Measurement of the τ lepton polarization in Z boson decays using CMS detector

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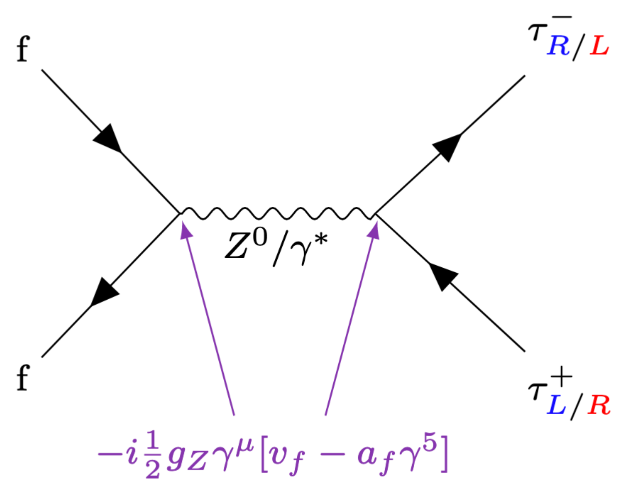
Dec 5th 2023
Tau 2023 conference, Louisville, KY

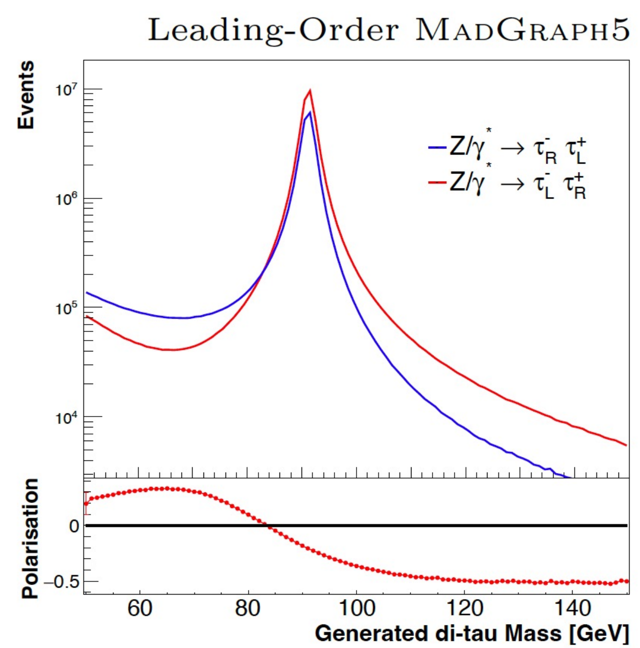
Motivation

- 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 τ lepton
- Aim of this analysis:
  - Measure average polarisation of leptons in Z/γ events:

$$\langle \mathcal{P}_\tau \rangle = \frac{N(pp \to Z/\gamma \to \tau_R^- \tau_L^+) - N(pp \to Z/\gamma \to \tau_L^- \tau_R^+)}{N(pp \to Z/\gamma \to \tau_R^- \tau_L^+) + N(pp \to Z/\gamma \to \tau_L^- \tau_R^+)}$$

  - Convert polarisation into effective weak mixing angle $\sin^2\theta_w$
- Any deviation from SM reveals a new physics beyond SM!





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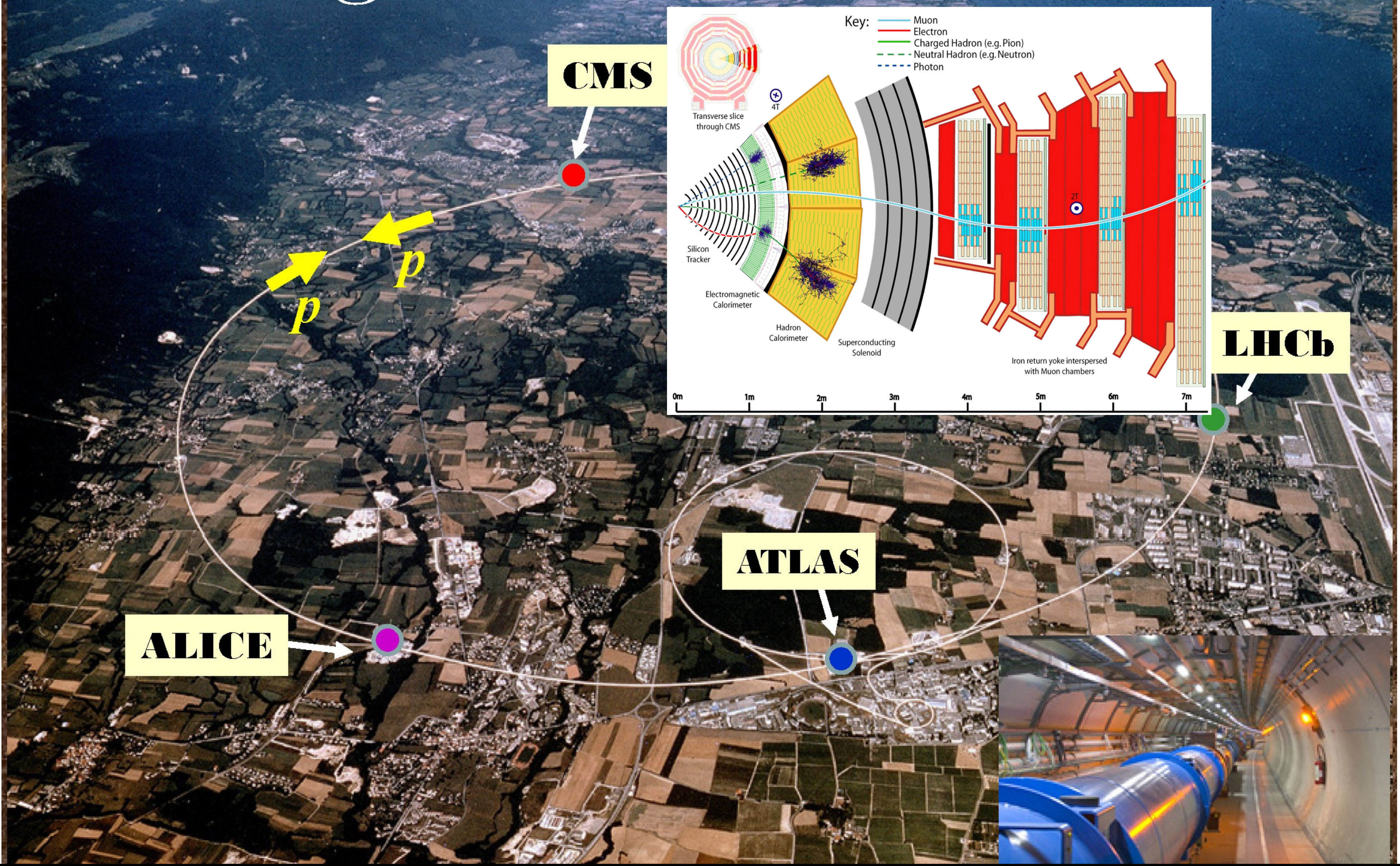
Large Hadron Collider



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Tau reconstruction at CMS

τ CMS reconstruction

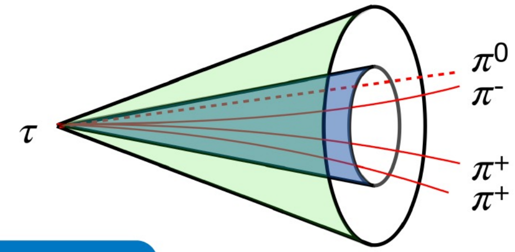
More in Valeria's talk

Decay mode	Resonance	$\mathcal{B}(\%)$
Leptonic decays		35.2
$\tau^- \to e^- \overline{\nu}_e \nu_\tau$		17.8
$\tau^- \to \mu^- \overline{\nu}_\mu \nu_\tau$		17.4
Hadronic decays		64.8
$\tau^- \to h^- \nu_\tau$		11.5
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho(770)$	25.9
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1(1260)$	9.5
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1(1260)$	9.8
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8
Other		3.3

τ_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 $\pi^0 \to \gamma\gamma$
- intermediate resonances in the decay

Many decay modes $\to$ different signatures to be captured by the same algorithm



Jet anti-k_T (AK4) reconstruction → Decay-mode reconstruction → Decay-mode identification → Mis-ID e/μ/jet

Seed for the τ_h → Hadron-Plus-Strips (HPS) algo: Reconstruct $\pi^\pm$ and π^0 → MVA τ_h decay-mode → DeepTau Neural Network

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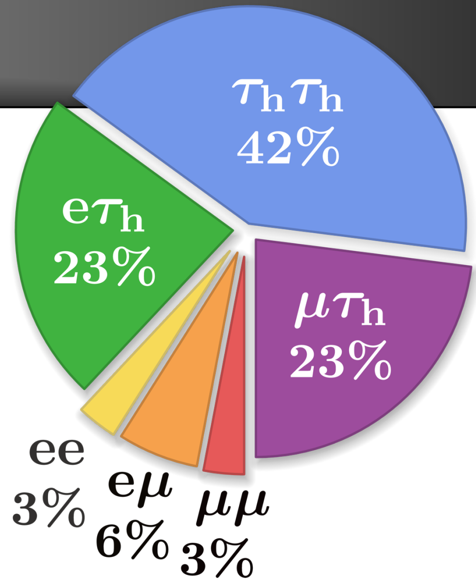
Event selection



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*

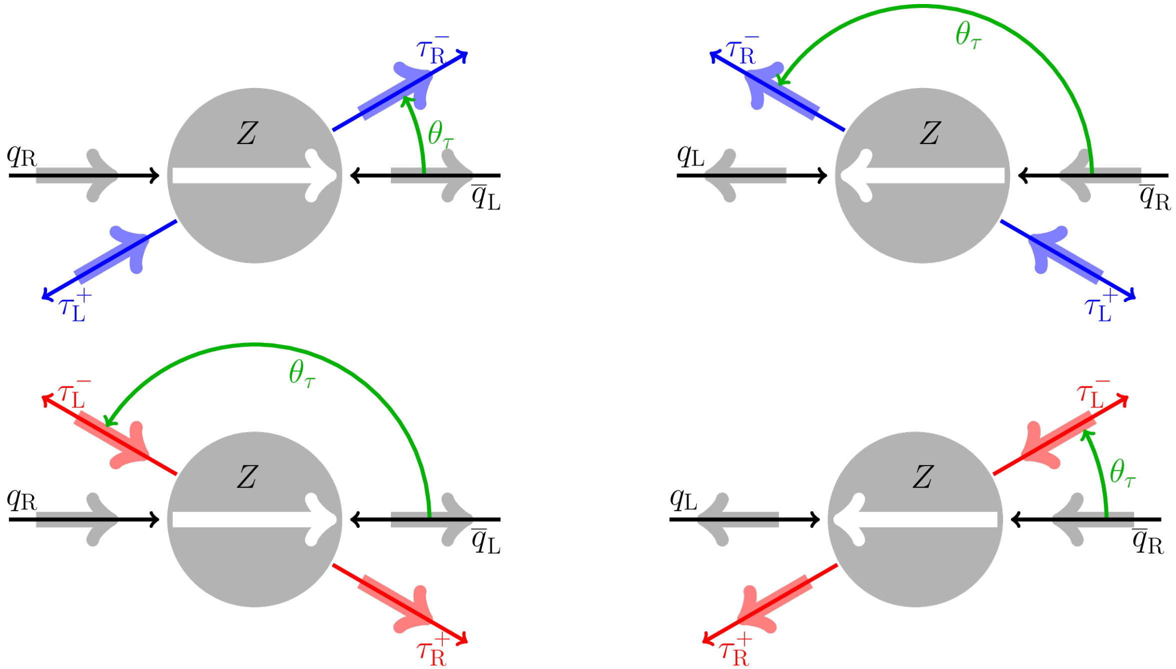
Electron :

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

Muon :

- $p_T(\mu) > 15$ GeV
  (> 24 GeV if *Mu23_Ele12*)
- $|\eta(\mu)| < 2.4$

Helicity states of incoming quarks and outgoing τ leptons.

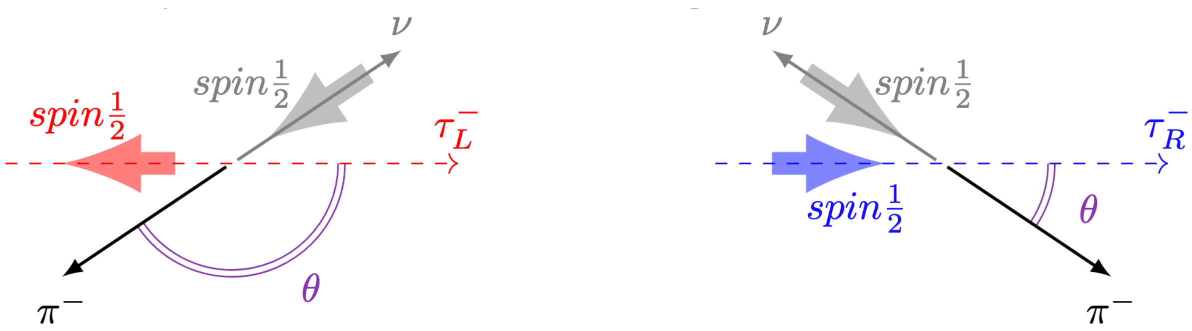


- The angle θ_τ is the scattering angle of the τ −lepton with respect to the quark momentum in the rest frame of the Z boson

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

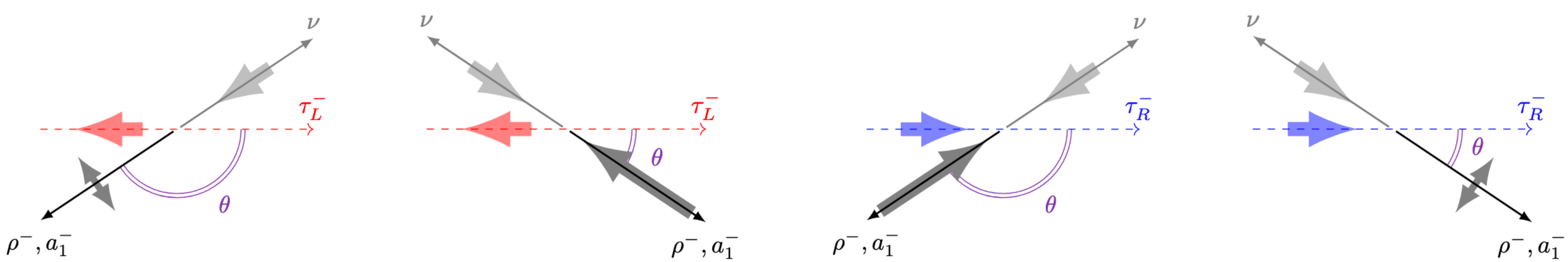
- The helicity of τ leptons from Z boson decays can be measured from energy and angular distributions of the τ lepton decay products.

Helicity of τ leptons - Angle θ in τ rest frame



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

Intermediate spin-0 resonance (π^-) ⇒ angle θ contains full helicity information



Intermediate spin-1 resonances (ρ^-, a_1^-) ⇒ angle θ depends on the polarisation of the resonance. Not sensitive enough to analyse by itself the τ − polarisation. <u>Need more discrminative variables</u>

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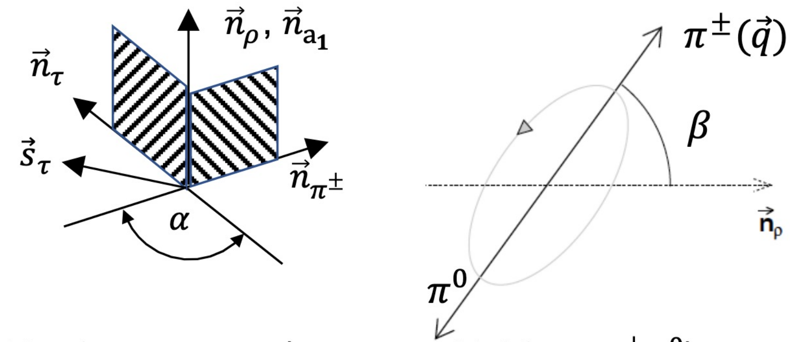
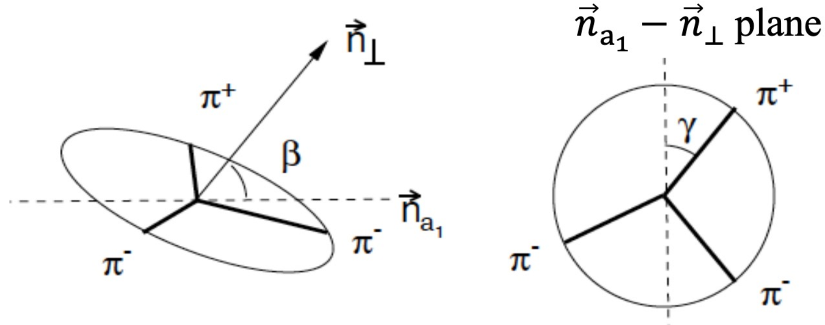
Helicity of τ leptons - Angles β, α and γ



(a) $\alpha(\tau \rightarrow \nu_\tau + \rho, a_1)$ (b) $\beta(\rho \rightarrow \pi^\pm \pi^0)$



(c) $\beta(a_1 \rightarrow \pi^- \pi^+ \pi^-)$ (d) $\gamma(a_1 \rightarrow \pi^- \pi^+ \pi^-)$

Angular kinematics of τ decays are full described by 1-4 angles :

- $\tau^\pm \rightarrow \pi^\pm \nu$: θ
- $\tau^\pm \rightarrow a_1^\pm \nu \rightarrow 3\pi^\pm \nu$: θ, β, α, γ
- $\tau^\pm \rightarrow \rho^\pm \nu \rightarrow \pi^\pm \pi^0 \nu$: θ, β, α (β can be reconstructed from four-momenta of pions)

Discriminant Observables (optimal variables)

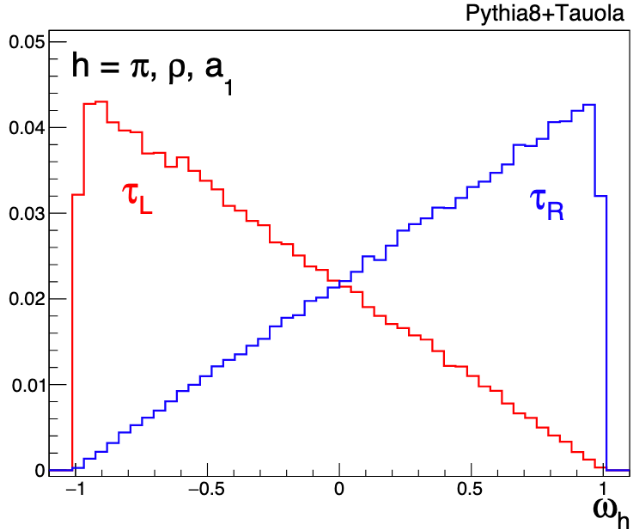
Definition : ratio of matrix elements (number of considered angles depends on decay mode)

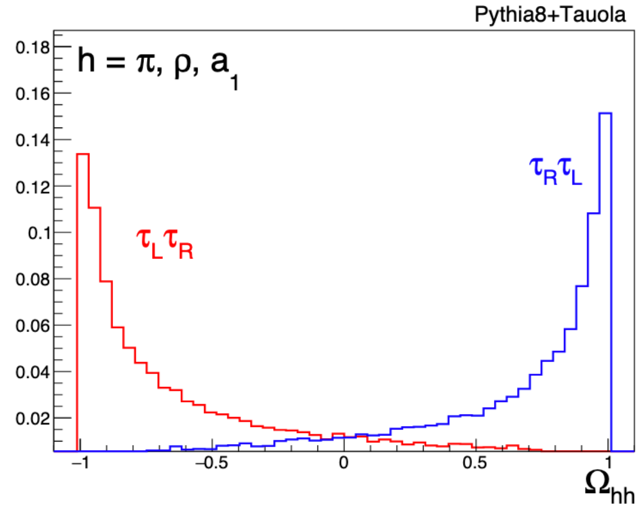
$$\omega(\tau = \theta, \beta, \alpha, \gamma) = \frac{|M(\theta,\beta,\alpha,\gamma|\tau_R)|^2 - |M(\theta,\beta,\alpha,\gamma|\tau_L)|^2}{|M(\theta,\beta,\alpha,\gamma|\tau_R)|^2 + |M(\theta,\beta,\alpha,\gamma|\tau_L)|^2}$$

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

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

$$\Omega(\tau^-, \tau^+) = \frac{\omega(\tau^-) + \omega(\tau^+)}{1 + \omega(\tau^-)\cdot\omega(\tau^+)}$$





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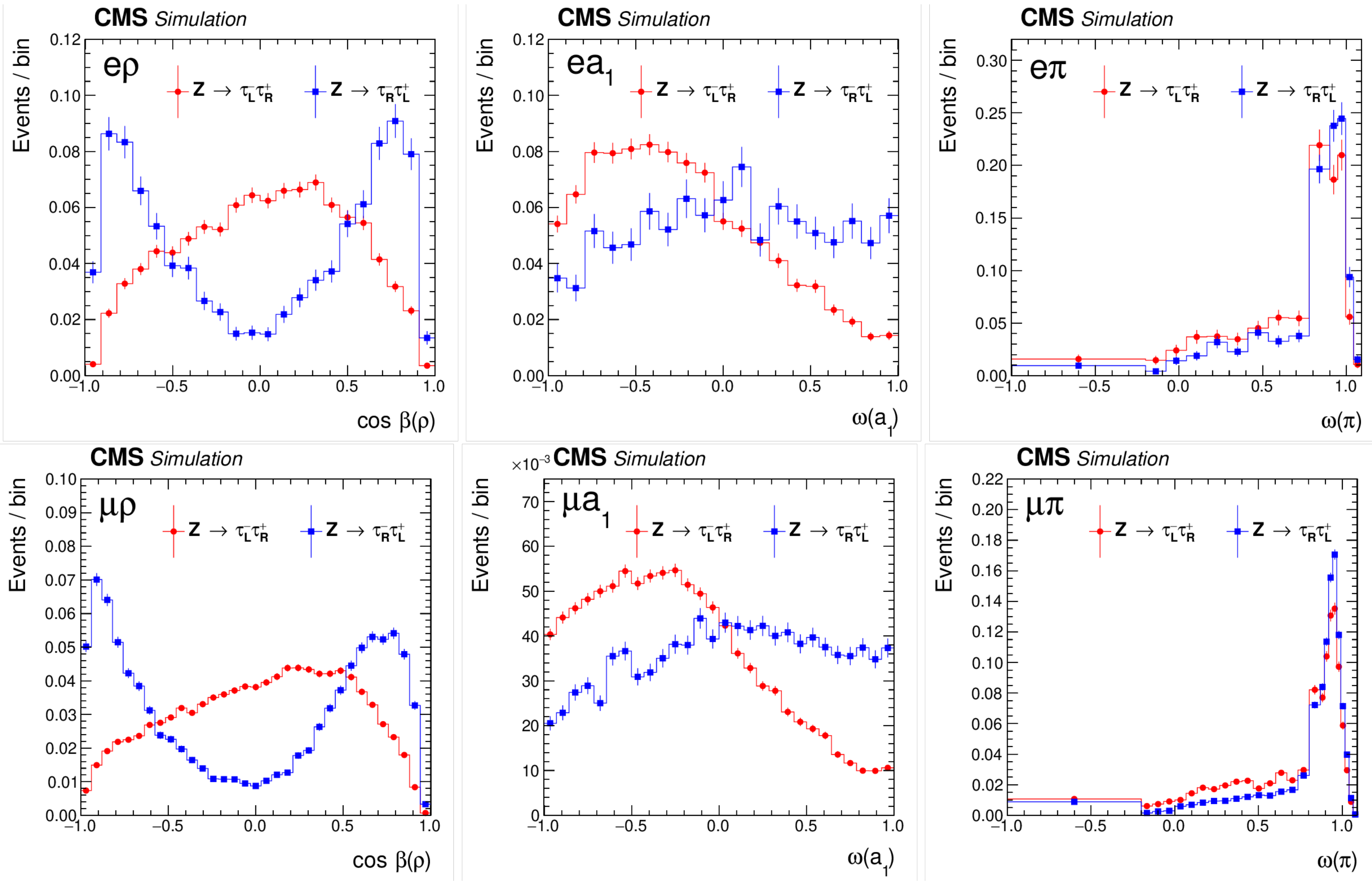
Final Choice of Discriminators

Channel	Category	Discriminator	
$\tau_e\tau_\mu$	$e+\mu$	$m_{\mathrm{vis}}(e,\mu)$	visible mass
$\tau_e\tau_{\mathrm{h}}$	$e+a_1$	$\omega(a_1)$	optimal observable with SVfit
	$e+\rho$	$cos\beta(\rho)$	visible optimal observable
	$e+\pi$	$\omega(\pi)$	optimal observable with SVfit
$\tau_\mu\tau_{\mathrm{h}}$	$\mu+a_1$	$\omega(a_1)$	optimal observable with SVfit
	$\mu+\rho$	$cos\beta(\rho)$	visible optimal observable
	$\mu+\pi$	$\omega(\pi)$	optimal observable with SVfit
$\tau_{\mathrm{h}}\tau_{\mathrm{h}}$	a_1+a_1	$m_{\mathrm{vis}}(a_1,a_1)$	visible mass
	$a_1+\pi$	$\Omega(a_1,\pi)$	combined optimal observable with SVfit
	$\rho+\tau_{\mathrm{h}}$	$cos\beta(\rho)$	visible optimal observable (for leading ρ)
	$\pi+\pi$	$m_{\mathrm{vis}}(\pi,\pi)$	visible mass

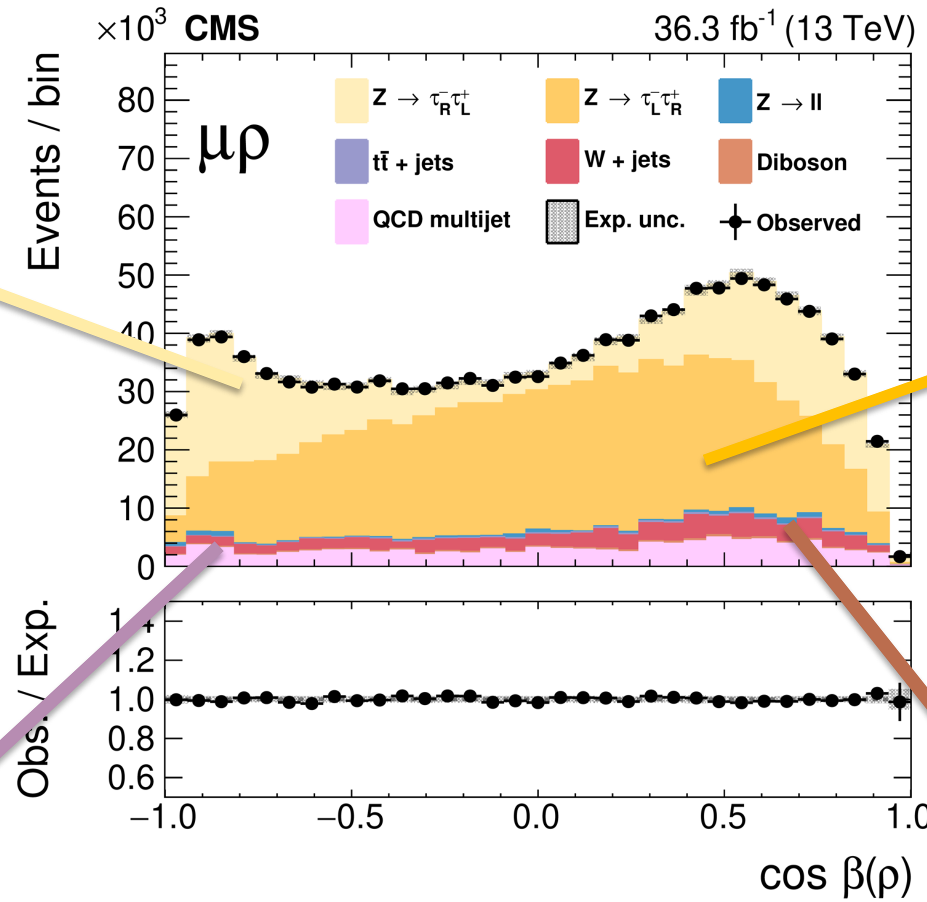
Discriminant Observables



Signal and background definition

Right-helicity Signal split at generator level

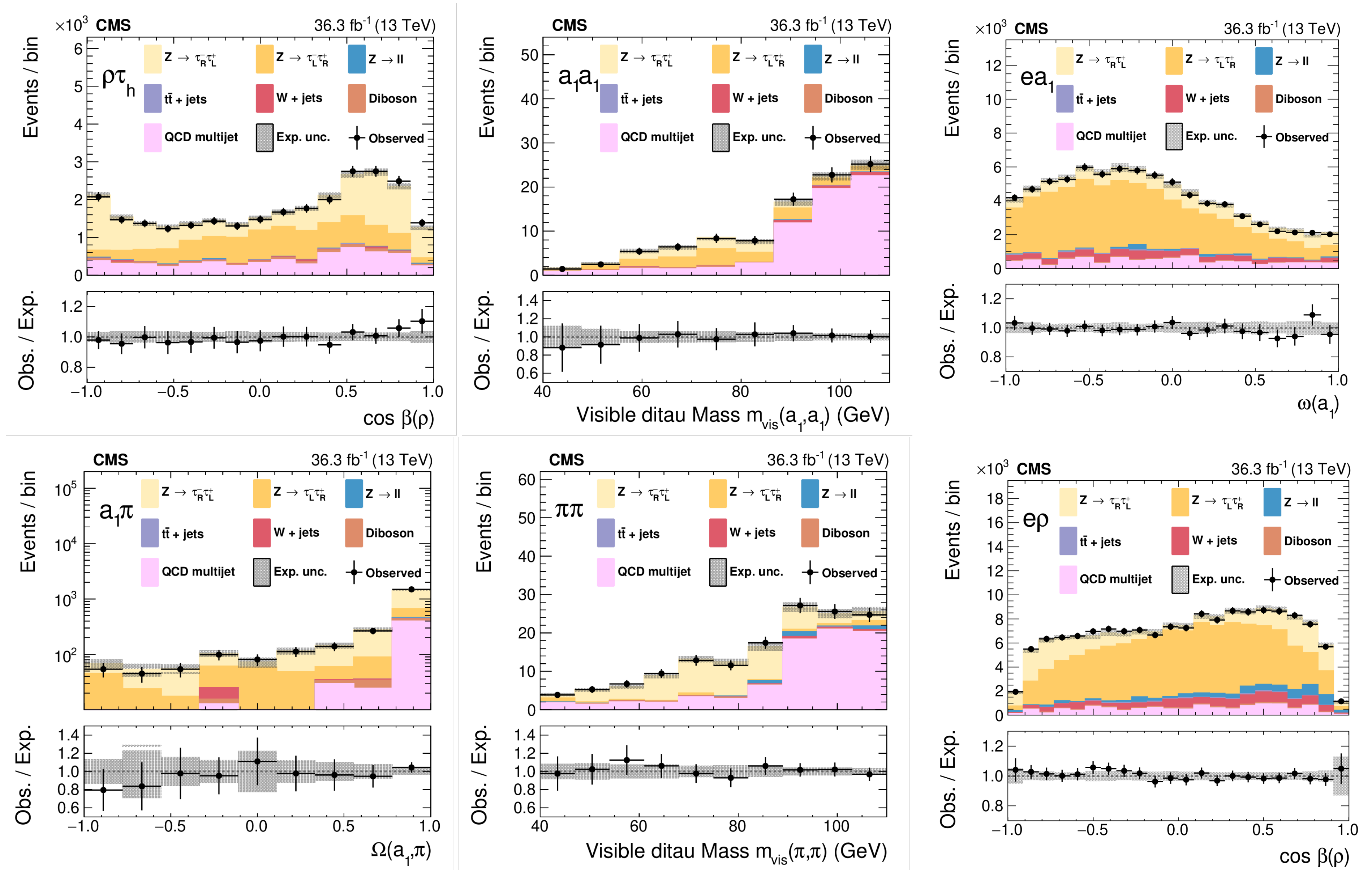
Left-helicity Signal split at generator level



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

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

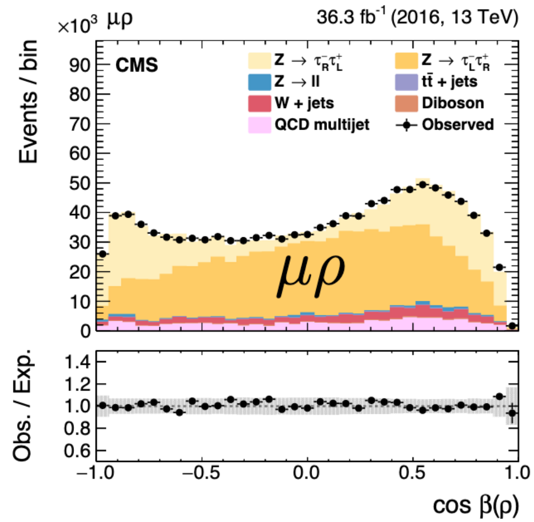
Final Observables



Extraction of Polarisation by Template Fit

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

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



Two parameters of interest :

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

Signal templates :

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

templates for right- and left-handed τ

(splitting is done with MadGraph5 spin flag)

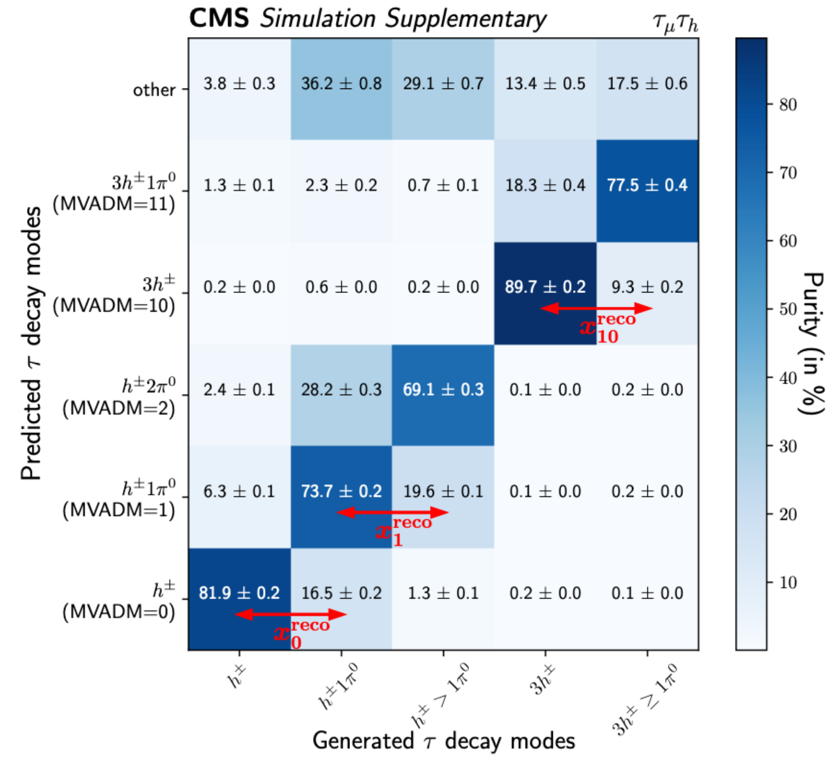
Background processes :

$Z^0/\gamma^* \to e^- e^+ / \mu^- \mu^+$, $t\bar{t}$ + jets , di-boson , W + 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

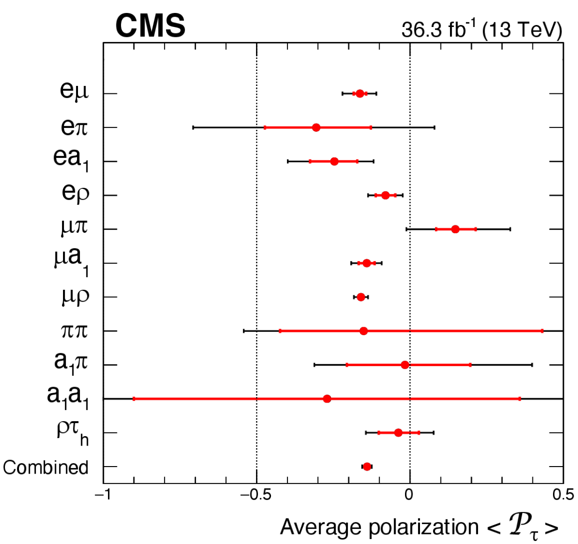
Systematic Source - τ DM Migrations

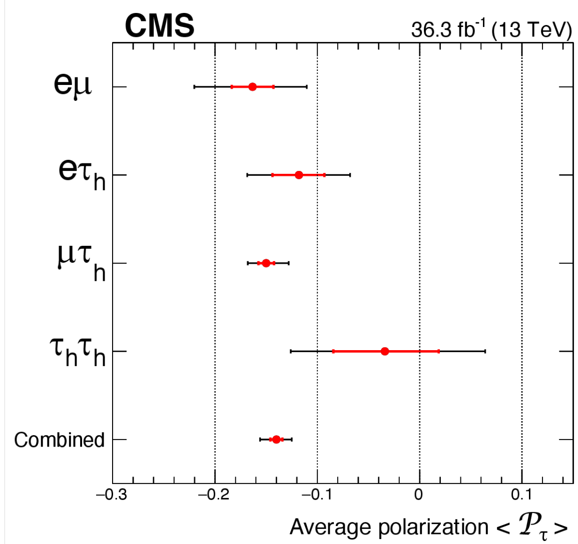
- Does MC simulation describes decay-mode reconstruction in data well ?
- Variations of migrations have strong impact on polarisation measurement :
  - Problem of normalisation inside categories
  - Discriminant variables are optimised for a given τ decay-mode
- Define 3 most important migrations :
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

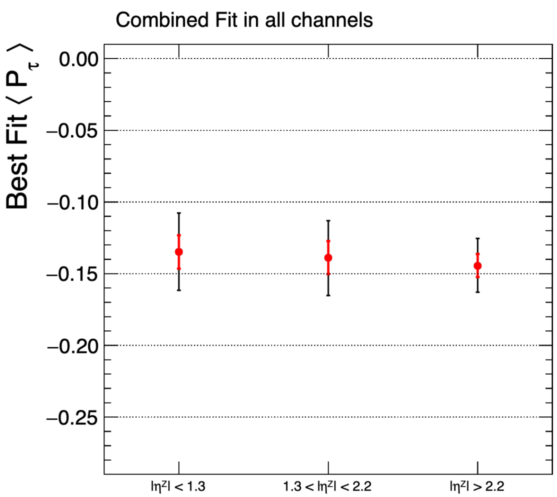


Parameters x_i^{reco} quantify the fraction of all events in a given reconstructed DM i that migrate differently in data compared to MC.

Results of the Average τ Polarisation







$$\langle \mathcal{P}_\tau \rangle_{75-120\,\mathrm{GeV}} = -0.140 \pm 0.006\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst}) = -0.140 \pm 0.015.$$

$\mathcal{P}_\tau$ (Z) = −0.144 ±0.015

$$\mathcal{P}_\tau = -A_\tau = -\frac{2 v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2\frac{v_\tau}{a_\tau} = -2(1 - 4\sin^2\theta_W^{\mathrm{eff}}).$$

$$\sin^2\theta_W^{\mathrm{eff}} = 0.2319 \pm 0.0008\,(\mathrm{stat}) \pm 0.0018\,(\mathrm{syst}) = 0.2319 \pm 0.0019.$$

- Sensitivity is mostly driven by μτ channel following by eτ, eμ, and ττ.
- No dependence on the pseudo-rapidity of the Z_0 boson

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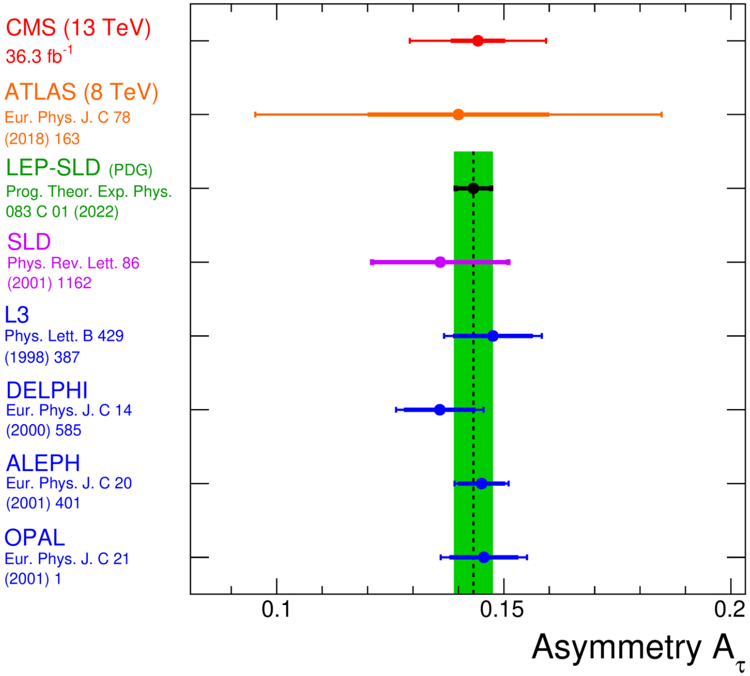
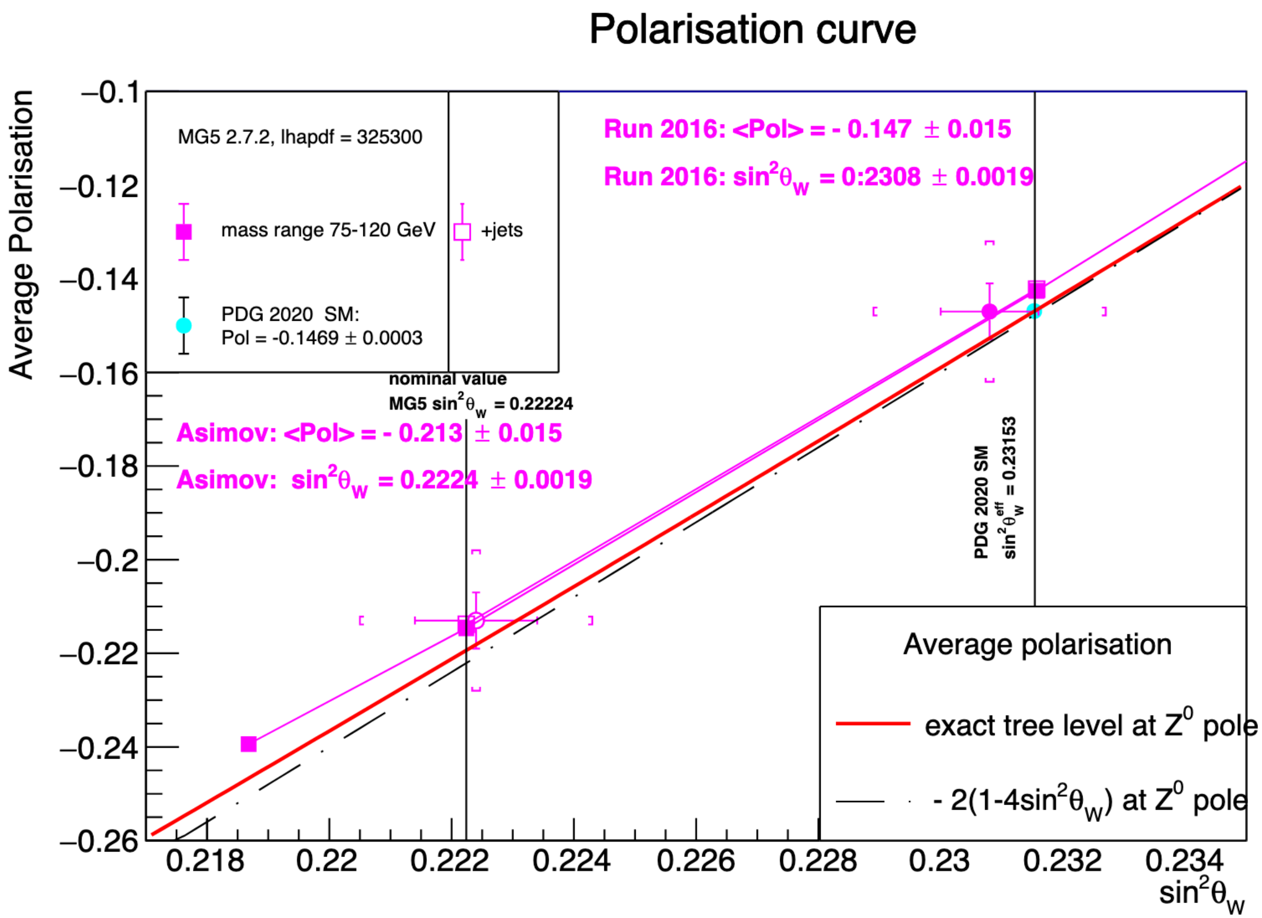
Summary

- Polarization of τ^- 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 τ^- lepton polarization, **$\mathcal{P}_\tau$ (Z) = −0.144 ±0.015**, is in good agreement with the SLD, LEP and ATLAS results.
- The measured polarization constrains the effective couplings of τ^- leptons to the Z boson and determines the effective weak mixing angle to be **$\sin^2\theta^{eff}_W = 0.2319 \pm 0.0019$**
- No deviation from SM! Improving the sensitivity requires both more data and more importantly, better understanding/reducing the systematics.



Backup

Polarization curve



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