Status of electroweak parameters measurements

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on behalf of the ATLAS, CMS and LHCb Collaborations

- introduction
- m_W, Γ_W
- $\sin^2(\theta_W)$
- $\Gamma(Z \rightarrow \text{inv})$
- m_{top}

Introduction

- **Rich variety of electroweak interaction derived from symmetry principles**
- **Mass of electroweak gauge bosons and interaction strength predicted precisely from g, g′, v, λ**

$SU(2)_L \times U(1)_Y$

$\Rightarrow W^+, W^-, Z, \gamma$

- **Parameters of the Standard Model**
  - four input parameters, e.g. α_{QED}, G_F, m_Z and m_H
  - interconnected with each other
    - at Tree level

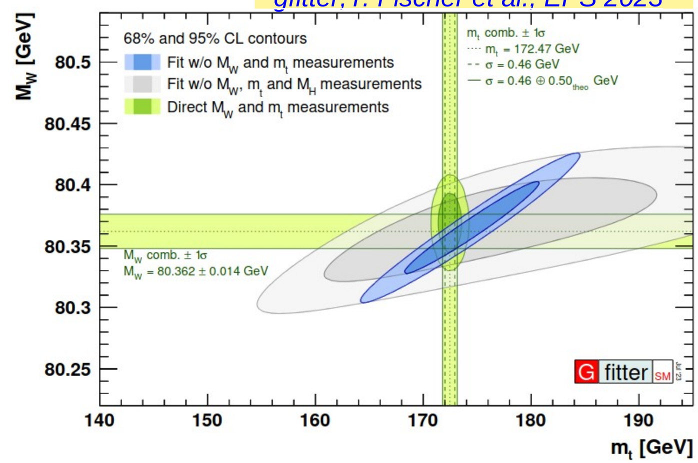
$$m_W = \frac{gv}{2}, m_Z = \frac{\sqrt{g^2+g'^2}\,v}{2}, \sin^2\theta_W = \frac{g^2}{g^2+g'^2} = 1 - m_W^2/m_Z^2, G_F = \frac{\sqrt{2}\,g^2}{8\,m_W^2}$$

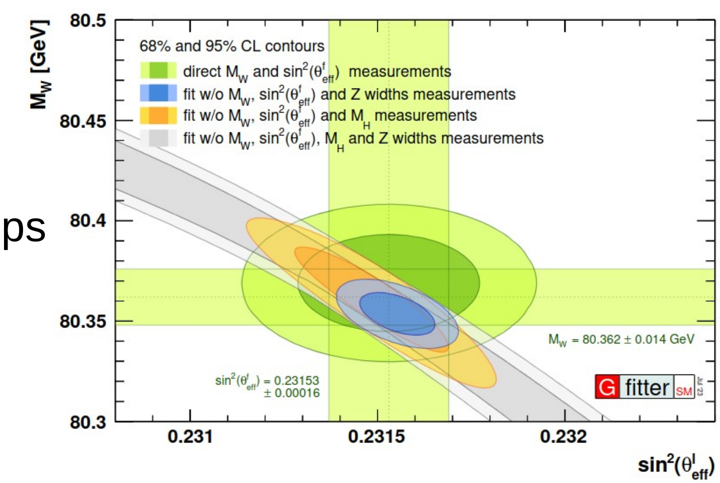
    - at leading order $\sin^2\theta^{\ell}_{eff} \propto (1 - g_v/g_a)$
      related to the real effective (leptonic) vector and axial-vector couplings of the Z boson
    - at higher orders

$$m_W = \left(\frac{\pi\alpha_{QED}}{\sqrt{2}\,G_F}\right)^{1/2} \frac{\sqrt{1+\Delta r}}{\sin\theta_W}, \sin^2\theta^{\ell}_{eff} = \kappa \sin^2\theta_W, \kappa \sim 1.037$$

  - radiative corrections Δr modify propagator and decay vertices
    - sensitivity to a wide range of physics through quantum loops
    - largest contributions from m_t^2, $\log(m_H)$
- **Precision measurements**
  - test self-consistency of SM theory in global EW fits
  - tensions could be signs of BSM effects

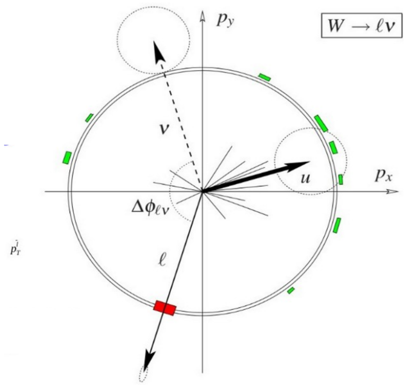
gfitter,Y. Fischer et al., EPS 2023



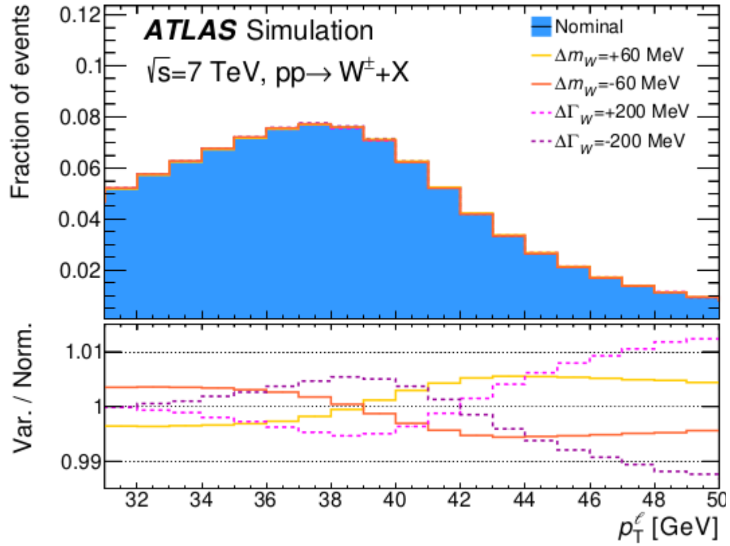


Measurement of the W boson mass and width

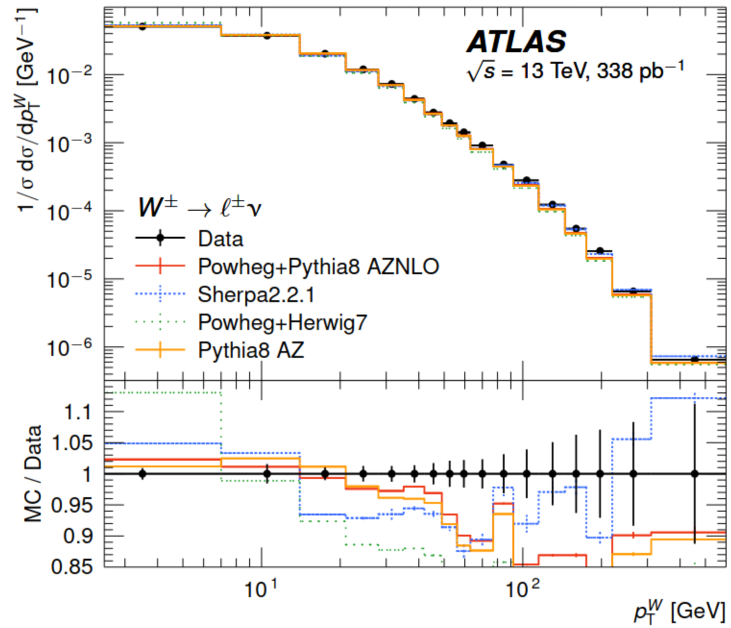
arXiv:0901.0512



arXiv:2403.15085



arXiv:2404.06204



- **ATLAS**
  - revisit 2011 (7 TeV) data, favourable experimental environment for measurement of m_W
  - measured from p_T^{ℓ} and m_T^{W} distributions in $W \to \ell\nu$ decays
  - checks of p_T^{W} modelling in dedicated measurements
  - more modern PDF sets : CT18 (was CT10nnlo)
  - small update to uncertainties for higher-order electroweak corrections
  - key change : use profile likelihood fit (was χ^2 fit)
    - constrain systematic uncertainties in situ
    - directly determine their correlations
    - challenge: m_W now also correlated with some syst. variations

    → extensive validation of method to avoid biases

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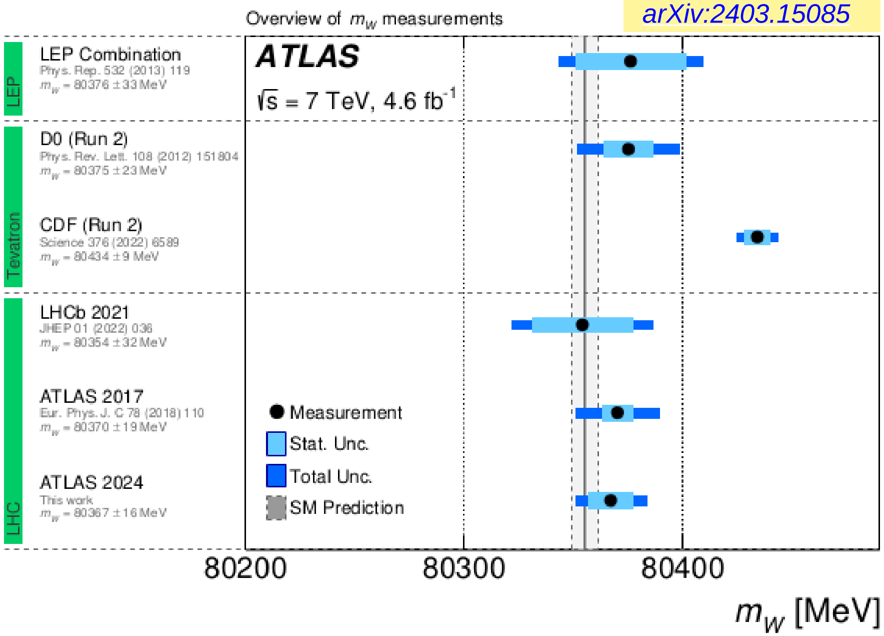
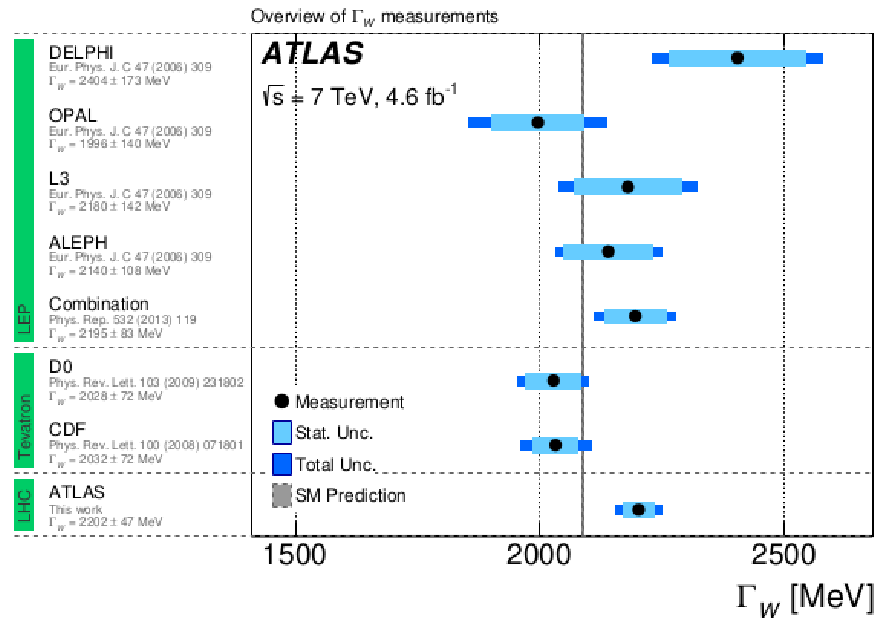




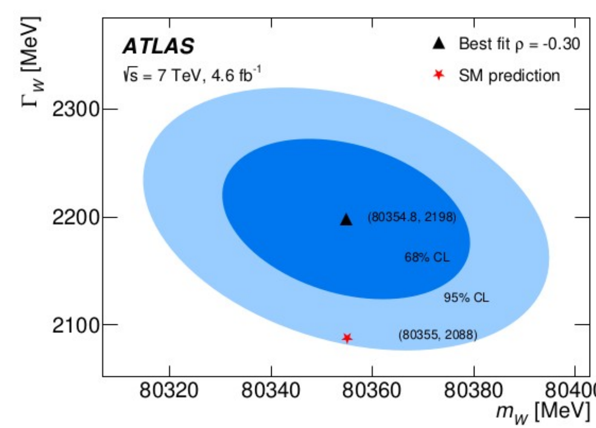
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18

- separate measurement of mass and width :

$$m_W = 80366.5 \pm 15.9 \text{ MeV}$$

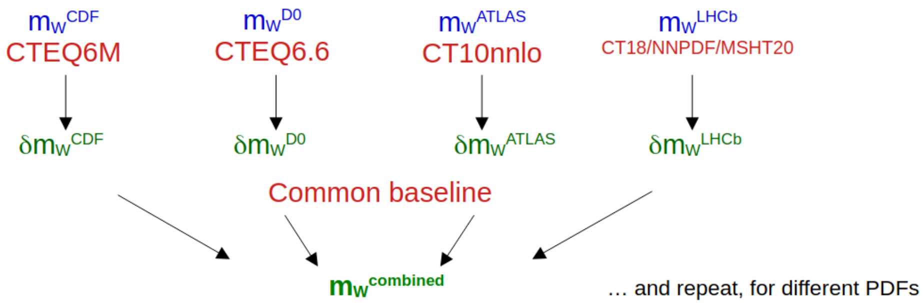
$$\Gamma_W = 2202 \pm 47 \text{ MeV}$$



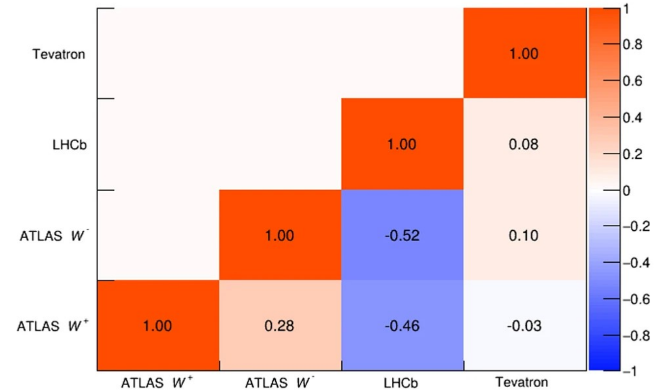
- … as well as simultaneous extraction
- most precise single-experiment measurement of Γ_W

Measurement of the W boson mass m_W

- **Combination « ATLAS, LHCb, D0, CDF »** *EPJ C (2024) 84:451*
  - measurements performed at different times, using different baseline PDFs and QCD tools : existing result extrapolated to a common baseline
  - two-step procedure :
    - correct to common theory and modelling
    - combine including correlations (proton structure)



M. Boonekamp, LHC EW WG General Meeting, July 2024



PDF uncertainty correlation matrices for the CT18 PDF set

LHCb : m_W determination in the forward acceptance strongly suppresses the PDF uncertainty in an LHC m_W average due to complementary geometry.
It is only a 2016 dataset analysis, with a full Run 2 analysis still possibly coming ! *JHEP 01 (2022) 036*

m_W = 80364 ± 32 MeV

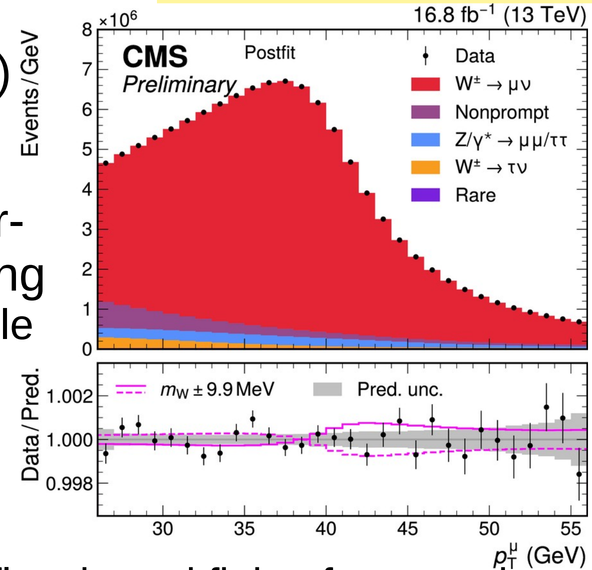
Tension between « ATLAS, LHCb, D0 » combination and CDF W mass is of 3.6 σ

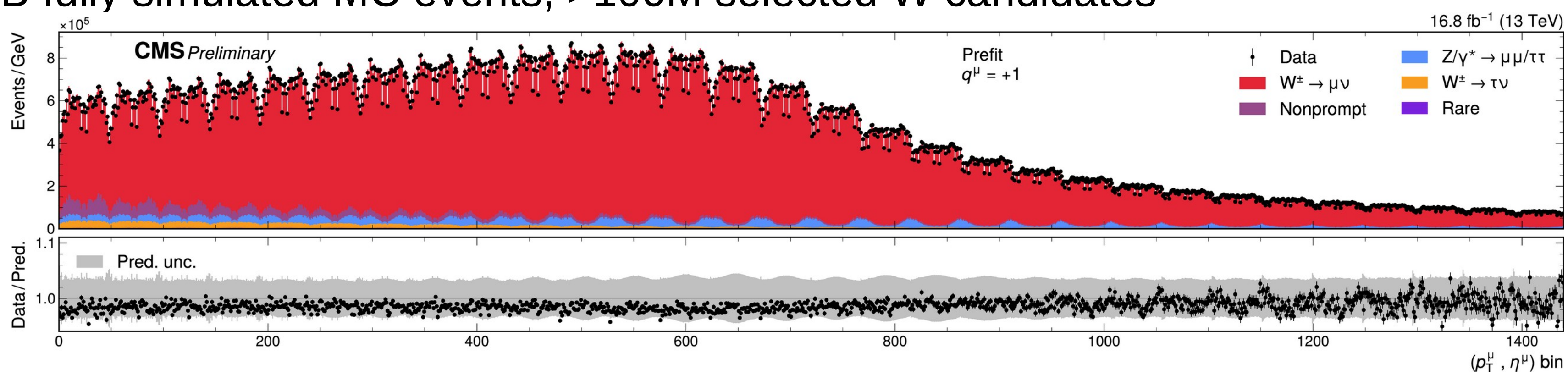
« ATLAS, LHCb, D0 » : m_W = 80369.2 ± 13.3 MeV

Measurement of the W boson mass

CMS-PAS-SMP-23-002
J. Bendavid, CMS CERN seminar

- **CMS**
  - use well-understood subset of 13 TeV data: 16.8 fb^{-1} from later part of 2016 run (∼30 mean interactions per crossing)
    - focus on muon channel and kinematics
    - larger experimental syst. for electrons and hadronic recoil
  - strategy : exploit large dataset, accurate modeling of uncertainties for maximal in-situ contraints on theoretical modeling
    - reserve Z data as independent cross-check as much as possible
    - muon calibration from J/ψ, validated with Z
    - in-situ constraints on theory modeling from W data itself, independent validation with Z
  - m_W extracted from profile likelihood fit to μ (η, p_T, charge)
    - thousands of bins and systematic variations ;optimized Tensorflow-based fitting framework
  - building on experimental techniques, tools, and experience from W-like m_Z measurement (2016) and W rapidity-helicity measurement (2020) which established strong in-situ constraints on PDFs from charged lepton kinematics
  - 4B fully simulated MC events, >100M selected W candidates





Measurement of the W boson mass

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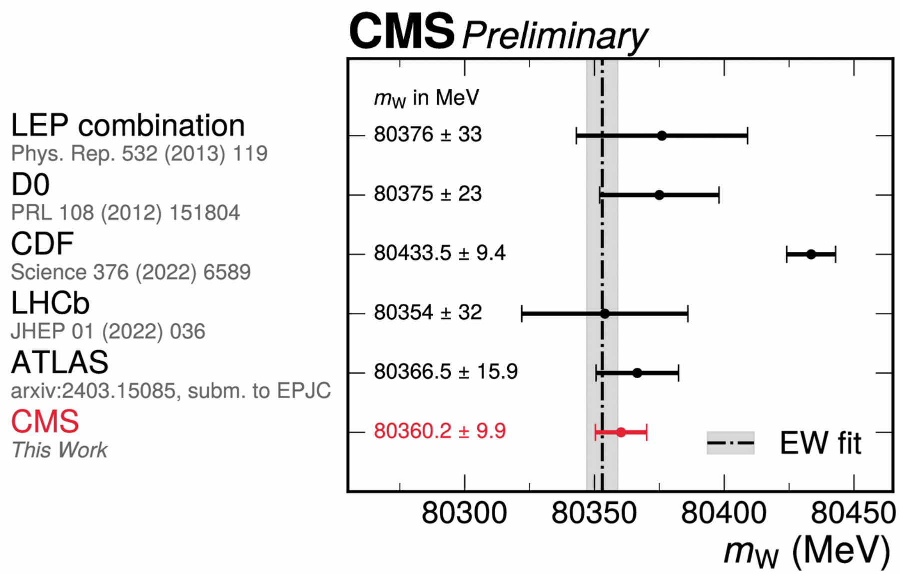
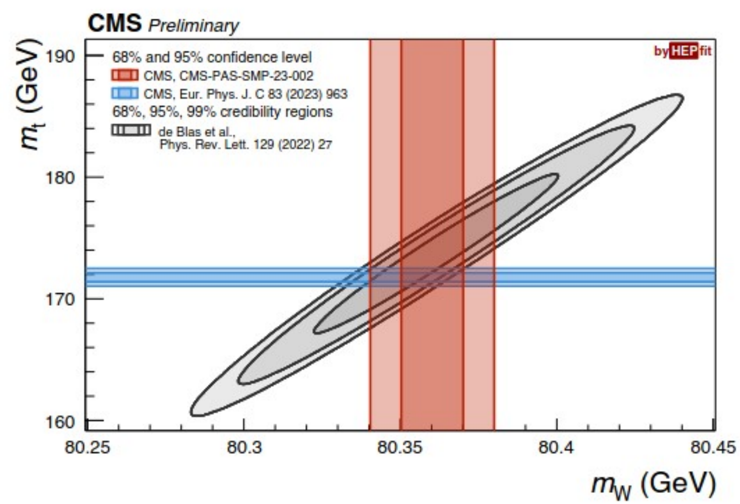


Source of uncertainty	Impact (MeV) Nominal in m_Z	Nominal in m_W	Global in m_Z	Global in m_W
Muon momentum scale	5.6	4.8	5.3	4.4
Muon reco. efficiency	3.8	3.0	3.0	2.3
W and Z angular coeffs.	4.9	3.3	4.5	3.0
Higher-order EW	2.2	2.0	2.2	1.9
p_T^V modeling	1.7	2.0	1.0	0.8
PDF	2.4	4.4	1.9	2.8
Nonprompt background	–	3.2	–	1.7
Integrated luminosity	0.3	0.1	0.2	0.1
MC sample size	2.5	1.5	3.6	3.8
Data sample size	6.9	2.4	10.1	6.0
Total uncertainty	13.5	9.9	13.5	9.9

$m_W = 80360.2 \pm 9.9$ MeV

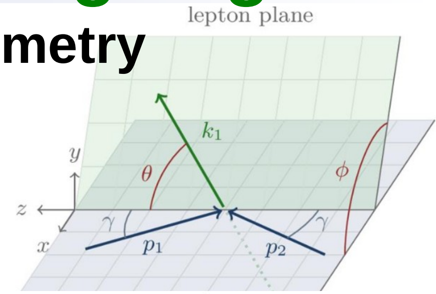
Towards the electroweak fit precision



- first m_W measurement from CMS
- in agreement with the SM prediction
- measurement is performed with ~10% of Run 2 data
- major advances in experimental and theoretical techniques from the basis for further improved precision and additional measurements in the future

Measurement of the effective weak mixing angle

- **Measurement of $pp \to Z/\gamma^* \to \ell^+\ell^-$ Forward-Backward asymmetry**



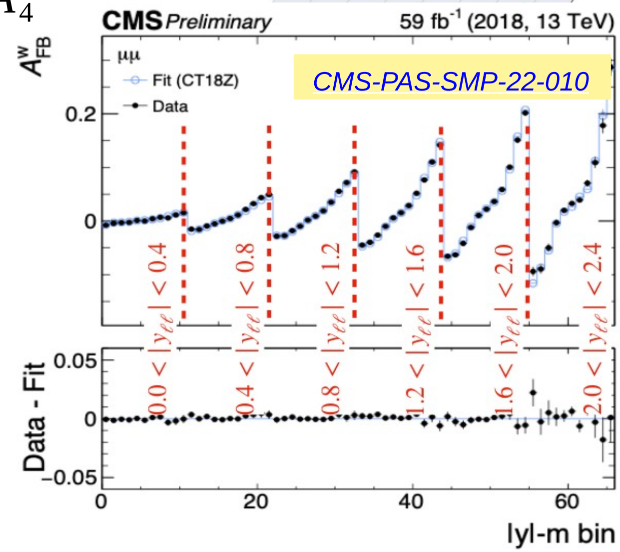
○ use Collins-Soper frame (Z boson at rest)

- z axis defined by quark direction
- using final state leptons angular distribution

$$\frac{d\sigma}{d\cos\theta} \sim 1+\cos^2\theta + \frac{1}{2}A_0\left(1-2\cos^2\theta\right) + A_4\cos\theta \quad , A_{FB} = \frac{3}{8}A_4$$

○ the Forward-Backward asymmetry A_{FB} increases with the Z boson rapidity

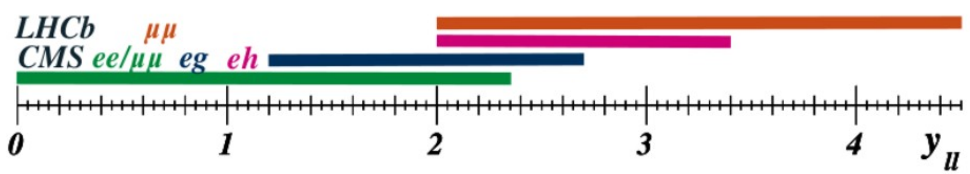
- only valence quarks contribute to the A_{FB}
- ambiguity in quark direction resolved through rapidity-dependent measurement

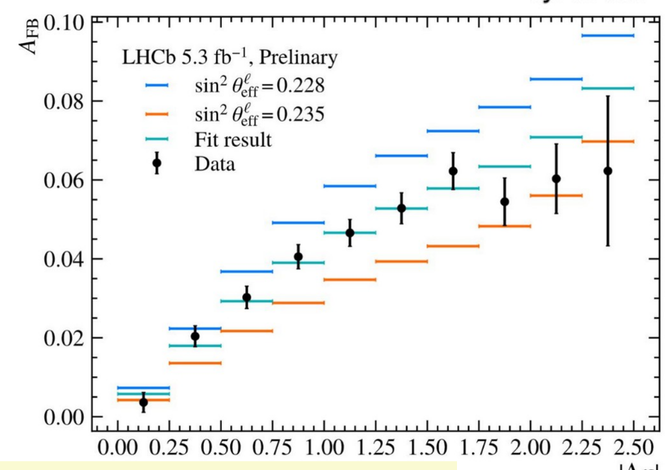


○ experimentally defined as

$$A_{FB} = \frac{N(\cos\theta>0) - N(\cos\theta<0)}{N(\cos\theta>0) + N(\cos\theta<0)} \qquad A_{FB} = \frac{N(\eta^- > \eta^+) - N(\eta^- < \eta^+)}{N(\eta^- > \eta^+) + N(\eta^- < \eta^+)}$$

- reconstruction of muons in CMS up to |η|<2.4
  3 categories for electrons : « e » tracker only (|η|<2.5),
  «g» in FCAL (2.5<|η|<2.87),
  «h» in forward HCAL (2.5<|η|<2.87),
- high quality muon reconstruction in LHCb in 2.0<|η|<4.5





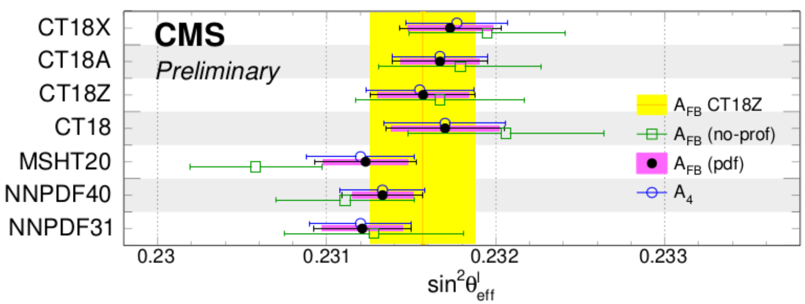
LHCb-PAPER-2024-028 in preparation
(*link* to CERN seminar)

Measurement of the effective weak mixing angle

- **CMS**
  - total uncertainty dominated by PDFs
  - PDF reweighted/profiled in fit of A_{FB} and A_4 to determine $\sin^2\theta^{\ell}_{eff}$
    - reduces PDF uncertainties by a factor of 2
    - results in better agreement between different PDF sets
  - CT18Z chosen as 'default' pdf set before unblinding
    - its uncertainty covers best other central values

- **LHCb**
  - the uncertainty from the PDF is estimated following the prescription provided by the groups responsible for each of the PDF sets used
  - considering variations in the PDF "replicas"
  - the PDF uncertainty ≪ statistical uncertainty (~4.4×10^{-4}) because of the use of the LHCb acceptance
  - don't need to use profiling to reduce the PDF uncertainty

CMS-PAS-SMP-22-010



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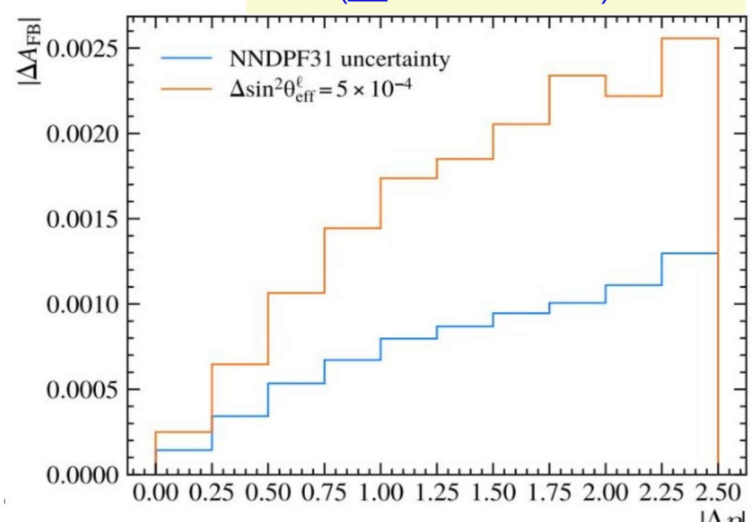
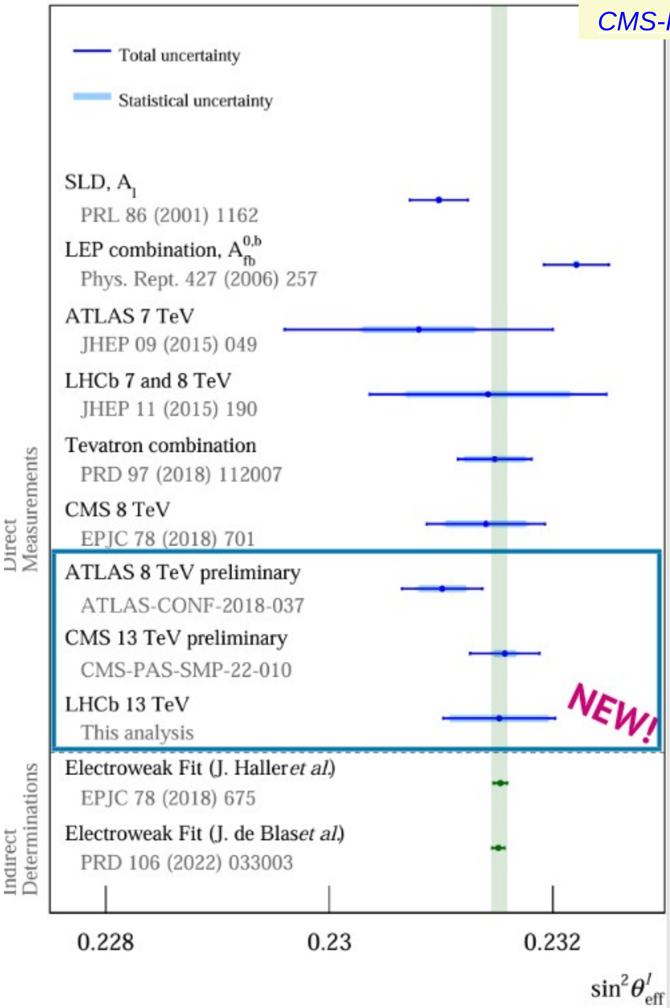


Measurement of the effective weak mixing angle

LHCb-PAPER-2024-028 in preparation
(*link* to CERN seminar)

- **Precise measurements from hadron colliders**
  - precisions comparable to the most precise single measurements at LEP A^b_{FB} and SLD A_{LR} determination
  - to be compared to calculation from SM using precise experimental inputs
    $\sin^2\theta^\ell_{eff}$ = 0.23155 ± 0.00004 (SM)

CMS-PAS-SMP-22-010



CMS : $\sin^2\theta^\ell_{eff}$ = 0.23157 ± 0.00010 (stat) ± 0.00015 (syst) ± 0.00009 (theo) ± 0.00027 (PDF)
LHCb : $\sin^2\theta^\ell_{eff}$ = 0.23152 ± 0.00044 (stat) ± 0.00005 (syst) ± 0.00022 (theo/PDF)

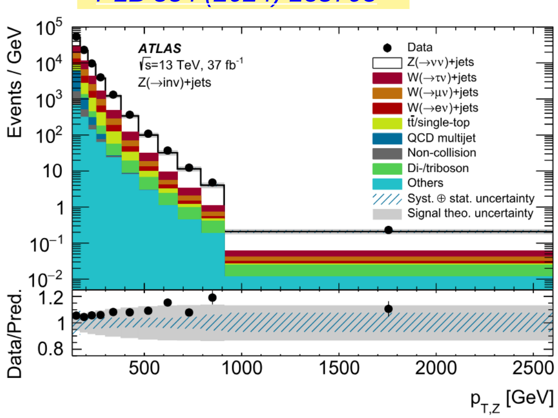
Z boson invisible width

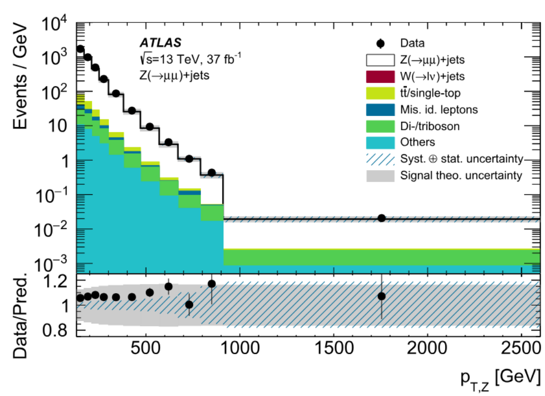
- **Width of Z boson for decays into invisible states $\Gamma(Z\rightarrow \text{inv})$ sensitive to**
  - number of light neutrinos ($m_\nu < m_Z/2$)
  - potential BSM contributions from new particles

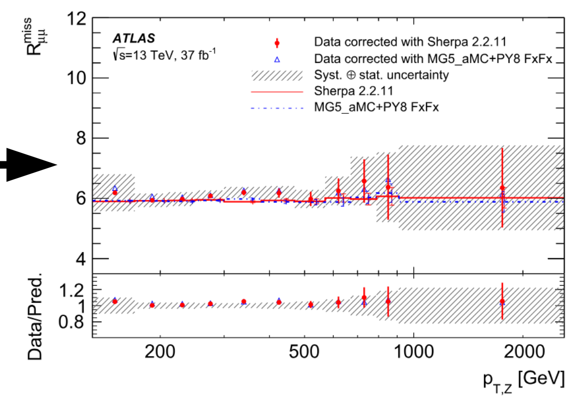
1. correct $Z\rightarrow$inv and $Z\rightarrow \ell\ell$ to common phase-space
2. take ratio
3. fit constant $\hat{R}^{\text{miss}}$

$$R^{\text{miss}}(p_{\text{T,Z}}) \equiv \left(\frac{d\sigma(Z(\rightarrow \text{inv}) + \text{jets})}{d\,p_{\text{T,Z}}}\right) \Big/ \left(\frac{d\sigma(Z(\rightarrow \ell\ell) + \text{jets})}{d\,p_{\text{T,Z}}}\right)$$

PLB 854 (2024) 138705







Z boson invisible width

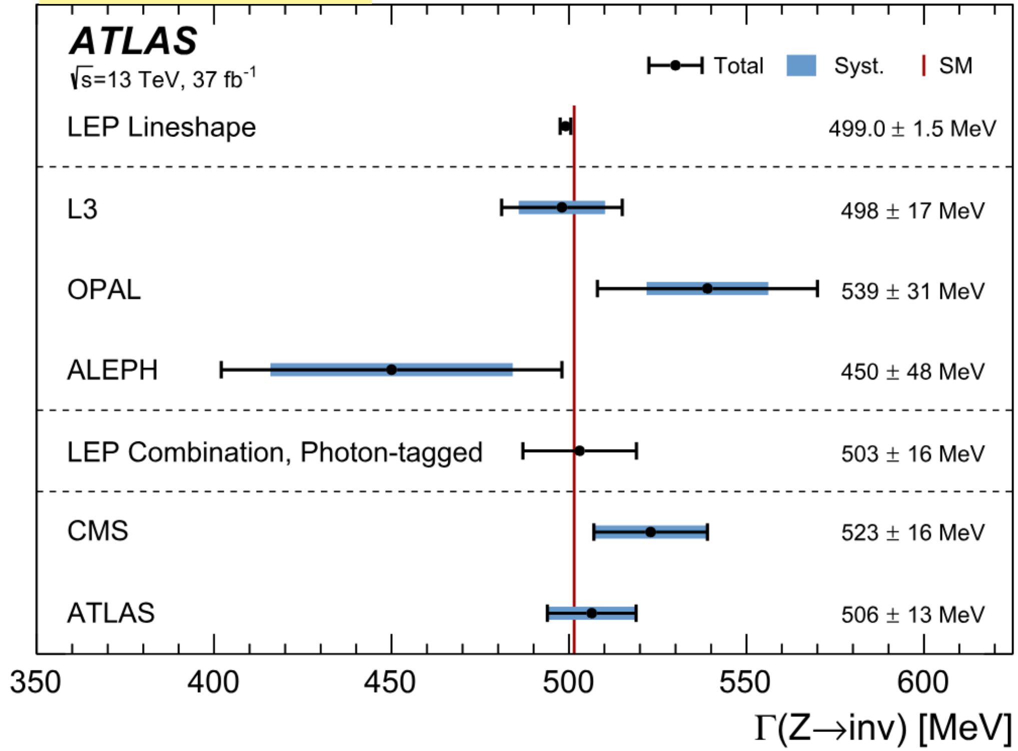
Convert fitted constant to Z boson invisible width by combining with $Z \to \ell\ell$ width measurement from LEP

$$\Gamma(Z \to \mathrm{inv}) = \hat{R}^{\mathrm{miss}} \cdot \Gamma(Z \to \ell\ell)$$

Most precise recoil-based result

Precision limited by lepton systematic uncertainties in $Z \to \ell\ell$ events

PLB 854 (2024) 138705



ATLAS : $\Gamma(Z \to \mathrm{inv})$ = 506 ± 13 MeV

PLB 854 (2024) 138705

CMS : $\Gamma(Z \to \mathrm{inv})$ = 523 ± 16 MeV

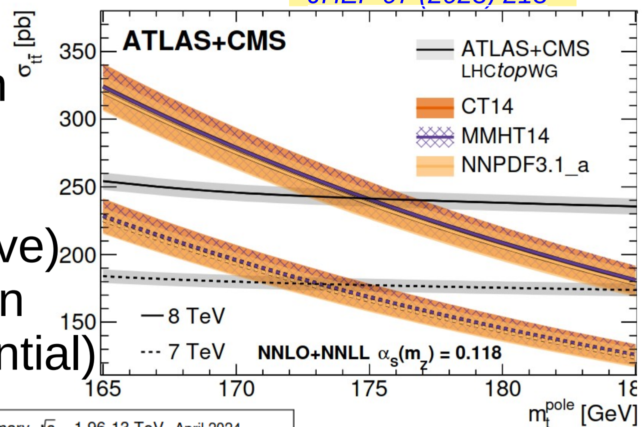
Phys. Lett. B 842 (2023) 137563

Measuring the top-quark mass m_t

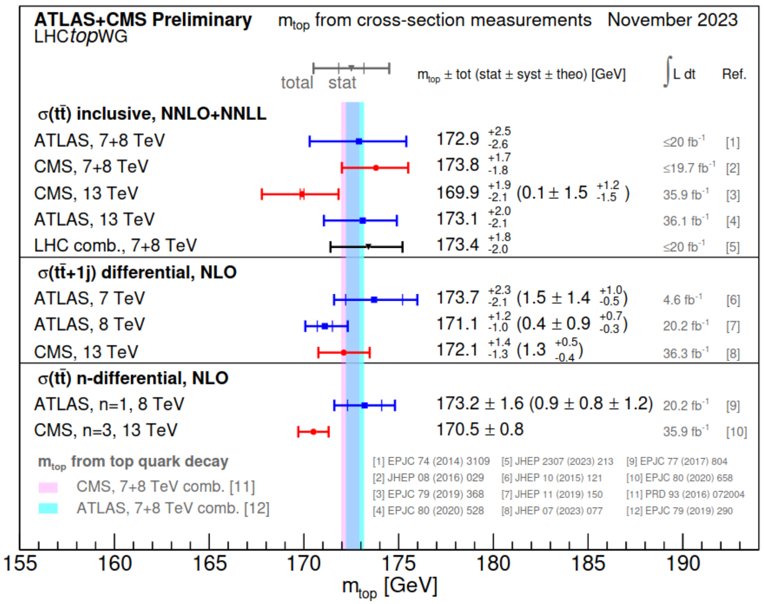
- **Significant improvements over the past years**
  - better calibrations, alternative techniques, improved theoretical modelling
  - more than 40 publications by ATLAS and CMS collaborations

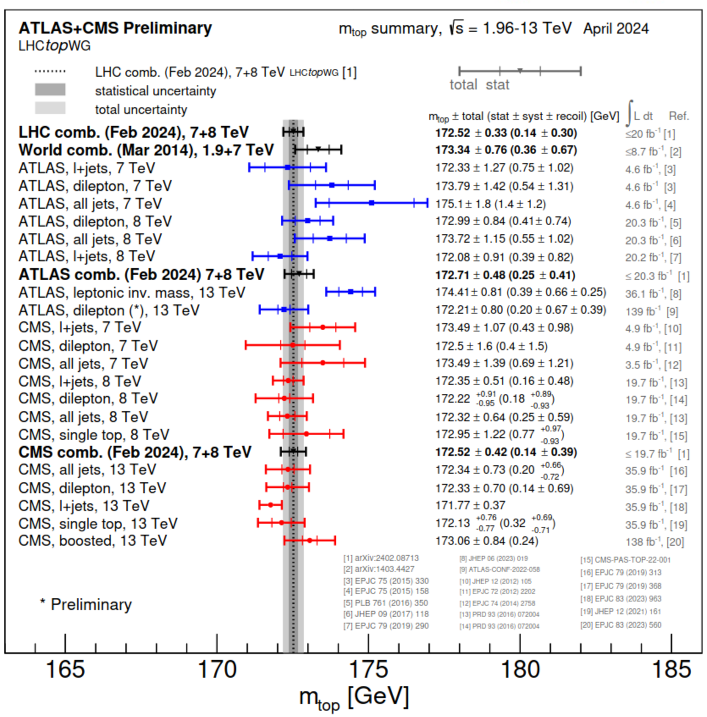
- **« Indirect »**
  - from cross-section measurements
  - ~1% precision on pole mass (inclusive)
  - ~0.4% precision on pole mass (differential)

JHEP 07 (2023) 213



LHCTopWGSummaryPlots





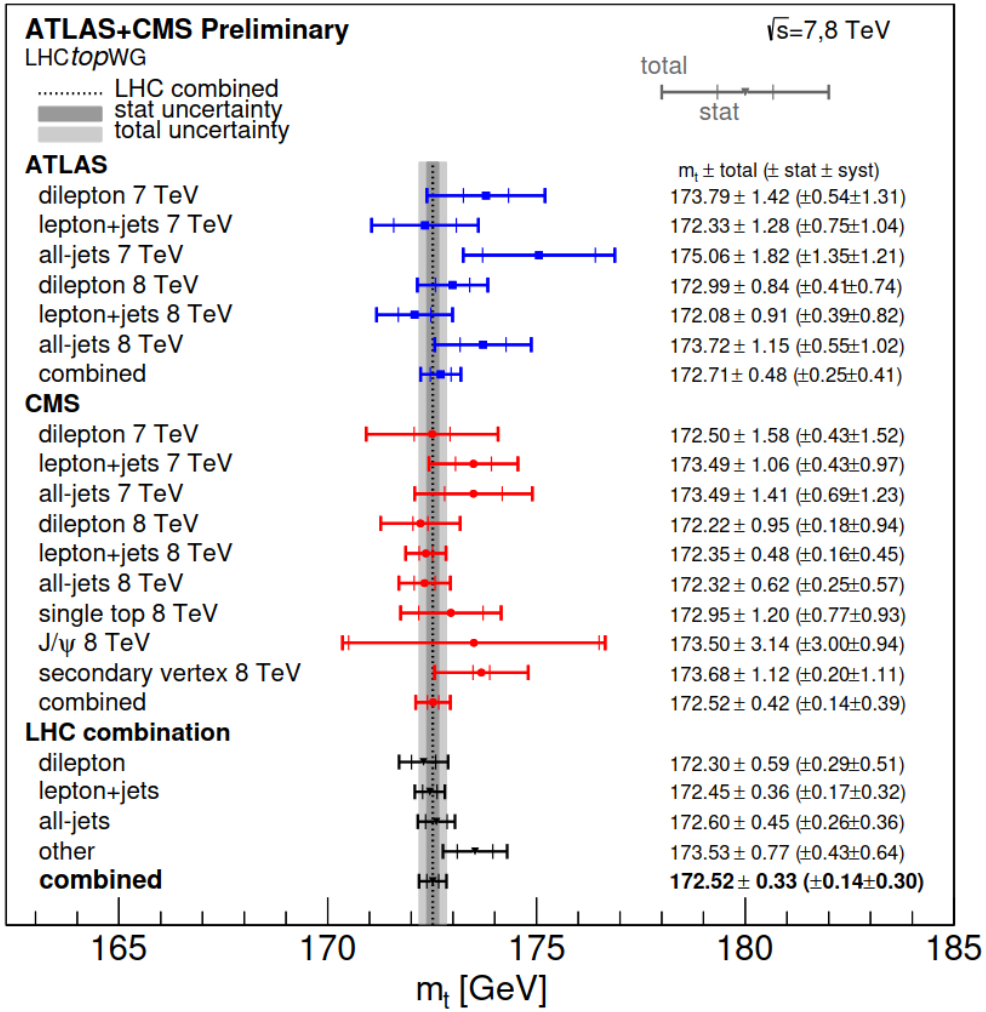
- **« Direct »**
  - extract m_t from decay products (ℓ+jets, ℓℓ)
  - ~0.2% precision single most precised measurements @13 TeV

CMS ℓ+jet : m_t = 171.77 ± 0.37 GeV — *EPJC 83 (2023) 963*

ATLAS ℓℓ : m_t = 172.21 ± 0.80 GeV — *ATLAS-CONF-2022-058*

Measuring top-quark mass m_t : Run 1 combination

A combination of fifteen top-quark mass measurements performed by the ATLAS and CMS experiments at the LHC



LHCTopWGSummaryPlots
Phys. Rev. Lett. 132, 261902

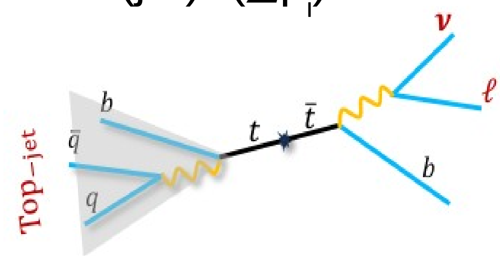
- using BLUE[1], calculate or estimate the correlation between measurements, then calculates the corresponding uncertainty on the physics parameter
- ATLAS inputs 6 measurements, CMS the same channels plus single top, J/ψ and secondary vertex at 8TeV
- to see compatibility run “simultaneous” BLUE with two m_t parameters, m_t(ATLAS) and m_t(CMS), excellent agrement
- resulting precision is below 2 per mil
- 31% improvement over most precise single input

[1] Nucl. Inst. and Meth. A 270 (1988) 110

m_t=172.52±0.14 (stat)±0.30 (syst) GeV, with a total uncertainty of 0.33 GeV

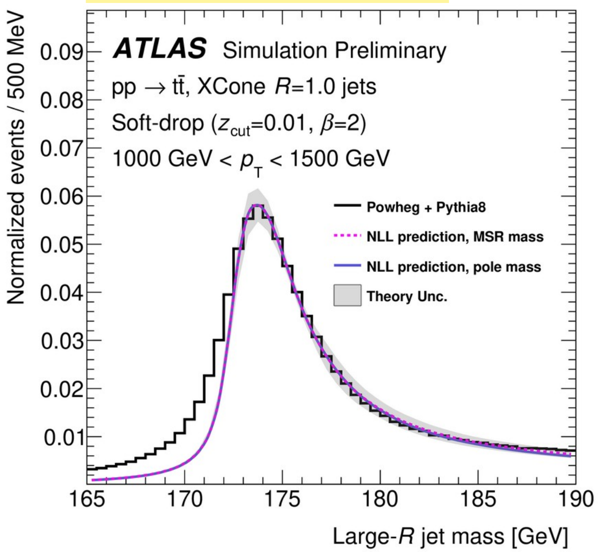
Measuring m_t : boosted channels

- **Direct measurements from top-quark decays**
  - extract well defined m_t from boosted top-jet using large-radius jet : $m^2(\text{jet})=(\sum p_i)^2$
  - compare measurement to well defined field theory parameter
    - no additional uncertainty for $m_{top}^{MC} \rightarrow m_{top}^{MSR}$
  - phase-space of theory and experiment different
    - calculations only at $p_T \geq 750$ GeV and experiment at $p_T \geq 400$ GeV



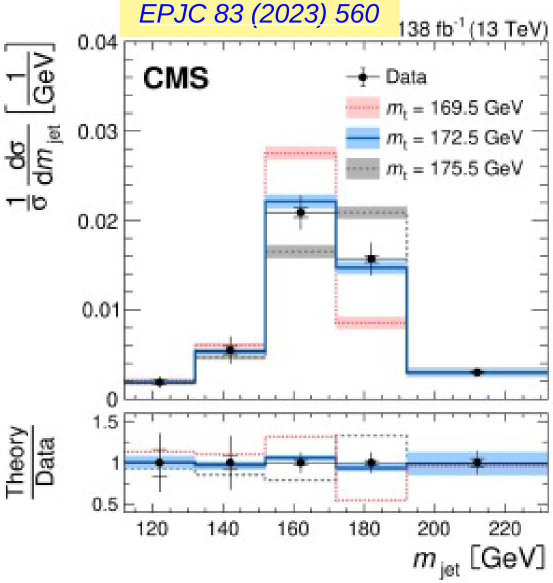
- **CMS**
  - improved jet reconstruction in Run 2 ⇒ improvement in jet resolution
  - unfolding, differential cross-section measurement
  - reduced dominant uncertainties : calibration of Jet Mass Scale, modeling of FSR

ATL-PHYS-PUB-2021-034

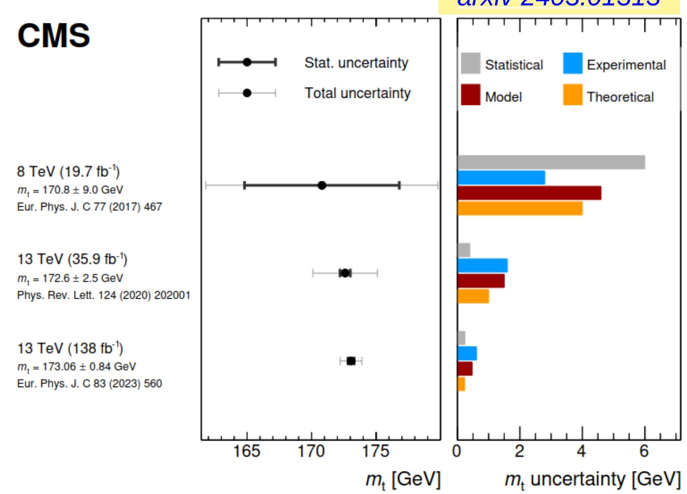


$$\Delta^{MSR} = m_t^{\mathrm{MC}} - m_t^{\mathrm{MSR}}(1\ \mathrm{GeV}) = 80^{+350}_{-400}\ \mathrm{MeV}$$

EPJC 83 (2023) 560



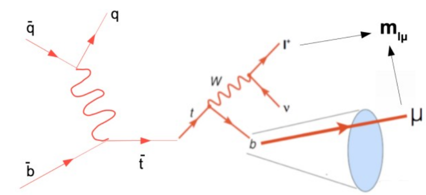
arxiv 2403.01313



m_t = 173.06 ± 0.84 GeV

Measuring m_t : alternative channels

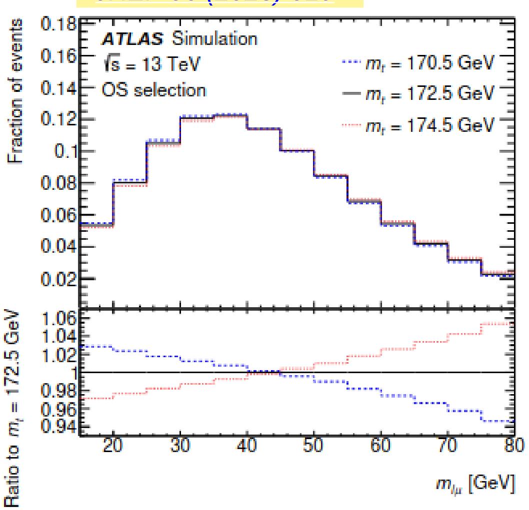
- **Direct measurements from top-quark decays**
  - alternative measurements ⇒ sensitive to different systematics



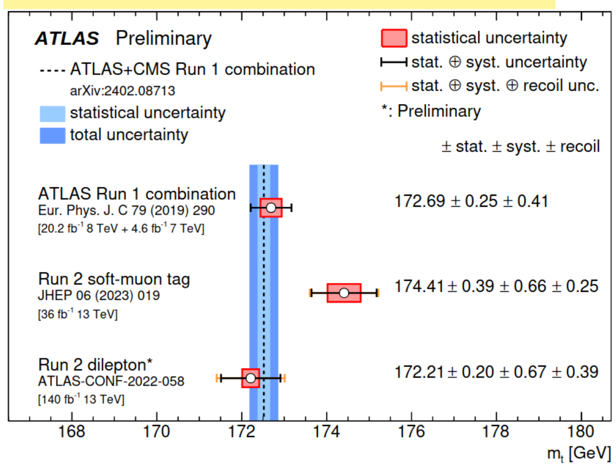
ATLAS

- construct templates of leptonic-only $m_{l\mu}$, lepton from W and soft μ from a b-hadron
  - smaller sensitivity to jet energy scale & resolution
  - less sensitivity to top-quark production modeling than previously showed measurement
- binned-template profile likelihood fit used to find best value for m_t, systematics included as Gaussian-constrained nuisance parameters

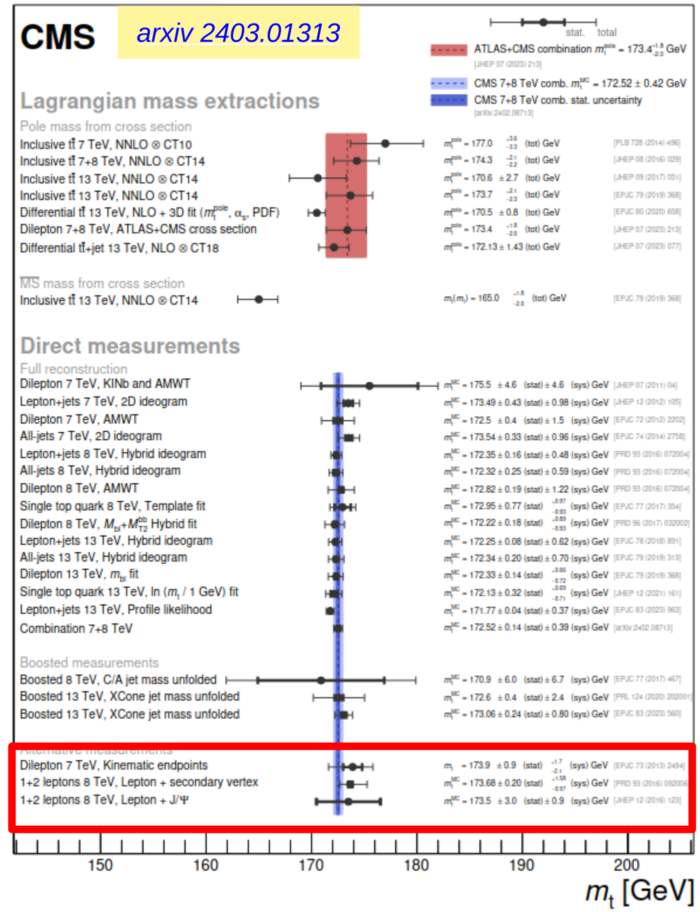
JHEP 06 (2023) 019



arXiv:2404.10674, sub. to Physics Reports



arxiv 2403.01313



m_t = 174.41 ± 0.39 (stat.) ± 0.66 (syst.) ± 0.25 (recoil) GeV

"Alternative": limited by modeling of b-quark fragmentation

Summary

- **Numerous results of precision electroweak physics released in the last 12 months!**

- **The LHC is competing with previous machines in electroweak precision**

- **Facilitated by large datasets, detailed understanding of the detectors, dedicated reconstruction techniques and state-of-the-art theory predictions**

- **New measurements of key electroweak parameters**
  m_W (precision at 0.2 per mil), Γ_W and $\sin^2\theta^{\ell}_{eff}$

- **They join precision probes in improving our understanding of electroweak symmetry breaking**
  - top-quark mass measurements in different channels, with increasing precision ATLAS+CMS Run-1 combination lead to a precision already around 0.3 GeV (precision below 2 per mil)
  - precise measurements of $\Gamma(Z \rightarrow inv)$

Backup slides

Introduction

- **Parameters of the Standard Model**
  - at Tree level, simple relations after BEH mechanism with $\phi=\begin{pmatrix}0\\ v/2\end{pmatrix}$
    - $m_W=\frac{gv}{2} \quad m_Z=\frac{\sqrt{g^2+g'^2}\,v}{2}$
  - radiative corrections Δr modify propagator and decay vertices
    - sensitivity to a wide range of physics through quantum loops
    - largest contributions from m_t, $\log(m_H)$

$$G_F \propto \frac{g^2}{m_W^2} \qquad m_W=\left(\frac{\pi\alpha_{QED}}{\sqrt{2}G_F}\right)^{1/2}\frac{\sqrt{1+\Delta r}}{\sin\theta_W}$$

$$\sin^2\theta_W=1-m_W^2/m_Z^2$$

$$\sin^2\theta_{eff}^{\ell}=\kappa\sin^2\theta_W,\ \kappa\sim1.037$$

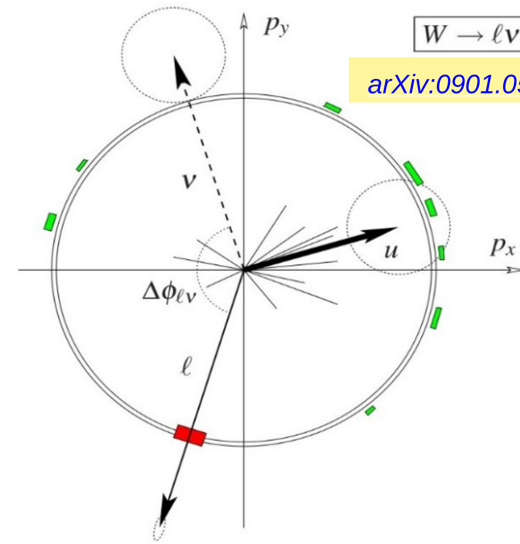
2

- **Precision measurements**
  - test self-consistency of SM theory in global EW fits
  - tensions could be signs of BSM effects
  - probe BSM beyond reach of searches

Measurement of the W boson mass m_W

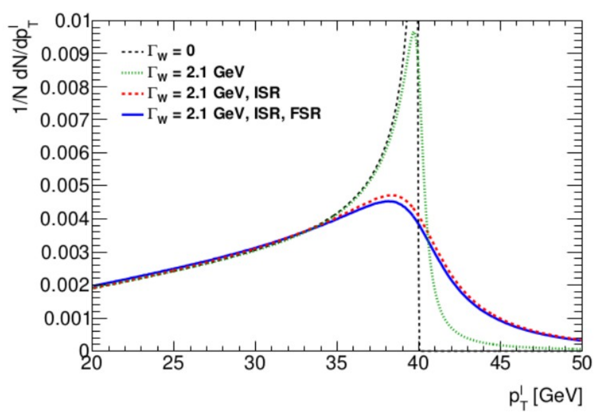
- **The W boson mass in proton collisions**
  - incomplete kinematics (due to missing neutrino)
    - no invariant mass; rely on measured quantities, and exploit momentum conservation in the transverse plane
  - event representation
    - main signature : electron or muon $\vec{p}_T^{\,\ell}$
    - recoil : sum of « everything else » reconstructed in the calorimeters $\vec{u}_T = \sum \vec{E}_T^i \Rightarrow$ a measure of $p_T^{W,Z}$
    - derived quantities[i]

$$\vec{p}_T^{\,miss} = -(\vec{p}_T^{\,\ell} + \vec{u}_T) \qquad m_T = \sqrt{2\, p_T^{\ell}\, p_T^{miss} (1 - \cos\Delta\phi)}$$

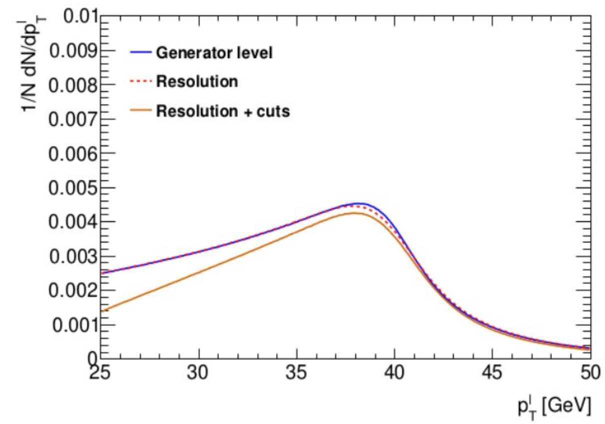


arXiv:0901.0512

- physics correction :
  - Γ_W, QCD and QED ISR and FSR, PDFs, …
  - all carry uncertainties to be quantified !



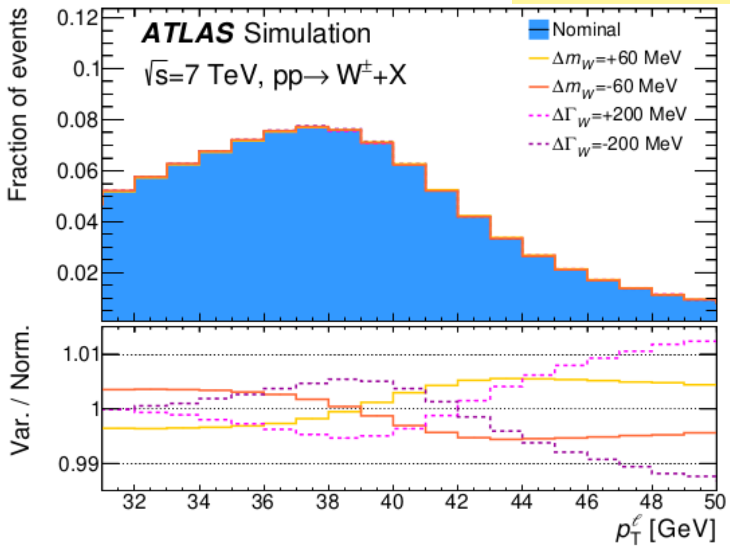
- detector effects, with uncertainties
  - lepton calibration and resolution; Missing ET resolution ~ 5 – 15 GeV
  - efficiencies and acceptance ~15% (with non-trivial kinematic dependence !)



Measurement of the W boson mass m_W

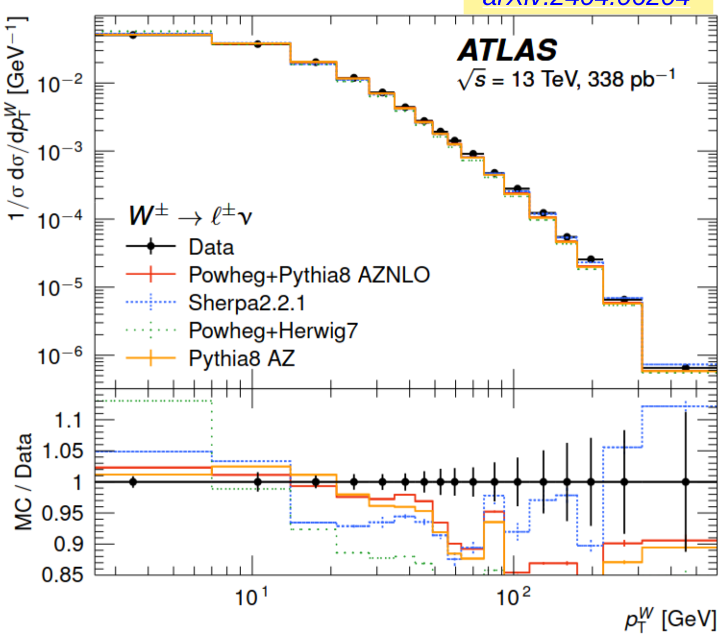
- **ATLAS**
  - revisit 2011 (7 TeV) data, favourable experimental environment for measurement of m_W
  - unchanged from previous analysis
    - 15 M $W \to e\nu$ and $W \to \mu\nu$ candidates
    - lepton p_T : Jacobian edge at $m_W/2$
    - transverse mass m_T: Jacobian edge at m_W, more sensitive to Γ_W in tails
    - template fits using kinematic observables sensitive to m_W and Γ_W

arXiv:2403.15085



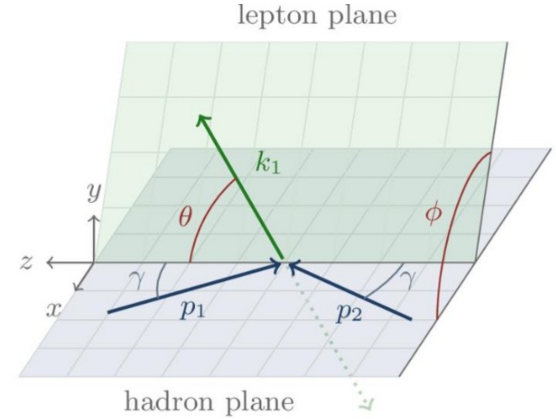
- **Improvement since first measurement**
  - checks of p_T^W modelling in dedicated measurements
  - update to QCD background estimation
  - more modern PDF sets : CT18 (was CT10nnlo)
  - small update to uncertainties for higher-order electroweak corrections
  - key change : profile likelihood fit
    - constrain systematic uncertainties in situ
    - directly determine their correlations
    - challenge: m_W now also correlated with some syst. variations → extensive validation of method to avoid biases

arXiv:2404.06204



Measurement of the effective weak mixing angle

- **Measurement of pp → Z/γ* → ℓ⁺ℓ⁻ Forward-Backward asymmetry**
  - the Forward-Backward asymmetry A_{FB} increases with the Z boson rapidity
    - only valence quarks contribute to the A_{FB}
    - the forward region direction is given by the valence quark i.e. the system boost direction
  - use Collins-Soper frame
    - z axis defined by quark direction
    - using final state leptons angular distribution in this frame



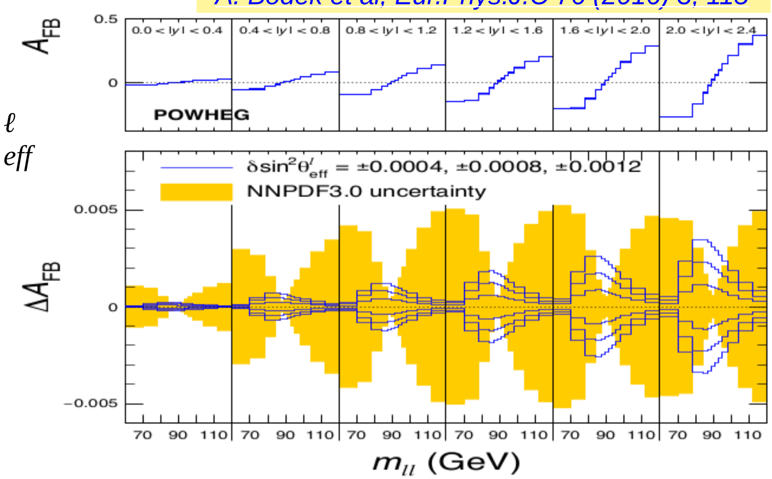
$$\frac{d\sigma}{d\cos\theta} \sim 1+\cos^2\theta+\frac{1}{2}A_0(1-2\cos^2\theta)+A_4\cos\theta \qquad A_{FB}=\frac{3}{8}A_4$$

  - at the Z peak, A_{FB} yields a measurement of $\sin^2\theta^{\ell}_{eff}$
    - strong PDF dependence
  - experimentally defined as

$$A_{FB}=\frac{N(\cos\theta>0)-N(\cos\theta<0)}{N(\cos\theta>0)+N(\cos\theta<0)}$$

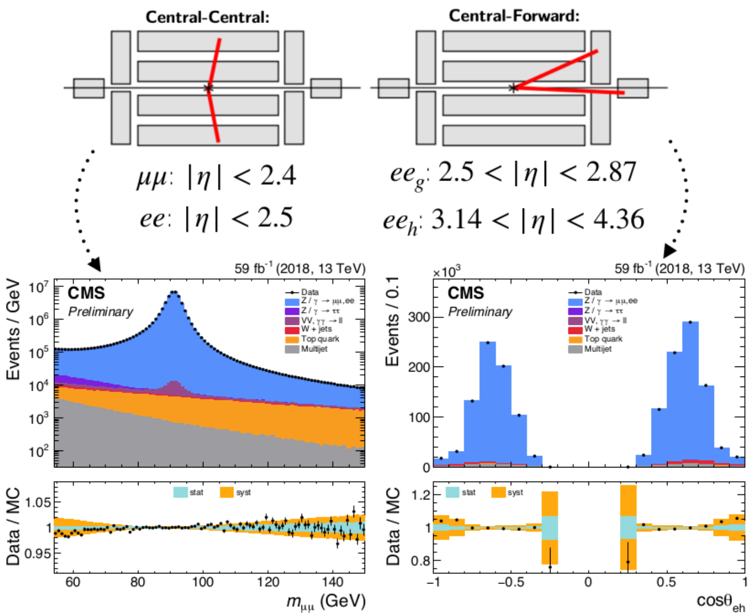
$$A_{FB}=\frac{N(\eta^->\eta^+)-N(\eta^-<\eta^+)}{N(\eta^->\eta^+)+N(\eta^-<\eta^+)}$$

A. Bodek et al, Eur.Phys.J.C 76 (2016) 3, 115



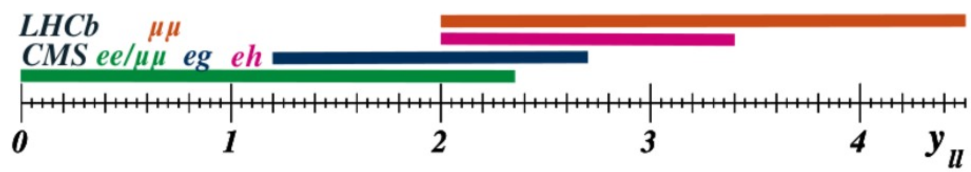
Measurement of the effective weak mixing angle

- **CMS analysis strategy**
  - full Run 2 dataset (137 fb^{-1})



  - background events
    - QCD multijets,
    - W+jets, …
    - others (MC samples)
  - systematic uncertainties
    - experimental : MC stat., efficiency, momentum calibration. backgrounds
    - theory : QCD scales, pT(ll), QED FSR virtual EW, **PDFs**

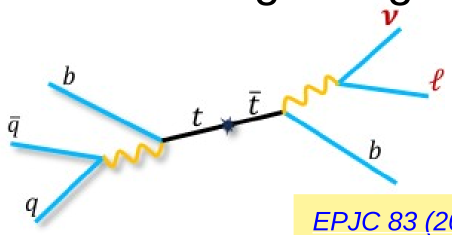
- **LHCb analysis strategy**
  - 2016-2018 dataset (5.3 fb^{-1})
  - measure A_{FB} in tens interval of $|\Delta\eta|$ up to $|\Delta\eta|<2.5$ using $Z\to\mu\mu$ decays
  - identified μ candidate matched to a single muon trigger path in a fiducial region $2.0<|\eta_\mu|<4.5$, $p_T(\mu)>20$ GeV $66<m(\mu\mu)<116$ GeV



  - background events
    - HF backgrounds are suppressed to the % level by a muon impact parameter requirement
    - hadronic background suppressed to the % level by an isolation requirement and muon track fit requirement
  - yields
    - roughly 860k events are selected

Measuring m_t : direct measurements

- « Direct » measurements from top-quark decays
  - better precision ; extract m_t from decay products
- CMS
  - most precise individual measurement performed in ℓ+jets channel
    - construct m_t from three jets
    - m_{top}^{MC} from minimizing a negative log-likelihood



EPJC 83 (2023) 963

m_t = 171.77 ± 0.37 GeV

- ATLAS
  - most precise individual measurement performed in ℓℓ+jets channel
  - construct templates of m_{lb}
  - m_{top}^{MC} from template fits on data

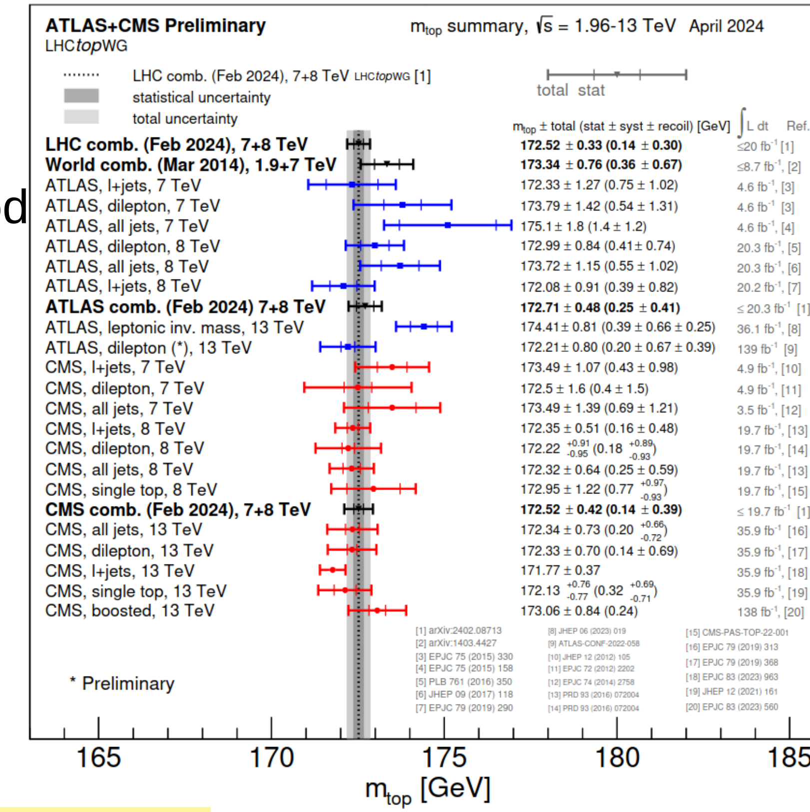
ATLAS-CONF-2022-058

m_t = 172.21 ± 0.20(stat) ± 0.67(syst) ± 0.39(recoil) GeV

- Combination 7-8 TeV

m_t = 172.52 ± 0.33 GeV

LHCTopWGSummaryPlots
Phys. Rev. Lett. 132, 261902



“Conventional” biggest challenges are JES uncertainties and b-JES calibration