph/0307331]
Luminosity scaling (without systematics)

Lepton collider, $Z$ to $\nu\nu$ removed, $1\sigma$ and $2\sigma$ lines intersecting LLR

$2\sigma$

(17 degrees) $\Delta = 0.10$

$\Delta = 0.08$

$\Delta = 0.06$

$\Delta = 0.05$

$\Delta = 0.04$

$\Delta = 0.03$

$\Delta = 0.02$ (2.3 degrees)

CEPC or FCC-ee lum. is 30% smaller
Lepton Collider Prospects

- Systematics will affect high luminosity estimates
- Expect some minor sensitivity losses from detector resolution

<table>
<thead>
<tr>
<th>ILC (1 ab⁻¹)</th>
<th>CEPC (ab⁻¹)</th>
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</tr>
<tr>
<td>Accuracy</td>
<td>4.4°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CEPC1</th>
<th>CEPC5</th>
<th>CEPC10</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5°</td>
<td>2.5°</td>
<td>1.7°</td>
</tr>
</tbody>
</table>
LHC prospects

• Consider $h+j$ events ("boosted" $\tau_{\text{had}} \tau_{\text{had}}$ sample)

• At the LHC, need to approximate neutrino momenta
  - Have (8-2-2-2=) 2 unknown four-momentum components
  - Will use collinear approximation for neutrino momenta
    • In this approximation, $\Theta$ is identical to pp acoplanarity angle
    • Other approximations considered tended to wash out or distort the sinusoidal shape of the $\Theta$ distribution
  - First proposal to measure $\Delta$ at the LHC with prompt tau decays and kinematics
Collinear amplitude is about 25% of the truth \( \Theta \) amplitude.
LHC14 simulation details

• Use MadGraph5 for h+j and Z+j events at LHC14
  – Mimic cuts for 1-jet, hadronic taus Higgs search category
  – Impose preselection of $p_T(j) > 140$ GeV, $|\eta(j)| < 2.5$
  – Normalize to MCFM NLO $\sigma(h+j)=2.0$ pb, $\sigma(Z+j)=420$ pb
  – No pileup or detector simulation, aside from tau-tagging efficiencies
    • Pileup degrades primary vertex determination for charged pion tracks and adds ECAL deposits that reduce neutral pion resolution
    • Tracking and detector resolution will clearly smear the $\Theta$ distribution
Yields for 3 ab$^{-1}$ LHC

• Signal region:

  \[
  \text{MET} > 40 \text{ GeV}, \ p_T(\rho) > 45 \text{ GeV}, \ |\eta(\rho)| < 2.1, \ m_{\text{coll}} > 120 \text{ GeV}
  \]

  – Inject an additional 10% contribution to (flat) Zj background to account for QCD multijets

\[
\begin{array}{|c|c|c|}
\hline
 & h j & Z j \\
\hline
\text{Inclusive } \sigma & 2.0 \text{ pb} & 420 \text{ pb} \\
\text{Br}(\tau^+\tau^- \text{ decay}) & 6.1\% & 3.4\% \\
\text{Br}(\tau^- \rightarrow \pi^-\pi^0\nu) & 26\% & 26\% \\
\text{Cut efficiency} & 18\% & 0.24\% \\
\hline
\text{N}_{\text{events}} & 1100 & 1800 \\
\hline
\end{array}
\]

$N_{\text{events}}$ for 3 ab$^{-1}$ with $\tau$-tagging 50% efficiency
Yields for 3 ab$^{-1}$ LHC

- Consider $\tau$ tagging efficiency benchmarks of 50% and 70%, use likelihood analysis testing different $\Delta$

<table>
<thead>
<tr>
<th>$\tau_t$ efficiency</th>
<th>50%</th>
<th>70%</th>
</tr>
</thead>
<tbody>
<tr>
<td>3$\sigma$</td>
<td>$L = 550$ fb$^{-1}$</td>
<td>$L = 300$ fb$^{-1}$</td>
</tr>
<tr>
<td>5$\sigma$</td>
<td>$L = 1500$ fb$^{-1}$</td>
<td>$L = 700$ fb$^{-1}$</td>
</tr>
<tr>
<td>Accuracy ($L = 3$ ab$^{-1}$)</td>
<td>11.5°</td>
<td>8.0°</td>
</tr>
</tbody>
</table>

- Discriminating pure scalar vs. pure pseudoscalar at 3$\sigma$ requires 550 (300) fb$^{-1}$ with 50% (70%) $\tau$ tagging efficiency
- For 5$\sigma$, require 1500 (700) fb$^{-1}$ with 50% (70%) $\tau$ tagging efficiency

- Again, detector effects and pileup are neglected
Luminosity scaling (without systematics)

\[ -2 \log(L/L_{\Delta=0}) \]

LHC, \( \tau \text{ eff.}=70\% \), \( 1\sigma \) and \( 2\sigma \) lines intersecting LLR

\[ \Delta = 0.30 \]
(17 degrees)

\[ \Delta = 0.20 \]

\[ \Delta = 0.16 \]
(8 degrees)

\[ \Delta = 0.14 \]

\[ \Delta = 0.12 \]

\[ \Delta = 0.08 \]
(4.6 degrees)
Improving the measurement of the tau Yukawa CP phase

• Consider including MET information for LHC analyses
  – e.g. MELA-type likelihood incorporating signal hypotheses with different $\Delta$
• Consider other tau decay modes or add decay vertex information
• Improve tau tagging efficiency
• Dedicated di-tau hadronic trigger
• Consider VBF production, $Zh$ production
  – For VBF, 3 ab$^{-1}$, expect 52k $\pi^+\pi^0\nu\pi^-\pi^0\nu$ total events (no cuts)
  • S/B is about 0.4 from ATLAS 8 TeV BDT analysis
Incorporate detector effects

- Amplitude of Theta distribution diluted by about half
Summary

• New CP phases are motivated from general baryogenesis arguments
• Many physics studies are needed to motivate the physics case of future machines
• Have a new suite of measurements to perform in Higgs physics
  – Fermionic CP phases play a special role
  – Look forward to implementing this analysis in future Higgs studies
  – Can also consider prospects at FCC-hh and SPPC

<table>
<thead>
<tr>
<th>Colliders</th>
<th>LHC</th>
<th>HL-LHC</th>
<th>ILC (1 ab(^{-1}))</th>
<th>CEPC1</th>
<th>CEPC5</th>
<th>CEPC10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy</td>
<td>25°</td>
<td>8.0°</td>
<td>4.4°</td>
<td>5.5°</td>
<td>2.5°</td>
<td>1.7°</td>
</tr>
</tbody>
</table>
$\mathcal{L}_{\text{tree}} = \mathcal{L}_{\text{SM} - y_t}$

\[
+ |D\Phi|^2 - m_\Phi^2 |\Phi|^2 - \lambda_\Phi |\Phi|^4
- (y H \ell_{3L}^\dagger \tau_R + y' \Phi \ell_{3L}^\dagger \tau_R + \lambda'(\Phi^\dagger H)|H|^2 + \text{c.c.}),
\]

$\mathcal{L}_{\text{dim-6}} = \frac{|\lambda'|^2}{m_\Phi^2} |H|^6 + \left(\frac{\lambda' y'}{m_\Phi^2} |H|^2 H \ell_{3L}^\dagger \tau_R + \text{c.c.}\right)$. 
Matrix element calculation assumptions

\[ M_{\text{full}} \propto \bar{u}_\nu - \left( \rho_{\pi^-} - \rho_{\pi^0-} \right) P_L \left( \rho_{\tau^-} + m_\tau \right) \times \left( \cos \Delta + i \gamma_5 \sin \Delta \right) \times \left( -\rho_{\tau^+} + m_\tau \right) \left( \rho_{\pi^+} - \rho_{\pi^0+} \right) P_L v_\nu^+ \]

- Neglect \( \pi^0 \) exchange (spatially separated; the \( \tau \)'s are boosted and back-to-back in the Higgs rest frame)
- All intermediate particles assumed on-shell
- Neglect \( \pi^\pm - \pi^0 \) mass difference
- Obtain

\[ M_{\text{full}} \propto \bar{u}_\nu - \left( e^{i\Delta} \rho_{\tau^-} - e^{-i\Delta} \rho_{\tau^+} \right) q_+ + P_L v_\nu^+ \]

with

\[ q_\pm \equiv p_{\pi^\pm} - p_{\pi^0\pm} \]

- Recall \( \rho_\pm \) polarization is generally aligned with \( q_\pm \)
Calculating the Theta Variable

• Introduce the variable with coefficients

\[ k_{\pm}^{\mu} \equiv y_{\pm} q_{\pm}^{\mu} + r p_{\nu \pm}^{\mu} \]

\[ y_{\pm} \equiv \frac{2q_{\pm} \cdot p_{\tau \pm}}{m_{\tau}^2 + m_{\rho}^2} = \frac{q_{\pm} \cdot p_{\tau \pm}}{p_{\rho \pm} \cdot p_{\tau \pm}}, \]

\[ r \equiv \frac{m_{\rho}^2 - 4m_{\pi}^2}{m_{\tau}^2 + m_{\rho}^2} \approx 0.14. \]

• We then write the squared matrix element as

\[ |M|^2 \propto P_{\Delta, s} + P_{\Delta, \bar{s}} + P_{\Delta, s} + P_{\Delta, s}^* \]

where the most interesting piece is

\[ P_{\Delta, s} \equiv -e^{2i\Delta} \left[ (k_- \cdot p_{\tau +})(k_+ \cdot p_{\tau -}) - (p_{\tau -} \cdot p_{\tau +})(k_- \cdot k_+) \right. \]

\[ \left. - i\epsilon_{\mu \nu \rho \sigma} k_\mu^\nu p_{\tau -}^\rho k_+^\sigma p_{\tau +}^\sigma \right]. \]
Calculating the Theta Variable

\[ P_{\Delta, s} \equiv -e^{2i\Delta} \left[ (k_- \cdot p_{\tau+})(k_+ \cdot p_{\tau-}) - (p_{\tau-} \cdot p_{\tau+})(k_- \cdot k_+) \right. \]

\[ \left. - i\varepsilon_{\mu\nu\rho\sigma} k_\mu^\rho p_{\tau-}^\nu - k_+^\rho p_{\tau+}^\sigma \right]. \] (26)

- We can define an antisymmetric 2\textsuperscript{nd}-rank tensor

\[ F_{\pm}^{\mu\nu} \equiv k_\pm^\mu p_{\tau\pm}^\nu - k_\pm^\nu p_{\tau\pm}^\mu = -F_{\pm}^{\nu\mu} \]

\[ P_{\Delta, s} = e^{2i\Delta} \left( \frac{1}{2} F_{-\mu\nu} F_{\tau+}^{\mu\nu} + \frac{i}{4} \varepsilon_{\mu\nu\rho\sigma} F_{-\mu\nu} F_{\tau+}^{\rho\sigma} \right) \]

- Or, even better, identify “electric” and “magnetic” components

\[ E_\pm^i \equiv F_{\pm}^{i0}, \quad B_\pm^i \equiv -\frac{1}{2} \varepsilon^{ijk} F_{\pm jk} \]

\[ P_{\Delta, s} = -e^{2i\Delta} \left[ (\vec{E}_- + i\vec{B}_-) \cdot (\vec{E}_+ + i\vec{B}_+) \right] \]
Calculating the Theta Variable

\[ F_\pm^{\mu\nu} = k_\pm^\mu p_\tau^{\nu\pm} - k_\pm^\nu p_\tau^{\mu\pm} = -F_\pm^{\nu\mu} \]

• We can calculate

\[ \vec{B}_\pm = \vec{p}_\tau^{\pm} \times \vec{k}_\pm = \vec{v}_\tau^{\pm} \times \vec{E}_\pm \]

• Specialize to Higgs rest frame (back-to-back taus)
  – E_+B_+ and E_-B_- planes are parallel
  – Motivate a new acoplanarity between E_+v_+ and E_-v_- planes

\[ \Theta = \text{sgn}\left[ \vec{v}_{\tau+} \cdot (\vec{E}_- \times \vec{E}_+) \right] \text{Arccos} \left[ \frac{\vec{E}_+ \cdot \vec{E}_-}{|\vec{E}_+||\vec{E}_-|} \right] \]

\[ P_{\Delta, s} = -2e^{i(2\Delta - \Theta)} |\vec{E}_+||\vec{E}_-| \]
Yields for 3 ab$^{-1}$ LHC

Green = SM signal
Red = pseudoscalar signal
Purple = Cosine fit to SM
Blue = Cosine fit to pseudoscalar

For lower luminosity, the amplitude is the same but the significance of a non-zero phase shift is less.
Tau measurement details

- Method relies on reconstructing neutral and charged pions with good resolution and efficiency

![Graph showing relative yields for different reconstructed decay modes of tau particles.](image-url)
Measuring Higgs to $\tau\tau$

- Use SVFit to reconstruct $m_{\tau\tau}$ (creates likelihood function based on observed kinematics)
  - Anticipating the CP phase measurement, focus on the fully hadronic analysis
Measuring Higgs to $\tau\tau$

- Use SVFit to reconstruct $m_{\tau\tau}$ (creates likelihood function based on observed kinematics)
  - Anticipating the CP phase measurement, focus on the fully hadronic analysis

<table>
<thead>
<tr>
<th>Process</th>
<th>1-Jet</th>
<th>VBF</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \tau\tau$</td>
<td>428 ± 90</td>
<td>47 ± 28</td>
</tr>
<tr>
<td>QCD</td>
<td>210 ± 31</td>
<td>61 ± 10</td>
</tr>
<tr>
<td>EWK</td>
<td>41 ± 9</td>
<td>4 ± 1</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>29 ± 6</td>
<td>2 ± 2</td>
</tr>
<tr>
<td>Total Background</td>
<td>709 ± 95</td>
<td>114 ± 30</td>
</tr>
<tr>
<td>$H \rightarrow \tau\tau$</td>
<td>9 ± 4</td>
<td>4 ± 2</td>
</tr>
<tr>
<td>Observed</td>
<td>718</td>
<td>120</td>
</tr>
</tbody>
</table>

Signal Eff.

<table>
<thead>
<tr>
<th>Process</th>
<th>$gg \rightarrow H$</th>
<th>$qq \rightarrow H$</th>
<th>$qq \rightarrow Ht$ or VH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$2.52 \cdot 10^{-4}$</td>
<td>$5.93 \cdot 10^{-4}$</td>
<td>$9.13 \cdot 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$4.99 \cdot 10^{-5}$</td>
<td>$1.20 \cdot 10^{-3}$</td>
<td>$3.59 \cdot 10^{-5}$</td>
</tr>
</tbody>
</table>

CMS Preliminary, $\sqrt{s} = 7-8$ TeV, $L = 24.3$ fb$^{-1}$, $H \rightarrow \tau\tau$

$m_H = 125$ GeV

$\mu \mu$
$e\mu$
$\tau_h \tau_h$
$e\tau_h$
$\mu \tau_h$
$VH \rightarrow \tau\tau + l$

Combined: $\mu = 1.1 \pm 0.4$
ATLAS Update

- Use BDT output to categorize events
ATLAS Update

- Use BDT output to categorize events
• Focus on fully hadronic channel
  – Main backgrounds are still irreducible $Z \rightarrow \tau\tau$ and QCD multijets

<table>
<thead>
<tr>
<th>Process/Category</th>
<th>VBF</th>
<th>Boosted</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.85-0.9</td>
<td>0.9-0.95</td>
</tr>
<tr>
<td>BDT score bin edges</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ggF</td>
<td>0.39 ± 0.17</td>
<td>0.35 ± 0.16</td>
</tr>
<tr>
<td>VBF</td>
<td>0.57 ± 0.18</td>
<td>0.72 ± 0.22</td>
</tr>
<tr>
<td>WH</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>ZH</td>
<td>&lt; 0.05</td>
<td>&lt; 0.05</td>
</tr>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>3.2 ± 0.6</td>
<td>3.4 ± 0.7</td>
</tr>
<tr>
<td>Multijet</td>
<td>3.3 ± 0.6</td>
<td>2.9 ± 0.6</td>
</tr>
<tr>
<td>Others</td>
<td>0.38 ± 0.09</td>
<td>0.49 ± 0.12</td>
</tr>
<tr>
<td>Total Background</td>
<td>6.9 ± 1.3</td>
<td>6.8 ± 1.3</td>
</tr>
<tr>
<td>Total Signal</td>
<td>0.97 ± 0.29</td>
<td>1.09 ± 0.31</td>
</tr>
<tr>
<td>S/B</td>
<td>0.14</td>
<td>0.16</td>
</tr>
<tr>
<td>Data</td>
<td>6</td>
<td>6</td>
</tr>
</tbody>
</table>
**Table 1.** Branching fractions of the dominant hadronic decays of the $\tau$ lepton and the symbol and mass of any intermediate resonance [9]. The $h$ stands for both $\pi$ and $K$, but in this analysis the $\pi$ mass is assigned to all charged particles. The table is symmetric under charge conjugation.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Resonance</th>
<th>Mass (MeV/c$^2$)</th>
<th>Branching fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^- \rightarrow h^- \nu_\tau$</td>
<td>$\rho^-$</td>
<td>770</td>
<td>11.6%</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- \pi^0 \nu_\tau$</td>
<td>$a^-_1$</td>
<td>1200</td>
<td>26.0%</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau$</td>
<td>$a^-_1$</td>
<td>1200</td>
<td>9.5%</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- h^+ h^- \nu_\tau$</td>
<td>$a^-_1$</td>
<td>1200</td>
<td>9.8%</td>
</tr>
<tr>
<td>$\tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau$</td>
<td>$a^-_1$</td>
<td>1200</td>
<td>4.8%</td>
</tr>
</tbody>
</table>
Tau measurement details

Table 4. The MC predicted $\tau_h$ misidentification rates and the measured data-to-MC ratios, integrated over the $p_T$ and $\eta$ phase space typical for the $Z \rightarrow \tau \tau$ analysis.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>QCD</th>
<th>QCD$\mu$</th>
<th>W + jets</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MC (%)</td>
<td>Data/MC</td>
<td>MC (%)</td>
</tr>
<tr>
<td>HPS “loose”</td>
<td>1.0</td>
<td>1.00 ± 0.04</td>
<td>1.0</td>
</tr>
<tr>
<td>HPS “medium”</td>
<td>0.4</td>
<td>1.02 ± 0.06</td>
<td>0.4</td>
</tr>
<tr>
<td>HPS “tight”</td>
<td>0.2</td>
<td>0.94 ± 0.09</td>
<td>0.2</td>
</tr>
<tr>
<td>TaNC “loose”</td>
<td>2.1</td>
<td>1.05 ± 0.04</td>
<td>1.9</td>
</tr>
<tr>
<td>TaNC “medium”</td>
<td>1.3</td>
<td>1.05 ± 0.05</td>
<td>0.9</td>
</tr>
<tr>
<td>TaNC “tight”</td>
<td>0.5</td>
<td>0.98 ± 0.07</td>
<td>0.4</td>
</tr>
</tbody>
</table>