COURSE ON PHYSICS AT THE LHC

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Precision measurement of the W boson decay branching fractions in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Collaboration: CMS

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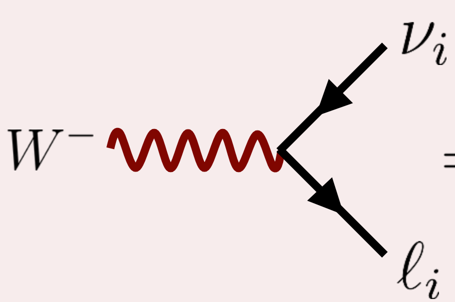
W boson branching fractions provide a test of the Standard Model

$$\mathcal{B}(W \to \ell\bar{\nu},\, q\bar{q}') = \frac{\Gamma(W \to \ell\bar{\nu},\, q\bar{q}')}{\Gamma_{W,\text{total}}}$$

Leptonic decays

Lepton flavour universality



$$= i\frac{g}{\sqrt{2}}\gamma^\mu P_L$$

$$R_{\tau/\ell} \equiv \frac{\mathcal{B}_\tau}{\mathcal{B}_\ell} = 0.9996$$

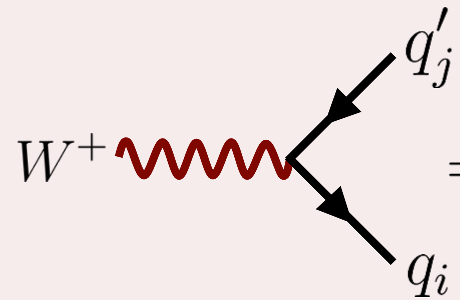
2.6σ departure from the SM

LEP: $\boxed{R_{\tau/(e+\mu)} = 1.066 \pm 0.025}$

ATLAS: $R_{\tau/\mu} = 0.992 \pm 0.013$

Hadronic decays

CKM unitarity & strong coupling



$$= i\frac{g}{\sqrt{2}}V_{ij}\gamma^\mu P_L$$

$$\frac{\mathcal{B}_q}{1-\mathcal{B}_q} = \underbrace{\boxed{\sum_{u,c,d,s,b} |V_{ij}|^2}}_{=2}\left[1 + \sum_{i=1}^{4} c_i \left(\frac{\alpha_S}{\pi}\right)^i + c_{\text{EW}} + c_{\text{mix}}(\alpha_S)\right]$$

- ✓ CKM unitarity of first two rows
- ✓ V_{cs} coupling

Beyond the Standard Model

Heavy Neutral Leptons

LFU

$$\Gamma(W \to \ell_\alpha \bar{\nu}) = \frac{g^2 m_W}{48\pi} \boxed{\sum_{i=1}^{3} |U_{\alpha i}|^2}$$

HNL make the lepton mixing matrix non-unitary, modifying the SM prediction of LFU in W decays

Vector-like Quarks

CKM unitarity

$$V = \begin{pmatrix} \boxed{\begin{matrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{matrix}} & \begin{matrix} V_{uB} \\ V_{cB} \\ V_{tB} \end{matrix} \end{pmatrix}$$

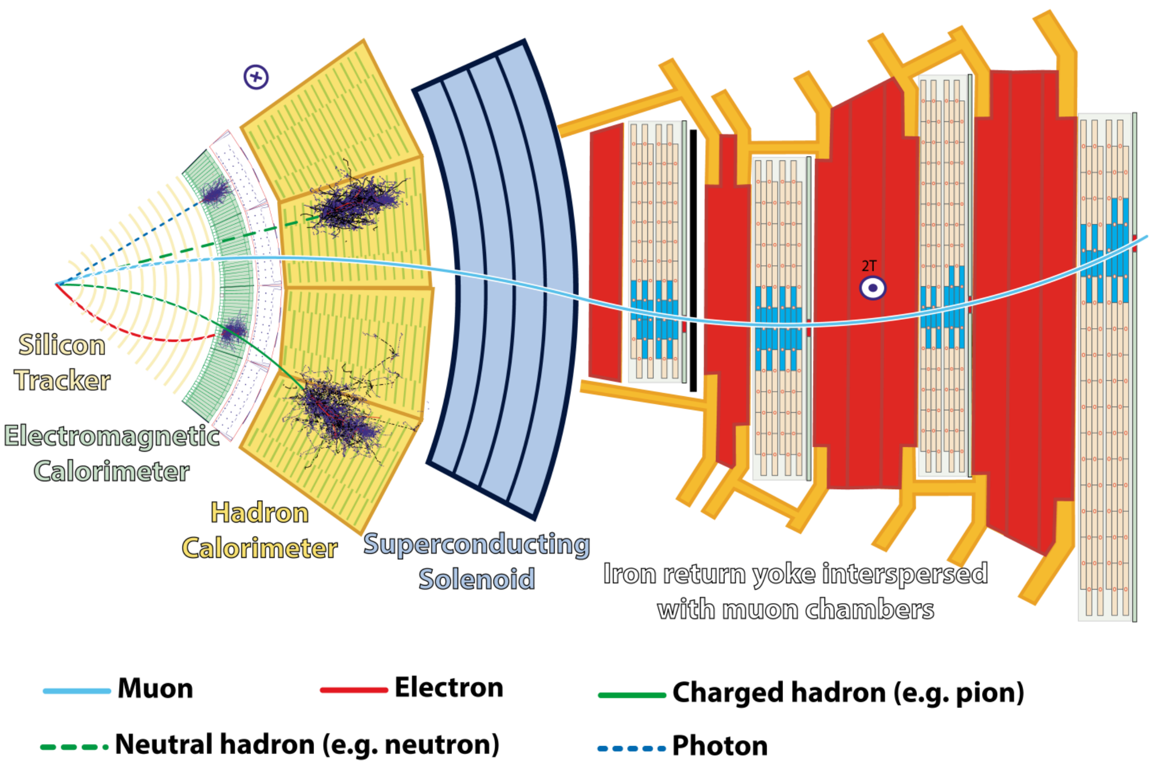
A down-type $SU(2)_L$ singlet VLQ induces non-unitarity in the effective CKM matrix

Minimal extensions of the SM may alter these observables!

The CMS detector (2016)

Centre-of-mass energy $\sqrt{s}$
13 TeV

Integrated luminosity
35.9 fb^{-1}



Charged Particles: trajectories measured by silicon pixel and strip trackers

Electron / photon / jets of hadrons: Energy measured by calorimeters

Muon: identified and measured in gas-ionization detectors

Neutrino: inferred as missing transverse momentum

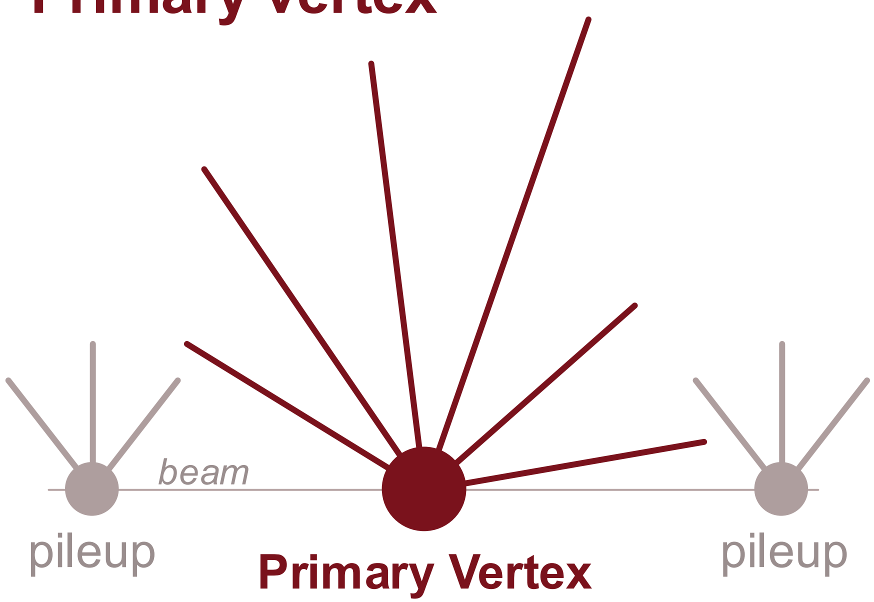
Event Selection and Reconstruction

Two-tier trigger

LHC collisions 40 MHz → **Level-1 trigger ~100 kHz** → **High-Level Trigger ~1 kHz** → **Recorded for analysis**

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

Primary vertex



- The **PV** is the candidate vertex with the **largest summed physics-object p_T^2**
- Physics objects are the jets, clustered together using the anti-k_T jet finding algorithm
- Quality requirements ensure the **PV comes from a hard-scattering interaction**

Event Selection and Reconstruction

Lepton reconstruction

Electron

- Reconstructed by combining information from the **ECAL** and tracking system
- **p_T > 10 GeV; $|\eta|$ < 2.5**
- Isolation Criteria:

$$I_{\mathrm{PF}} = I_{\mathrm{ch}} + \max\left(0, I_{\mathrm{neu}} + I_{\gamma} - \rho A_{\mathrm{eff}}(\eta_e)\right)$$

Barrel: $I_{\mathrm{PF}}/p_T^e < 0.0588$

Endcap: $I_{\mathrm{PF}}/p_T^e < 0.0571$

Muon

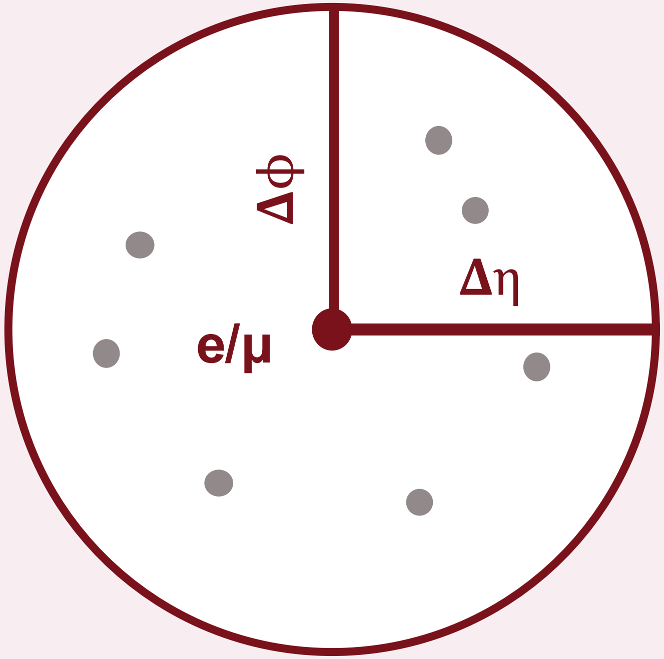
- Reconstructed using both the **muon** and **tracker subsystems**
- **p_T > 5 GeV; $|\eta|$ < 2.4**
- Isolation Criteria:

$$I_{\mathrm{PF}} = I_{\mathrm{ch}} + \max\left(0, I_{\mathrm{neu}} + I_{\gamma} - 0.5 I_{\mathrm{pileup}}\right)$$

$$I_{\mathrm{PF}}/p_T^{\mu} < 0.15$$

Lepton isolation

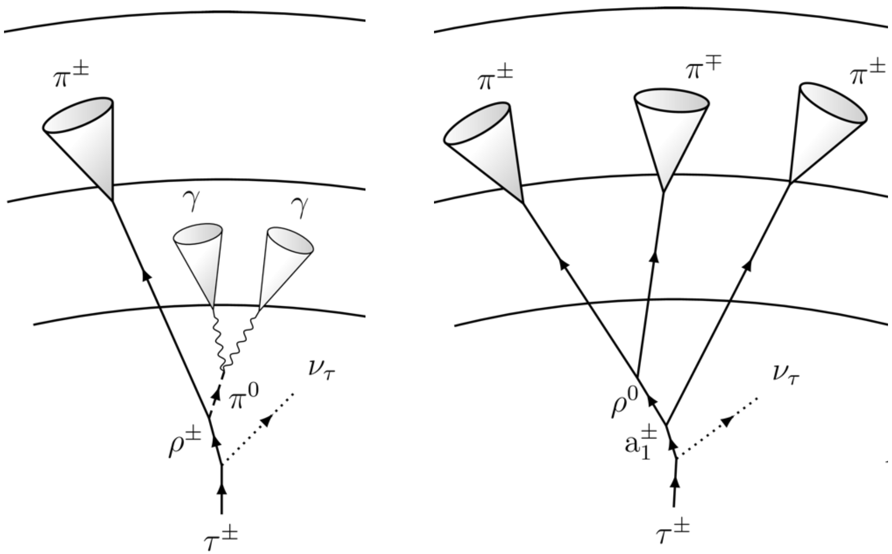
To select leptons that originated from the prompt decay of an electroweak boson



$\Delta R = 0.4$

Event Selection and Reconstruction

Images by Izaak Neutelings in tikz.net

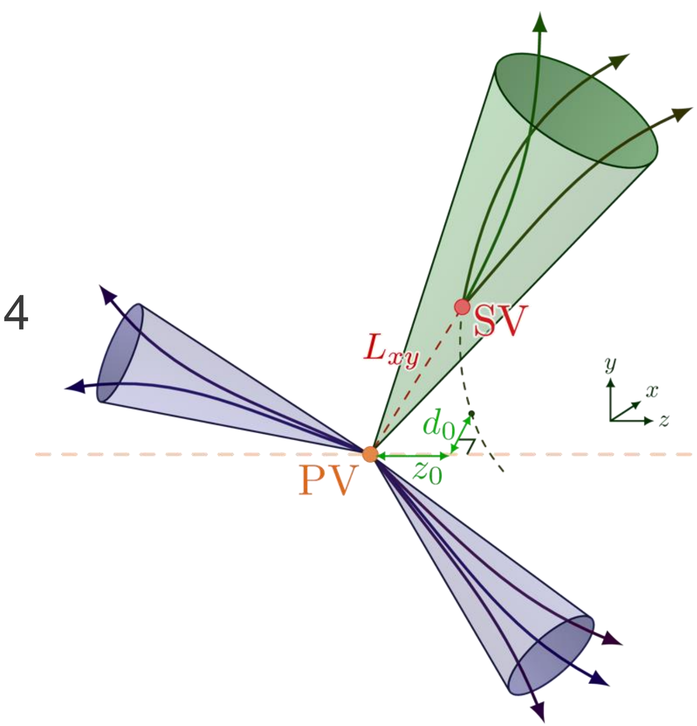


Hadronic τ (τ_h)

- Reconstructed with the **hadron-plus-strips algorithm**, seeded by a PF jet consistent with a single or triple charged-pion decay
- Any τ_h overlapping with μ/e is rejected
- **p_T > 20 GeV, $|\eta|$ < 2.3**

Jets

- Reconstructed from PF candidates, clustered with the anti-kT algorithm with a distance parameter of 0.4
- Vetoed if jets overlap ($\Delta R = 0.4$) with any reconstructed μ, e, or τ_h
- **p_T > 30 GeV, $|\eta|$ < 2.4**
- Jets from the **hadronization of b quarks** are identified using the combined **secondary vertex b tagging algorithm**



Event Categorization

Percentages = share of selected W decays

pp collision

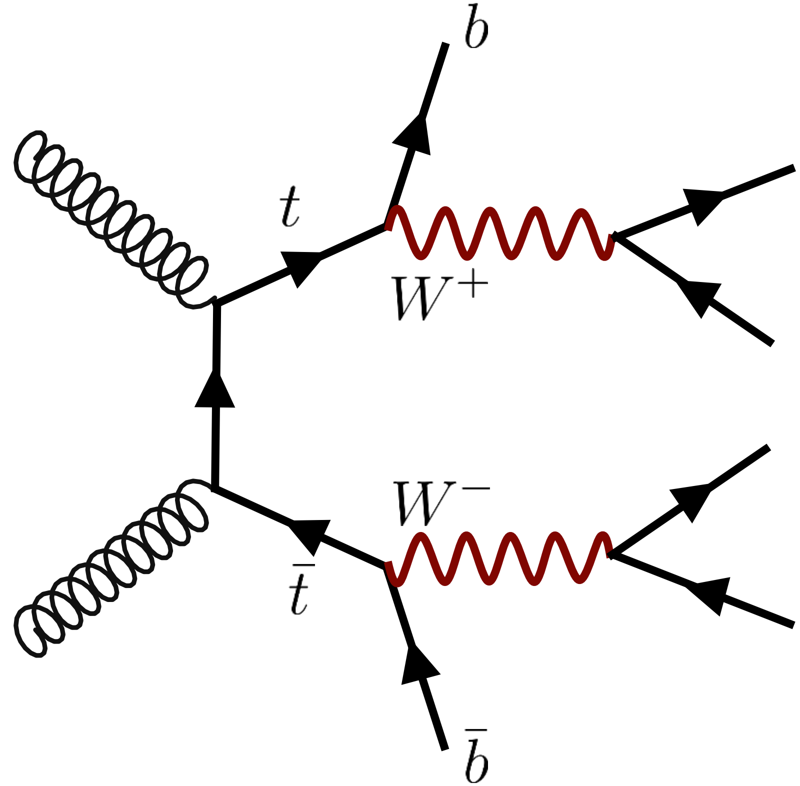
↓

$t\bar{t}$ production
90%

tW	WW	$W + jets$
4.4%	1.4%	4.2%

↓

$W \to \ell\nu$ | **$W \to qq'$**



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

Event Categorization

- **Categorization of events** passing the reconstruction criteria, based on their **jet and b-tagged multiplicities**, used to define signal enriched and control regions
- **$e\tau_h$ and $\mu\tau_h$ categories** with **at least one jet that is not b-tagged** are required to satisfy $\mathbf{40 \leq m_{\ell\tau_h} \leq 100}$ **GeV**, $\boldsymbol{\Delta\phi(\ell, \tau_h) > 2.5}$, and $\boldsymbol{m_T^{\ell} < 60}$ **GeV**, and are used in **control regions for the τ_h identification**

<table>
<tr><th></th><th>$N_j = 0$</th><th>$N_j = 1$</th><th>$N_j = 2$</th><th>$N_j = 3$</th><th>$N_j \geq 4$</th></tr>
<tr><td>$N_b = 0$</td><td>$e\tau_h$, $\mu\tau_h$, $e\mu$</td><td>$e\tau_h$, $\mu\tau_h$, $e\mu$</td><td colspan="3">$e\tau_h$, $\mu\tau_h$, $e\mu$</td></tr>
<tr><td rowspan="3">$N_b = 1$</td><td rowspan="3"></td><td rowspan="2">$e\tau_h$, $\mu\tau_h$, $e\mu$</td><td>$e\tau_h$, $\mu\tau_h$</td><td colspan="2">$e\tau_h$, $\mu\tau_h$</td></tr>
<tr><td colspan="3">ee, $\mu\mu$, $e\mu$</td></tr>
<tr><td colspan="3"></td><td>eh, μh</td></tr>
<tr><td rowspan="3">$N_b \geq 2$</td><td rowspan="3" colspan="2"></td><td>$e\tau_h$, $\mu\tau_h$</td><td colspan="2">$e\tau_h$, $\mu\tau_h$</td></tr>
<tr><td colspan="3">ee, $\mu\mu$, $e\mu$</td></tr>
<tr><td colspan="2"></td><td>eh, μh</td></tr>
</table>

Extraction of Branching Fractions

The determination of the W branching fractions is carried out using a Maximum Likelihood Estimation (MLE)

The branching fractions are encoded in the vector

$$\beta' = \{\beta_e, \beta_\mu, \beta_\tau t_e, \beta_\tau t_\mu, \beta_\tau t_h, \beta_h\}$$

W-pair decay combinations

$$\mathbf{B} = \beta' \otimes \beta'$$

Estimated number of events in bin i and category j

$$N_{ij} = \sum_{k \in \mathrm{sig}} \sigma_k \mathcal{L} \, E_{ij}^k \, \mathcal{B}_{ij} + \sum_{l \in \mathrm{bkg}} N_l$$

σ = process cross section ·ℒ = luminosity
E= selection efficiency · N = background yield
ℬ= branching fraction

- ee — subleading electron p_T
- $\mu\mu$ — subleading muon p_T
- $e\mu$ — subleading lepton p_T
- $e\tau_h$, $\mu\tau_h$ — hadronic τ p_T
- eh, μh — lepton p_T

Extraction of Branching Fractions

Predicted yield in each bin and category

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

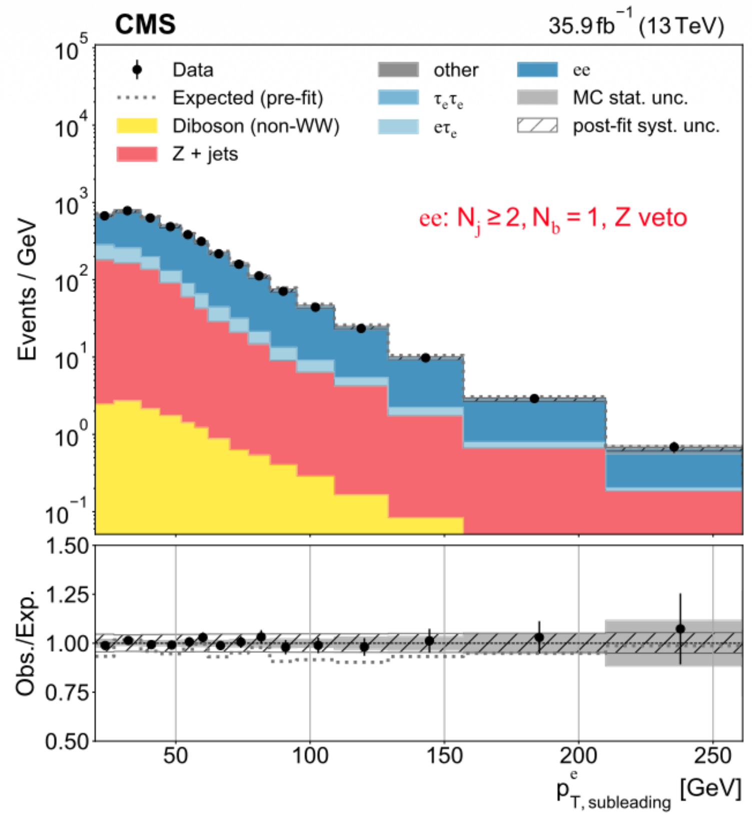
Templates depend on the W branching fractions and **nuisance parameters θ**, which **account for the effects of systematic uncertainties**

Negative log-likelihood

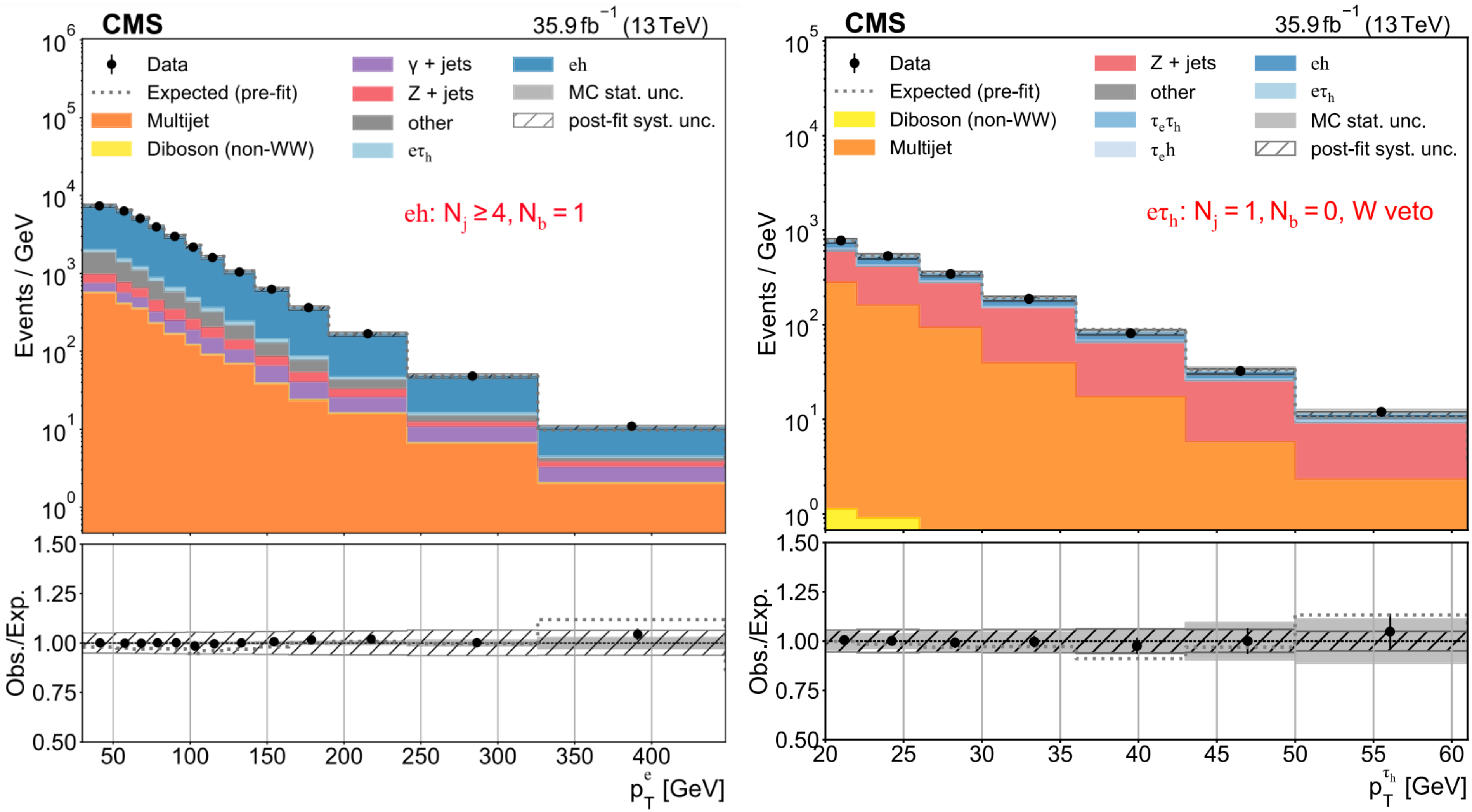
$$L(\boldsymbol{\beta},\boldsymbol{\theta}) = \sum_{j\in\text{category}} \sum_{i\in p_T\,\text{bin}} \left[-y_{ij}\ln f_{ij}(\boldsymbol{\beta},\boldsymbol{\theta}) + f_{ij}(\boldsymbol{\beta},\boldsymbol{\theta})\right] + \sum_{\theta\in\Theta}\pi(\theta)$$

y = measured data yield · π= prior uncertainty

Branching fractions are estimated by minimizing the negative log-likelihood with respect to all parameters over all categories simultaneously



Extraction of Branching Fractions



Systematic Uncertainties

Impacts quoted as a **percent** of the **total systematic uncertainty**

Largest impacts of each source of uncertainty for each W branching fraction

$W \rightarrow e\bar{\nu}_e$

electron reconstruction efficiency

50%

$W \rightarrow \mu\bar{\nu}_\mu$

$t\bar{t}$ production QCD scale

47%

$W \rightarrow \tau\bar{\nu}_\tau$

τ_h measurement reconstruction efficiency

21-46%

$W \rightarrow q\bar{q}'$

tW normalization

46%

The precision of the measurement is virtually entirely determined by the systematic uncertainty

Results

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

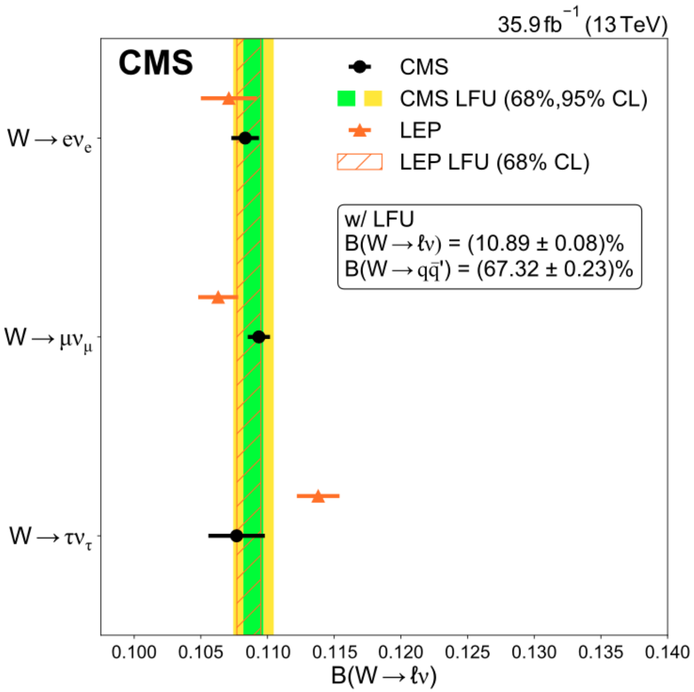
Measurements 3–10 times more precise statistically than those from LEP

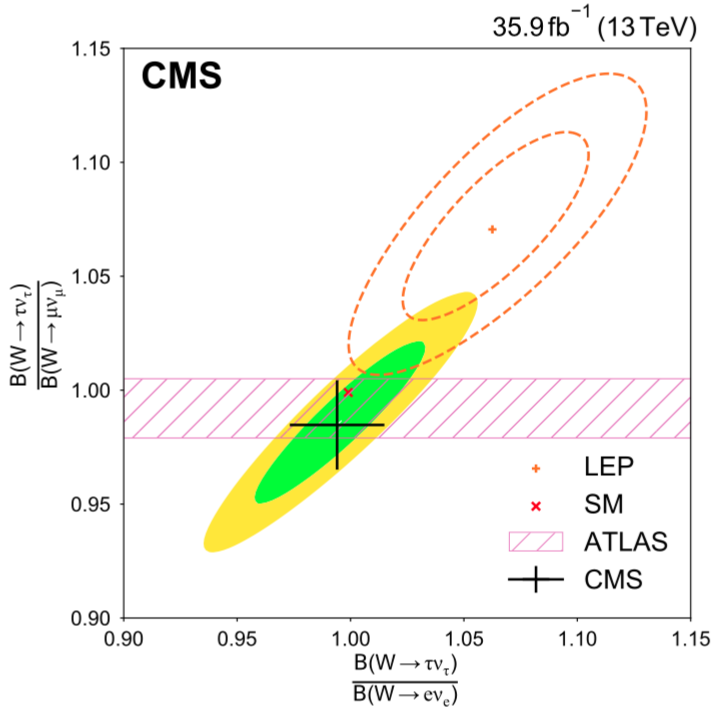
The e and μ branching fractions are measured about 1.5 times more precisely than at LEP

τ have similar total uncertainties but mostly systematic origin in the CMS case

Assuming LFU, the inclusive hadronic branching uncertainty is 15% smaller than LEP

Results: Lepton Flavour Universality





CMS result is consistent with LFU at the 1 σ level

	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	...	...	...	...

Updated Results: Lepton Flavour Universality

$R_{\mu/e} = 0.9995 \pm 0.0045$

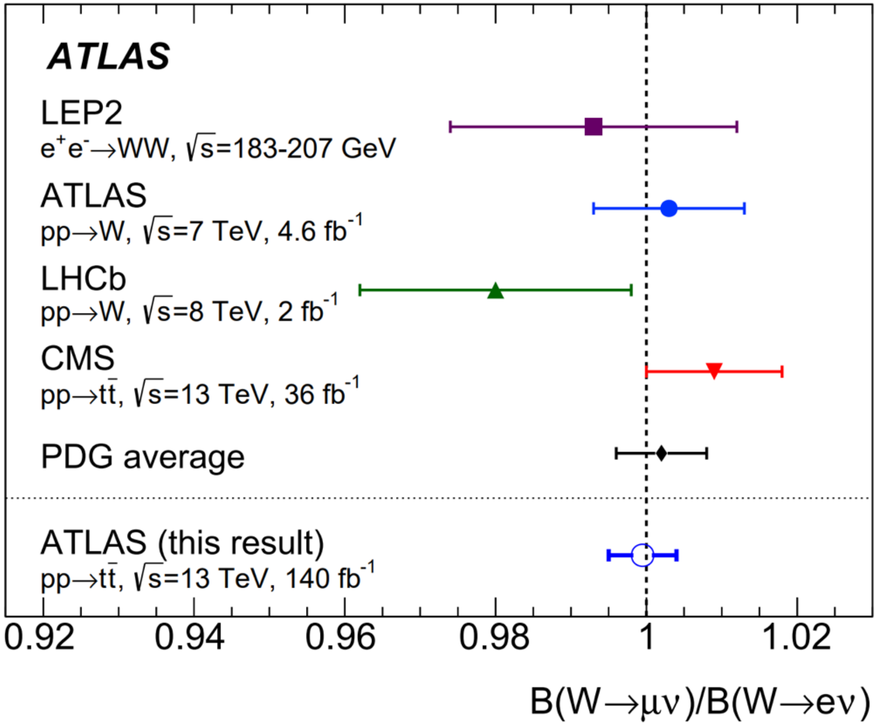
ATLAS · 2024

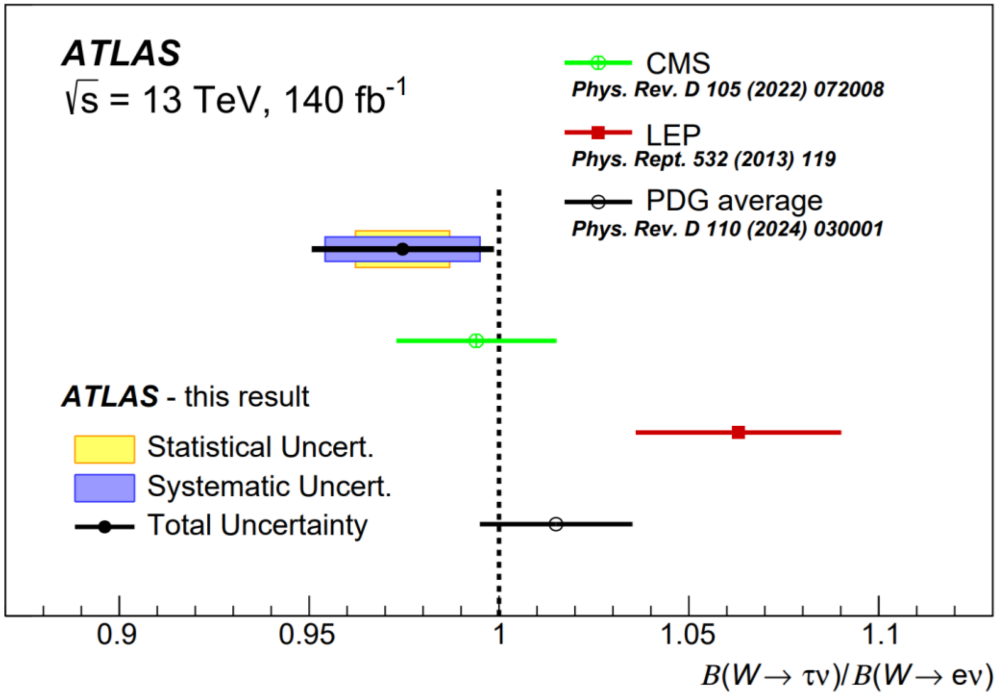
arXiv: 2403.02133

$R_{\tau/e} = 0.975 \pm 0.012 \pm 0.020$

ATLAS · 2024

arXiv: 2412.11989





Results: Hadronic Decays

Assumptions

- α_s extraction assumes CKM unitarity
- $|V_{cs}|$ extraction additionally uses the better-known CKM elements from the first two rows and the world-average α_s
- CKM-sum extraction assumes the world-average α_s

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

α_S: useful, but not competitive

The uncertainty is much larger than the world average, but remains a promising handle for future colliders such as ***FCC-ee*** *or* ***CEPC***

$|V_{cs}|$: comparable precision at the time

Direct determination from semileptonic D and leptonic D_s decays is now more precise: $|V_{cs}| = 0.969 \pm 0.005$ *(PDG 2024)*

CKM unitarity: no deviation

The measured value is within 1σ of the expected value coming from unitarity

Summary and Outlook

The ***W* boson branching fractions** $\mathcal{B}(W \to \ell\bar{\nu})$, $\mathcal{B}(W \to q\bar{q}')$ are measured, allowing tests of the SM and the extraction of further parameters:

- The CMS result is **consistent with LFU at the 1σ level**;
- $|V_{cs}| = 0.967 \pm 0.011$ and $\Sigma|V_{ij}|^2 = 1.984 \pm 0.021$, **consistent with CKM unitarity**;
- Strong coupling $\alpha_S(m_W^2) = 0.095 \pm 0.033$: bigger uncertainty than world average but **promising for future colliders**.

All results agree with the **Standard Model** and are several times **more precise statistically** than the earlier **LEP** measurements

Thank you !