W Boson Precision Measurements at CMS

Course on Physics at the LHC 2022

Guilherme Soares
gmachado@cern.ch

Laboratory of Instrumentation and Experimental Particle Physics

17 June 2022

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Introduction

Current W boson paradigm :

- There have been recent LHCB (2016) and ATLAS (2017) precision measurements on the W boson (low luminosity from Run 1)
- Branching Fraction given by combined fit from 4 LEP experiments (2004)
- Best single measurement has an error of $\pm 0.37_{\text{stat.}} \pm 0.15_{\text{syst.}}\%$ for hadronic branching fraction
- Most recent precision measurement comes from ATLAS using data from Run 2 ($R_{\tau/\mu}$)

Why are branching fraction studies important ?

- Several hints of departure from **Lepton Flavour Universality**
- W boson has fully leptonic decays
- Several SM constants can be derived from W boson branching ratios

$$\Gamma(W \to q\bar{q}) = \frac{\sqrt{2}G_F N_c}{12\pi} m_W^3 \sum_{i,j} |V_{ij}|^2$$

$$\left[1 + \sum_{k=1}^{4} c_{\text{QCD}}^{(i)} \left(\frac{\alpha_S}{\pi}\right)^k + \delta_{\text{EW}}(\alpha) + \delta_{\text{mix}}(\alpha\alpha_S)\right]$$

The CMS Detector and Particle Reconstruction

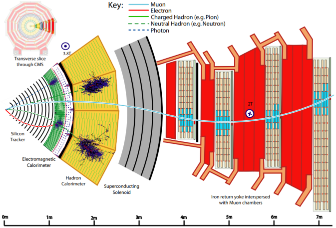
Detector :

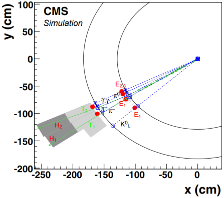
- Silicon Tracker (ST)
- Electric Calorimeter (ECal)
- Hadronic Calorimeter
- Superconducting Solenoid
- Muon Chambers (MC)

Particles are reconstructed according to an optimized **Particle Flow** algorithm

- Correlate tracks and clusters to identify final particles
- Charged Hadrons : geometrical connection between tracks and cal. clusters
- Photons and Neutral Hadrons : clusters with no track link
- Electrons : track and ECal provide a momentum to ratio energy 1
- Muons : tracks in ST connect to tracks in MC

By 2016, 2 years into Run 2 of the LHC the CMS detector had collected an integrated luminosity of 35.9 fb^{-1} of proton on proton collisions at a center-of-mass energy of 13 TeV.





Study Samples and Monte Carlo

Abridged goal : Accumulate as many events containing W bosons as possible.

Production of top quarks always creates a W boson through $t \rightarrow b + W$

$$\Downarrow$$

Signal includes most processes that produce top quarks or W bosons.

Signal :

- $t\bar{t}$ POWHEG v2 (NLO)
- tW POWHEG v2 (NLO)
- WW POWHEG v2 (NLO)
- W + jets MadGraph (LO)

Background :

- Z + jets MadGraph (LO)
- γ + jets MadGraph5_aMC@NLO (NLO)
- WZ POWHEG v2 (NLO) and MadGraph5_aMC@NLO (NLO)
- ZZ POWHEG v2 (NLO) and MadGraph5_aMC@NLO (NLO)

Monte Carlo engines used to simulate processes and their precision is stated after the sample

Multi-jet contribution is estimated using data samples

Pythia8 is used for parton distribution and hadronization, with propagation and detector interaction simulated with Geant4.

Pileup is simulated by superimposing pp events and re-weighting everything.

Event Selection

Triggers :

We want W bosons that decay into generic jets

$\Downarrow$

Cannot trigger on random jets
Always need to flag at least 1 charged lepton

Require detection of a single muon (electron) with $p_T > 24(27)$GeV and $|\eta| < 2.4(2.5)$

This is mainly for selection of t$\bar{\text{t}}$ events, since t $\rightarrow \ell^{\pm} + X$ necessitates the presence of a W boson

No b-tagging required since we also want to accept tW, WW and W + jets production, but is useful to distinguish from background

Selection Criteria :

- Electrons : $p_T > 10$ GeV, $|\eta| < 2.5$ and isolation criterion based on transverse momentum in a cone of $\Delta R = 0.4$, with $I_{\text{PF}}/p_T^e <\approx 6\%$
- Muons : Isolation criterion around $\Delta R = 0.4$ with $I_{\text{PF}}/p_T^{\mu} < 0.15$
- Hadronic Decaying Taus (τ_h) : Only decays to single or triple neutral pions are accepted, with $p_T > 20$ GeV and $|\eta| < 2.3$. Must not overlap with muons or electrons.
- Jets from PF candidates : $p_T > 30$ GeV and $|\eta|2.4$. Must not overlap with letons withing $\Delta R < 0.4$

, with $I_{\text{PF}} = I_{ch} + max(0, I_{neu} + I_{\gamma} - I_{pileup})$, where I_i is the transverse momentum for charmed hadrons, neutral hadrons, photons and a pileup contribution

Offline Event Selection and Categorization

Event categorization :

- Leptons
- Jets

Additionally, depending on their category, new selection criteria are applied.

Trigger	Label	N_e	N_μ	N_{τ_h}	N_j	N_b	Kinematic requirements	Target W boson branching fractions	Approx. num. of W decays
e	ee	2	0	0	≥2	≥1	$p_T^e > 30, 20\,\text{GeV}$, $\lvert m_{ee} - m_Z \rvert > 15\,\text{GeV}$	$W \to e\bar{\nu}_e, \tau\bar{\nu}_\tau$	1.1×10^5
	eμ	1	1	0	≥0	≥0	$p_T^e > 30\,\text{GeV}$, $p_T^\mu > 10\,\text{GeV}$	$W \to e\bar{\nu}_e, \mu\bar{\nu}_\mu, \tau\bar{\nu}_\tau$	4×10^5
	eτ_h	1	0	1	≥0	≥0	$p_T^e > 30\,\text{GeV}$, $p_T^{\tau_h} > 20\,\text{GeV}$	$W \to e\bar{\nu}_e, \tau\bar{\nu}_\tau$	8×10^4
	eh	1	0	0	≥4	≥1	$p_T^e > 30\,\text{GeV}$, $p_T^j > 30\,\text{GeV}$	$W \to e\bar{\nu}_e, q\bar{q}'$	1.4×10^6
μ	μe	1	1	0	≥0	≥0	$p_T^\mu > 25\,\text{GeV}$, $p_T^e > 20\,\text{GeV}$	$W \to e\bar{\nu}_e, \mu\bar{\nu}_\mu, \tau\bar{\nu}_\tau$	2×10^5
	$\mu\mu$	0	2	0	≥2	≥1	$p_T^\mu > 25, 10\,\text{GeV}$, $\lvert m_{\mu\mu} - m_Z \rvert > 15\,\text{GeV}$	$W \to \mu\bar{\nu}_\mu, \tau\bar{\nu}_\tau$	3×10^5
	$\mu\tau_h$	0	1	1	≥0	≥0	$p_T^\mu > 25\,\text{GeV}$, $p_T^{\tau_h} > 20\,\text{GeV}$	$W \to \mu\bar{\nu}_\mu, \tau\bar{\nu}_\tau$	1.3×10^5
	μh	0	1	0	≥4	≥1	$p_T^\mu > 25\,\text{GeV}$, $p_T^j > 30\,\text{GeV}$	$W \to \mu\bar{\nu}_\mu, q\bar{q}'$	2.1×10^6

Offline Event Selection and Categorization

Events with $\ell\tau_h$ and at least 1 b-tag are further subdivided.

2 jets exactly $\Rightarrow t\bar{t} \rightarrow W^- b\, W^+ \bar{b}$

3 jets or more $\Rightarrow$ Likely miss-identified τ_h from hadronic W decays
if $N_b \leq 1 \Rightarrow (40 \leq m_{\ell\tau_h} \leq 100$ GeV$), \ \Delta\phi(\ell, \tau_h) > 2.5$ and $m_T^\ell < 60$ GeV

	$N_j = 0$	$N_j = 1$	$N_j = 2$	$N_j = 3$	$N_j \geq 4$
$N_b = 0$	$e\tau_h, \mu\tau_h,$ $e\mu$	$e\tau_h, \mu\tau_h,$ $e\mu$	$e\tau_h, \mu\tau_h$ $e\mu$		
$N_b = 1$		$e\tau_h, \mu\tau_h,$ $e\mu$	$e\tau_h, \mu\tau_h$	$e\tau_h, \mu\tau_h$	
			$ee, \mu\mu, e\mu$		
					eh, μh
$N_b \geq 2$			$e\tau_h, \mu\tau_h$	$e\tau_h, \mu\tau_h$	
			$ee, \mu\mu, e\mu$		
					eh, μh

Background contributions are further estimated based on control regions where the presence of background events is enhanced (e.g. kinematically select τ_h samples so that we increase the expected miss-identified τ). Extrapolation of these background to regions of interest is done with a second control region, so that a transfer function can be determined.

Branching Fractions

Like in most studies, the results will be obtained through a **Maximum Likelihood Estimation** (MLE) approach.

Histogram templates from the signal and background estimates (MC and Control Samples) fit the data!!!

MLE fits require both a model that describes the data, as well as **estimations of the number of events for each given final state**.

A single W boson can be defined by the branching fraction vector $\beta' = \{\beta_e, \beta_\mu, \beta_\tau t_e, \beta_\tau t_\mu, \beta_\tau t_h, \beta_h\}$, where t is the tau branching fraction.

W + jets sample can be defined by β'. All others samples have a matrix **B** of possibilities given by **B**$= \beta' \times \beta'$

Corresponding selection and identification efficiency matrix **E** is needed for accurate estimations

Each category defined previously has one such matrix attributed.

Expected yield is given by

$$N_{ij} = \sum_{k \in \text{sig}} \sigma_k \mathcal{L} E_{ij}^k B_{ij} + \sum_{l \in \text{bkg}} N_l$$

, with σ_k the cross-section for each signal process k that contributes to a given W boson decay, $\mathcal{L}$ the integrated luminosity and N_l the predicted number of events for background process l

Likelihood Function

Binning based on their categories :

- $\ell\ell$: subleading lepton p_T
- $e\mu$: subleading lepton p_T
- $\ell\tau_h$: hadronic τ p_T
- ℓh : lepton p_T

This enhances the discrimination between $W \to \ell^+\ell^-$ and $W \to \ell^\pm\tau_\ell^\mp$

Our fitting function is then described by :

$$f_{ij}(\beta,\theta) = \sum_{k\in sig} s_{ij,k}(\beta,\theta) + \sum_{l\in bkg} b_{ij,l}(\theta)$$

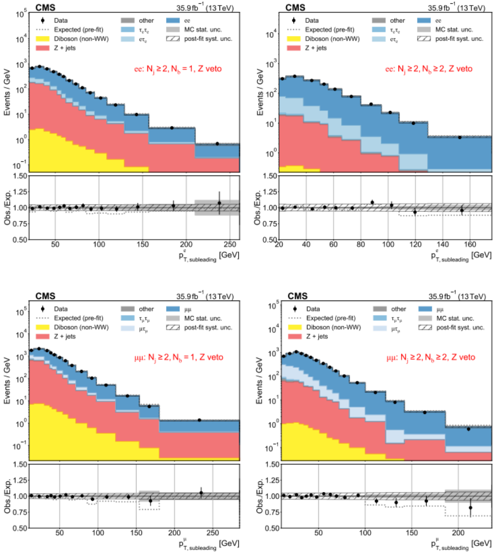
, for bin i, category j and where systematic uncertainties are encompassed in the nuissance parameter θ.

The **Likelihood Function** that is to be minimized simultaneously for all variables and categories is then given by :

$$L(\beta,\theta) = \sum_{j\in \text{category}} \sum_{i\in p_T \text{bins}} \left[-y_{ij}\ln f_{ij}(\beta,\theta) + f_{ij}(\beta,\theta)\right] + \sum_{\theta_l\in\theta} \pi(\theta_l)$$

, with y_{ij} the measured value for bin i in category j, and $\pi(\theta)$ the prior uncertainty of the nuissance parameters.

Distributions used on Maximum Likelihood Function

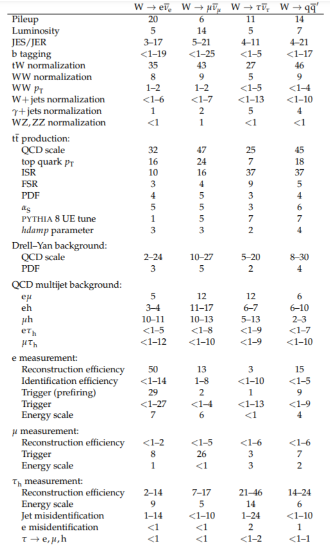


Systematic Uncertainties

Detailed knowledge of systematic uncertainties is basal to precision studies.

In general, the biggest factors contributing to the systematic uncertainties are :

- Triggering on the lepton that is part of the decay
- Reconstruction inefficiency for *e* and *tau*
- QCD scale on tt production and Drell-Yan background estimation
- tW normalization

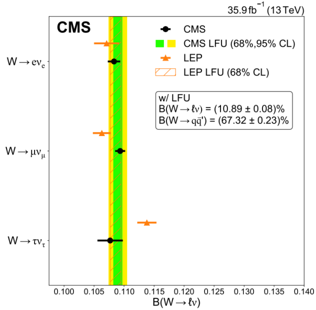


	$W \to e\bar{\nu}_e$	$W \to \mu\bar{\nu}_\mu$	$W \to \tau\bar{\nu}_\tau$	$W \to q\bar{q}'$
Pileup	20	6	11	14
Luminosity	5	14	5	7
JES/JER	3–17	5–21	4–11	4–21
b tagging	<1–19	<1–25	<1–5	<1–17
tW normalization	35	43	27	46
WW normalization	8	9	5	9
WW p_T	1–2	1–2	<1–5	<1–4
W+jets normalization	<1–6	<1–7	<1–13	<1–10
γ+jets normalization	1	2	5	4
WZ, ZZ normalization	<1	1	<1	<1
$t\bar{t}$ production:				
QCD scale	32	47	25	45
top quark p_T	16	24	7	18
ISR	10	16	37	37
FSR	3	4	9	5
PDF	4	5	3	4
α_S	5	5	3	6
PYTHIA 8 UE tune	1	5	7	7
hdamp parameter	3	3	2	4
Drell–Yan background:				
QCD scale	2–24	10–27	5–20	8–30
PDF	3	5	2	4
QCD multijet background:				
$e\mu$	5	12	12	6
eh	3–4	11–17	6–7	6–10
μh	10–11	10–13	5–13	2–3
$e\tau_h$	<1–5	<1–8	<1–9	<1–7
$\mu\tau_h$	<1–12	<1–10	<1–9	<1–10
e measurement:				
Reconstruction efficiency	50	13	3	15
Identification efficiency	<1–14	1–8	<1–10	<1–5
Trigger (prefiring)	29	2	1	9
Trigger	<1–27	<1–4	<1–13	<1–9
Energy scale	7	6	<1	4
μ measurement:				
Reconstruction efficiency	<1–2	<1–5	<1–6	<1–6
Trigger	8	26	3	7
Energy scale	1	<1	3	2
τ_h measurement:				
Reconstruction efficiency	2–14	7–17	21–46	14–24
Energy scale	9	5	14	6
Jet misidentification	1–14	<1–10	1–24	<1–10
e misidentification	<1	<1	2	1
$\tau \to e, \mu, h$	<1	<1	<1–2	<1–1

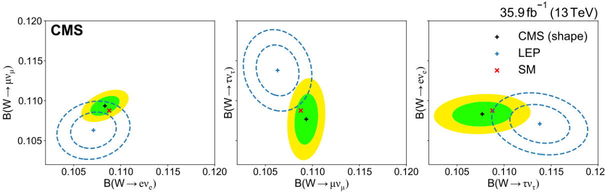
Results : Individual Branching Ratios

From the fits we get 2 immediate results :

- All **branching ratios** are **free** parameters
- Impose **Lepton Flavour Universality**

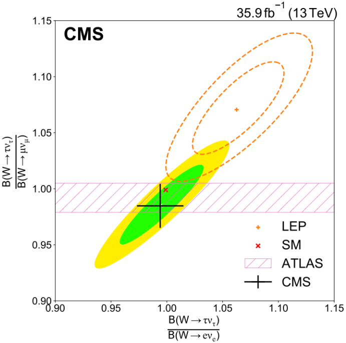


	CMS	LEP
$\mathcal{B}(W \to e\overline{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(W \to \mu\overline{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(W \to \tau\overline{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(W \to q\overline{q}')$	$(67.46 \pm 0.04 \pm 0.28)\%$	—
Assuming LFU		
$\mathcal{B}(W \to \ell\overline{\nu})$	$(10.89 \pm 0.01 \pm 0.08)\%$	$(10.86 \pm 0.06 \pm 0.09)\%$
$\mathcal{B}(W \to q\overline{q}')$	$(67.32 \pm 0.02 \pm 0.23)\%$	$(67.41 \pm 0.18 \pm 0.20)\%$



Results : Lepton Flavour Universality Tests

Comparing the CMS results with those of the experiments that only measured **ratios of branching fractions**, we get :



	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	—	—	—	—
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	—	—	—
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	—	—	—	—

Results : Hadronic Ratios and CKM Matrix Inferences

Hadronic Decay Width :

$$\Gamma(\mathrm{W} \to q\bar{q}) = \frac{\sqrt{2}\mathrm{G_F} N_c}{12\pi} m_W^3 \sum_{i,j} |V_{ij}|^2$$

$$\left[1 + \sum_{k=1}^{4} c_{\mathrm{QCD}}^{(i)} \left(\frac{\alpha_S}{\pi}\right)^k + \delta_{\mathrm{EW}}(\alpha) + \delta_{\mathrm{mix}}(\alpha\alpha_S)\right]$$

This implies that, by fixing the other parameters to their world average values, we can obtain :

- $\sum_{i=(u,c),j=(d,s,b)} |V_{ij}|^2$
- $\alpha_S(m_W^2)$
- $|V_{cs}|$

The ratio of branching fractions then yields :

$$\frac{\mathcal{B}(W \to q\bar{q}')}{1 - \mathcal{B}(W \to q\bar{q}')} = \sum_{i=(u,c),j=(d,s,b)} |V_{ij}|^2$$

$$\left[1 + \sum_{k=1}^{4} c_{\mathrm{QCD}}^{(i)} \left(\frac{\alpha_S}{\pi}\right)^k + \delta_{\mathrm{EW}}(\alpha) + \delta_{\mathrm{mix}}(\alpha\alpha_S)\right]$$

With this, the **results** obtained are :

$$\frac{\mathcal{B}(W \to q\bar{q}')}{1 - \mathcal{B}(W \to q\bar{q}')} = 2.060 \pm 0.021$$

$\alpha_S(m_W^2)$	$\lvert V_{cs}\rvert$	$\sum_{ij} \lvert V_{ij}\rvert^2$
0.095 ± 0.033	0.967 ± 0.011	1.984 ± 0.021

Final Remarks

- This is a much needed update on W boson precision measurements
- Results that are more precise than the long standing LEP measurements, mostly due to the vastly bigger statistics
- Very good agreement with the SM and the most recent ATLAS publication, and tension with the LEP results
- Ratio of hadronic branching fractions precises the CKM matrix values at the current tabled precision
- Ratio of the hadronic branching fractions cannot measure α_S precisely, but shows feasibility in leptonic colliders

The **next step** is to include all the data from the Run 2 at LHC, so that the CMS result can show an equivalent statistical error to that obtained by ATLAS.