Charged lepton flavour violation/lepton number violation searches and studies with the CMS experiment

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on behalf of theCMS Collaboration

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Overview

Motivation

- Observation of lepton flavour violation in neutrino sector:
  - Search for lepton flavour violation in the charged leptons
  - Highly suppressed in the Standard Model
  - → Striking signature for new physics

- New beyond the Standard Model (BSM) particles might decay lepton flavour violating
  - Little standard model background
Motivation

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Approach

- Search for resonances decaying with lepton flavour violation
  - Z boson ($\rightarrow e\mu$)
  - H boson ($\rightarrow e\tau$ or $\mu\tau$)
  - BSM particles ($\rightarrow e\mu$)

- $Z$ boson ($91 \text{ GeV}$)
- H boson ($125 \text{ GeV}$)
- BSM particles ($\text{few } 100 \text{ GeV - multi TeV}$)
Presented analysis

- Medium and heavy mass resonances decaying with lepton flavour violation
- Personal selection of presented analysis

Some other CMS LFV analyses

- Search for lepton flavour violating decays of the Higgs boson to $e\tau$ and $e\mu$ in proton-proton collisions at $\sqrt{s} = 8$ TeV PLB 763C (2016) 472
- Search for heavy Majorana neutrinos in $e^\pm e^\pm$ plus jets and $e^\pm \mu^\pm$ plus jets events in proton-proton collisions at $\sqrt{s} = 8$ TeV 1603.02248
- Search for displaced leptons in the $e - \mu$ channel EXO-16-022
- Search for R-parity violating supersymmetry with displaced vertices 1610.05133
- Search for R-parity violating supersymmetry in dilepton channels SUS-14-018
Outline

1. Introduction
   - Overview
   - LHC & CMS

2. Z-Boson

3. Higgs-Boson

4. BSM particle

5. Summary

\[ M = 1.9 \text{ TeV} \]
Key figures
Key figures

- $\sqrt{s} = 13$ TeV
**Key figures**

- $\sqrt{s} = 13 \text{ TeV}$
- $\mathcal{L} = 1.53 \cdot 10^{34} \text{s}^{-1} \text{cm}^{-2}$
High rate
(HL) Trigger rate up to 1 kHz
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High resolution
e.g. muon $p_T$
resolution $< 8\%$ at $p_T = 1 \text{ TeV}$
**High rate**  
(HL) Trigger rate up to 1 kHz

**High resolution**  
e.g. muon $p_T$  
resolution $< 8\%$ at  
$p_T = 1$ TeV

**High efficiency**  
e.g. Hadronically decaying tau  
reconstruction and identification  
efficiency: $> 55\%$ for  
$p_T > 30$ GeV
Very successful data taking over many years

- LFV Z decays: 2012, 8 TeV
- LFV BSM particle decays: 2015, 13 TeV
- LFV H decays: 2016, 13 TeV
Outline

1. Introduction
2. Z-Boson
   - Introduction
   - Result
3. Higgs-Boson
4. BSM particle
5. Summary

\[ M_{e\mu} = 1.9 \text{ TeV} \]
Motivation

- $Z \to e\mu$ suppressed in the SM ($\text{BR} < 4 \cdot 10^{-60}$)
- Clear signature for new physics ($\mu^+e^- \text{ or } \mu^-e^+$)
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Analysis key points

- 2012 data set of up to $19.7 \text{ fb}^{-1}$ of proton-proton data at $\sqrt{s} = 8 \text{ TeV}$
- Search for $Z$ mass resonance
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Event selection
- Trigger: electron + muon ($E_T > 17 \text{ GeV}$ and $E_T > 8 \text{ GeV}$)
- Particle flow identification/isolation criteria for electron / muon
- Veto other leptons, high $p_T$ Jets, $m_T(\mu, E_T^{\text{miss}}) < 60 \text{ GeV}$, $p_T^{e\mu} < 10 \text{ GeV}$
- Selection efficiency: 6.6%
Result

![Graph showing data and backgrounds.](image)

**Events / 3.00**

- **Data**
- **Bkg uncertainty**
- **Signal, B(Z → eμ) = 1 x 10^{-6}**
- **Z → ττ**
- **tt, tW, TW**
- **Diboson, Z → ee/μμ**
- **Misidentified leptons**

**CMS Preliminary**

19.7 fb^{-1} (8 TeV)

**Data/Bkg.**

- 0.5
- 1
- 1.5

**m_{eμ} (GeV)**

- 80
- 85
- 90
- 95
- 100

- **Misidentified leptons** (8 TeV)

- 19.7 fb

**CMS Preliminary**
Systematic uncertainties

Effect on background (signal) > 1%

- Luminosity: 2.6%
- Pileup: 3.3% (0.8%)
- $\mu$ p_T scale: 2.9% (0.2%)
- e E_T scale: 3.1% (1.1%)
- E_T^{miss}: 0.6% (2.2%)
- e\mu p_T: 0.4% (1.1%)
- PDF: 1.0% (1.0%)
- N(MC events): 10.6% (1.2%)
- Normalisation: 6.8% (3.3%)
Result

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87 (obs.), 83 ± 9 (SM exp.) events in signal region
(88 − 94 GeV)

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\[ \mathcal{B}(Z \rightarrow e\mu) < (6.7^{+2.8}_{-2.0}) \cdot 10^{-7} \]

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**Result**

**Expected limit**

\[ \mathcal{B}(Z \rightarrow e\mu) < \left(6.7^{+2.8}_{-2.0}\right) \cdot 10^{-7} \]

**Observed limit**

\[ \mathcal{B}(Z \rightarrow e\mu) < 7.3 \cdot 10^{-7} \]

**Systematic uncertainties**

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\[ M_{\text{e\mu}} = 1.9 \text{ TeV} \]
Introduction

Basic idea

- Lepton flavour violating Higgs decay
- Two studied decays ($H \rightarrow e\tau / H \rightarrow \mu\tau$)
- Four final states ($\mu\tau_h$, $\mu\tau_e$, $e\tau_h$ and $e\tau_\mu$)
Basic idea

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Analysis key points

- 2016 data set of $35.9\, fb^{-1}$ of proton-proton data at $\sqrt{s} = 13\, TeV$
- Two analysis methods: boosted decision tree (BDT) and cut based (as cross check)
- Derive limit on BR and Yukawa couplings
Introduction

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Event selection

- Isolated lepton triggers ($e$ or $\mu$)
- Split analysis in production channels ($n_{Jet}$ and/or $M_{jj}$)
Processes with prompt leptons (e.g. $t\bar{t}$, Diboson and $H \rightarrow \tau\tau$)

- Estimated from Monte Carlo simulation
- Corrected for known mis-modelling effects

Contribution from misidentified leptons

- Estimated from collision data with inverted isolation
Result for $\mu\tau$

**Cut based analysis**

- $p_T^\mu > 26$ GeV and $|\eta^\mu| < 2.4$
- $p_T^{\tau_h} > 30$ GeV and $|\eta^{\tau_h}| < 2.3$
- Cut on $M_T (\tau_h)$
Result for $\mu\tau$

**Cut based analysis**
- $p_T^\mu > 26$ GeV and $|\eta^\mu| < 2.4$
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**BDT analysis**
- Input variables:
  - $p_T^\mu$, $p_T^{\tau_e}$, $M_{Col}$, $E_T^{miss}$, $M_T(\tau_e)$, $\Delta\eta(\mu,\tau_e)$, $\Delta\phi(p_T^\mu,p_T^{\tau_e})$ and $\Delta\phi(p_T^{\tau_e}, E_T^{miss})$
Result for $\ell\tau$

**Cut based analysis**

- $p_T^\ell > 26$ GeV and $|\eta^\ell| < 2.1$
- $p_T^\tau > 30$ GeV and $|\eta^\tau| < 2.3$
- Cut on $M_T(\tau_h) < 60$ GeV
Result for $e\tau$

**Cut based analysis**
- $p_T^e > 26$ GeV and $|\eta^e| < 2.1$
- $p_T^{\tau_h} > 30$ GeV and $|\eta^{\tau_h}| < 2.3$
- Cut on $M_T (\tau_h) < 60$ GeV

**BDT analysis**
- Input variables:
  - $p_T^e$, $p_T^{\tau_\mu}$, $M_{Col}$, $E_{miss}^T$, $M_T (\tau_\mu)$, $\Delta\eta (e, \tau_\mu)$, $\Delta\phi (p_T^e, p_T^{\tau_\mu})$, $M_{vis}$ and $\Delta\phi (p_T^{\tau_\mu}, E_{miss}^T)$
Interpretation for $\mu \tau$

### Limits
- Observed and expected limit on $\mathcal{B}(H \rightarrow \mu \tau)$

---

**Graph:**
- **$\mu_{\text{had}}$:**
  - 0 Jets: 0.51% (0.43%)
  - 1 Jet: 0.53% (0.56%)
  - 2 Jets: 0.56% (0.94%)
  - VBF: 0.51% (0.58%)
- **$\mu_{\text{VBF}}$:**
  - 0 Jets: 1.30% (0.83%)
  - 1 Jet: 1.34% (1.19%)
  - 2 Jets: 2.27% (1.98%)
  - VBF: 1.97% (1.62%)
- **$H \rightarrow \mu \tau$:**
  - 0.25% (0.25%)

**Observed and expected limit on $\mathcal{B}(H \rightarrow \mu \tau)$**
- $35.9 \text{ fb}^{-1}$ (13 TeV)
- **CMS Preliminary**

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**Table:**

<table>
<thead>
<tr>
<th>Process</th>
<th>Observed</th>
<th>Median expected</th>
<th>68% expected</th>
<th>95% expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\text{had}}$: 0 Jets</td>
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### Interpretation for $\mu\tau$

**Limits**
- Observed and expected limit on $\mathcal{B}(H \rightarrow \mu\tau)$

**Reinterpretation**
- Treat as LFV Yukawa coupling $Y_{\mu\tau}$
- Limit:
  \[
  \sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \cdot 10^{-3}
  \]

**Observed and expected limit on $\mathcal{B}(H \rightarrow \mu\tau)$, %**

### CMS Preliminary

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<tr>
<th>Channel</th>
<th>Expected 68%</th>
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- **CMS 8TeV**
- CMS Preliminary
- **35.9 fb$^{-1}$ (13 TeV)**
Interpretation for $e\tau$

**Limits**

- Observed and expected limit on $\mathcal{B}(H \rightarrow e\tau)$
Interpretation for $e\tau$

**Reinterpretation**

- Treat as LFV Yukawa coupling $Y_{e\tau}$
- Limit:
  \[ \sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \times 10^{-3} \]

**Limits**

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Outline

1. Introduction
2. Z-Boson
3. Higgs-Boson
4. BSM particle
   - Introduction
   - Result
   - RPV SUSY
   - QBH
5. Summary

\[ M_{e\mu} = 1.9 \text{ TeV} \]
Introduction

Motivation

- R-parity violating SUSY model (RPV $\tilde{\nu}_\tau$)
- Quantum black holes (QBH)
- Decay to high mass $e\mu$ pairs
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Analysis key points
- 2015 data set of $2.7\text{ fb}^{-1}$ of proton-proton data at $\sqrt{s} = 13\text{ TeV}$
- Search for high mass resonances
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Event selection

- Dedicated high $E_T/p_T$ identification criteria for electrons/muons
- Final selection efficiency at $M_{\tilde{\nu}_\tau} = 1 \text{ TeV}$: $\sim 65\%$ (similar for QBH)
Mass distribution

Number of events
- Expected: 10379 ± 1557
- Observed: 9608
Mass distribution

Systematic uncertainties
- Luminosity: 2.7%
- Normalisation: 5%
- $\mu$ $p_T$ scale: ~ 10%
- Top background shape: ~ 20%
- Total uncertainty:
  - 15% at 200 GeV
  - 31% at 2 TeV

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Introduction RPV

- R-parity violating supersymmetry (RPV SUSY) model
- Resonant sparticle production is allowed
  - Assume $\tilde{\nu}_\tau$ to be the LSP
  - Assume two dominant couplings $\lambda'_{311}$ (production) and $\lambda_{132}$ (decay)

- $e\mu$ resonance with narrow width

$$\Gamma_{\text{tot}} = \left(3\lambda'_{311}^2 + 2\lambda_{132}^2\right) \mathcal{M}(\tilde{\nu}_\tau)/16\pi$$

- Three model parameters: $\lambda'_{311}$, $\lambda_{132}$ and $\mathcal{M}(\tilde{\nu}_\tau)$
**Exclusion limits**

- Excluded cross section $\times$ BR
- Mass limit for $\lambda = 0.01$ of 1.0 TeV
RPV Result

Exclusion limits

- Excluded cross section \( \times \) BR
- Mass limit for \( \lambda = 0.01 \) of 1.0 TeV
- Limit also in the \( M_{\tilde{\nu}_\tau} - \lambda_{311} \)-plane
Quantum black holes (QBH):
- Can be produced in low scale gravity scenarios at the LHC
- Planck scale smaller than a few TeV
- No Hawking radiation (many particle final state)
- Decay into $e + \mu$

Spin-0, colorless, neutral QBH

Model parameters:
- Threshold mass: $M_{th}$
- Number of extra dimensions: $n$
- Extra dimension model: Randall-Sundrum (RS) or Arkani-Hamed-Dimopoulos-Dvali (ADD)

Signal shape:
- Threshold of QBH production
- Signal falls for high mass due to PDFs
QBH Result

Exclusion limits
- Excluded cross section $\times$ BR
- Mass threshold limit for $n = 1$ ($n = 6$) of 2.5 TeV (4.5 TeV)
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\[ M_{e\mu} = 1.9 \text{ TeV} \]
**Summary**

**Z Boson (CMS PAS-EXO-13-005)**
- Search for $Z \rightarrow e\mu$ decays
- Limit on the branching ratio $\mathcal{B}(Z \rightarrow e\mu) < 7.3 \cdot 10^{-7}$

**H Boson (CMS PAS-HIG-17-001)**
- Search for $H \rightarrow e\tau$ and $H \rightarrow \mu\tau$ decays
- Limit on $\mathcal{B}(H \rightarrow e\tau/\mu\tau)$ of $< 0.61 \%$ / $< 0.25 \%$
- Limit on LFV Yukawa coupling
  - $\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.26 \cdot 10^{-3}$
  - $\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 1.43 \cdot 10^{-3}$

**BSM particles (CMS PAS-EXO-16-001)**
- Search for new high mass particles decaying to $e\mu$
- Limit on RPV: $M_{\tilde{\nu}_\tau} > 1.0$ TeV for $\lambda = 0.01$
- Limit on QBH: $M_{\text{th}} > 4.5$ TeV for $n = 6$

All CMS physics results can be found at [link](#).
Backup
Search for Lepton Flavor Violation in Z decays in pp collisions at sqrt(s)=8 TeV.

Search for lepton flavour violating decays of the Higgs boson to μτ and eτ in proton-proton collisions at \( \sqrt{s} = 13 \) TeV.

Search for high-mass resonances and quantum black holes in the eμ final state in proton-proton collisions at \( \sqrt{s} = 13 \) TeV.
Eventdisplay $r - z$ view
 Tau ID performance

CMS Simulation Preliminary

\[ p_T^{\tau_h} > 20 \text{ GeV}, \mid \eta_{\tau_h} \mid < 2.3 \]
13 TeV, 20 pileup at 25ns

Efficiency : Z' (2TeV) → \tau\tau MC
Fake rate : QCD multi-jet MC (20 < p_T < 1000 GeV)

- Cut-based
- MVA-based

Mis-ID probability vs \( \tau_h \) identification efficiency
Peak luminosity (2016)

CMS Peak Luminosity Per Day, pp, 2016, $\sqrt{s} = 13$ TeV

Data included from 2016-04-22 22:48 to 2016-10-27 14:12 UTC

Max. inst. lumi.: 15.30 Hz/nb

Date (UTC)

Peak Delivered Luminosity (Hz/nb)
$Z \rightarrow e\mu \text{ jet } p_T$
Datadriven background estimate

Define regions: Signal (I), background enriched (III) and control (II and IV)

<table>
<thead>
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<th>Region II</th>
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<tr>
<td>$\ell_2^\mp$ (non-isolated)</td>
<td>$\ell_2^\pm$ (non-isolated)</td>
</tr>
</tbody>
</table>

Misidentification rate defined as (with $i = e, \mu, \tau$):

$$f_i = \frac{N_i (\text{region I})}{N_i (\text{region III}) + N_i (\text{region I})}$$

Number of misidentified events in the signal region:

$$N_i (\text{misidentified}) = \frac{f_i}{1 - f_i} N_i (\text{region III})$$
μτ_h channel, 0 Jets

Cut based analysis

BDT analysis

2016, 35.9 fb^{-1} (13 TeV)

CMS Preliminary

μτ_h, 0 jet

Observed

Z→ττ

Z→ee/μμ

tt, t+jets

Diboson

Reducible

SM H→ττ

H→μτ (B=5%)

Bkg. unc.

Obs./Exp.

0.5

1

1.5

Collinear Mass [GeV]

BDT discriminator

0

0.2

0.4

0.6

0.8

1

BDT analysis
Cut based analysis

BDT analysis

\( \mu \tau_e \) channel, 0 Jets

Cut-based analysis

BDT analysis
µτₑ channel, 1 Jets

Cut based analysis

BDT analysis
Cut based analysis

BDT analysis

CMS Preliminary
μτ, 2 jets gg-enriched

2016, 35.9 fb⁻¹ (13 TeV)

Collinear Mass [GeV]

Events/bin

Obs./Exp.

0 0.5 1 1.5

0 100 200 300

Z→ττ
Z→ee/µµ
t¯t+jets
Diboson
Reducible
SM H→ττ
H→µτ (B=5%)

Bkg. unc.

BDT discriminator

0.4
−0.2
0
0.2

Obs./Exp.

0.5 1 1.5

0

−0.4 −0.2 0 0.2

BDT discriminator

CMS Preliminary
μτ, 2 jets gg-enriched

2016, 35.9 fb⁻¹ (13 TeV)

Observed
Z→ττ
Z→ee/µµ
t¯t+jets
Diboson
Reducible
SM H→ττ
H→µτ (B=5%)

Bkg. unc.

τ
τ→Z
Z→µµ/ee
µ
SM H→ττ
(B=5%)

τµ→HUnc.

(13 TeV)

2016, 35.9 fb⁻¹ CMS Preliminary, 2 jets gg-enriched
Cut based analysis

BDT analysis

\(\mu \tau_e\) channel, 2 Jets (gg)
**μτ_h channel, 2 Jets (VBF)**

Cut based analysis

BDT analysis
$\mu\tau_e$ channel, 2 Jets (VBF)

Cut based analysis

BDT analysis

[Graphs showing distributions of observed and expected events for different mass bins and BDT discriminator values, labeled as CMS Preliminary, 2016, 35.9 fb$^{-1}$ (13 TeV)].
μτ results

Cut based analysis

BDT analysis
**eτh channel, 0 Jets**

**Cut based analysis**

**BDT analysis**

---

**Histograms and Graphs**

- **Collinear Mass [GeV]**
  - Observed vs. Expected
  - Events/bin
  - 2016, 35.9 fb\(^{-1}\) (13 TeV)

- **BDT discriminator**
  - 0.6
  - -0.4
  - -0.2
  - 0
  - 0.2
  - Observed vs. Expected

---

**Legend**

- **Events/bin**
  - 0
  - 5000
  - 10000
  - 15000
  - 20000
  - 25000
  - 30000

- **Collinear Mass [GeV]**
  - 0
  - 100
  - 200
  - 300

- **BDT discriminator**
  - 0.6
  - -0.4
  - -0.2
  - 0
  - 0.2

---

**Graph Details**

- **Labels**
  - Observed
  - Z→ττ
  - Z→ee/µµ
  - tt, t+jets
  - Diboson
  - Reducible
  - SM H→ττ
  - H→eτ (B=5%)
  - Bkg. unc.
$e\tau_\mu$ channel, 0 Jets

Cut based analysis

BDT analysis
eτh channel, 1 Jets

Cut based analysis

BDT analysis
Cut based analysis

BDT analysis

CMS Preliminary

$e\tau_\mu$, 1 jet

2016, 35.9 fb$^{-1}$ (13 TeV)

Obs./Exp. 0.5 1 1.5

Events/bin 0 2000 4000 6000 8000 10000 12000

Observed

$Z\rightarrow\tau\tau$

$Z\rightarrow ee/\mu\mu$

$tt$, $t\bar{t}$+jets

Diboson

Reducible

SM $H\rightarrow\tau\tau$, WW

$H\rightarrow e\tau$ (B=5%)

Bkg. unc.

Collinear Mass [GeV]

BDT discriminator

0.6

−0.4

−0.2

0

0.2

1

1.5

0

0.5

−0.6

−0.4

−0.2

0

0.2

Bkg. unc.
**e\(\tau_h\) channel, 2 Jets (gg)**

**Cut based analysis**

**BDT analysis**
eτμ channel, 2 Jets (gg)

Cut based analysis

BDT analysis
$e\tau_h$ channel, 2 Jets (VBF)

Cut based analysis

BDT analysis

2016, 35.9 fb$^{-1}$ (13 TeV)

2016, 35.9 fb$^{-1}$ (13 TeV)
**e\(\tau\mu\) channel, 2 Jets (VBF)**

*Cut based analysis*

*BDT analysis*
eτ results

Cut based analysis

![Cut based analysis graph]

BDT analysis

![BDT analysis graph]

h→eτ: Mass Fit
- Observed
- Median expected

68% expected
95% expected

h→eτ: BDT Fit
- Observed
- Median expected

68% expected
95% expected
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>H → μτ(_e)</th>
<th>H → μτ(_h)</th>
<th>H → eτ(_μ)</th>
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<td>Electron trigger/ID/isolation</td>
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<td>Hadronic τ efficiency</td>
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<td>Z → ττ +jets background</td>
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<td>10%±5%</td>
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<td>W + jets background</td>
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<td>WW, ZZ background</td>
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<tr>
<td>tt background</td>
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<td>(μ \rightarrow τ_h) background</td>
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<td>Bin-by-bin</td>
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<td>2.5%</td>
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<td>Pile-up</td>
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</tbody>
</table>
BDT input for $H \rightarrow \mu \tau_h$
BDT input for $H \rightarrow \mu \tau_e$
BDT input for $H \rightarrow e\tau_h$
BDT input for $H \rightarrow e\tau_\mu$
Comparison to other analysis

- **CMS 8 TeV (19.7 fb⁻¹):** PLB 749 (2015) 337
- **CMS 13 TeV (2015, 2.3 fb⁻¹):** HIG-16-005
- **CMS 13 TeV (2016, 35.9 fb⁻¹):** HIG-17-001

- **ATLAS 8 TeV (20.3 fb⁻¹):** EPJC 77 (2017) 70

**Best Fit to B(H → μτ), %**

- CMS: 0.84 ±0.39 % (-0.37)
- ATLAS: -0.76 ±0.81 % (-0.84)

**95% CL Limit on Br(H → μτ), %**

- CMS: <1.20 (1.62) %
- ATLAS: <1.51 (0.75) %