Precision measurement of the W mass at the CERN LHC

CMS Collaboration: arXiv:2412.13872, submitted to Nature

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Outline

- Tests of the Standard Model
- W physics before 2021: Tevatron, LEP
- The 2021 CDF result
- Tests at the LHC: ATLAS and LHCb
- CMS: the one muon method
- Results and conclusion

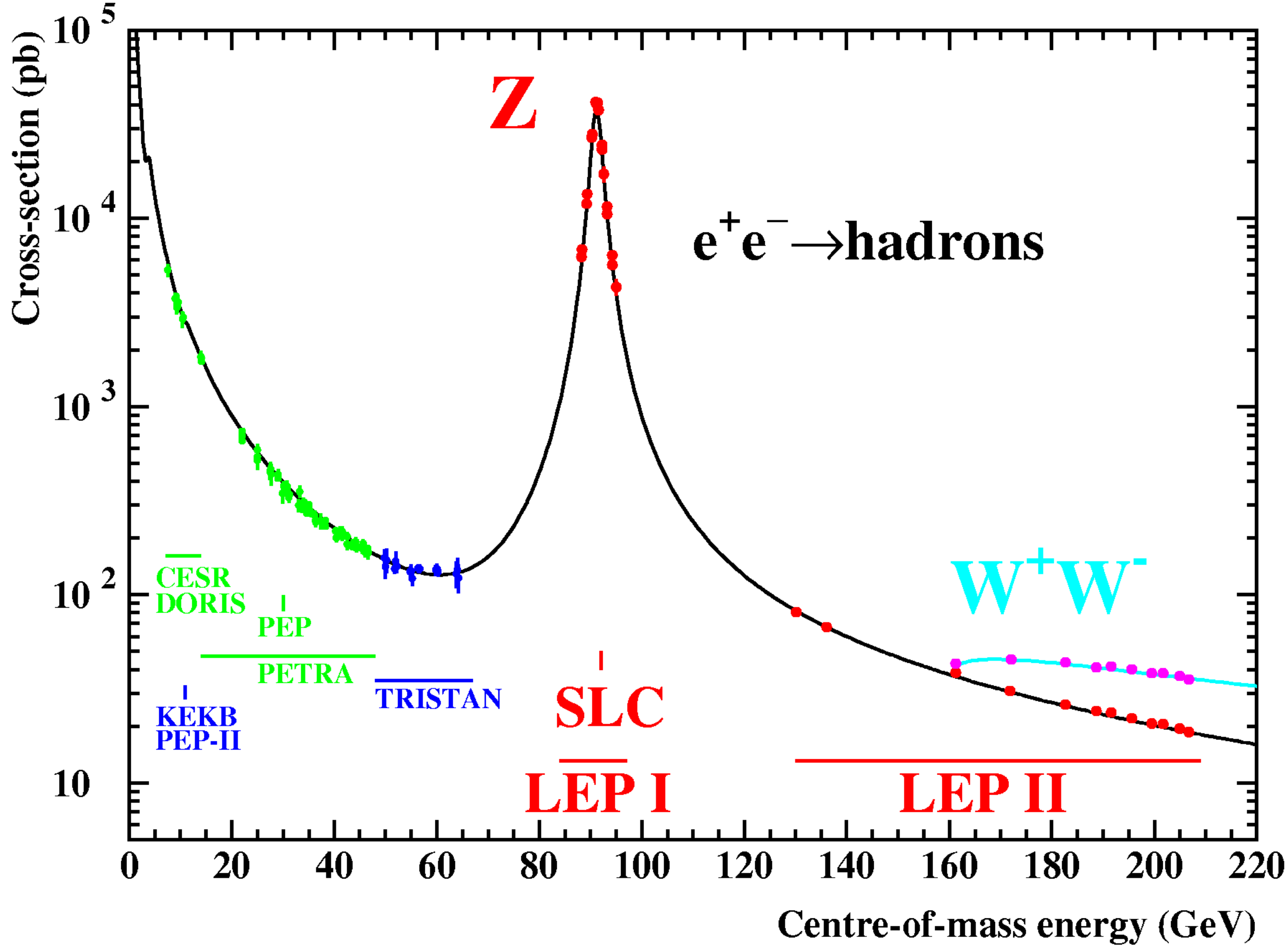
Breakthrough Prize 2025

USD 3 million to ALICE, ATLAS, CMS, and LHCb for Standard Model studies in Run2 of the CERN LHC

(going to the CERN & Society Foundation)

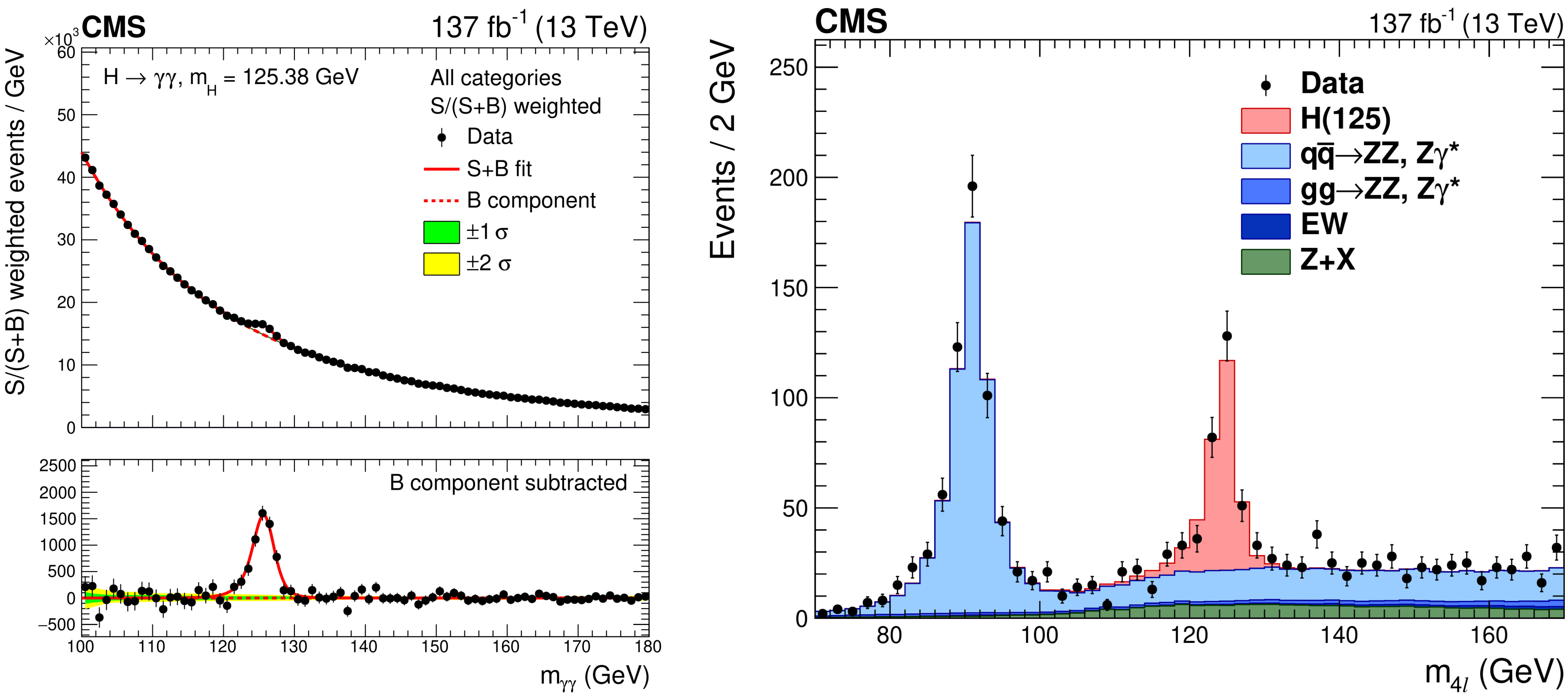
CERN LEP: Tests of the Standard Model

$\sigma(e^+e^- \to Z \to q\bar{q})$



Note the agreement between theory and all experiments

CERN LHC: Higgs boson, 2012-18



Two of the Higgs boson mass spectra measured by CMS at 13 TeV p-p collisions: H $\to \gamma\gamma$ and H $\to$ ZZ* $\to 4\ell^{\pm}$

Standard Model fitting, 2018

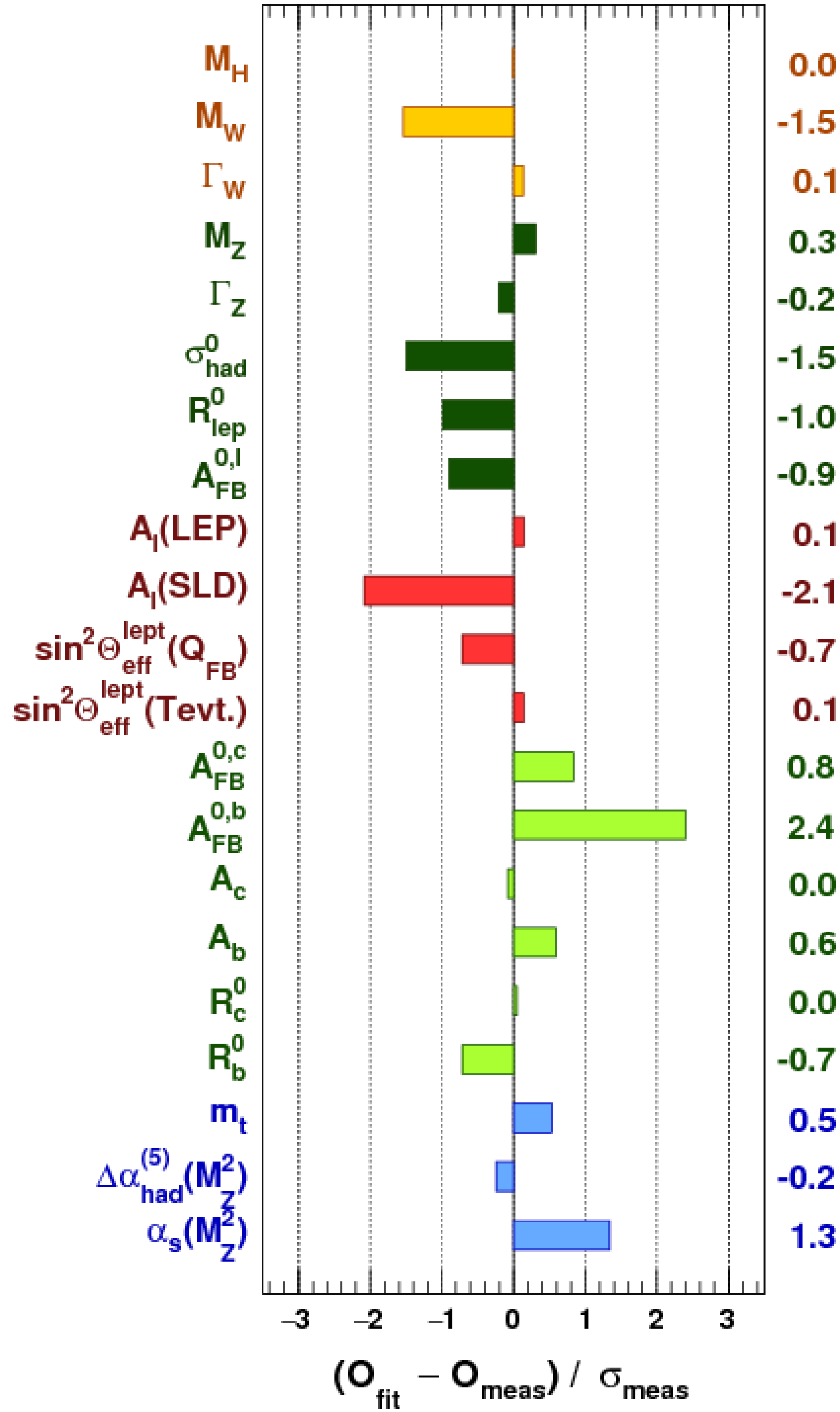
$$\frac{\text{Expt} - \text{theory}}{\text{uncertainty}}$$

Measurements by all experiments

Global EW fit

All within statistics

J. Haller et al, arXiv:1803.01853



Standard Model fitting, 2018

$$\frac{\text{Expt} - \text{theory}}{\text{uncertainty}}$$

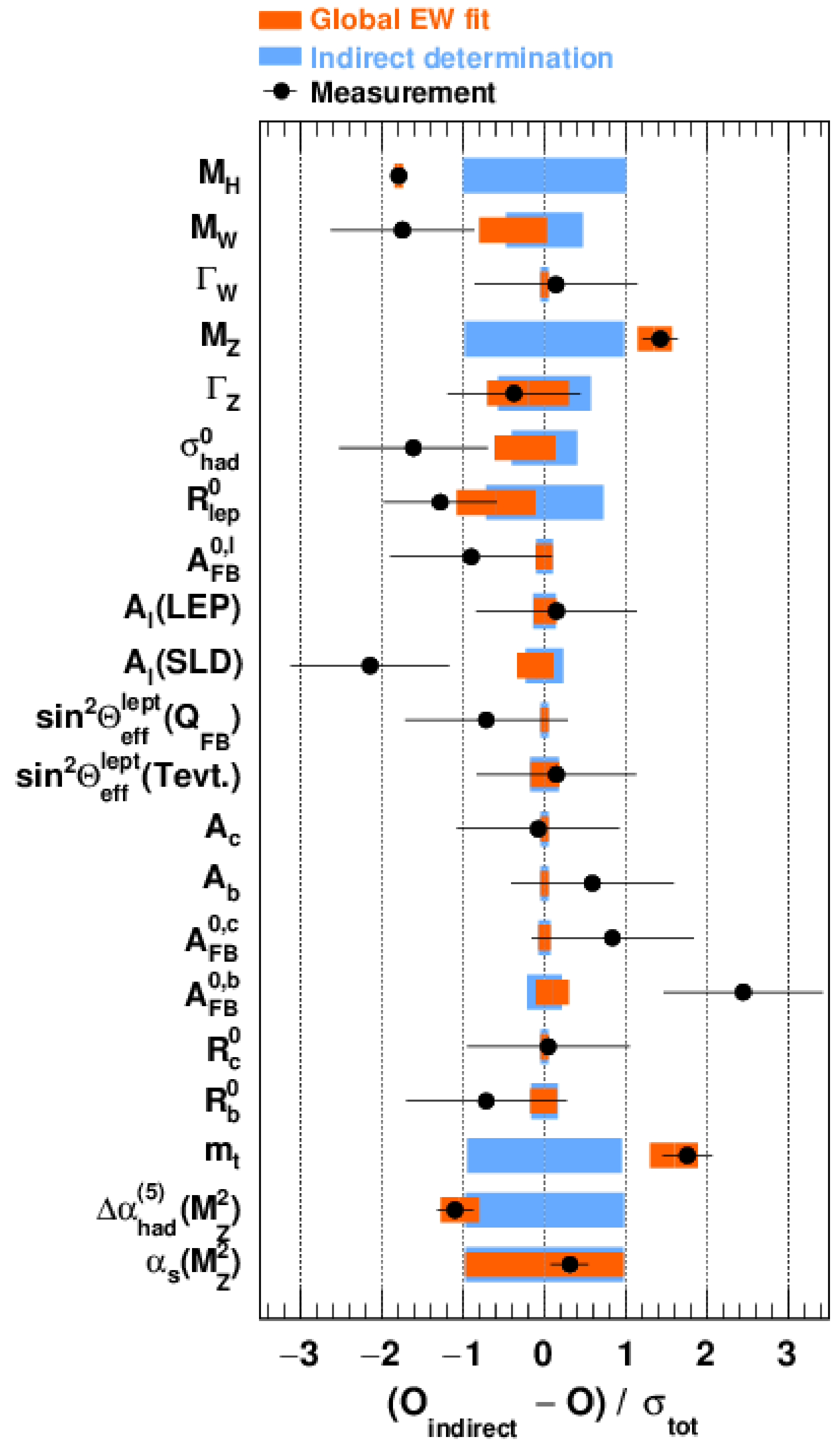
Measurements by all experiments

Fit w/o measured value of given parameter

How well the parameter is determined by the SM?

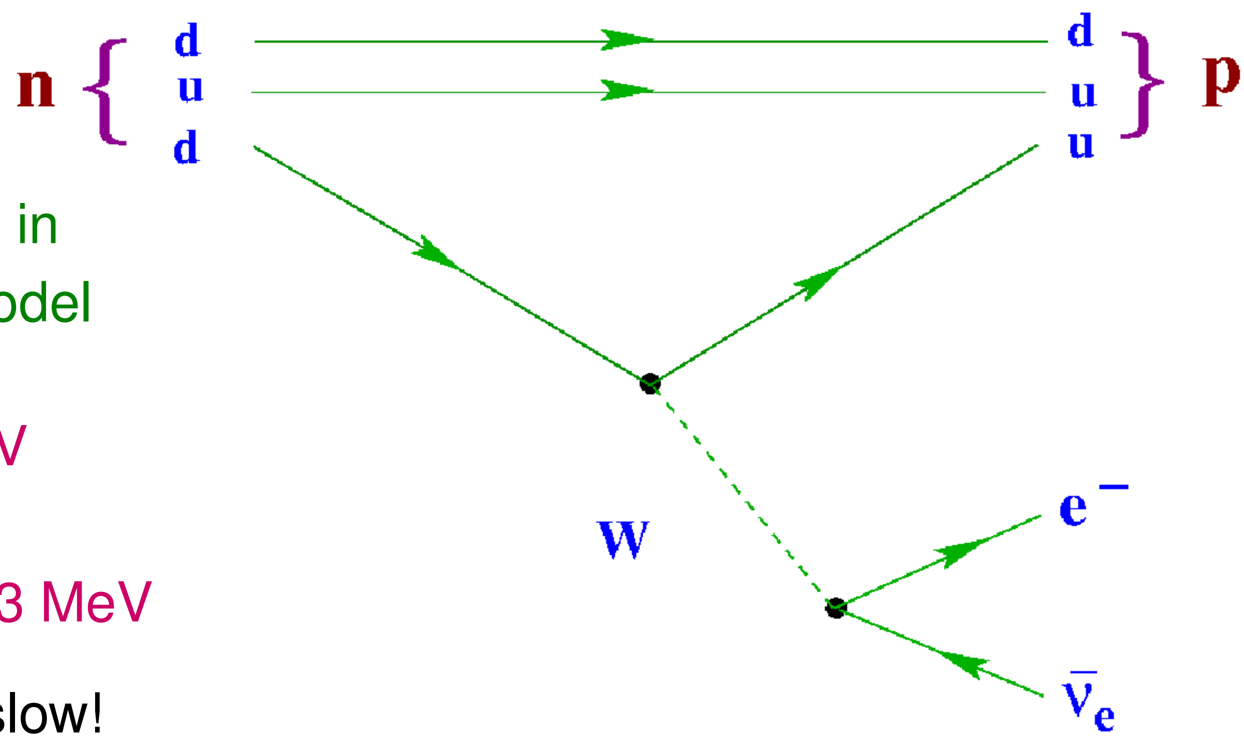
All within statistics

J. Haller et al, arXiv:1803.01853



Why to measure the W mass?

- Directly determines the charged weak ($\beta^{\pm}$) decay
- Predicted to ± 6 MeV by the BEH-mechanism in the Standard Model
- Deviation from the SM can lead to new physics



Neutron decay in the Standard Model

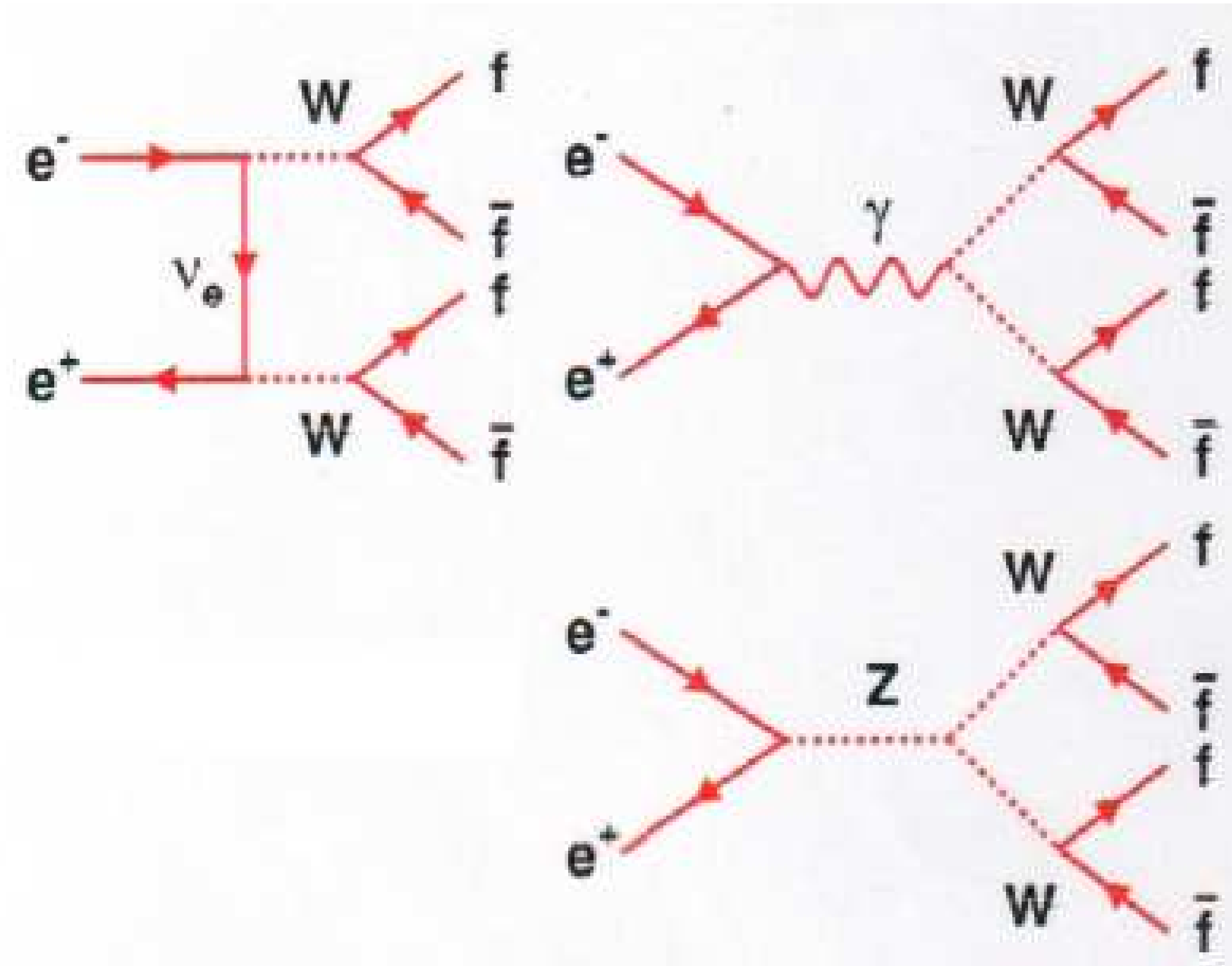
$M_W = 80$ GeV

$\Updownarrow$

$M(n) - M(p) = 1.3$ MeV

No wonder it is slow!

LEP studies: $e^+e^- \to W^+W^-$



46% qqqq, 44% qq$\ell\nu$, 10% $\ell\nu\ell\nu$

LEP: ~ 12000 WW per experiment (5 million Z!)

Typical
OPAL event

$E_{\mathrm{CM}} = 161$ GeV

$e^+e^- \rightarrow W^+W^-$

$\Downarrow$

4 quarks

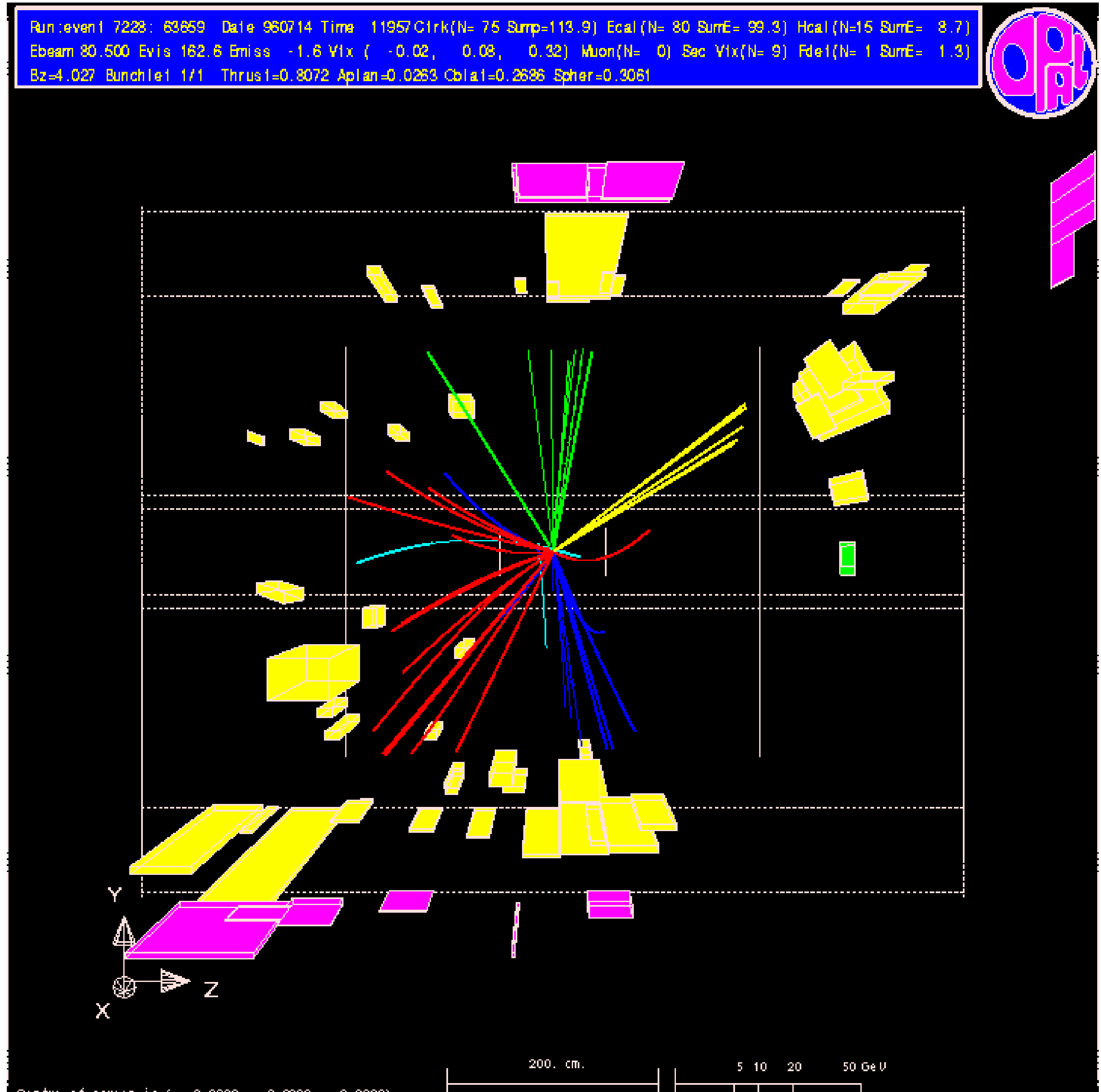
$\Downarrow$

4 hadron jets

$\Downarrow$

75 charged particles

80 particles in calorimeters



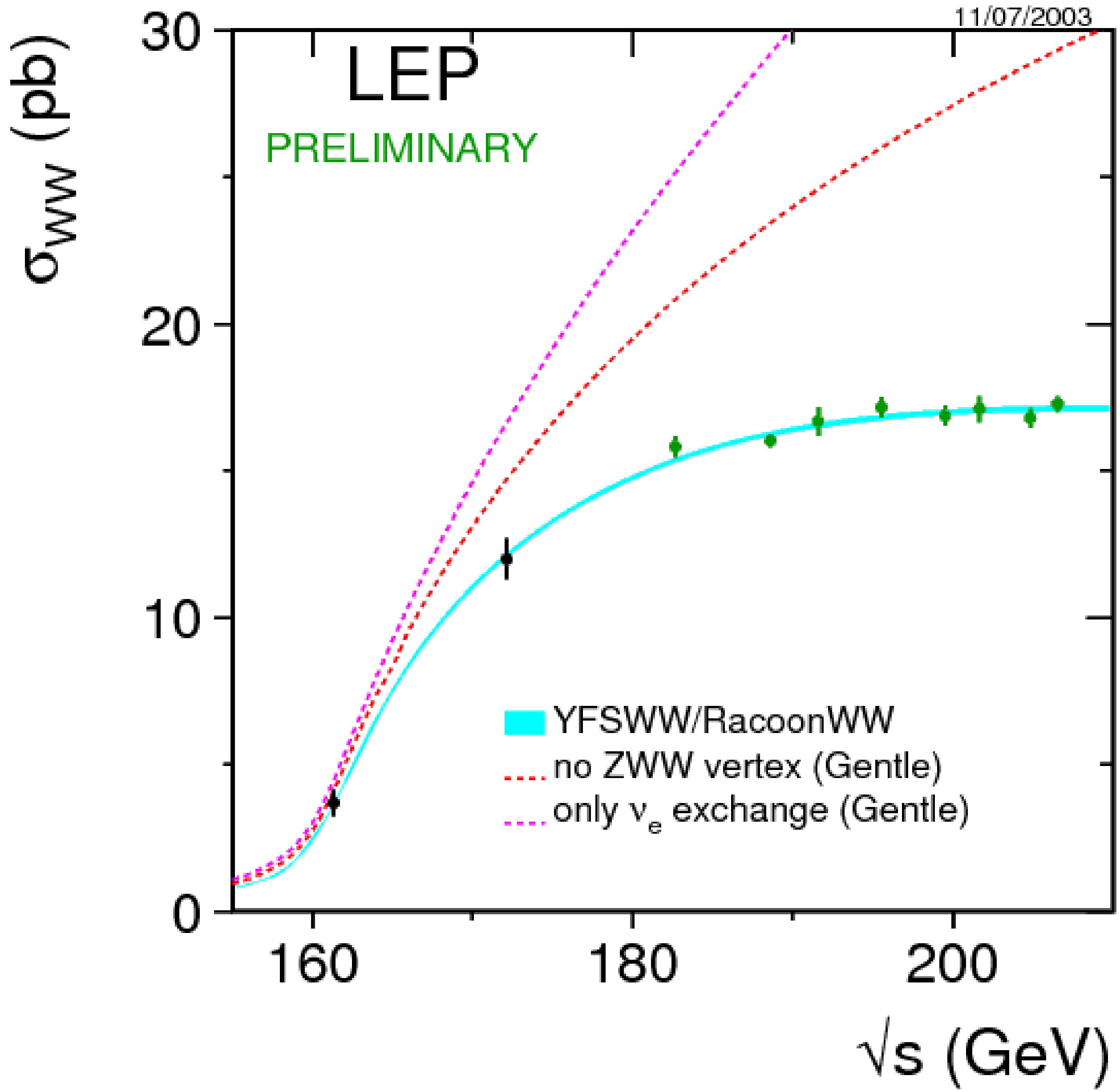
$e^+e^- \to W^+W^-$: production

Non-abelian interaction

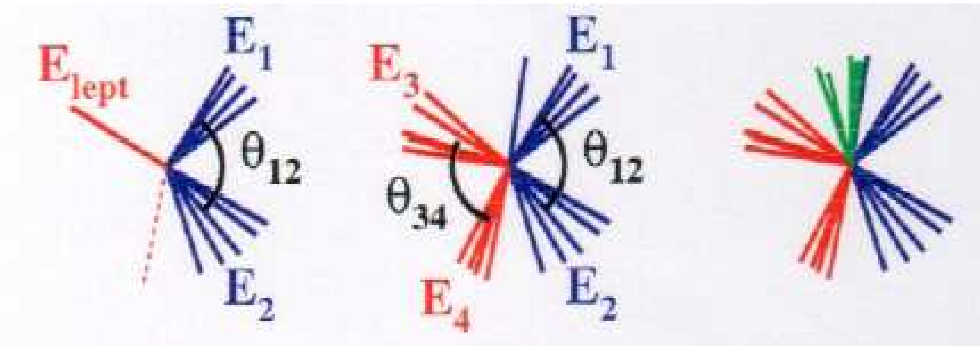
$\gamma \to \mathbf{WW}$
and
$\mathbf{Z} \to \mathbf{WW}$

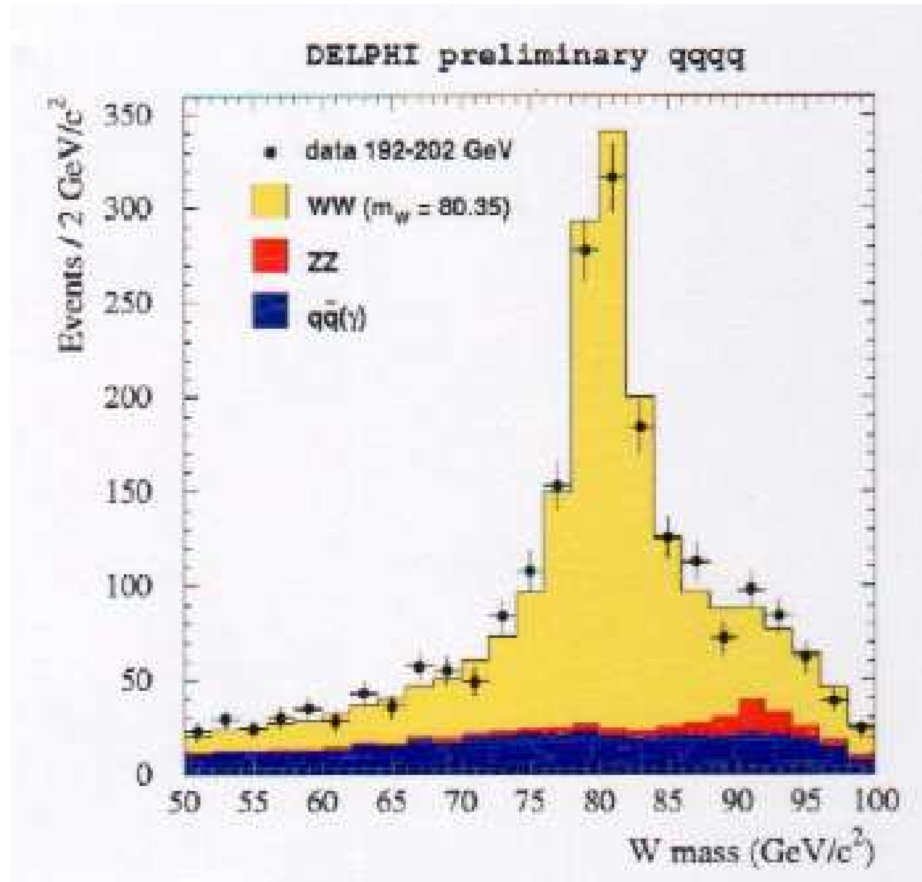
$\Downarrow$

Interference



$e^+e^- \to W^+W^-$: W-mass





Invariant mass:

$$M_{12}^2 = 2E_1E_2(1 - \cos\Theta_{12})$$

Kinematic fit:
5 constraints for qqqq
E, $\underline{p}$ conserved, $M_{12} = M_{34}$
But: pairing uncert.,
gluon may give 5th hadron jet

WW $\rightarrow$ qq$\ell\nu$: 2 constraints

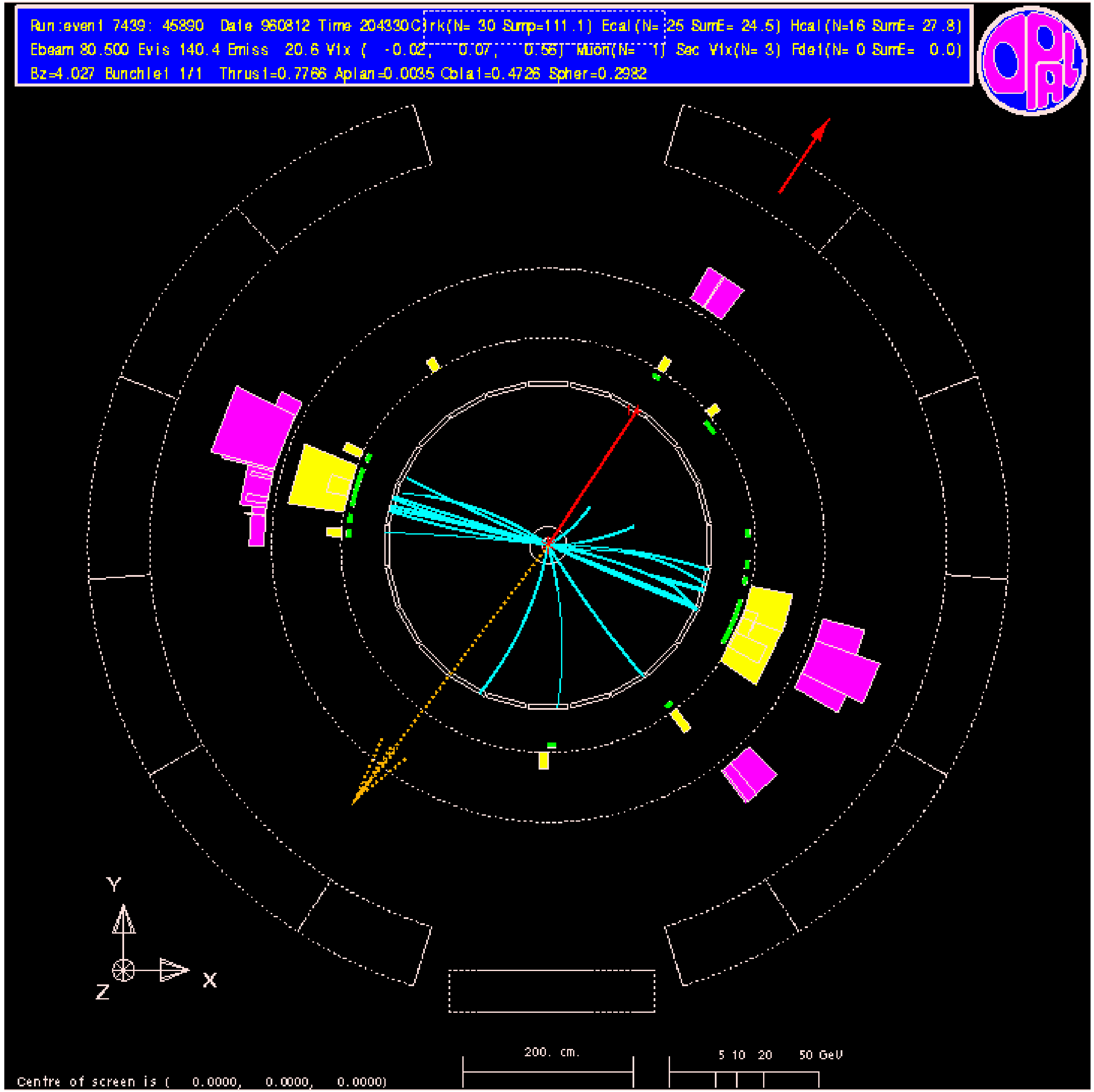
fit missing p_ν

$\Downarrow$

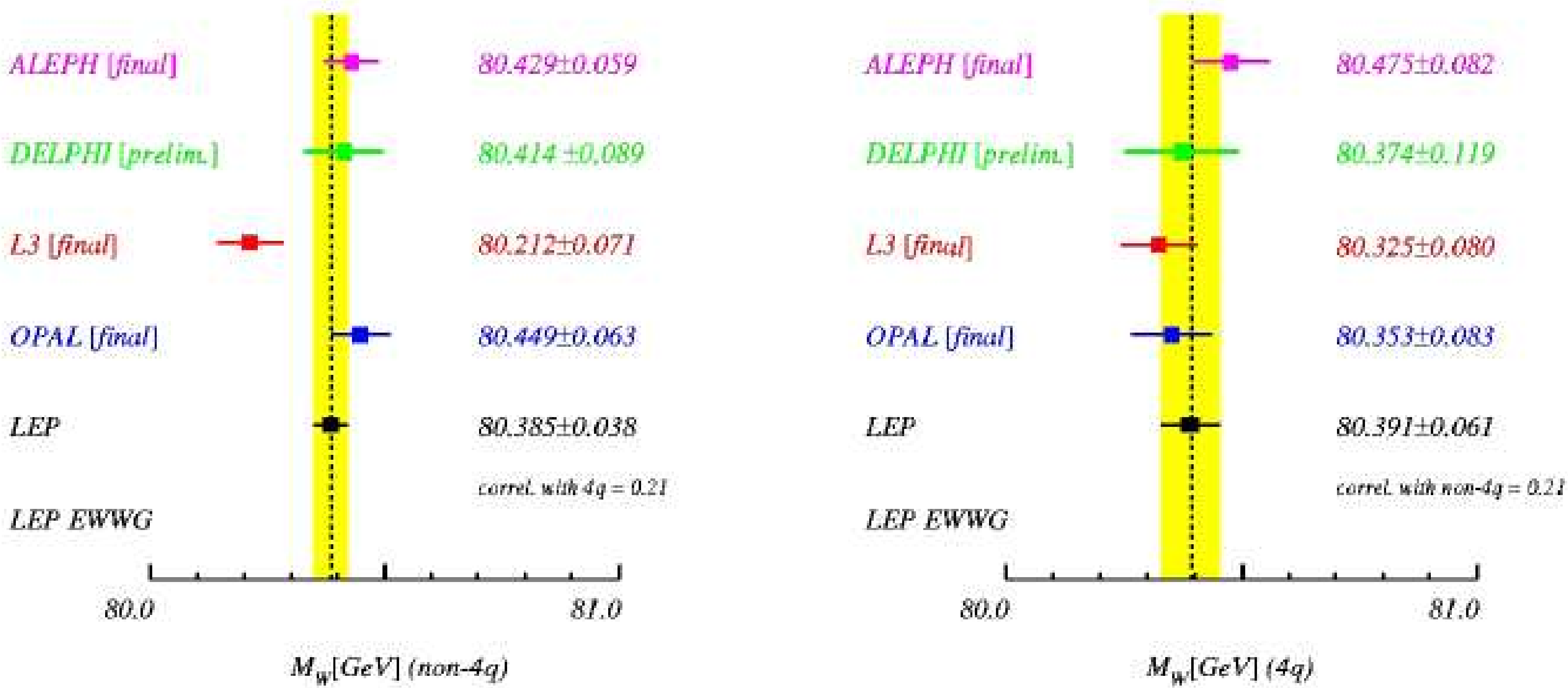
$E(\mathrm{e^+e^-}) =$
$E(\mathrm{W^+W^-})$

$M_{12} = M_{34}$

Missing energy,
but unambiguous
hadron jets



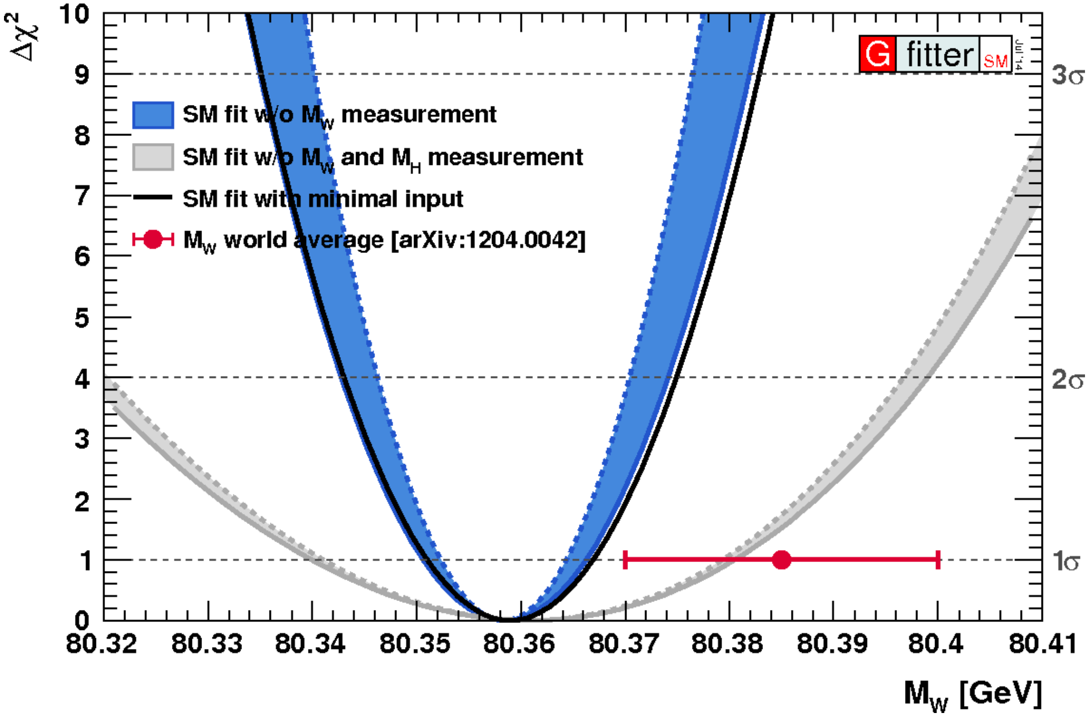
W mass at LEP (2006!?)

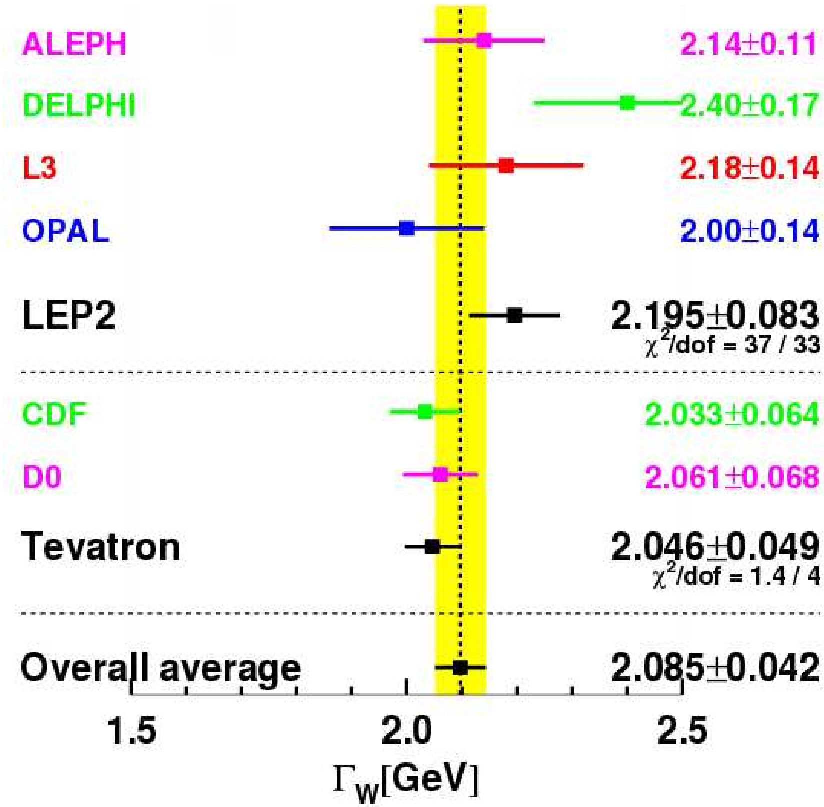


$W \to qq\ell\nu$ and $\ell\nu\ell\nu$ $\qquad$ $W \to qqqq$

Two channels: 20% correlation!

W: mass and width (SM fit, 2014)





With no M_W measurement

With no M_W and M_H measurement

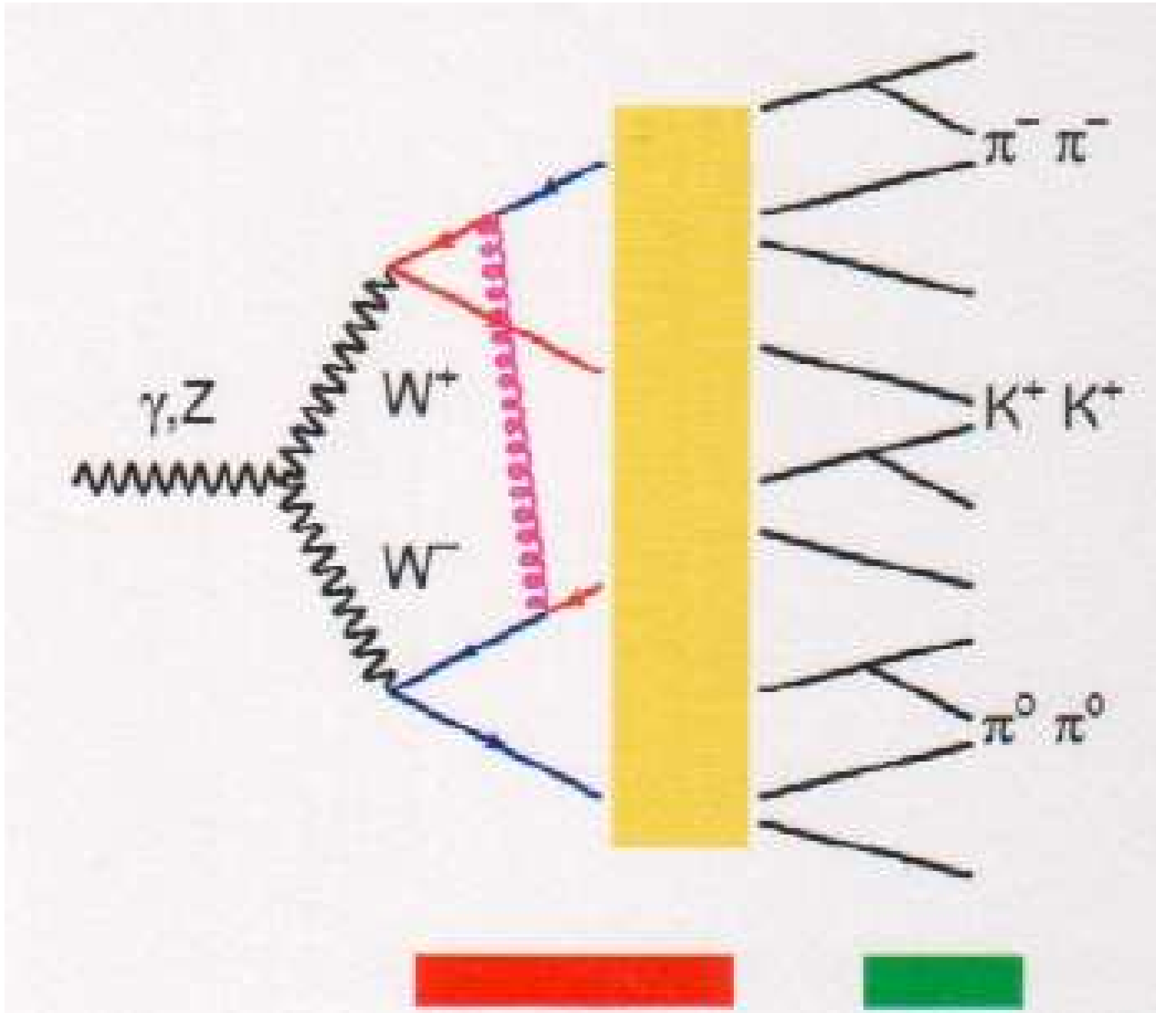
Average measured values

Γ_W measurement

4 LEP and 2 Tevatron experiments

Theoretical calculation

W mass: systematic uncertainties



colour reconnection

Bose-Einstein correlation

Main sources of W mass uncertainties

$$e^+e^- \to W^+W^-$$

	$q\bar{q}\ell\nu$	$q\bar{q}q\bar{q}$	Combined
ISR/FSR	8	10	8
Hadronisation	26	23	24
LEP energy	17	17	17
Colour reconn.	—	50	13
Bose-Einstein	—	25	7
Total syst.	35	64	36
Stat. ≈	38	34	30

The LEP measurement was systematically limited

Tevatron: W mass

Tevatron, Fermilab, 1.96 TeV $\mathrm{p} - \overline{\mathrm{p}}$ collisions: 2001–2011

Hadron collider: big hadron showers (jets)

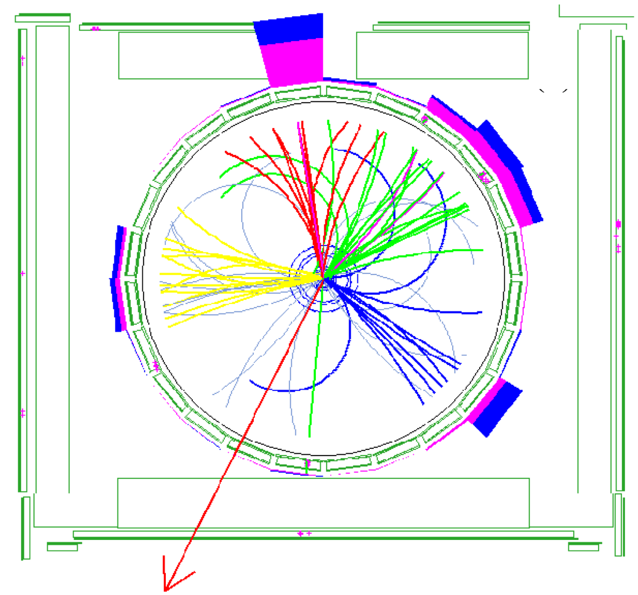
Rely on leptons (ℓ = $e^{\pm}$, $\mu^{\pm}$)

Measured transverse momentum p_T^{ℓ} of the charged lepton and missing transverse momentum $p_T^{miss} = -\sum_{all} p_T$ for the neutrino.

$M_W \approx 80$ GeV shared between ℓ and ν

$\Rightarrow$ Jacobian peaks for both around

$p_T \approx M_W/2$



CDF event: 4 jets + missing momentum

Transverse mass: $M_T^W = \sqrt{2 p_T^{\ell} p_T^{miss} (1 - \cos \Delta\Phi)}$ (depends on p^W)

$\Delta\Phi = \Phi(\underline{p}_T^{\ell}) - \Phi(\underline{p}_T^{miss})$: azimuth angle diff.

Tevatron W mass: CDF, D0

Main experiments: CDF, D0. Evolution of M(W):

CDF, 2012 (2.2 fb^{-1} eν, $\mu\nu$):
80 387 $\pm$ 12 (stat) $\pm$ 15 (syst) = 80 387 $\pm$ 19 MeV

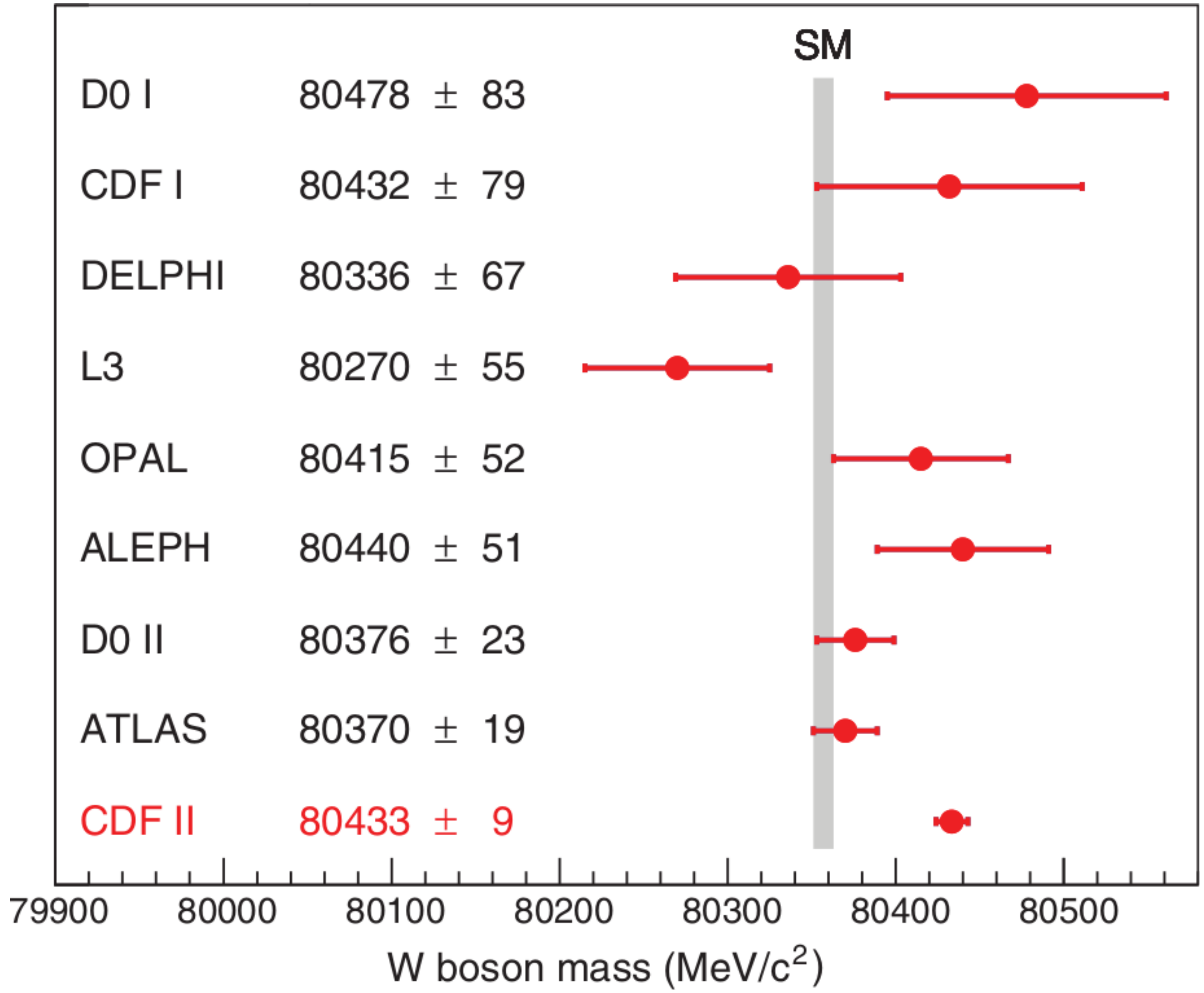
D0, 2012 (4.3 fb^{-1} eν):
80 367 $\pm$ 13 (stat) $\pm$ 22 (syst) = 80 367 $\pm$ 26 MeV

CDF + D0, 2014 (same data):
80 387 $\pm$ 16 MeV;

CDF + D0 + LEP, 2014:
80 385 $\pm$ 15 MeV

CDF, 2021 (8.8 fb^{-1} eν, $\mu\nu$)
80 433.5 $\pm$ 6.4 (stat) $\pm$ 6.9 (syst) = 80 433.5 $\pm$ 9.4 MeV

W mass, 2022



CDF, 2021: 7σ deviation from the standard model!

W mass, 2022

What is so much better at 10 years after the stop of the Tevatron?

CDF, 2012 (2.2 fb^{-1} $e\nu$, $\mu\nu$):

80 387 $\pm$ 12 (stat) $\pm$ 15 (syst) = 80 387 $\pm$ 19 MeV

CDF, 2022 (8.8 fb^{-1} $e\nu$, $\mu\nu$):

80 433.5 $\pm$ 6.4 (stat) $\pm$ 6.9 (syst) = 80 433.5 $\pm$ 9.4 MeV

Luminosity 4X higher, 4.2 million W bosons

Detector calibration, simulation improved

Parton density function in proton–antiproton:

syst. contribution 10 MeV $\rightarrow$ 3.9 MeV

Not everybody agrees. D0: no new analysis

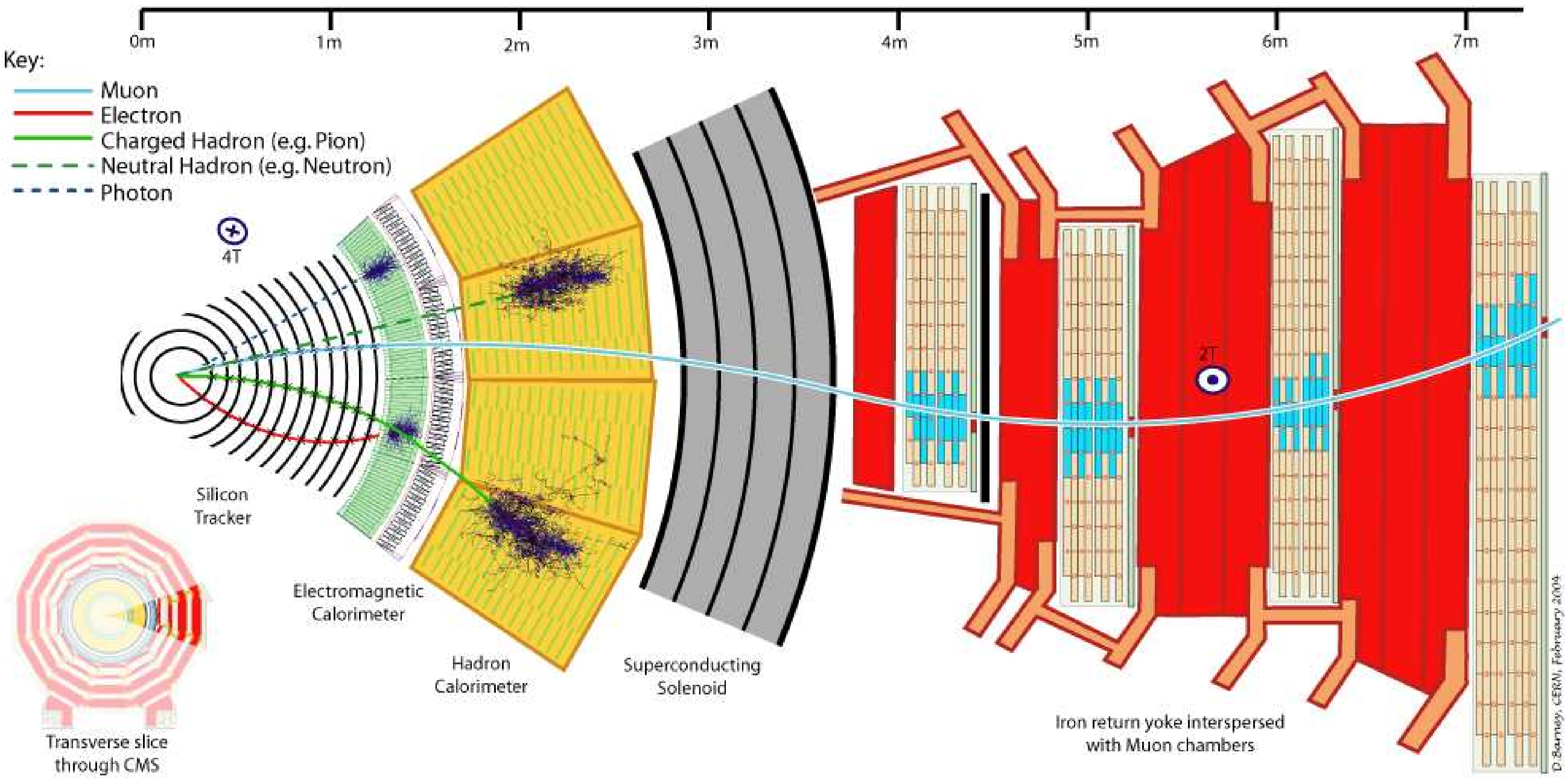
ATLAS, 2017 (7 TeV p-p): agrees with previous:

80370 $\pm$ 7 (stat.) $\pm$ 11 (exp. syst.) $\pm$ 14 (mod. syst.) MeV

ATLAS, 2024 (7 TeV p-p): new analysis, same result

80366.5 $\pm$ 9.8 (stat.) $\pm$ 12.5 (syst.) MeV = 80366.5 $\pm$ 15.9 MeV.

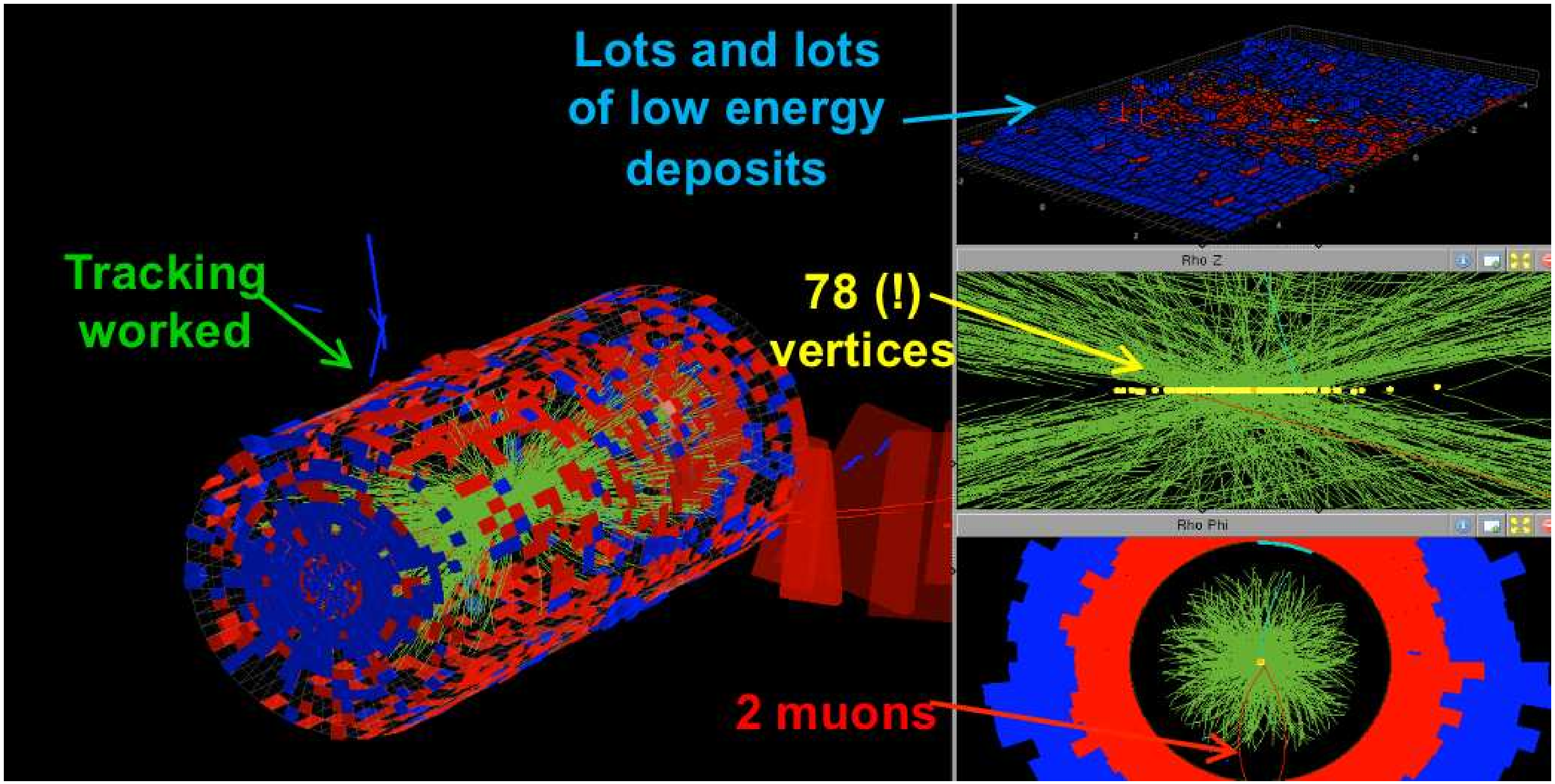
Compact Muon Solenoid (CMS)



The fast muon flies through every part of the detector. The tracker follows its orbit in the 3.8 T magnetic field. The muons are selected by a muon trigger, but their transverse mmentum is measured by their orbit curvature using the silicon pixel and strips tracker.

W mass, 2024: LHC, 13 TeV

Huge data set at 13 TeV, but $50 \ldots 60$ p-p collisions in every event (*pileup*).



78 identified vertices in one CMS event (bunch crossing!). Increased data quantity, but more involved analysis. Hard to use hadronic decays and to measure missing momentum for semileptonic ones.

W mass, CMS, 13 TeV: single muons!

CMS decided to use single muon p_{T}^{μ} for measuring the W mass

Most precise determination of p_{T}^{μ} by the curved muon trajectory in the tracker

Fit the p_{T} distribution with M_{W} as parameter.

$M_{\mathrm{T}}^{\mathrm{W}}$ is less useful at the LHC due to the pileup, particles from previous and succeding beam crossings (± 25 ns).
$\Rightarrow$ Missing momentum is less precise.

p_{T}^{μ} calibration by $\mu^+\mu^-$ decays of $\mathrm{J}/\Psi = [\mathrm{c}\bar{\mathrm{c}}]$, $\Upsilon = [\mathrm{b}\bar{\mathrm{b}}]$ mesons, and of the Z boson.

Muons in CMS at 13 TeV

Characteristic signatures, parameters:

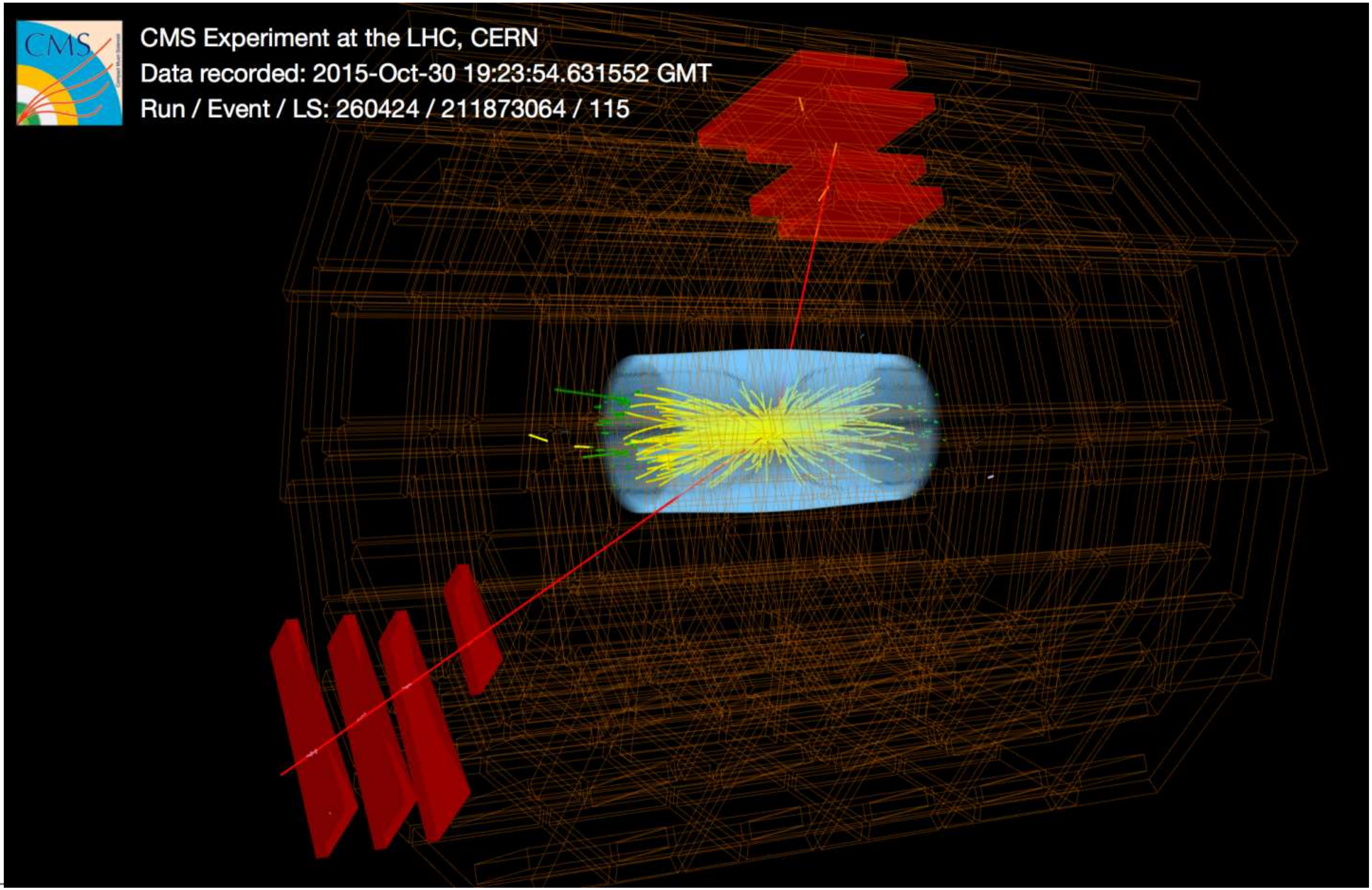
- transverse momentum, p_T^μ,
- exit angle θ of the muon to the beam direction (using pseudorapidity $\eta = -\ln\tan(\Theta/2)$),
- the charge of the muon.

In 3D histogram, the first 2 measured in a very fine grid, the third is a sign.

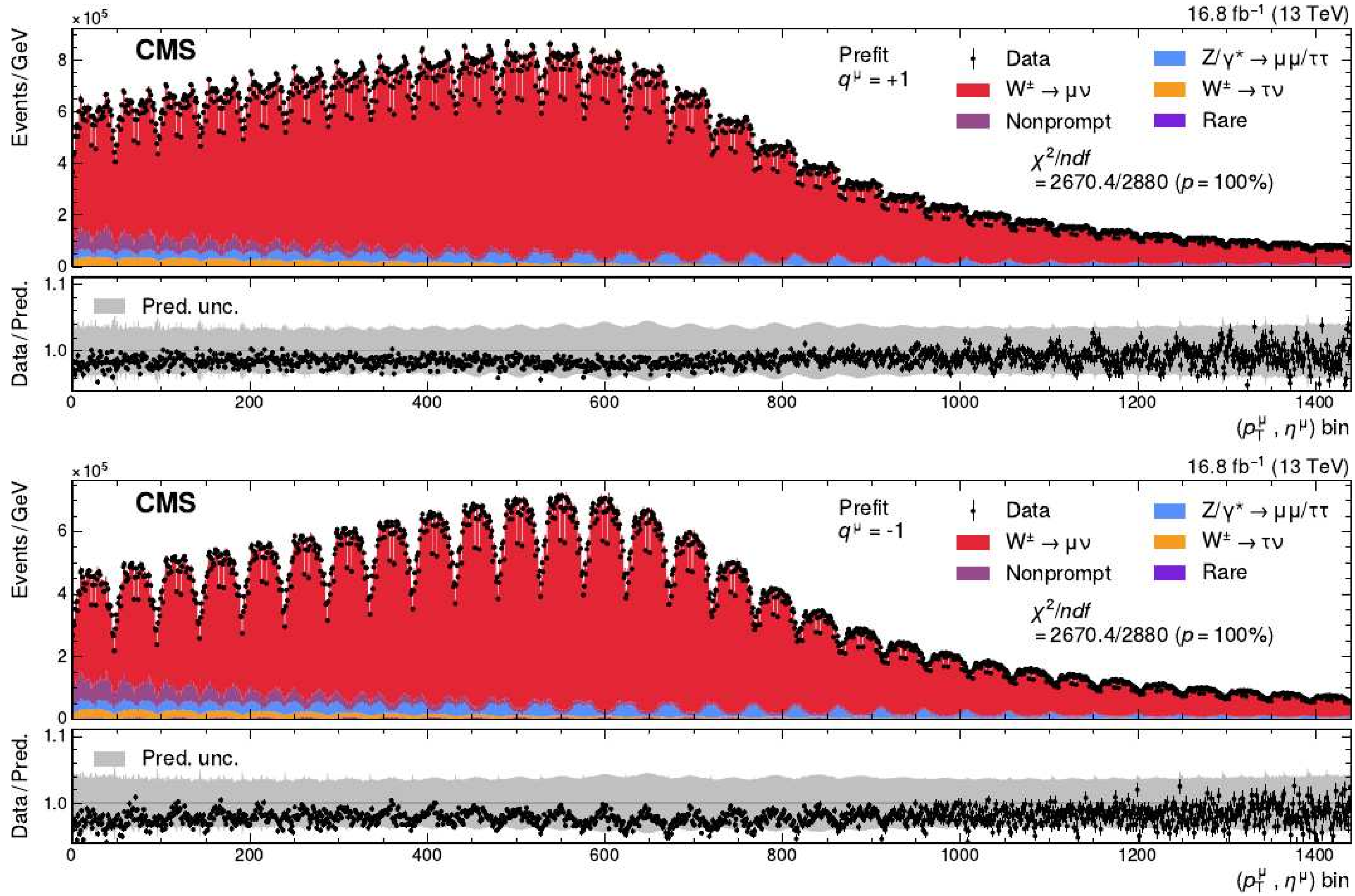
117 million events selected of the 16.8 fb^{-1} luminosity data set collected in 2016.

CMS Collaboration: *High-precision measurement of the W boson mass with the CMS experiment at the LHC*, arXiv:2412.13872, submitted to Nature

CMS: Dimuon event detected at 13 TeV

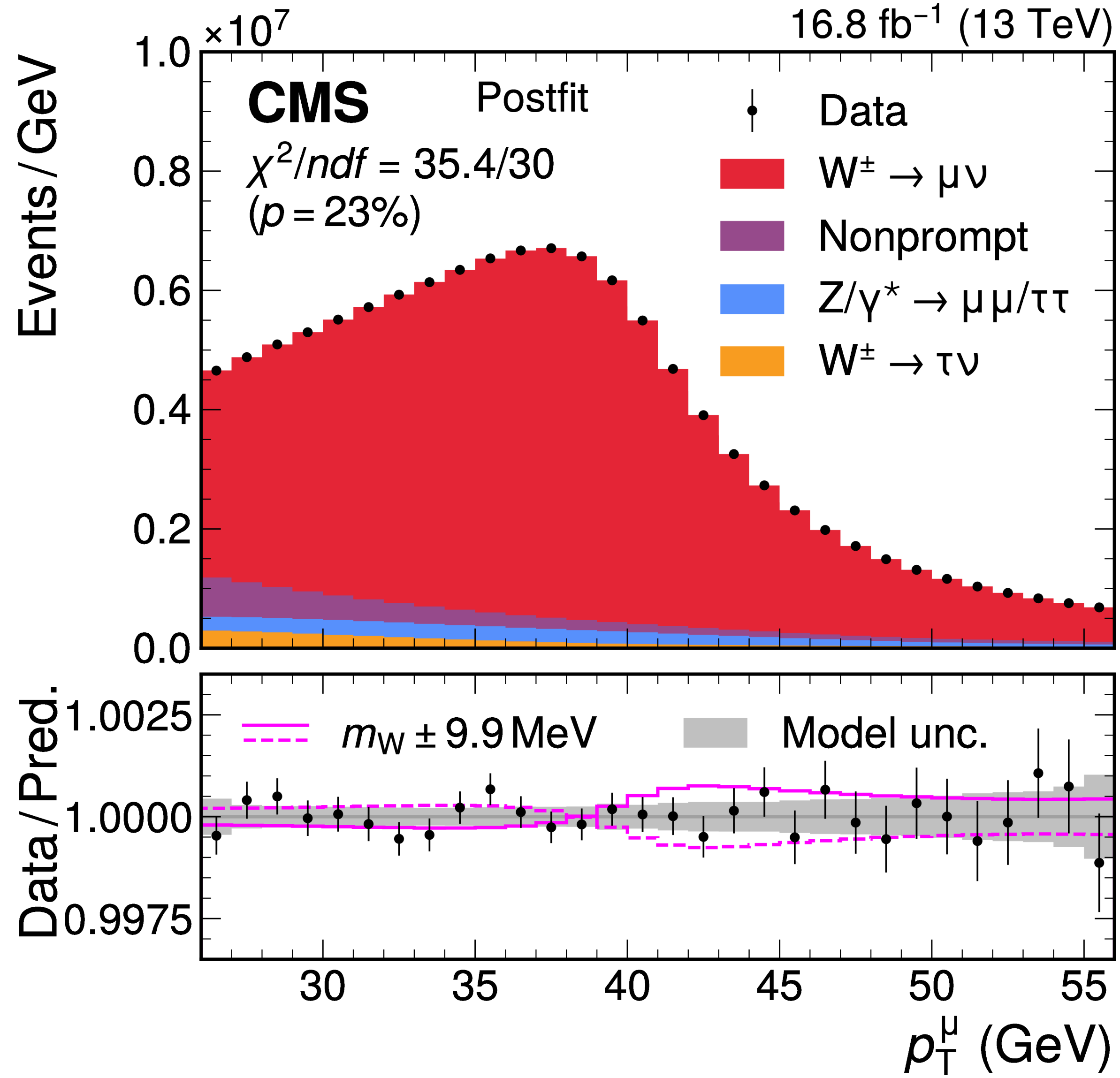


W mass: Single muon (p_T^μ, η^μ)



2D (p_T^μ, η^μ) *rolled-out* distributions for positive (upper) and negative (lower) muons. Note the good fitting.

W mass: Single muon p_T^μ



M_W = 80 360.2 ± 2.4 (stat) ± 9.6 (syst) = 80 360.2 ± 9.9 MeV.

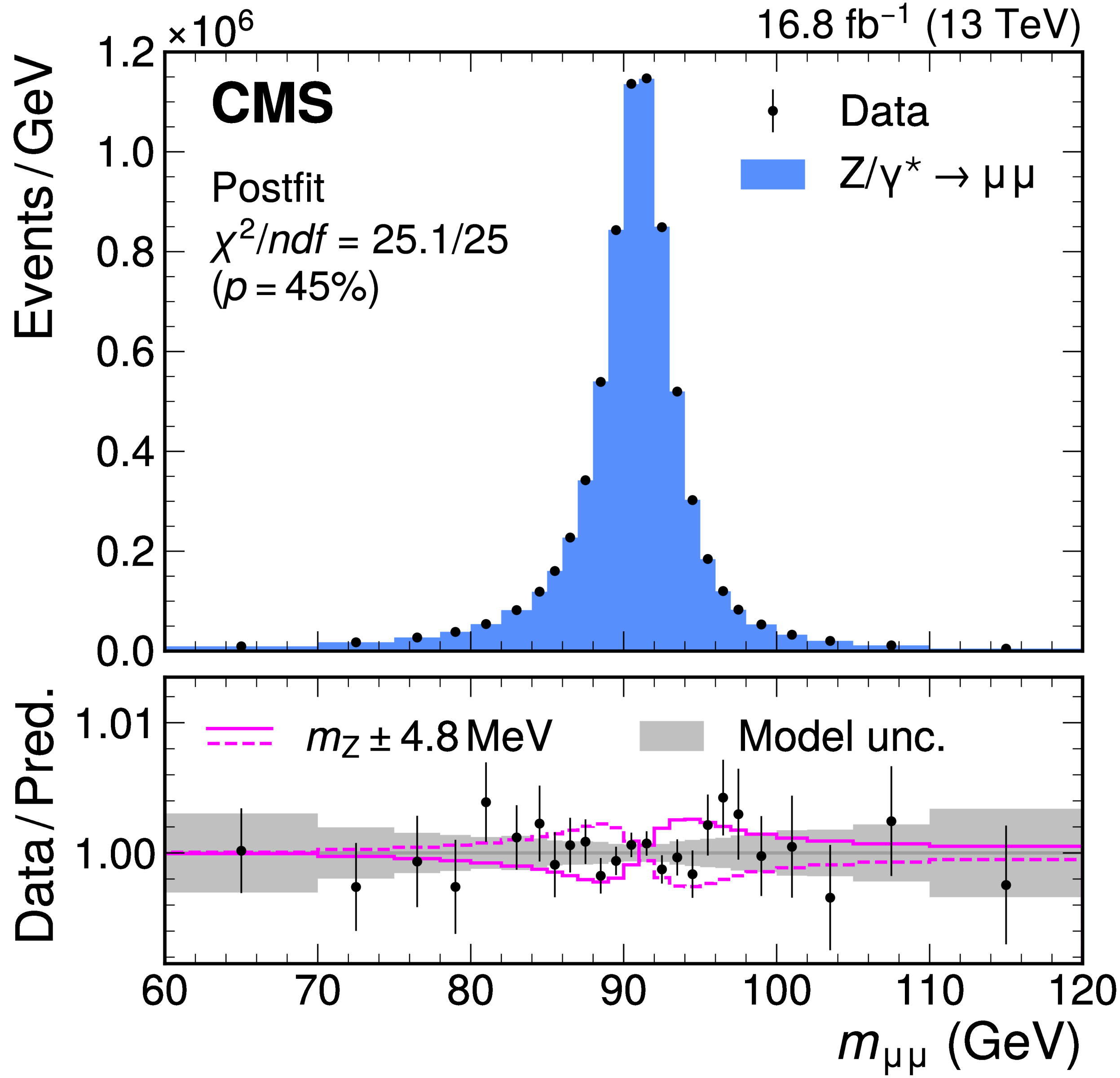
Validation: Z mass from $Z \to \mu\mu$

$M_Z^{\mu\mu} - M_Z^{PDG} =$
$-2,2 \pm 4,8$ MeV

Correlated with M_Z^{PDG} for systematics, not a new measurement

Validates our theoretical (modelling) assumptions and the simulation.

Reflects the uncertainty of the p_T^μ calibration



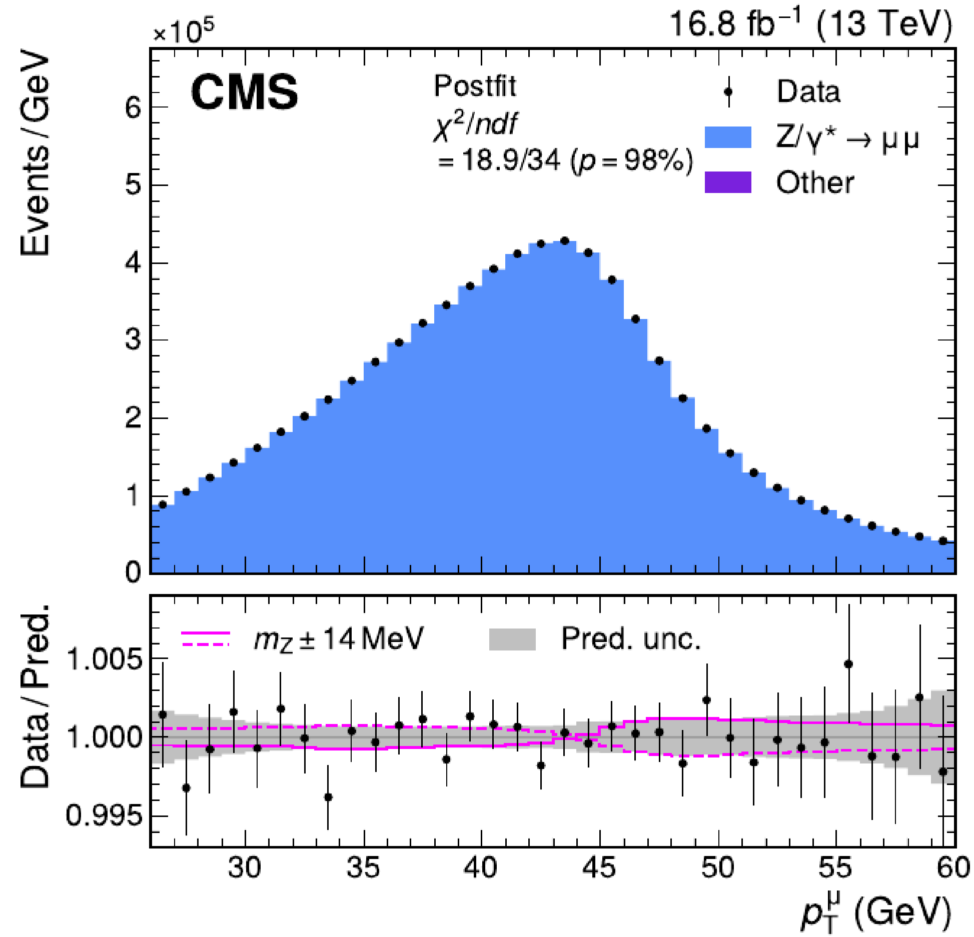
Validation: Z mass from $Z \to \mu\mu$, W-like

W-like analysis with single muons of the same $Z \to \mu\mu$ data:

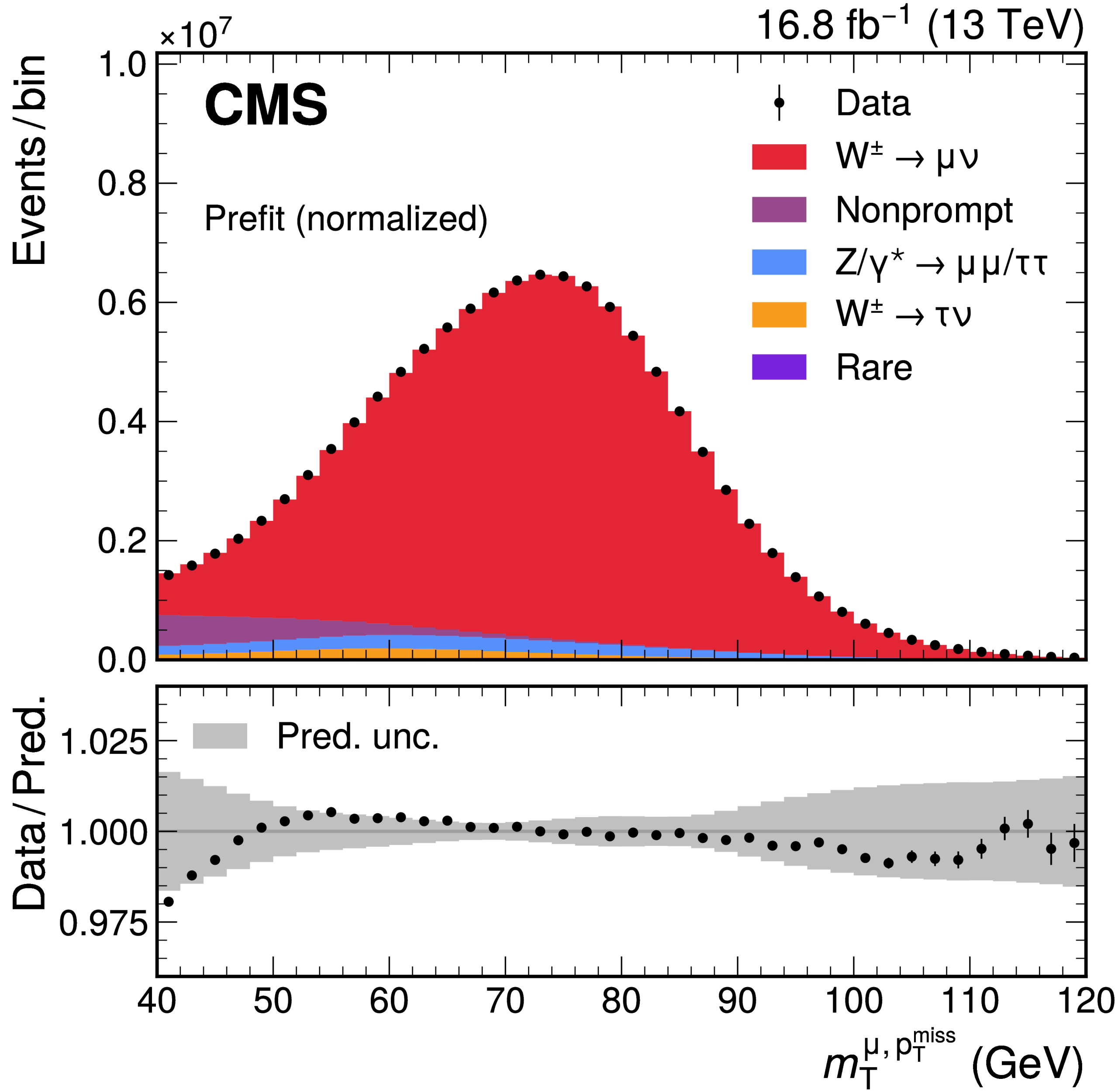
$$M_Z^W - M_Z^{PDG} = -6 \pm 7(\text{stat}) \pm 12(\text{syst})\ \text{MeV} = -6 \pm 14\ \text{MeV}$$

Within 1σ (one uncertainty)!

Validates the analysis method including modelling uncertainties..



Validation: M_T^W



Systematics studies

for the m_{Z} and M_{W} analyses

- Event selection with modelling algorithms
- Efficiency corrections, scale factors from simulation
- Hadronic recoil calibration (acts on $p_{\mathrm{T}}^{\mathrm{W}}$)
- Background simulation
- Muon momentum calibration (± 4.8 MeV)
- Modelling of $p_{\mathrm{T}}^{\mathrm{W}}$ and $p_{\mathrm{T}}^{\mathrm{Z}}$ distributions
- Modelling of leptonic decays of W and Z (angular distr.)
- Parton distribution functions (7 sets compared)
- Higher-order electroweak corrections
- Fitting M_{W} with less model assumptions (new physics?)

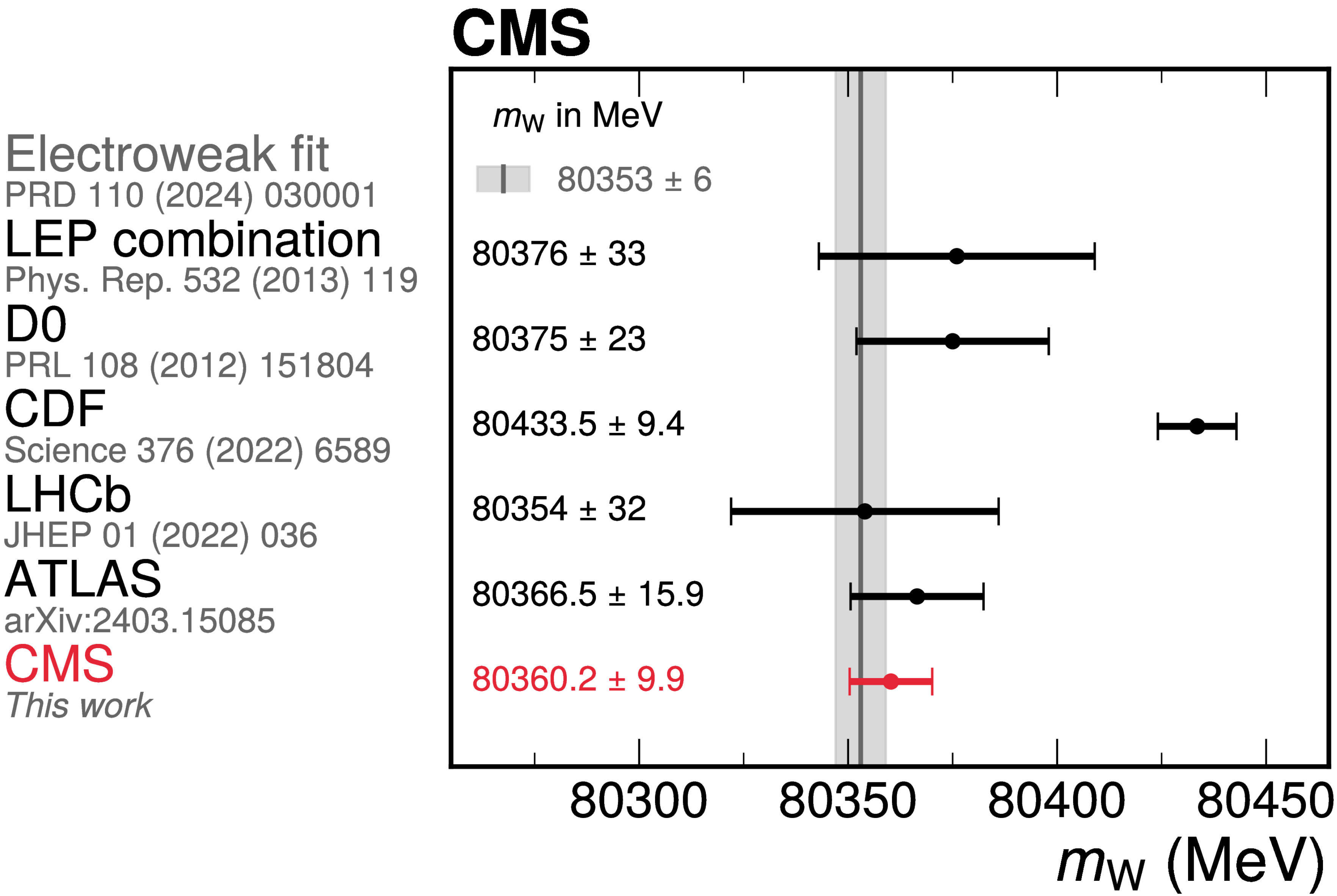
Systematic uncertainties

for the W-like m_Z and M_W analyses

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-muon 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

Nominal (CMS): individual contributions summed with correlations. Global (ATLAS): effects of changes to all other parameters. Same total.

W mass, 2024: CMS, 13 TeV



Conclusion

- W mass is an important fundamental constant.
- It is measured and calculated very precisely.
- The 2021 CDF result with much higher precision disagrees with the theory and all previous measurements.
- The 2024 CMS result has a similar precision and confirms the Standard Model.