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Measurement of the τ lepton polarization in Z boson decays by CMS at the LHC

I. Physics introduction

II. LHC and CMS, event selection and reconstruction

III. Polarisation variables

IV. Fits to data

V. Results

VI. Interpretation and summary

Ulrich Goerlach
On behalf of the CMS collaboration

PAS-SMP-18-010

PhD thesis 2022 **Clement Grimault**,

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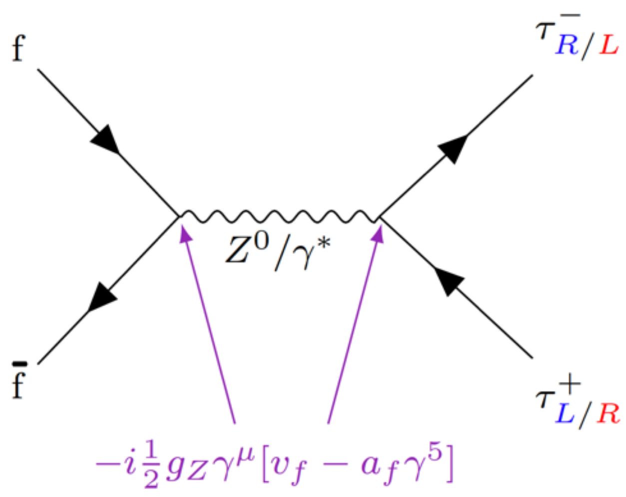
I. Physics introduction

- **SM electroweak theory → different coupling of Z^0 to left and right handed fermions:**



- **Described by the asymmetry parameter:** $A_f = \frac{2v_f a_f}{v_f^2 + a_f^2}$

$$\left.\begin{aligned} v_f &= I_W^3 - 2Q sin^2\theta_W^{\text{eff}} \\ a_f &= I_W^3 \end{aligned}\right\} sin^2\theta_W^{\text{eff}} = \frac{1}{2QI_W^3}\left(1 - \frac{v_f}{a_f}\right)$$

- **τ lepton polarisation was pioneered at LEP:**

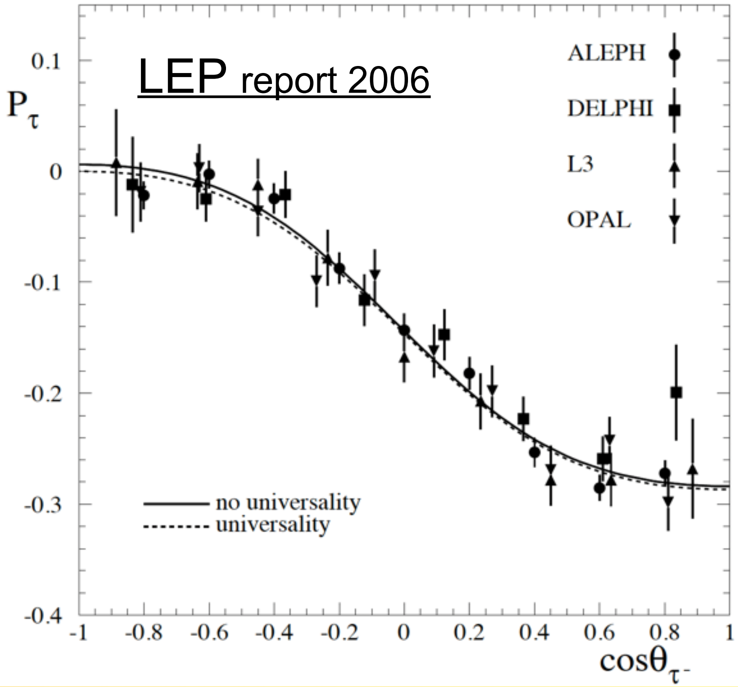
$$\frac{d\sigma}{dcos\theta_\tau} = F_0(\hat{s})(1 + cos^2\theta_\tau) + 2F_1(\hat{s})cos\theta_\tau - \boldsymbol{h_\tau}[F_2(\hat{s})(1 + cos^2\theta_\tau) + 2F_3(\hat{s})cos\theta_\tau]$$

Structure functions $F_i(\hat{s})$: γ –exchange, γ-Z^0 interference and Z^0 exchange

At Z-pole ($\sqrt{\hat{s}} = M_Z$)

$$P_\tau = -A_\tau = -\frac{2v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2 \cdot \frac{v_\tau}{a_\tau} = -2(1 - 4\sin^2\theta_W^{\text{eff}})$$

$$P_\tau = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$



Polarisation is a unique way to determine $\sin^2\theta_W^{eff}$ only based on the coupling of Z^0 to τ leptons

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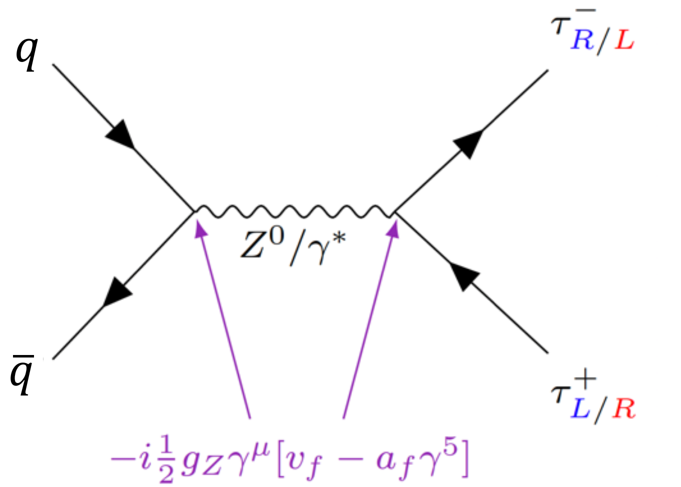
I. Physics introduction

LHC pp collisions: situation is more difficult:

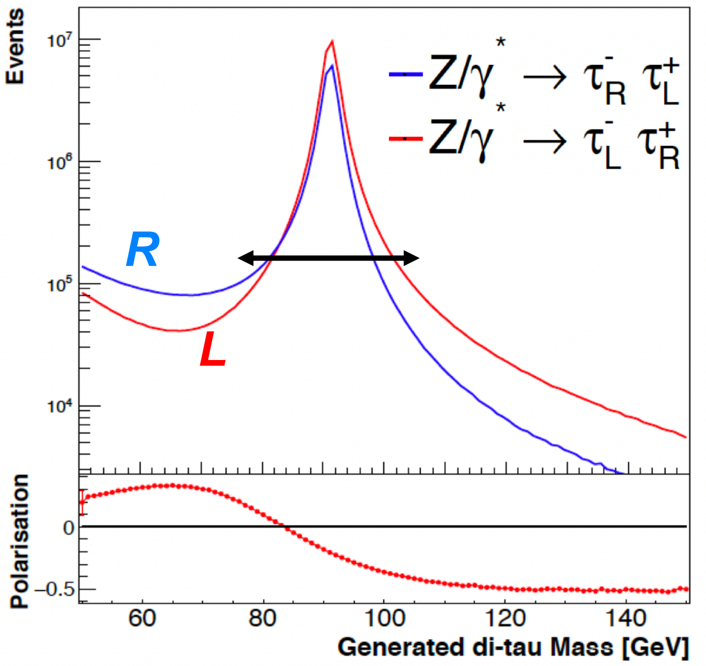
- no fixed $\sqrt{\hat{s}}$, average over a finite interval in $\sqrt{\hat{s}}$
- $\cos\theta_\tau$ is not easily accessible, average includes integration over $\cos\theta_\tau$
- pp collisions are symmetric wrt $\pm\cos\theta_\tau$
- Parton distribution functions, PDFs → boost in rapidity
- Trigger imposes relatively high thresholds on $p_T(\tau)$
- Difficult environment for tau reconstruction

Spin correlations are important for measurements of the CP structure of the Higgs (see talk M. Sessini)

Deviations to the SM predictions may occur in the presence of new physics at higher energy



Leading-Order MadGraph5



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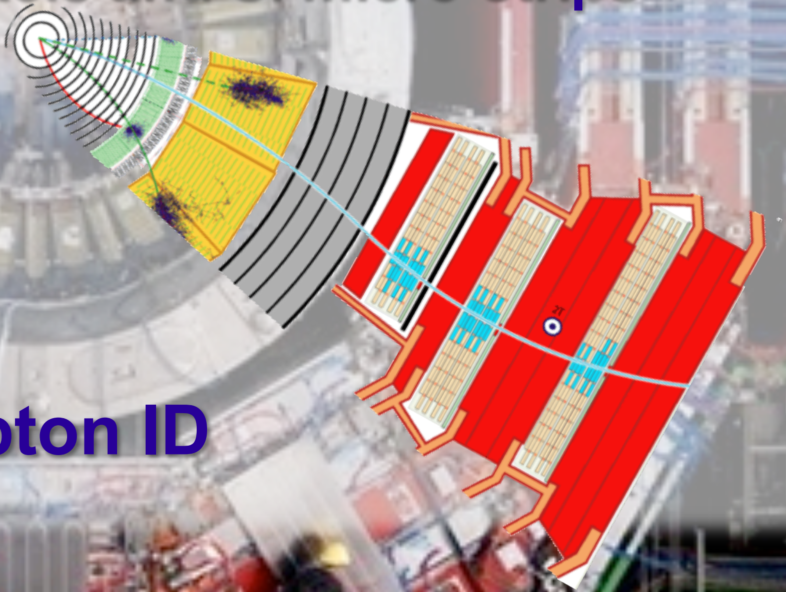
CMS @ LHC

- LHC $\sqrt{s} = 13\text{TeV}$ Run 2: 2016-2018
- CMS detector:
  - Solenoid 3.8 Tesla
  - Tracker composed of Si pixels and Si micro-strips
  - Calorimeters
    - Electromagnetic
    - Hadronic
  - Muon system
- All systems used for τ lepton ID

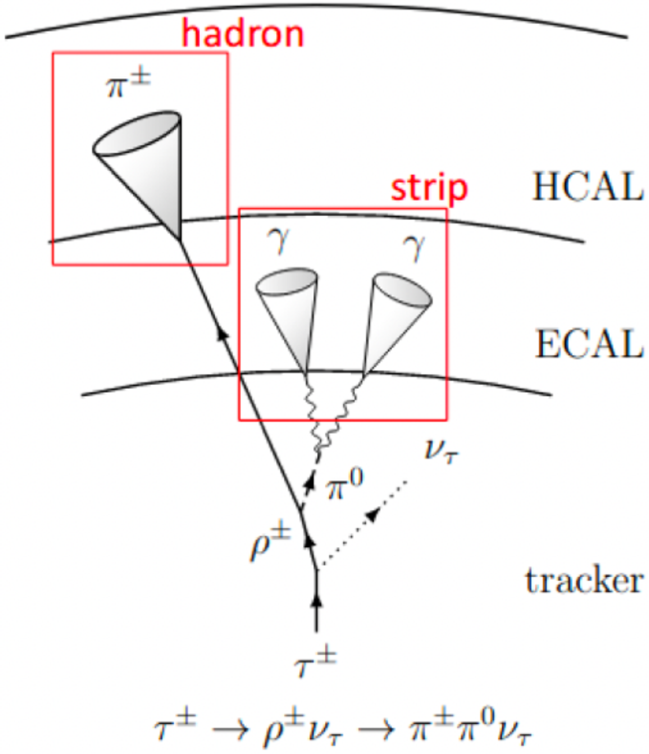


II. Event selection and reconstruction

- **Data of 2016, integrated luminosity 36.3 fb^{-1}, (13 TeV)**
- **Tau-Trigger p_T thresholds between 30 and 45 GeV**

Final state	Trigger	Lepton selection
$\tau_h\tau_h$	τ_h (35 GeV)τ_h (35 GeV)	$p_T^{\tau_h} > 45(40)$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.1$
$\tau_\mu\tau_h$	μ(22 GeV) or μ(19 GeV)τ_h (20 GeV)	$p_T^{\mu} > 23$ GeV, $\lvert\eta^{\mu}\rvert < 2.1$ $p_T^{\mu} > 20$ GeV, $p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$
$\tau_e\tau_h$	e(25 GeV)	$p_T^{e} > 30$ GeV, $\lvert\eta^{e}\rvert < 2.1$ $p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$
$\tau_e\tau_\mu$	μ(8 GeV)e(23 GeV) or μ(23 GeV)e(12 GeV)	$p_T^{e} > 15$ GeV, $\lvert\eta^{e}\rvert < 2.4$ $p_T^{\mu} > 15$ GeV, $\lvert\eta^{\mu}\rvert < 2.4$ $p_T^{\ell} > 24$ GeV for lead trigger leg

- **Much of analysis follows** Higgs→$\tau\tau$ and CP-property of the Yukawa coupling…
- **Offline identification of τ leptons**
- **Reconstruction of Decay modes**
- **Backgrounds by simulation and data driven**



Tau reconstruction

- Narrow isolated jets (anti-k_T, AK4)
- Hadron-Plus-Strip (HPS) to reconstruct $\pi^\pm$ and π^0
- MVA decay-mode identification
- DeepTau Neural Network to reject e/mu/jet
- False decay mode id most difficult systematics (ref_1, ref_2, ref_3)

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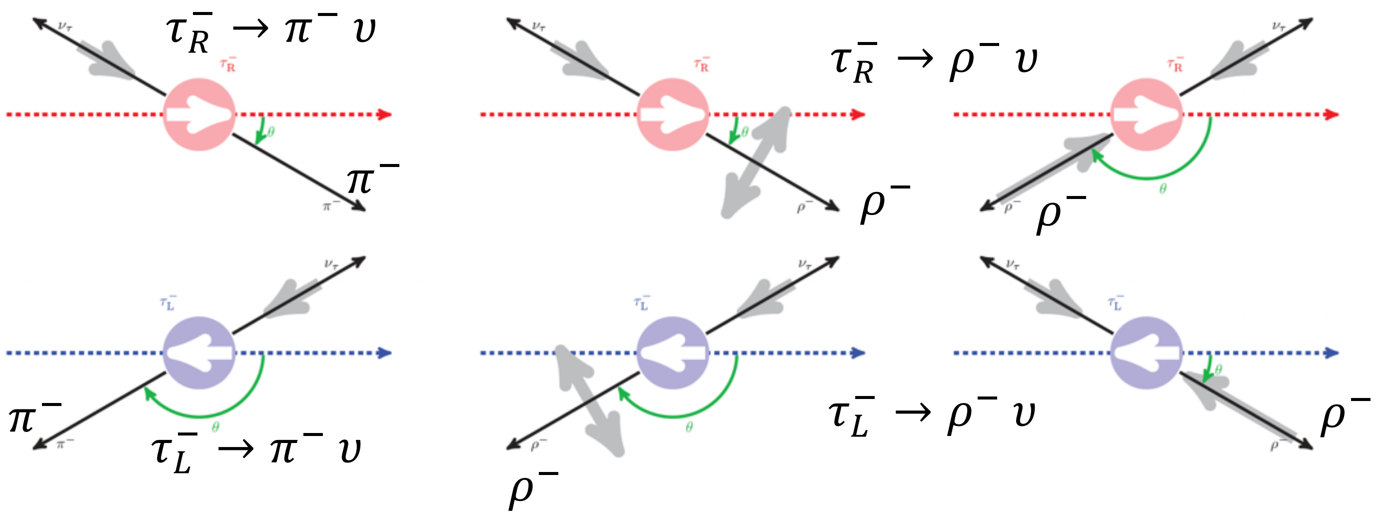
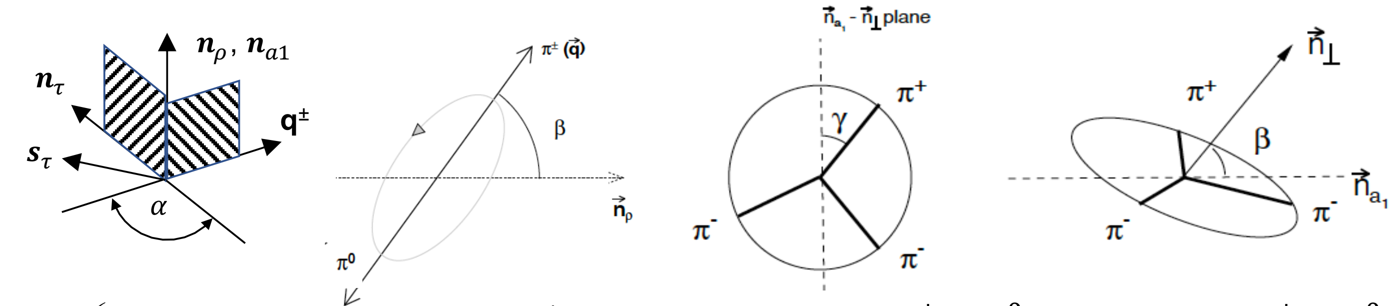
III. Polarisation variables





a: $\alpha(\tau \to \rho, a_1)$ b: $\beta(\rho \to \pi^\pm \pi^0)$ c: $\gamma(a_1 \to \pi^+\pi^-\pi^0)$ d: $\beta(a_1 \to \pi^+\pi^-\pi^0$

- **τ spin is encrypted into kinematics of decay**
- **→ π (spin = 0)**
- **→ ρ and a_1 (spin = 1)**
- **Combine angles into "optimal variables" $\omega(\pi), \omega(a_1)$**

  LEP: M. Davier, et al. Phys. Lett. B 306 (1993) 411
- **Other "directly visible" variables:**

  $\omega_{vis}(\rho) = \cos\beta$; $m_{vis}(\pi,\pi)$; $m_{vis}(e,\mu)$
- **We consider 11 combinations of hadronic and leptonic τ decays**
- **→ 11 templates of discriminants used to extract polarisation**

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III. Polarisation variables

τ^- negative helicity L
τ^- positive helicity R

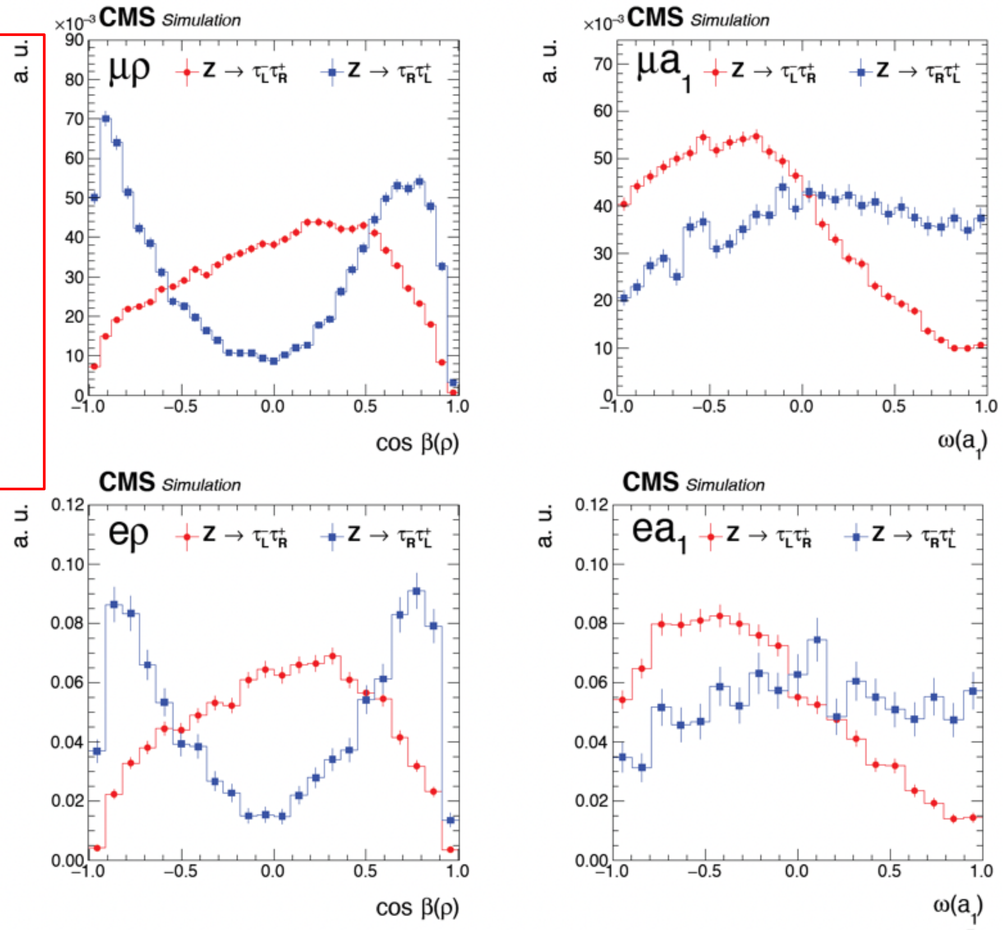
Channel	Category	Discriminator
$\tau_e\tau_\mu$	$e+\mu$	$m_{\rm vis}(e,\mu)$
$\tau_e\tau_{\rm h}$	$e+a_1$	$\omega(a_1)$
	$e+\rho$	$\omega_{\rm vis}(\rho)$
	$e+\pi$	$\omega(\pi)$
$\tau_\mu\tau_{\rm h}$	$\mu+a_1$	$\omega(a_1)$
	$\mu+\rho$	$\omega_{\rm vis}(\rho)$
	$\mu+\pi$	$\omega(\pi)$
$\tau_{\rm h}\tau_{\rm h}$	a_1+a_1	$m_{\rm vis}(a_1,a_1)$
	$a_1+\pi$	$\Omega(a_1,\pi)$
	$\rho+\tau_{\rm h}$	$\omega_{\rm vis}(\rho)$
	$\pi+\pi$	$m_{\rm vis}(\pi,\pi)$

$m_{vis}(1,2)$ = visible mass

$\boldsymbol{\omega_{vis}(\rho) = \cos\beta}$

$\omega(\pi), \omega(a_1) = opt.obs.$

$$\Omega(a_1,\pi) = \frac{\omega(\pi)+\omega(a_1)}{1+\omega(\pi)\omega(a_1)}$$



- **Templates produced by simulation for each channel** (*MADGRAPH5 aMC@NLO / PYTHIA8*)
- **Choice of discriminants is based on a likelihood scan to maximise the significance of the polarisation**
- **Stability of templates wrt PDF variations verified**

The normalisation of templates refers to zero average polarisation over an interval of 75-120 GeV of the generated $q\bar{q}$ centre of mass energy $\sqrt{\hat{s}}$

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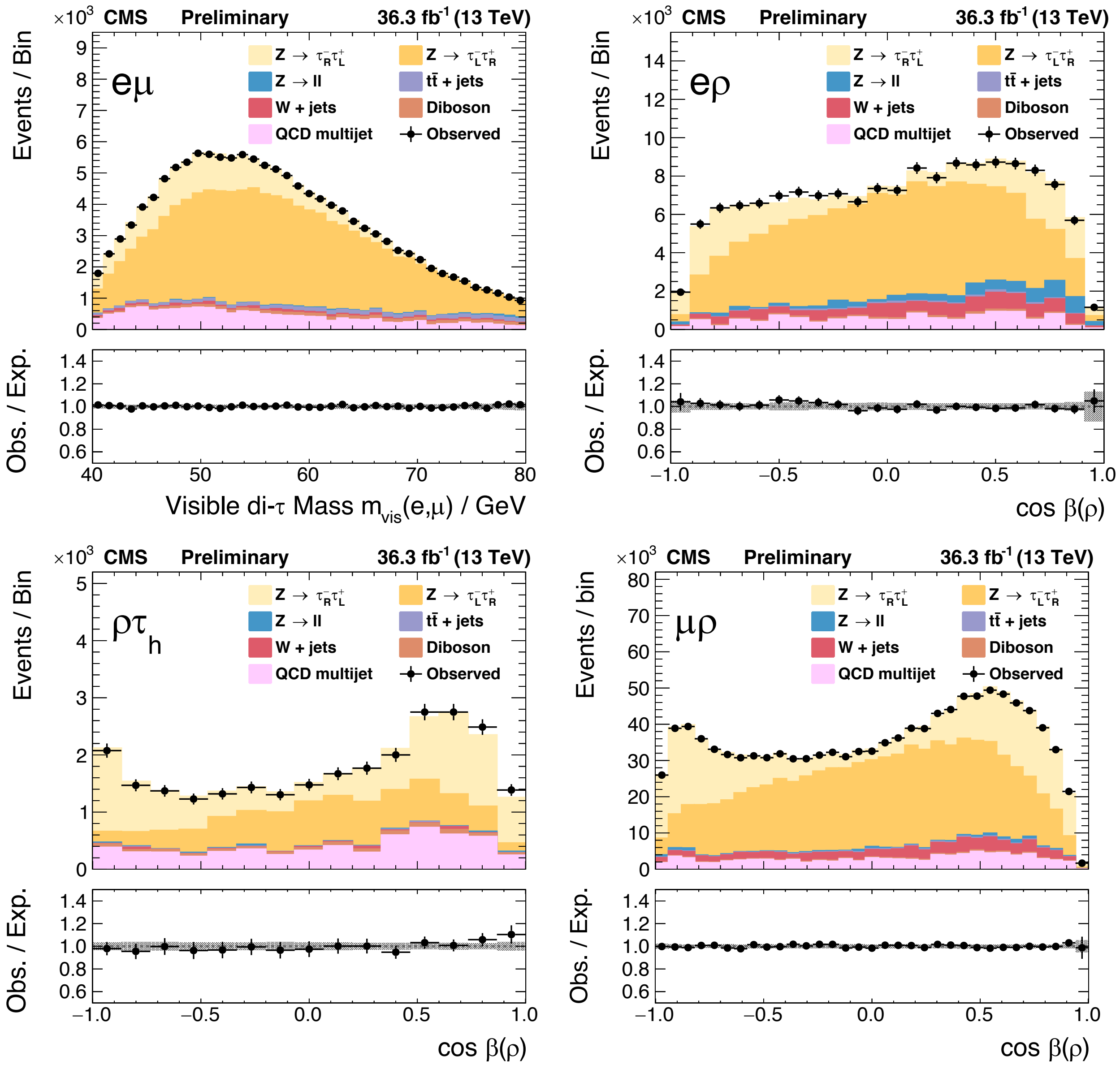
IV. Fits to data

- Templates are adjusted by a fit to data for all 11 channels
- These fits give the average polarisation with respect to the interval of 75-120 GeV in $\sqrt{\hat{s}}$ of the generated $q\bar{q}$ pair
- A combined fit yields results for each category and the total average polarisation.
- Stability of the result was verified by combined fits as function of rapidity

Some Post-fit examples of templates



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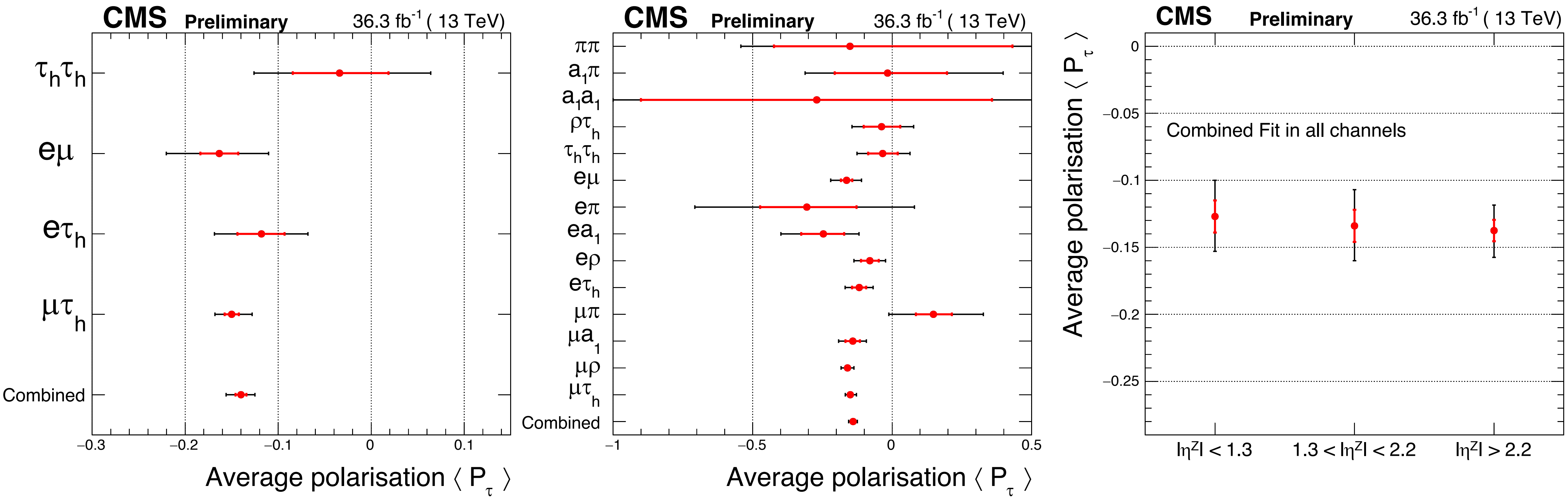
V. Results:

Average polarisation by category, channel and rapidity



We use MADGRAPH5 aMC@NLO to correct the average polarisation by -0.004 to the value at the Z^0 pole:

Total uncertainty is dominated by systematics, particular decay mode migrations

$$\mathcal{P}_\tau(Z^0) = -0.144 \pm 0.015 = -0.144 \pm 0.006\,(\text{stat}) \pm 0.014\,(\text{syst})$$

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VI. Interpretation and summary

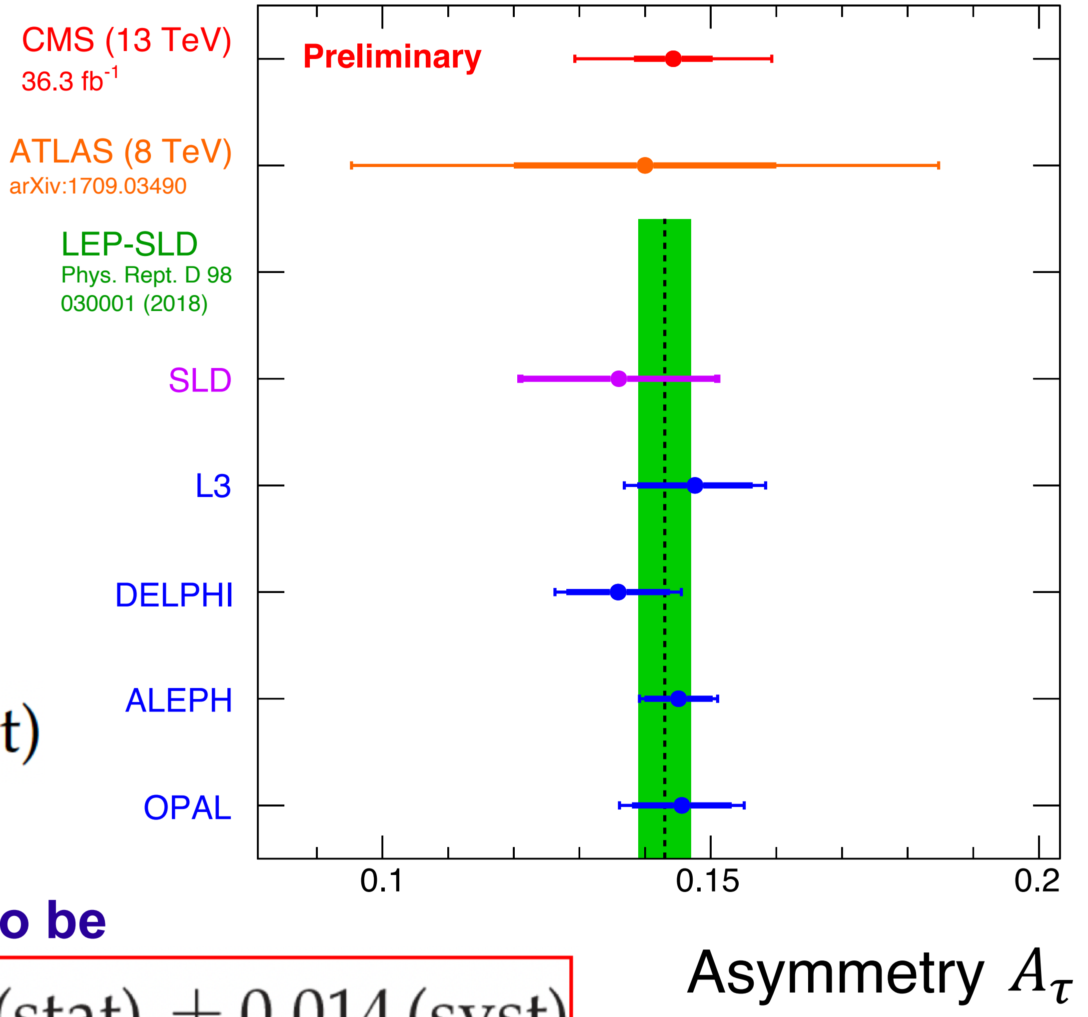
The negative polarisation at the Z^0 pole is equal to the asymmetry parameter A_τ and can be compared to LEP

A_τ is directly related to the effective electroweak mixing angle:

$$A_\tau \approx 2\left(1 - 4\sin^2\theta_W^{eff}\right)$$

Our value of A_τ gives:

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



Summary:

- **CMS has measured the $\tau-$ polarisation at the Z^0 pole to be**

$$\mathcal{P}_\tau(Z^0) = -0.144 \pm 0.015 = -0.144 \pm 0.006\,(\mathrm{stat}) \pm 0.014\,(\mathrm{syst})$$

- **τ lepton spin correlations can be used in the harsh LHC environment to reveal (B)SM physics**

See the talk by M.Sessini on CP in Higgs

BACK-UP

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Polarisation

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

$$\mathcal{P}_\tau(\cos\theta_{\tau^-}) = -\frac{\mathcal{A}_\tau(1+\cos^2\theta_{\tau^-}) + 2\mathcal{A}_e \cos\theta_{\tau^-}}{(1+\cos^2\theta_{\tau^-}) + \frac{8}{3} A_{FB}^{\tau} \cos\theta_{\tau^-}}.$$

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

$$F_1(s) = \frac{\pi\alpha}{4s}[2Re\chi(s) q_q q_\tau a_q a_\tau + |\chi(s)|^2 2 v_q a_q 2 v_\tau a_\tau],$$

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

$$F_3(s) = \frac{\pi\alpha}{4s}[2Re\chi(s) q_q q_\tau a_q v_\tau + |\chi(s)|^2 2 v_q a_q (v_\tau^2 + a_\tau^2)].$$

$$P_\tau = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$$

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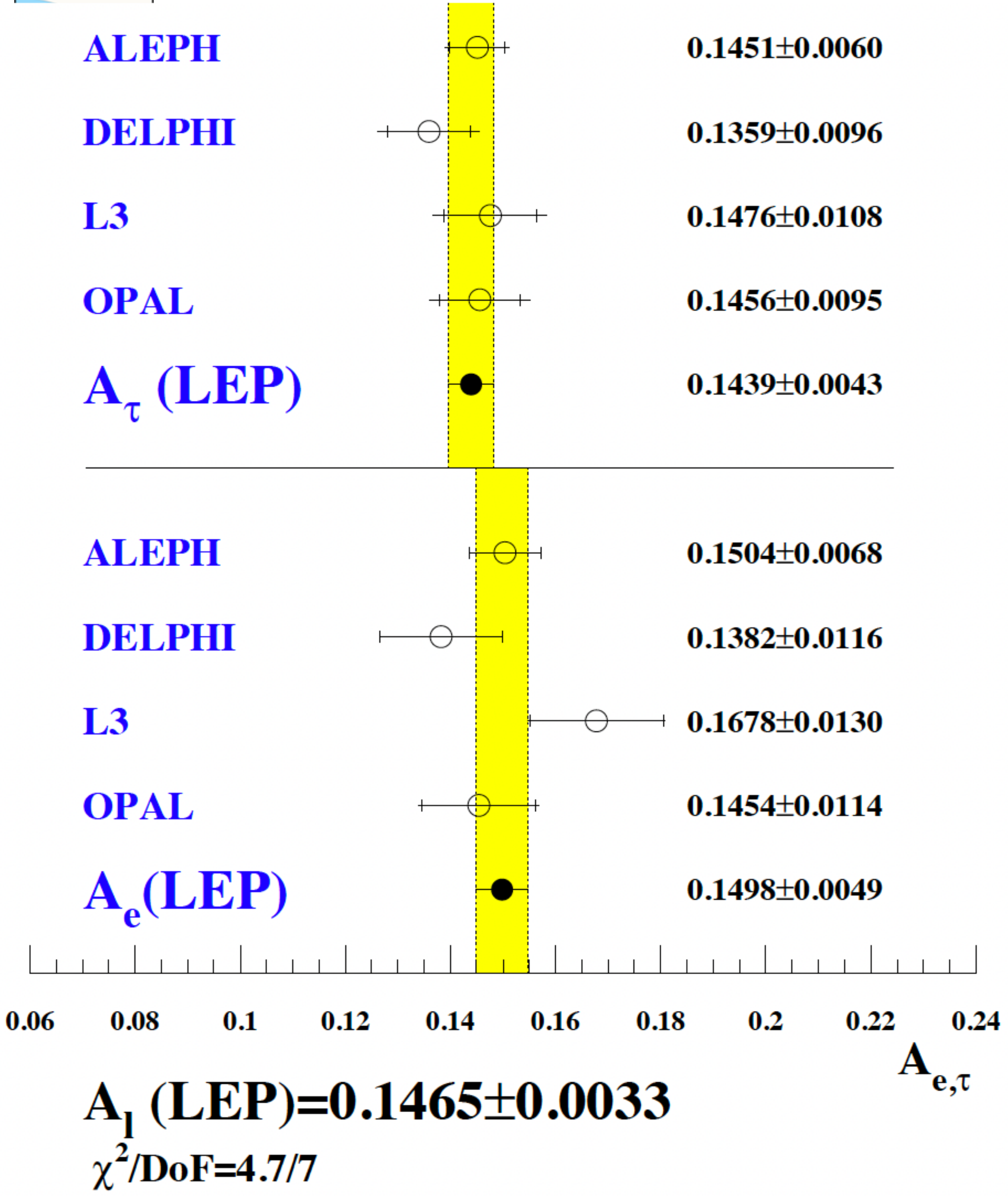
LEP results



Experiment	$\mathcal{A}_\tau$	$\mathcal{A}_e$
ALEPH	$0.1451 \pm 0.0052 \pm 0.0029$	$0.1504 \pm 0.0068 \pm 0.0008$
DELPHI	$0.1359 \pm 0.0079 \pm 0.0055$	$0.1382 \pm 0.0116 \pm 0.0005$
L3	$0.1476 \pm 0.0088 \pm 0.0062$	$0.1678 \pm 0.0127 \pm 0.0030$
OPAL	$0.1456 \pm 0.0076 \pm 0.0057$	$0.1454 \pm 0.0108 \pm 0.0036$
LEP	$0.1439 \pm 0.0035 \pm 0.0026$	$0.1498 \pm 0.0048 \pm 0.0009$

LEP results for $\mathcal{A}_\tau$ and $\mathcal{A}_e$. The first error is statistical and the second systemati

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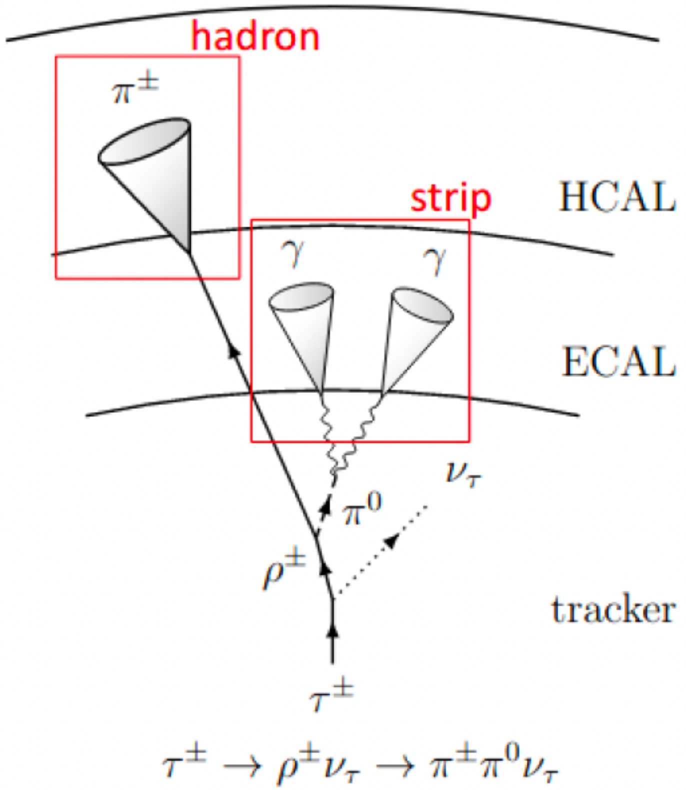
Decay mode definitions



- DM 0 : $\tau_h \to \pi^\pm$
- DM 1 : $\tau_h \to \pi^\pm + \pi^0$
- DM 2 : $\tau_h \to \pi^\pm + 2\pi^0$
- DM 10 : $\tau_h \to 2\pi^\pm + \pi^\mp$
- DM 11 : $\tau_h \to 2\pi^\pm + \pi^\mp + \pi^0$

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Table 1: Selections applied in the data processing of this analysis.

Final state	Trigger	Lepton selection	Additional selection	
$\tau_h \tau_h$	τ_h (35 GeV)τ_h (35 GeV)	$p_T^{\tau_h} > 45(40)$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.1$	Med DeepTau iso	
$\tau_\mu \tau_h$	μ(22 GeV)	$p_T^{\mu} > 23$ GeV, $\lvert\eta^{\mu}\rvert < 2.1$	$I_{rel}(\mu) < 0.15$	$m_T^{\mu} < 50$ GeV
	or μ(19 GeV)τ_h (20 GeV)	$p_T^{\mu} >$20 GeV, $p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$	Med DeepTau iso	
$\tau_e \tau_h$	e(25 GeV)	$p_T^{e} > 30$ GeV, $\lvert\eta^{e}\rvert < 2.1$	$I_{rel}(e) < 0.15$	$m_T^{e} < 50$ GeV
		$p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$	Med DeepTau iso	
$\tau_e \tau_\mu$	μ(8 GeV)e(23 GeV)	$p_T^{e} > 15$ GeV, $\lvert\eta^{e}\rvert < 2.4$	$I_{rel}(e) < 0.15$	
	or μ(23 GeV)e(12 GeV)	$p_T^{\mu} > 15$ GeV, $\lvert\eta^{\mu}\rvert < 2.4$	$I_{rel}(\mu) < 0.20$	
		$p_T^{\ell} > 24$ GeV for lead trigger leg		

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Event Selection - Summary

$\tau_h\tau_h$ channel

Trigger : *DoubleMediumIsoPFTau35*

Hadronic taus : $p_T(\tau_h) > 40$ GeV and $|\eta(\tau_h)| < 2.1$
45 for leading

$\tau_\mu\tau_h$ 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 :

- $p_T(e) > 30$ 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*)
- $|\eta(\mu)| < 2.4$

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Discriminants for polarisation

$$\cos\beta = \mathbf{q}\cdot\mathbf{n}_\rho = \frac{m_\rho}{\sqrt{m_\rho^2 - 4m_\pi^2}} \cdot \frac{E_{\pi^-} - E_{\pi^0}}{|p_{\pi^-} - p_{\pi^0}|}, \qquad m_{\mathrm{vis}} = \sqrt{2E_1E_2(1-\cos\sphericalangle(\tau_1^{\mathrm{vis}}, \tau_2^{\mathrm{vis}}))},$$

Table 2: Final choice of discriminators in the different event categories

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
	$e+\rho$	$\omega_{\mathrm{vis}}(\rho)$	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
	$\mu+\rho$	$\omega_{\mathrm{vis}}(\rho)$	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
	$\rho+\tau_\mathrm{h}$	$\omega_{\mathrm{vis}}(\rho)$	visible optimal observable (for leading ρ)
	$\pi+\pi$	$m_{\mathrm{vis}}(\pi,\pi)$	visible mass

$m_{vis}(1,2)$ = visible mass

$\boldsymbol{\omega_{vis}(\rho)} = \cos\boldsymbol{\beta}$

$\omega(\pi, a_1) = opt.obs.$

$\boldsymbol{\Omega}(a_1,\pi) = \frac{\omega(\pi)+\omega(a_1)}{1+\omega(\pi)\omega(a_1)}$

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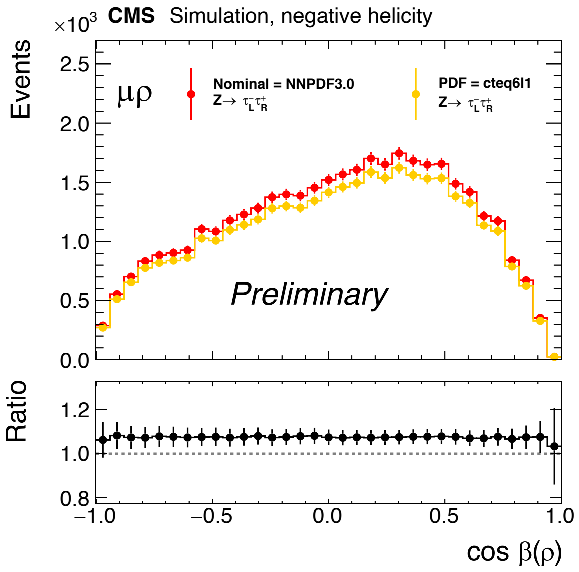
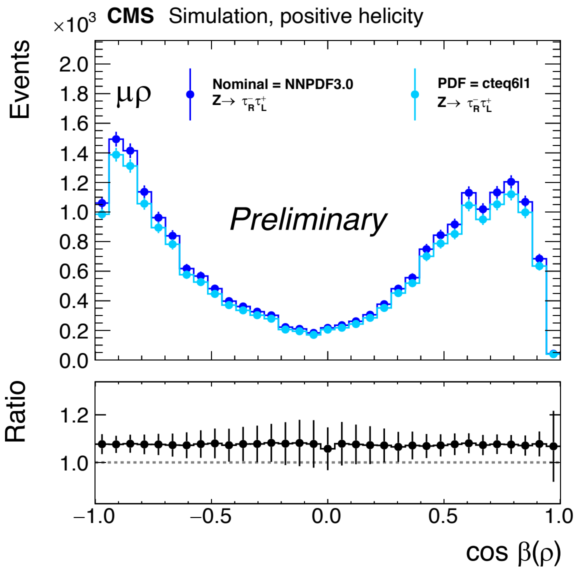
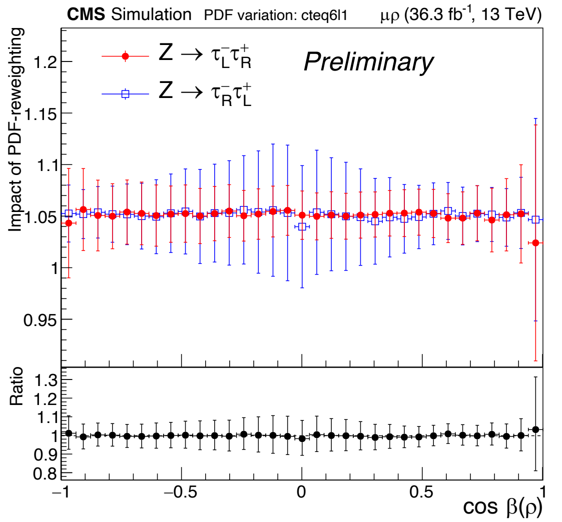
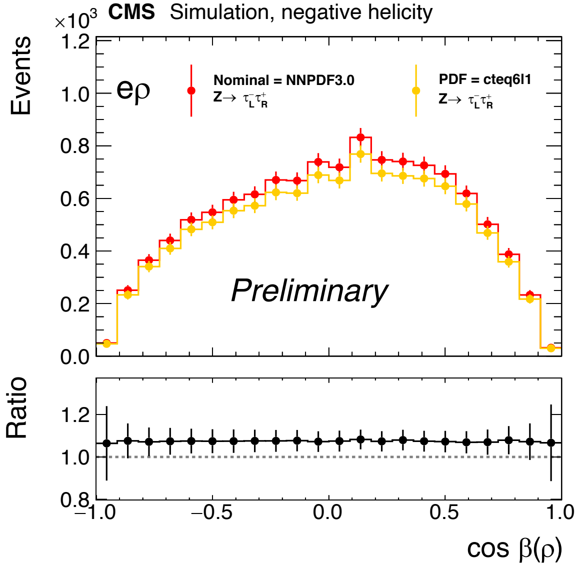
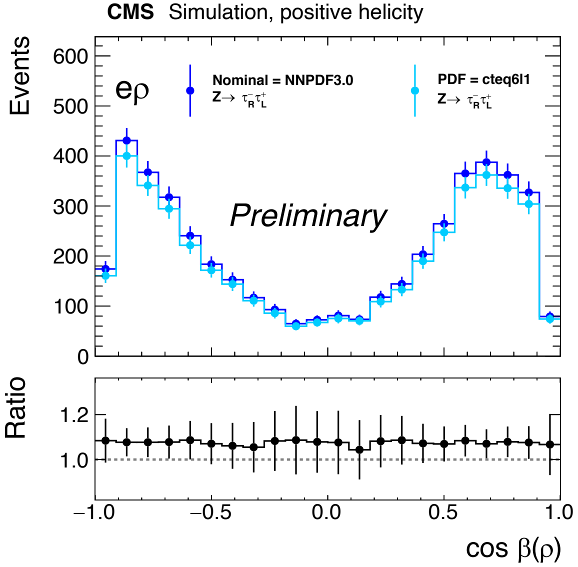
Stability of templates wrt pdf variations

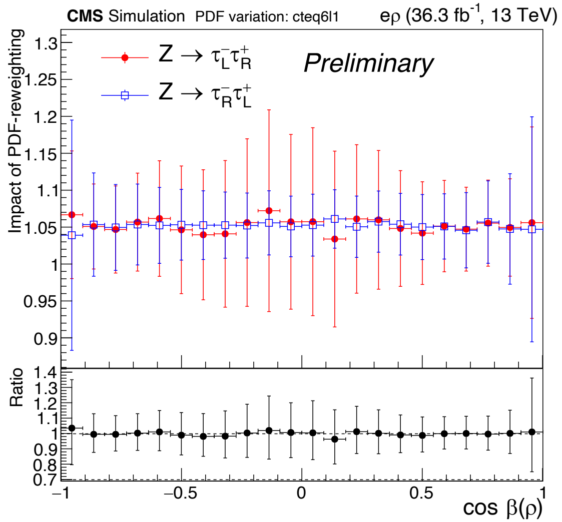












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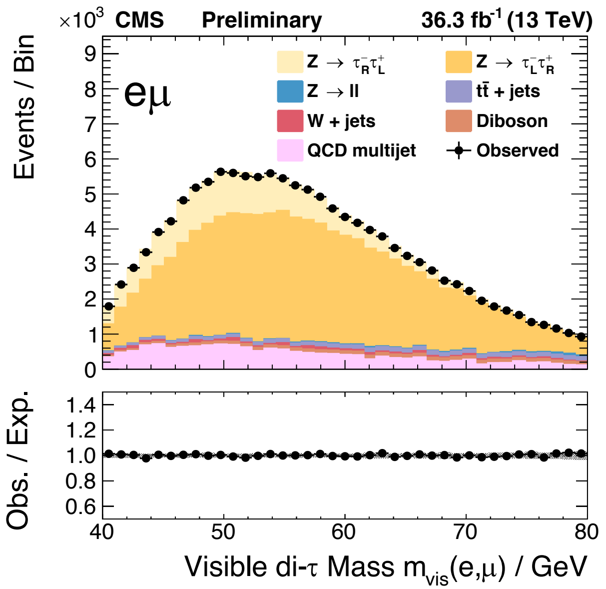
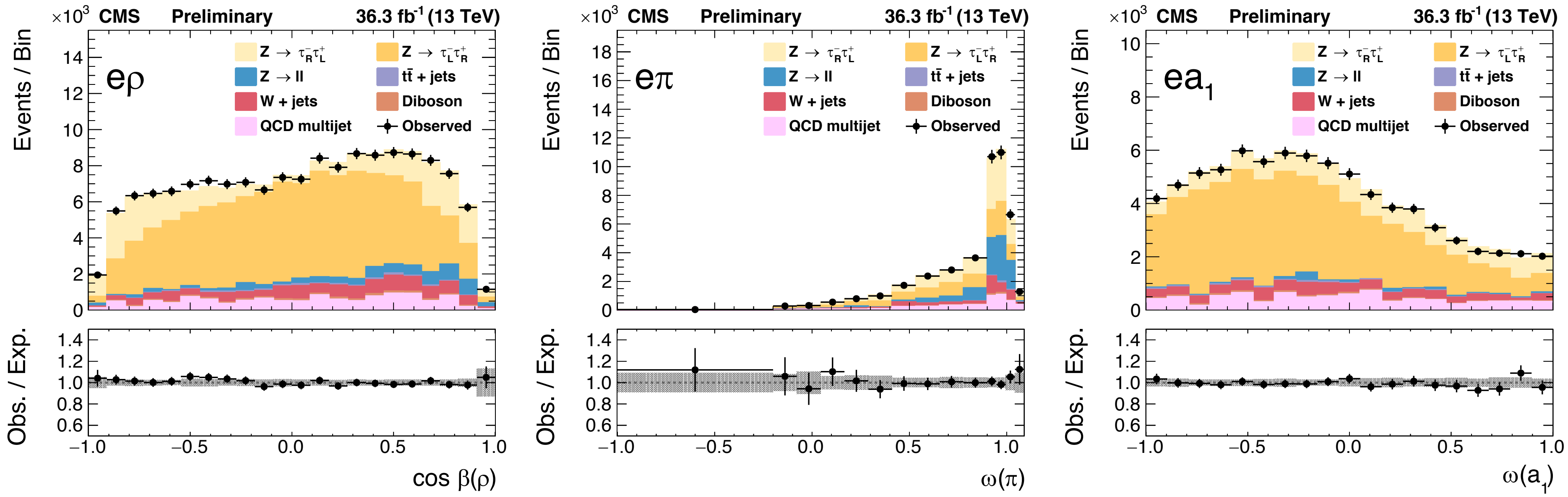
Post fits of templates



$\tau_e - \tau_\mu$

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

$\tau_e - \tau_{had}$



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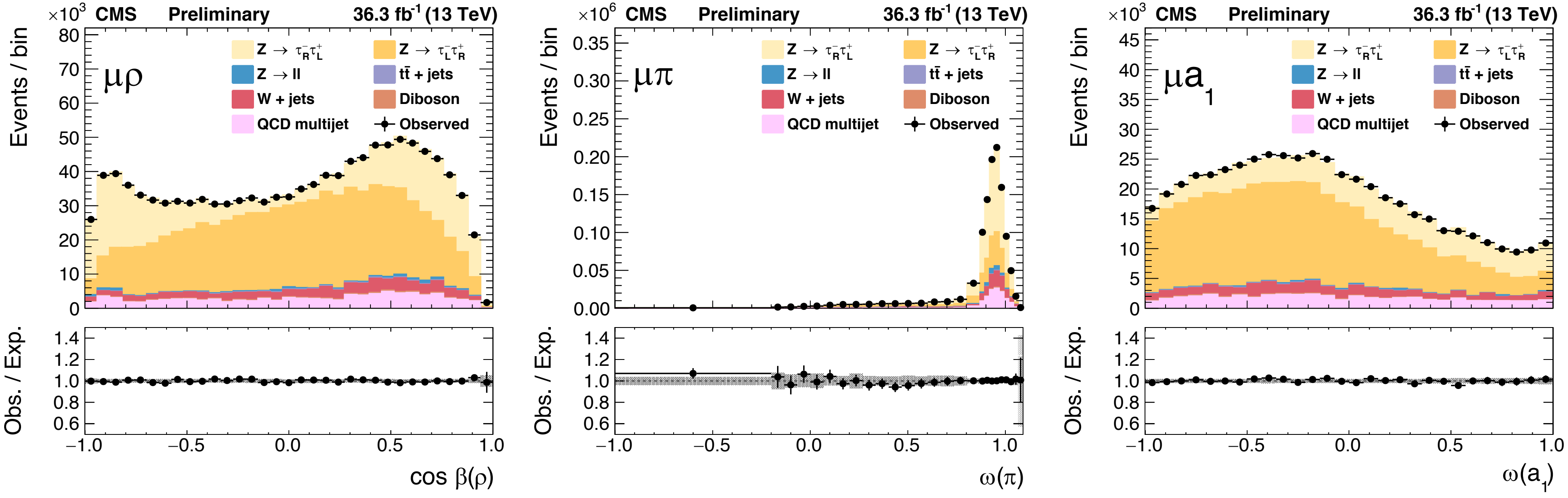
Post fits of templates

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

$$\tau_\mu - \tau_{had}$$



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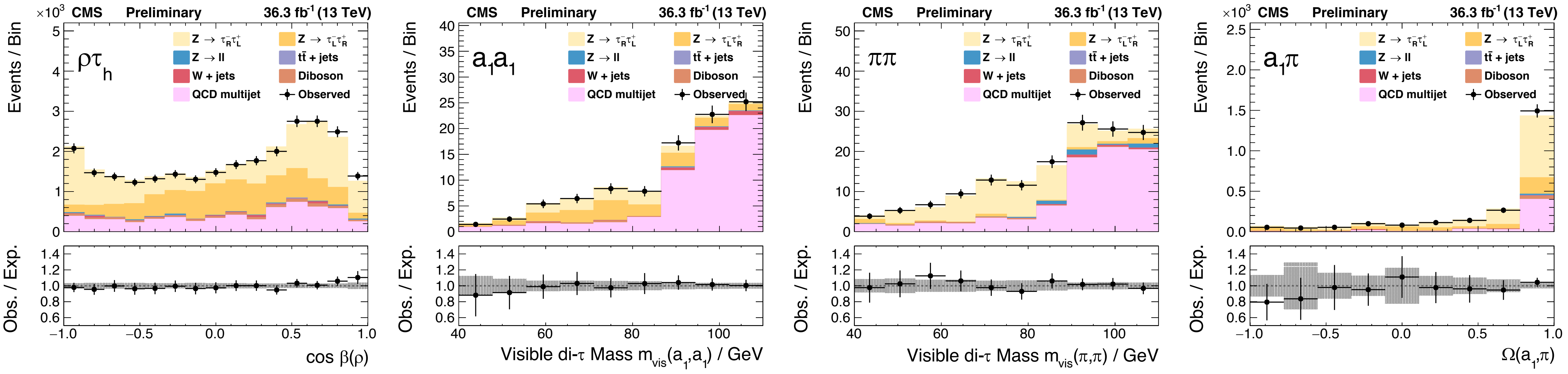
Post fits of templates

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

$$\tau_{had} - \tau_{had}$$



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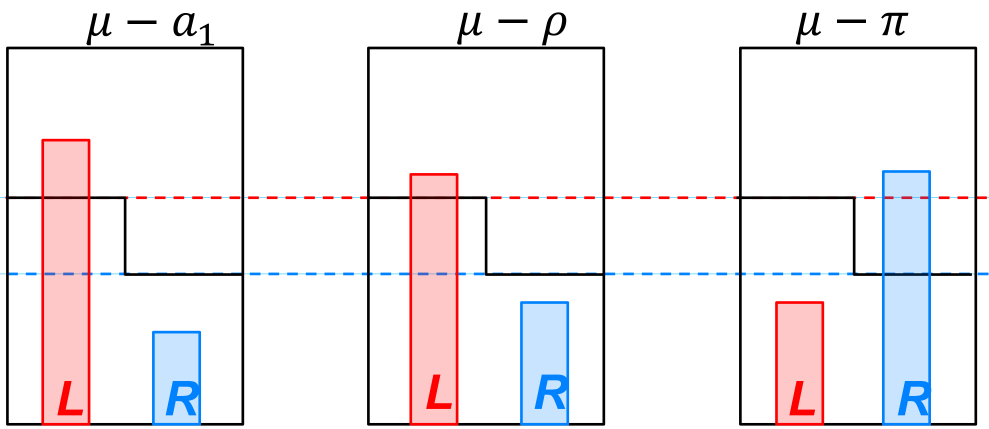
Renormalisation of templates to zero polarisation

Relative yield

L generated

R generated



L reconstructed   *R* reconstructed

Average Polarisation at generator level for interval $75 < \sqrt{\hat{s}_{q\bar{q}}} < 120$ GeV

$Z^0 \rightarrow \tau_L^- \tau_R^+$

$Z^0 \rightarrow \tau_R^- \tau_L^+$

$< P > = -0.213$ MG5: $\sin^2\theta_W^{eff} = 0.22224$

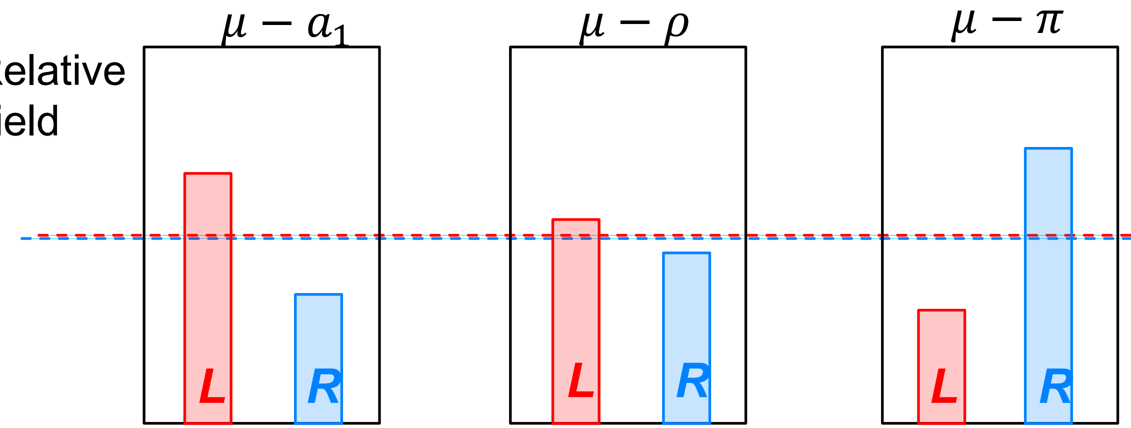
Apply normalisation factor: $s_{RL/LR} \cdot s_{\text{tot}}$

$$s_{RL/LR} = \frac{1}{N_{\text{gen}}(Z \rightarrow \tau_{L/R}^- \tau_{R/L}^+)},$$

$$s_{\text{tot}} = N_{\text{gen}}(Z \rightarrow \tau_R^- \tau_L^+) + N_{\text{gen}}(Z \rightarrow \tau_L^- \tau_R^+).$$

Renormalisation of Templates preserving normalisation

Relative yield



L reconstructed   *R* reconstructed

$< P > = 0$ **Reference of new templates**

$75 < \sqrt{\hat{s}_{q\bar{q}}} < 120$ GeV at generator level

Schematic view only !