# Electroweak Precision Physics at CMS and the FCC Plans

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# Breaking the Standard Model

**Standard model holds strong, but we know it's not the complete picture to describe the universe**

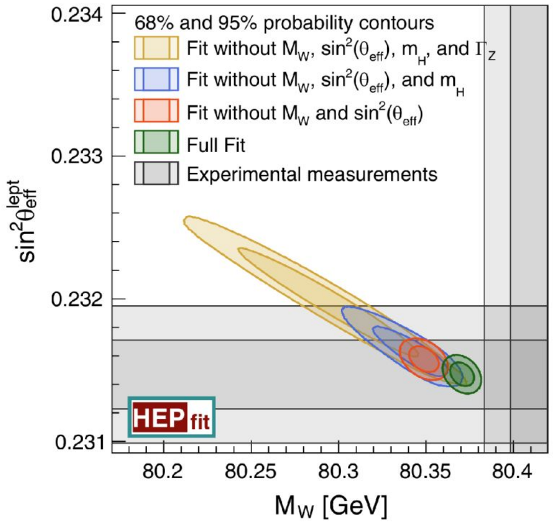
- So far no direct evidence of new physics at the LHC
- LHC will put (or not) limits on higher mass scales and beyond SM physics

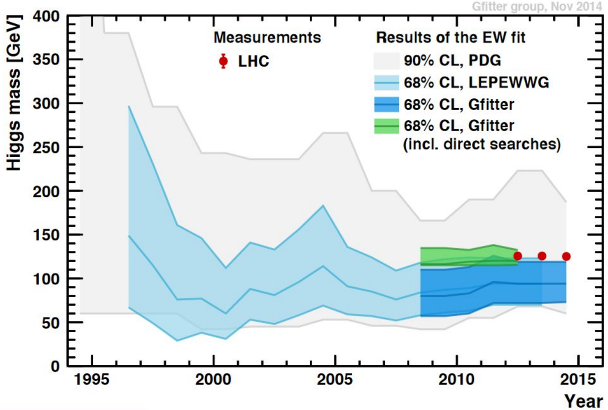
**After the Higgs discovery, the SM electroweak sector is overconstrained**

- Direct measurements of each parameter with high precision allows to test the self-consistency of the SM
- Any deviations can be accounted for as new physics at higher energy scales than can be reached at the LHC

**Establish precision physics programme for the next decades**

- Vast amount of data will be delivered by the LHC leading to precise measurements – *proof will be given today!*
- Looking at next colliders to go beyond the precision delivered by the LHC



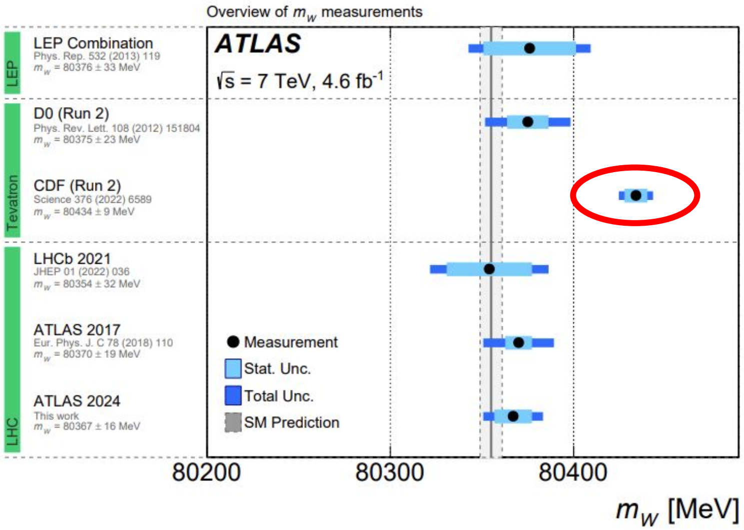
# The W boson mass

## W boson mass predicted via SM relationships

- Based on inputs from precisely measured electroweak parameters
- Depends on higher order corrections $\Delta r$ from top and Higgs

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_\mu}(1+\Delta r)$$

- Uncertainty from electroweak fit amounts to $m_W$ = 80353 ± 6 MeV
- Crucial to measure $m_W$ with similar precision



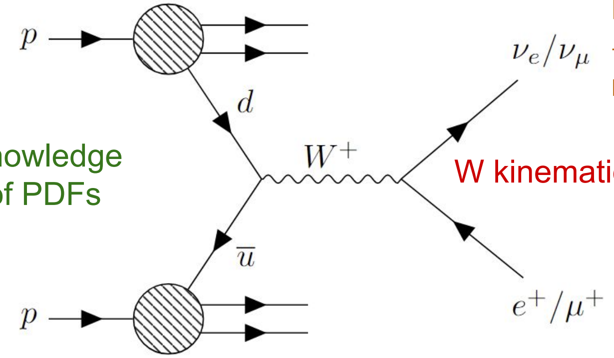

## Experimentally challenging to measure it

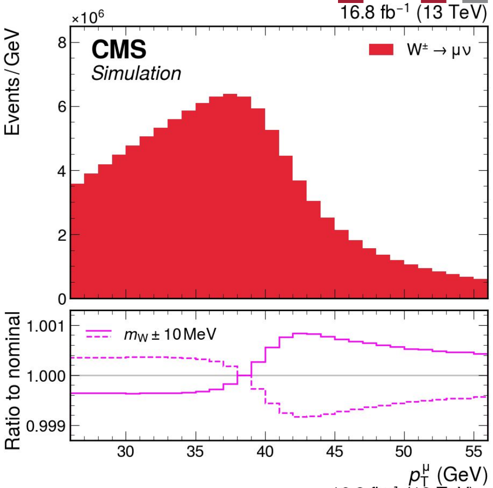
- Several measurements at the LEP and Tevatron experiments, ATLAS and LHCb
- Current combined experimental value $m_W$ = 80369 ± 13 MeV
- Latest CDF measurement from 2022 $m_W$ = 80434 ± 9 MeV
  - The most precise measurement
  - In significant tension with EWK prediction other experimental values

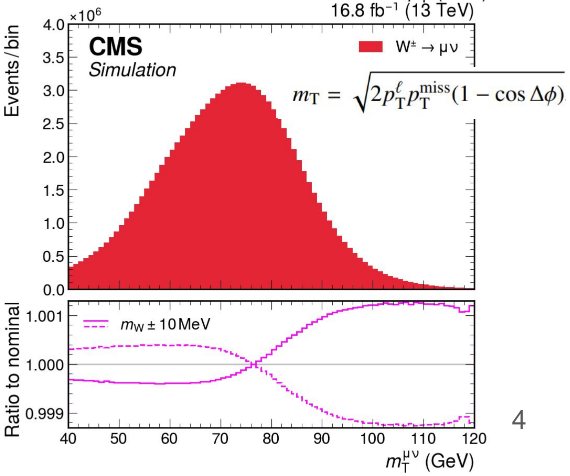
*CMS W boson mass measurement to be delivered and shed light on the CDF ambiguity*

# Measurement of W mass at hadron colliders

**Environment of hadron collider requires leptonic decays of the W boson**



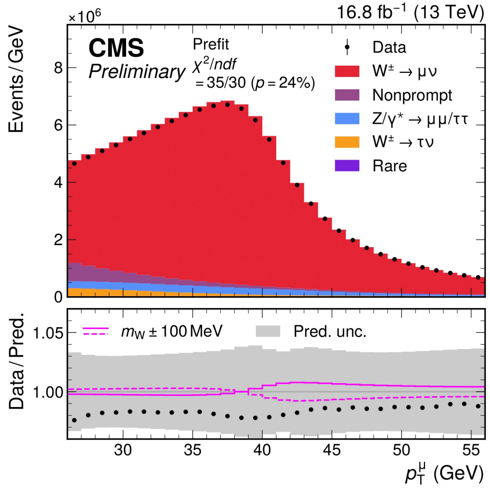




- Direct reconstruction of W → qq difficult: overwhelming backgrounds and limited hadronic resolution
- Instead infer $m_W$ from leptonic and/or transverse mass distributions
- Theoretical inputs and modeling is crucial: parton distribution functions (PDFs), W boson production and decay kinematics (perturbative and non-perturbative QCD)

# Strategy of the W boson mass measurement at CMS

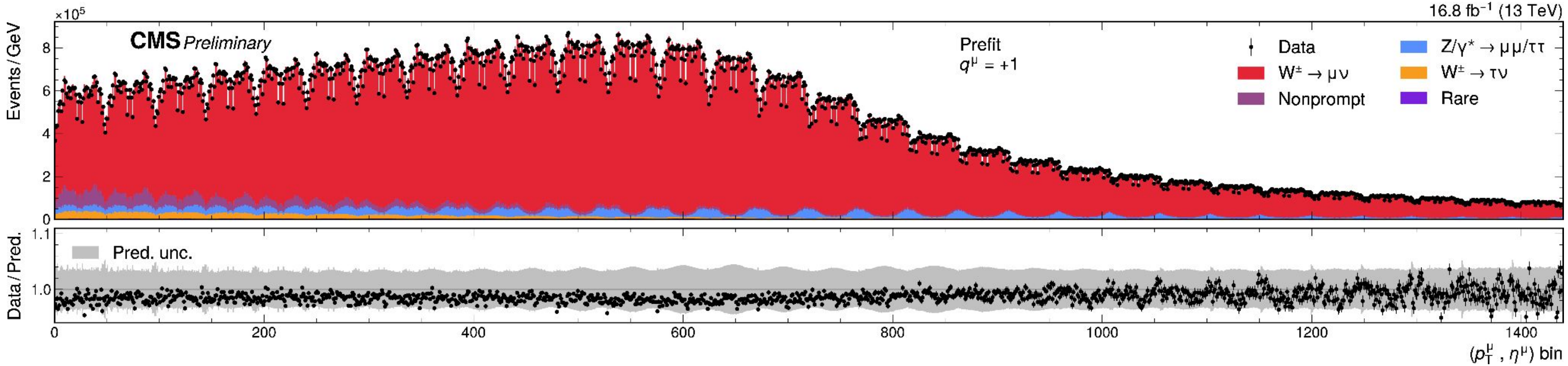
**Used a well-studied dataset taken in 2016 corresponding to 16.8 fb$^{-1}$**

- Over 100M selected muon W candidates W $\rightarrow \mu\nu$
- Accompanied by 4B fully simulated MC events




**Key ingredients**

- Use muon kinematics *only* ($\eta$, $p_T$): precise calibration of the muon momentum scale
- Theoretical modeling: use state-of-the-art theoretical models and constrain in-situ by data
- W boson mass extracted by fitting a granular 3 dimensional space ($\eta$, $p_T$, q)
- Reserve Z data as an independent cross-check as much as possible



# Muon momentum scale calibration

**Accurate momentum calibration necessary to $10^{-4}$ level as $\delta m_W \sim \delta p_T$**

- Calibration based on the inner tracking system, muon system only used for trigger and identification
- Requires accurate understanding of **magnetic field**, **detector material and particle interaction model**, **alignment**

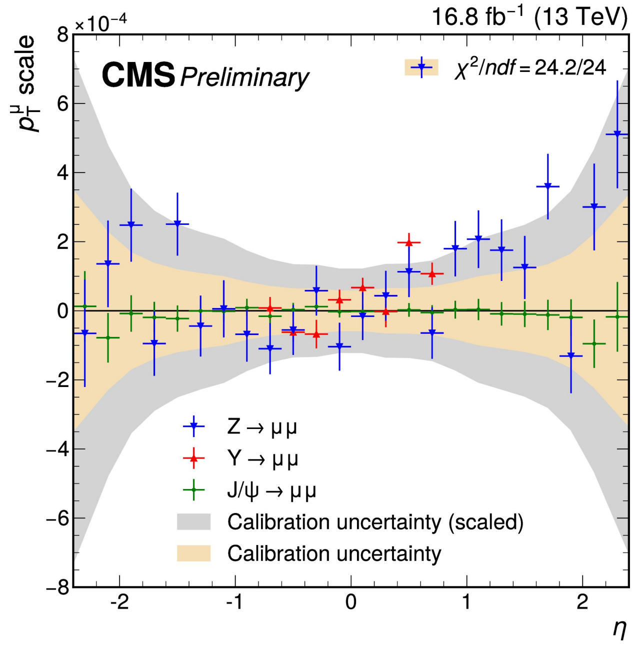
$$\frac{\delta k}{k} = A - \epsilon k + qM/k \qquad (k = 1/p_T)$$

**Use advanced track refit and quarkonia resonances to correct mismatches between data and simulation**

- Rely on $J/\psi \to \mu\mu$ only, use the Z (and Y) resonance as validation
- Done in different regions of the detector (24 bins in $\eta$)

**Extrapolation momentum range of $J/\psi$ to Z based on parametric model**

- Validated by extracting closure on the $Z \to \mu\mu$ events
- Scale statistical uncertainties of the calibration to cover for residual differences and possible biases

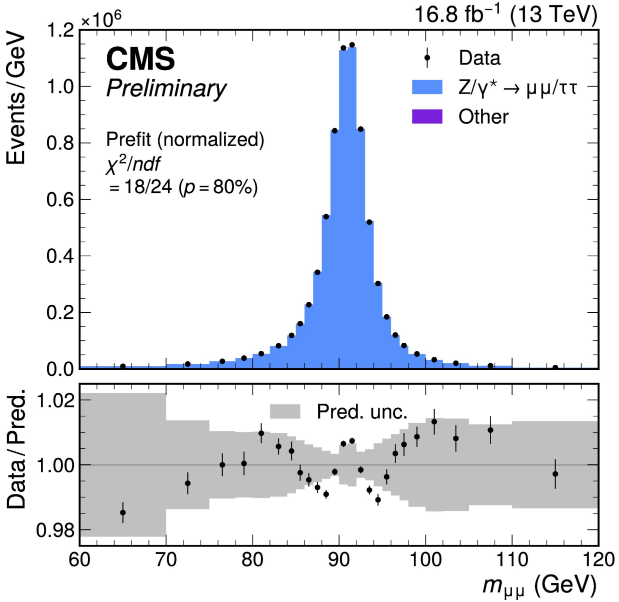


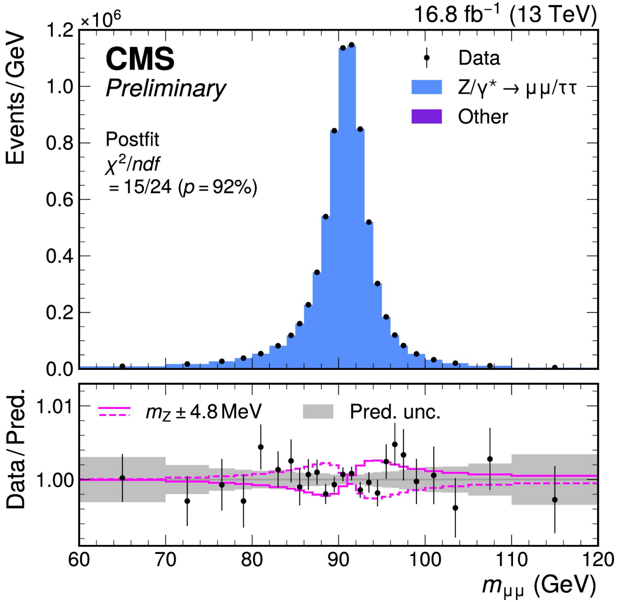
# Validation of the muon momentum scale

**Validation of muon momentum scale and uncertainties by fitting the dilepton mass spectrum**

$$m_Z - m_Z^{\mathrm{PDG}} = -2.2 \pm 4.8\,\mathrm{MeV} = -2.2 \pm 1.0\,(\mathrm{stat}) \pm 4.7\,(\mathrm{syst})\,\mathrm{MeV}$$

- Uncertainties fully dominated by muon momentum scale
- Cannot claim an independent Z mass measurement as the non closure is used in the uncertainty model



# In-situ theoretical modeling

**Theoretical modeling challenging at hadron colliders as it involves the parton distribution functions (PDF), perturbative and non-perturbative QCD and electroweak effects**

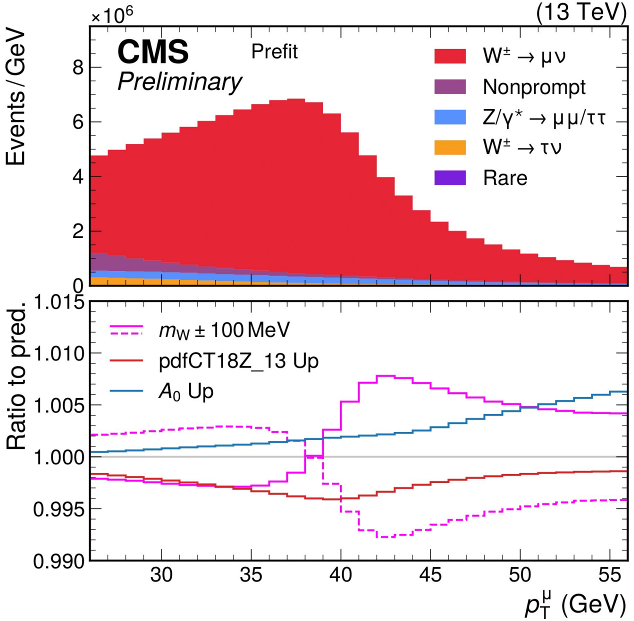
- Typically to cope with large theoretical uncertainties as generally higher-order calculations are missing
- In previous measurements at hadron colliders (ATLAS, CDF) is to tune the theoretical modeling to the well known Z

**Our approach is to let the data directly constrain the theory model**

- Use state-of-the-art theory predictions as a starting point
- Well-defined uncertainties to distinguish theoretical variations from mass variations → factorize different theory contributions

**→ Allows to use the Z as validation only**

**→ Smaller impact on $m_W$ thanks to the statistical power of the data**

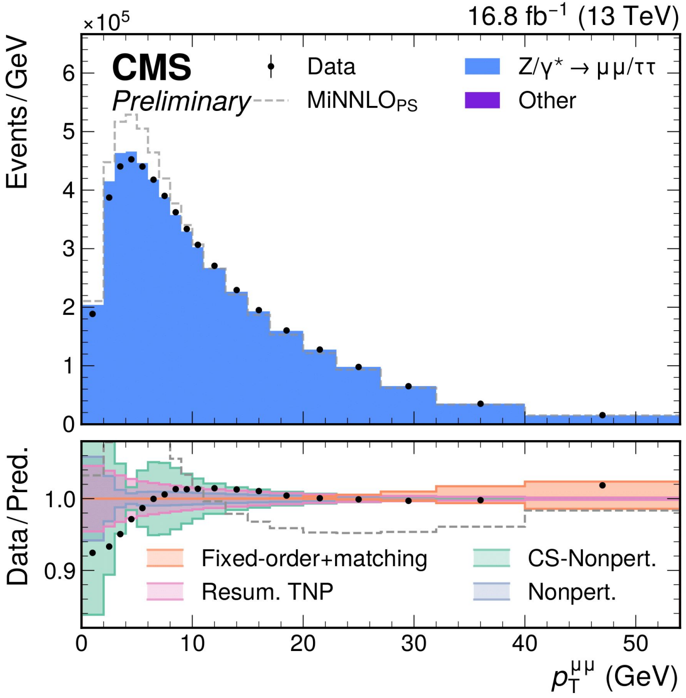


# Modeling of the boson $p_T$

**Simulation using MiNNLOPS + Pythia 8 + Photos**

$$\frac{d\sigma}{dp_T^2\, dm\, dy\, d\cos\theta^*\, d\phi^*} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^2\, dm\, dy} \left[ (1+\cos^2\theta^*) + \sum_{i=0}^{7} A_i(p_T, m, y) P_i(\cos\theta^*, \phi^*) \right]$$

- Next-to-next leading order in $\alpha_s$
- Limited in logarithmic accuracy for W/Z $p_T$: correct $\sigma^{U+L}$ using resummed SCETLIB prediction matched to fixed order DYTurbo prediction ($N^3LL$)




**Resummation –** "Theory nuisance parameters"

- Corresponding to the terms appearing in the resummed calculation
- Well-defined correlation model across phase-space and between W and Z

**Non-perturbative**

- Account for transverse motion of partons in the protons (TMD PDF)
- Empirical model: Gaussian smearing of parton momenta – large a-priori unc

**Fixed-order**

- Missing higher orders in $\alpha_s$ assessed through $\mu_r$ and $\mu_f$ variations

# Parton distribution functions

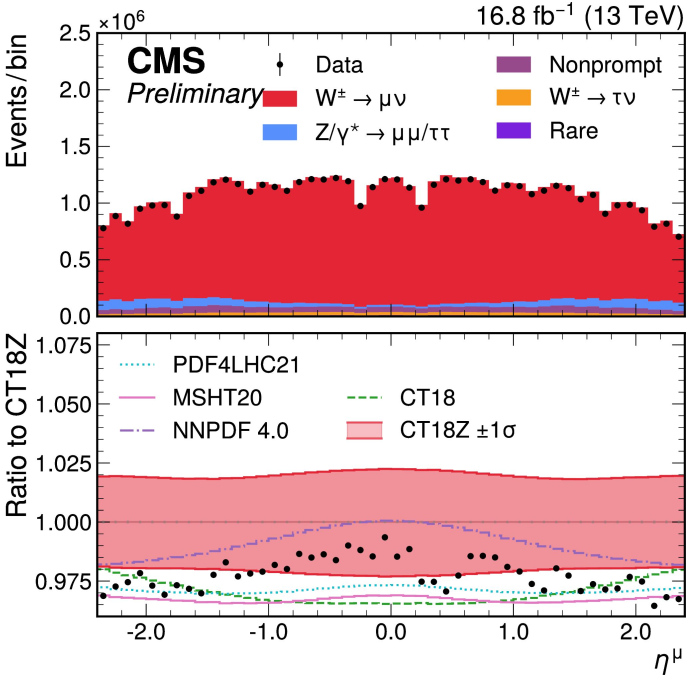
**PDF uncertainties also constrained in situ**

- Strong constraining power from the $\eta$-dimension (48 bins)

**Several PDF sets available with their own set of uncertainties and well-defined correlations**

- Central values and uncertainties do not always agree with each other
- Scale prefit PDF uncertainties to ensure consistency between sets
- CT18Z chosen a priori as the nominal as it requires no inflation and gives the smallest uncertainty (after scaling)

| PDF set | Scale factor | Impact in $m_W$ (MeV) Original $\sigma_{PDF}$ | Scaled $\sigma_{PDF}$ |
|---|---|---|---|
| CT18Z | – | 4.4 | |
| CT18 | – | 4.6 | |
| PDF4LHC21 | – | 4.1 | |
| MSHT20 | 1.5 | 4.3 | 5.1 |
| MSHT20aN3LO | 1.5 | 4.2 | 4.9 |
| NNPDF3.1 | 3.0 | 3.2 | 5.3 |
| NNPDF4.0 | 5.0 | 2.4 | 6.0 |



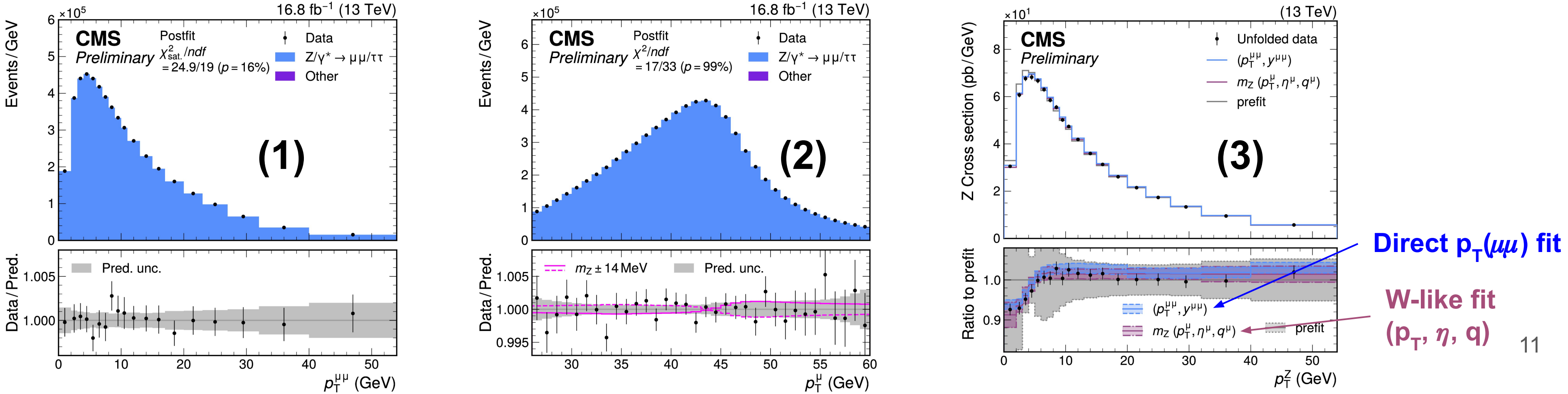
# Validation of theoretical modeling

## Validation of the theory and uncertainty model on Z data

1. Direct fit to the the $p_T(\mu\mu)$ distribution shows excellent agreement with the data
2. "W-like" measurement by measuring the Z mass from single lepton kinematics ($p_T$, $\eta$, q)
   - Similar fit to extract the W boson mass
   - Result in good agreement with PDG value and quoted uncertainty
3. Directly test the theory model by comparing the unfolded $p_T$(Z) spectrum with the direct fit

$$m_Z - m_Z^{\mathrm{PDG}} = -6 \pm 14\,\mathrm{MeV}$$

**Confidence the W boson mass can be measured without tuning $p_T$(W) using Z data**



# Result of the CMS W boson mass measurement

**All ingredients in place to measure the W boson mass**

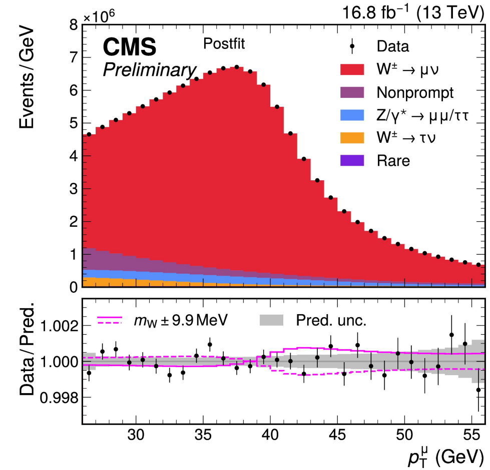
- Validated the theory model and muon momentum scale
- Data-driven non-prompt background from QCD multijet events, mostly heavy flavour

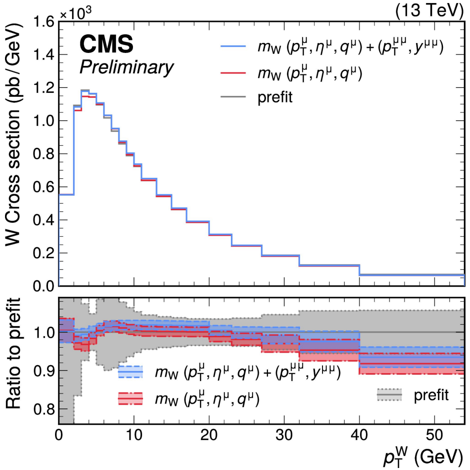
**Result $m_W$ = 80360.2 ± 9.9 MeV, compatible with the Standard Model**

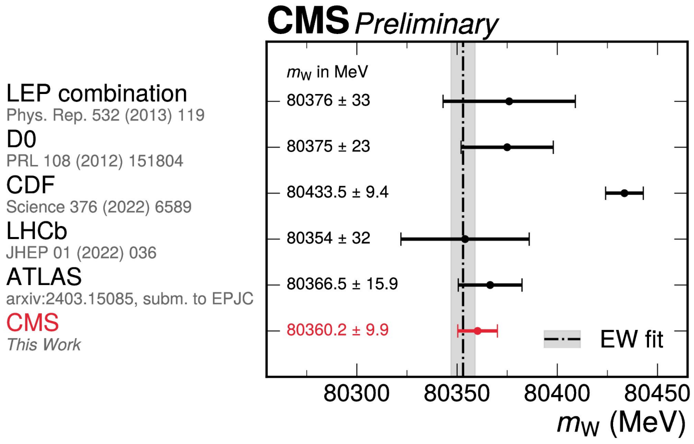
→ **Most precise measurement at the LHC**

Our graduate student Tianyu Justin Yang successfully defended his thesis on the W mass measurement

| Source of uncertainty | Nominal in $m_Z$ | Nominal in $m_W$ |
|---|---|---|
| Muon momentum scale | 5.6 | 4.8 |
| Muon reco. efficiency | 3.8 | 3.0 |
| W and Z angular coeffs. | 4.9 | 3.3 |
| Higher-order EW | 2.2 | 2.0 |
| $p_T^V$ modeling | 1.7 | 2.0 |
| PDF | 2.4 | 4.4 |
| Nonprompt background | – | 3.2 |
| Integrated luminosity | 0.3 | 0.1 |
| MC sample size | 2.5 | 1.5 |
| Data sample size | 6.9 | 2.4 |
| Total uncertainty | 13.5 | 9.9 |



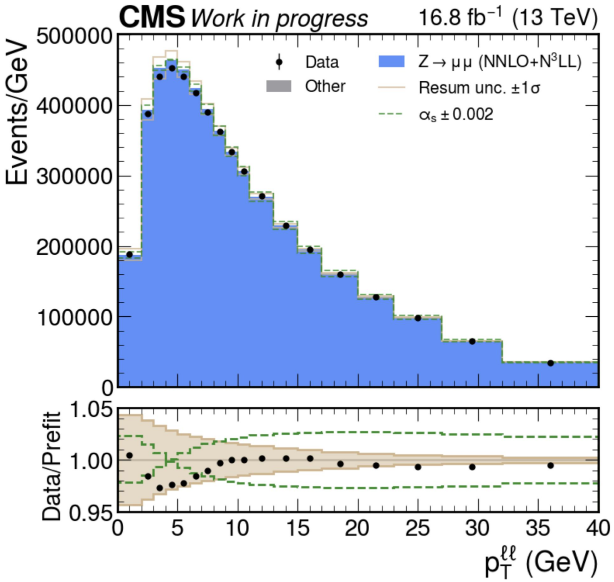
# Next steps in precision electroweak physics

## Demonstrated precision physics can be done at the LHC

- Developed technical tools to cope with large datasets → opens up for analysis of even larger datasets (e.g. full Run2)
- Very well understood dataset that can directly be used to measure other electroweak parameters

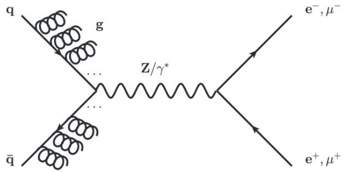
## Measurement of the Z boson mass

- Current muon scale calibration amounts to 4.8 MeV
- First-step improvements in uncertainty model allows for a first Z mass measurement at hadron collider (~ 4–5 MeV)
- Next-step improvements in calibration to further calibrate to LEP level (~ 2 MeV)




## Strong coupling constant $\alpha_S$

- Gluon radiation before qq annihilation couples to $\alpha_S$ and changes transverse momentum of the Z boson
- Experimental $p_T(\mu\mu)$ distribution used to extract $\alpha_S$
- Benefit from state-of-the-art theoretical implementations to decouple $\alpha_S$ from other variations (PDFs, non-perturbative)



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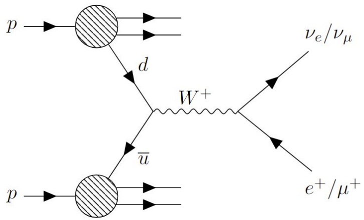
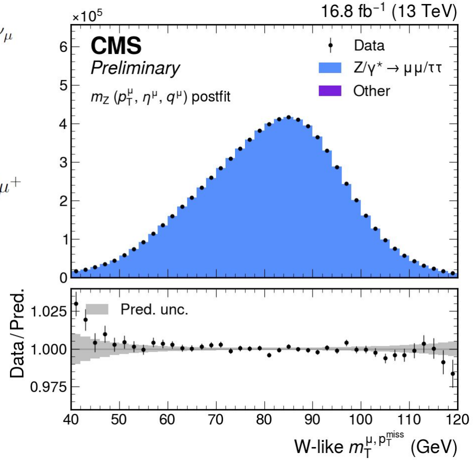


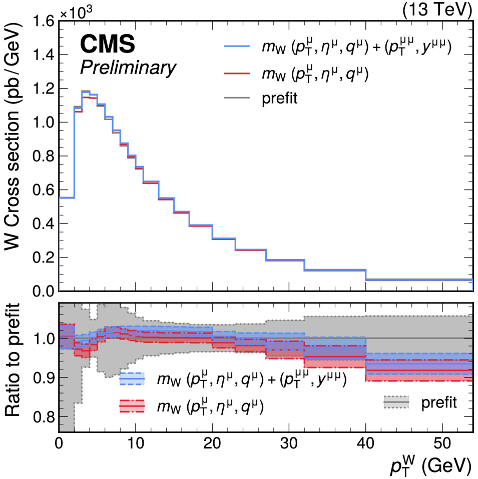

## Improved W boson mass measurement

- Use missing energy as a proxy of the undetected neutrino
- Allows to fully exploit the W boson kinematics
- Requires excellent calibration of the missing energy:
  - Extensive developments over the past years proven to calibrate the hadronic recoil below percent level
- Can further pin down the W boson mass uncertainty
- Simultaneously measure the W boson width, sensitivity in tails of transverse mass




## Differential measurement $p_T$(W)

- Crucial to *directly* validate theoretical models on W data
- Analysis ongoing by measuring unfolded spectra using the hadronic recoil of the W boson using low pileup datasets taken in 2017
- Comparison with the the unfolded $p_T$(W) from W mass



# Future of The Energy Frontier

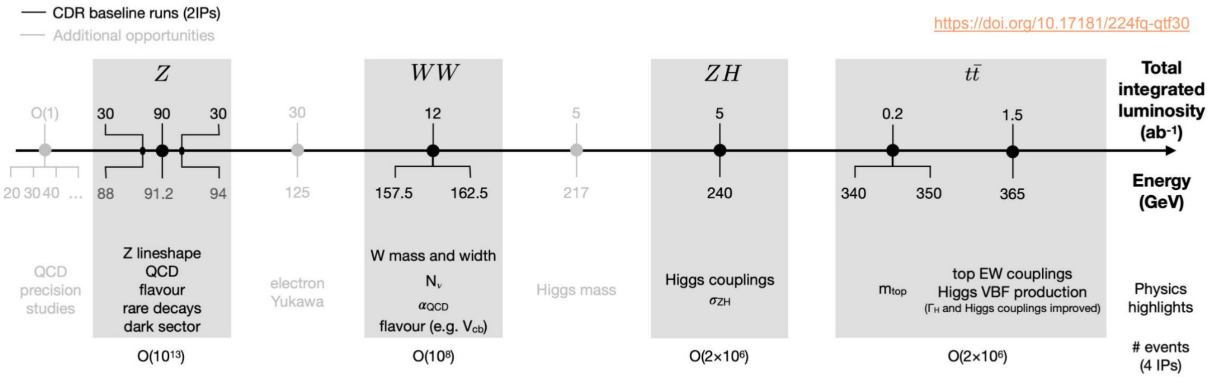
**LHC can and will offer competitive precision physics**

- With a lot of data delivered by LHC (and HL) we can understand better our detector and improve experimental systematics
- Although some measurements will ultimately remain systematically limited → no benefit of more data

**An electron-positron machine is the next step towards high precision physics to measure precisely the Higgs and Top properties ("Higgs/Top factories")**

**FCC-ee meets these physics goals and extends the physics reach to the entire electroweak sector**

- Increase the precision by order(s) of magnitude for Z/W physics
- Precisely study the Higgs and top quark properties
- Flavor factory from Z→bb/cc



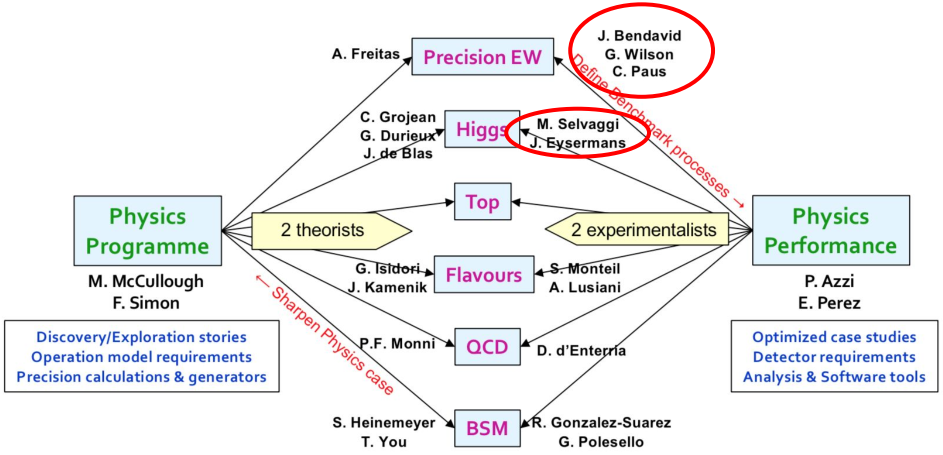

**$m_Z$ ~ 100 keV** **$m_W$ ~ 500 keV** **$m_H$ ~ 4 MeV** **$m_t$ ~ 15 MeV**

# Feasibility study report

**Provide by 2025 conclusions on the technical and financial feasibility of the FCC integrated project, to be submitted/approved at the next European Strategy in 2026**

**Physics, Experiments and Detectors (PED) structure created in 2021 to help completion (part of) the FSR**

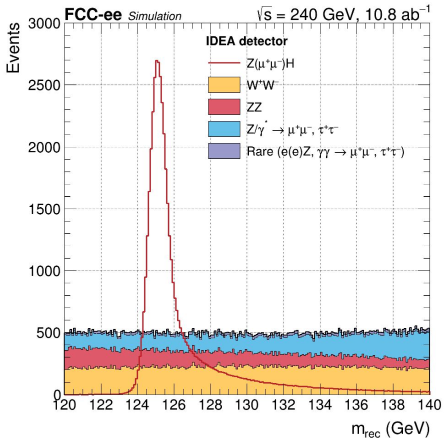
- Establish physics programme and goals
- Assess physics performance and the detector requirements
- Also other aspects involved (computing and detector studies and development, machine-detector interface, …)

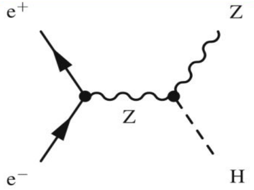



**MIT strongly involved in physics performance and computing with electroweak and Higgs/Top**

- Successfully delivered the mid-term review of feasibility study in 2023
- On track for deliverables for the final report

# Higgs mass and detector requirements




**Higgs mass measured from the ℓℓ system of Z(ℓℓ)H recoil**

**Extended studies performed regarding detector/accelerator effects on the Higgs mass**

**Nominal configuration**

**Crystal ECAL to Dual Readout**

**Nominal 2 T → field 3 T**

**IDEA drift chamber → CLD Si tracker**

**Impact of Beam Energy Spread uncertainties**

**Perfect (=gen-level) momentum resolution**

| **Fit configuration** | $\mu^+\mu^-$ channel | $e^+e^-$ channel | combination |
|---|---|---|---|
| Nominal | 4.10 (4.88) | 5.17 (5.85) | 3.14 (4.01) |
| Inclusive | 4.84 (5.53) | 6.16 (6.73) | 3.75 (4.50) |
| Degradation electron resolution (*) | 4.10 (4.88) | 5.98 (6.49) | 3.32 (4.11) |
| Magnetic field 3T | 3.38 (4.28) | 4.30 (5.00) | 2.60 (3.54) |
| CLD 2T (silicon tracker) | 5.51 (6.07) | 6.20 (6.70) | 4.01 (4.66) |
| BES 6% uncertainty | 4.10 (5.01) | 5.17 (6.10) | 3.14 (4.09) |
| Disable BES | 2.27 (3.42) | 3.11 (4.04) | 1.80 (2.99) |
| Ideal resolution | 2.89 (3.95) | 3.89 (4.56) | 2.39 (3.33) |
| Freeze backgrounds | 4.10 (4.88) | 5.17 (5.85) | 3.14 (4.00) |
| Remove backgrounds | 3.37 (4.34) | 3.85 (4.80) | 2.49 (3.56) |

# Future of The Energy Frontier


**Precision measurements of Z, W, Higgs boson & top quark physics**

- Z lineshape $\Delta m_Z$ ~ 4 keV → improve uncertainty by factor of 500 (almost 3 order of magn.)
- W boson mass $\Delta m_W$ ~ some few hundreds keV
- Higgs boson couplings to percent levels, independent full width measurement

**Starting to work on R&D for CMOS MAPS vertex detector using simulations**

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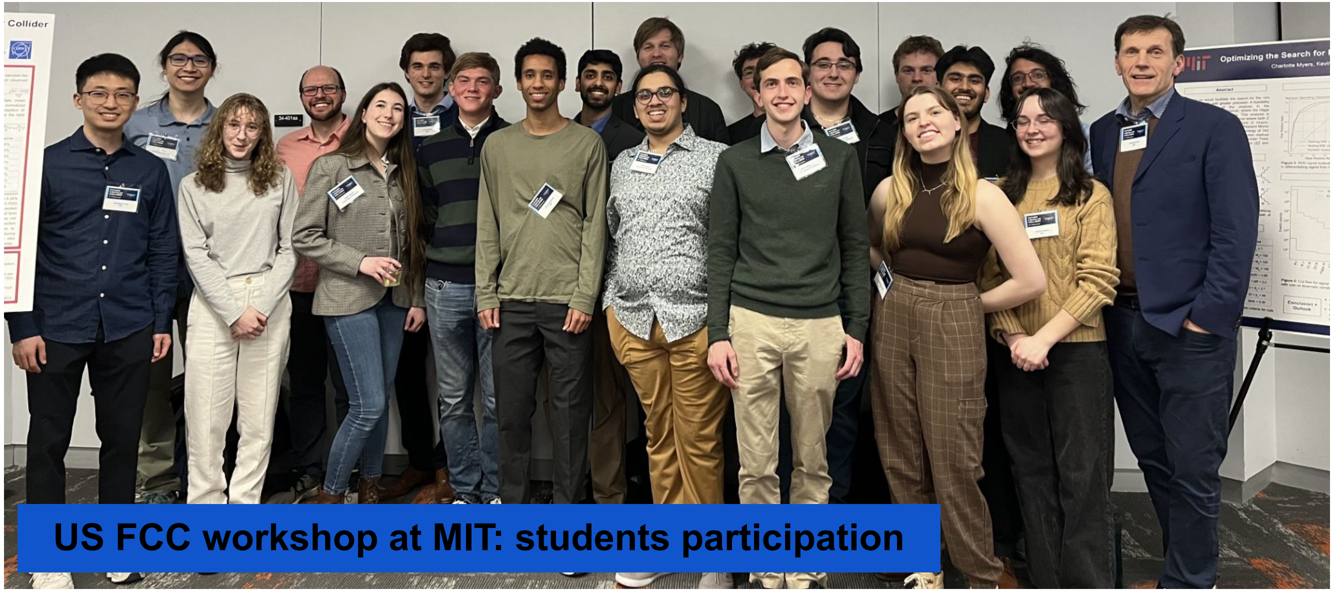


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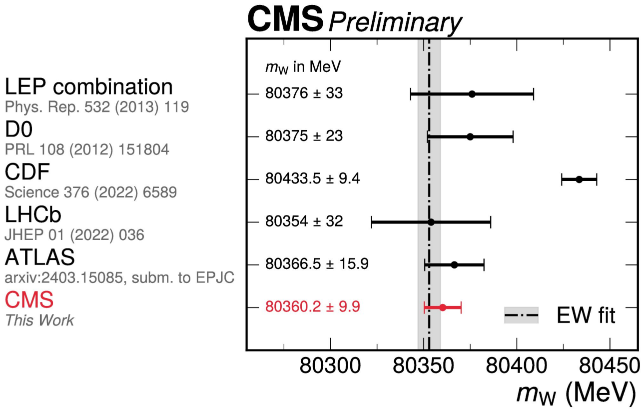
# Concluding remarks

**MIT leads the CMS electroweak precision program**

- First W boson mass measurement from CMS
- Using a large dataset with innovative theoretical modeling in-situ constraints
- Unprecedented calibration of the momentum scale down to 5 MeV
- **Measurement in agreement with SM and in strong tension with CDF**
- Plans for subsequent measurements on W boson mass and electroweak physics in general




**FCC and the Future of The Energy Frontier**

- Electroweak and Higgs/Top physics performance studies for the FCC
- Involve (under)graduate students in contributing to analyses and physics studies