Recent results on W mass and branching fraction

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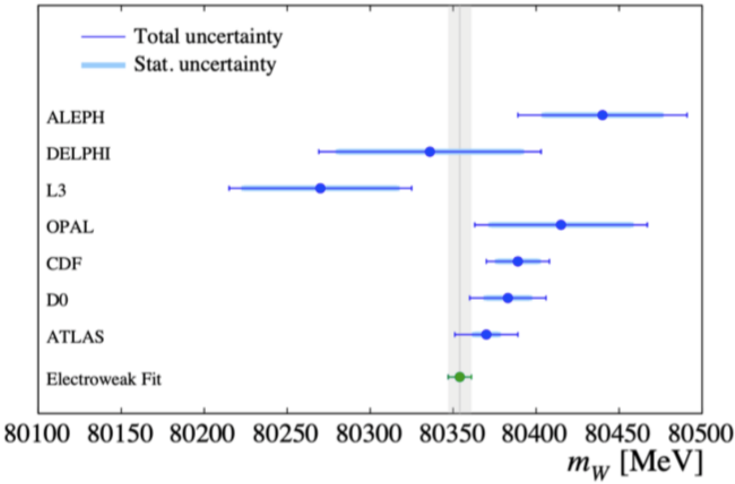
Standard Model @ LHC, Switzerland CERN

04/11/2022

m_W status

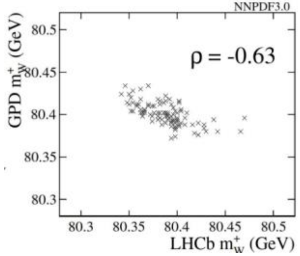
- Long term goal: close gap in precision between direct and indirect determinations
- Global EW fit provides prediction with **7 MeV** precision: **almost half the uncertainty** of the PDF average of the PDG average of direct measurement (12MeV)
- Hadron Collider measurements already available form ATLAS, CDF and D0
  - Most precise measurements at LHC to data achieve **19 MeV** precision



m_W measurement at LHCb

[Eur. Phys. J. C 75, 601 (2015)]

CMS & ATLAS



- High precision measurement of m_W is possible at LHCb, PDF systematic uncertainty can be **reduced by a factor 2**
- Sensitivity to the m_W by carefully measuring the muon p_T
- Modelling of W production and decay in 5D

Unpolarized part: POWHEG + Pythia8

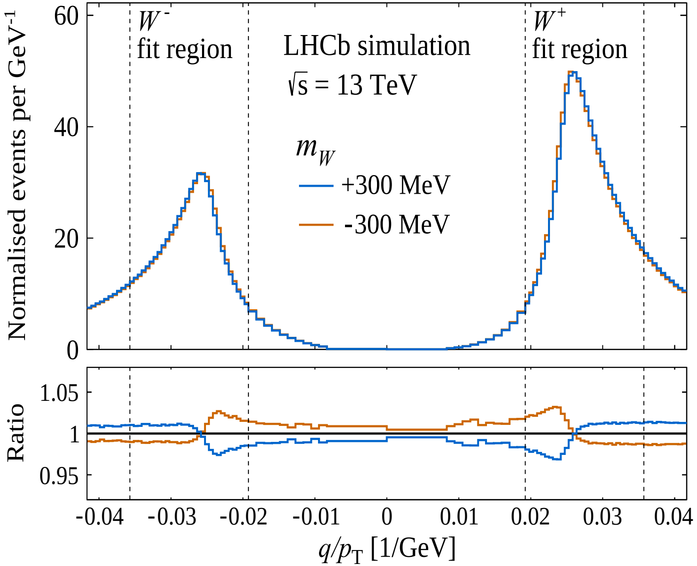
$$\frac{d\sigma}{dp_T^W\, dy\, dM\, d\cos\vartheta\, d\varphi} = \frac{3}{16\pi}\frac{d\sigma^{\text{unpol.}}}{dp_T^W\, dy\, dM}$$

(At order α_s^2)

$$\Big\{(1+\cos^2\vartheta) + A_0\frac{1}{2}(1-3\cos^2\vartheta) + A_1\sin 2\vartheta\cos\varphi + A_2\frac{1}{2}\sin^2\vartheta\cos 2\varphi + A_3\sin\vartheta\cos\varphi + A_4\cos\vartheta + A_5\sin^2\vartheta\sin 2\varphi + A_6\sin 2\vartheta\sin\varphi + A_7\sin\vartheta\sin\varphi\Big\}$$

Angular part: DYTurbo

[JHEP 01 (2022) 036]



m_W uncertainties at LHCb

Source [JHEP 01 (2022) 036]	Size [MeV]
Parton distribution functions	9
Theory (excl. PDFs) total	17
Transverse momentum model	11
Angular coefficients	10
QED FSR model	7
Additional electroweak corrections	5
Experimental total	10
Momentum scale and resolution modelling	7
Muon ID, trigger and tracking efficiency	6
Isolation efficiency	4
QCD background	2
Statistical	23
Total	32

Average of NNPDF31, CT18, MSHT20

Envelope from five different models

Uncorrelated scale variation

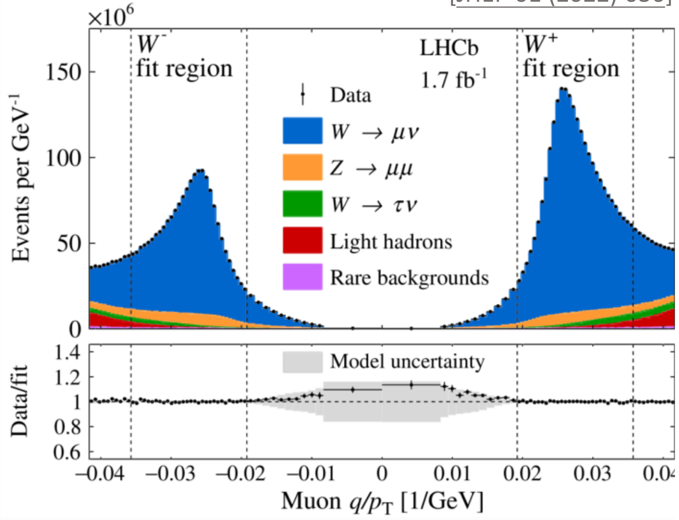
Envelope of the QCD FSR from Pythi8, Photos and Herweig7

Includes statistical uncertainties, details of the methods (e.g. binning, smoothing

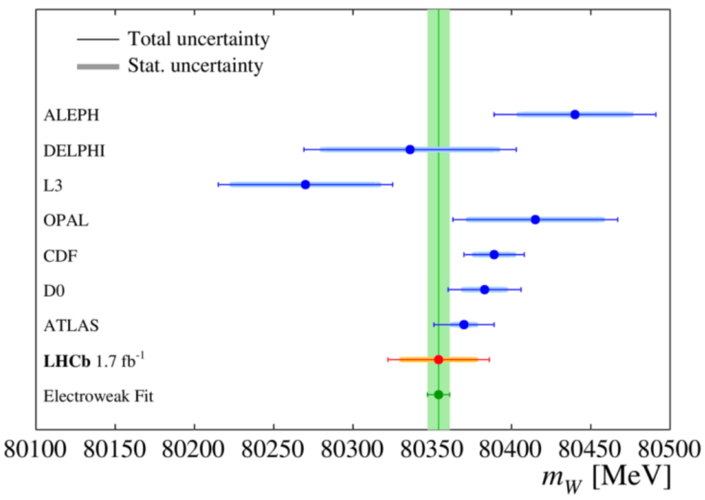
m_W results at LHCb

- LHCb achieves a precision of ∼32 MeV using roughly 1/3 of the Run-II dataset
- **An overall precision ∼20 MeV is achievable with all existing LHCb data**

[JHEP 01 (2022) 036]



[JHEP 01 (2022) 036]

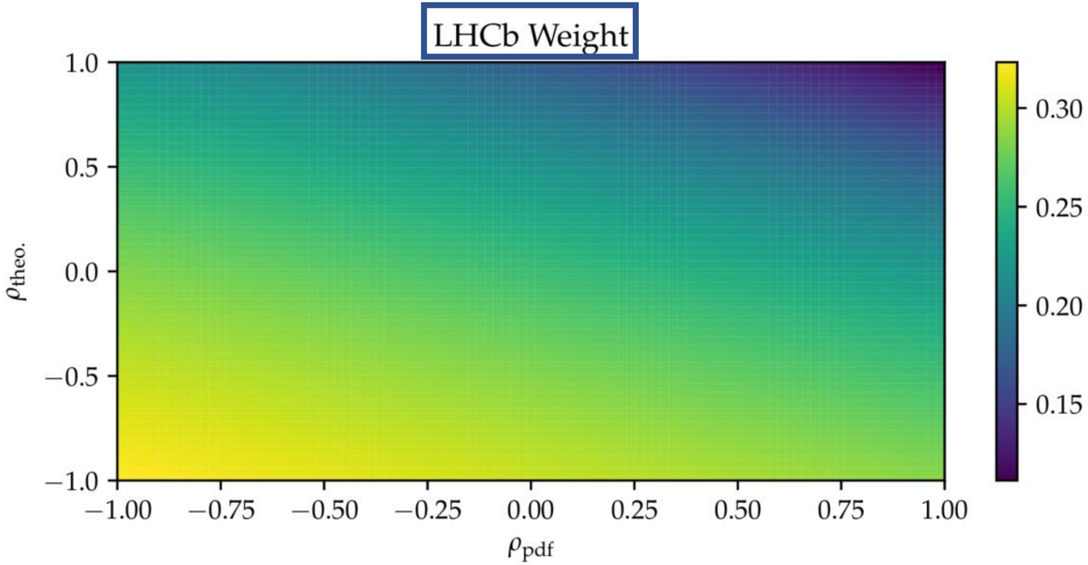


$$m_W = 80354 \pm 23_{\text{stat.}} \pm 10_{\text{exp.}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

Future Prospects – LHC average

[Nucl. Instrum. Meth. A 270 (1988) 110]
[Nucl, Instrum. Meth. A 500 (2003) 391]

- Combine with ATLAS results using Best Linear Unbiased Estimator method
  - Assuming experimental uncertainties are uncorrelated
  - Consider different assumptions for the correlation of theoretical and PDF uncertainties



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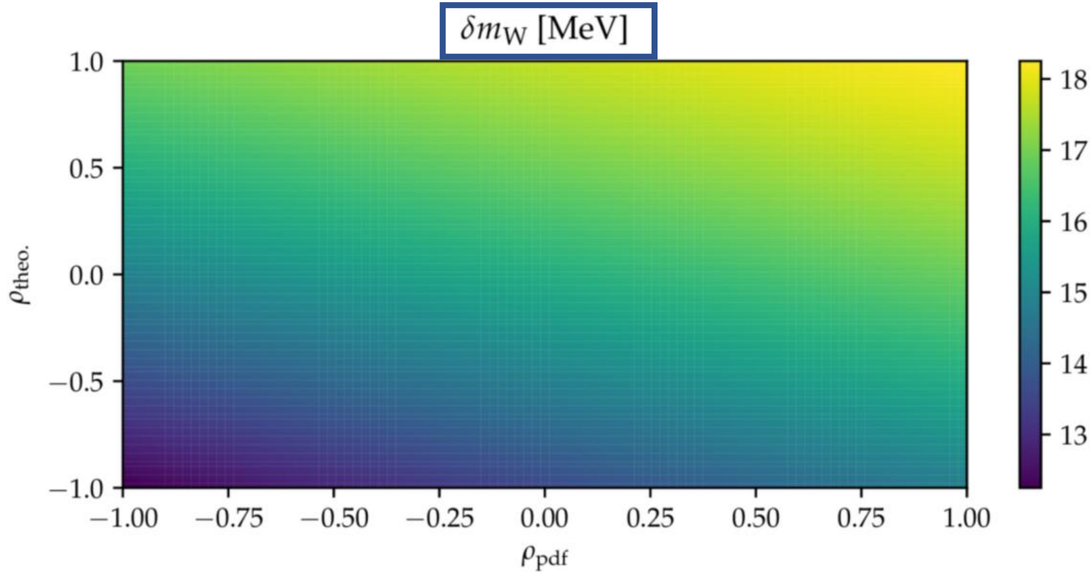
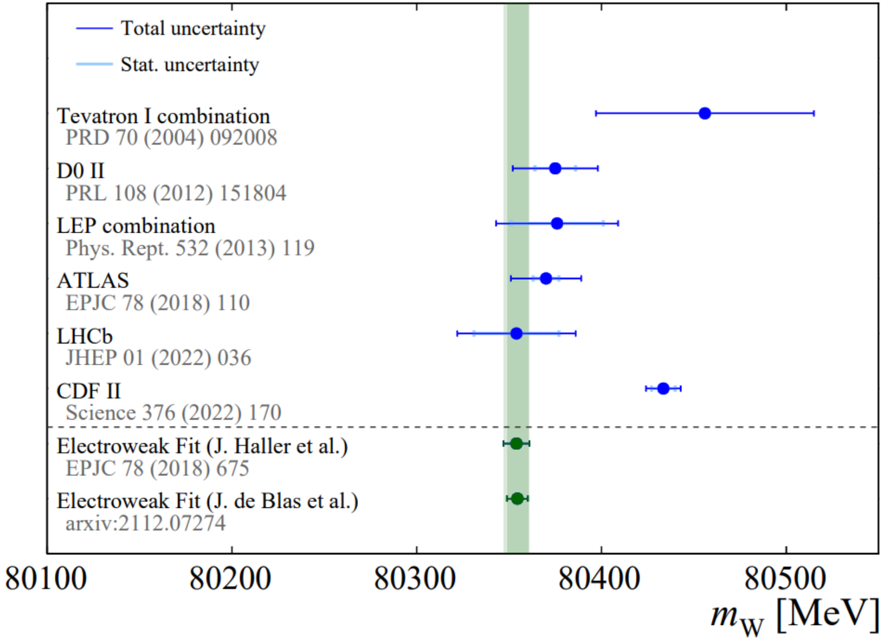


Latest m_W results from CDF [Science 376 (2022) 170]

- The precision is impressive
- The result is tension with SM and other experiments

$$m_W = 80433.5 \pm 6.4_{stat.} \pm 6.9_{syst.}\ \text{MeV}$$

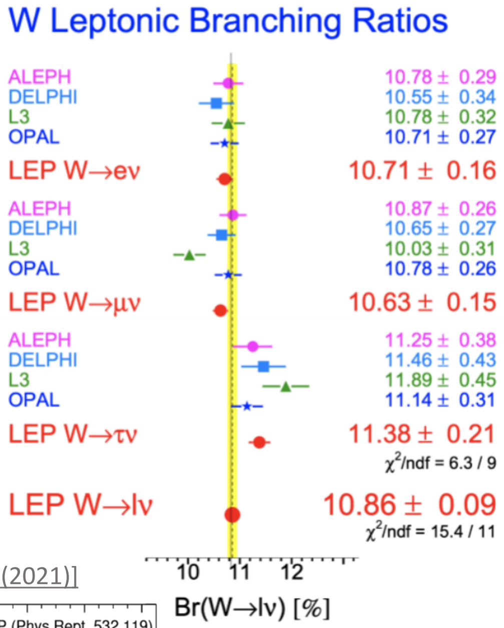
plot link



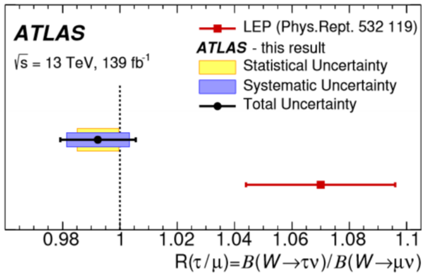
Current state of W boson branching fraction measurements

[PR 532, 119-244 (2013)]

- The most precise values come from LEP experiments
  - Good agreement between $B(W \to e)$ and $B(W \to \mu)$
  - $R_{\tau/(e+\mu)} = \frac{2\mathcal{B}(W\to\tau\overline{\nu_\tau})}{\mathcal{B}(W\to e\overline{\nu_e})+\mathcal{B}(W\to\mu\overline{\nu_\mu})}$ shows **2.6σ** from the SM expectation of 0.9996 [PRD 62.0730101 (2000)]
- At LHC , **large ross section for the production of $t\bar{t}$** offers a sizable high-purity of W boson pairs
- ATLAS has precisely measured B_τ/B_μ
  - Consistent with lepton flavour universality (LFU)

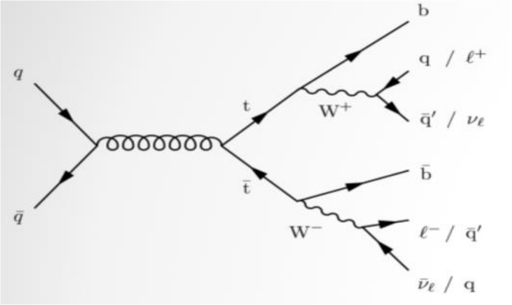


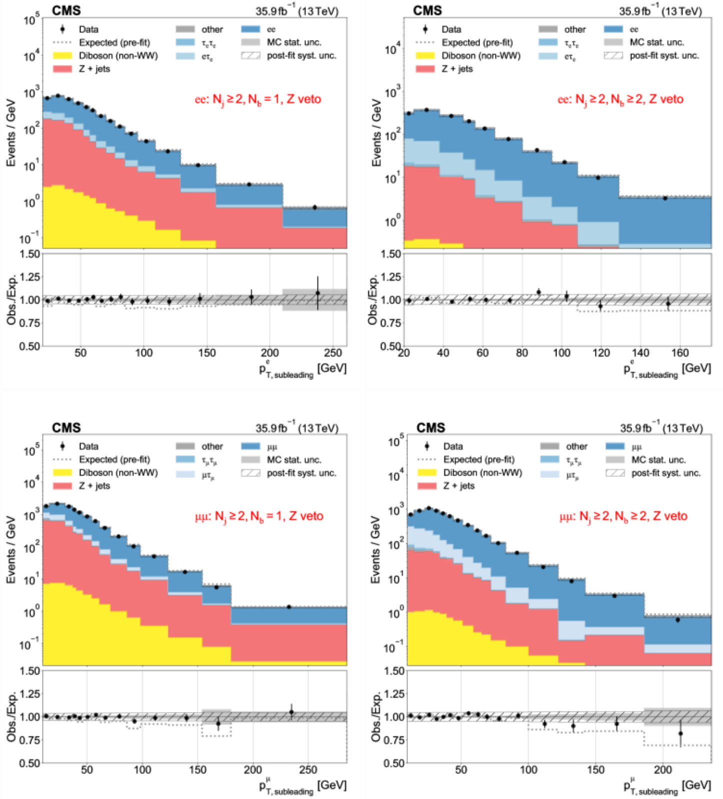
[Nat. Phys. 17, 813–818 (2021)]



W boson branching fractions at CMS

- Three leptonic decay branching fractions of the W boson as well as the average leptonic and inclusive hadronic branching fractions assuming LFU
- Datasets: 2016 data at 13TeV $\sim 35.9\ \mathrm{fb}^{-1}$
- Max likelihood fit of all W BR with histogram templates for leptons p_T

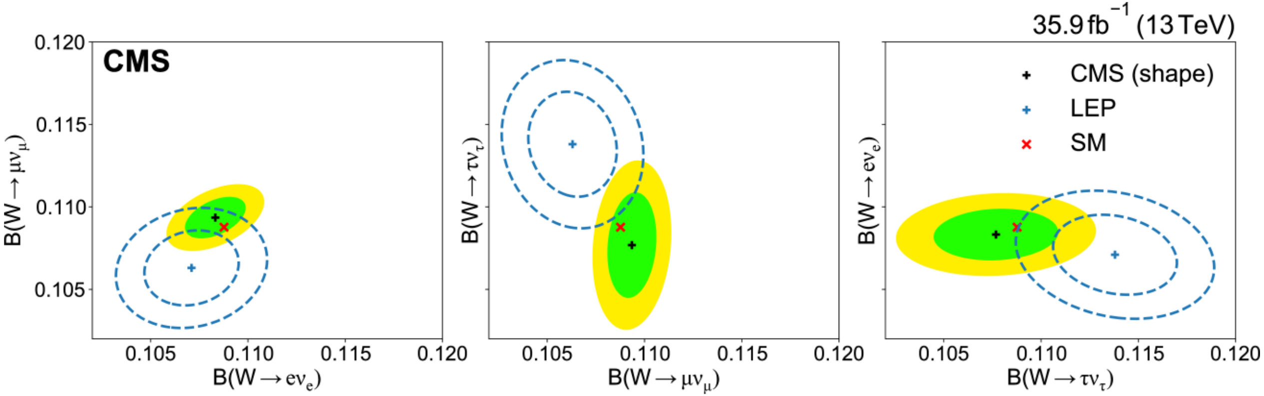


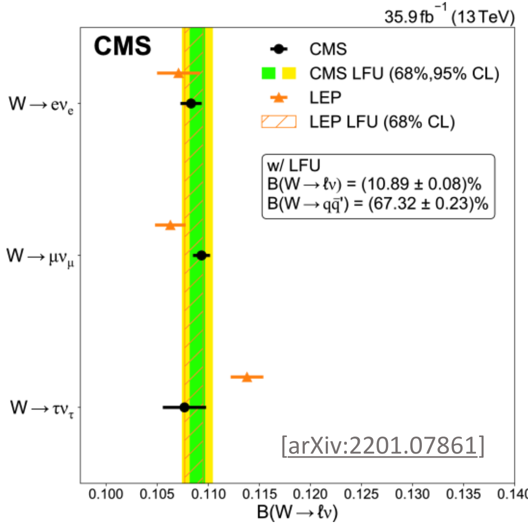


Branching fraction results at CMS

- $B(W \to e\nu_e)$ and $B(W \to \mu\nu_\mu)$ are ~1.5 times more precisely than at LEP
- $B(W \to \tau\nu_\tau)$ have similar total uncertainty
- $B(W \to l\nu)$ is consistent with LEP, but **much more statistically precise**
- Inclusive hadronic $B(W \to q\bar{q})$ is about 70%, uncertainty is ~ **15% smaller** than LEP

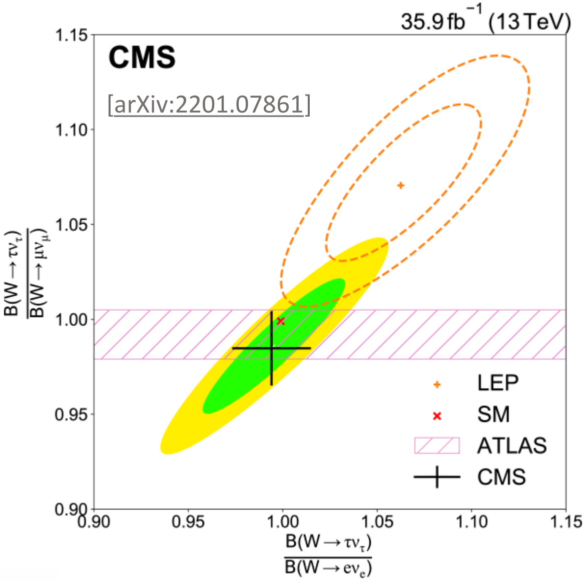
[arXiv:2201.07861]





Ratios of leptonic branching fractions at CMS

- Ratios between branching fractions give a quick check of LFU
- The ratio between the τ and e/μ ratios is calculated assuming partial LU, i.e., $B_e = B_\mu \neq B_\tau$



	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	—	—	—	—

[arXiv:2201.07861]

Other SM parameters at CMS

- The measured values of the leptonic branching fractions can also be used as to derive several other quantities of interest
  - $\alpha_S(m_W^2)$: although not competitive compared with the current world average, confirms the usefulness of the W boson decays to constrain this fundamental standard model parameter at future colliders
  - Using the world average value of $\alpha_S(m_W^2)$, $\sum_{ij}|Vij|^2$ providing a precise check of CKM unitarity
  - $|V_{CS}|$: is as precise as the current $|V_{CS}|$ = 0.987 ± 0.011 result obtained from direct D meson decay data

$$\frac{\mathcal{B}(\mathrm{W}\to \mathrm{q\bar{q}'})}{1-\mathcal{B}(\mathrm{W}\to \mathrm{q\bar{q}'})} = \sum_{\substack{i=(\mathrm{u,c}),\\ j=(\mathrm{d,s,b})}} |V_{ij}|^2 \left[1+\sum_{i=1}^{4} c_i \left(\frac{\alpha_S}{\pi}\right)^i + c_{\mathrm{EW}}(\alpha) + c_{\mathrm{mix}}(\alpha\alpha_S)\right]$$

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

[arXiv:2201.07861]

Summary

[JHEP 01 (2022) 036]
[Eur. Phys. J. C 78 (2018) 110]
[Science 376 (2022) 170]]

- **W boson mass measurement**
  - An overall precision **< 20 MeV** looks achievable with existing LHCb Run 2 datasets
  - ATLAS achieve **19 MeV** precision, the most precise measurements at LHC to data
  - **LHCb+ ATLAS** results combinations could have about **16 MeV** precision
  - CDF latest m_W results is **tension** with the SM and other experiments, with **impressive precision**
- **W branching fraction measurement**
  - ATLAS has precisely measured B_τ/B_μ at 13TeV , the result is consistent with LFU
  - The precision **CMS result** exceeds the previous best result obtained by LEP and confirms the ATLAS result
  - LHCb measurement is ongoing

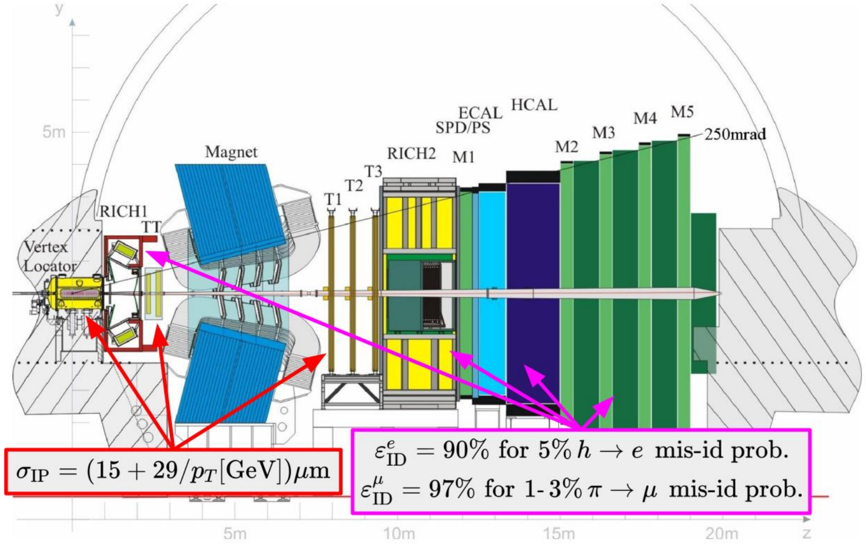
[arXiv:2201.07861]
[Nat. Phys. 17, 813–818 (2021)]

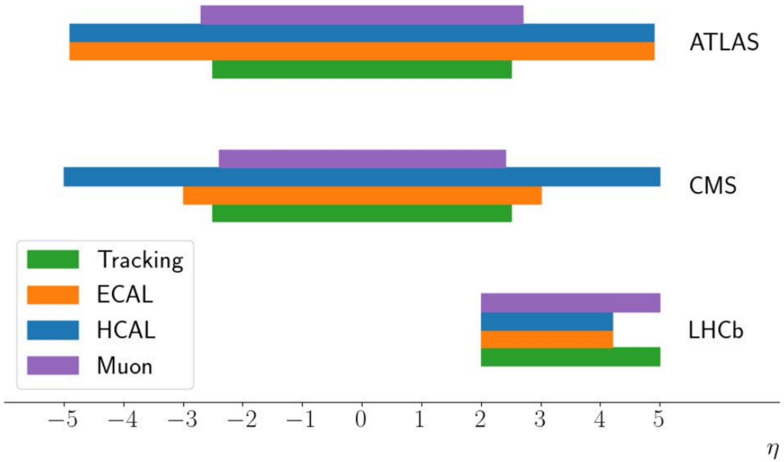
BACKUP

Peculiarities of the LHCb detector

[JINST 3 (2008) S08005]
[Int. J. Mod. Phys. A 30 (2015) 1530022]

- Detector in the forward region with excellent momentum and vertex resolutions
- Coverage is complementary to ATLAS and CMS (with some lverlapping at low pseudoratpidity)

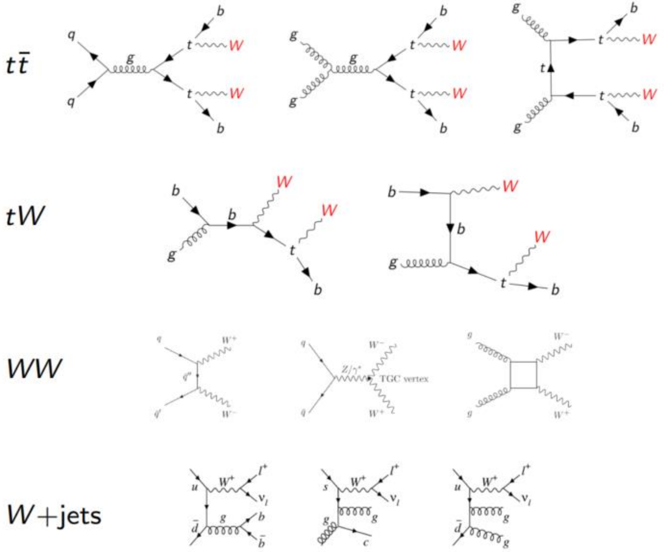


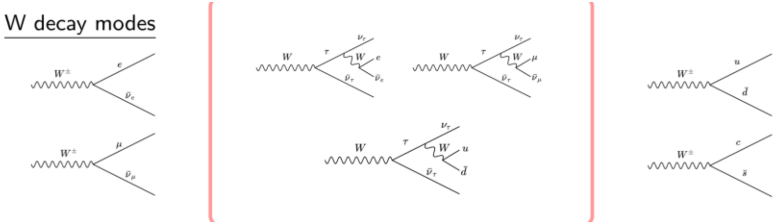


Interesting process @ LHC

- **Take advantage of $t\bar{t}$ production**
  - Abundantly produced ($\sigma_{t\bar{t}}$ = 832 pb ≫ σ_{WW} = 120 pb
  - Unique signature (multiple jets, b tagging) allows selection of high purity sample
  - Well understood systematic uncertainties

- Also consider as signal: tW, WW and W+jets
- Main challenge: account for overlap between prompt W decays vs. W decays with intermediate τ





Categorization

- **Base line selection**
  - One muon with $p_T > 25$ GeV or one electron with $p_T > 30$ GeV
  - Select events with additional electrons, muons, hadronic tau leptons, or jets
  - Overlap in object reconstruction prioritizes $\mu \rightarrow e \rightarrow \tau \rightarrow h$
- **Categorization by N_{jets} and $N_{b\ tags}$**
  - Main selection isolates $t\bar{t}$ and tW production
  - Finer binning of l_τ categories improves purity of hadronic τ ID
  - Enriched in $Z \rightarrow \tau\tau$ used for reducing τ reconstruction systematic uncertainties

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

Main systematics uncertainty sources

- Lepton reconstruction efficiencies and p_T scale
- Normalization of simulation and data-driven backgrounds
- Modelling of $t\bar{t}$

	$W \to e\bar{\nu}_e$	$W \to \mu\bar{\nu}_\mu$	$W \to \tau\bar{\nu}_\tau$	$W \to q\bar{q}'$
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

W branching fractions and correlations

	CMS	LEP	CMS+LEP*
w/o LU			
$W \to e\nu$	$(\mathbf{10.83} \pm \mathbf{0.01} \pm \mathbf{0.10})\%$	$(10.71 \pm 0.14 \pm 0.07)\%$	$(10.800 \pm 0.085)\%$
$W \to \mu\nu$	$(\mathbf{10.94} \pm \mathbf{0.01} \pm \mathbf{0.08})\%$	$(10.63 \pm 0.13 \pm 0.07)\%$	$(10.883 \pm 0.071)\%$
$W \to \tau\nu$	$(\mathbf{10.77} \pm \mathbf{0.05} \pm \mathbf{0.21})\%$	$(11.38 \pm 0.17 \pm 0.11)\%$	$(11.035 \pm 0.146)\%$
w/ LU			
$W \to h$	$(\mathbf{67.32} \pm \mathbf{0.02} \pm \mathbf{0.23})\%$	$(67.41 \pm 0.18 \pm 0.20)\%$	$(67.365 \pm 0.163)\%$

Correlations matrices for leptonic branching fractions

CMS

$$\begin{bmatrix} 1 & +0.439 & +0.138 \\ +0.439 & 1 & +0.190 \\ +0.138 & +0.190 & 1 \end{bmatrix}$$

LEP

$$\begin{bmatrix} 1 & +0.136 & -0.201 \\ +0.136 & 1 & -0.122 \\ -0.201 & -0.122 & 1 \end{bmatrix}$$

CMS+LEP

$$\begin{bmatrix} 1 & +0.383 & -0.045 \\ +0.383 & 1 & 0.005 \\ -0.045 & 0.005 & 1 \end{bmatrix}$$