# Measurement of the polarization of $\tau$–leptons produced in $Z^0$ decays at CMS and determination of the effective weak mixing angle $\sin^2\theta_{eff}$

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## Introduction

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

## Measurements at LEP

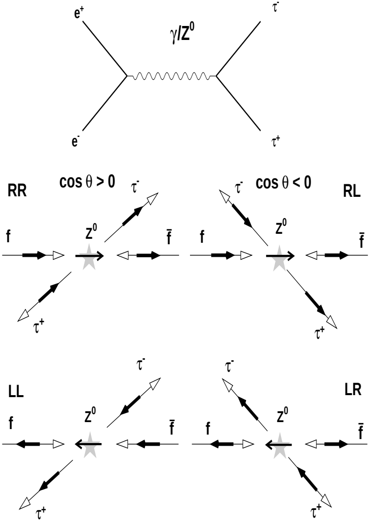
# Neutral current coupling measurements in $e^+e^-$ annihilation

$$\frac{d\sigma_{Born}}{d\cos\theta} = (1+\cos^2\theta)F_0(s) + 2\cos\theta F_1(s) + P_\tau[(1+\cos^2\theta)F_2(s) + 2\cos\theta F_3(s)]$$

$$A_{FB} = \frac{\sigma(\cos\theta>0)-\sigma(\cos\theta<0)}{\sigma_{total}} = \frac{3F_1(s)}{4F_0(s)} = \frac{3}{4}\frac{2v_e a_e}{v_e^2+a_e^2}\frac{2v_\tau a_\tau}{v_\tau^2+a_\tau^2}$$

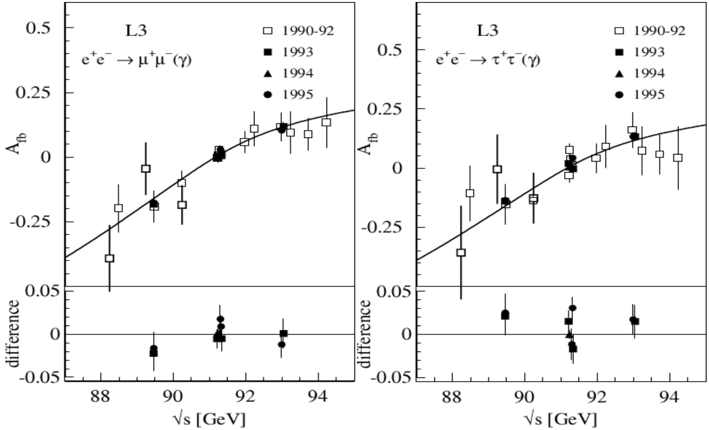
$$A_{pol} = \frac{\sigma(h_\tau=+1)-\sigma(h_\tau=-1)}{\sigma_{total}} = -\frac{F_2(s)}{F_0(s)} = -\frac{2v_\tau a_\tau}{v_\tau^2+a_\tau^2}$$

$$A_{FB}^{pol} = A_{pol}(\cos\theta>0) - A_{pol}(\cos\theta<0) = -\frac{3F_3(s)}{4F_0(s)} = -\frac{3}{4}\frac{2v_e a_e}{v_e^2+a_e^2}$$



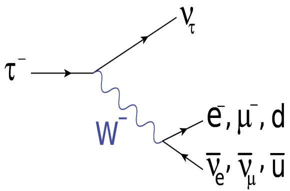
# Measurements at LEP

Forward-backward asymmetry of muons(left) and taus(right) from $Z \to \mu\mu(\gamma)$ and $\tau\tau(\gamma)$ at L3.



# Polarization observables (some examples)

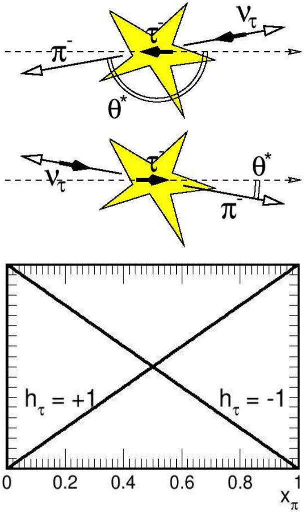
**Assuming (V-A)**




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

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

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



# Measurements at LEP

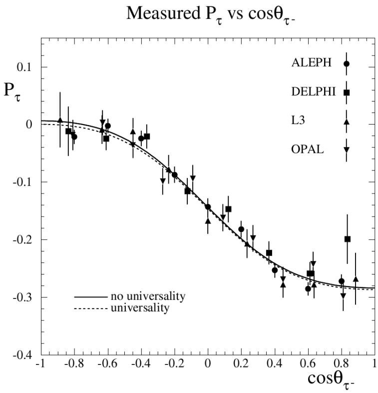
$$A_e = \frac{2v_e a_e}{v_e^2 + a_e^2} = 0.1498 \pm 0.0049$$

$$A_\tau = \frac{2v_\tau a_\tau}{v_\tau^2 + a_\tau^2} = -P_\tau = 0.1439 \pm 0.0043$$

$$A_\tau \approx 2\frac{v_\tau}{a_\tau} = 2(1 - 2|Q|\sin^2\theta_W)$$

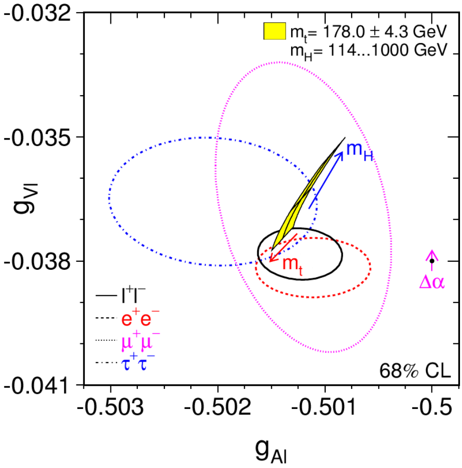
$$\sin^2\theta_W = 0.23159 \pm 0.00041$$

$\sin^2\theta_W$ is called the effective weak mixing angle and contains higher order corrections predictable in the Standard Model.



# Measurements at LEP

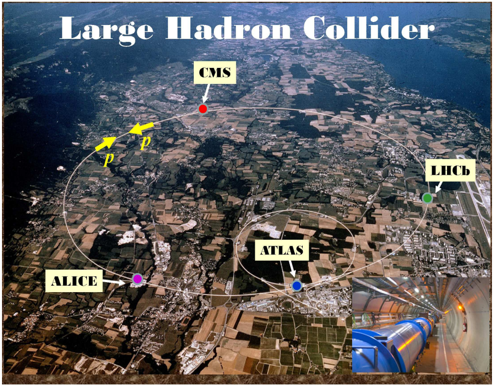
- Measurement of the neutral current couplings for leptons
- Lepton Universality
- Measurement of $\sin^2 \theta_{eff}$
- Constraints on top and higgs masses



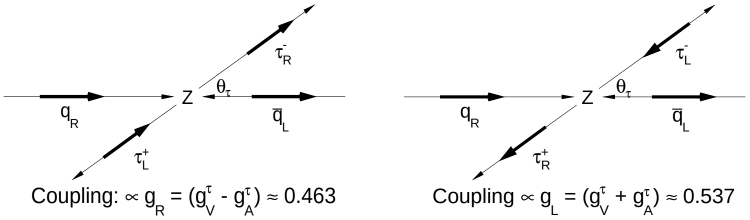
# Measurements at LHC

AT LHC the luminosity is $10^3$ times larger, but:

- The Z is produced in $q\bar{q}$ annihilation and initial flavor is unknown.
- The Z is not at rest in the centre-of-mass system (no beam energy constraint).
- Pile up of many interactions.



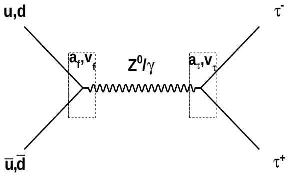
## Asymmetry in the process $q\bar{q} \to Z \to \tau\tau$




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

$\tau$ helicity state has to be accessed

# Measurements at LHC

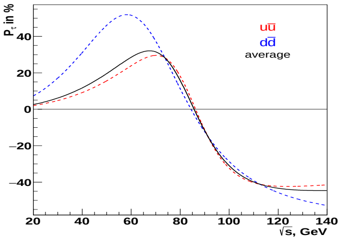


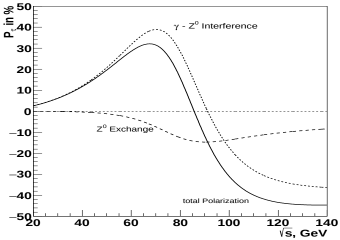

$$F_0(s) = \frac{\pi\alpha}{4s}[q_q^2 q_\tau^2 + 2Re\chi(s)q_q q_\tau v_q v_\tau + |\chi(s)|^2(v_q^2 + a_q^2)(v_\tau^2 + a_\tau^2)]$$

$$F_2(s) = \frac{\pi\alpha}{4s}[2Re\chi(s)q_q q_\tau v_q a_\tau + |\chi(s)|^2(v_q^2 + a_q^2)2v_\tau a_\tau]$$

Since $P_\tau = -\frac{F_2}{F_0}$

- the quark couplings cancel out at the Z pole
- away from the Z pole u and d quarks give different contributions and $\gamma/Z$ interference matters

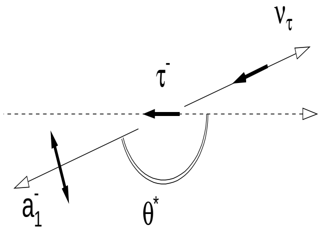


## $\tau$ polarization observables in the decay $\tau \to a_1\nu \to 3\pi\nu$

## 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 $\tau^{-}$ rest frame:

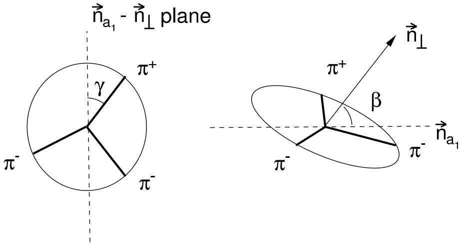



The combined distribution: $\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta^*} \propto 1 + \alpha_{a_1} P_\tau cos\theta^*$;

# Spin observables II

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

- $\gamma$ describes the relative pions orientation within its plane
- $\beta$ is the angle between laboratory and the $3\pi$ plane



## Optimal observable

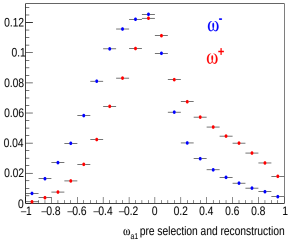
The measured decay distribution depends linearly on the weighting of two helicity states, $P_\tau$

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

$\vec{\xi_i} = (\cos\theta^*, \gamma, \beta ...)$ - multidim. vector of spin sensitive variables

One dimensional variable:

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

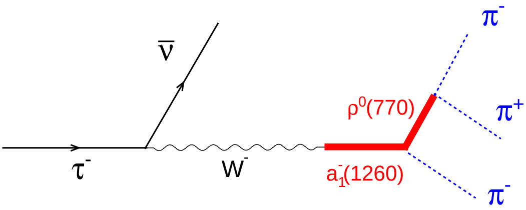



All polarization sensitive variables $\vec{\xi}$ can be converted into one-dimensional $\omega$ without loss of sensitivity (M. Davier et al. The optimal method for the measurement of tau polarization. Phys. Lett. B 306 (1993) 411-417 )

reconstruction of $\xi$ and hence $\omega$ requires the rest frame of tau!

# Model of $\tau^- \to a_1(1260)^- + \nu_\tau$

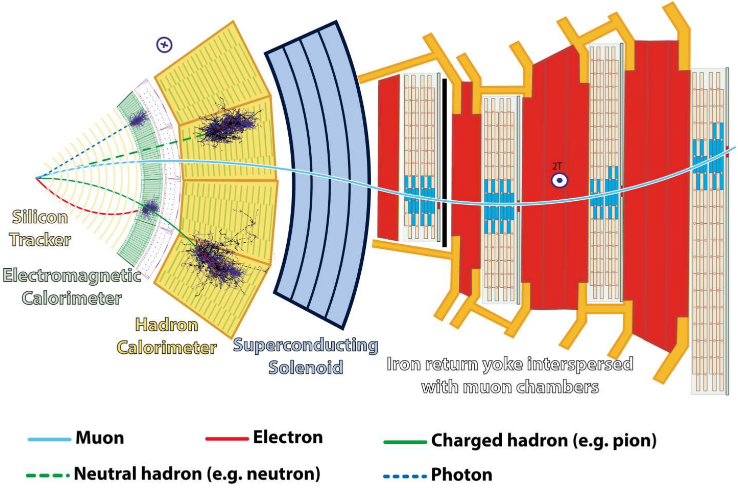
The decay of $\tau^- \to a_1(1260)^- + \nu_\tau$ mainly followed by
$a_1^- \to \rho(770) + \pi \to 3\pi$



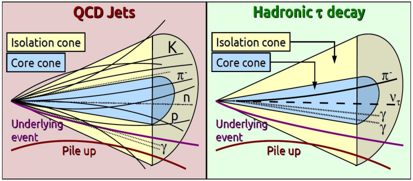

- The decay model mediated by $\rho\pi_{S-wave}$ is used ( J.H.Kuhn and E.Mirkes, Z.Phys.C – Particle and Fields 56, 661-671 (1992) )
- The effect of scalar ($\pi(1300)$) contribution, contribution of $\rho\pi_{D-wave}$, etc are assigned as systematic uncertainties.

# CMS detector and default $\tau$ reconstruction

# The CMS detector

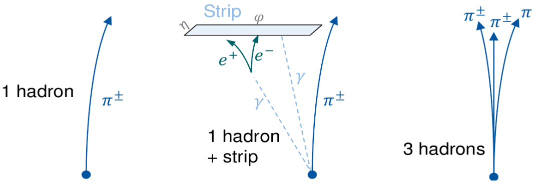


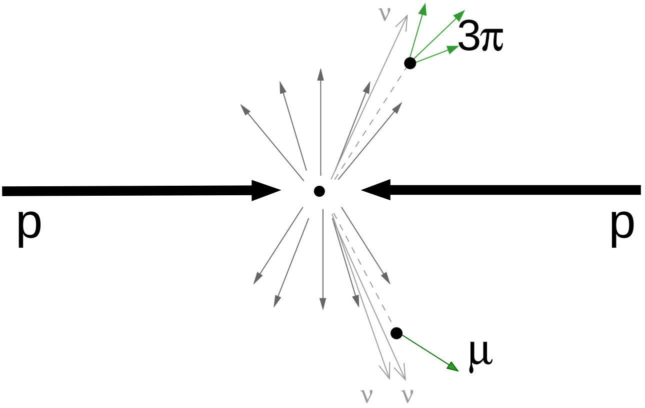
# Tau Leptons in CMS




## Signatures of $\tau$ pairs in CMS

- Two muons or two electrons
- One muon and one electron
- One electron(muon) and low multiplicity collimated hadronic jet
- Low missing transverse energy

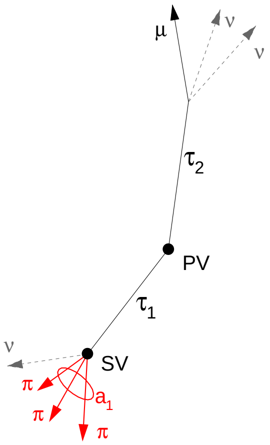





**Event reconstruction intended to recover escaped neutrinos momenta is performed in three steps**

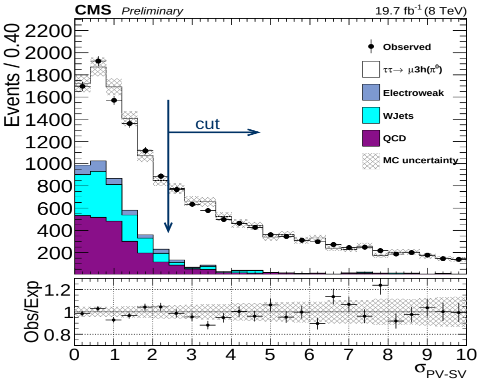
# Reconstruction of $Z \rightarrow \tau\tau \rightarrow \mu\nu\nu, 3\pi\nu$

- Select the event with $\mu$ and $\tau$-like jet
- Run $\tau$-reco algorithm to find 3 tracks for $\tau \rightarrow 3\pi\nu$ candidate
- Fit secondary vertex (SV) using 3 pions (point of the $\tau_1$ decay)
- Fit primary vertex (PV) - the point of interraction



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

The reconstruction relies on the ability of CMS detector to measure flight direction of $\tau_{a1}$



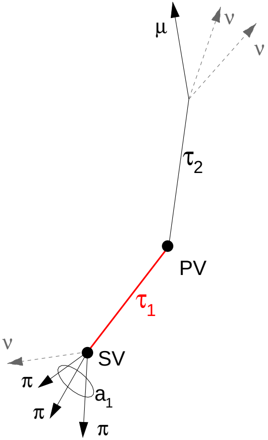

The distance between primary vertex and point of $\tau$ decay in units of uncertainties.

## Reconstruction of $Z \rightarrow \tau\tau \rightarrow \mu\nu\nu, 3\pi\nu$

- Assume two-body decay
  $\tau \rightarrow a_1\nu$

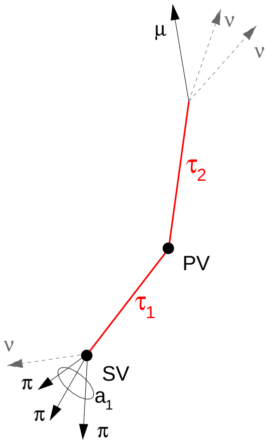
- Solve equation for $\tau$ momentum
  $(P_\tau - P_{a_1})^2 = P_\nu^2 = 0$

With the measured $a_1$ momentum ($3\pi$) and $\tau_1$ direction ($\vec{SV} - \vec{PV}$) two possible solutions $\rightarrow$ ambiguity!



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

- Assume taus from Z decay and apply constraints:
  - Invariant mass of two taus is equal to $M_Z$
  - Pt "balance" of two taus
  - constraints on $\tau$ letpons direction using muon helix and measured vertices

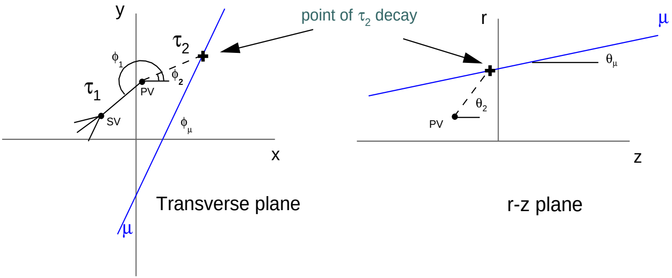



+1 overconstraint fit allows to solve the ambiguity from step2 and reconstruct momentum of $\tau_\mu$!

Fully reconstructed system with kinematic of both $\tau$ leptons

# Angular constraints

Projections of di-tau system onto xy and rz planes:




- The muon track is approximated by a straight line
- Find the angles of $\tau_\mu$ assuming that it must have a common point with muon track

Alternatively one can assume $\theta_2 = \theta(\mu)$ (valid for highly boosted taus)

# Constrained Fits

Experimental input:

- $\vec{PV}$, $\vec{SV}$, $\vec{p}_{a_1}$ and muon helix parameters;

General problem:

- Measured momentum of $\tau_1$ (w/ or w/o ambiguity)$\rightarrow$ **y**
- New post-fit momentum of $\tau_1 \longrightarrow$ **a**
- Not measured momentum of $\tau_2 \longrightarrow$ **b**
- Accessible constraints

Likelihood:
write in a form: $L = \chi^2 \quad + SoftConstraints \quad + \quad HardConstraints$

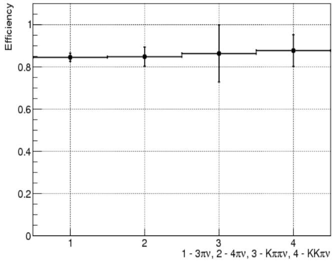
$$L = (\mathbf{y} - \mathbf{a})^T V_y^{-1}(\mathbf{y} - \mathbf{a}) + \mathbf{f}(\mathbf{a}, \mathbf{b})^T V_f^{-1}\mathbf{f}(\mathbf{a}, \mathbf{b}) \quad + \quad 2\lambda^T H(\mathbf{a}, \mathbf{b})$$

$$f = \begin{cases} P_x^{\tau_1} + P_x^{\tau_2} - p_x^{a_1} - p_x^{\mu} - MET_x \\ P_y^{\tau_1} + P_y^{\tau_2} - p_y^{a_1} - p_y^{\mu} - MET_y \end{cases} \qquad H = \begin{cases} M_{\tau\tau} - M_Z \\ p_z^{\tau_2} - |p^{\tau_2}| \cos\theta_2 \end{cases}$$

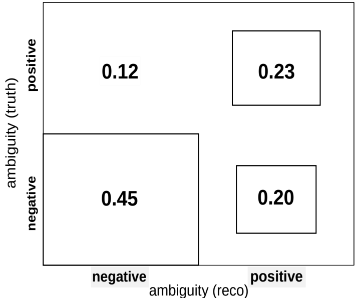
Solution:
Parameters of interest **a** and **b** are found by minimizing L;

# Event Fit performance I

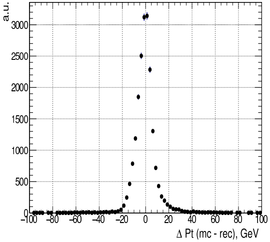
Event Fit efficiency for various $\tau$ decay channels



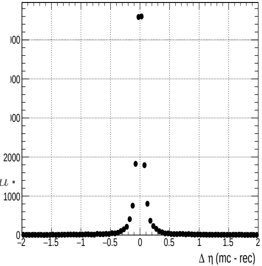

Ambiguity for $\tau_{a_1}$ kinematic is solved running minimization two times: $L(correct) < L_{min}(wrong)$



# Event Fit performance II

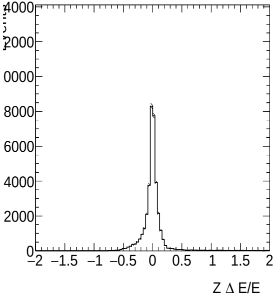



Transverse momentum resolution of $\tau_{a_1}$, $\Delta p_T / p_T \approx$ 10%



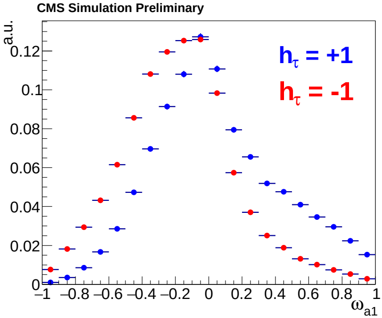

Pseudorapidity resolution of $\tau_\mu$.

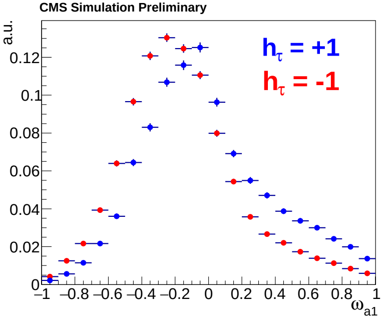
Relative energy resolution of Z ($\tau_1 + \tau_2$), over 70% of the events with resolution better than 20%.



# Optimal observable distribution

The distribution of $\omega_{a_1}$ in Monte Carlo simulation




- Generator level
- After reconstruction

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

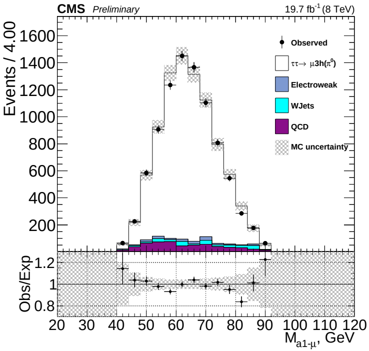
# $Z \to \tau_\mu \tau_{3\pi}$ control sample

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

- $\mu - \tau_h$ trigger
- Isolation of $\tau$ candidates
- $\tau_h$ decay mode
- Flight length of $\tau_{a_1}$
- 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

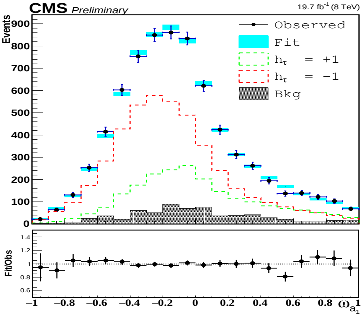


# Polarization fit using $Z \to \tau_\mu \tau_{a_1}$ decay

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

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

This is the polarization averaged over the Z resonance shape.

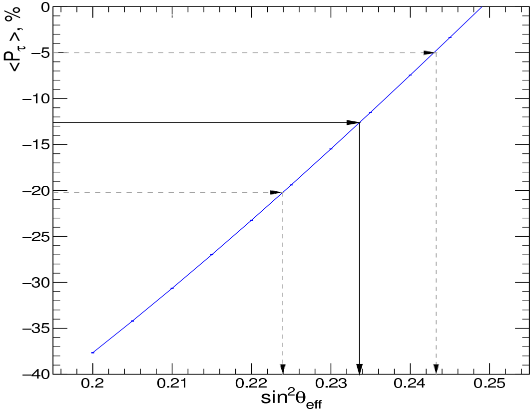



**Extracted value :**

$$< P_\tau > = -0.126 \pm 0.066(data) \pm 0.032(MC) \pm 0.015(theor.) \pm 0.008(syst.)$$

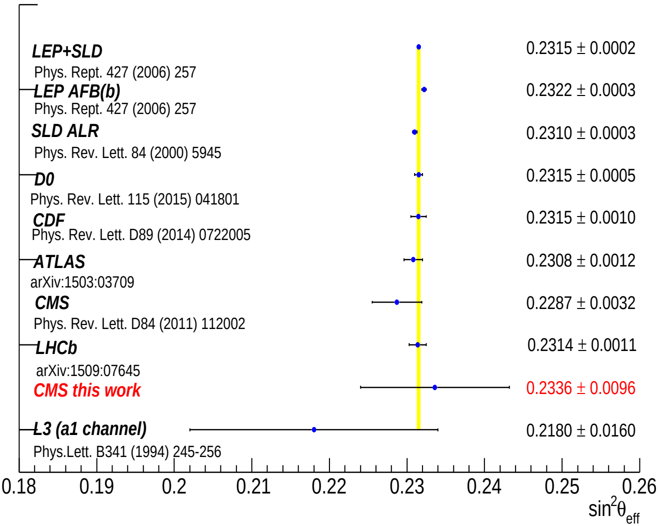
# $< P_\tau >$ and $\sin^2\theta_{eff}$

The gauge curve between $< P_\tau >$ and $\sin^2\theta_{eff}$ obtained using ZFitter and proton pdfs.




The obtained value $\sin^2\theta_{eff} = 0.2336 \pm 0.0096$

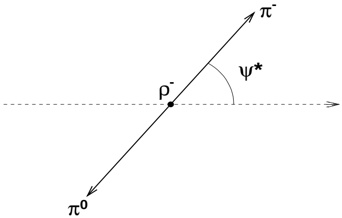
# Comparing to other measurements



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

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

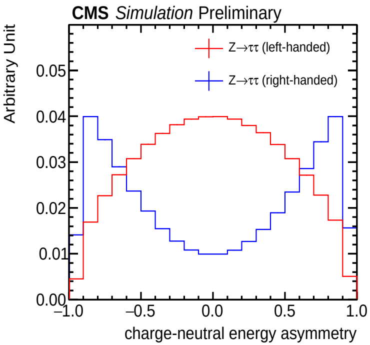
- In the tau decay, $\tau \to \rho\nu \to \pi^{\pm}\pi^{0}\nu$, the energy asymmetry between $\pi^{\pm}$ and $\pi^{0}$ is a spin-sensitive variable
- $\cos\psi^{*} \sim [E(\pi^{\pm}) - E(\pi^{0})]/[E(\pi^{\pm}) + E(\pi^{0})]$
- The charge-neutral energy asymmetry is used to measure $\tau$ polarziation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

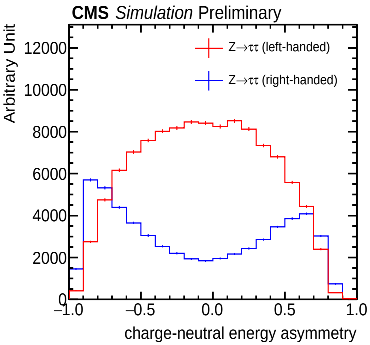



$$\cos\psi^{*} = \frac{m_{\rho}}{\sqrt{m_{\rho}^{2} - 4m_{\pi}^{2}}} \frac{E_{\pi^{-}} - E_{\pi^{0}}}{|\vec{P}_{\pi^{-}} + \vec{P}_{\pi^{0}}|}$$

## Energy asymmetry distribution (CERN-CMS-DP-2016-060)

The charge-neutral energy asymmetry in Monte Carlo simulation




- Generator level
- After reconstruction

Different $\tau_\rho$ helicity states are well separated!

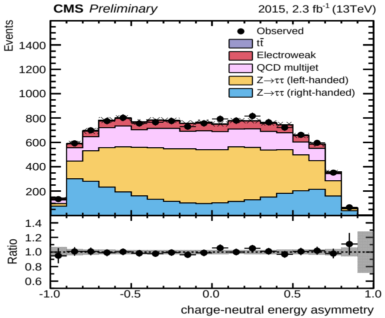
# Polarization fit using $Z \to \tau_\mu \tau_\rho$ decay (CERN-CMS-DP-2016-060)

The $\tau$ 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 $\tau$ candidates
- $\tau_h$ decay mode
- Missing transverse mass, $M_T(\mu, E_T^{miss})$

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

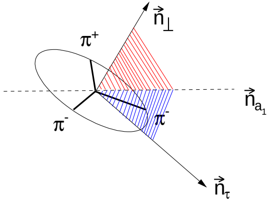



**results in progress**

# Tau Polarization, what is next?

**In $a_1$ channel include additional spin sensitive angle**

$\omega_{a_1}(\cos\theta^*, \gamma, \beta, \alpha)$ in progress...




10-15% gain in sensitivity is expected

**Other decays**

$Z \to \tau\tau \to e-\rho/e-a_1$ can $\approx$ double statistics

**Polarization of $\tau^-$ and $\tau^+$ are 100% anticorrelated $\longrightarrow$ look at both sides!**

- $\Omega_{a_1-a_1}$
- $\Omega_{a_1-\rho}$
- $\Omega_{a_1-\pi}$

  Total B.R. of $Z \to \tau\tau$ decays $\approx$ 15% ($\mu - a_1$ is 3%)

LEP statistical uncertainty can be reached analyzing $\approx$ 100-150 1/fb (very conservative)

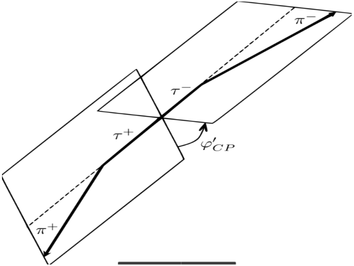
- LHC data $\Rightarrow J^P = 0^+$
  $h \to ZZ$ (Phys. Rev. Lett. 110, 081803)
- CP-odd component not yet excluded

**CP study with $h \to \tau\tau$**

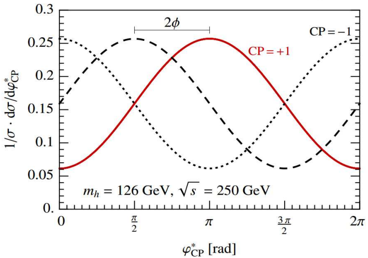
Sensitive to a CP odd component
$\mathcal{L}_Y = g_\tau(\cos\alpha_\tau \bar{\tau}\tau + \sin\alpha_\tau \bar{\tau}\gamma_5\tau)$

Transverse spin-spin correlation of $\tau$ leptons in $h \to \tau\tau$ is sensitive to $\alpha_\tau$

Example of observable in
$h \to \tau^-\tau^+ \to \pi^-\pi^+ + 2\nu_\tau$




S. Berge, arXiv:1308.2674

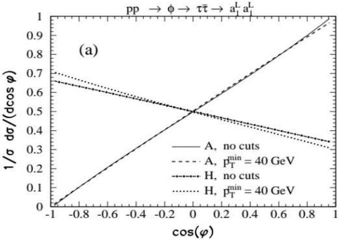


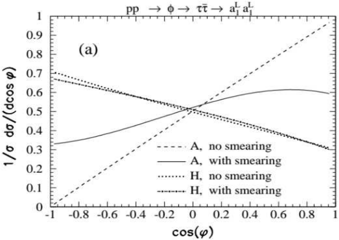
# Higgs CP with $H \to \tau\tau$

- Direction of both $\tau$'s can be measured in $H \to \tau\tau \to a_1 a_1 + 2\nu$
- Polarimeter: $\cos\phi = \angle(a_1, a_1')$ (both $a_1$ in its $\tau$ frame)

S. Berge, arXiv:0801.2297v1

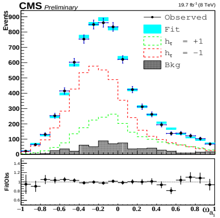
- $\tau$-spin analyzing power is given as a relative contribution of T and L components.
- For $\tau \to a_1\nu$: $\frac{M_T}{M_L} \approx 1$
- Max. analyzing power $\tau \to \pi\nu$
- The event fit allows to recover the full kinematic of $H \to \tau\tau \to a_1\pi + 2\nu$ and $H \to \tau\tau \to a_1\rho + 2\nu$

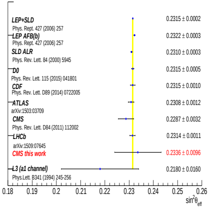


# Summary

- First measurements of $\tau$ polarization at LHC have started.
- Analysis of $\tau \to \rho\nu$ and $\tau \to a_1\nu$ indicates the feasibility of this measurement.
- The obtained value is $\sin^2\theta_{eff}$ = 0.2336 $\pm$ 0.0096
- The ratio of vector to axial-vector neutral current couplings for $\tau$ leptons $g_V^\tau/g_A^\tau = 0.0656 \pm 0.0384$
- Estimated systematic uncertainties do not limit the precision
- The precision will grow including more data and other $\tau$ decay channels.

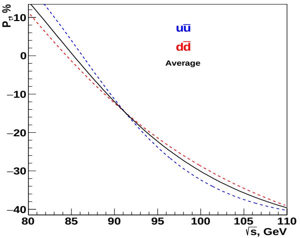


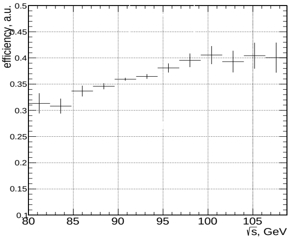
# backup

# Average Polarization

- $< P_\tau >^{meas} = \frac{\int P_\tau(s)\epsilon(s)\hat{\sigma}(s)ds}{\int \epsilon(s)\hat{\sigma}(s)ds}$;
- $\epsilon(s)$ acceptance
- $\hat{\sigma}(s) = \sum_q \sigma_q(q\bar{q} \to \tau\tau)(f_q f_{\bar{q}} + q \leftrightarrow \bar{q})(1 + HO)$
- PDFs $f_q$ from MSTW08




- EWK corrections are calculated using ZFitter
- QCD corrections evaluated to the first order




- $< P_\tau >$ is calculated for 10 values of $\sin^2\theta_{eff}$ including uncertainties on PDFs and acceptance