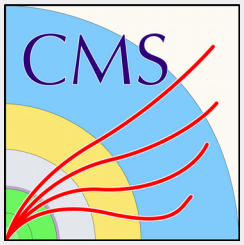
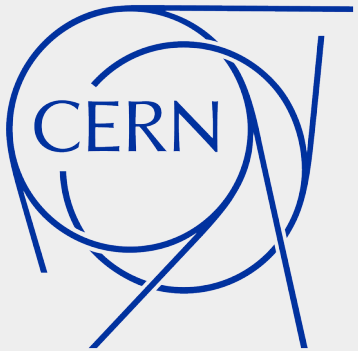




Electroweak physics results and outlook from the LHC

Ricardo González López

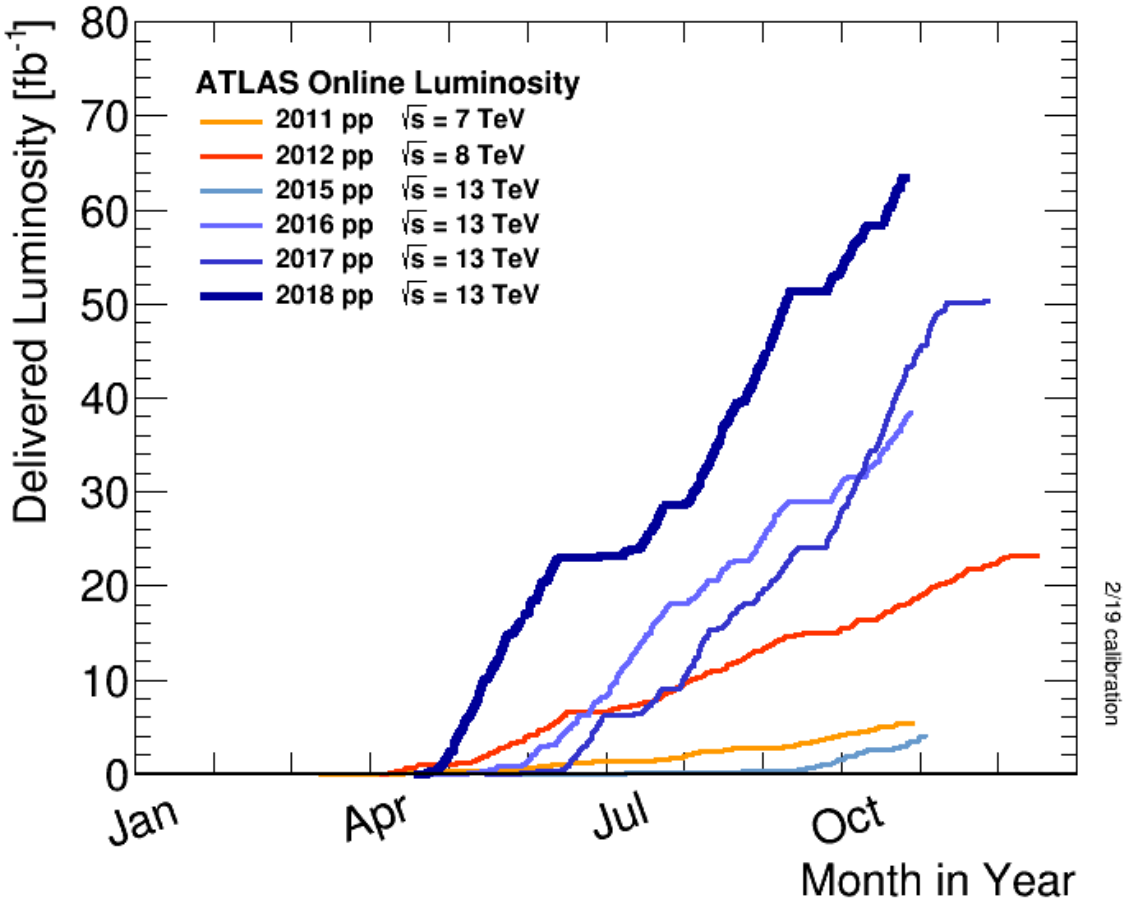
On behalf of the ATLAS, CMS and LHCb Collaborations

Aspen2022: New methods and ideas at the frontiers of particle physics

21/03/22

Introduction

- Wealth of data available at LHC:
  - ~5 fb^{-1} @ $\sqrt{s}$=7 TeV
  - ~20 fb^{-1} @ $\sqrt{s}$=8 TeV
  - ~140 fb^{-1} @ $\sqrt{s}$=13 TeV
- Large statistics set systematics as the limiting factor → precision studies involve crucial and detailed systematic uncertainties assessment
- They also allow to explore rarer EWK processes, many first time observations at LHC...

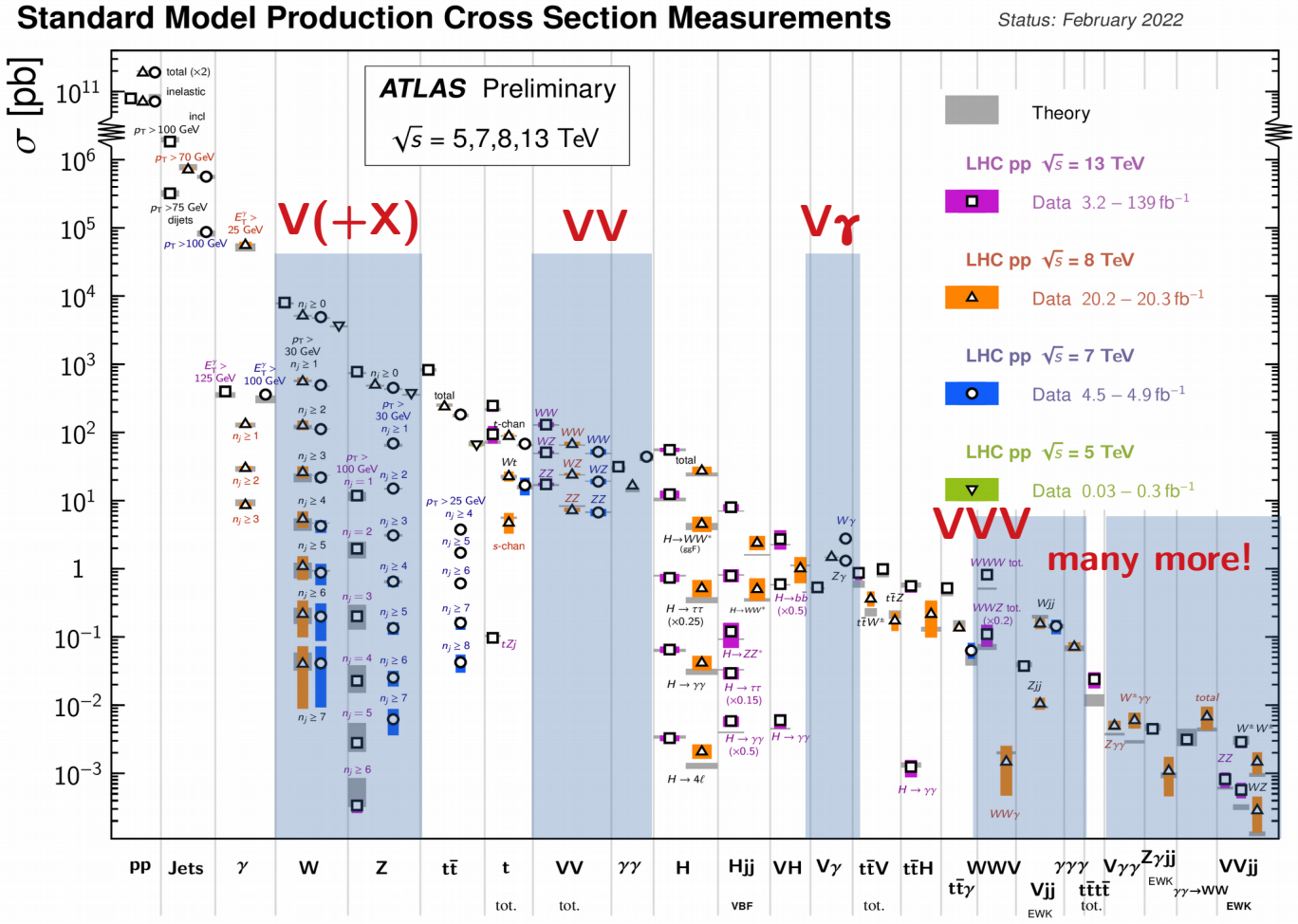


Introduction

- So much data gives many places to look at!
- In today's talk:
  - Drell-Yan analyses
  - Diboson(+X) measurements
  - Triboson observations

Full publication lists:

- **ATLAS**: link
- **CMS**: link
- **LHCb**: link

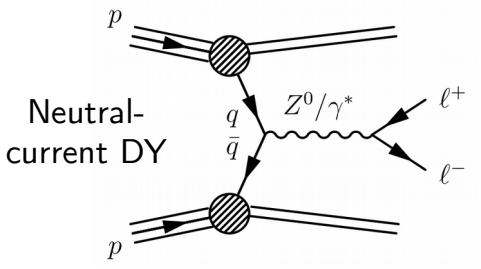


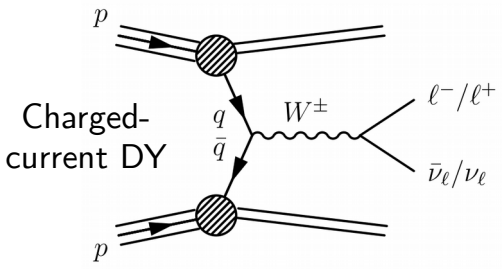
Introduction

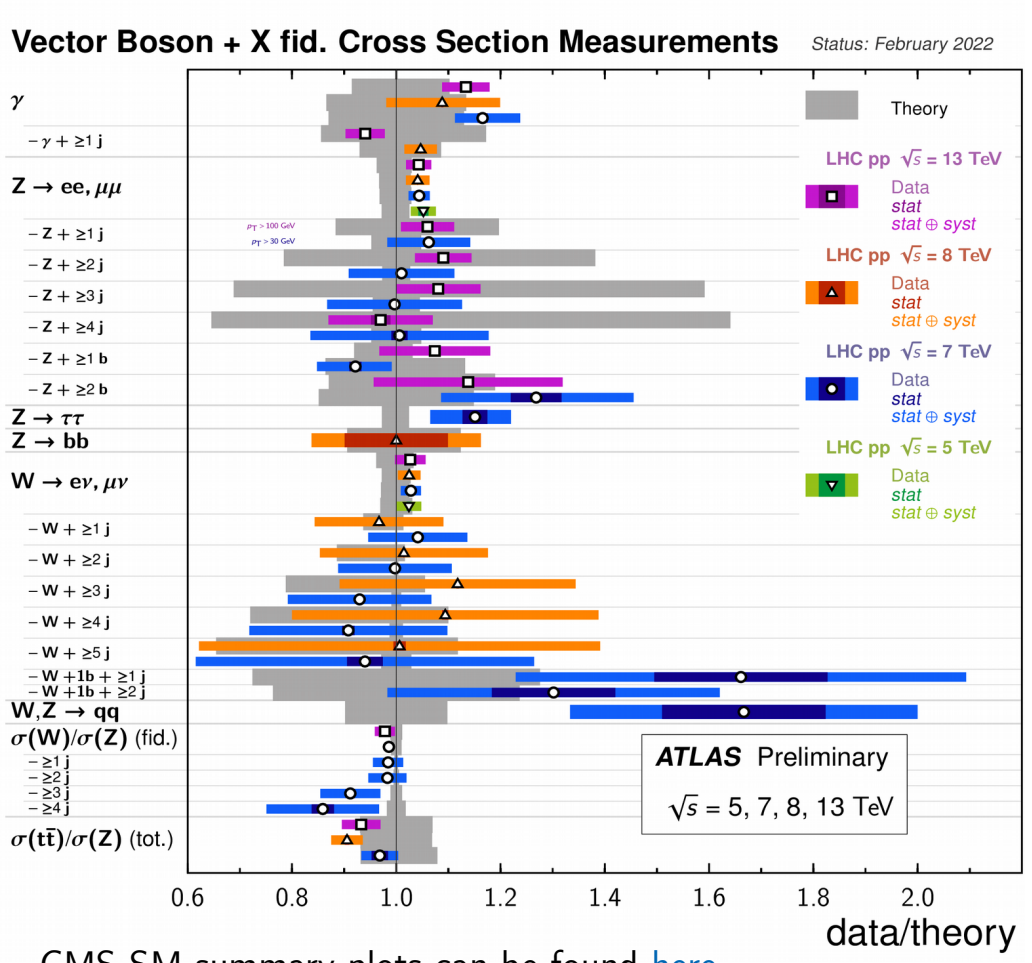
- Electroweak analyses at LHC cover a wide range of objectives:
  - Validate our SM knowledge
    - Test detector performance on well-known processes
    - Validate and constrain SM backgrounds
    - Provide crucial input to PDF fits
    - Test higher order QCD and EW corrections
  - First time observation of predicted SM processes
  - Indirect searches for new physics (Lepton Flavour Universality tests, EFTs...)

Single boson (+X) production

- Studies on Drell-Yan processes are of great importance
  - Benchmark for SM understanding
  - PDF fitting
  - Measurement of EW parameters
  - Lepton Flavour Universality tests
- Plenty of measurements from LHC available at different energies, including combined production with jets
  - Studies on associated production with jets covered in Sandeep Kaur's talk!







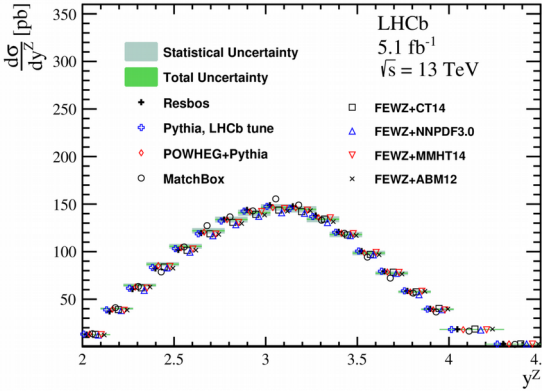
CMS SM summary plots can be found here

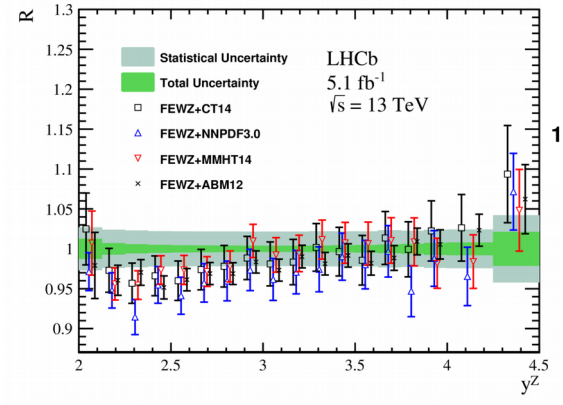
Z boson measurements: forward μμ production

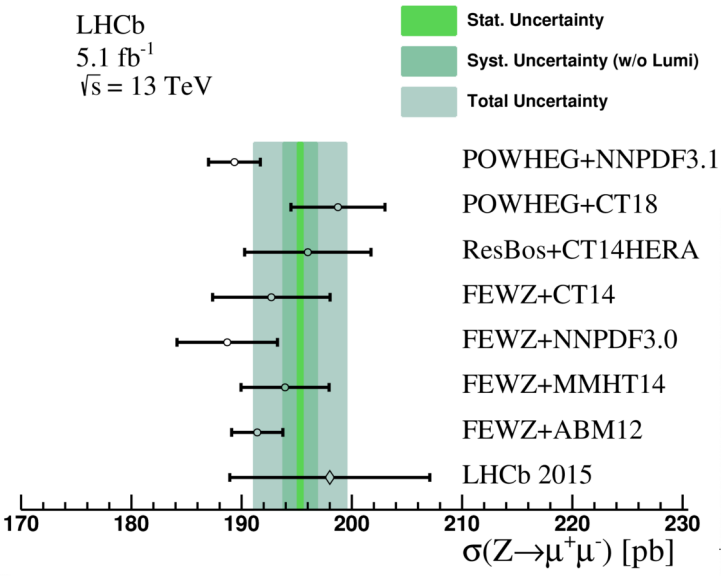
- Measurement of the Z production cross-section in a unique phase space to other LHC experiments: $2.0 < \eta < 4.5$
- Inclusive and (double) differential measurement: $y_Z \otimes p_T$ + $y_Z \otimes \Phi^*$

arXiv:2112.07458

- LHCb also published the measurement of the angular distribution of forward muon pairs: arXiv:2203.01602



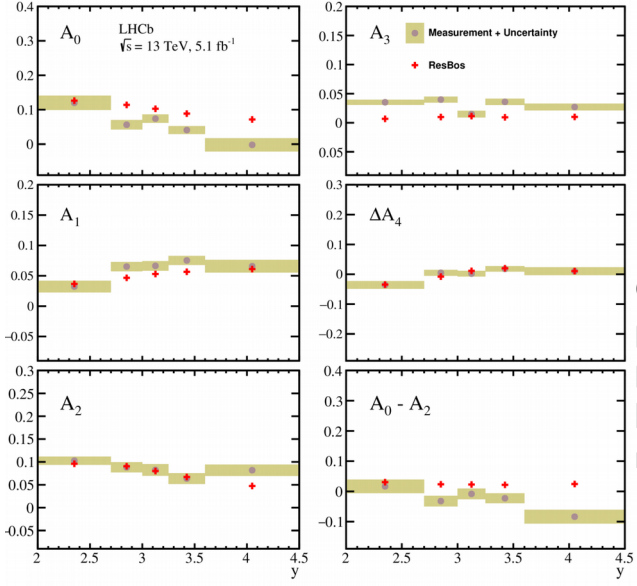




Good agreement overall, but there's potential to constrain PDFs at low and high-x

Born-level NCDY xsec:

$$\frac{d\sigma}{d\cos\theta d\phi} \propto A_0(1-3\cos^2\theta) + A_1 \sin 2\theta \cos\phi + A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta + \ldots$$

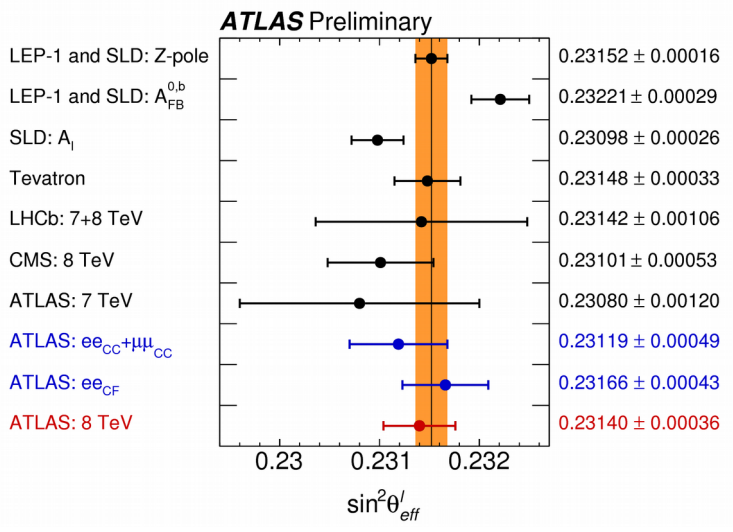


θ,Φ: polar and azimuthal angles of ℓ^+ in Collins-Soper frame

Coefficients provided vs p_T and y_Z, at low and high mass.

Effective weak mixing angle

- Weak mixing angle, θ^{f}_{eff}, determines the relatives strengths of vector and axial-vector couplings between fermions and Z, $M_W^2 = M_Z^2 \cos^2\theta^{f}_{eff}$
- Measured at LHC using two different approaches:
  - ATLAS: extracted from A_4 coefficients via effective linear dependence
  - CMS: fit $A_{FB}(m_{\ell\ell}, y)$ using predictions depending on $\sin^2\theta^{f}_{eff}$



LHCb results: JHEP 1511(2015) 190

NCDY cross section, θ^*: polar angle of ℓ^- in Collins-Soper frame

$$\frac{d\sigma}{d\cos\theta^*} = A \cdot \left((1+\cos^2\theta^*) + A_4 \cdot \cos\theta^*\right)$$

Forward-backward asymmetry, experimentally measured

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B} = \frac{3}{8} A_4$$

HL-LHC prospects aim at better precision than LEP!
ATL-PHYS-PUB-2018-037
CMS-PAS-FTR-17-001

- Results so far based on Run 1 data.
  - Dominant uncertainties are PDF and statistics
  - Expected improvements with Run 2 data + updated PDFs
- **ATLAS** ATLAS-CONF-2018-037

  $\sin^2\theta^{f}_{eff} = 0.23140 \pm 0.00021\ (stat.) \pm 0.00024\ (PDF) \pm 0.00016\ (syst.)$
- **CMS** Eur. Phys. J. C 78 (2018) 701

  $\sin^2\theta^{f}_{eff} = 0.23101 \pm 0.00036\ (stat.) \pm 0.00031\ (PDF) \pm 0.00018\ (syst.) \pm 0.00016\ (theo.)$

W decays tension

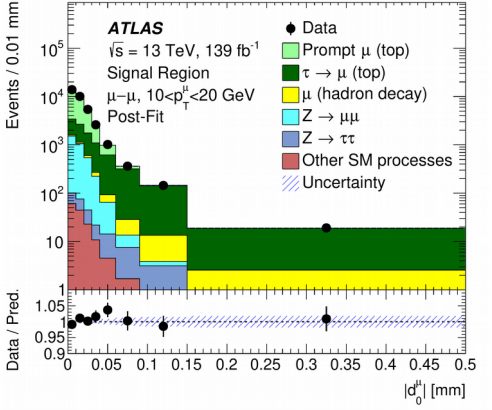
- LEP reported a 2.6σ tension between τ and e/μ W decays: Phys Rept. 532 (2013) 119

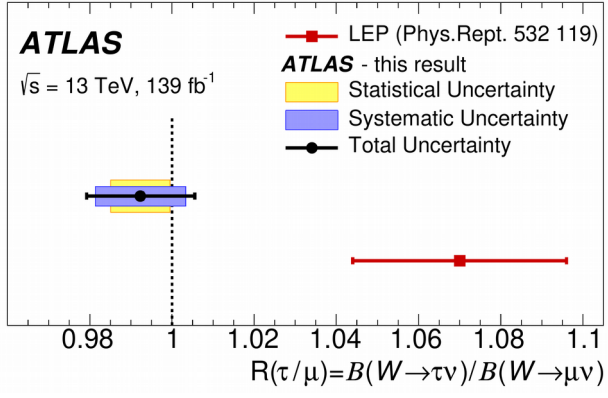
$$R_{\tau/(e+\mu)} = \frac{2\mathcal{B}(W \to \tau\bar{\nu}_\tau)}{\mathcal{B}(W \to e\bar{\nu}_e) + \mathcal{B}(W \to \mu\bar{\nu}_\mu)} = 1.066 \pm 0.025$$

- LHC data has helped shed some light into this mystery:

ATLAS: R(τ/μ) Nature 17, 813 (2021)

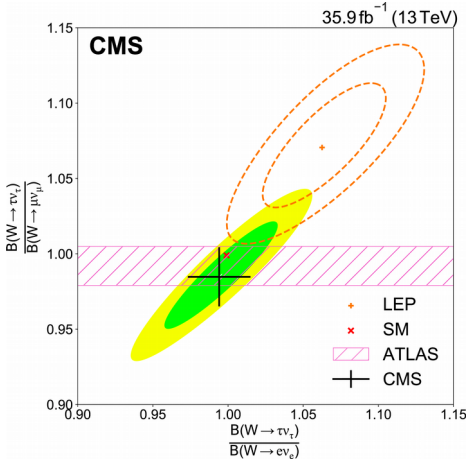
- Ratio measured from top-antitop events. Analysis focuses on $W\to\mu\nu_\mu$ and $W\to\tau\nu_\tau\to\mu\nu_\mu\nu_\tau\nu_\tau$ decays.
- A fit is performed exploiting the shape difference between these decays and background distributions of the muon's transverse impact parameter d_0 and momentum p_T.
- $R(\tau/\mu) = 0.992\pm0.013$ [±0.007(stat)±0.011(syst)]





CMS: $B(W\to\ell\nu_\ell)$ CMS-SMP-18-011

- Using top-antitop, tW, WW and W+jet processes to measure W branching fractions.
- Subleading lepton's p_T in ee/μμ/eμ pairs is used to discriminate prompt e/μ from those coming from τ decays.
- Assuming lepton universality: $B(W\to\ell\nu_\ell)=(10.89 \pm 0.01 \pm 0.08)\%$

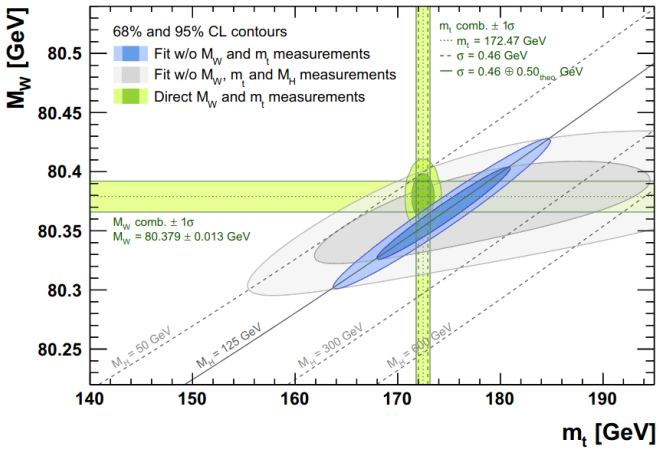


Great statistical uncertainty reduction with respect to LEP

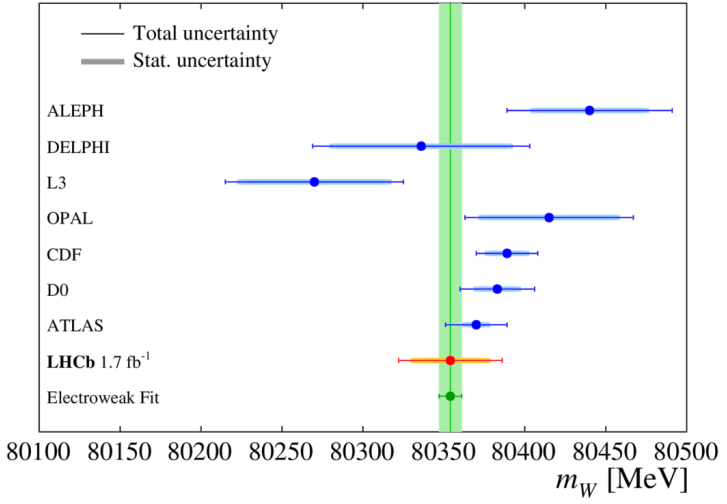
W mass measurement at LHCb

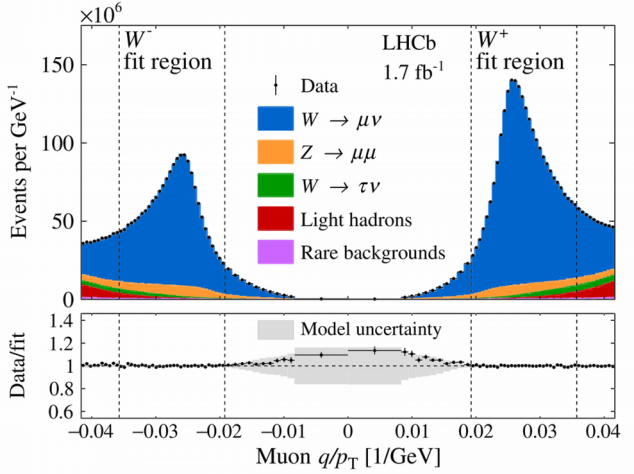
- Measurement of a <u>fundamental</u> parameter of SM
- Global electroweak fit currently sets a 7 MeV uncertainty (right)
- **LHCb** measurement uses a simultaneous fit to q/p_T^W of $W\to\mu\nu$ candidates and Φ^* of $Z\to\mu\mu$ candidates: JHEP 01 (2022) 036
  - Φ^* preferred over p_T^Z to reduce modelling uncertainties
  - Note: only 1.7 fb^{-1} used, 1/3 of Run 2
- $m_W = 80354 \pm 23_{stat} \pm 10_{exp} \pm 17_{theo} \pm 9_{PDF}$ MeV $\rightarrow \Delta m_W \approx 32$ MeV
- Expected LHCb precision <20 MeV with full Run1+2 datasets

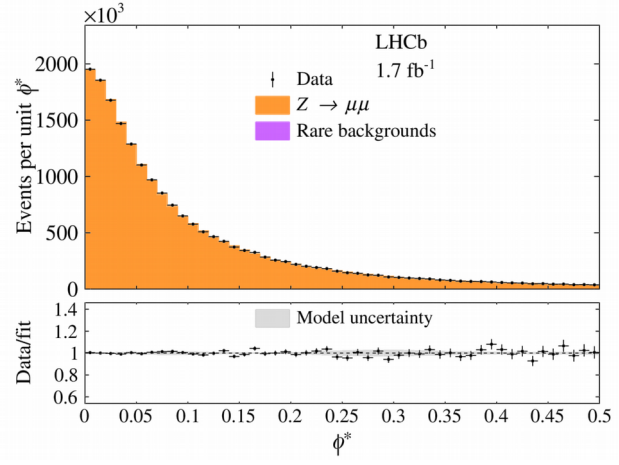
EPJC 78 (2018) 675



ATLAS @ $\sqrt{s}$ = 7 TeV result: EPJC 78 (2018) 110

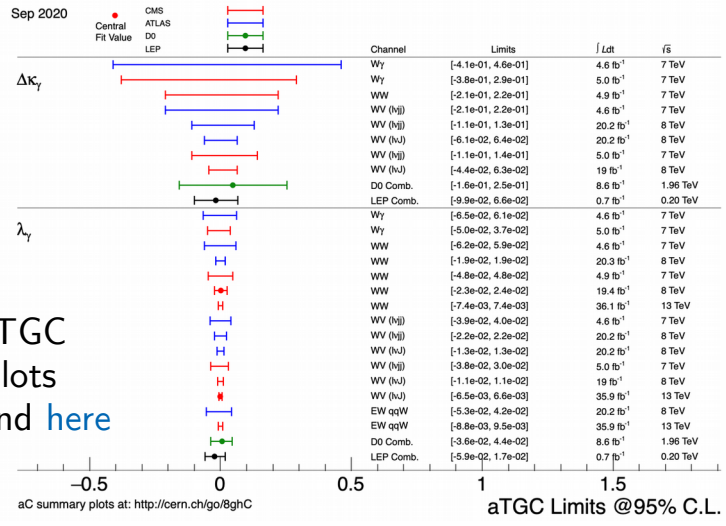




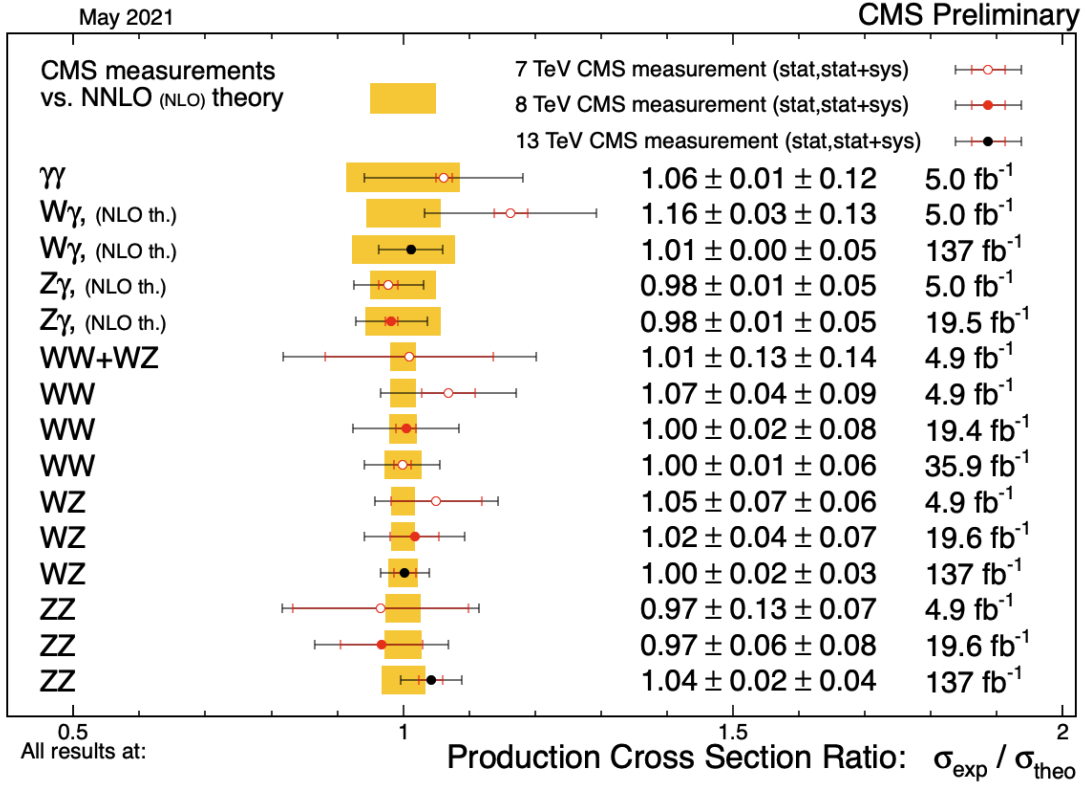


Diboson (+X) production

- <u>All</u> diboson production mechanisms have been measured at LHC:
  - Looking into many different decay modes of the vector bosons.
  - Systematic uncertainties dominate most of the Run 2 measurements.
  - Good agreement with NNLO predictions.
- Vital input for limits on Anomalous Gauge Coupling constraints



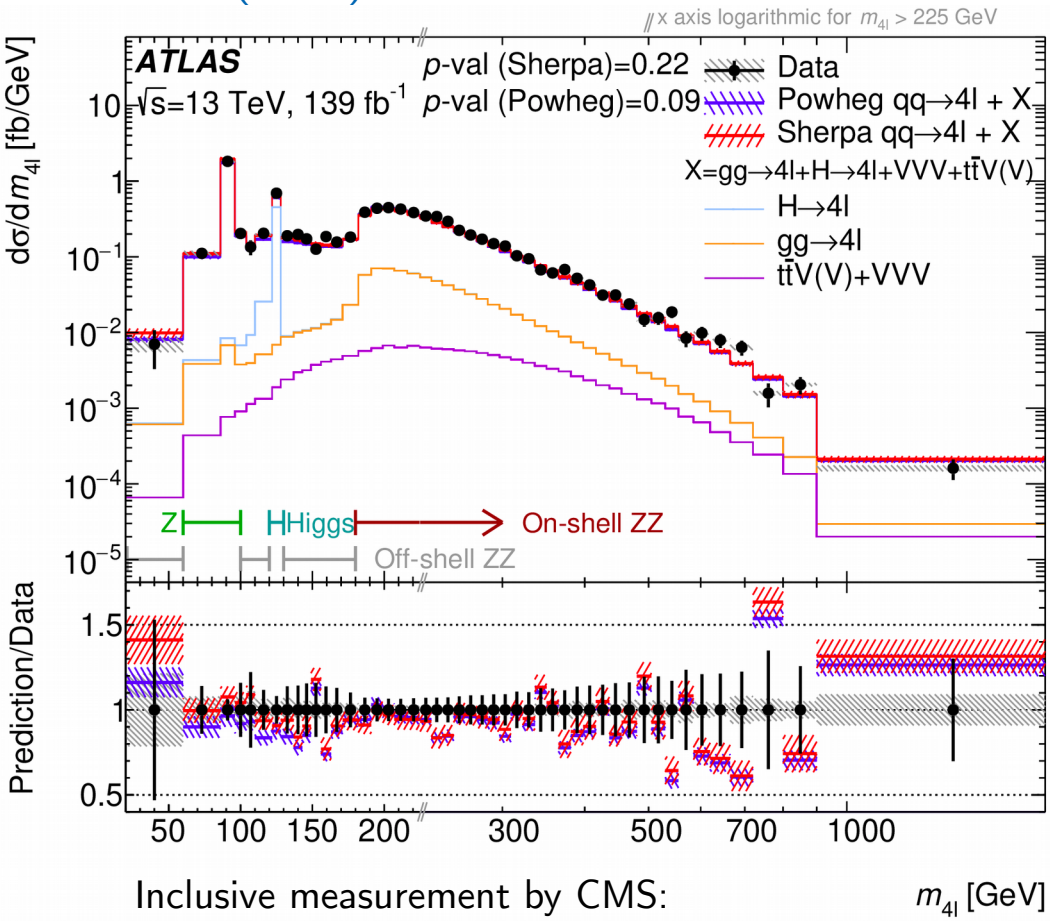
All CMS aTGC summary plots can be found here



ATLAS summary plot can be found here

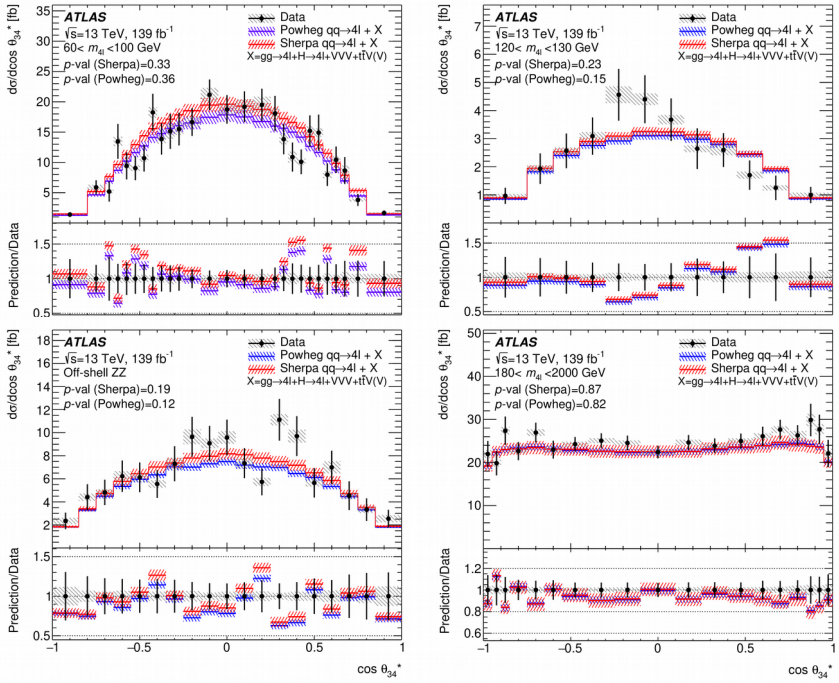
4ℓ production

JHEP 07 (2021) 005



Inclusive measurement by CMS:
Eur. Phys. J. C 78 (2018) 165

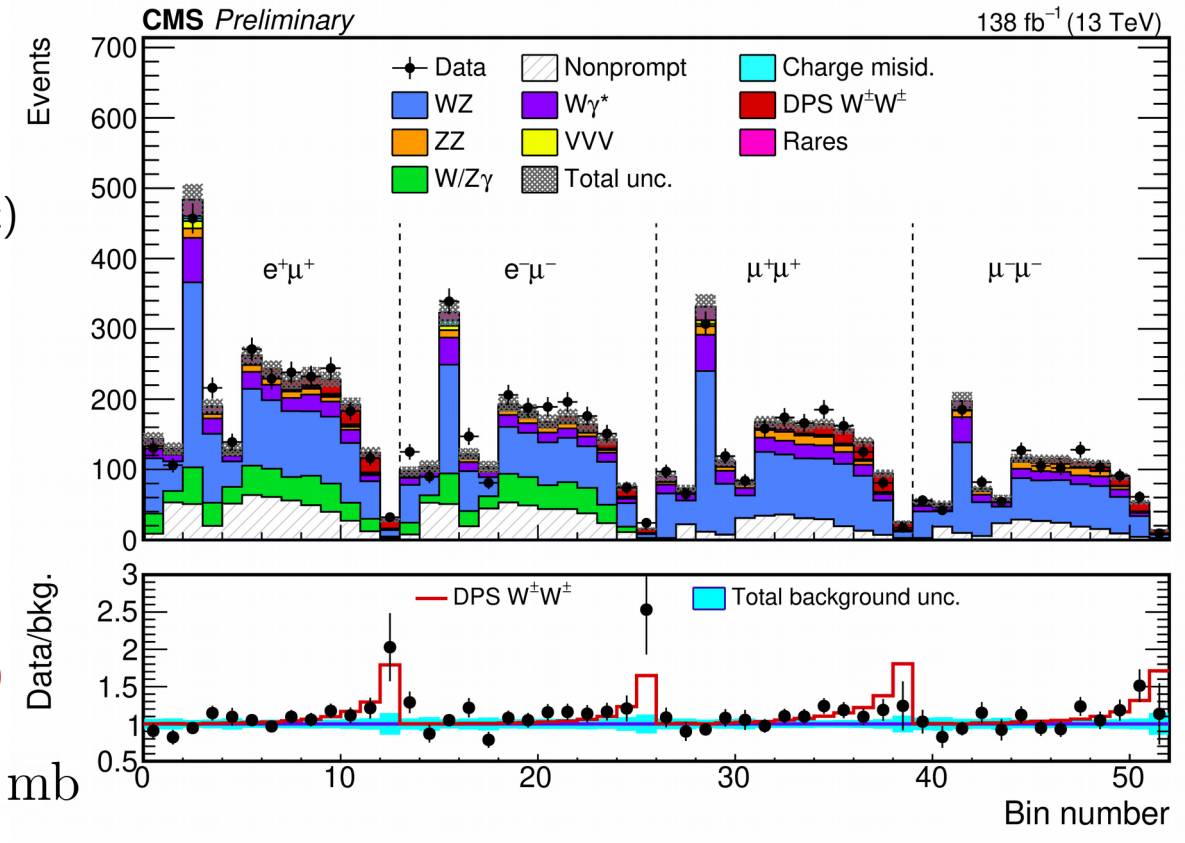
- Accounting for Z and Higgs decays, as well as on- and off-shell ZZ production.
- Measurement of differential and inclusive cross section.
  - Many variables studied in the 4 regions listed above.

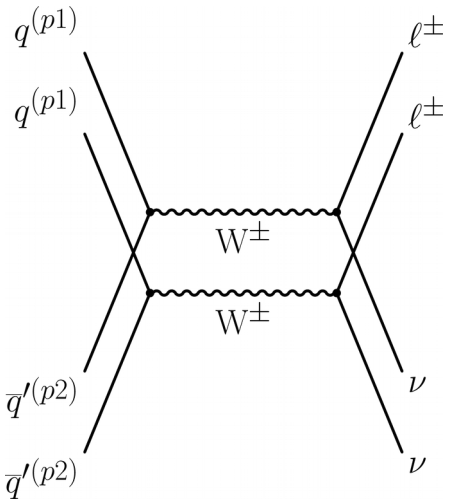


Double-parton scattering WW production

- First observation of WW production from DPS.
- Boosted decision trees used for background rejection (right plot).
- $\sigma^{\text{DPS WW}}_{\text{incl.}} = 0.16 \pm 0.02\ (\text{stat}) \pm 0.02\ (\text{syst}) \pm 0.02\ (\text{model})\ \text{pb}$

CMS-PAS-SMP-21-013





Can be used to estimate the effective cross section:

$$\sigma_{\text{AB}}^{\text{DPS}} = \frac{n}{2}\frac{\sigma_{\text{A}}\sigma_{\text{B}}}{\sigma_{\text{eff}}}$$

$$\sigma_{\text{eff}} = 12.16^{+2.88}_{-2.17}\ \text{mb}$$

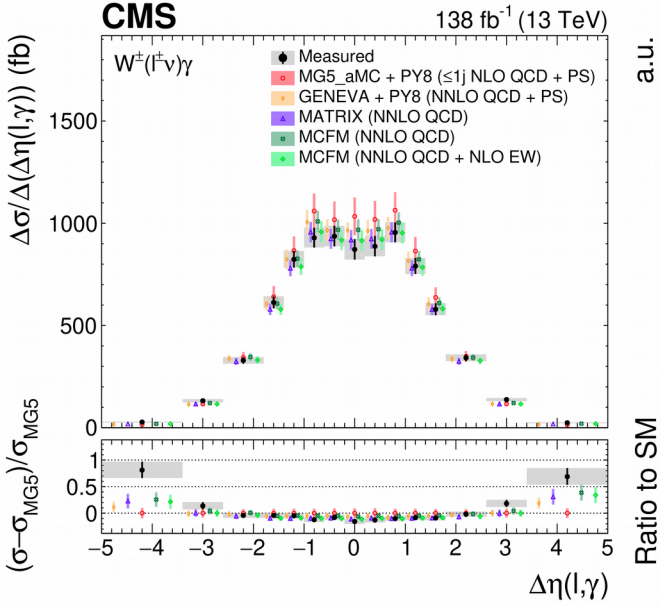
Vγ measurements

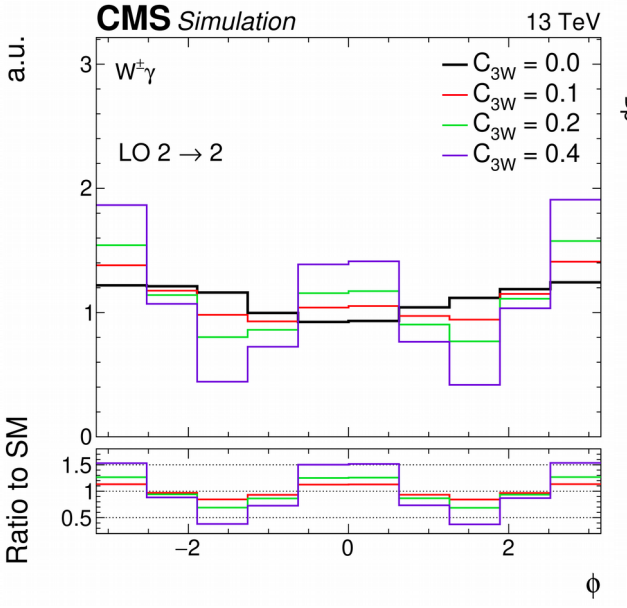
- Great benchmark to test high-order corrections (NNLO QCD+NLO EW) in more complex processes.
- High sensitivity for BSM phenomena, including EFT interpretations.

CMS: Wγ CMS-SMP-20-005

- Radiation-zero due to destructive interference of LO diagrams, explored via $\Delta\eta(\ell,\gamma)$. Sensitive to BSM contributions.
- Azimuthal angle in W rest frame, Φ, sensitive to EFTs.

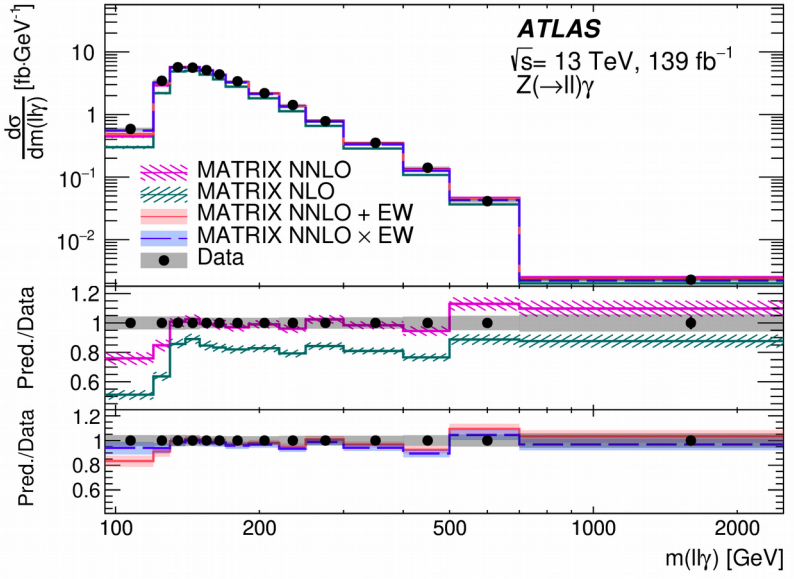
More on EFTs in Gauthier's **talk**!





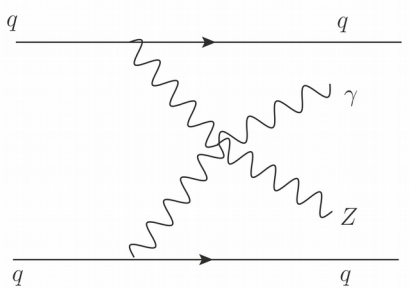
ATLAS: Zγ JHEP 03 (2020) 054

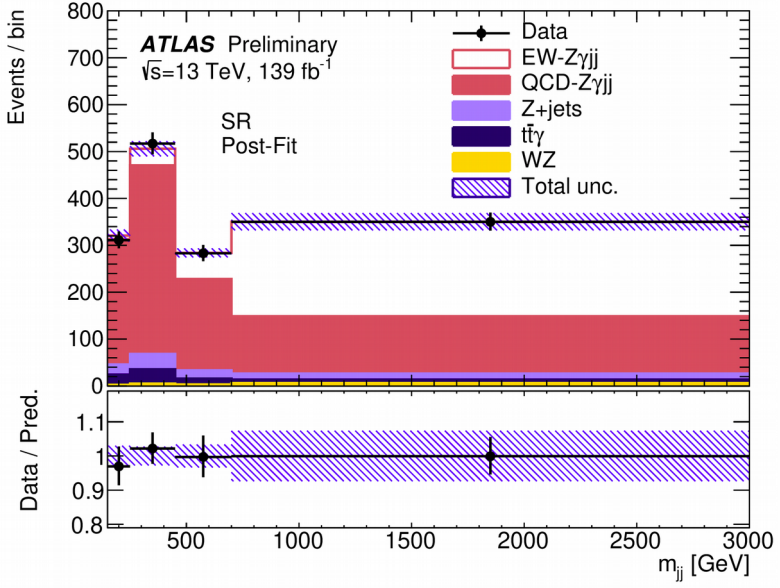
2.9% precision on inclusive cross-section, x2 improvement with respect to 8 TeV

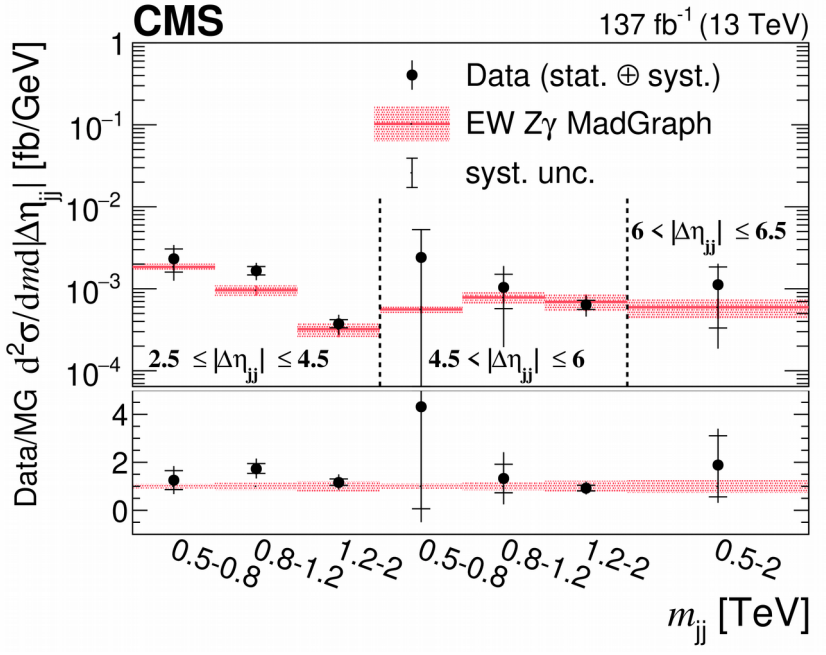


Zγjj measurement

- VBS Z(→ℓℓ)γ production observed by ATLAS and CMS. Single and double differential cross sections available.
  - **ATLAS** ATLAS-CONF-2021-038
  - **CMS** Phys. Rev. D 104 (2021) 072001
- Fiducial cross section measurements in accordance between experiments
- CMS' aQGC interpretation provides leading constraints to some of the dim-8 operators







ATLAS also first observed the EWK production of Z(→νν)γ

Eur. Phys. J. C 82 (2022) 105

The measurement includes a search for Higgs decays into invisible particles.

No significant excess was found and limits are set on the decay's BR.

New observations of VBS processes

- The Run 2 dataset has allowed for the first time observation of some diboson processes:

ZZjj

ATLAS arXiv:2004.10612 [hep-ex]

CMS Phys. Lett. B 812 (2021) 135992

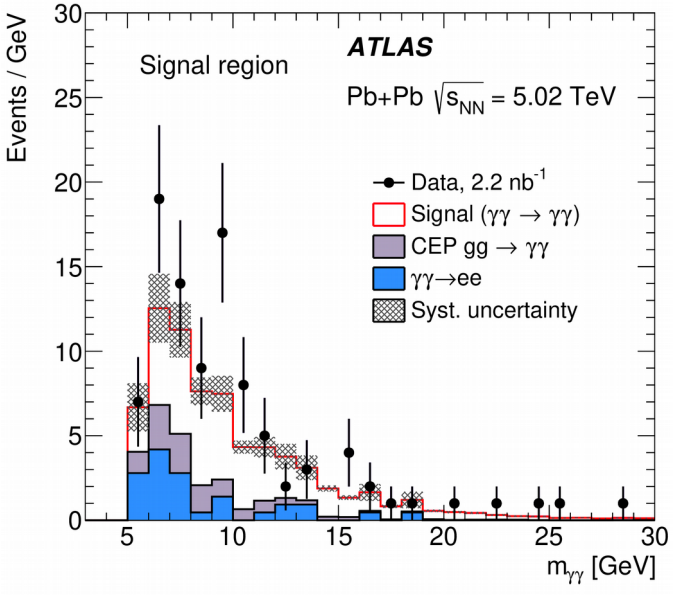
CMS observes a 4.0σ significance in the 4ℓ final state, ATLAS expands to 5.5σ adding the 2ℓ2ν final state.

Same-sign WW + two jets

ATLAS PRL 123 (2019) 161801

CMS Phys. Lett. B 809 (2020) 135710

- Production observed by both experiments of a process well understood at NLO QCD and NLO EW (bottom right).
- Opposite-sign also observed by CMS: SMP-21-001

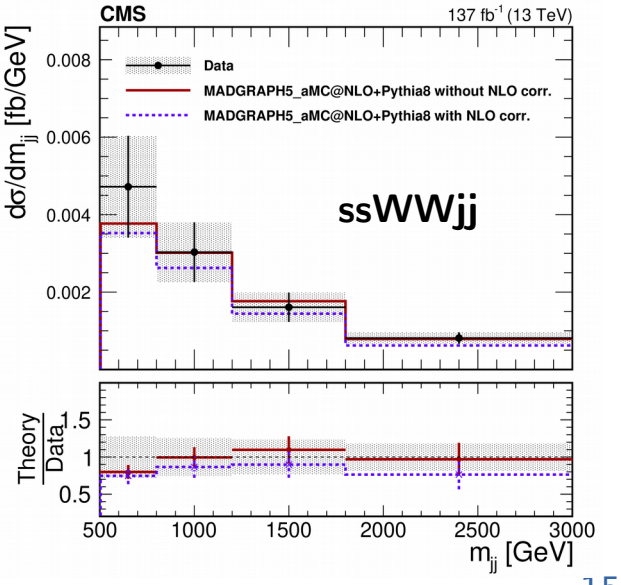


Photon-induced diboson production

WW PLB 816 (2021) 136190

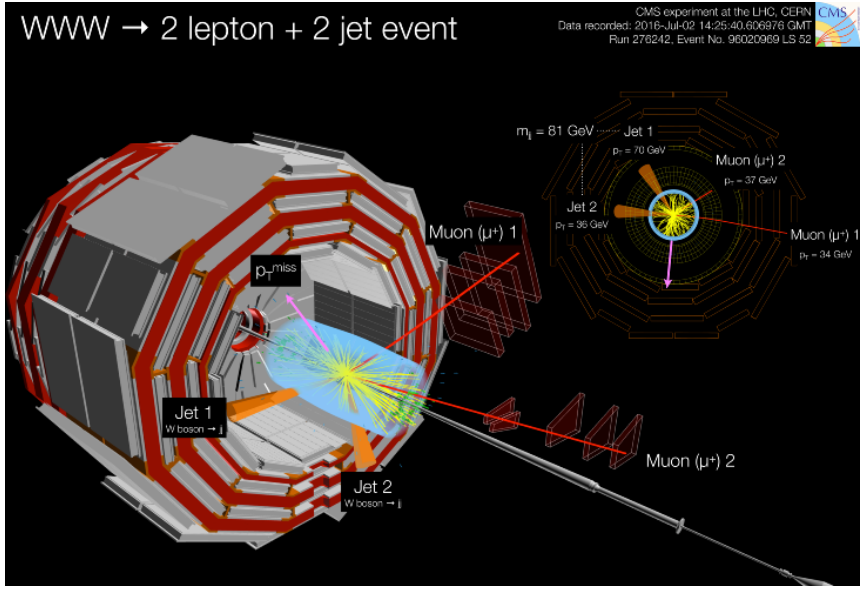
γγ JHEP 03 (2021) 243

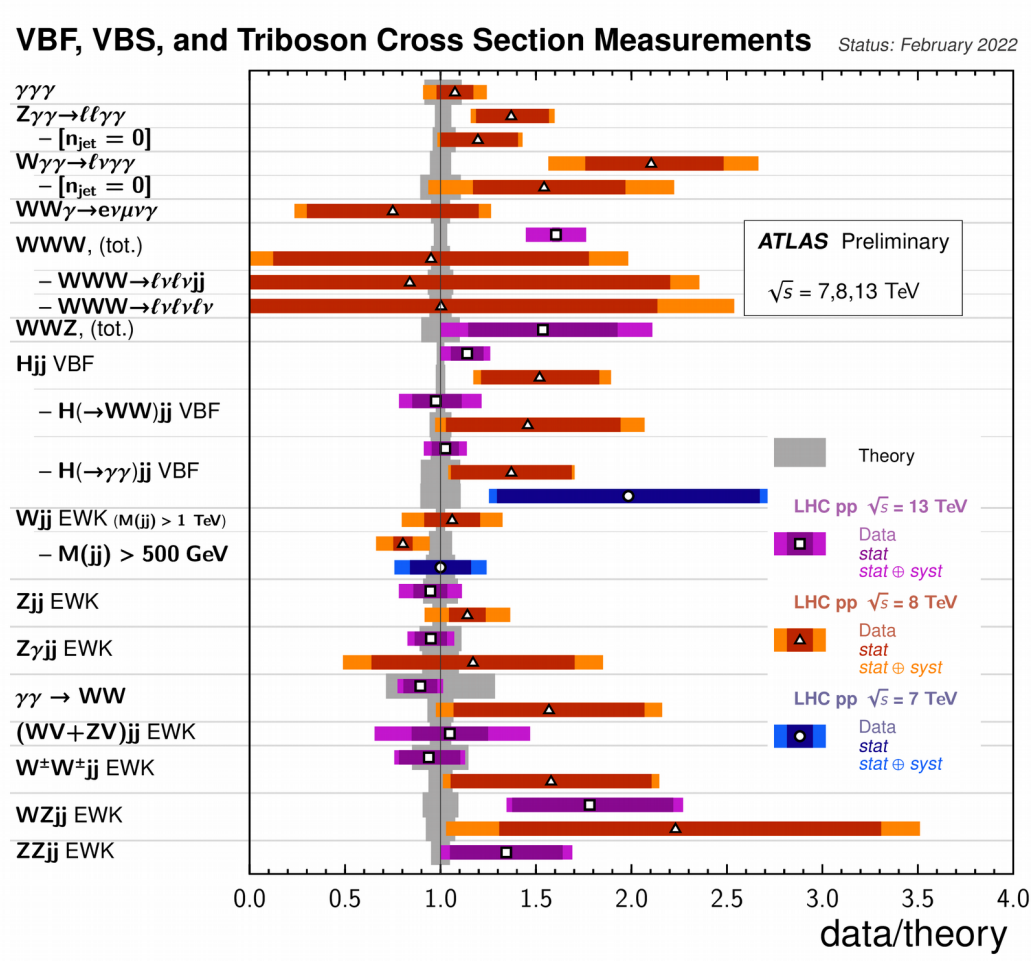
- WW observed in proton-proton collisions requiring 0 tracks associated to vertex.
- Light-by-light scattering observed in PbPb collisions (left)
- **CMS + TOTEM** published a search for anomalous γγ→VV→hadrons production. No excess over SM was found, but limits were placed on dim-6, dim-8 and aQG couplings: CMS-PAS-SMP-21-014



Triboson production

- Search for these processes with Run 1 + early Run 2 could only find evidence for production.
- Large statistics accumulated through 2015-2018 allowed for the observation of combined production of three vector bosons.



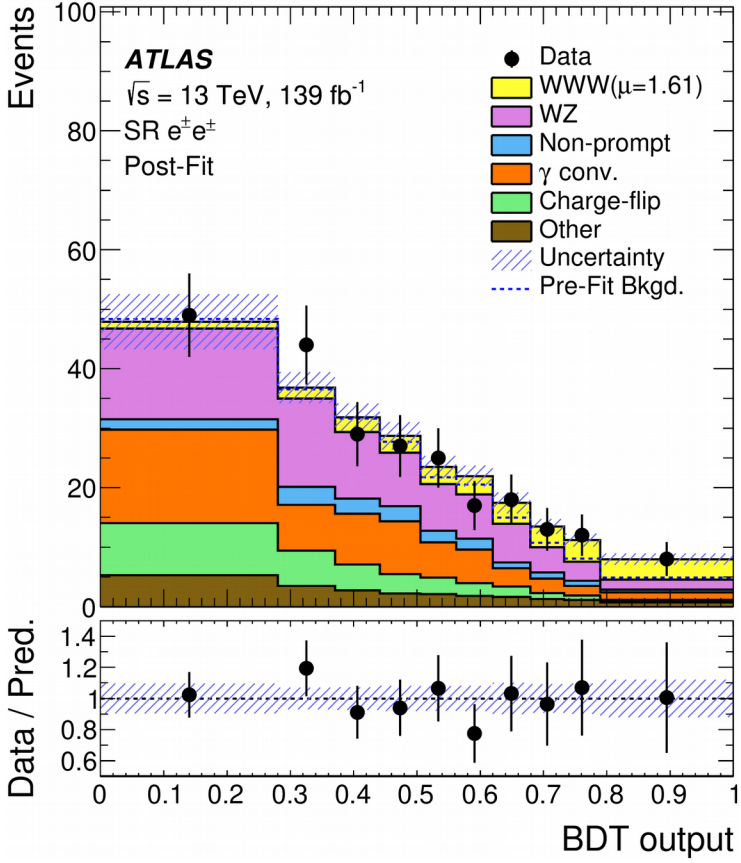


Left: candidate WWW event as reported in SMP-19-014

Triboson measurements at LHC

ATLAS arXiv:2201.13045 [hep-ex]

Observation of WWW production. Multi-variate analysis used to discriminate background, observed significance of 8.0σ.



σ(pp→ WWW) = 820 fb ± 100(stat.) ± 80(syst.)

CMS WWW search with early Run 2 data: Phys. Rev. D 100 (2019) 012004

σ(pp→ Wγγ) = 13.6 fb ± 1.9(stat.) ± 4.0(syst.)

σ(pp→ Zγγ) = 5.41 fb $^{+0.58}_{-0.55}$(stat.) $^{+0.64}_{-0.70}$(syst.)

CMS PRL 125 (2020) 151802

Observation of VVV production

All individual searches combined for an observed significance of 5.7σ

ATLAS Phys. Lett. B 798 (2019) 134913

Evidence of WVV production

WWZ and WZZ searches combined for an observed significance of 4.1σ

CMS JHEP 10 (2021) 174

Observation of Vγγ production

First measurement of the process at √s=13 TeV, limited by systematics (photon reconstruction and misidentified jets)

ATLAS results @ √s=8 TeV

Wγγ: PRL 115 (2015) 031802

Zγγ: Phys. Rev. D 93 (2016) 112002

Conclusions and outlook

- Plenty of results coming from a thriving LHC electroweak physics program, exploring a plethora of final states
  - Test and validation of our well established knowledge of the Standard Model and shedding light on some of the unexplored parts of it.
- Precision measurements take time, reduced statistical uncertainties require a careful assessment of systematics.
  - Key work needed on better detector understanding and optimizing observables to reduce uncertainties.
  - Many Run 2 results still to come!
- Run 3 is just around the corner, providing increased data statistics and a slight energy bump, exciting times coming up!

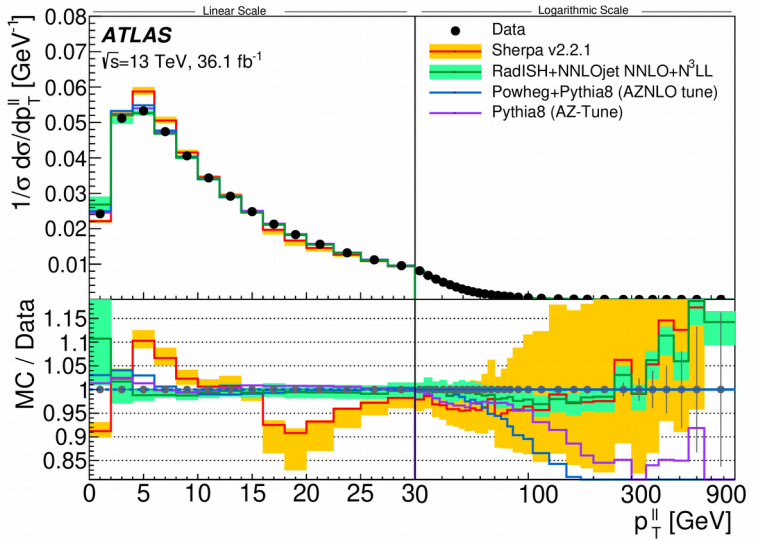
Many thanks for
your attention!

Transverse momentum distribution of DY lepton pairs

- Precision tests of state-of-the art theory calculations.
  - Crucial input for MC tuning
- Sensitive to soft QCD ISR at low-p_T → validation of gluon resummation techniques

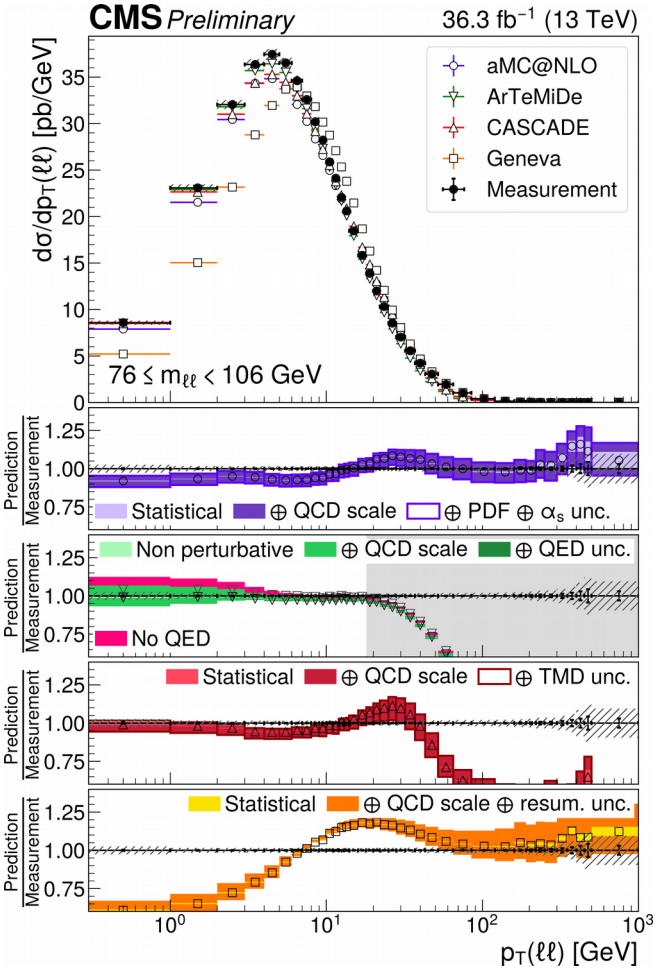
ATLAS Eur. Phys. J. C 80 (2020) 616

- Measurement at the Z-mass peak: $66<m_{\ell\ell}<116$ GeV
- Data accuracy below % level across most p_T spectra.
- Pythia8 only includes LO ME, higher order corrections missing.
- Sherpa presents matching problem at p_T~20 GeV



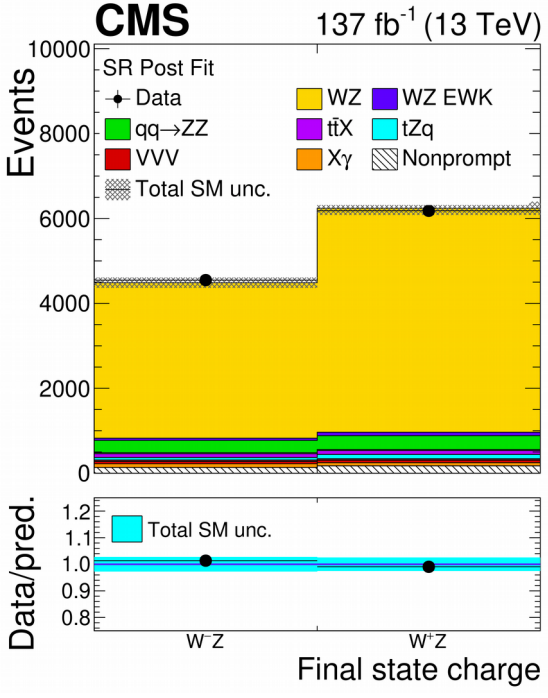
CMS CMS-PAS-SMP-20-003

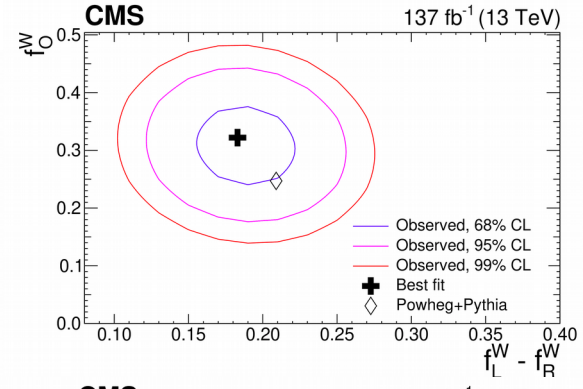
- Showing results on-shell, off-shell also available (double-differential measurement).
- Measurement of both inclusive Z and $n_{jet} \geq 1$.
- Compared to transverse momentum dependent (TMD) parton showers.

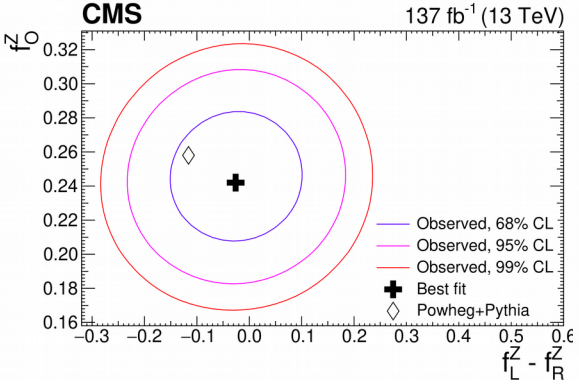


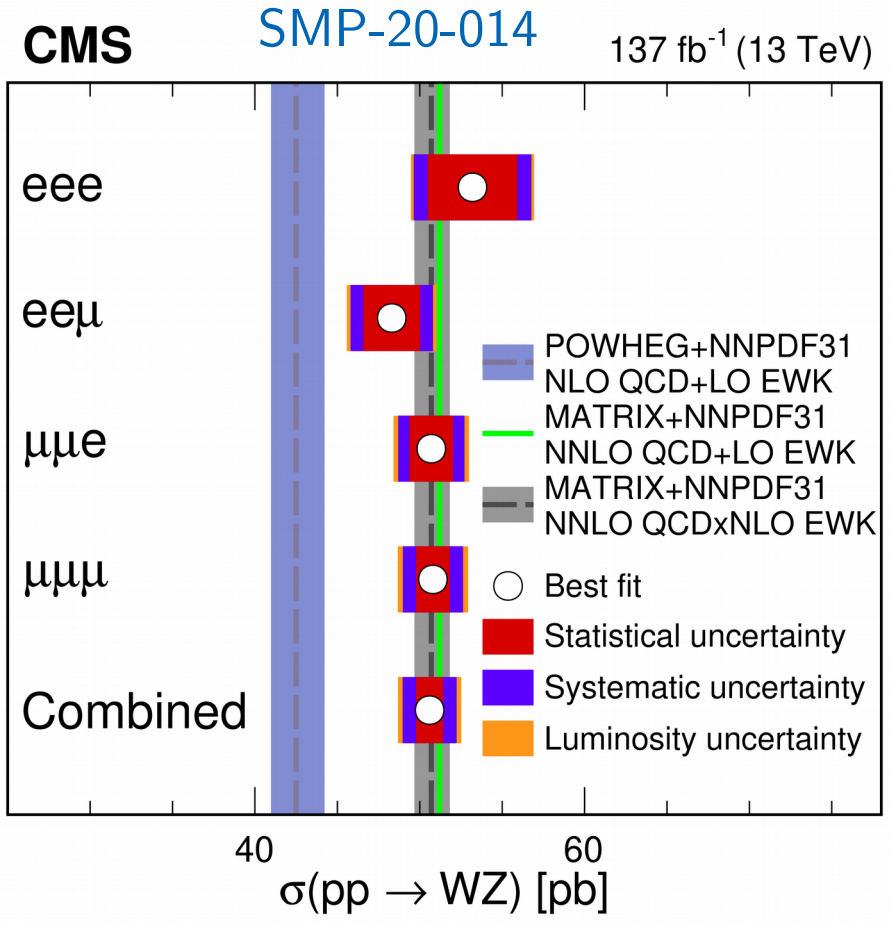
WZ cross section

- Inclusive and differential cross section measurement.
  - NNLO corrections needed to provide an accurate description.
- Provides also charge asymmetry and (single boson) polarisation measurements









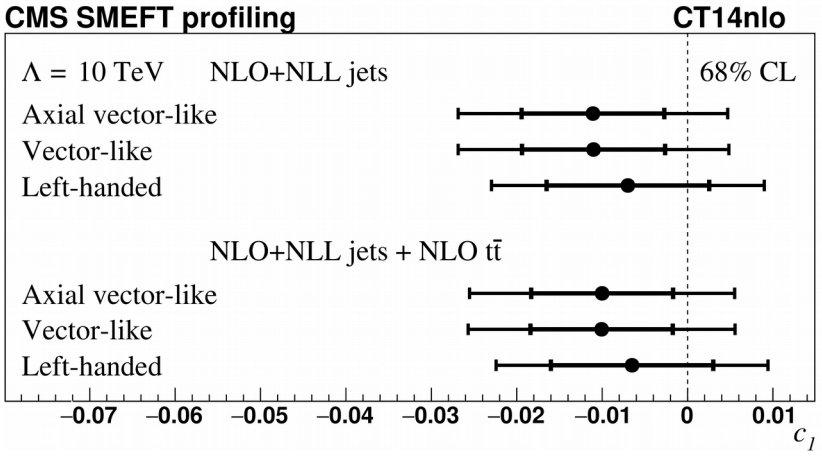
Corresponding measurement by ATLAS:
Eur. Phys. J. C 79 (2019) 535

Electroweak inputs to EFT interpretations

- Electroweak processes can help constraint limits on high dimensional operators modifying fermion couplings (4-fermion interactions) and vector boson interactions.
- Can be combined to Higgs and top studies in global fits to maximize the sensitivity of our results.

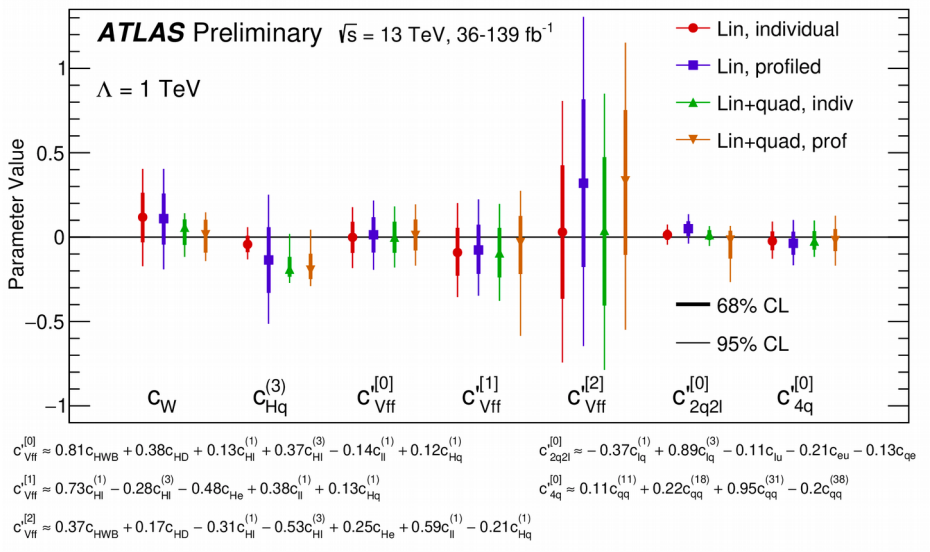
CMS JHEP 02 (2022) 142

Using the double-differential inclusive jet cross section to provide limits on Wilson coefficients for contact interaction models.



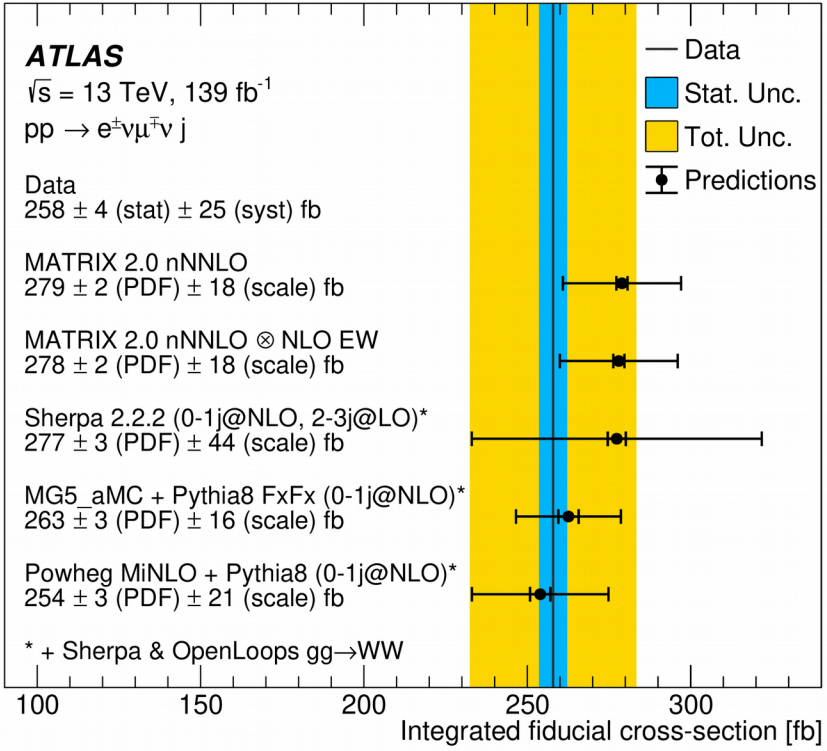
ATLAS ATL-PHYS-PUB-2021-022

- Combined interpretation of WW, WZ, ZZ and VBF Z production.
- Sensitive to 33 different operators, 15 directions in parameter space are constraint.
- To be expanded in a combined ATLAS+CMS fit.

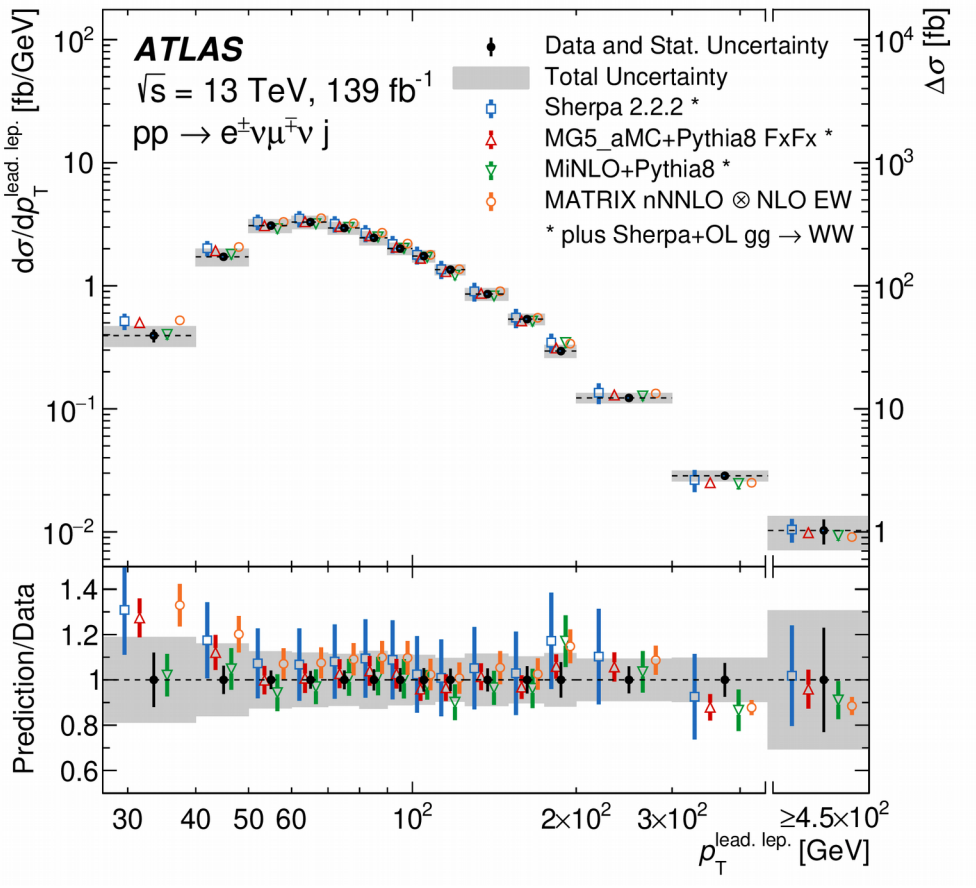


WW+jets production

- Inclusive and differential cross section measurement.
- Good agreement with latest NNLO corrections.
- Used to set limits on EFT operators, to be used as part of the ATLAS global EFT fits.



JHEP 06 (2021) 003



Corresponding measurement by CMS:
CMS-SMP-20-013