Perspectives for a measurement of τ polarization in $Z \to \tau\tau$ with CMS

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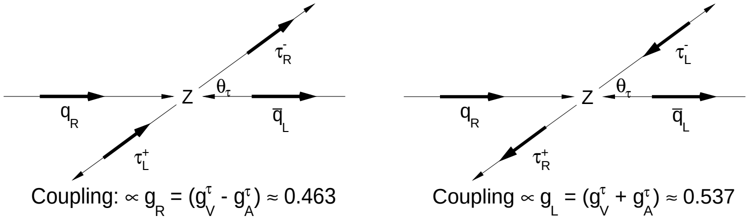
Introduction

- The parity violation in the weak neutral current introduces the polarization asymmetry of τ leptons produced in $Z \rightarrow \tau\tau$ decay. Knowledge of τ polarization provides:
  - Measurement of the ratio of vector to axial-vector neutral couplings for τ leptons
  - Measurement of effective weak mixing angle $\sin^2\theta_{eff}$
  - Techniques to analyze the spin of τ leptons can be used to measure CP properties of Higgs boson in the decay $H \rightarrow \tau\tau$
  - First step towards precision measurements at LHC with τ leptons
- A first look at τ polarization at LHC in the decay $Z \rightarrow \tau\tau$ is performed using $\tau \rightarrow \rho\nu$ and $\tau \rightarrow a_1\nu$ decays

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

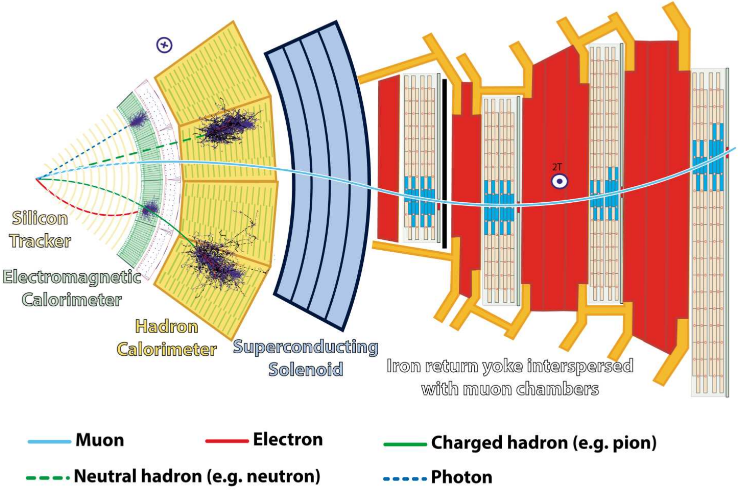


- τ^- are preferably with helicity -1
- Polarization asymmetry: $A_{pol} = \frac{1}{\sigma}[\sigma(h_\tau = +1) - \sigma(h_\tau = -1)]$
- At the Z-pole $A_{pol} \approx 2\frac{g^\tau_V}{g^\tau_A} \approx 2 - 8\sin^2\theta_W$

τ helicity state has to be accessed

CMS detector and default τ reconstruction

The CMS detector



Tau Reconstruction and identification (2016 JINST 11 p01019)

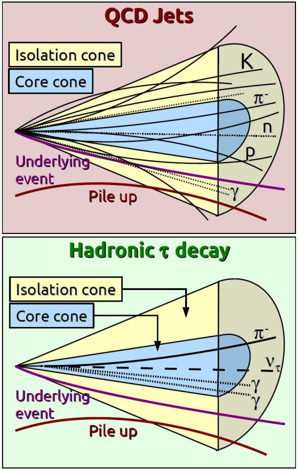
The main challenge in tau reconstruction is to discriminate between τ_{had} and QCD jets.

The experimental signatures of hadronically-decaying taus:

- collimated jet
- low multiplicity (up to three charged hadrons and up to two π^0's)
- decay products are isolated (require low detector activity around tau-jet direction)

A good performance in terms of efficiency&fake-rate is achieved by analyzing jet constituents and building individual decay modes: $\pi^{\pm}\nu_\tau$,$\pi^{\pm}\pi^0\nu_\tau$, $(\pi\pi\pi)^{\pm}\nu_\tau$

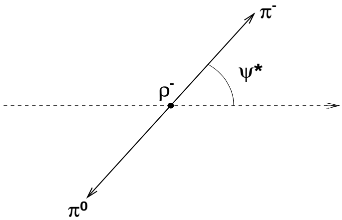
For more details see talk by Olivier Davignon on Tau-ID at CMS.



τ polarization observables in the decay $\tau \to \rho\nu \to \pi^{\pm}\pi^{0}\nu$

The charge-neutral energy asymmetry in the decay $\tau \rightarrow \rho\nu \rightarrow \pi^{\pm}\pi^{0}\nu$

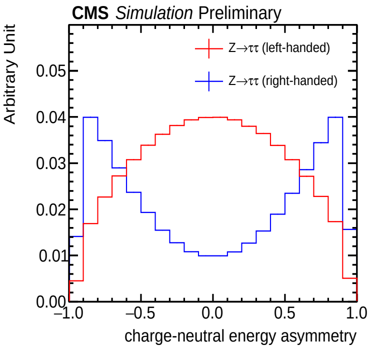
- In the tau decay, $\tau \rightarrow \rho\nu \rightarrow \pi^{\pm}\pi^{0}\nu$, the energy asymmetry between $\pi^{\pm}$ and π^{0} is a spin-sensitive variable
- $\cos\psi^{*} \sim [E(\pi^{\pm}) - E(\pi^{0})]/[E(\pi^{\pm}) + E(\pi^{0})]$
- The charge-neutral energy asymmetry is used to measure τ polarziation in the decay $Z \rightarrow \tau_{\mu}\tau_{\rho}$

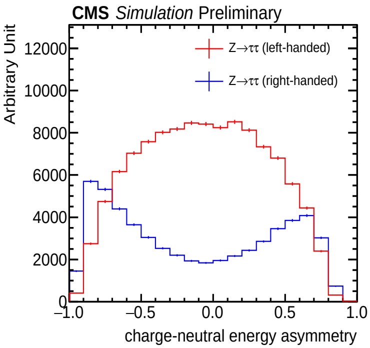


$$\cos\psi^{*} = \frac{m_{\rho}}{\sqrt{m_{\rho}^{2} - 4m_{\pi}^{2}}} \frac{E_{\pi^-} - E_{\pi^0}}{|\vec{P}_{\pi^-} + \vec{P}_{\pi^0}|}$$

Energy asymmetry distribution

The charge-neutral energy asymmetry in Monte Carlo simulation





- Generator level
- After reconstruction

Different τ_ρ helicity states are well separated!

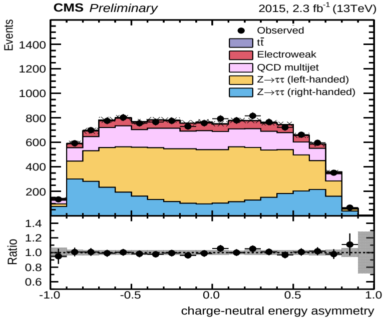
Polarization fit using $Z \to \tau_\mu \tau_\rho$ decay

The τ polarization is measured using $Z \to \tau\tau$ events selected from 2.3 fb^{-1} collected by CMS detector at 13 TeV.

The control sample selection:

- $\mu - \tau_h$ trigger
- Isolation of τ candidates
- τ_h decay mode
- Missing transverse mass, $M_T(\mu, E_T^{miss})$

ML fitting with right- and left-handed templates to observed distribution in data.



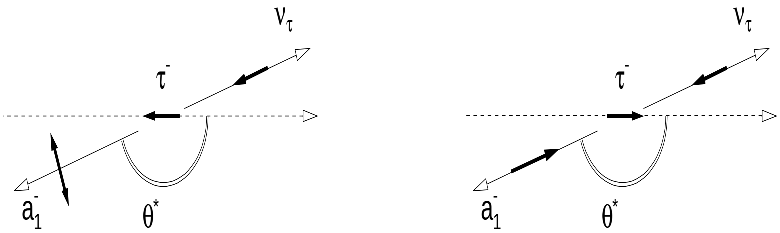
Extracted value (dependent on the acceptance efficiency) :

$$< P_\tau > = (-33.6 \pm 3.7(stat.\ only))\%$$

τ polarization observables in the decay $\tau \to a_1\nu \to 3\pi\nu$

Spin observables for the decay $\tau^{\pm} \to a_1^{\pm}\nu \to 3\pi^{\pm}\nu$

Spin configurations for the decay $\tau^- \to a_1^- \nu_\tau$ in the τ^- rest frame:

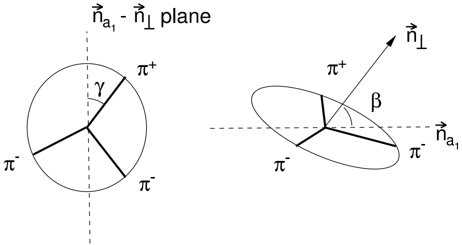


The combined distribution: $\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta^*} \propto 1 + \alpha_{a_1} P_\tau cos\theta^*$;

Spin observables II

Spin analyzers for $a_1 \to 3\pi$ decay in a_1 rest frame:

- γ describes the relative pions orientation within its plane
- β is the angle between laboratory and the 3π plane



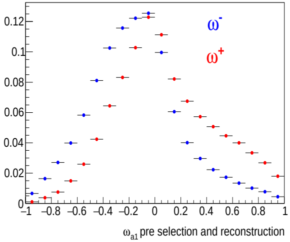
Optimal observable (M. Davier et al., Phys. Lett. B 306 (1993) 411-417)

The measured decay distribution depends linearly on the weighting of two helicity states, P_τ

For any tau decay: $\frac{1}{\Gamma_i}\frac{d^n\Gamma_i}{d^n\vec{\xi_i}} = f_i(\vec{\xi_i}) + P_\tau g_i(\vec{\xi_i})$

$\vec{\xi_i} = (\cos\theta^*, \gamma, \beta ...)$

One dimensional variable:
$\omega = \frac{|M_+(\vec{\xi})|^2 - |M_-(\vec{\xi})|^2}{|M_+(\vec{\xi})|^2 + |M_-(\vec{\xi})|^2} = \frac{g(\vec{\xi})}{f(\vec{\xi})}$

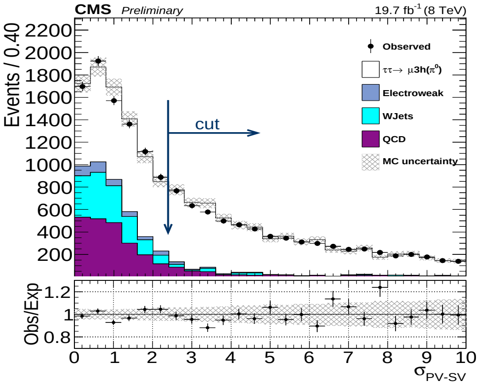


All polarization sensitive variables $\vec{\xi}$ can be converted into one-dimensional ω without loss of sensitivity

reconstruction of ξ and hence ω requires the rest frame of tau!

Reconstruction of $Z \to \tau\tau \to \mu\nu\nu, 3\pi\nu$

The measurement relies on the ability of CMS detector to measure flight direction of τ_{a1}



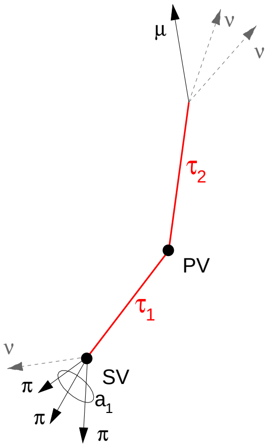
The distance between primary vertex and point of τ decay in units of uncertainties.

Reconstruction of $Z \to \tau\tau \to \mu\nu\nu, 3\pi\nu$ (Event Fit)

- Reconsctruction of τ_{a_1} direction
- Calculation of τ_{a_1} momentum
- Assume τ leptons from Z decay and apply constraints:
    - Invariant mass of two taus is equal to M_Z (PDG)
    - Transverse momentum balance of τ pair
    - Constraints on τ leptons direction using muon helix and measured vertices

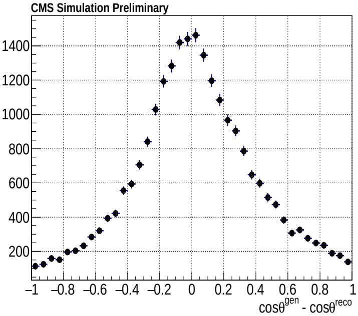
+1 overconstrained fit allows to fully reconstruct system with kinematic of both τ leptons

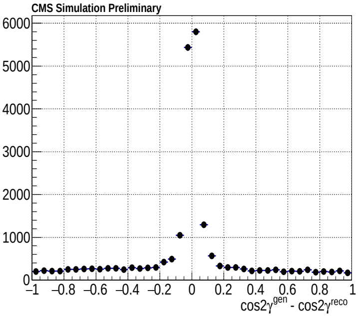
The procedure is applicable to any decay $\tau\tau \to X, 3\pi\nu$



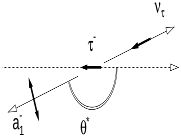
Reconstruction of spin sensitive angles

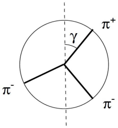
The knowledge of τ lepton kinematics allows to reconstruct the spin sensistive angles



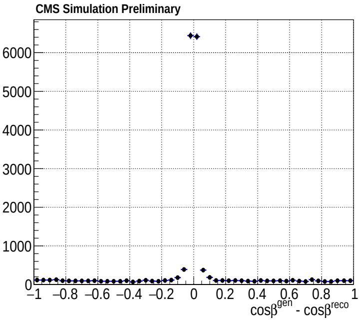


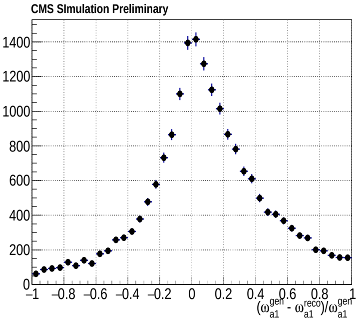
- Resolution of angle θ^*
- Resolution of angle γ



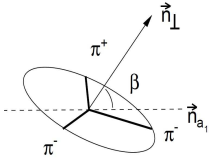


Reconstruction of spin sensitive angles





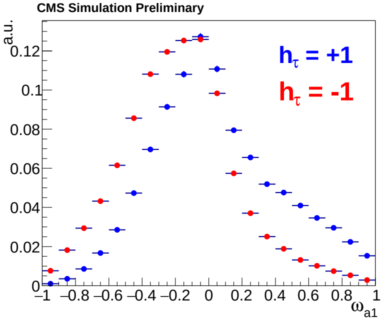
- Resolution of angle β

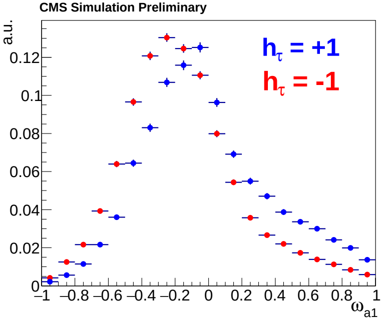


- resolution of the combined observable ω_{a_1}

Optimal observable distribution

The distribution of ω_{a_1} in Monte Carlo simulation





- Generator level
- After reconstruction

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

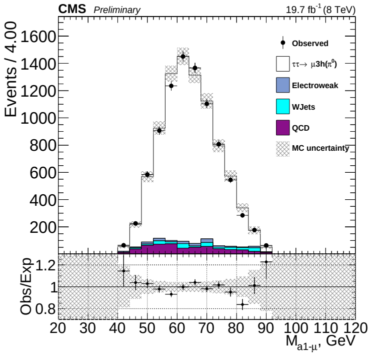
Z$\to \tau_\mu \tau_{3\pi}$ control sample

Selection of Z$\to \tau_\mu \tau_{3\pi}$ using 19.7 fb^{-1} collected at 8 TeV

- $\mu - \tau_h$ trigger
- Isolation of τ candidates
- τ_h decay mode
- Flight length of τ_{a_1}
- Missing transverse mass, $M_T(\mu, E_T^{miss})$

- Main background contribution from QCD multijet and W+Jets events are estimated from data

Mass of visible decay products

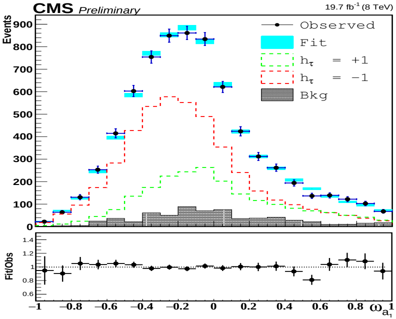


Polarization fit using $Z \to \tau_\mu \tau_{a_1}$ decay

The τ polarization is measured using $Z \to \tau\tau$ events selected from 19.7 fb^{-1} collected by CMS detector at 8 TeV.

Strategy similar to $\tau \to \rho\nu$:

Fitting the observed distribution of ω_{a_1} by left- and right- handed templates with their relative fraction as a free parameter.

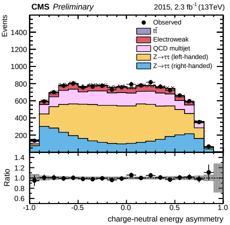


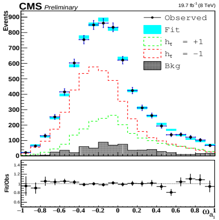
Extracted value (dependent on the acceptance efficiency) :

$$< P_\tau > = (-35.5 \pm 6.4(stat.\ only))\%$$

Summary

- First measurements of τ polarization at LHC have started.
- Analysis of $\tau \rightarrow \rho\nu$ and $\tau \rightarrow a_1\nu$ indicates the feasibility of this measurement.
- The obtained results in both channels are consistent with expected values.
- Systematic uncertainties and bias correction require a bit more efforts.
- The precision will grow including more data and other τ decay channels.





Backup

Hadron Plus Strips Algorithm (HPS)

1. Cluster photons within the jet into strips accounting for possible broadening due to photon conversions
2. Combine charged particles in the jet with strips and reconstruct individual τ_h decay mode: $\pi^{\pm}\nu_{\tau}$,$\pi^{\pm}\pi^{0}\nu_{\tau}$, $(\pi\pi\pi)^{\pm}\nu_{\tau}$
3. Highest pT decay "hypothesis" with compatible visible mass is given preference