A measurement of the weak mixing angle from τ polarization at CMS

Vladimir Cherepanov and AC tau group.

III.Phys.Institut B, RWTH Aachen

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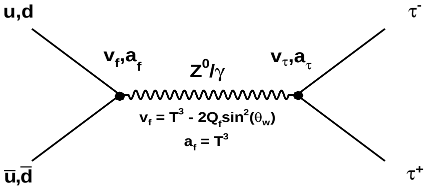
τ–lepton polarization

Inequality of weak couplings to left-handed and right-handed particles results in a polarization of τ leptons

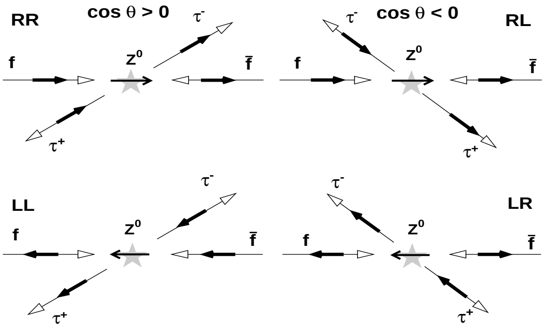


Coupling	Value
a_l	-0.50123 $\pm$ 0.00026
v_l	-0.03783 $\pm$ 0.00041

$$\frac{d\sigma}{dcos\theta_\tau} = F_0(s)(1+cos^2\theta_\tau)+2F_1(s)cos\theta_\tau - h_\tau[F_2(s)(1+cos^2\theta_\tau)+2F_3(s)cos\theta_\tau]$$

- A first measurement of τ polarization from Z decays at hadron colliders.
- Towards the precision measurements at CMS (can be comeptetive to LEP with more stat. collected)
- Test for lepton universality in the neutral current

Asymmetries



$$\sigma = \Sigma_{h_\tau} \int \frac{d\sigma}{dcos\theta_\tau} dcos\theta_\tau \qquad = \sigma_{RR} + \sigma_{LL} + \sigma_{RL} + \sigma_{LR}$$

$$A^{FB} = \frac{1}{\sigma}[\sigma(cos\theta_\tau > 0) - \sigma(cos\theta_\tau < 0)] \qquad = \frac{1}{\sigma}[\sigma_{RR} + \sigma_{LL} - (\sigma_{RL} + \sigma_{LR})] \approx \frac{3}{4} A_f A_\tau$$

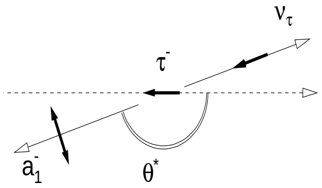
$$A_{pol} = \frac{1}{\sigma}[\sigma(h_\tau = +1) - \sigma(h_\tau = -1)] \qquad = \frac{1}{\sigma}[\sigma_{RR} + \sigma_{LR} - (\sigma_{RL} + \sigma_{LL})] \approx -A_\tau$$

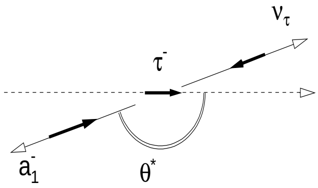
$$A^{FB}_{pol} = \frac{1}{\sigma}[A_{pol}(cos\theta_\tau > 0) - A_{pol}(cos\theta_\tau < 0)] = \frac{1}{\sigma}[\sigma_{RR} - \sigma_{LL} - (\sigma_{RL} - \sigma_{LR})] \approx -\frac{3}{4} A_f$$

where $A_\tau = \frac{2 v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx 2 \frac{v_\tau}{a_\tau}$

Polarization observables I (for the decay $\tau \to a_1\nu(\to 3\pi^{\pm})\nu$)

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





$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta^*} \propto \frac{m_\tau^2}{m_{a_1}^2}(1 + h_\tau cos\theta^*)$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta^*} \propto 2(1 - h_\tau cos\theta^*)$$

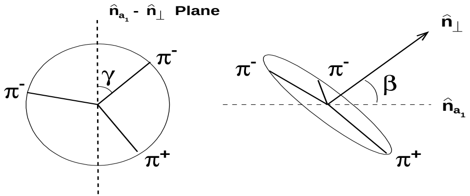
The combined distribution: $\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta^*} \propto 1 + \alpha_{a_1} P_\tau cos\theta^*$;

$$\alpha_{a_1} = \frac{m_\tau^2 - 2m_{a_1}^2}{m_\tau^2 + 2m_{a_1}^2} \approx 0.021 \quad (\alpha_\rho \approx 0.45,\ \alpha_\pi = 1)$$

Polarization observables II

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

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



The variables $(\theta, \beta, \gamma, s_1, s_2, Q^2)$ are used to describe the martix element of the decay $\tau \longrightarrow \pi\pi\pi\nu$ (P. Privitera. Structure functions in $\tau \to 3\pi\nu$ and the τ polarization measurement. Phys.Lett B **308** (1993) 163-173)

Optimal Observable

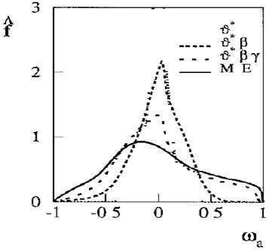
The measured decay distribution depends linearly on the weighting of two helicity states, P_τ

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

$\vec{\xi}_i$ - multidim. vector of spin sensitive variables

One dimensional variable:

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



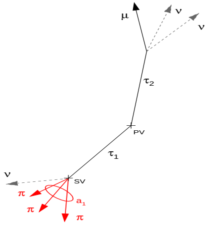
All polarization sensitive variables $\vec{\xi}$ can be converted into one-dimensional ω without loss of sensitivity (M. Davier et al. The optimal method for the measurement of tau polarization. Phys. Lett. B 306 (1993) 411-417)

To reconstruct $\vec{\xi}$ (and hence ω_{a_1}) the rest frame of τ is required!

Event reconstruction (Global Event Fit)

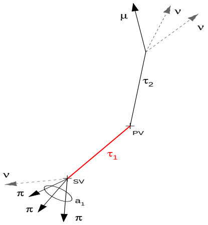
Event reconstruction I

The Global Event Fit consist in 3 steps.



Step 1

- Select the event with μ and τ-like jet
- HPS algorithm to find 3 tracks for $\tau \longrightarrow 3\pi\nu$ candidate
- Reconstruct the vertex of 3 pions (SV)
- Repeat reconstruction of PV without particles identified as products of τ decays



Step 2

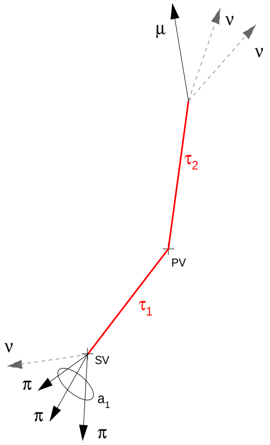
- Assume two-body decay $\tau \longrightarrow a_1\nu$
- Solve equation for τ momentum $(P_\tau - P_{a_1})^2 = P_\nu^2 = 0$
- With the measured a_1 momentum (3π) and τ_1 direction $(\vec{SV} - \vec{PV})$ two possible solutions $\rightarrow$ ambiguity!

Event reconstruction II

The Step 3 solves the ambiguity from Step 2 and reconstructs the kinematic of the second τ ($\tau \rightarrow \mu\nu\nu$)

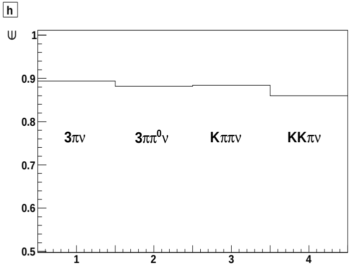
- Constraints:
  - Invariant mass of two tau leptons (assume tau pair is produced in Z decay)
  - Pt "balance" of two taus (accounting for transversal boost of Z)
  - Angular constraints on tau leptons flight direction (derived from measured kinematic of a_1 and μ)

The full event kinematic is recovered, including all 3 neutrinos!

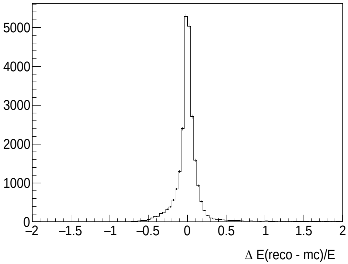


Event reconstruction III (basic performance plots)

- Efficiency of the Event Fit for signal decay (1st bin) and for irreducible contributions from the decays with similar signature.



- Relative energy resolution of the di-tau rest frame (Z).



Selection & Background

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

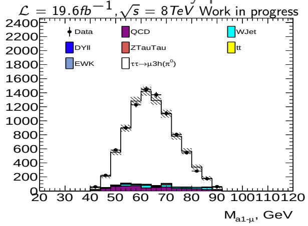
Cut flow:

- Trigger requiring muon $P_T > 20$ GeV and tau $P_T > 20$ GeV
- Object selection: good muon and τ_h candidates
- Flightlenght of τ_h
- Event based cuts: pair charge, $M_T(\mu, E_T^{miss})$

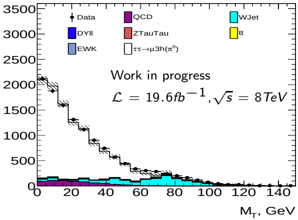
Backgrounds:

- Major background contribution (QCD, W + jets) are estimated from data
- Small contributions (Di-Boson, $t\bar{t}$, DY) taken from MC

Mass of visible decay products



Missing transverse mass

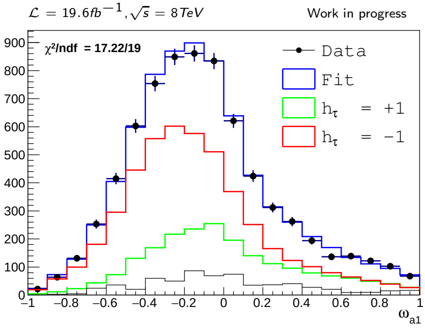


Polarization Fit

Polarization fit

The τ polaristion is measured by fitting the linear combination of two templates for variable ω_{a_1} taken from MC[a] to the observed distribution in data.

[a] Z.Was, et al., TauSpinner, CERN-PH-TH-20011-307

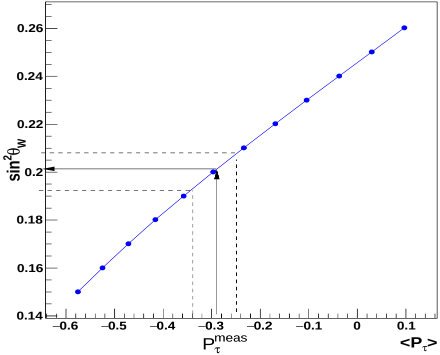


Preliminary result

Extracted value $P_\tau = -0.291 \pm 0.045(stat)$

Mixing angle

ZFitter was used to perform the expected value for the average polarization for different values of $sin^2\theta_W$



The obtained value $sin^2\theta_W = 0.201 \pm 0.007$ (stat).

Summary & Outlook

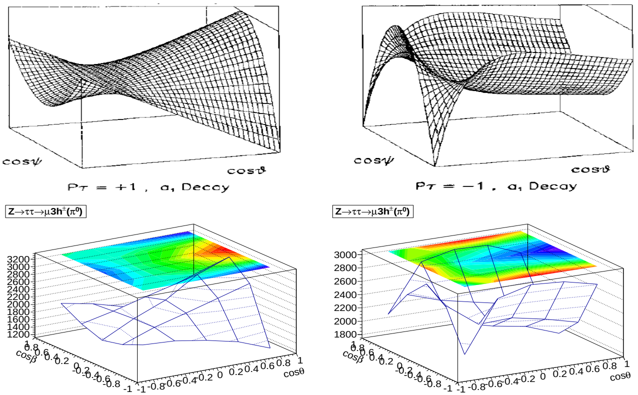
1. A first measurement of the tau polarization at CMS with $a_1\nu$ final state is presented
2. The mixing angle $sin^2\theta_W$ is derived using ZFitter. The obtained value is 0.201 ± 0.007 (stat).
3. Evaluation of the systematic uncertainties is in progress

- Additional independent measurement can be performed with the other final states (e.g. e/a_1, l/ρ)
- The developed Global Event Fit is applicable to many other topics besides the presented.

backup

Angular distributions for a_1 decay of τ–lepton

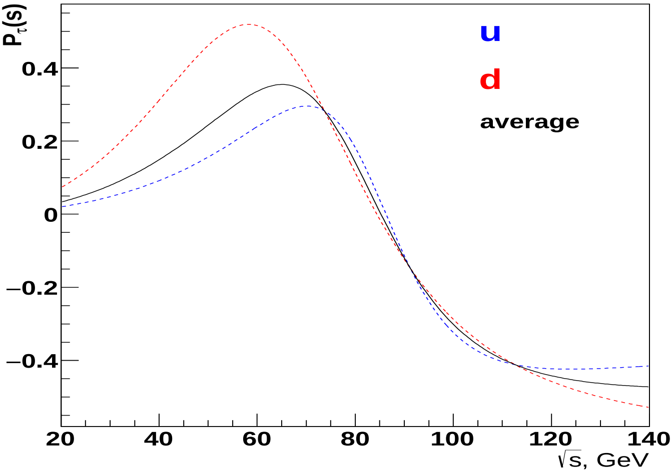
Distributions of $cos\theta$ and $cos\beta$ for $+1$ and -1 τ helicities;
Analytical and MC without any cuts and reconstruction;



Sensitivity is better in CMS of τ–leptons (rest frame of Z boson)

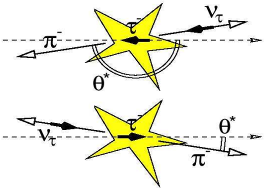
Polarization for $u\bar{u}$,$d\bar{d}$ and pp (tree level)

The actual polarization $P_\tau(s) = -\frac{F_2(s)}{F_0(s)}$

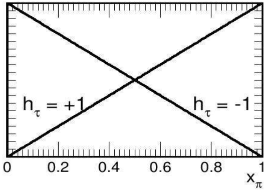


Polarization observables (some examples)

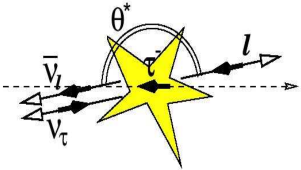
$\tau \to \pi\nu$



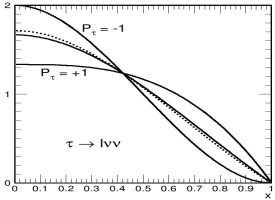
$$\frac{d\Gamma}{dx_\pi} \propto 1 + h_\tau (2x_\pi - 1).$$



$\tau \to l\nu\nu$



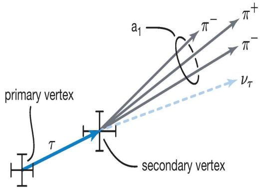
$$\frac{d\Gamma}{dx} = \frac{G_F^2 m_\tau^5}{192\pi^3}\left[\frac{5}{3} - 3x^2 + \frac{4}{3}x^3 - h_\tau\left(-\frac{1}{3} + 3x^2 - \frac{8}{3}x^3\right)\right].$$

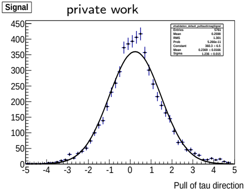


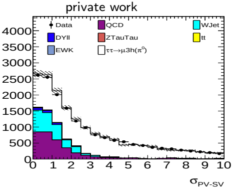
x here is a scaled π/μ energy, eg. $x_\pi = E_\pi/E_\tau$. Quantities in lab frame.

Reconstruction of 3-prong τ_h

- Reconstruct secondary vertex (SV) using tracks corresponding to τ–lepton
- Reconstruct primary vertex (PV) from non-τ tracks
- Reconstruct direction of τ lepton as SV - PV.
- Direction of τ and visible energy allow to calculate full momentum of τ–lepton: $(P_\tau - P_{a_1})^2 = P_\nu^2 = 0$ – two solutions possible

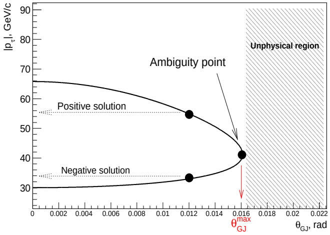


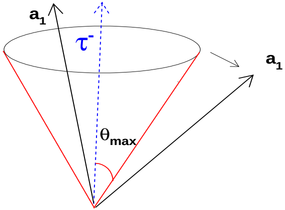




Ambiguity of tau kinematics

unknown τ energy in pp collisions leads to an ambiguity:





In physical region two allowed values for $|P_\tau|$ for a given τ–lepton direction and visible momentum

- Ambiguity can be solved by using information from opposite hemisphere and applying event fit (next slide)

If measured angle is in unphysical region tau cone is rotated until angle reaches its maximum allowed value

- No ambiguity in this case but slightly incorrect value for tau kinematic

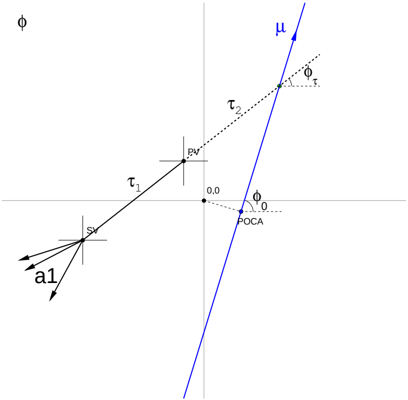
Event Fit

Event Fit Flow:

- Select pair of τ candidates
- Estimate direction of τ_μ
- Apply kin. fit with 2 constraints:
  - P_T balance of two taus
  - Z mass constraint
- Run fit 2 times for each ambiguity points and pick one with better χ^2 probability
- Stay with "rotated" τ if unphysical
- Fully reconstructed system → rest frame of Z boson!

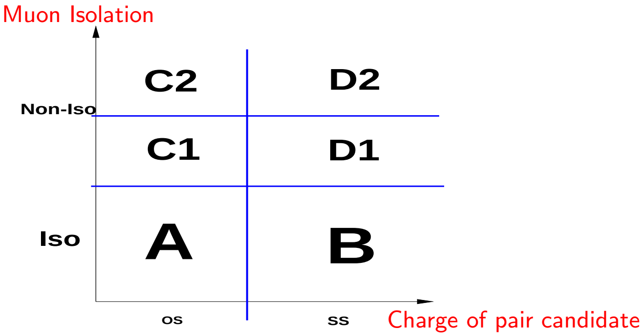
Note:

Fit can be applied to any di-τ systems like $\tau_{3\pi}\tau_x$.



Background estimation I

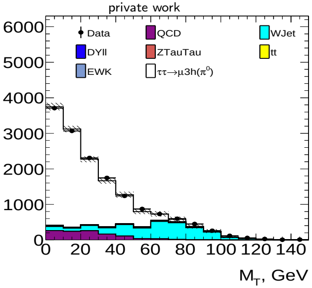
QCD is difficult to model in MC



- measure OS/SS ratio in events with non-isolated muons: $f^{OS/SS} = \frac{C2}{D2} = 1.19$
- apply measured charge ratio to events selected in SS isolated muon region(non-QCD background subtracted): $QCD_A = QCD_B * f^{OS/SS}$

Background estimation II

W+jets background is taken from data



- W+Jets normalization determined using $M_T > 70$ GeV sideband:
  $f^{SC} = \frac{N^{MC}_{M_T<cut}}{N^{MC}_{M_T>70}}$
- Background in signal region is estimated as: $N^{data}_{M_T<cut} = f^{SC} * N^{data}_{M_T>70}$
- Data driven estimation agrees with MC within 3%

Constrained Fits

General problem

- 3 measured parameters $\mathbf{y}$ ($\vec{p}_{\tau_{a1}}$ from step 2) and post-fit parameters $\mathbf{a}$
- Unmeasured particle $\rightarrow$ 3 additional parameters $\mathbf{b}$: $(p_x, p_y, p_z)_{\tau_\mu}$
- constraints $\mathbf{H}(\mathbf{a}, \mathbf{b}) = 0$;

Linearized function L

$$L = (\mathbf{y} - \mathbf{a})^T V^{-1}[y](\mathbf{y} - \mathbf{a}) + 2\lambda^T[\mathbf{A}(\mathbf{a} - \mathbf{a}_0) + \mathbf{B}(\mathbf{b} - \mathbf{b}_0) + \mathbf{c}(\mathbf{a}_0, \mathbf{b}_0)]$$

here: A,B - Jacobians of constraints H w.r.t **a** and **b** evaluated at the linearization points $\mathbf{a}_0$ and $\mathbf{b}_0$

solution is from minimizing L w.r.t **a**,**b** and λ

fitting with soft constraints

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

$$L = (\mathbf{y} - \mathbf{a})^T V^{-1}[y](\mathbf{y} - \mathbf{a}) + \mathbf{f}^T V^{-1}[f]\mathbf{f} + 2\lambda^T[\mathbf{A}(\mathbf{a} - \mathbf{a}_0) + \mathbf{B}(\mathbf{b} - \mathbf{b}_0) + \mathbf{c}(\mathbf{a}_0, \mathbf{b}_0)]$$

Soft constraints have to be linearized as well:
$\mathbf{f}(\mathbf{a}, \mathbf{b}) = \mathbf{f}_0(\mathbf{a}_0, \mathbf{b}_0) + \mathbf{F}_\mathbf{a}(\mathbf{a} - \mathbf{a}_0) + \mathbf{F}_\mathbf{b}(\mathbf{b} - \mathbf{b}_0)$

$\mathbf{F}_\mathbf{a}$ and $\mathbf{F}_\mathbf{b}$ - Jacobians of SC w.r.t **a** and **b** at linearization points.

minimization wrt to **a**,**b** and λ gives the solution:

$$\begin{pmatrix} V^{-1} + F_a^T V_f^{-1} F_a & F_a^T V_f^{-1} F_b & A^T \\ F_b^T V_f^{-1} F_a & F_b^T V_f^{-1} F_b & B^T \\ A & B & \mathbf{0} \end{pmatrix} \begin{pmatrix} a \\ b \\ \lambda \end{pmatrix} = \begin{pmatrix} V^{-1} y - F_a^T V_f^{-1}(f_0 - F_a a_0 - F_b b_0) \\ -F_b^T V_f^{-1}(f_0 - F_a a_0 - F_b b_0) \\ A a_0 + B b_0 - c \end{pmatrix}$$

find parameters **a**,**b** ,λ and iterate convergency requirements are fullfiled