A precision measurement of the W boson decay branching fractions in pp collisions at $\sqrt{s} = 13$ TeV

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Outline

1. Introduction
   - Theoretical Motivation
   - Experimental Setup
2. Analysis
   - Event Selection
   - Event Reconstruction
   - Systematic Uncertainties
3. Results
4. Conclusions

Introduction

Theoretical Motivation I

- Standard Model (SM) $\Longrightarrow$ Lepton Universality (LU);
- Rare semileptonic B decays $\Longrightarrow$ hints of LU violation;
- W branching fractions $\Longrightarrow$ clean test of LU.

- LEP $\Longrightarrow R_{\tau/l} = 1.066 \pm 0.025$ has 2.6 standard deviations from

$$R_{\tau/l} = \frac{2\mathcal{B}(W \to \tau\bar{\nu}_\tau)}{\mathcal{B}(W \to e\bar{\nu}_e) + \mathcal{B}(W \to \mu\bar{\nu}_\mu)} = 0.9991 \tag{1}$$

- ATLAS $\Longrightarrow R_{\tau/\mu} = 0.992 \pm 0.013$ in tension with LEP, supports LU.

Introduction

Theoretical Motivation II

- $W \to h$ branching fraction $\Longrightarrow$ high order in perturbation theory;
- Measure $\mathcal{B}(W \to h)$ $\Longrightarrow$ test unitarity in the first two rows of V;
- Measure $\sum_{u,c,d,s,b} |V_{ij}|^2$ $\Longrightarrow$ determine $|V_{cs}|$ indirectly.

$$\Gamma_{W\to h} = \frac{G_F m_W^3}{2\sqrt{2}\pi} \sum_{i,j} \left|V_{ij}\right|^2 \left[1 + \sum_{i=1}^{4} c_{QCD}^{(i)} \left(\frac{\alpha_S}{\pi}\right)^i + \delta_{EW}(\alpha) + \delta_{mix}(\alpha\alpha_S)\right] \quad (2)$$

Introduction

Experimental Setup

- Data sample of *pp* collisions;
- Center-of-mass (COM) energy of 13 TeV;
- Integrated luminosity of $L_{int} = 35.9\ \mathrm{fb}^{-1}$;
- Recorded during the 2016 run.

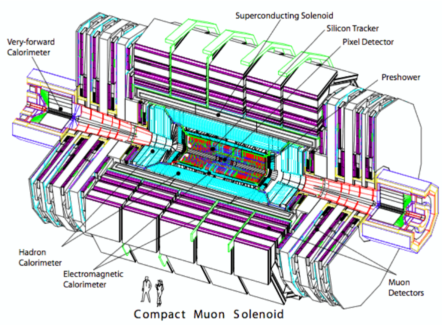

Figure: Standard CMS detector picture.

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Analysis

Event Selection

- Signal processes $\Longrightarrow$ $\mathbf{t\bar{t}}$, tW, WW, $W+$jets;
- Background processes $\Longrightarrow$ $Z+$jets, WZ, ZZ.

state	momentum	N_{jet}	$N_{jet,b}$
ee	$p_T^e > 30\text{-}20\ \mathrm{GeV},\ \Upsilon_e > 15\ \mathrm{GeV}$	≥ 2	≥ 1
$e\mu$	$p_T^e > 30\ \mathrm{GeV},\ p_T^\mu > 10\ \mathrm{GeV}$	≥ 0	≥ 0
$e\tau$	$p_T^e > 30\ \mathrm{GeV},\ p_T^\tau > 20\ \mathrm{GeV}$	≥ 0	≥ 0
eh	$p_T^e > 30\ \mathrm{GeV},\ p_T^{jet} > 30\ \mathrm{GeV}$	≥ 4	≥ 1
μe	$p_T^\mu > 25\ \mathrm{GeV},\ p_T^e > 20\ \mathrm{GeV}$	≥ 0	≥ 0
$\mu\mu$	$p_T^\mu > 25\text{-}10\ \mathrm{GeV},\ \Upsilon_\mu > 15\ \mathrm{GeV}$	≥ 2	≥ 1
$\mu\tau$	$p_T^\mu > 25\ \mathrm{GeV},\ p_T^\tau > 20\ \mathrm{GeV}$	≥ 0	≥ 0
μh	$p_T^\mu > 25\ \mathrm{GeV},\ p_T^{jet} > 30\ \mathrm{GeV}$	≥ 4	≥ 1

Table: Event selection triggers, $\Upsilon_i = |m_{ii} - m_Z|$. Also, isolation criterias are used.

- Background contributions $\Longrightarrow$ simulate QCD, subtract from signal.

Analysis

Event Reconstruction I

- Particle-flow $\Longrightarrow$ follow each individual particle in *pp* collision:
  - $\gamma \rightarrow$ energy deposits in electromagnetic calorimeter not connected to charged particle trajectories from the tracker;
  - $e \rightarrow$ charged particle trajectories from tracker, plus connected energy deposit in electromagnetic calorimeter and bremsstrahlung-γ;
  - $\mu \rightarrow$ trajectories in the muon system, plus expected energy deposits in calorimeters;

Analysis

Event Reconstruction II

- Particle-flow $\Longrightarrow$ follow each individual particle in *pp* collision:
  - $h^+ \rightarrow$ charged particle trajectory not identified as e, μ;
  - $h^0 \rightarrow$ energy deposits in hadronic calorimeter not identified as h^+;
  - $\tau \rightarrow$ single or triple charged pion decays are assumed;
  - Jets $\rightarrow$ PF candidates clustered using the anti-k_T algorithm.

Analysis

Systematic Uncertainties

- Introduce nuisance parameters to acount for systematic uncertainties:
  - Integrated luminosity → scale each event with global factor;
  - QCD simulations and PDFs → renormalization and factorization scales;
  - Lepton reconstruction → p_T dependent nuisance parameters;
  - Jet reconstruction → energy scale and resolution;
  - Other sources include data-driven QCD background estimates and *b*-tag modelling.
- Propagate nuisance parameters to final results for assessing impact.

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Results

Results I

	LEP	CMS
$\mathcal{B}(W \to e\bar{\nu}_e)$	$(10.71 \pm 0.14 \pm 0.07)\%$	$(10.83 \pm 0.01 \pm 0.10)\%$
$\mathcal{B}(W \to \mu\bar{\nu}_\mu)$	$(10.63 \pm 0.13 \pm 0.07)\%$	$(10.94 \pm 0.01 \pm 0.08)\%$
$\mathcal{B}(W \to \tau\bar{\nu}_\mu)$	$(11.38 \pm 0.17 \pm 0.11)\%$	$(10.77 \pm 0.05 \pm 0.21)\%$

Table: Comparing LEP measurements with current results.

	LEP	CMS
$\mathcal{B}(W \to l\bar{\nu})$	$(10.86 \pm 0.06 \pm 0.09)\%$	$(10.89 \pm 0.01 \pm 0.08)\%$
$\mathcal{B}(W \to h)$	$(67.41 \pm 0.18 \pm 0.20)\%$	$(67.32 \pm 0.02 \pm 0.23)\%$

Table: Comparing LEP measurements with current results, assuming LU.

Results

Results II

- Evaluate $\mathcal{B}(W \to h) = 1 - \mathcal{B}(W \to l\bar{\nu})$:

$$\frac{\mathcal{B}(W \to h)}{1 - \mathcal{B}(W \to h)} = \left[1 + \frac{\alpha_S(m_W^2)}{\pi}\right] \sum_{j=d,s,b}^{i=u,c} |V_{ij}|^2 = 2.060 \pm 0.021 \qquad (3)$$

- CKM unitary $\Longrightarrow \alpha_S(m_W^2) = 0.094 \pm 0.033$;
- World-average $\alpha_S(m_W^2) \Longrightarrow \sum_{ij} |V_{ij}|^2 = 1.989 \pm 0.021$;
- World-average $\alpha_S(m_W^2) \Longrightarrow |V_{cs}| = 0.969 \pm 0.011$;

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Conclusions

- LU hypothesis is consistent with experimental data:
  - Unlike ATLAS, still consistent with LEP;
- Unitary CKM is consistent with experimental data:
  - $|V_{cs}|$ compatible with current world-average.

- W branching fractions remain cleanest test of LU $\Longrightarrow$ no violation;
- In the future, may become best method for determining $|V_{cs}|$.