HIG-14-005

Very informal journal club

Higgs boson → leptons

	7 TeV	8 TeV
gg	15	19
VBF	1.2	1.6
VH	0.9	1.1
ttH	0.1	0.1
	17.4	22.1

~20 fb

(57 fb @ 14 TeV)

$\tau\tau$: 6% → 31 ev. @ 5+20 fb^{-1}

$\mu\mu$: 0.02% → 0.1 ev @ 〃

$\tau\tau$ ATL $\mu = 1.42^{+0.44}_{-0.38}$ … 4.5σ evidence (gg, VB, VH)

CMS $\mu = 0.91 \pm 0.27$, 3.8σ evidence (〃 + ttH)

$\mu\mu$ ATL $\mu < 7.0$ (95%) (gg, VB, VH)

CMS –

- $H \to \tau\mu$?

CMS : 2.5σ excess

$$\begin{cases} \mu\tau_h & 0j : +0.08\sigma \\ & 1j : +0.10\sigma \\ & 2j : +1.23\sigma \\ \mu\tau_e & 0j : +0.89\sigma \\ & 1j : +0.69\sigma \\ & 2j : +0.16\sigma \end{cases} \to 2.6\sigma!!$$

All oneside for 6-regions:
$2 \times (\frac{1}{2})^6 = 1.6\%$ (2.15σ)

- What is this?
  - statistical dispersion!

- But it is good time to review this exp. & theories.

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CMS PAS HIG-14-005

EXPERIMENT

- target signal

$H \to \tau^{\pm} \mu^{\mp}$

$\tau^{\pm} \to$ hadron $+ \nu_\tau$ [$H \to \tau_h \mu$]

$\tau^{\pm} \to \mu^{\pm} \nu_\mu \nu_\tau$

$\tau^{\pm} \to e^{\pm} \nu_e \nu_\tau$ [$H \to \tau_e \mu$]

$\tau \to e$: 18%
μ : 17%
1p : 30%
3p : 15%

- BKG

② $H \to \tau_h \mu$: τ-misid in QCD, $t\bar{t}$, W+j , $Z \to \tau\tau$, $Z \to j$, $Z \to t\bar{t}$
$\Downarrow$ HUGE BKG!

① $H \to \tau_e \mu$: $Z \to \tau_e \tau_\mu$, fake leptons in $t\bar{t}$, W+j, QCD
$\Downarrow$ $\Delta\phi$, M_T ; $\Downarrow$ jet veto, b-veto, $\Delta\phi$, M_T

~~∘ τ-id "hadron plus strips" (HPS):~~ discuss after selection!!

- trigger $\tau_h \mu$: $1\mu^{isol}24$ ($|\eta| < 2.1$)
$\tau_e \mu$: $1\mu 17 \wedge 1e\,8$ ($|\eta| < 2.5, 2.4$)

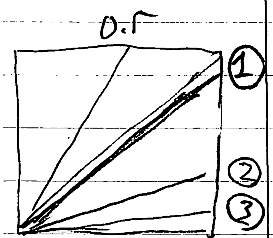
- Reco. PF, anti k_T-0.5, τ-id w. "hadron plus strip" (HPS)
b-tag w. "combined secondary vertex"

$$\frac{\tau \to \mu\nu\nu}{\tau \to e\nu\nu} = \frac{0.1741(4)}{0.1783(4)} = 0.976(4)$$

SM: $\Gamma \propto f\left(\frac{m_\ell^2}{m_\tau^2}\right)$ w. $f(x) = \underbrace{1 - 8x}_{\Rightarrow 0.9720} + 8x^3 - x^4 \underbrace{- 12x^2 \ln x}_{\Rightarrow 0.9729}$ … perhaps kinematics

j: $|\eta| < 4.7$
e: $|\eta| < 2.3$
μ: $|\eta| < 2.1$

- b-veto not applied for
  - $\tau_h\mu$ 1j because τid ⊕ Bid is bad … (?)
  - VBF because forward



· Event selection

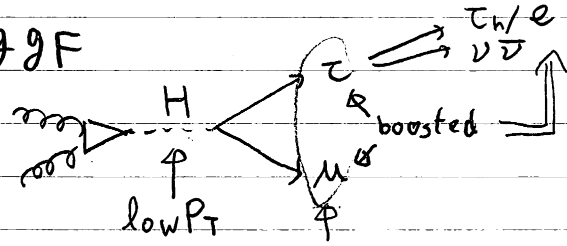
$H \to \tau_e \mu$ 0j30 OS μ50 e10 – $\Delta\phi > 2.7$, $\Delta\phi_{e\not{E}} < 0.5$, $M_{T\mu} > 50$, $e < 65$
1j30 OS μ45 e10 – $\Delta\phi > 1.0$, 0b, 〃 < 0.5, $e < 65$, $\mu > 40$
VBF OS μ25 e10 — , 〃 < 0.3, $e < 25$, $\mu > 25$

$H \to \tau_h \mu$ 0j30 OS μ40 τ35 – $\Delta\phi > 2.7$, $M_T(\tau_h) < 50$
1j30 OS μ35 τ40 — , 〃 < 35
VBF OS μ30 τ40 — , 〃 < 35

(VBF : 2j30 w. $\Delta\eta > 3.5$ & $m_{jj} > 550$ GeV)

- ggF　　0j ∋ ggF
- VBF　　1j ∋ ggF & VH
- ZH, WH　　2j ∋ VBF

- ggF



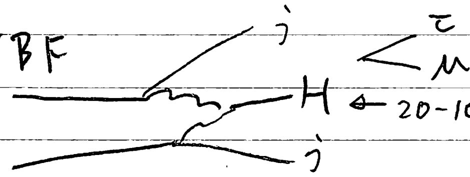
] collinear : $\Delta\phi \sim 0$

boosted

low P_T (≲20)

opposite $\Delta\phi \sim \pi$
(with ISR/FSR, $\Delta\phi < \pi$)

- VBF



] collinear

← 20-100 GeV P_T

∘ Transverse mass

$$M_T(\ell) := \sqrt{2 P_T(\ell) \not{E}_T (1 - \cos \Delta\phi_{\ell\not{E}})}$$

Assuming $\mathbb{P}_\nu \parallel \mathbb{P}_{\bar\nu}$,

$$(E_\ell + E_\nu + E_{\bar\nu})^2 - \|\mathbb{P}_\ell + \mathbb{P}_\nu + \mathbb{P}_{\bar\nu}\|^2$$

$$\simeq m_\ell^2 + 2 P_\ell \not{E} (1 - \cos\theta_{\ell\not{E}}) \xrightarrow{\text{transverse}} 2P_T(\ell)\not{E}(1-\cos\Delta\phi)$$

In $H \to \tau_e \mu$, $M_T(e) \sim m_\tau$

$$M_T(\mu)^2 = 2 P_T(\mu) \not{E}_T (1 - \cos\Delta\phi_{\mu\not{E}})$$

$$\sim 2 P_T(\tau) \not{E}_T (1 - \cos(\pi - \Delta\phi_{\tau\not{E}}))$$

$$= 2 P_T(\tau) \not{E}_T (1 + \cos\Delta\phi_{\tau\not{E}})$$

$$\Rightarrow M_T(\mu) \gtrsim 2\sqrt{P_T(\tau)\not{E}_T}$$

∘ BKG estimation

- $Z \to \tau\tau$: $Z \to \mu\mu|_{data} \otimes \mu \xrightarrow{\text{REPLACE}} \tau_{\text{simulated}}$

$$M_T^2 = (\Sigma E_{T i})^2 - \|\Sigma \mathbb{P}_{T i}\|^2 = (i=2)\ m_1^2 + m_2^2 + 2(E_{T1} \cdot E_{T2} - \mathbb{P}_{T1} \cdot \mathbb{P}_{T2})$$

$$E_{T} = \sqrt{m^2 + \|\mathbb{P}_T\|^2}$$

$$\Downarrow$$

$$(m=0)\ (2\|\mathbb{P}_{T1}\|\|\mathbb{P}_{T2}\| - 2\mathbb{P}_{T1}\cdot\mathbb{P}_{T2})$$

$$= 2 P_{T1} P_{T2} (1 - \cos\theta)$$

$$\cancel{= (\ell\nu\bar\nu)\ m_\ell^2 + 2 E_{T\ell}(P_\nu + P_{\bar\nu}) + 2 P_\nu P_{\bar\nu} - 2\mathbb{P}_\nu\cdot\mathbb{P}_{\bar\nu} - 2\mathbb{P}_\ell\cdot(\mathbb{P}_\nu + \mathbb{P}_{\bar\nu})}$$

$$\cancel{= m_\ell^2 + 2 E_{T\ell}(P_\nu + P_{\bar\nu}) + (P_\nu + P_{\bar\nu})^2 - \|\mathbb{P}_T\|^2 - 2\mathbb{P}_\ell\cdot\mathbb{P}_T}$$

$$\cancel{= m_\ell^2 +}$$

BKGs evaluation

- $Z \to \tau\tau$: $Z \to \mu\mu|_{\text{data}} \otimes \mu \mapsto \tau^{\text{simulated}}$

- fake lepton, fake τ ... data-driven

$$N_{SR,\text{fake}} = \Big[N_{SR \text{ but one-lepton not isolated}} - N_{MC}^{\text{diboson}} \Big] \times \frac{N_{ev}\left(\substack{Z\to\mu\mu \\ \oplus \\ \text{extra } \mu \text{ isl}}\right)}{N_{ev}\left(\substack{'' \\ \text{extra} \\ \text{non-isl}}\right)}$$

$\sim N_{QCD+Wj}$ $\times$ trigger correction

After all cuts,

$H \to \mu\tau_e$
- $Z \to \tau\tau$ ... syst 6~13%
- fake ℓ ... 40%
- VV ... 15%

$H \to \mu\tau_h$
- $Z \to \tau\tau$ ... 6~13%
- fake τ ... 30-40%

Results

$Br(H \to \tau\mu) < 1.57\%$ [expected $< 0.75 \pm 0.38\%$]

$Br(H \to \tau\mu) = 0.89 \pm ^{0.40}_{0.37}\%$

... split SR into 6SR, and assumed 'correlated' BKG

$\Rightarrow$ relatively large "excess"

◎ UNDERLYING THEORIES

$L = \begin{pmatrix} \nu_L \\ l_L \end{pmatrix}$

$\bar{E} = (\bar{e})_R$

$H = \begin{pmatrix} 0 \\ v \end{pmatrix}$

SM: $\mathcal{L} \supset Y_{ij} H^a L^a_i \bar{E}_j \quad \left(+ Y'_{ij} \varepsilon^{ab} H^a L^b_i \bar{N}_j \right)$

$$\Downarrow \qquad\qquad \Downarrow$$

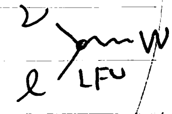
$$(v+h) Y_{ij}\, l_L \bar{e}_R \qquad -(v+h) Y'_{ij}\, \nu_L \bar{\nu}_R$$

$$\Downarrow \qquad\qquad \Downarrow$$

define leptons as "mass eigenstate" : $L_i \xrightarrow{\text{rotate}} U_{ij} L_j$ etc

$$\Downarrow \qquad\qquad \Downarrow$$

$$(v+h) Y_i\, l_i \bar{e}_i \qquad -(v+h) Y_i\, \bar{\nu}_i \nu_i \;\oplus$$



$H \to \mu\tau$ occurs if $\mathcal{L} \supset m_{ij} + h Y_{ij}$

NOT PROPORTIONAL

- Toy (effective) lagrangian

$$\mathcal{L} \supset m_i\, l_i \bar{e}_i + Y_{ij}\, h\, l_i \bar{e}_j$$

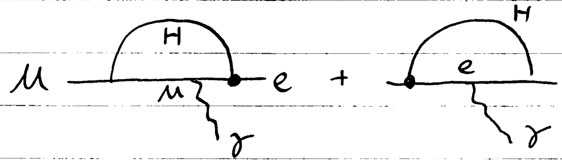
can be a "mass eigenstate" @ 126 GeV

[higher-order terms (with, say ∂_μ) are not included]

1202.5704
1209.1397

◦ Constraints

$Br(\mu \to e\gamma) < 5.7\times10^{-13}$ (90%) [1303.0754] [1209.1397]



$$\Rightarrow \sqrt{|Y_{\mu e}|^2+|Y_{e\mu}|^2} < 1.8\times10^{-6}$$

$$\Rightarrow Br(\mu\to e\gamma) < 2\times10^{-9}$$

For $Br < 2.4E-12$,
$\sqrt{\ } < 3.6E-6$.

Similarly $\tau\to e\gamma \Rightarrow \sqrt{|Y_{e\tau}|^2+|Y_{\tau e}|^2} < 0.014$

$\tau\to\mu\gamma \Rightarrow \quad < 0.016$

$\hookrightarrow Br(H\to\tau\ell) < 15\%$

$$Br(H\to l_a l_b) = \frac{\Gamma(H\to l_a l_b)}{\Gamma_{SM}+\Gamma(H\to l_a l_b)} \quad ; \quad \Gamma = \frac{m_h}{8\pi}\left(|Y_{ab}|^2+|Y_{ba}|^2\right)$$

Γ_{SM} ↑ 4.1 MeV

$$\Rightarrow \sqrt{|Y_{e\tau}|^2+|Y_{\tau\mu}|^2} < 0.0036$$

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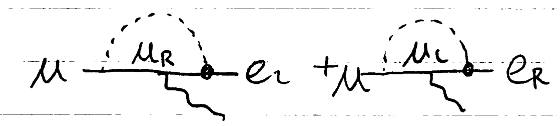
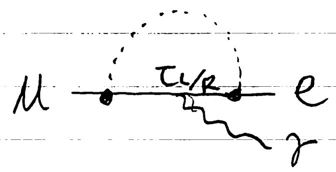
Constraints Summary

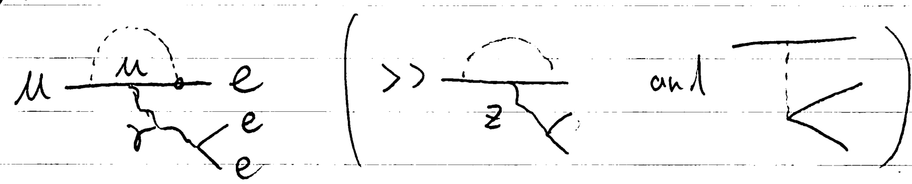
∘ $l_a \to l_b \gamma$





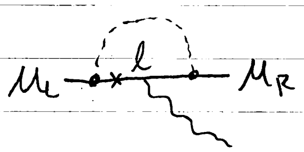
$\Rightarrow Y_{\mu\mu}\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2}$ $\quad \Rightarrow \sqrt{|Y_{\mu\tau} Y_{e\mu}|^2 + |Y_{\tau e} Y_{\tau\mu}|^2}$

∘ $l_a \to 3 l_b$



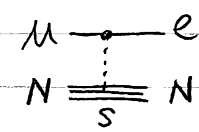
$\Rightarrow$ SAME as $\mu \to e\gamma$

∘ EDM / $g-2$



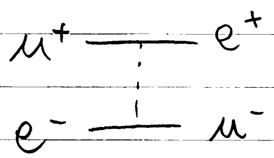
$\Rightarrow m_l Y_{\mu l} Y_{l\mu}$

∘ $\mu - e$ conversion



$\Rightarrow \sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2}$

∘ $M - \bar{M}$ osc



$\Rightarrow |Y_{\mu e} + Y_{e\mu}|^2$

$\mu \to e\gamma$ for	"$e\mu$"	$< O(10^{-6})$
$\tau \to e\gamma$ for	"τe"	< 0.014
$\tau \to \mu\gamma$	"	< 0.016

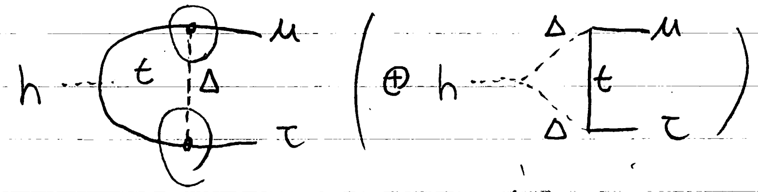
$Y_\tau \sim 0.003$

Br
MSSM: $\lesssim O(10^{-4})$

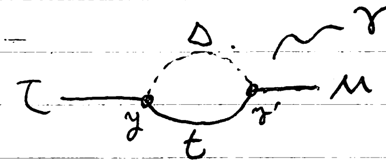
Models for $Y \sim 0.003$ ($\Gamma(H\to\tau\mu) \sim 1\% = 0.04\,\mathrm{MeV}$)

- scalar leptoquark ... loop-level
- vector-like lepton ... tree
- Type III 2HDM ... 〃

∘ lepto quark Δ (scalar) ... $(\Delta \bar{t} \mu)$ & $(\Delta \bar{t} \tau)$



but induces $\tau \to \mu\gamma$: EXCLUDED



$< 4.4\mathrm{e}{-8} = 2.3\times10^{-6}\,\mathrm{MeV} \times 4.4\mathrm{e}{-8}$
$= 1.0\times10^{-13}\,\mathrm{MeV}$

$\Gamma(H\to\tau\mu)$-upper bound $\sim 1.0\times10^{-13}\,\mathrm{MeV} \times \dfrac{m_H}{m_\tau} = 7.6\times10^{-11}\,\mathrm{MeV}$

$\Rightarrow O(10^{+9})$ stricter

($|y\cdot y'| \sim O(10^4)$ stricter)

$\Rightarrow$ loop-induced process is difficult

... Introduce VL top to fine-tunedly cancel $\tau \to \mu\gamma$
No Refs found

Sho Iwamoto

No. Date

1312.5329 Falkowski Straub Vicente

- VL - leptons

$$\begin{pmatrix} SM & & VLL \\ l, \bar{e} & \oplus & L_L, L_R, E_L, E_R \end{pmatrix} \times 3 \text{ gens}$$

$$-\mathcal{L} \supset M L \bar{L} + M' E \bar{E} + \left(Y L_L H \bar{E}_R + Y' L_R H \bar{E}_L + h.c. \right)$$

$$+ M \left(l_L \lambda_l L_R + \bar{E}_L \lambda_e e_R \right)$$

l, e gets mass only from this mixing (No higgs coupling ..by sym?)

h

$\bar{e}_L \quad L_R \quad \bar{L}_L \quad E_R \quad \bar{E}_L \quad e_R$

mix $\quad M \quad Y \quad M \quad$ mix

.. "Y_1" v

$h \quad h \quad h$

$\bar{e}_L \quad L_R \quad \bar{L}_L \quad E_R \quad \bar{E}_L \quad L_R \quad \bar{L}_L \quad E_R \quad \bar{E}_L \quad e_R$

mix $\quad M \quad M \quad M \quad M \quad$ mix

... "Y_2" $\dfrac{v^3}{M^2}$

$$\Rightarrow \mathcal{L} \supset v \left(Y_1 + \frac{v^2}{M^2} Y_2 \right) l e$$

$$+ \left(Y_1 + \frac{3v^2}{M^2} Y_2 \right) l e h \Big)$$

-- Ruled out for $\tau \to \mu \gamma$

1409.7690 Sierra Vicente

- 2HDM-type 3

Allowing all Yukawa: $H_1 L \bar{E} + H_2 L \bar{E}$
$+ H_1 L \bar{N} + H_2 L \bar{N}$ $\to \mathcal{L}e$

~~1408.0138~~

1408.1371 — Deny, Efrati, Nir, Soreq, Susič

∘ MFV (higher-dimensional) … too small.

1408.1652 — Campos, Hernández, Päs, Schumacher

S_4-flavor symmetry

~~1409.4439~~

1410.6803 — lepton-flavored DM MFV : $SU(3)_L \times SU(3)_{\bar{E}} \times SU(3)_{\bar{N}}$ - sym,

DM = (3, 1, 1) - SM singlet scalar

$$\mathcal{L} \supset |\partial S|^2 + \cdots + H^\dagger H \underbrace{\tilde{S}^\dagger \tilde{S}}_{\text{flavor structure}}$$

but to obtain 1%-Br, coupling must be $\underset{\sim}{2-\eta}$ [MFV motivated]

L	(e_R, μ_R)	τ_R	ϕ	η
3′	2	1	3′	1′

$$\Rightarrow \mathcal{L} \supset \phi L \bar{E}_R + \phi L \bar{\tau}_R + \frac{\phi L E_R \eta + \cancel{\phi L \tau_R \eta}}{\Lambda}$$

$\Rightarrow$ FlV structure

[IF $\phi^0_{a,b}$ degenerated w. ϕ^0_c, 0.89% is obtained.]

∘ LFV only w. $\tau^\pm \to \mu^\pm \mu^\pm e^\mp$

S_4:

	1	1′	2	3	3′
e	1	1	2	3	3
(1,2)	1	−1	0	1	−1
(1,2,3)	1	1	−1	0	0
(1,2,3,4)	1	−1	0	−1	1
(1,2)(3,4)	1	1	2	−1	−1

S_3: 1, 1′, 2 ;

$1' \otimes 1' = 1$

$1' \otimes 2 = 2$

$2 \otimes 2 = 1 + 1' + 2$

$$\begin{pmatrix} 1 & 1 & 2 \\ 1 & -1 & 0 \\ 1 & 1 & -1 \end{pmatrix}$$

S_4: 1, 1′, 2, 3, 3′

$1' \otimes 1' = 1$ $\quad 2 \otimes 2 = 1 + 1' + 2$

$1' \otimes 2 = 2$ $\quad 2 \otimes 3 = 2 \otimes 3' = 3 \oplus 3'$

$1' \otimes 3 = 3'$ $\quad 3 \otimes 3 = 3' \otimes 3' = 1 + 2 + 3 + 3'$

$1' \otimes 3' = 3$ $\quad 3 \otimes 3' = 1' + 2 + 3 + 3'$

∘ MFV, FN -- $h \to \tau\mu$ relates to $\mu \to e\gamma$

$\Uparrow$ must be broken

↳ ∘ MFV : ν - seesaw

∘ FN : use holomorphic zero which can arise in MSSM to suppress $Y_{e\mu}$ compared to $Y_{\mu\tau}$

- Collinear mass
  - τ-decay products in the same direction ✓
  - $\not{E}_T$ comes from ν and $\bar{\nu}$. (✓)

In $H \to \tau\tau$.

$$\begin{cases} P_{\tau^\pm} = (1+\alpha_\pm) P_{v^\pm} \\ \not{E}_T = \alpha_+ P_{Tv^+} + \alpha_- P_{Tv^-} \end{cases}$$

$$\therefore \alpha_+ = \frac{\| \not{E}_T \times P_{Tv^-} \|}{\| P_{Tv^+} \times P_{Tv^-} \|}$$

$\Rightarrow$ BAD if $P_{T\tau^+} \parallel P_{T\tau^-}$

In $H \to \mu\tau$, $\| p_T^{\tau\text{-mis}} \| \simeq \not{E}_T \cdot \hat{p}_T^{\tau\text{-vis}}$

$$p^\tau = p^{\tau\text{-vis}} + p^{\tau\text{-mis}} = p^{\tau\text{-vis}} \left(1 + \frac{\| p_T^{\tau\text{-mis}} \|}{\| p_T^{\tau\text{-vis}} \|} \right)$$

$$\therefore p^\mu(\tau) \simeq \begin{pmatrix} \| p^\tau \| \\ p^\tau \end{pmatrix}, \quad P(H) \simeq \begin{pmatrix} \| p^\tau \| + \| p^\mu \| \\ p^\tau + p^\mu \end{pmatrix}$$

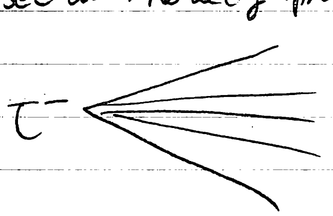
$\tau^\pm \to \pi^+ \nu_\mu$: 100% ($\gtrsim 7$m)

$\pi \to 2\gamma$: 99%

10^{-10} sec

- HPS τ-id. [1109.6034]

"to see all the decay products"



$\in \underbrace{\pi^\pm, K^\pm}_{\text{stable}}$, $\pi^0 \to \gamma\gamma$ (99%. 10^{-10} sec) $\otimes$ $\gamma \to e^+e^-$

- find most energetic e or γ ... strip seed
- find most energetic e or γ near the strip and merge (recalc. strip) ...

recursive until $(\Delta\phi, \Delta\eta) = (0.2, 0.05)$.

$\tau^- \to h^- \nu_\tau$: 11.6%
$h^- \pi^0 \nu_\tau$: 26.0%
$h^- \pi^0 \pi^0 \nu_\tau$: 9.5%
$h^+ h^- h^- \nu_\tau$: 9.8%
$h^+ h^- h^- \pi^0 \nu_\tau$: 4.8%

61.7%

rest ~3%

65%

No. B

Date

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- $\tau^- \to h^- \nu$ ← 1h
- $\tau^- \to h^- \pi^0 \nu$ ← 1h + 1s
- $\tau^- \to h^- \pi^0 \pi^0 \nu$ ← 1h + 2s
- $\tau^- \to h^- h^+ h^+ \nu$ ← 3h
- $\tau^- \to h^- h^+ h^+ \pi^0 \nu$

- reconstructed jet is id. as τ if
  - the reco momentum p^{had} is $\Delta R < 0.1$ from original PF jet
  - mass in resonance (50-200 MeV for π^0, 0.3-1.3 GeV for ρ, 0.8-1.5 GeV for a')
  - isolated - $\Delta R < 0.5$

	ε	mis
loose	~ 0.5	$\sim 1\%$
med	~ 0.4	$\sim 0.01\%$
tight	~ 0.25	$\sim 10^{-6}$

(faster better)

CMS Search for $H \to \mu\tau$

Sho Iwamoto*

3 Nov. 2014

A good presentation slides can be found in `https://particles.golem.ph.utexas.edu/forum/forums/lhc-leptons-x/topics/discussion-session-102914`[*1]

Experiments

- CMS conf-note of $h \to \mu\tau$ [1]
- CMS τ-id (HPS) [2]

Constraints

- Refs. [3, 4]

BSM Models (1)

- Leptoquark discussed in the above presentation
  - no refs found for leptoquark model with fine-tune suppression of $\tau \to \mu\gamma$
- Vector-like lepton [5]
- Type-III 2HDM [6]

BSM Models (2)

- Minimal flavor violation (MFV) or Froggatt–Nielsen (FN) [7]
- S_4 flavor symmetry with separated $(e_{\mathrm{R}}, \mu_{\mathrm{R}})$–$(\tau_{\mathrm{R}})$ [8]
- Lepton-flavored DM with MFV [9]

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*1 Direct link: `https://utexas.app.box.com/s/jxw5uogaj0d4fv3gc5ru`

References

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