Measurement of the $\tau$ lepton polarization in Z boson decays using CMS detector

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Dec 5th 2023
Tau 2023 conference, Louisville, KY
Motivation

- Electroweak mixing angle, $\sin^2\theta_w$, is related to the effective vector and axial-vector couplings of the fermions to the Z boson.
  - Such a mixing angle leads to different couplings for right- and left-handed fermions in weak neutral currents.
- The polarization measures the ratio of vector to axial-vector neutral current couplings of the $\tau$ lepton.
- Aim of this analysis:
  - Measure average polarisation of leptons in $Z/\gamma$ events:
    \[
    \langle P_\tau \rangle = \frac{N(pp \rightarrow Z/\gamma \rightarrow \tau_R^- \tau_L^+) - N(pp \rightarrow Z/\gamma \rightarrow \tau_L^- \tau_R^+)}{N(pp \rightarrow Z/\gamma \rightarrow \tau_R^- \tau_L^+) + N(pp \rightarrow Z/\gamma \rightarrow \tau_L^- \tau_R^+)}
    \]
  - Convert polarisation into effective weak mixing angle $\sin^2\theta_w$.
  - Any deviation from SM reveals a new physics beyond SM!
Large Hadron Collider

Key:
- Muon
- Electron
- Charged Hadron (e.g., Pion)
- Neutral Hadron (e.g., Neutron)
- Photon

CMS
ATLAS
LHCb
ALICE
\( \tau \) CMS reconstruction

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Resonance</th>
<th>( B(%) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leptonic decays</td>
<td></td>
<td>35.2</td>
</tr>
<tr>
<td>( \tau^- \rightarrow e^- \bar{\nu}<em>e \nu</em>\tau )</td>
<td></td>
<td>17.8</td>
</tr>
<tr>
<td>( \tau^- \rightarrow \mu^- \bar{\nu}<em>\mu \nu</em>\tau )</td>
<td></td>
<td>17.4</td>
</tr>
<tr>
<td>Hadronic decays</td>
<td></td>
<td>64.8</td>
</tr>
<tr>
<td>( \tau^- \rightarrow h^- \nu_\tau )</td>
<td></td>
<td>11.5</td>
</tr>
<tr>
<td>( \tau^- \rightarrow h^- \pi^0 \nu_\tau )</td>
<td>( \rho(770) )</td>
<td>25.9</td>
</tr>
<tr>
<td>( \tau^- \rightarrow h^- \pi^0 \pi^0 \nu_\tau )</td>
<td>( a_1(1260) )</td>
<td>9.5</td>
</tr>
<tr>
<td>( \tau^- \rightarrow h^- h^+ h^- \nu_\tau )</td>
<td>( a_1(1260) )</td>
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</tr>
<tr>
<td>( \tau^- \rightarrow h^- h^+ h^- \pi^0 \nu_\tau )</td>
<td></td>
<td>4.8</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td>3.3</td>
</tr>
</tbody>
</table>

\( \tau_h \) appear in the detector with:

- 1 or 3 charged hadrons (mainly \( \pi^\pm, K^\pm \), CMS does not distinguish them)
- 1 or more neutral pions that undergo the decay \( \pi^0 \rightarrow \gamma \gamma \)
- Intermediate resonances in the decay

Many decay modes → different signatures to be captured by the same algorithm
Event Selection - Summary

$\tau_h \tau_h$ channel
Trigger: DoubleMediumIsoPFTau35
Hadronic taus: $p_T(\tau_h) > 40$ GeV and $|\eta(\tau_h)| < 2.1$

$\tau_\mu \tau_h$ channel
Trigger:
- IsoMu22
- IsoMu19_LooseIsoPFTau20

Muon:
- $p_T(\mu) > 20$ GeV
  (> 23 GeV if IsoMu22)
- $|\eta(\mu)| < 2.1$

Hadronic tau:
- $p_T(\tau_h) > 30$ GeV
- $|\eta(\tau_h)| < 2.3$

$\tau_e \tau_h$ channel
Trigger:
- Ele25

Electron:
- $p_T(e) > 26$ GeV
- $|\eta(e)| < 2.1$

Hadronic tau:
- $p_T(\tau_h) > 30$ GeV
- $|\eta(\tau_h)| < 2.3$

$\tau_e \tau_\mu$ channel
Trigger:
- Mu8_Ele23
- Mu23_Ele12

Electron:
- $p_T(e) > 15$ GeV
  (> 24 GeV if Mu8_Ele23)
- $|\eta(e)| < 2.4$

Muon:
- $p_T(\mu) > 15$ GeV
  (> 24 GeV if Mu23_Ele12)
- $|\eta(\mu)| < 2.4
The angle $\theta_{\tau}$ is the scattering angle of the $\tau$–lepton with respect to the quark momentum in the rest frame of the Z boson

$$\frac{d\sigma}{d \cos \theta_{\tau}} = F_0(\hat{s})(1 + \cos^2 \theta_{\tau}) + 2F_1(\hat{s}) \cos \theta_{\tau} - \lambda_{\tau}\left[F_2(\hat{s})(1 + \cos^2 \theta_{\tau}) + 2F_3(\hat{s}) \cos \theta_{\tau}\right].$$

The helicity of $\tau$ leptons from Z boson decays can be measured from energy and angular distributions of the $\tau$ lepton decay products.
Helicity of $\tau$ leptons - Angle $\theta$ in $\tau$ rest frame

Intermediate spin-0 resonance ($\pi^-$) \( \Rightarrow \) angle $\theta$ contains full helicity information

\[
\cos \theta = \vec{n}_\tau \cdot \vec{n}_{h^\pm} = 2 \frac{E(h^\pm)}{E(\tau^\pm)} - 1
\]

Intermediate spin-1 resonances ($\rho^-, a_1^-$) \( \Rightarrow \) angle $\theta$ depends on the polarisation of the resonance. Not sensitive enough to analyse by itself the $\tau$ polarisation. Need more discriminative variables
Helicity of $\tau$ leptons - Angles $\beta$, $\alpha$ and $\gamma$

Angular kinematics of $\tau$ decays are fully described by 1-4 angles:

- $\tau^\pm \rightarrow \pi^\pm \nu : \theta$
- $\tau^\pm \rightarrow a_1^\pm \nu \rightarrow 3\pi^\pm \nu : \theta, \beta, \alpha, \gamma$
- $\tau^\pm \rightarrow \rho^\pm \nu \rightarrow \pi^\pm \pi^0 \nu : \theta, \beta, \alpha$ ($\beta$ can be reconstructed from four-momenta of pions)
**Definition**: ratio of matrix elements (number of considered angles depends on decay mode)

\[ \omega(\tau = \theta, \beta, \alpha, \gamma) = \frac{|M(\theta, \beta, \alpha, \gamma | \tau_R)|^2 - |M(\theta, \beta, \alpha, \gamma | \tau_L)|^2}{|M(\theta, \beta, \alpha, \gamma | \tau_R)|^2 + |M(\theta, \beta, \alpha, \gamma | \tau_L)|^2} \]

\(\theta, \beta, \alpha, \gamma\): angles approximately estimated from the decay data

**Combination**: helicity information from both taus is 100% anti-correlated (on generator level)

\[ \Omega(\tau^-, \tau^+) = \frac{\omega(\tau^-) + \omega(\tau^+)}{1 + \omega(\tau^-) \cdot \omega(\tau^+)} \]
## Final Choice of Discriminators

<table>
<thead>
<tr>
<th>Channel</th>
<th>Category</th>
<th>Discriminator</th>
</tr>
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<tbody>
<tr>
<td>( \tau_e \tau_\mu )</td>
<td>( e + \mu )</td>
<td>( m_{\text{vis}}(e, \mu) )</td>
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<tr>
<td>( \tau_e \tau_h )</td>
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<td>( \omega(a_1) )</td>
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<tr>
<td></td>
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<td>( \cos \beta(\rho) )</td>
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<tr>
<td></td>
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<td>( \Omega(a_1, \pi) )</td>
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Discriminant Observables
signal and background definition

right-helicity signal split at generator level

left-helicity signal split at generator level

QCD multijet events estimated from data using jet to tau fake rate

W+jet background normalization estimated from data from high MT control region
Final Observables

\[ \times 10^3 \text{CMS} \]

- **Events / bin**
  - CMS: \( Z \rightarrow \tau^+ \tau^- \)
  - CMS: \( Z \rightarrow \mu^+ \mu^- \)
  - CMS: \( Z \rightarrow \text{II} \)
  - CMS: \( W + \text{jets} \)
  - CMS: \( W + \text{Diboson} \)
  - CMS: QCD multijet
  - CMS: Exp. unc.
  - CMS: Observed

- **Visible dijet Mass** \( m_{\text{vis}}(a_1a_1) \) (GeV)

- **Obs. / Exp.**

- **Cosine of the dijet Mass** \( \cos \beta(\rho) \)

\[ \times 10^3 \text{CMS} \]

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- **Visible dijet Mass** \( m_{\text{vis}}(\pi\pi) \) (GeV)

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Extraction of Polarisation by Template Fit

Fitting data distributions of optimal observables with templates for $Z \to \tau\tau$ signal and background:

$$\mathcal{T}(\text{data}) = \mathcal{T}(\text{sig}, \langle \mathcal{P}_\tau \rangle, r) + \mathcal{T}(\text{bkg})$$

Two parameters of interest:

- average tau polarisation $\langle \mathcal{P}_\tau \rangle$
- signal strength $r$

Signal templates:

$$\mathcal{T}(\text{sig}, \langle \mathcal{P}_\tau \rangle, r) = r \cdot \left[ \frac{1 + \langle \mathcal{P}_\tau \rangle}{2} \right] \cdot \mathcal{T}(Z \to \tau^- \tau^+) + \frac{1 - \langle \mathcal{P}_\tau \rangle}{2} \cdot \mathcal{T}(Z \to \tau^-_L \tau^+_R)$$

Background processes:

- $Z^0/\gamma^* \to e^-e^+/\mu^-\mu^+$
- $t\bar{t} + \text{jets}$, di-boson, $W + \text{jets}$ (normalisation from data) and QCD (normalisation and shape from data)

Closure test: The average polarisation of MC MADGRAPH5 is found back by extracting polarisation with templates
Systematic Source - $\tau$ DM Migrations

- Does MC simulation describes decay-mode reconstruction in data well?
- Variations of migrations have strong impact on polarisation measurement:
  - Problem of normalisation inside categories
  - Discriminant variables are optimised for a given $\tau$ decay-mode
- Define 3 most important migrations:
  - $x_0^{\text{reco}} \equiv x^{\text{reco}} (h^\pm \leftrightarrow h^\pm \pi^0)$
  - $x_1^{\text{reco}} \equiv x^{\text{reco}} (h^\pm \pi^0 \leftrightarrow h^\pm \pi^0 \pi^0)$
  - $x_{10}^{\text{reco}} \equiv x^{\text{reco}} (3h^\pm \leftrightarrow 3h^\pm \pi^0)$

Parameters $x_i^{\text{reco}}$ quantify the fraction of all events in a given reconstructed DM $i$ that migrate differently in data compared to MC.
Results of the Average $\tau$ Polarisation

\[ \langle P_{\tau} \rangle_{75-120\text{ GeV}} = -0.140 \pm 0.006 \text{ (stat)} \pm 0.014 \text{ (syst)} = -0.140 \pm 0.015. \]

\[ P_{\tau} (Z) = -0.144 \pm 0.015 \]

\[ P_{\tau} = -A_{\tau} = -\frac{2v_{\tau}a_{\tau}}{v_{\tau}^2 + a_{\tau}^2} \approx -2 \frac{v_{\tau}}{a_{\tau}} = -2(1 - 4\sin^2 \theta_W^{\text{eff}}). \]

\[ \sin^2 \theta_W^{\text{eff}} = 0.2319 \pm 0.0008 \text{ (stat)} \pm 0.0018 \text{ (syst)} = 0.2319 \pm 0.0019. \]

- Sensitivity is mostly driven by $\mu\tau$ channel following by $e\tau$, $e\mu$, and $\tau\tau$.
- No dependence on the pseudo-rapidity of the $Z_0$ boson.
Polarization of $\tau^-$ leptons in the decay of $Z$ bosons produced in pp collisions using CMS detector is presented to an integrated luminosity of 36.3 fb$^{-1}$.

The measured $\tau^-$ lepton polarization, $P_{\tau}(Z) = -0.144 \pm 0.015$, is in good agreement with the SLD, LEP and ATLAS results.

The measured polarization constrains the effective couplings of $\tau^-$ leptons to the $Z$ boson and determines the effective weak mixing angle to be $\sin^2 \theta_{\text{eff}}^W = 0.2319 \pm 0.0019$.

No deviation from SM! Improving the sensitivity requires both more data and more importantly, better understanding/reducing the systematics.
Backup
Polarization curve

\[ P_\tau = -A_\tau = - \frac{2v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2 \frac{v_\tau}{a_\tau} = -2 \left(1 - 4 \sin^2 \theta_W^{\text{eff}}\right). \]