Imperial College London

A Search for New Physics With Tau Leptons at the CMS Experiment

Author:
George Uttley

Supervisor:
Prof. David Colling

Abstract

The Standard Model of Particle Physics is currently the best model of the fundamental particles and their interactions. However, there are still significant theoretical issues and recently seen experimental tensions with the model. The theoretical issues include the hierarchy problem which forecasts the breakdown of the Standard Model when looking at the size of corrections needed to calculate the mass of the newest found member of the theory, the Higgs boson particle. The current experimental tensions include the B-anomalies and the g-2 measurement. These results, although they do not yet sit at the required 5σ deviation for a discovery, offer the most prominent leads into where new physics may be hiding. Looking for signatures of theoretical explanations of these anomalies offers excellent search options for new fundamental particles. This thesis describes the search for new physics that can explain both the theoretical problems and experimental tensions. This is done using tau leptons seen during Run-2 of the Large Hadron Collider (LHC) at the Compact Muon Solenoid (CMS) experiment. The Beyond Standard Model theories searched for range from Supersymmetry, leptoquarks, to type-X two Higgs doublet models. Each theory is separately studied and an analysis is tailored to find its most sensitive signature. In the process of optimisation, data-driven background modelling is improved to aid the reliability of the results. The results are currently blinded however the expected limits offer some of the largest constraints that are placed on these prominent Beyond Standard Model Theories.

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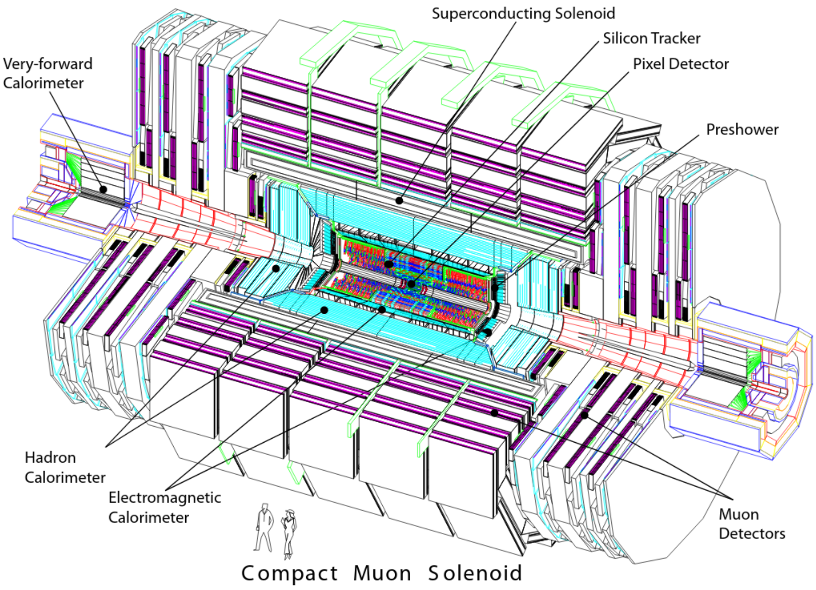

Figure 1: A perspective view of the CMS detector [?].

3.3 Event Reconstruction

4 Tau Identification

Decay Mode	Branching Fraction
Leptonic Decay (e, μ)	**35.2%**
$e^- \bar{\nu}_e \nu_\tau$	17.8%
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.4%
Hadronic Decay (τ_h)	**64.8%**
$h^- \pi^0 \nu_\tau$	25.9%
$h^- \nu_\tau$	11.5%
$h^- 2\pi^0 \nu_\tau$	9.3%
$\pi^- \pi^- \pi^+ \nu_\tau$	9.0%
$\pi^- \pi^- \pi^+ \pi^0 \nu_\tau$	2.7%
other	6.4%

Table 1: Measured branching fractions, that are greater than 2%, for the tau lepton. h represents a charged hadron either a pion or a kaon.

5 BSM H/A $\to \tau^+\tau^-$ Analysis

5.1 Theoretical Motivation

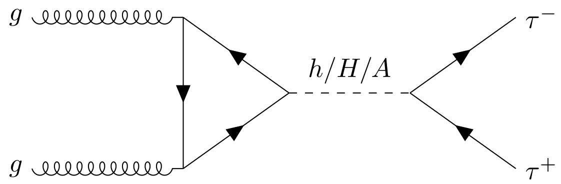

Figure 2

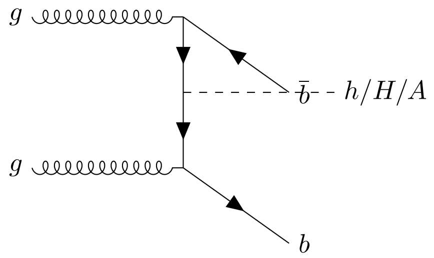

Figure 3

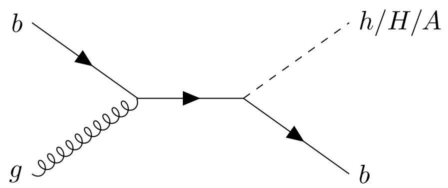

Figure 4

5.2 Event Selection

Channel	Branching Fraction
$\tau_h\tau_h$	42.0%
$e\tau_h$	23.1%
$\mu\tau_h$	22.6%
$e\mu$	6.2%
ee	3.2%
$\mu\mu$	3.0%

Table 2

5.3 Background Modelling

5.4 Fake Factor Method

5.4.1 Future Improvements to the Fake Factor Method

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6 Vector Leptoquark Reinterpretation of the BSM H/A $\rightarrow \tau^+\tau^-$ Analysis

6.1 Theoretical Motivation

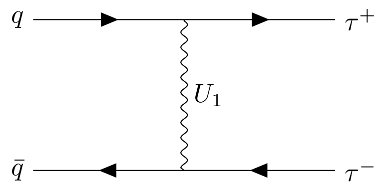


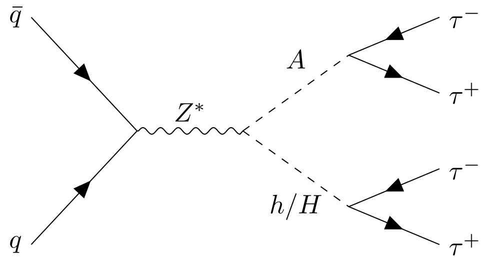
Figure 5: Feynman diagram showing the vector leptoquark t-channel interaction that produces a tau pair from a pair of bottom quarks.

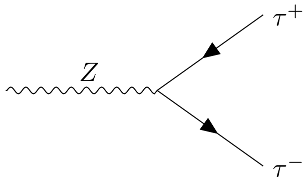
6.2 Analysis Strategy

6.3 Signal Modelling

6.4 Results

6.5 Future Improvements to Vector Leptoquark Search





7 BSM $Z^* \to$ HA $\to \tau^+\tau^-\tau^+\tau^-$

7.1 Theoretical Motivation

7.2 Event Selection

Channel	Branching Fraction
$e\tau_h\tau_h\tau_h$	19.4%
$\mu\tau_h\tau_h\tau_h$	18.9%
$\tau_h\tau_h\tau_h\tau_h$	17.6%
$e\mu\tau_h\tau_h$	15.6%
$ee\tau_h\tau_h$	8.0%
$\mu\mu\tau_h\tau_h$	7.6%
$ee\mu\tau_h$	4.3%
$e\mu\mu\tau_h$	4.2%
$eee\tau_h$	1.5%
$\mu\mu\mu\tau_h$	1.4%
$eee\mu$	1.4%
$ee\mu\mu$	0.6%
$eee\mu$	0.4%
$e\mu\mu\mu$	0.4%
$eeee$	0.1%
$\mu\mu\mu\mu$	0.1%

Table 3

Channel	Branching Fraction
$\tau_h^+\tau_h^+\tau_h^-\tau_h^-$	17.6%
$\tau_h^+\tau_h^-\tau_h^-e^+$	9.7%
$\tau_h^+\tau_h^+\tau_h^-e^-$	9.7%
$\mu^-\tau_h^+\tau_h^+\tau_h^-$	9.5%
$\mu^+\tau_h^+\tau_h^-\tau_h^-$	9.5%
$\tau_h^+\tau_h^-e^+e^-$	5.3%
$\mu^-\tau_h^+\tau_h^-e^+$	5.2%
$\mu^+\tau_h^+\tau_h^-e^-$	5.2%
$\mu^+\mu^-\tau_h^+\tau_h^-$	5.1%
$\mu^-\tau_h^+\tau_h^+e^-$	2.6%
$\mu^+\tau_h^-\tau_h^-e^+$	2.6%
$\mu^-\tau_h^+e^+e^-$	1.4%
$\mu^+\tau_h^-e^+e^-$	1.4%
$\mu^+\mu^-\tau_h^-e^+$	1.4%
$\mu^+\mu^-\tau_h^+e^-$	1.4%
$\tau_h^-\tau_h^-e^+e^+$	1.3%
$\tau_h^+\tau_h^+e^-e^-$	1.3%
$\mu^-\mu^-\tau_h^+\tau_h^+$	1.3%
$\mu^+\mu^+\tau_h^-\tau_h^-$	1.3%
$\tau_h^-e^+e^+e^-$	0.7%
$\tau_h^+e^+e^-e^-$	0.7%
$\mu^-\tau_h^-e^+e^+$	0.7%
$\mu^+\tau_h^+e^-e^-$	0.7%
$\mu^-\mu^-\tau_h^+e^+$	0.7%
$\mu^+\mu^+\tau_h^-e^-$	0.7%
$\mu^+\mu^-\mu^-\tau_h^+$	0.7%
$\mu^+\mu^+\mu^-\tau_h^-$	0.7%
$\mu^+\mu^-e^+e^-$	0.4%
$\mu^-e^+e^+e^-$	0.2%
$\mu^+e^+e^-e^-$	0.2%
$\mu^+\mu^-\mu^-e^+$	0.2%
$\mu^+\mu^+\mu^-e^-$	0.2%
$e^+e^+e^-e^-$	0.1%
$\mu^-\mu^-e^+e^+$	0.1%
$\mu^+\mu^+e^-e^-$	0.1%
$\mu^+\mu^+\mu^-\mu^-$	0.1%

Table 4

$$\mathcal{L}_{\rm yukawa}^{\rm 2HDM} = -\sum_{f=u,d,l}\left(\frac{m_f}{\nu}\xi_h^f\bar{f}fh+\frac{m_f}{\nu}\xi_H^f\bar{f}fH-i\frac{m_f}{\nu}\xi_A^f\bar{f}\gamma_5fA\right)-\left[\frac{\sqrt{2}V_{ud}}{\nu}\bar{u}(m_u\xi_A^uP_L+m_d\xi_A^dP_R)dH^++\frac{\sqrt{2}m_l\xi_A^d}{\nu}\bar{\nu}_Ll_RH^++h.c.\right] \tag{1}$$

	g_h^u	g_h^d	g_h^l	g_H^u	g_H^d	g_H^l	g_A^u	g_A^d	g_A^l
Type I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$1/t_\beta$	$-1/t_\beta$	$-1/t_\beta$
Type II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$1/t_\beta$	t_β	t_β
Type X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	$1/t_\beta$	$-1/t_\beta$	t_β
Type Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	$1/t_\beta$	t_β	$-1/t_\beta$

Table 6

In the alignment limit, for the normal scenario $h_{SM} = h$, $sin(\beta - \alpha) = 1$, $\implies$ $c_\alpha/s_\beta = 1$, $s_\alpha/c_\beta = -1$, $s_\alpha/s_\beta = -1/t_\beta$, $c_\alpha/c_\beta = t_\beta$.

Channel	Triggers
$e\tau_h\tau_h\tau_h$	EleTau, singleEle, diTau
$\mu\tau_h\tau_h\tau_h$	MuonTau, singleMuon, diTau
$\tau_h\tau_h\tau_h\tau_h$	diTau
$e\mu\tau_h\tau_h$	MuonEle, diTau
$ee\tau_h\tau_h$	diEle, diTau
$\mu\mu\tau_h\tau_h$	diMuon, diTau

Table 5

	g_h^u	g_h^d	g_h^l	g_H^u	g_H^d	g_H^l	g_A^u	g_A^d	g_A^l
Type I	1	1	1	$-1/t_\beta$	$-1/t_\beta$	$-1/t_\beta$	$1/t_\beta$	$-1/t_\beta$	$-1/t_\beta$
Type II	1	1	1	$-1/t_\beta$	t_β	t_β	$1/t_\beta$	t_β	t_β
Type X	1	1	1	$-1/t_\beta$	$-1/t_\beta$	t_β	$1/t_\beta$	$-1/t_\beta$	t_β
Type Y	1	1	1	$-1/t_\beta$	t_β	$-1/t_\beta$	$1/t_\beta$	t_β	$-1/t_\beta$

Table 7

In the alignment limit, for the inverted scenario $h_{SM} = H$, $cos(\beta - \alpha) = 1 \implies c_\alpha/s_\beta = 1/t_\beta$, $s_\alpha/c_\beta = t_\beta$, $s_\alpha/s_\beta = 1$, $c_\alpha/c_\beta = 1$.

	g_h^u	g_h^d	g_h^l	g_H^u	g_H^d	g_H^l	g_A^u	g_A^d	g_A^l
Type I	$1/t_\beta$	$1/t_\beta$	$1/t_\beta$	1	1	1	$1/t_\beta$	$-1/t_\beta$	$-1/t_\beta$
Type II	$1/t_\beta$	$-t_\beta$	$-t_\beta$	1	1	1	$1/t_\beta$	t_β	t_β
Type X	$1/t_\beta$	$1/t_\beta$	$-t_\beta$	1	1	1	$1/t_\beta$	$-1/t_\beta$	t_β
Type Y	$1/t_\beta$	$-t_\beta$	$1/t_\beta$	1	1	1	$1/t_\beta$	t_β	$-1/t_\beta$

Table 8

Trigger	HLT Path
SingleElectron	HLT_Ele25_eta2p1_WPTight_Gsf_v
DoubleElectron	HLT_Ele23_Ele12_CaloIdL_TrackIdL_IsoVL_DZ_v
TripleElectron	HLT_Ele16_Ele12_Ele8_CaloIdL_TrackIdL
SingleMuon	HLT_IsoMu24_v OR HLT_IsoTkMu24_v
DoubleMuon	HLT_Mu17_TrkIsoVVL_Mu8_TrkIsoVVL(_DZ)_v OR HLT_Mu17_TrkIsoVVL_TkMu8_TrkIsoVVL(_DZ)_v
TripleMuon	HLT_TripleMu_12_10_5
SingleTau	HLT_VLooseIsoPFTau120_Trk50_eta2p1_v OR HLT_VLooseIsoPFTau140_Trk50_eta2p1_v
DoubleTau	HLT_DoubleMediumIsoPFTau35_Trk1_eta2p1_Reg_v
Electron Tau Cross	HLT_Ele24_eta2p1_WPLoose_Gsf_LooseIsoPFTau20_SingleL1_v
Muon Tau Cross	HLT_IsoMu19_eta2p1_LooseIsoPFTau20_SingleL1_v

Table 9: 2016 HLT paths.

7.3 Background Modelling

7.4 Optimisation of Analysis

7.5 Signal Extraction

7.6 Results

m_A (GeV)	60			100			150		
m_ϕ (GeV)	100	200	300	100	200	300	100	200	300
Cross Section (pb)	0.66	0.089	0.023	0.29	0.057	0.035	0.12	0.035	0.013

e	μ	τ_h
$p_T > 15$ GeV $\lvert\eta\rvert < 2.5$ MVA 90% WP $I_{rel} < 0.15$	$p_T > 15$ GeV $\lvert\eta\rvert < 2.4$ Medium ID $I_{rel} < 0.15$	$p_T > 20$ GeV $\lvert\eta\rvert < 2.3$ HPS algorithm deepTauVSjet VVVLoose WP deepTauVSele VLoose WP deepTauVSmu VLoose WP

Method/ Channel	$\tau_h\tau_h\tau_h\tau_h$	$\mu\tau_h\tau_h\tau_h$	$e\tau_h\tau_h\tau_h$	$\mu\mu\tau_h\tau_h$	$ee\tau_h\tau_h$	$e\mu\tau_h\tau_h$
Selected by HPS and loose isolation	0.53	0.26	0.23	0.12	0.15	0.12
Selected by DeepTau and tight isolation	0.10	0.19	0.19	0.31	0.29	0.35
Selected objects from Higgs decay	0.88	0.90	0.89	0.93	0.91	0.91

Table 10

8 Conclusion

8.1 Global Interpretations of Results

8.2 Projections to Run-3 and HL-LHC

Method/ Channel	$\tau_h\tau_h\tau_h\tau_h$	$\mu\tau_h\tau_h\tau_h$	$e\tau_h\tau_h\tau_h$	$\mu\mu\tau_h\tau_h$	$ee\tau_h\tau_h$	$e\mu\tau_h\tau_h$
Minimum single ΔR	0.84	0.84	0.84	0.84	0.83	0.84
Minimum summed ΔR	0.87	0.87	0.86	0.86	0.87	0.87
Minimum single $\Delta\phi$	0.82	0.84	0.83	0.83	0.83	0.82
Minimum summed $\Delta\phi$	0.85	0.87	0.85	0.85	0.85	0.86

Table 11

Channel	Triggers	$(m_\phi, m_A) = (100, 60)$	$(m_\phi, m_A) = (300, 60)$	$(m_\phi, m_A) = (100, 100)$	$(m_\phi , m_A) = (300, 100)$
$e\tau_h\tau_h\tau_h$	$\tau_h^1\tau_h^2$	0.38	0.51	0.48	0.61

Table 12

Channel	Triggers	m_A (GeV)	60			100			150		
		m_ϕ (GeV)	100	200	300	100	200	300	100	200	300
$\tau_h\tau_h\tau_h\tau_h$	$\tau_h^1\tau_h^2$		0.41	0.5	0.52	0.5	0.6	0.62	0.56	0.65	0.7
	$\tau_h^1\tau_h^2$ or $\tau_h^1\tau_h^3$		0.47	0.59	0.64	0.57	0.7	0.73	0.64	0.74	0.79
	$\tau_h^1\tau_h^2$ or $\tau_h^1\tau_h^3$ or $\tau_h^1\tau_h^4$		0.48	0.62	0.67	0.59	0.72	0.75	0.66	0.76	0.8
	$\tau_h^1\tau_h^2$ or $\tau_h^1\tau_h^3$ or $\tau_h^1\tau_h^4$ or $\tau_h^2\tau_h^3$		0.53	0.67	0.73	0.65	0.78	0.82	0.72	0.82	0.87
	$\tau_h^1\tau_h^2$ or $\tau_h^1\tau_h^3$ or $\tau_h^1\tau_h^4$ or $\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$		0.54	0.68	0.75	0.65	0.79	0.83	0.72	0.83	0.88
	$\tau_h^1\tau_h^2$ or $\tau_h^1\tau_h^3$ or $\tau_h^1\tau_h^4$ or $\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$ or $\tau_h^3\tau_h^4$		0.54	0.69	0.76	0.66	0.79	0.84	0.73	0.84	0.88
$\mu\tau_h\tau_h\tau_h$	μ^1		0.64	0.71	0.76	0.69	0.75	0.78	0.7	0.77	0.8
	μ^1 or $\tau_h^2\tau_h^3$		0.75	0.85	0.89	0.82	0.88	0.91	0.84	0.9	0.93
	μ^1 or $\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$		0.76	0.86	0.9	0.83	0.9	0.93	0.86	0.92	0.95
	μ^1 or $\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$ or $\tau_h^3\tau_h^4$		0.76	0.87	0.91	0.84	0.9	0.94	0.87	0.92	0.95
	μ^1 or $\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$ or $\tau_h^3\tau_h^4$ or $\mu^1\tau_h^2$ or $\mu^1\tau_h^3$ or $\mu^1\tau_h^4$		0.82	0.9	0.93	0.87	0.93	0.95	0.91	0.95	0.96
	$\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$ or $\tau_h^3\tau_h^4$		0.39	0.53	0.58	0.5	0.61	0.68	0.58	0.68	0.74
	$\mu^1\tau_h^2$ or $\mu^1\tau_h^3$ or $\mu^1\tau_h^4$		0.67	0.73	0.77	0.7	0.77	0.79	0.74	0.79	0.81
	$\mu^1\tau_h^2$ or $\mu^1\tau_h^3$ or $\mu^1\tau_h^4$ or $\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$ or $\tau_h^3\tau_h^4$		0.78	0.85	0.89	0.83	0.89	0.92	0.88	0.92	0.94
$e\tau_h\tau_h\tau_h$	e^1		0.41	0.5	0.57	0.46	0.54	0.6	0.49	0.56	0.62
	e^1 or $\tau_h^2\tau_h^3$		0.6	0.7	0.77	0.67	0.77	0.82	0.74	0.8	0.85
	e^1 or $\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$		0.63	0.72	0.81	0.69	0.8	0.85	0.77	0.83	0.88
	e^1 or $\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$ or $\tau_h^3\tau_h^4$		0.64	0.75	0.83	0.71	0.81	0.87	0.78	0.85	0.9
	e^1 or $\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$ or $\tau_h^3\tau_h^4$ or $e^1\tau_h^2$ or $e^1\tau_h^3$ or $e^1\tau_h^4$		0.71	0.8	0.86	0.76	0.85	0.89	0.82	0.87	0.91
	$\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$ or $\tau_h^3\tau_h^4$		0.41	0.48	0.57	0.48	0.6	0.68	0.56	0.66	0.73
	$e^1\tau_h^2$ or $e^1\tau_h^3$ or $e^1\tau_h^4$		0.49	0.54	0.59	0.5	0.59	0.62	0.54	0.6	0.65
	$e^1\tau_h^2$ or $e^1\tau_h^3$ or $e^1\tau_h^4$ or $\tau_h^2\tau_h^3$ or $\tau_h^2\tau_h^4$ or $\tau_h^3\tau_h^4$		0.66	0.74	0.8	0.7	0.81	0.86	0.78	0.84	0.89
$e\mu\tau_h\tau_h$	e^1 or μ^2		0.78	0.86	0.9	0.82	0.86	0.92	0.86	0.91	0.93
	e^1 or μ^2 or $\tau_h^3\tau_h^4$		0.82	0.91	0.94	0.86	0.91	0.95	0.9	0.94	0.96
	e^1 or μ^2 or $\tau_h^3\tau_h^4$ or $e^1\mu^1$		0.84	0.92	0.94	0.88	0.92	0.96	0.91	0.95	0.97
	$e^1\mu^1$		0.62	0.7	0.75	0.66	0.72	0.76	0.69	0.75	0.77
	$e^1\mu^1$ or $\tau_h^3\tau_h^4$		0.69	0.78	0.83	0.74	0.82	0.86	0.78	0.85	0.88
	$\tau_h^3\tau_h^4$		0.19	0.27	0.31	0.26	0.35	0.4	0.3	0.38	0.45
$ee\tau_h\tau_h$	e^1		0.56	0.69	0.77	0.68	0.74	0.78	0.72	0.75	0.8
	e^1 or e^2		0.61	0.73	0.81	0.71	0.79	0.84	0.76	0.81	0.86
	e^1 or e^2 or $\tau_h^3\tau_h^4$		0.69	0.8	0.87	0.76	0.86	0.91	0.83	0.89	0.92
	e^1 or e^2 or $\tau_h^3\tau_h^4$ or $e^1\tau_h^3$ or $e^1\tau_h^4$ or $e^2\tau_h^3$ or $e^2\tau_h^4$		0.78	0.86	0.9	0.81	0.9	0.93	0.88	0.92	0.94
	$\tau_h^3\tau_h^4$		0.18	0.24	0.28	0.24	0.34	0.37	0.32	0.4	0.45
$\mu\mu\tau_h\tau_h$	μ^1		0.82	0.85	0.9	0.84	0.89	0.91	0.89	0.9	0.91
	μ^1 or μ^2		0.85	0.9	0.95	0.87	0.93	0.96	0.93	0.94	0.96
	μ^1 or μ^2 or $\tau_h^3\tau_h^4$		0.86	0.93	0.96	0.9	0.95	0.98	0.95	0.96	0.98
	μ^1 or μ^2 or $\tau_h^3\tau_h^4$ or $\mu^1\tau_h^3$ or $\mu^1\tau_h^4$ or $\mu^2\tau_h^3$ or $\mu^2\tau_h^4$		0.9	0.96	0.98	0.94	0.97	0.99	0.97	0.98	0.98
	$\tau_h^3\tau_h^4$		0.21	0.3	0.34	0.26	0.34	0.4	0.29	0.39	0.44