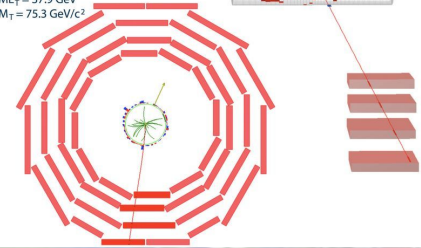
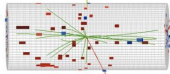


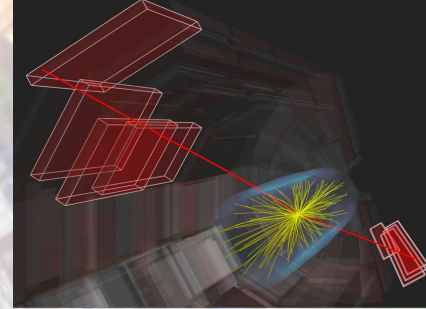


CMS Experiment at LHC, CERN
Run 133875, Event 1228182
Lumi section: 16
Sat Apr 24 2010, 09:08:46 CEST

Muon $p_T = 38.7$ GeV/c
 $E_T = 37.9$ GeV
 $M_T = 75.3$ GeV/c²



CMS Experiment at the LHC, CERN
Data recorded: 2017-Jun-26 03:27:24.199168 GMT
Run / Event / LS: 297503 / 410616674 / 223



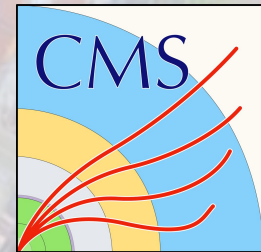
Physics with W/Z bosons at CMS

Saranya Ghosh

Indian Institute of Technology Hyderabad

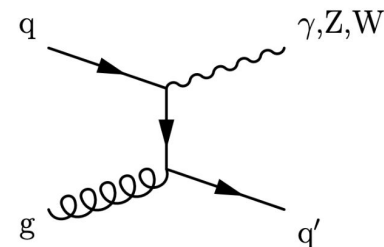
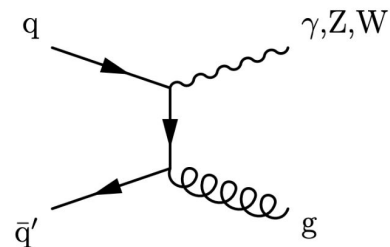
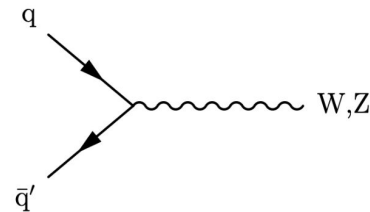


భారతీయ సాంకేతిక విజ్ఞాన సంస్థ హైదరాబాద్
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Indian Institute of Technology Hyderabad



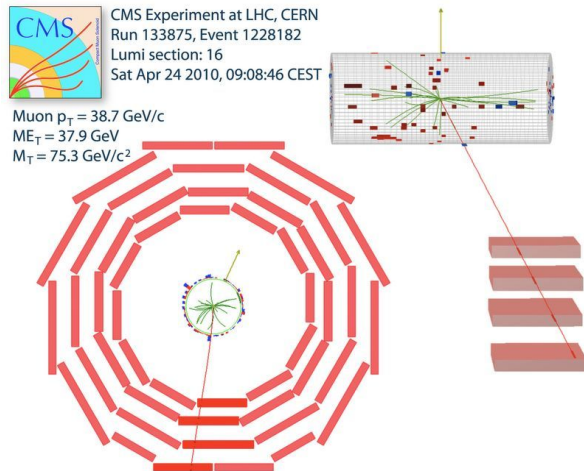
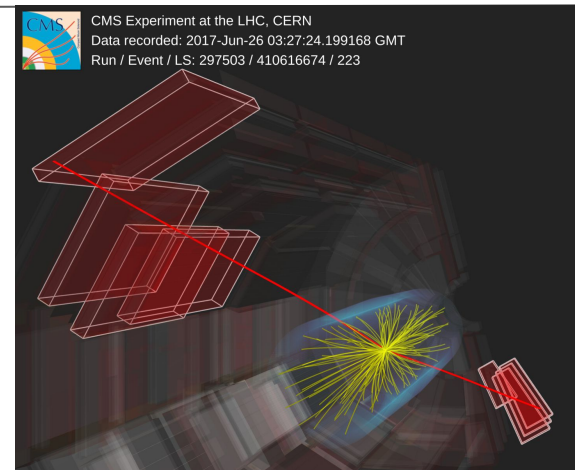
Physics of W, Z bosons at the LHC

- Comprehensive program of SM precision measurements possible with LHC delivering proton-proton collisions at much higher energies and luminosities than previous machines
 - Instantaneous luminosity at LHC exceeds previous hadron collider, Tevatron, by nearly two orders of magnitude.
 - Higher pp collision energy significantly increases all production cross sections.
- The unprecedented capabilities facilitate precise measurements of the properties of a wide array of processes, the most fundamental being cross sections.
 - Precise measurement of the W and Z boson production cross sections can be performed in CMS with data collected in one day of LHC operation with a precision similar to that obtained during several years of operation of the UA1 and UA2 experiments that discovered the W and Z bosons.
- For EW physics, the number of accessible final states at the LHC is without precedent.
 - States with single, double, or triple gauge bosons.
 - Many processes have only been observed at the LHC, which is the first collider that allows access to processes such as VBS.



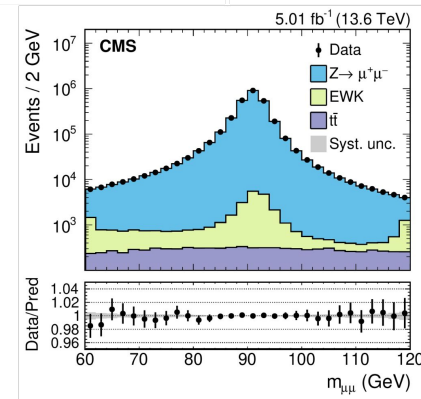
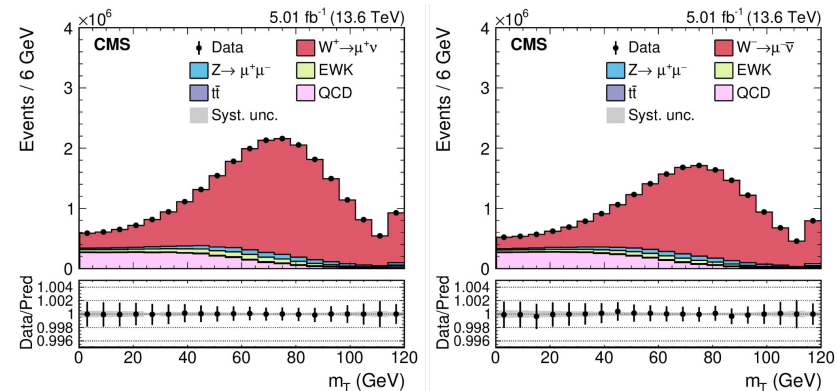
W, Z bosons at CMS

- W and Z bosons are efficiently reconstructed via their leptonic decays
 - $W^+ \rightarrow \ell + \nu_\ell$
 - $Z \rightarrow \ell + \ell^-$
 - where $\ell = \mu$ or e
- Backgrounds to $Z \rightarrow \ell + \ell^-$ decays are very low.
- Muons and electrons with $p_T > 20$ GeV are used in analysis with a single W boson.
- Analyses with Z bosons or multiple bosons often use thresholds as low as $p_T > 10$ GeV for a second lepton and $p_T > 5$ GeV for additional leptons.
- The W bosons are also selected by identifying events with $p_{T\text{miss}}$ or selecting events with large transverse mass m_T calculated using a lepton momentum and $p_{T\text{miss}}$
- Jet and flavour-tagging algorithms are used to identify jets and separately bottom and charm jets



W, Z bosons at CMS

- $W \rightarrow \ell \nu_\ell$ and especially $Z \rightarrow \ell\ell$ decay modes have low backgrounds
- Analysis strategy: template fits from MC to data in the transverse mass (m_T) for W and $M_{\ell\ell}$ for Z
- Size of the LHC data sets allows theoretical and experimental comparisons of total, differential, and often multidifferential distributions with good precision over wide ranges of energy, angle, and jet multiplicity.
- Together these processes provide a stringent test of SM predictions over a broad array of final states and kinematic configurations.
- The measurements of W & Z bosons is sensitive to PDFs and also the EW mixing angle θ_w .
- For comparisons of measurements to theory
 - The DY process has been predicted at N3LO accuracy in perturbative QCD using matching N3LO PDF sets.
 - PDF uncertainties, and higher-order QCD and EW radiative corrections limit the precision of current predictions.

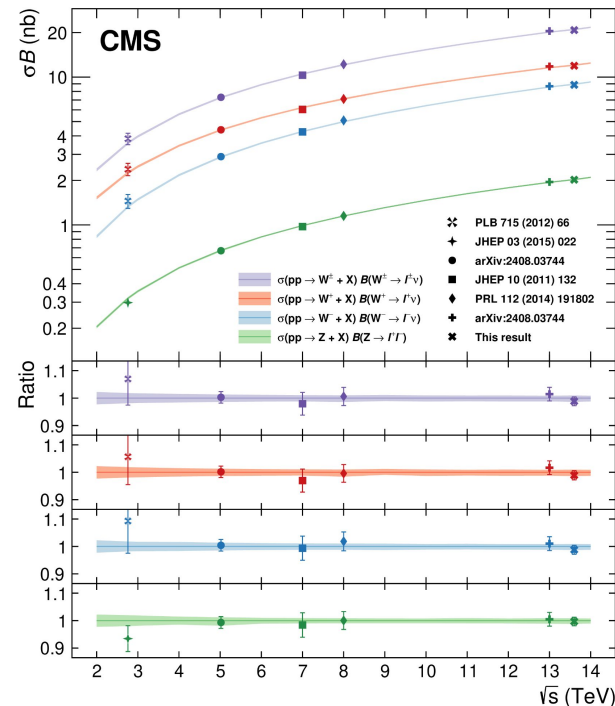


A photograph of a long, curved tunnel, likely part of a particle accelerator. On the left side, there is a large, blue, cylindrical structure, possibly a cryogenic storage vessel or a component of the accelerator. It has several red caps and a small white label with the number '110108'. Above this structure, there are various pipes and cables. On the right side, there is a track or a series of rails that curve along the length of the tunnel. The tunnel walls are made of concrete and have some structural elements. The lighting is bright, coming from overhead fixtures. The overall scene is industrial and technical.

W, Z cross section

W and Z cross sections

- CMS has performed inclusive cross section measurements for both the W and Z bosons at each energy at which the LHC has operated.
- Measurements at 2.76 and 5.02 TeV are based on the pp collision reference data for the heavy ion physics program.
- Large data sets of W and Z bosons result in small to negligible statistical uncertainty in the measurements.
 - Have ~2% precision primarily limited by the uncertainty in the integrated luminosity.
- Small systematic uncertainty is achieved due to
 - Large data sets for evaluating efficiency of lepton detection
 - Accurate MC simulations for estimating the acceptance for prompt leptons from W and Z boson decays,
 - Predicting physics backgrounds involving prompt leptons from other sources
 - Low backgrounds and reliable methods to predict the rates of hadrons and leptons in jets being misidentified as prompt leptons based on control samples in data.
- Measurements are first made in fiducial phase spaces and extrapolated to the full production cross sections



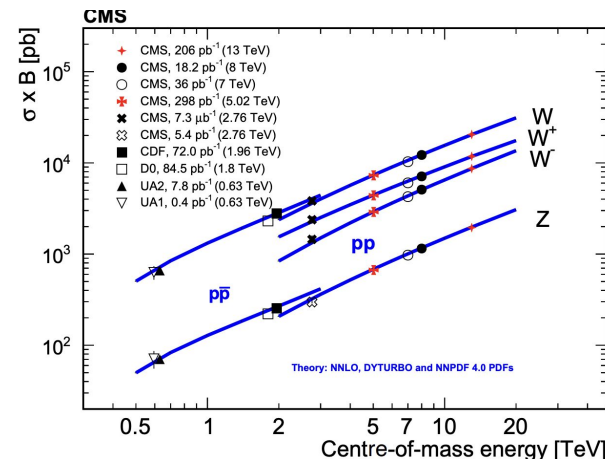
Comparison of measured total cross section x branching fractions for W and Z boson production at different center-of-mass energies with the corresponding theoretical prediction at NNLO+NNLL QCD accuracy obtained from DYTURBO. Uncertainties in theoretical prediction include variations of the renormalization and factorization scales, as well as the PDF uncertainty evaluated with the NNPDF 3.1 set.

W and Z cross sections

- Largest source of uncertainty in the measurements is the integrated luminosity.
- Most precise cross section measurements have been made with low-pileup data sets collected in short time periods that allow a more precise determination of the integrated luminosity.

$\sqrt{s}$ (TeV)	$\sigma(Z)$ (pb)	Tot. exp. unc.	$\sigma^{SM}(Z)$ (pb)
2.76 [218]	298 ± 10 (stat) (syst) ± 11 (lumi)	5.0%	313^{+1}_{-2}
5.02 [219]	669 ± 2 (stat) ± 6 (syst) ± 13 (lumi)	2.2%	$674.7^{+7.1}_{-7.4}$
7 [221]	986 ± 22 (syst) ± 22 (lumi)	3.1%	968^{+6}_{-7}
8 [223]	1138 ± 26 (syst) ± 30 (lumi)	3.5%	1124^{+7}_{-2}
13 [219]	1952 ± 4 (stat) ± 18 (syst) ± 45 (lumi)	2.5%	1940^{+15}_{-21}

Details of Z cross section measurement



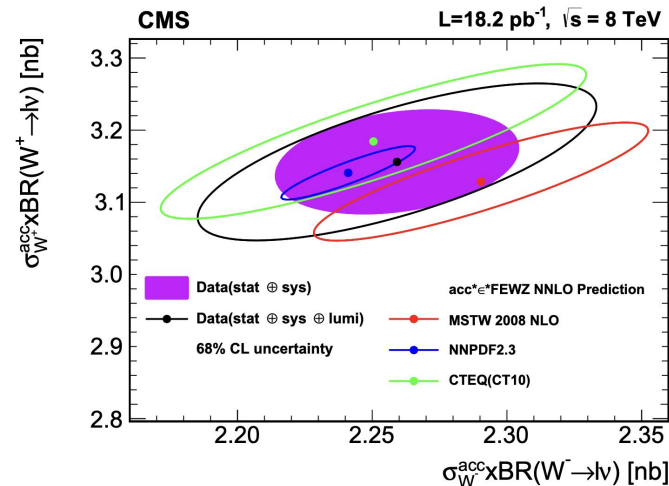
Production cross section of weak gauge bosons in pp collisions, measured by CMS, and in ppbar collisions, by the UA1, UA2, CDF, and D0 experiments. Theoretical predictions (blue lines) obtained at NNLO in QCD by using DYTURBO and the NNPDF4.0 PDF

W and Z cross sections

- Measuring the cross section in a fiducial phase space reduces the total systematic uncertainty by minimizing uncertainty from the extrapolation to the full production phase space.
- Ratios of cross sections can be measured with better than 0.5% precision in fiducial phase space
 - Sependence of the measurement on the integrated luminosity and the understanding of some reconstruction efficiencies is removed by forming a ratio of cross sections of similar production processes.

$\sqrt{s}$ (TeV)	Ratio	R_{exp}	Tot. exp. unc.	R_{SM}
5.02 [219]	R_{W^+/W^-}	$1.6232 \pm 0.0026 \text{ (stat)} \pm 0.0065 \text{ (syst)}$	0.43%	$1.631 \pm 0.98\%$
8 [222]	R_{W^+/W^-}	$1.40 \pm 0.01 \text{ (stat)} \pm 0.02 \text{ (syst)}$	1.6%	$1.42 \pm 1.4\%$
13 [219]	R_{W^+/W^-}	$1.3159 \pm 0.0017 \text{ (stat)} \pm 0.0053 \text{ (syst)}$	0.43%	$1.307 \pm 1.3\%$
5.02 [219]	$R_{W/Z}$	$12.505 \pm 0.037 \text{ (stat)} \pm 0.032 \text{ (syst)}$	0.39%	$12.51 \pm 0.96\%$
8 [222]	$R_{W/Z}$	$13.26 \pm 0.15 \text{ (stat)} \pm 0.21 \text{ (syst)}$	1.9%	$13.49 \pm 2.1\%$
13 [219]	$R_{W/Z}$	$12.078 \pm 0.028 \text{ (stat)} \pm 0.032 \text{ (syst)}$	0.35%	$12.02 \pm 2.3\%$

Theoretical predictions, R_{SM} , obtained at NNLO in QCD. Theoretical uncertainties are from renormalization and factorization scale variations, α_s , and the PDF uncertainty.



A perspective view down a long, industrial tunnel. On the left, a large blue cylindrical object, possibly a storage tank or part of a machine, runs along the wall. It has several red caps and a small white label with the number '110108'. Above it, various pipes and cables are visible. On the right, a track or conveyor system runs parallel to the blue object. The tunnel is illuminated by a series of bright lights at the far end, creating a strong perspective effect.

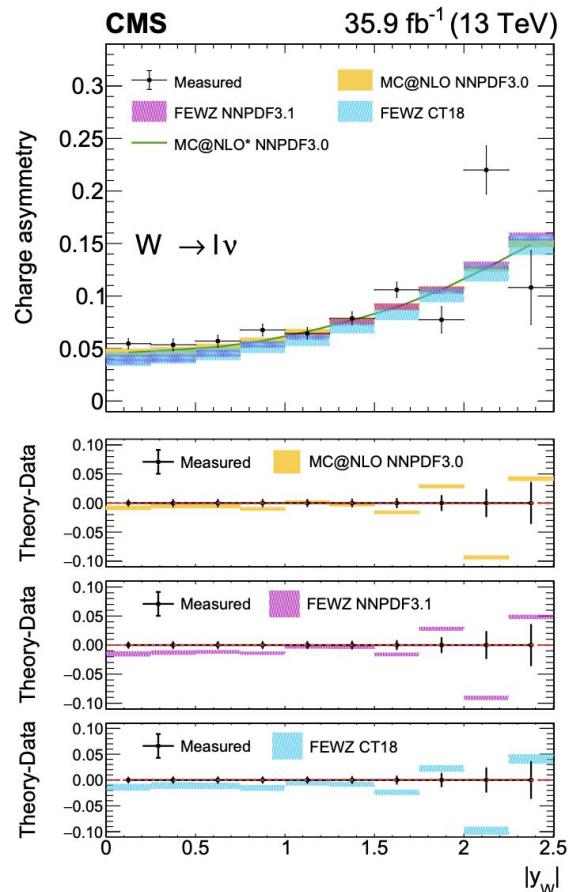
Differential Cross Sections

W charge asymmetry

- For W boson decays, differential measurements of the charge asymmetry has sensitivity to the PDFs of the quarks in the proton of the same charge sign as the W boson.

$$\mathcal{A}(|y_W|) = \frac{d\sigma/d|y_W|(W^+ \rightarrow \ell^+ \nu) - d\sigma/d|y_W|(W^- \rightarrow \ell^- \bar{\nu})}{d\sigma/d|y_W|(W^+ \rightarrow \ell^+ \nu) + d\sigma/d|y_W|(W^- \rightarrow \ell^- \bar{\nu})}$$

- The charge asymmetry in leptonic W boson decays has been measured in pp collisions at 7, 8, and 13 TeV,
 - At 13 TeV the charge asymmetry was also separately reported for the left- and right-handed W boson helicity states.
- Run 1 measurement with W+c also sensitive to s quark PDF

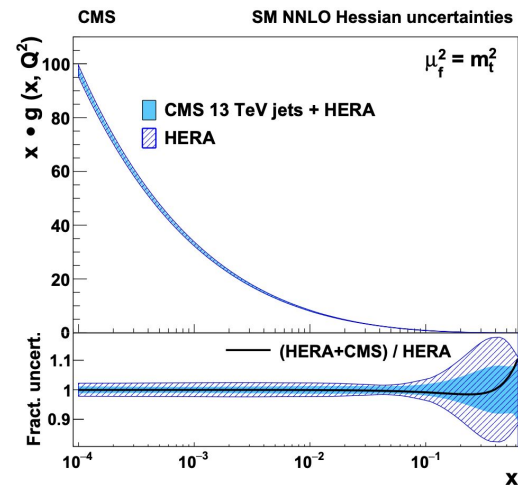


W charge asymmetry

- W charge asymmetry and other CMS measurements are useful for constraining PDFs
- To date, the majority of these measurements are used by the global PDFfit collaborations.
- Impact can be assessed by combining with DIS data from HERA using HERA fitter framework

Analysis	$\sqrt{s}$ (TeV)	HERA Data or PDF	QCD order	Best PDF constraint
W charge asym. [177], W+c [178]	7	HERA-I	NLO	u, d, s
Inclusive jet [144]	7	HERA-I	NLO	gluon
W charge asym. [179]	8	HERA-I + II	NLO	u and d
Inclusive jet [139]	8	HERA-I + II	NLO	gluon
3D dijet [180]	8	HERA-I + II	NLO	gluon
Inclusive jet [146], $t\bar{t}$ [181]	13	HERA-I + II, CT14nnlo	NNLO,NLO	gluon
Dijet mass [182]	13	HERA-I + II	NNLO	gluon

Different CMS measurements that have had an impact of PDF constraints



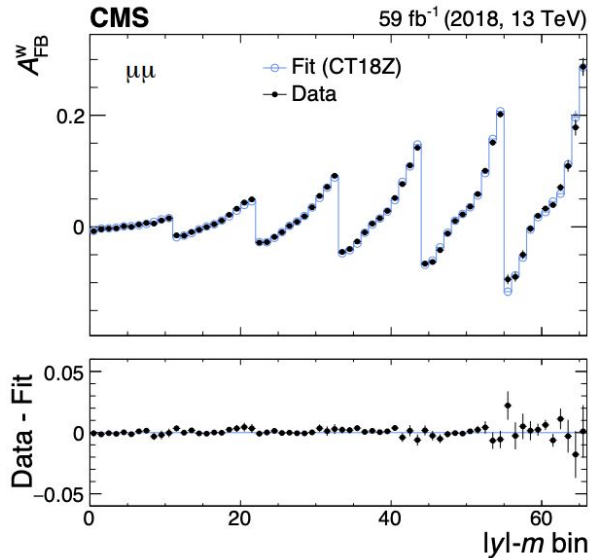
Forward-Backward asymmetry

- DY production of $\ell + \ell -$ pairs, when considering a wider range of masses around the Z boson peak, has the sensitivity to the EW mixing angle θ_w .

- Measurement of the forward-backward asymmetry is performed to probe the sensitivity:

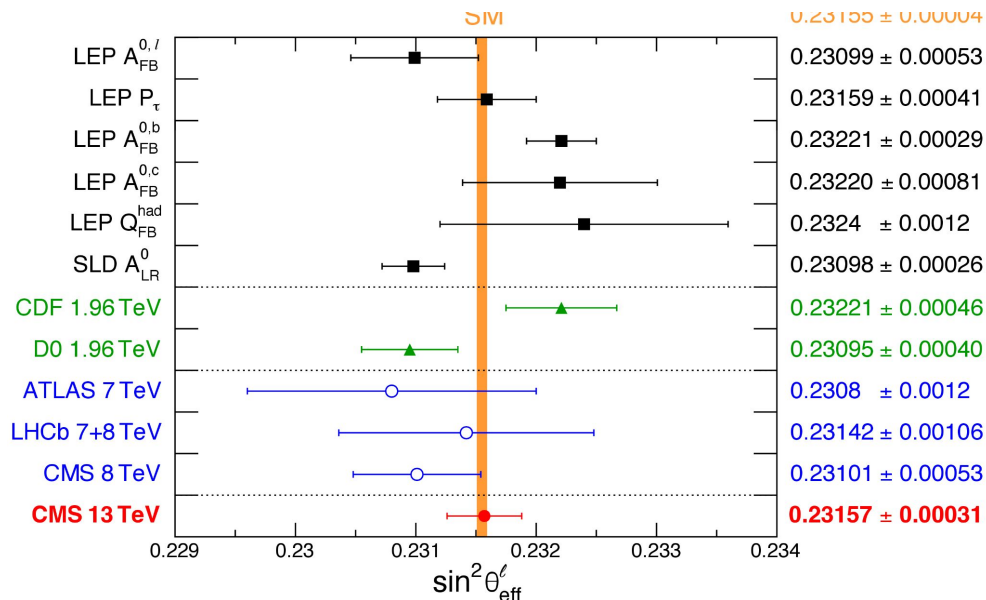
$$A_{\text{FB}} = \frac{\sigma_{\text{F}} - \sigma_{\text{B}}}{\sigma_{\text{F}} + \sigma_{\text{B}}},$$

- here σ_{F} (σ_{B}) is the total cross section for the forward (backward) events, defined by $\cos \theta^* > 0$ ($\cos \theta^* < 0$), where $\cos \theta^*$ is the angle between the negatively charged lepton and the Z boson momentum vector direction (in the laboratory frame) measured in the lepton pair centre-of-mass frame.
- The AFB depends on $m(\ell + \ell -)$, quark flavour, and the EW mixing angle.
 - Near the Z boson mass peak, the AFB is close to zero because of the small value of the charged lepton vector coupling to Z bosons.
 - Due to weak-electromagnetic interference, AFB is large and negative for m below the Z boson peak ($m < 80$ GeV) and large and positive above the Z boson peak ($m > 110$ GeV).
- Effective leptonic mixing angle ($\sin^2 \theta_{\text{eff}}$) is measured by fitting the $A_{\text{wFB}}(|y|, m)$ angular-weighted asymmetry to templates varying $\sin^2 \theta_{\text{eff}}$ and PDF set



Forward-Backward asymmetry: $\sin^2\theta_{\ell}^{\text{eff}}$

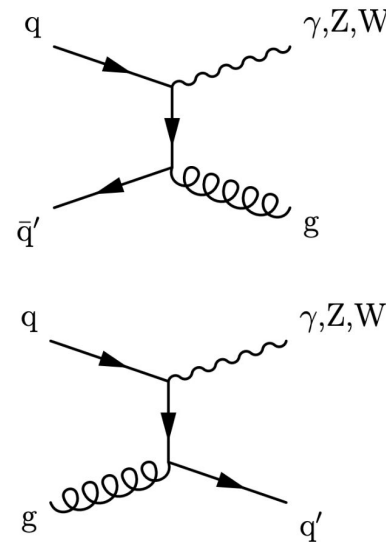
- Effective leptonic mixing angle ($\sin^2\theta_{\ell}^{\text{eff}}$) is measured by fitting the $A_{\text{WFB}}(|y|, m)$ angular-weighted asymmetry to templates varying $\sin^2\theta_{\ell}^{\text{eff}}$ and PDF set
- Using the CT18Z set of parton distribution functions we obtain
- $\sin^2\theta_{\ell}^{\text{eff}} = 0.23157 \pm 0.00010 \text{ (stat)} \pm 0.00015 \text{ (exp)} \pm 0.00009 \text{ (theo)} \pm 0.00027 \text{ (PDF)},$



Precision comparable to
LEP and SLD
measurements

Measurements differential in terms of jets

- Production of vector bosons in association with jets can be an excellent test of perturbative QCD predictions.
- Production of W and Z in association with jets, followed by the $W^+ \rightarrow \ell + \nu_\ell$ and $Z \rightarrow \ell + \ell^-$ decays, respectively, allows for some of the most stringent perturbative QCD tests.
- The NLO QCD diagrams for vector boson production can either involve a gluon in the initial state or the radiation of a gluon in the final state.
 - Including NLO diagrams is always necessary to get reasonably accurate cross section predictions.
- CMS measurements with topologies with up to 8 jets have been analyzed and compared with MC generators at LO, NLO, and NNLO accuracy



Measurements differential in terms of jets

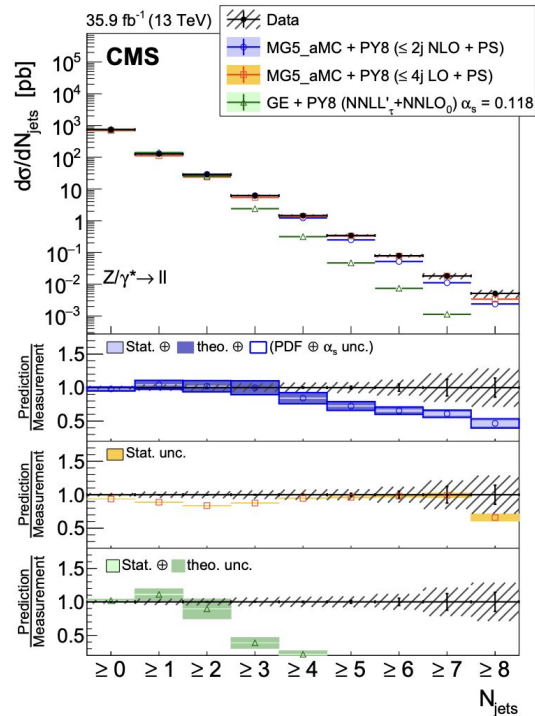


Figure 15: The differential cross section of $Z \rightarrow \ell^+\ell^- + \text{jets}$ production as a function of inclusive jet multiplicity, compared with the predictions calculated with MADGRAPH5.aMC@NLO (LO) + PYTHIA 8, MADGRAPH5.aMC@NLO (NLO) + PYTHIA 8, and GENEVA. The lower panels show the ratios of the theoretical predictions to the measurements. The measurement statistical (systematic) uncertainties are presented with vertical error bars (hashed areas). The boxes around the MADGRAPH5.aMC@NLO (NLO) + PYTHIA 8 to measurement ratio represent the uncertainty in the prediction as listed in the legend. Figure taken from Ref. [240].

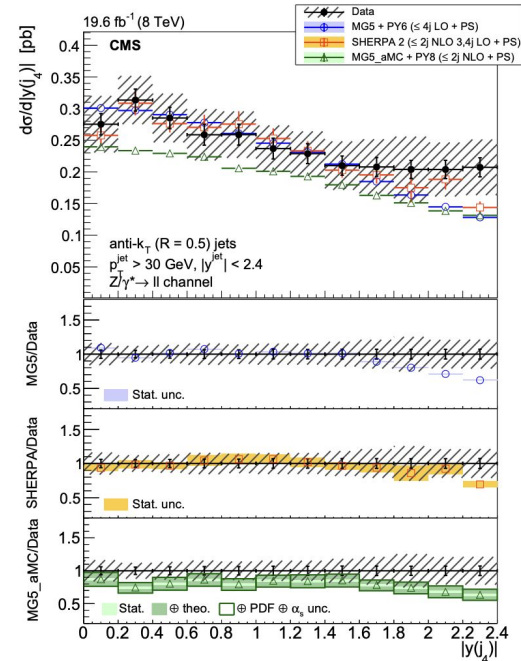


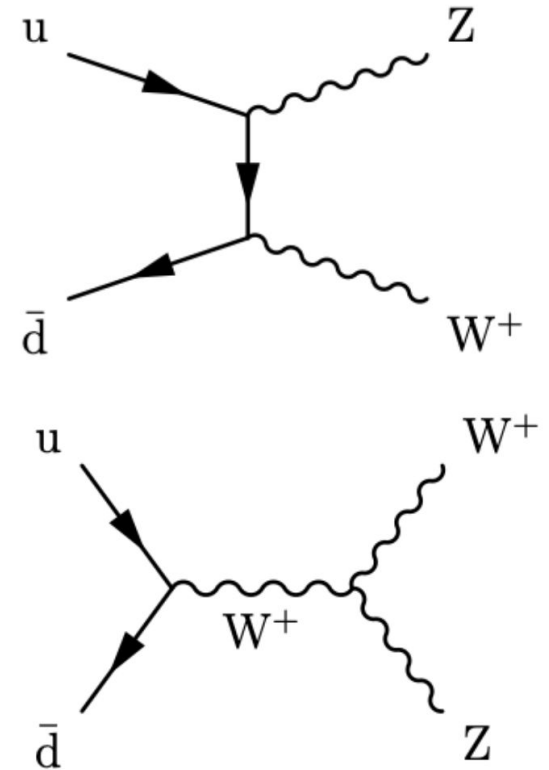
Figure 16: The differential cross section for $Z \rightarrow \ell^+\ell^- + \text{jets}$ production as a function of the absolute value of the 4th jet's rapidity compared with the predictions calculated with MADGRAPH 5+PYTHIA 6, SHERPA 2, and MG5.aMC +PYTHIA 8. The lower panels show the ratios of the theoretical predictions to the measurements. Error bars around the experimental points show the statistical uncertainty and the cross-hatched bands indicate the statistical and systematic uncertainties added in quadrature. The boxes around the MG5.aMC + PYTHIA 8 to measurement ratio represent the uncertainty in the prediction, including statistical, theoretical (from scale variations), and PDF uncertainties. The dark green area represents the statistical and theoretical uncertainties only and the light green area represents the statistical uncertainty alone. Figure taken from Ref. [248].



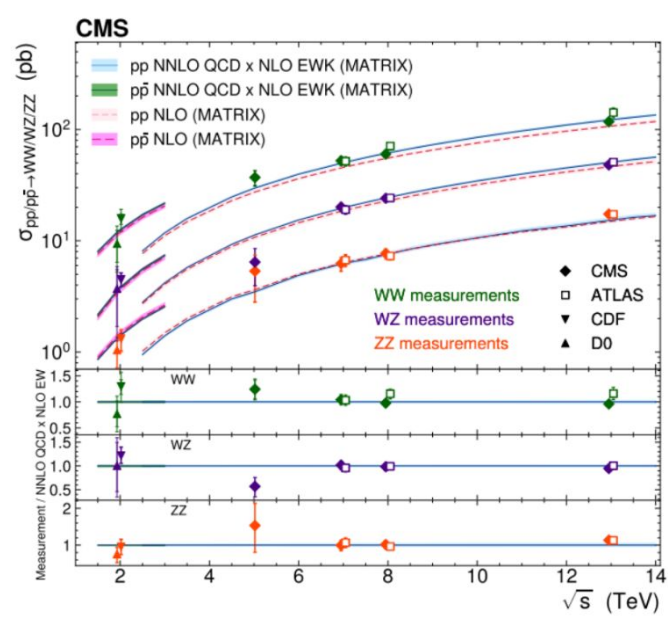
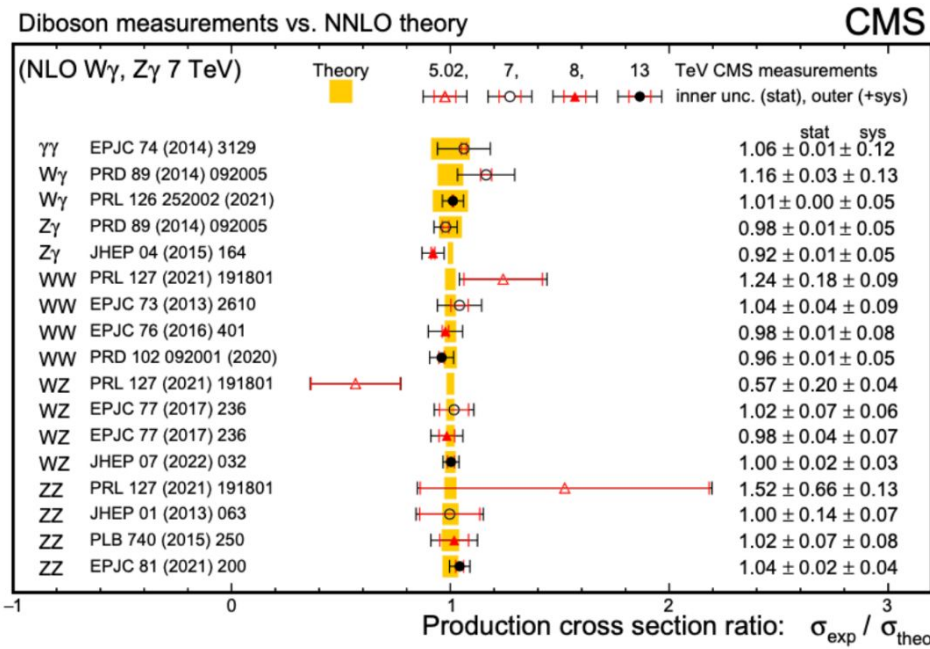
Multiboson Production / Interaction

Diboson

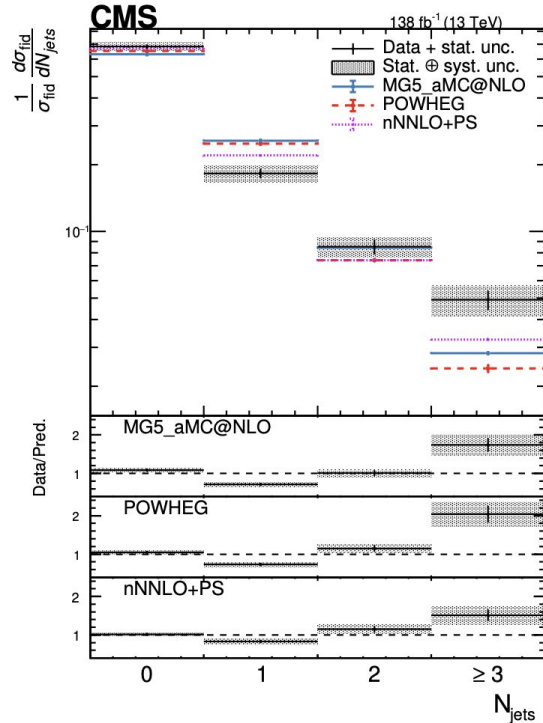
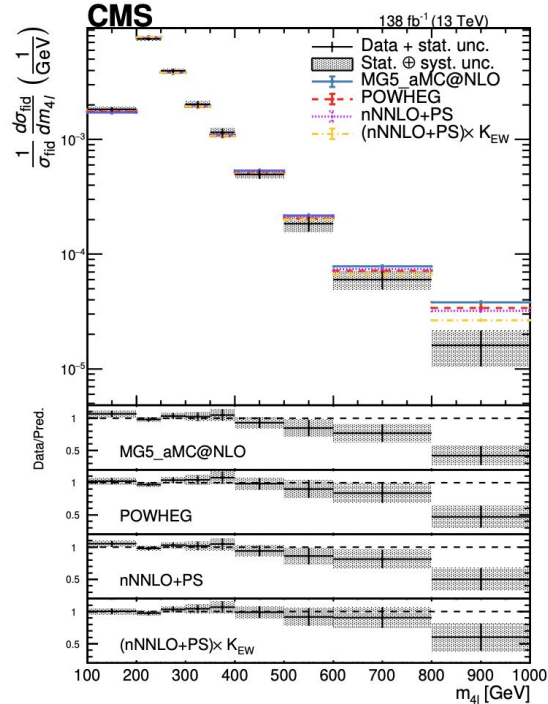
- Diboson production cross sections are among the most precisely measured by the CMS experiment.
- The combination of pure $W \rightarrow \ell \nu_\ell$ and $Z \rightarrow \ell\ell$ samples and the large integrated luminosity delivered by the LHC and collected by the CMS experiment provide a precision rarely achieved previously by hadron collider experiments.
- An understanding of diboson production is essential for the studies of the Higgs boson and searches for new physics where diboson production is often a significant SM background.
- Diboson production also has an indirect sensitivity to new physics that may occur in loop diagrams often characterised as anomalous additions to the SM TGC and QGC multiboson couplings.



Diboson

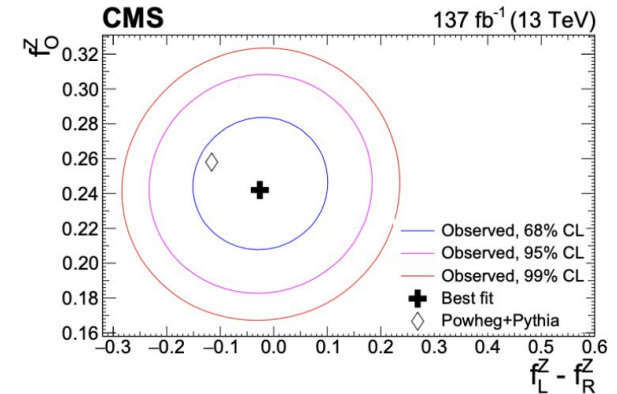


- Differential cross sections (for ZZ) have also been measured



Diboson

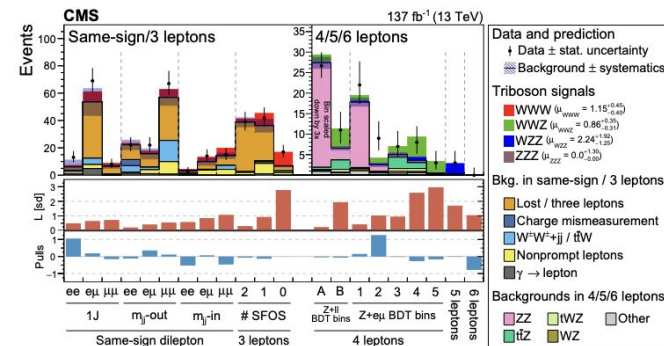
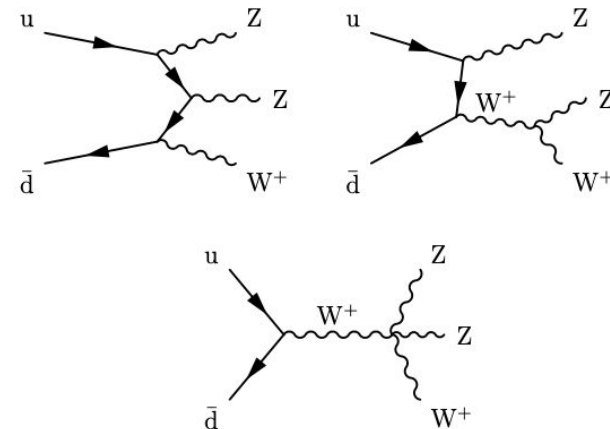
- An essential test of the EW interactions and the nature of the W and Z bosons is a measurement of their polarization.
- SM fractions of bosons produced in specific polarization states in pp collisions in both single and multiboson production are predicted by the EW theory.
- These fractions can be extracted from the angular distributions of the decay products of W and Z bosons.
- In cases with decays to charged leptons, the CMS experiment makes very accurate measurements of the angular distributions of the emitted leptons.
 - Lepton emission angles in the boson rest frame relative to the boson momentum direction in the laboratory frame, which are approximately expected to have simple trigonometric probability distributions based on first- and second-order sine and cosine functions for each polarization state, can be precisely reconstructed and the polarization fractions extracted by fitting the expected distributions for the fraction of each polarization.
 - In events with neutrinos, partial reconstruction of the full angular information can be used.
- The CMS experiment has measured boson polarization in the WW and WZ production. In the latter case, polarized production was observed.



The fitted longitudinal polarization fraction versus the difference of left and right polarization fractions for Z bosons in WZ production is shown demonstrating the ability of the measurement to distinguish the polarization states.

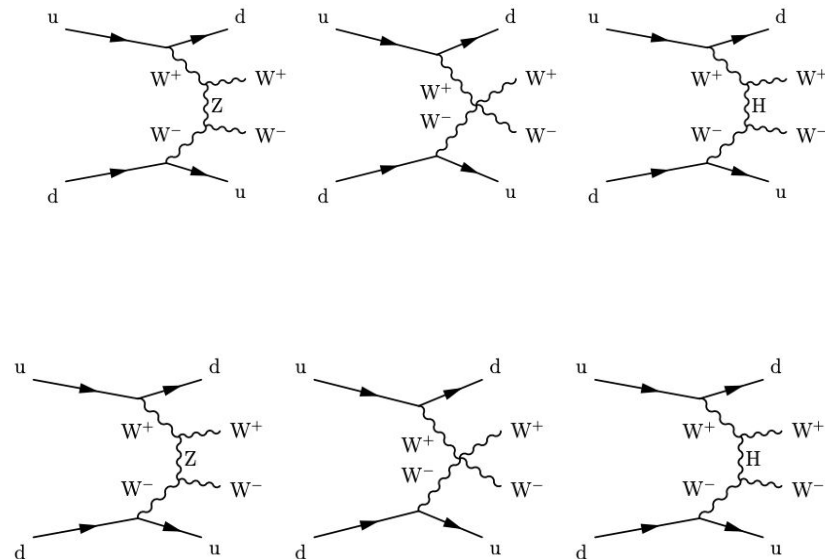
Triboson

- The high centre-of-mass collision energy and the large integrated luminosity produced by the LHC have made it possible to observe triboson production for the first time.
- The most challenging measurements are those of the production of three massive vector bosons.
- Quartic coupling diagram gives this type of process direct sensitivity to QGCs.
- CMS measured all possible massive triboson states simultaneously, categorizing them into all the possible final states involving electrons and muons, according to type and charge, and pairs of jets from hadronic boson decay.
 - This analysis achieved collective observation of WWW, WWZ, WZZ, and ZZZ, and individual evidence for WWW and WWZ production at 3.3 and 3.4 standard deviations, respectively



EWK production of W, Z bosons

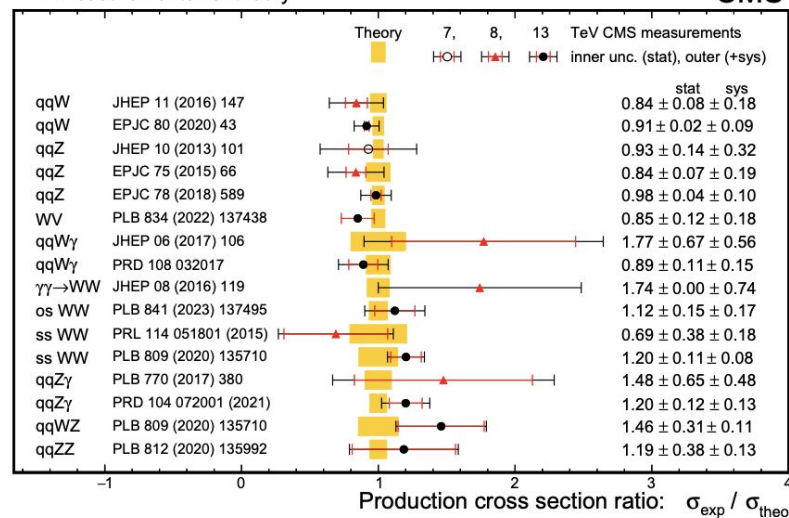
- Pure EW production of vector boson(s) with jets is an essential test of the EW sector of the SM where bosons are
 - Radiated off incoming quarks and either fuse to a single boson (VBF : Vector Boson Fusion)
 - Scatter to pairs of bosons (VBS)
- Vector boson fusion directly measures the TGCs of the SM.
- Vector boson scattering events can occur via the combination of double TGC interactions, in t- or s-channel; quartic coupling of bosons; or scattering via a Higgs boson, in t- or s-channel.



EWK production of W, Z bosons

- The CMS experiment has measured VBF of single W or Z bosons in 7, 8, 13 TeV pp interactions.
 - The extraction of the signal from a very large background of standard single boson + jets production requires the use of a multivariate discriminant.
 - These analyses have been used to set stringent limits on deviations from the expected SM TGC values.
- The first observed VBS process was WW production.
- The observation of the scattering of longitudinal vector bosons would be a clear sign of the presence of the Higgs boson scattering interaction as a component of VBS
 - It is considered one of the essential tests of the EW symmetry-breaking mechanism.
 - First measurement has been made of longitudinal VBS in this mode using 13 TeV data where a 2.3 standard deviation signal consistent with the SM expectation was measured.

EW measurements vs. theory



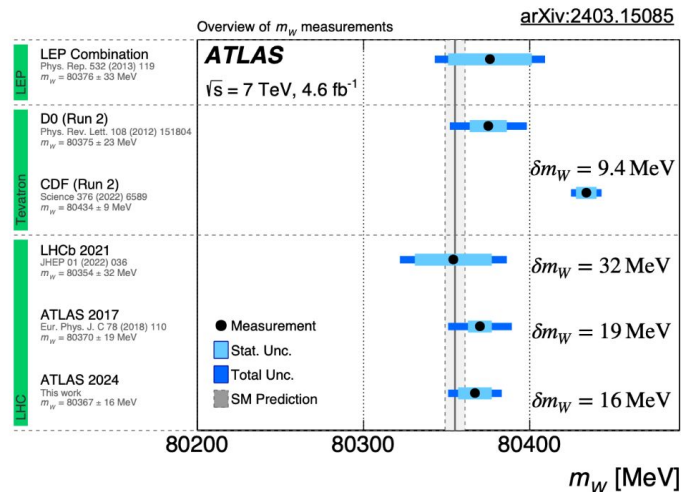
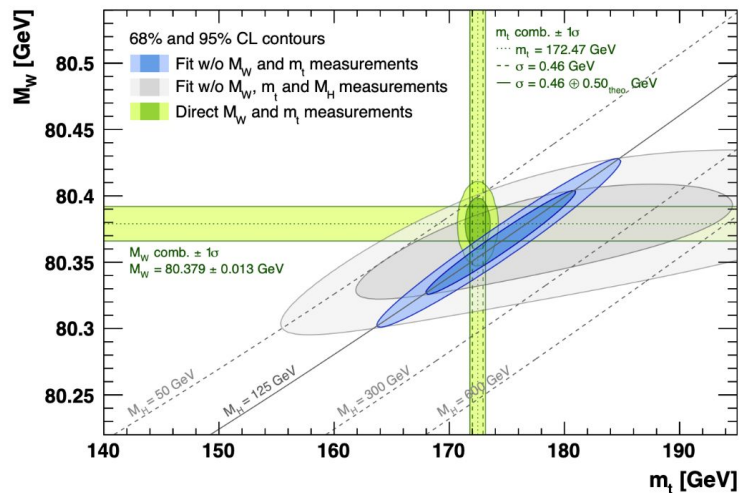


W boson mass

The image shows a perspective view down a long, curved tunnel. On the left side, there are large, blue, cylindrical structures, possibly part of a particle detector or accelerator. These structures have various pipes, cables, and red caps attached to them. Above the structures, there are numerous overhead pipes and conduits, some with yellow and black safety markings. The right side of the tunnel is a smooth, light-colored concrete wall. The floor is a dark, polished surface. The tunnel curves into the distance, with a series of bright lights visible on the right wall, creating a strong sense of depth and perspective.

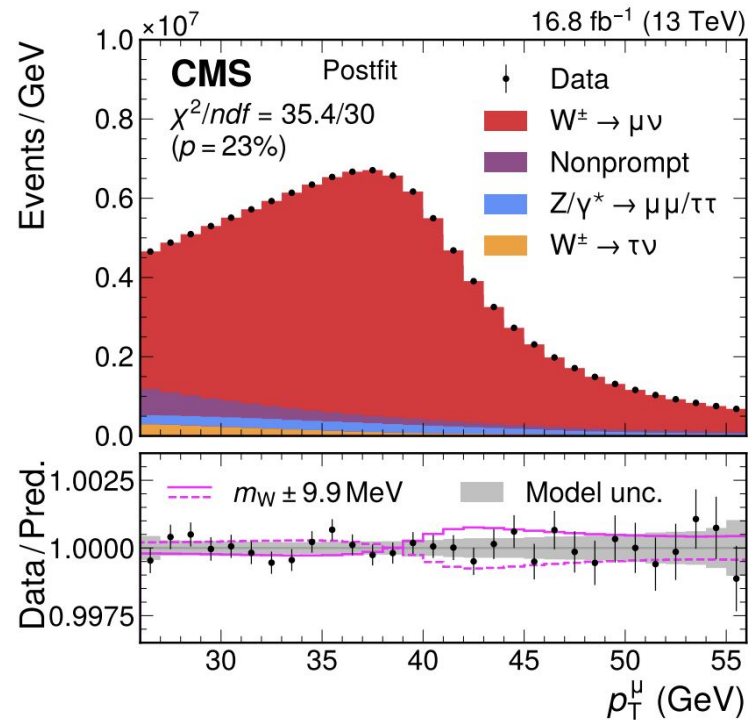
W boson mass

- Higgs boson discovery and mass measurement allowed for precise prediction of m_W , $\sin^2\theta_W$, and m_t from global EW fit of SM parameters
 - $\delta m_W \approx 6$ MeV from global EW fit ($< 10^{-4}$ precision)
 - $\delta m_W \sim 13$ MeV from PDG experimental average (excluding CDF Run 2 and ATLAS 2024)
- CDF Run 2 result in significant tension with SM (and other measurements)
- Goal: experimental precision measurement of m_W with precision < 10 MeV to test internal consistency of SM and possibly probe new physics (loop corrections to m_W from heavy new particles)



W boson mass

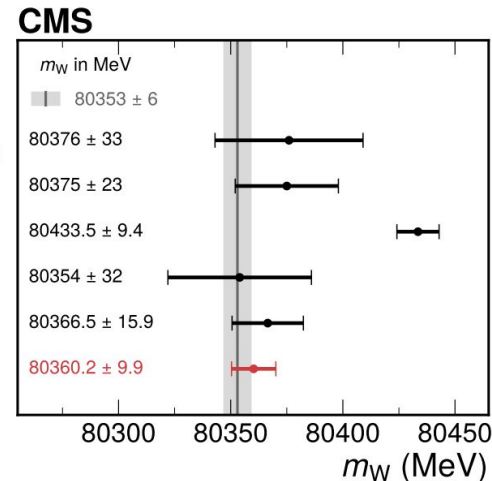
- Experimental challenge to have high precision measurement
 - Pileup, Missing pT etc.
- Use 13 TeV data, despite higher pileup compared to Run1 (ATLAS), but larger dataset
- Focus on well-understood subset of dataset (16.8/fb) in muon final state only
 - Multiple data driven corrections to reduce uncertainties
- Profile likelihood fit to 3D muon pT- η -charge distribution (minimal sensitivity to pileup), not mT
 - Binning chosen as a compromise between sensitivity and good statistical behaviour



W boson mass

- Measured value, $m_W = 80\,360.2 \pm 9.9$ MeV
- Agrees with the standard model expectation from the electroweak fit
- In disagreement with the measurement reported by the CDF Collaboration.
- CMS result has similar precision to the CDF Collaboration measurement and is significantly more precise than all other measurements.
 - Dominant sources of uncertainty are the muon momentum calibration and the parton distribution functions.
 - Uncertainties in the modeling of W boson production are subdominant due to novel approaches used to parameterize and constrain the predictions and their corresponding uncertainties in situ with the data.
- This result constitutes a significant step towards achieving an experimental measurement of m_W with a precision comparable to that of the EW fit

Electroweak fit
PRD 110 (2024) 030001
LEP combination
Phys. Rep. 532 (2013) 119
D0
PRL 108 (2012) 151804
CDF
Science 376 (2022) 6589
LHCb
JHEP 01 (2022) 036
ATLAS
arXiv:2403.15085
CMS
This work



A perspective view down a long, brightly lit tunnel. On the left side, a large, blue, cylindrical object, possibly a storage tank or part of a machine, is visible. It has several red caps and a white label with the number '110108'. Above it, there are various pipes and a yellow and grey mechanical component. On the right side, there is a track or a series of parallel lines that recede into the distance. The tunnel walls are light-colored and have some structural elements. The floor is dark and reflective. The overall atmosphere is industrial and futuristic.

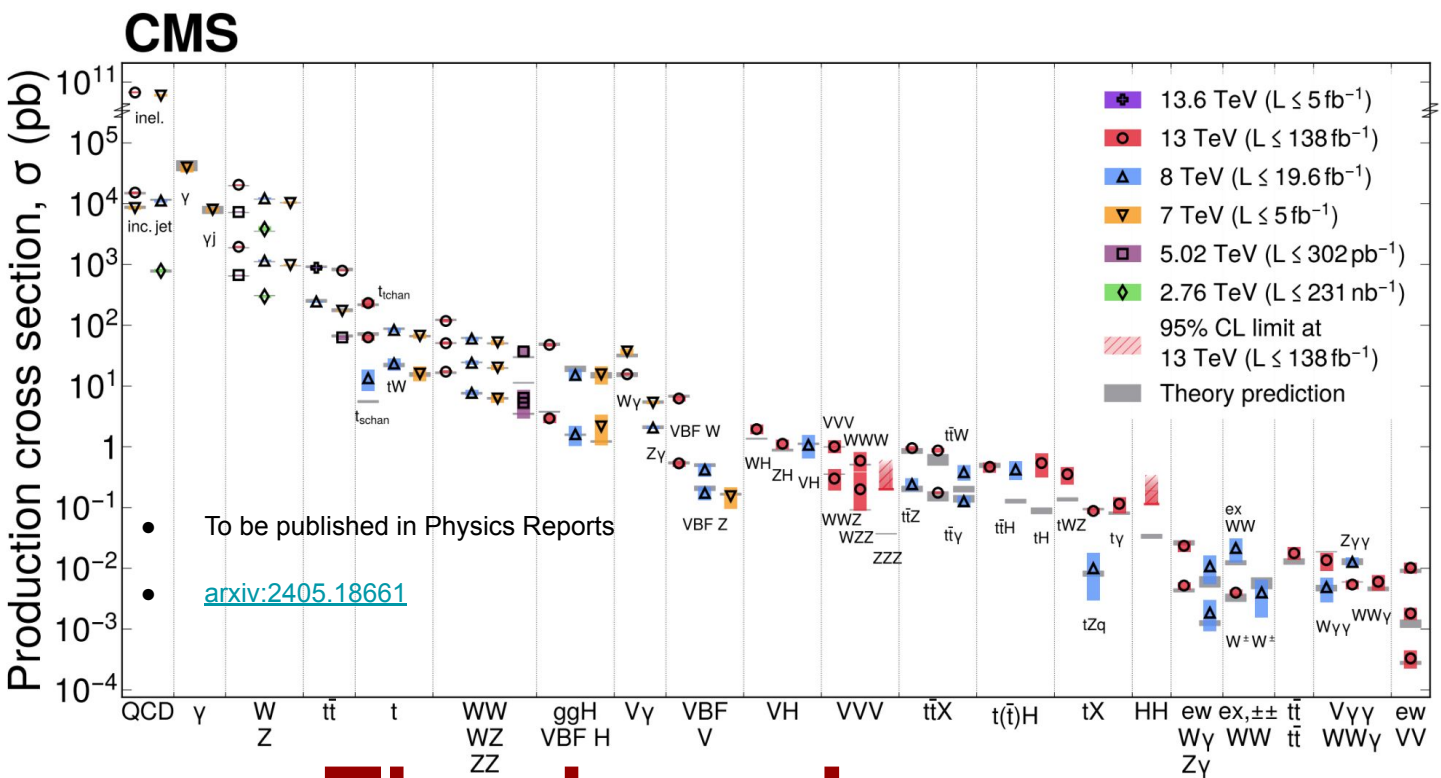
Summary

Summary

- The CMS Collaboration has carried out a broad array of QCD EW measurements. Have not covered all the results here...
- The precision of some measurements has reached the percent level and N3LO perturbative QCD theory computations are necessary to test the measurements at a similar level of precision.
- Differential measurements are also testing our ability to model SM processes and NNLO QCD, NLO EW, and integrated PDF and parton shower computations at the same perturbative order are necessary to model the data.
- In general, SM predictions model the data well.
- The theory community is actively engaged in confronting the LHC data, and in cases, new computations have improved the modelling of the data where previously there was disagreement.
- Measurements demonstrates the power of the CMS detector and of the LHC as instruments for precision measurements of the parameters of the standard model
- Future measurements with percent-level accuracy and studies of complex final states along with improved theoretical modelling will extend our ability to further investigate the complexities of the SM and search for BSM physics indirectly and in complex final states.

Stairway to discovery:

a report on the CMS programme of cross section measurements from millibarns to femtobarns



Thank you!



Backup

Measurements

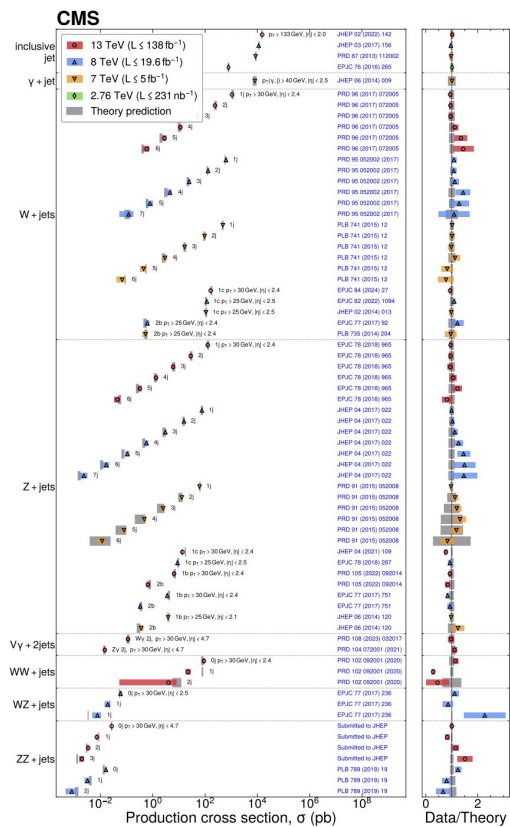


Figure 63: Summary of measurements of jet cross sections and electroweak processes in association with jets.

Luminosity

- Integrated Luminosity Recorded by CMS during proton collisions

