

Towards the measurement of the longitudinal and transverse spin correlation of tau leptons in the decays of Z and H

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Introduction

- Spin of tau lepton
 - A technique to analyse spin of τ leptons in pp collisions
 - The parity violation in the weak neutral current introduces the polarization asymmetry of τ leptons produced in $Z \rightarrow \tau\tau$ decay
 - Measurement of the ratio of vector to axial-vector neutral couplings for τ leptons, $\frac{a_\tau}{v_\tau}$ - lepton universality
 - Measurement of the effective weak mixing angle $\sin^2 \theta_{\text{eff}}^\tau$
- Transverse spin correlation of τ lepton in the decay Z/H
 - Precise determination of the EWK parameters
 - Probing the CP origin of the H boson

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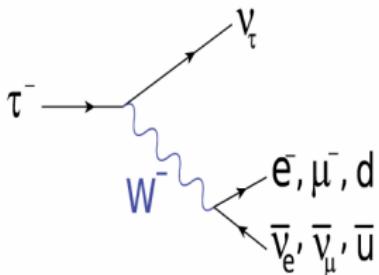
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Longitudinal τ^- spin state

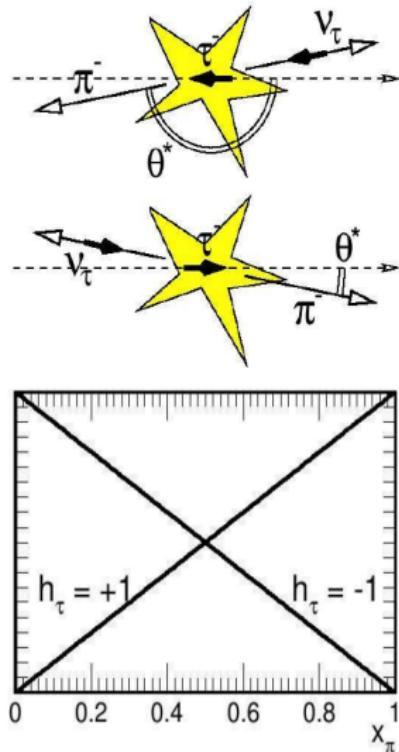
Assuming (V-A)



$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta^*} = \frac{1}{2} (1 + P_\tau \cos \theta^*)$$

$$\cos \theta^* = 2x_\pi - 1$$

$$x_\pi = \frac{E_\pi}{E_\tau} \text{ (In the lab. frame)}$$



Longitudinal τ spin state

A spin state of τ is extracted from angular distribution of decay products, wrt to τ and relative to each other.

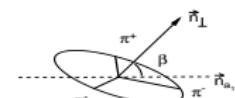
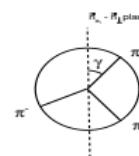
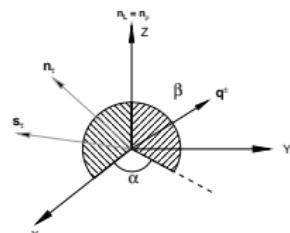
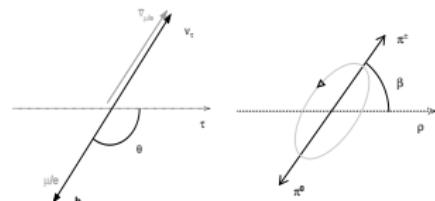
A full description of the decay maximises separation between τ helicity states \rightarrow statistical uncertainty.

Main τ decay modes that can be identified by CMS and ATLAS detectors:

- $\tau \rightarrow \mu/e\nu\nu$, $\tau \rightarrow \pi\nu$ - 1 angle
- $\tau \rightarrow \rho\nu \rightarrow \pi\pi\nu$ - 3 angles
- $\tau \rightarrow a1\nu \rightarrow (3\pi)^\pm\nu$ - 4 angles

Some angles require the τ rest frame:

- SVFit
- Global Event Fit



Optimal observable I

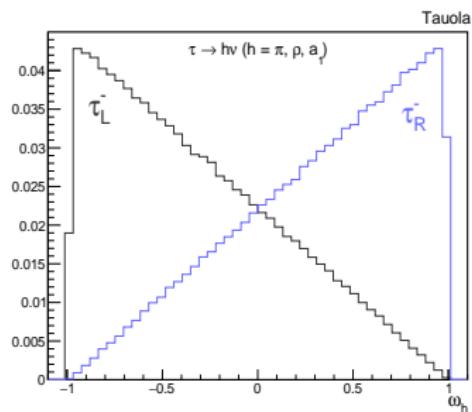
If all decay products are observed (all angles are reconstructed), for any τ decay the decay distribution:

$$W = \frac{1}{2}(1 + P_\tau \omega)$$

$$\omega = \cos_h = \vec{h} \vec{\tau}, P_\tau - \text{polarization value}$$

\vec{h} - **polarimetric vector** (the most probable direction of τ spin) reconstructed using kinematic of τ and decay products, i.e. available angles.

A full description provides a maximum possible separation of τ helicity states.



Optimal observable II

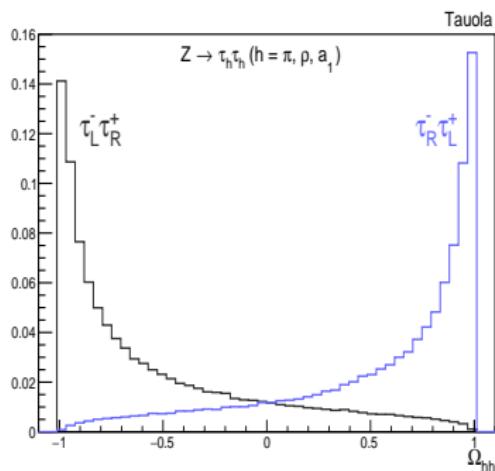
Spins of both τ leptons are $\approx 100\%$ anticorrelated

Analyse a pair of τ 's with combined observable $\Omega(\omega_1, \omega_2)$ derived from the common decay distribution

One observable for **all decay combinations**
 Ω_{hh} and Ω_{hl}

Most τ decay modes that can be identified at CMS are covered:

$Z \rightarrow \tau\tau \rightarrow \pi\pi, \pi\rho, \pi a_1, \rho\rho, \rho a_1, a_1 a_1$
 $Z \rightarrow \tau\tau \rightarrow e/\mu h (h = \pi, \rho, a_1)$



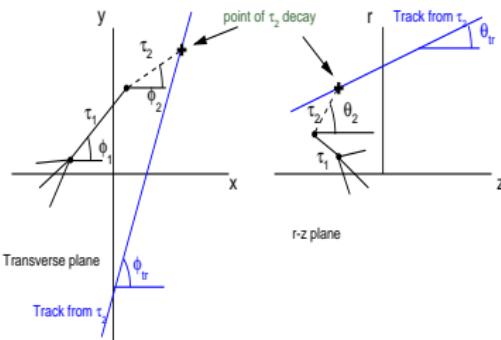
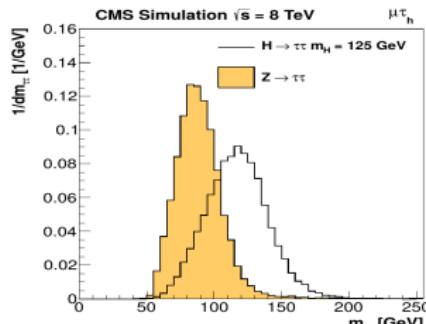
Reconstruction of $Z \rightarrow \tau\tau$ kinematic

SVFit (Lorenzo Bianchini et al., Nucl.Instrum.Meth. A862 (2017) 54–84 arXiv:1603.05910v3)

ME based algorithm computes for each event a likelihood function $P(M_{\tau\tau})$ which quantifies the level of compatibility of a mother particle mass hypothesis $M_{\tau\tau}$ with measured momenta of the visible τ decay products plus the missing transverse energy reconstructed in the event.

Global Event Fit (v. Cherepanov, A. Zotz, arXiv:1805.06988)

“Almost” model independent kinematic approach. The algorithm reconstructs the kinematic of τ pair in the decay decays $Z \rightarrow \tau\tau \rightarrow X + a_1\nu$ with a_1 resonance decaying into three charged pions. The method is based on iterative minimization of the likelihood built from the all available kinematic constraints on the event.



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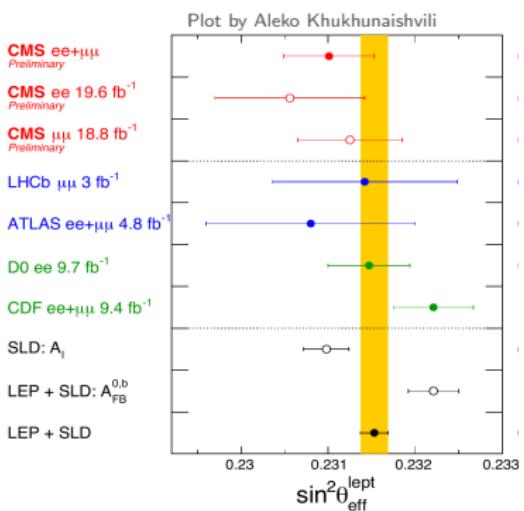
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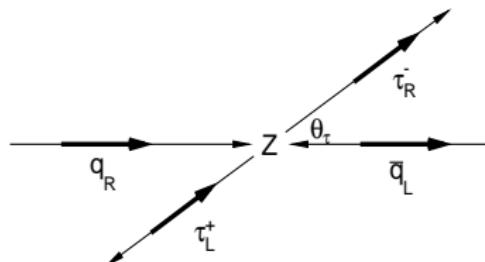
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Summary on effective weak mixing angle measurement

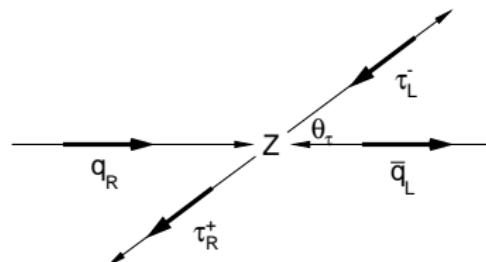


An independent measurement from $Z \rightarrow \tau\tau$ is complementary to other measurements at LHC.

Asymmetry in the process $q\bar{q} \rightarrow Z \rightarrow \tau\tau$



$$\text{Coupling} \propto g_R = (g_V^{\tau} - g_A^{\tau}) \approx 0.23$$



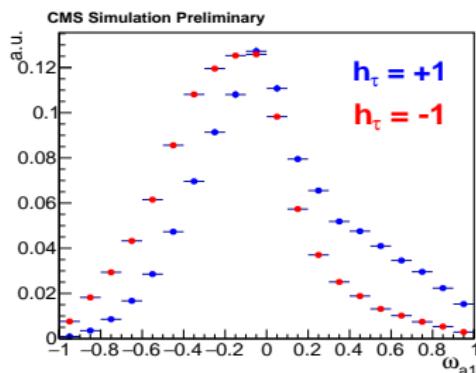
$$\text{Coupling: } \propto g_L = (g_V^{\tau} + g_A^{\tau}) = 0.27$$

- τ^- are preferably with helicity -1
- Polarization asymmetry: $A_{pol} = \frac{1}{\sigma} [\sigma(h_\tau = +1) - \sigma(h_\tau = -1)]$
- At the Z -pole $A_{pol} \approx 2 \frac{g_V^\tau}{g_A^\tau} \approx 2 - 8 \sin^2 \theta_W$

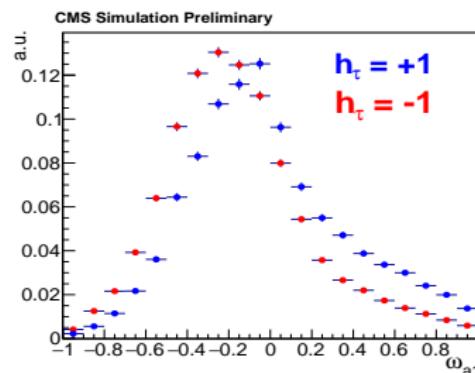
τ helicity state has to be accessed

τ polarization measurement at CMS with 8 TeV and 13 TeV data (CMS-DP-2016-060)

In 8 TeV data the feasibility study was performed using $\tau \rightarrow a_1 \nu$ decay channel



- Generator level

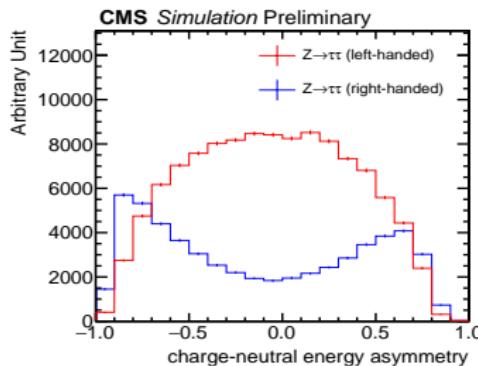
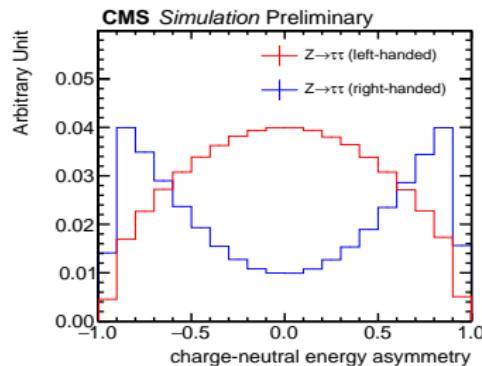


- After reconstruction

Sizeable separation of helicity states is achieved in $\tau \rightarrow a_1 \nu$ decay.

τ polarization measurement at CMS with 8 TeV and 13 TeV data (CMS-DP-2016-060)

The same study was performed using 2.3 fb^{-1} collected by CMS at 13 TeV.

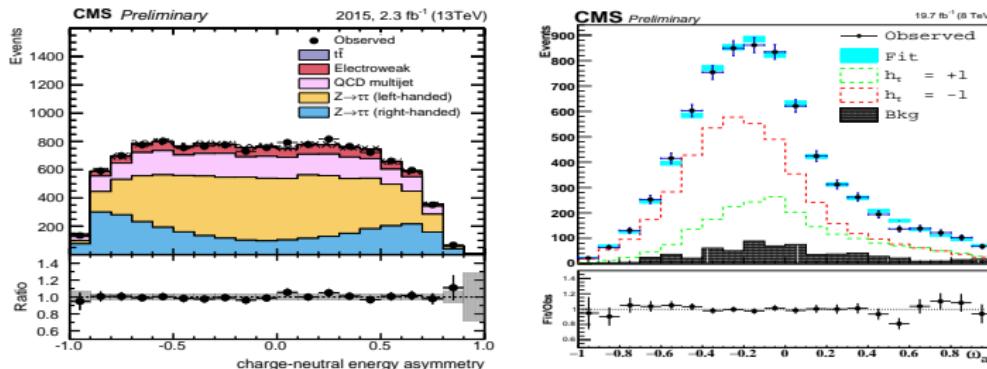


- Generator level
- After reconstruction

A good separation of different τ helicity states is achieved.

τ polarization measurement at CMS with 8 TeV and 13 TeV data (CMS-DP-2016-060)

The τ polarization asymmetry is measured by fitting MC templates for τ_R and τ_L to the observed distribution in data.



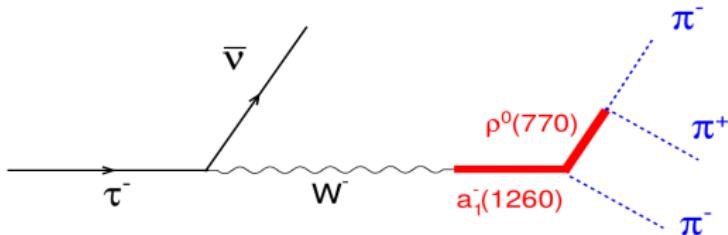
Extracted value (dependent on the acceptance efficiency) :

$$\langle P_\tau \rangle (\rho\text{channel}) = (-33.6 \pm 3.7(\text{stat. only}))\%$$

$$\langle P_\tau \rangle (a_1\text{channel}) = (-35.5 \pm 6.4(\text{stat. only}))\%$$

a1 decay model

The decay of $\tau^- \rightarrow a_1(1260)^- + \nu_\tau$ mainly followed by
 $a_1^- \rightarrow \rho(770) + \pi \rightarrow 3\pi$



The best parametrization by CLEO
arXiv:hep-ex/9902022

Resonance	L	Significance	Fraction, %
$\rho(770)\pi$	S	-	68.11
$\rho(1450)\pi$	S	1.4σ	0.30 ± 0.66
$\rho(770)\pi$	D	5.0σ	0.36 ± 0.18
$\rho(1450)\pi$	D	3.1σ	0.43 ± 0.29
$f_2(1270)\pi$	P	4.2σ	0.14 ± 0.06
$\sigma\pi$	P	8.2σ	16.18 ± 4.06
$f_0(1370)\pi$	P	5.4σ	4.29 ± 2.40

The systematic uncertainty on the τ polarization due to the a1 decay model is derived as: $\Delta P_\tau = (1.41 \pm 1.37) \times 10^{-4}$

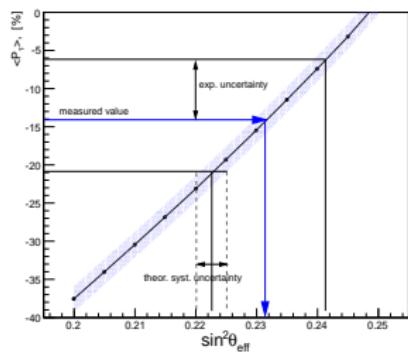
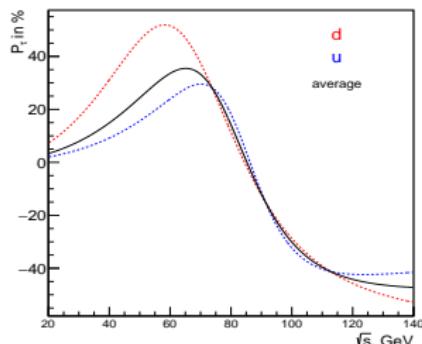
Previously quoted value :
 $\Delta P_\tau = 0.015 \pm 0.011$ (Phys.Lett. B308 (1993) 163-173)

Determination of $\sin^2 \theta_{\text{eff}}^\tau$

- $\langle P_\tau \rangle^{\text{meas}} = \frac{\int P_\tau(s) \epsilon(s) \hat{\sigma}(s) ds}{\int \epsilon(s) \hat{\sigma}(s) ds}$,
- $\epsilon(s)$ acceptance
- $\hat{\sigma}(s) = \sum_q \sigma_q(q\bar{q} \rightarrow \tau\tau)(f_q f_{\bar{q}} + q \leftrightarrow \bar{q})(1 + HO)$
- PDFs f_q from MSTW08

- EWK corrections are calculated using ZFitter
- QCD corrections evaluated to the first order
- Calculate $\langle P_\tau \rangle$ for 10 values of $\sin^2 \theta_{\text{eff}}$ including uncertainties on PDFs and acceptance

For more details see: V. Cherepanov, W. Lohmann, Methods for a measurement of polarization asymmetry in the decay $Z \rightarrow \tau\tau$ at LHC and determination of the effective weak mixing angle. arXiv:1805.10552



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Transverse spin correlation

- From LHC data $\Rightarrow J^P = 0^+$
 $H \rightarrow ZZ$ [Phys. Rev. Lett. 110, 081803](#)
- The CP-odd component not yet excluded [Phys. Rev. D 87, 055014](#)

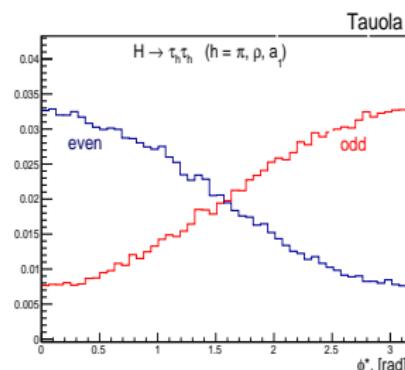
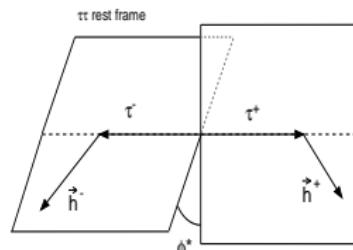
$$\Gamma(Z/H \rightarrow \tau\tau) \propto 1 \pm s_{||}^{\tau+} s_{||}^{\tau-} + s_{\perp}^{\tau+} R(2\theta) s_{\perp}^{\tau-}$$

$$R_Z = \begin{pmatrix} C_{TT} & C_{TN} \\ C_{TN} & C_{TT} \end{pmatrix} \text{ (in SM } C_{TT} = 1, C_{TN} = 0)$$

$$R_{H-even} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, R_{H-odd} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix},$$

Many papers describe how to access R_H , [S. Berge, W. Bernreuther, S. Kirchner, Eur. Phys. J. C \(2014\) 74: 3164](#)

- Reconstructing the accomplanarity angle ϕ^* using the visible decay products of τ leptons
- The sensitivity to odd/even contributions can be enhanced by analysing the transverse components of polarimetric vector exploiting the full kinematic (in progress)



Summary

- Technique to analyse the spin of τ leptons in LHC environment is presented
- The approach allows analyse the spin of τ lepton in general way for all τ decay channels that can be considered at CMS
- A measurement of the $\sin^2 \theta_{\text{eff}}^\tau$ and v_τ/a_τ at CMS using the improved method is ongoing
- Complementary to current efforts of measuring Higgs CP
 - Nice results come soon!