W/Z and multiboson production and properties

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Windows on the Universe

30th Anniversary Conference of the Rencontres du Vietnam

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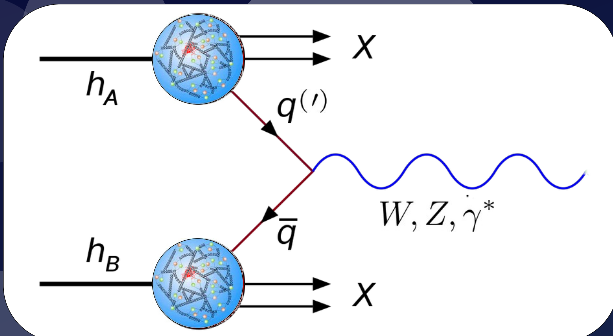
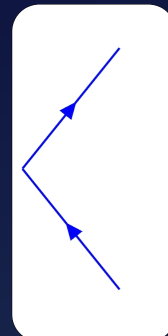
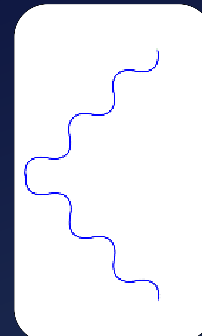
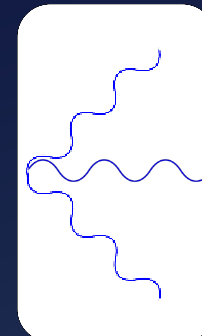
Weak bosons provide direct and indirect channels to SM and BSM physics. An already vast array of explorable processes continues to grow with increasing energy and data sets.









Perturbative and non-perturbative QCD

Single vector boson cross sections

Vector boson properties

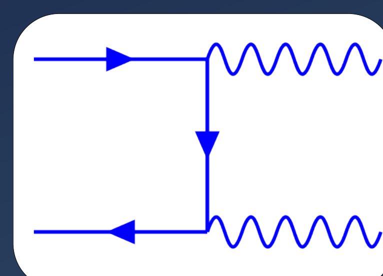
Electroweak parameters

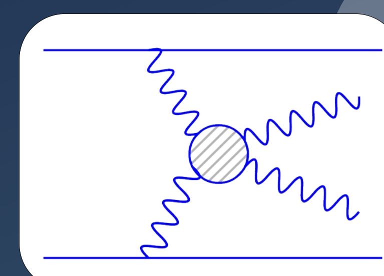
DiBoson production

EFT interpretations

Electroweak production of bosons

TriBoson production

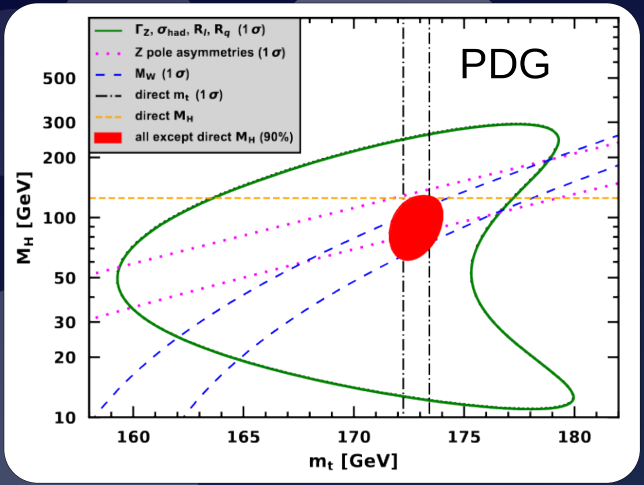




...

A small sampling will be presented here

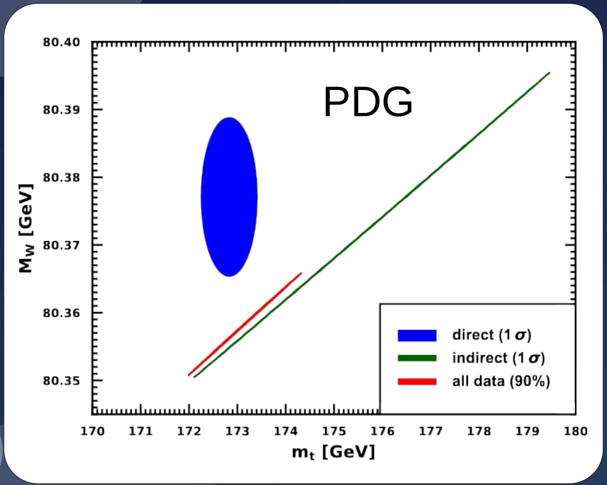
Global analyses of EW parameters probe the fundamental consistency of the SM



Three free parameters of electroweak symmetry breaking mechanism are **over constrained** by experimental observables

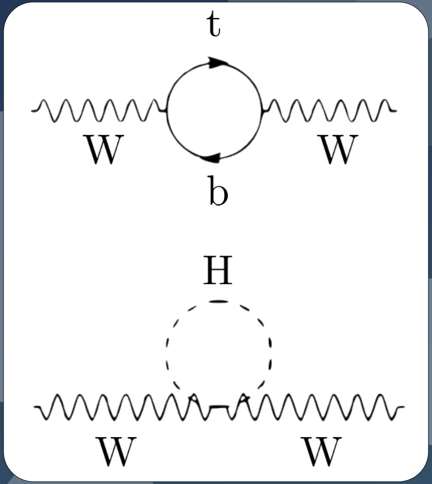
m_Z, G_F, α_{em}, (m_W, $\sin^2\theta_W/\sin^2\theta^{eff}_{lep}$, m_{top}, m_H)

$$sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \qquad m_W^2 sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}G_F}$$



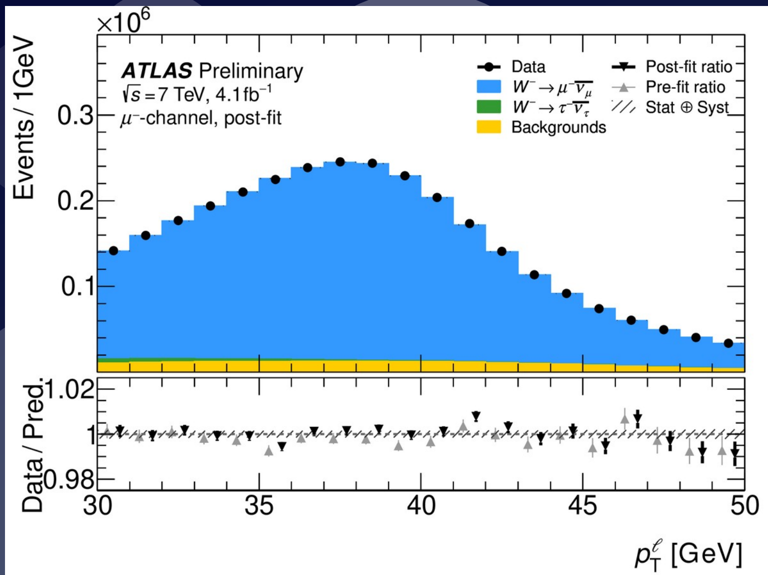
$$m_W^2 = \frac{m_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\pi\alpha(1+\Delta r)}{G_F m_Z^2}}\right)$$

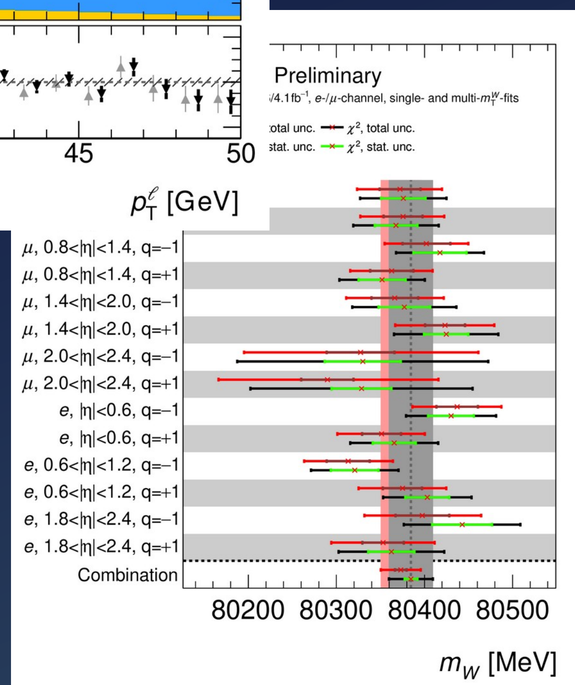
$$\Delta r = -\frac{3\alpha c_W^2}{16\pi s_W^4}\frac{m_t^2}{m_W^2} + \frac{11\alpha}{48\pi s_W^2} ln\frac{m_H^2}{m_W^2} + \ldots$$



Improved W mass measurement by ATLAS

Reanalysis using an improved fitting technique and updated PDFs





Follows the same approach as 2017 analysis

- $W \rightarrow e/\mu+\nu$; measue p_T and m_T distributions
- Precision calibrations
- Z, $W \rightarrow \tau\nu$, VV, top background estimated with MC; data-driven multijet bkg
- Fit to signal MC templates for a range of m_W values from reference MC – precise detector modeling, EW and QCD corrections, ...
- m_W is obtained from fits to p_T and m_T distributions, considering numerous event categories

Improved W mass measurement by ATLAS

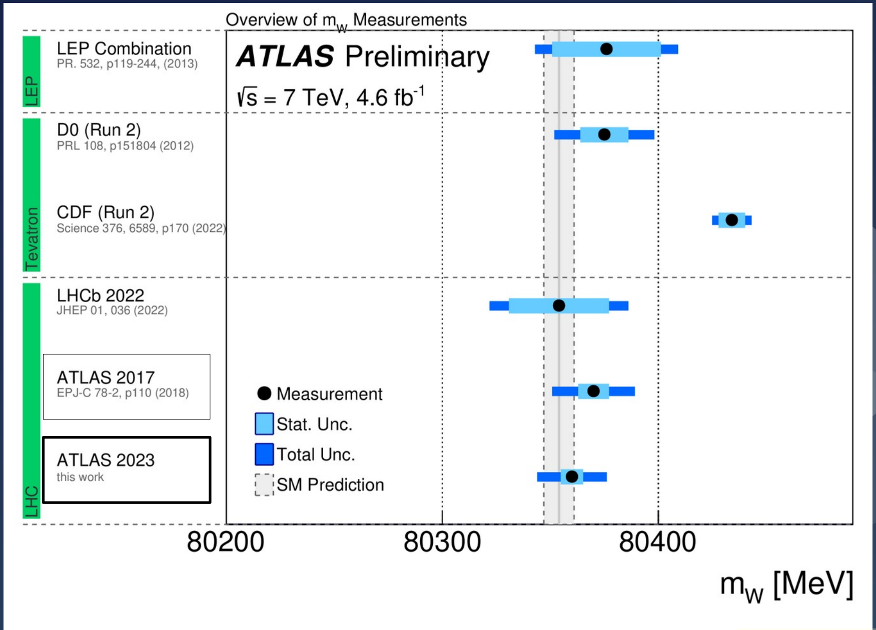
- Rigorous checks of modeling have been performed
  - Validation of pT(W) with a dedicated measurement
  - Improved application of EW corrections
- New statistical interpretation
  - Use profile max likelihood fitting – first application for W mass analysis (compared to stat-only χ^2 fit, systematics applied aposteriori)
  - Apply PCA/pruning to reduce nuisance parameters ~1000 => 200
- Baseline PDF updated from CT10 to CT18

New ATLAS result:

m_W = 80360 ± 5 (stat.) ± 15 (syst.) = 80360 ± 16 MeV

Uncertainty improved by 15%

Supersedes 2017 measurement: 80370 ± 19 MeV



Obs.	Mean [MeV]	Elec. Unc.	PDF Unc.	Muon Unc.	EW Unc.	PS & A_i Unc.	Bkg. Unc.	Γ_W Unc.	MC stat. Unc.	Lumi Unc.	Recoil Unc.	Total sys.	Data stat.	Total Unc.
p_T^ℓ	80360.1	8.0	7.7	7.0	6.0	4.7	2.4	2.0	1.9	1.2	0.6	15.5	4.9	16.3
m_T	80382.2	9.2	14.6	9.8	5.9	10.3	6.0	7.0	2.4	1.8	11.7	24.4	6.7	25.3
Improvements:			**15-30%**			**10-40%**								**15%**

SM summary plots
ATLAS , CMS

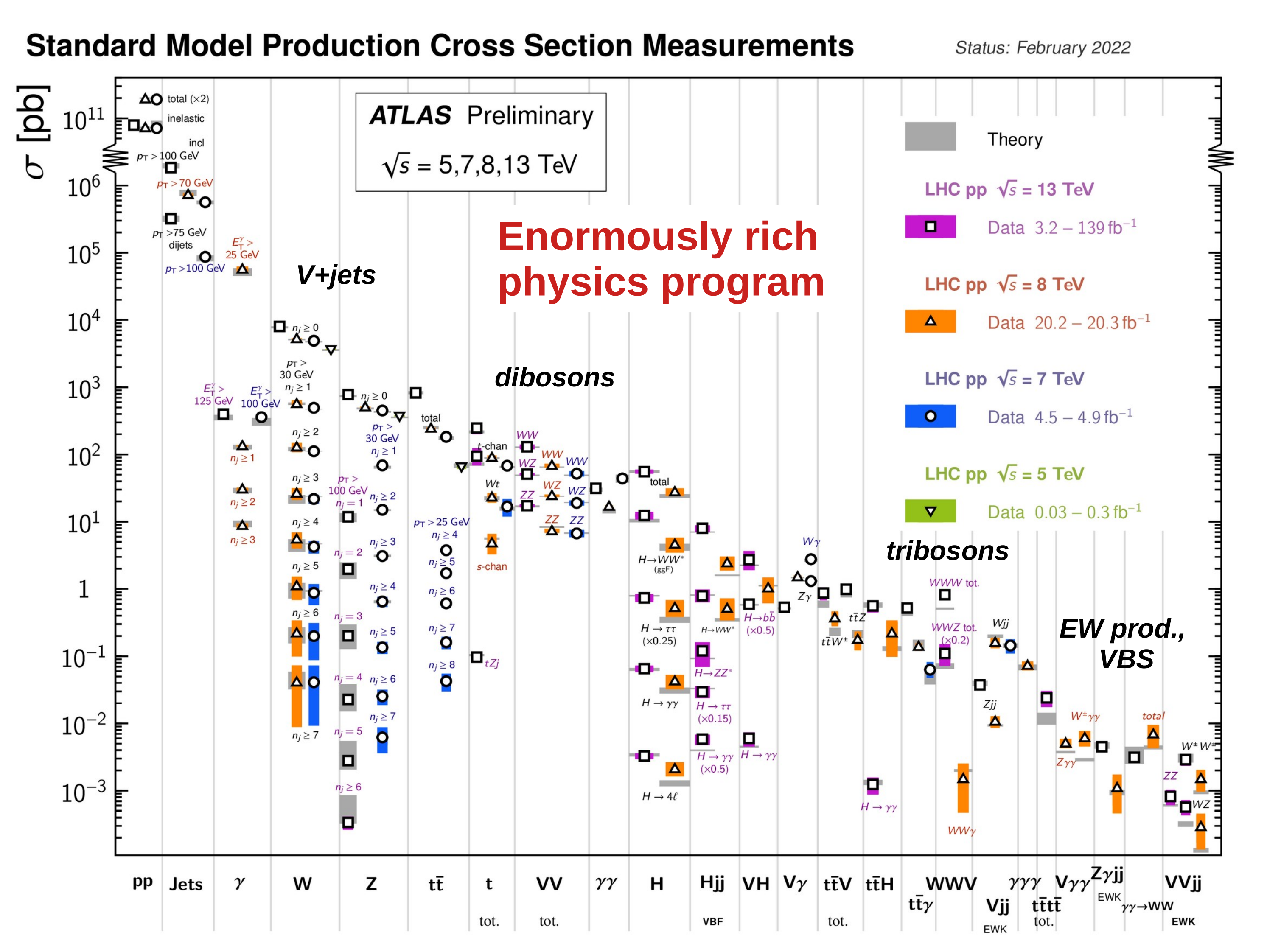
Physics with electroweak bosons

Production of EW bosons tests N^nLO generators, PDFs, nonperturbative physics

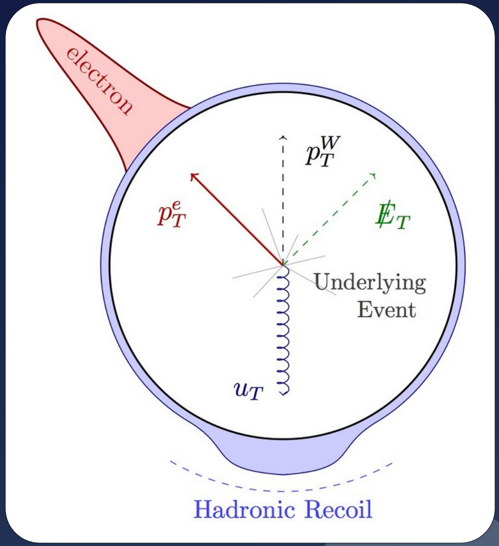
EW boson self interactions:

- rare proceses to probe SM predictions
- BSM portal to be interpreted through Effective Field Theories

Vector boson scattering tests details of electroweak symmetry breaking



Probing N^{n}LO, resummed models: Precise p_T(W/Z) spectrum

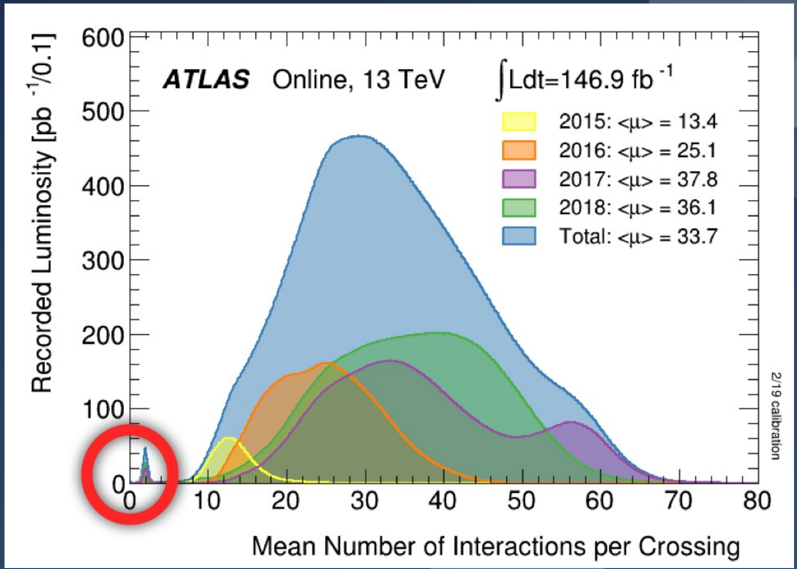


Precise modeling of p_T(W) is important in reducing the uncertainty for m_W

- Hadronic recoil is the main limitation in p_T(W) measurements
- Recoil resolution degrades with pileup

Precision measurements of p_T(W+, W-, Z) and ratios at 13 and 5.02 TeV are performed using **dedicated low-pileup runs** with <μ>~2

- 255 pb^{-1} at 5.02 TeV and 338 pb^{-1} at 13 TeV
- W→ℓν and Z→ℓℓ (ℓ=e or μ)



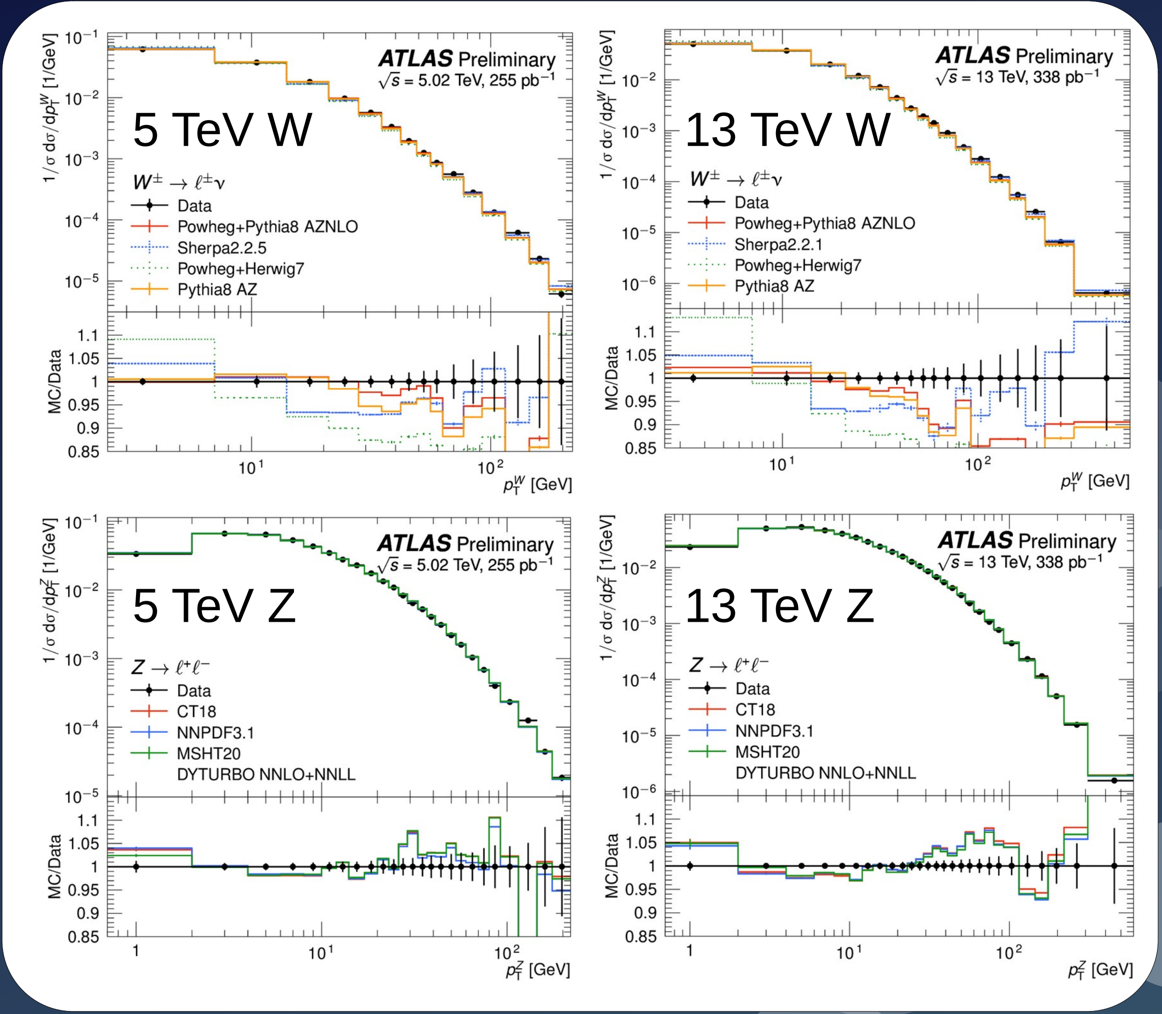
Unfolded distributions are compared to QCD calculations based on parton shower Monte Carlo generators and analytical resummation

Probing N^{n}LO, resummed models: Precise p_T(W/Z) spectrum

MC predictions show common deficiencies for W/Z cross sections.

With ATLAS tune for PYTHIA showers (from W mass measurement) the MC describe data reasonably at low p_T especially at $\sqrt{s}$=5.02 TeV

DYTURBO resummed predictions show best overall agreement, matching the data ~few percent level



See parallel talks as well

Luminosity from Z bosons

Luminosity at LHC can be determined from machine parameters
- A_{eff} from VdM scans (very low beam intensity)

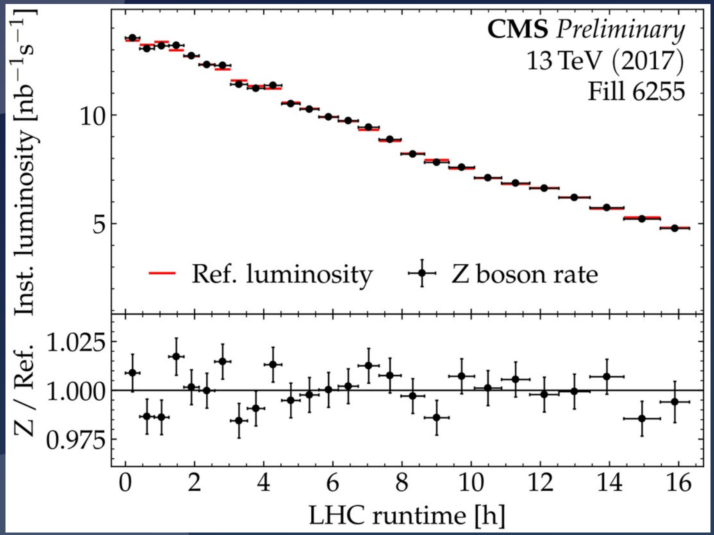
$$\mathcal{L} = \frac{\nu_r n_1 n_2}{A_{eff}}$$

Alternatively from pp collision products in fiducial phase space, eg
- Z → μμ rate measured with high precision
- but fiducial xsec only known to 2-3% precision

$$\mathcal{L}_Z = \frac{N^Z}{\sigma^Z_{\text{fid.}} \epsilon^Z}$$

Calibrate Z with a reference run, using 2017 low PU fills
- low PU lumi measured w/ very good precision, model independent
- PU-independent syst. uncertainties cancel out

$$\mathcal{L}_{\text{highPU}} = \frac{N^Z_{\text{highPU}}}{N^Z_{\text{lowPU}}} \mathcal{L}_{\text{lowPU}}$$



First quantitative uncertainty analysis of the use of Z bosons for the luminosity measurement

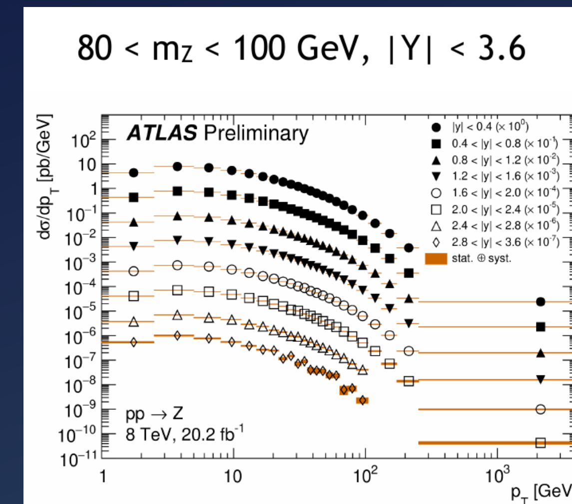
- **Good improvement wrt current nominal precision of 2.4%**

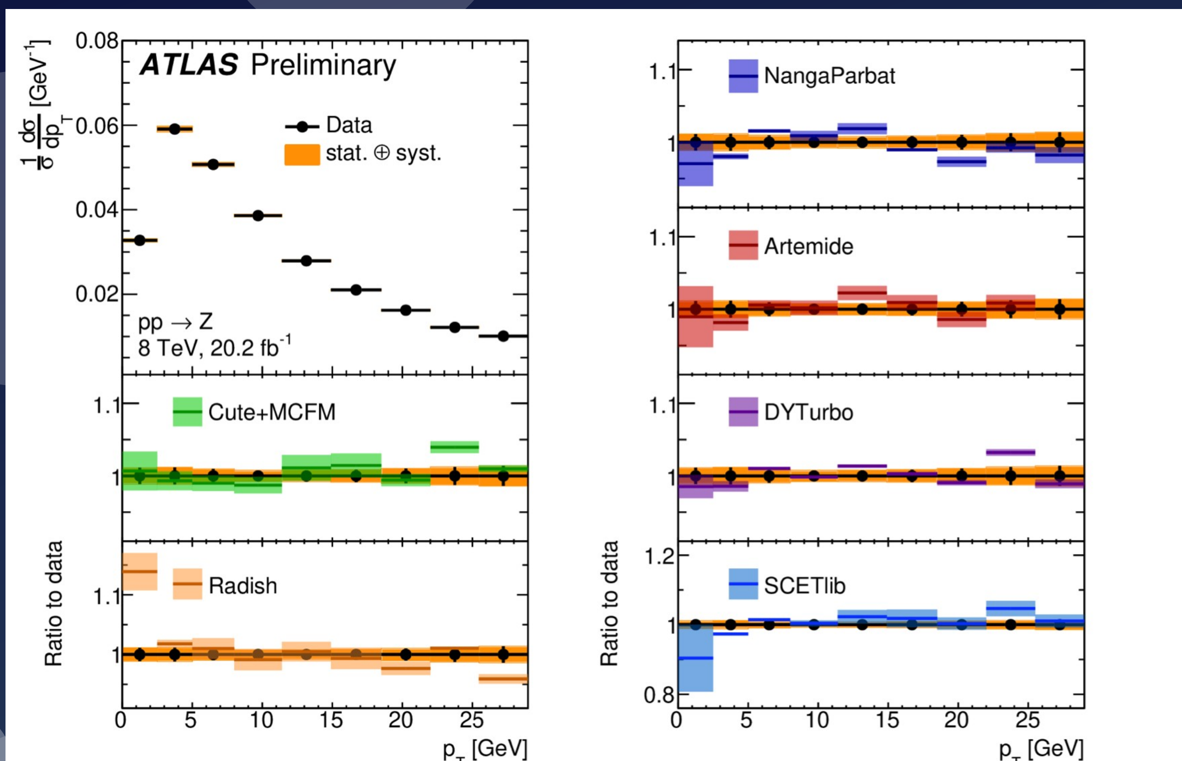
$$\delta\mathscr{L}_{\text{lowPU}} = 1.7\,\% \rightarrow \delta\mathscr{L}_{\text{highPU}} = \delta\left(\frac{N^Z_{\text{highPU}}}{N^Z_{\text{lowPU}}}\mathscr{L}_{\text{lowPU}}\right) = 1.73\,\%$$

ATLAS full phase space Z measurement

First precise measurement at the LHC in the full phase space for pp → Z→ℓℓ (ℓ=e or μ) ($\sqrt{s}$ = 8 TeV, L=20.2fb^{-1})

- Negligible theory uncertainties, no extrapolation to full phase space
- Statistically limited
- Cross sections are parameters in fit to 176 bins of Z p_T-rapidity





Measurements compared to N3LL/N4LL resummed predictions matched to O(α_s^3) from MCFM/NNLOJET, **N3LO QCD predictions (DYTurbo)**

See later talks for α_s extraction!

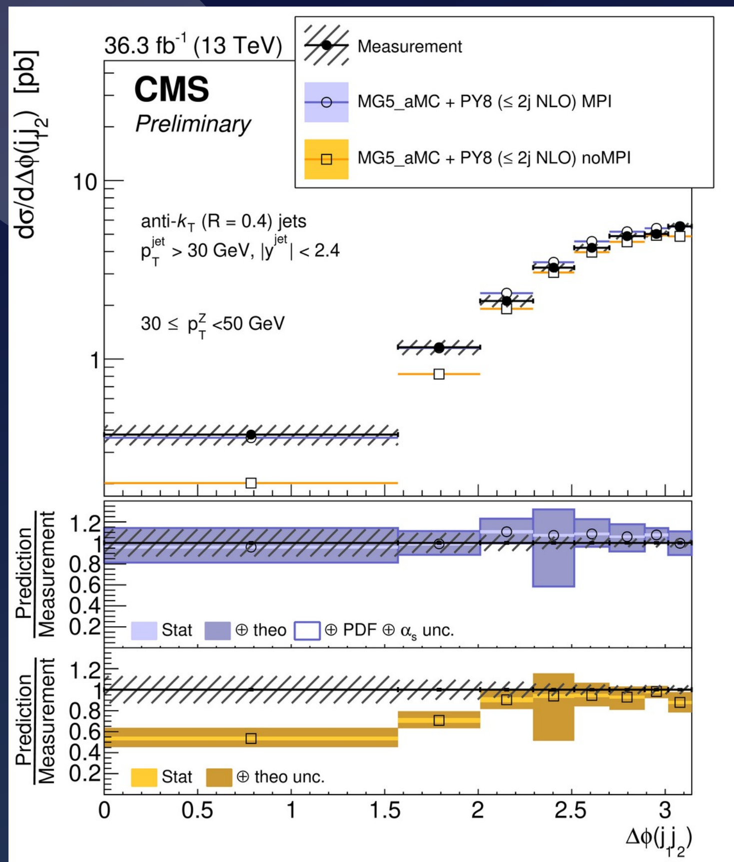
Also see CMS SMP-20-003 DY study

W/Z + jets

Azimuthal correlations in Z+jets events in p-p collisions at √s = 13 TeV

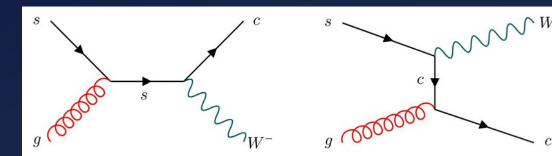
Measurement of njet multiplicity vs $p_T(Z)$. also azmiuthal correlations in final state objects

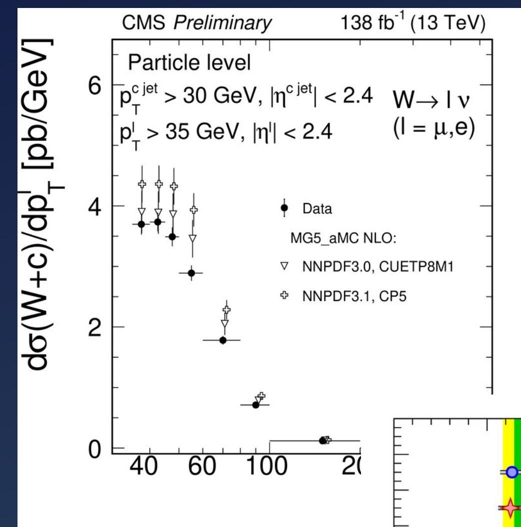
Compare unfolded distributions to N^nLO + PS MC



Multiple parton interactions found to important to correctly describe low $p_T(Z)$ regions

W+charm constrains s-quark component of PDF models

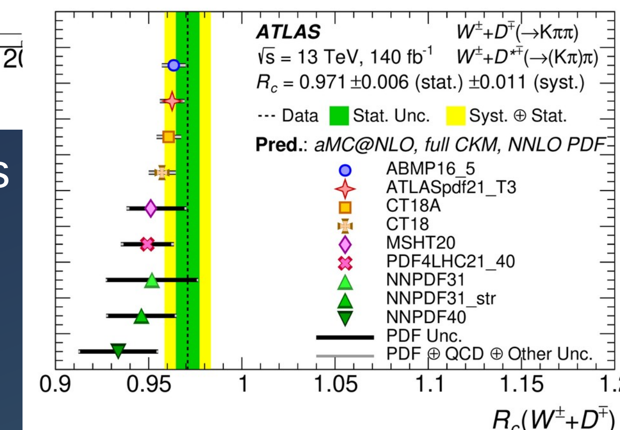




Inclusive and differential measurements in in lepton p_T, η

$$R_c^{\pm} = \frac{\sigma(W^{+}+\bar{c})}{\sigma(W^{-}+c)}$$

Predicted XS's generally higher than observed



See parallel talks as well

Precise measurement of Z invisible width

First precise measurement of Z invisible width at a hadron collider

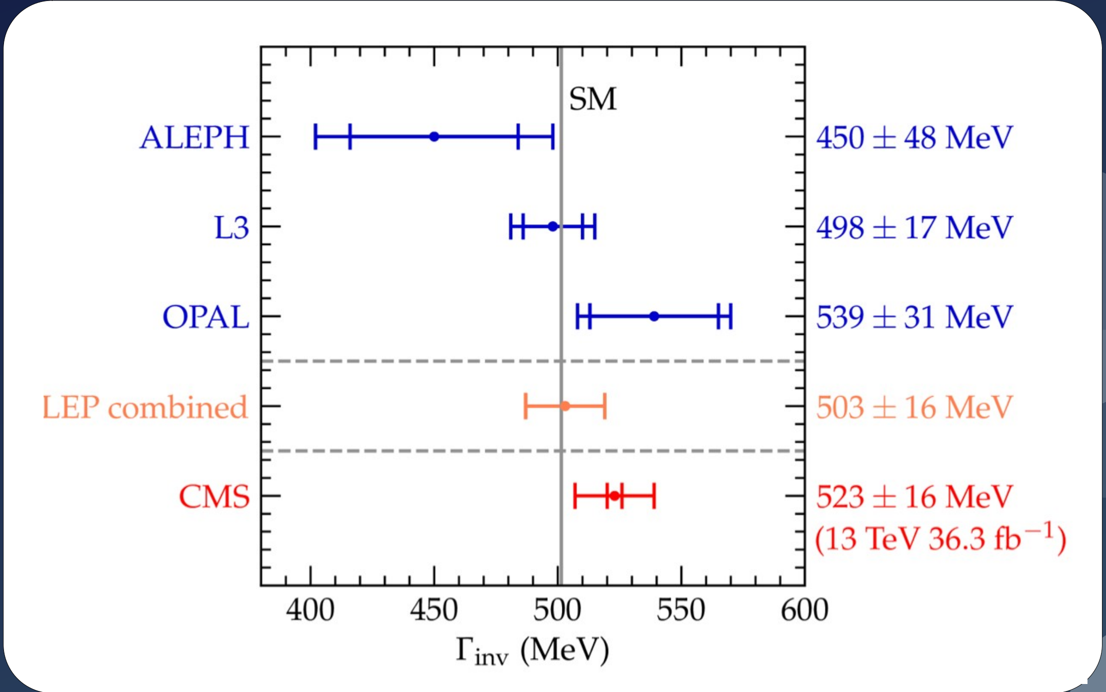
- Constrains the number of light neutrino species coupling to the Z boson
- Utilizes simultaneous fit of hadronic recoil in Z -> ℓℓ + jets and MET+jets regions
  - Scales Z -> νν process relative to Z -> ℓℓ

$$\Gamma(Z \to \nu\bar{\nu}) = \frac{\sigma(Z\text{+jets})\mathcal{B}(Z \to \nu\bar{\nu})}{\sigma(Z\text{+jets})\mathcal{B}(Z \to \ell\ell)}\Gamma(Z \to \ell\ell)$$

Dominant uncertainties: lepton eff. and jet energy scale

Source of systematic uncertainty	Uncertainty (%)
Muon identification efficiency (syst.)	2.1
Jet energy scale	1.8–1.9
Electron identification efficiency (syst.)	1.6
Electron identification efficiency (stat.)	1.0
Pileup	0.9–1.0

...



Single most precise direct measurement to date, competitive with the combined result of the direct measurements from the LEP experiments.

Diboson production at the LHC

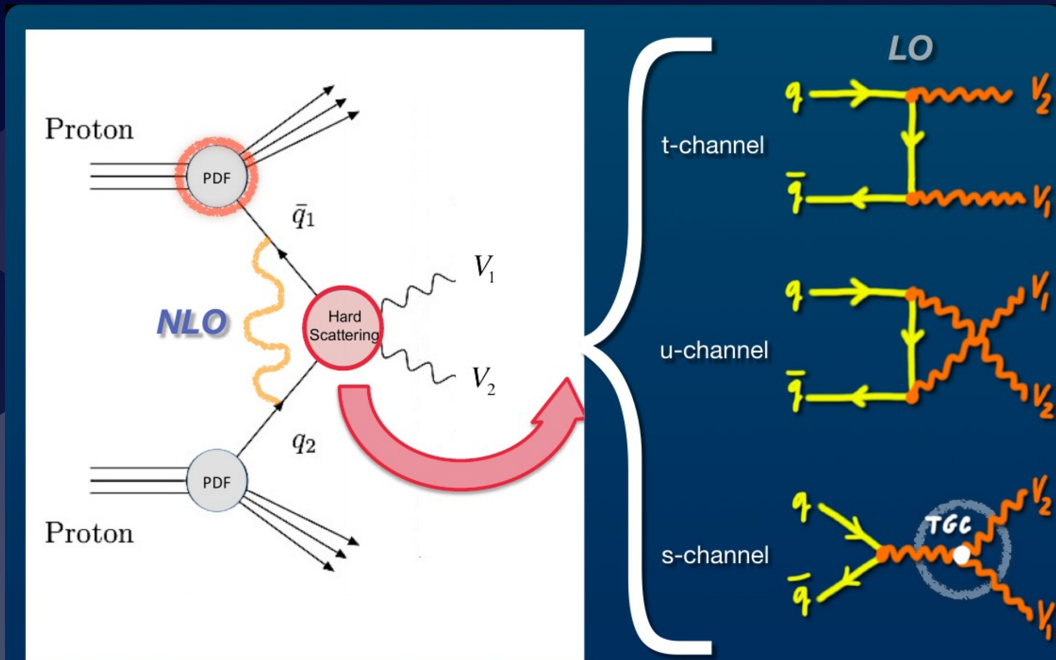
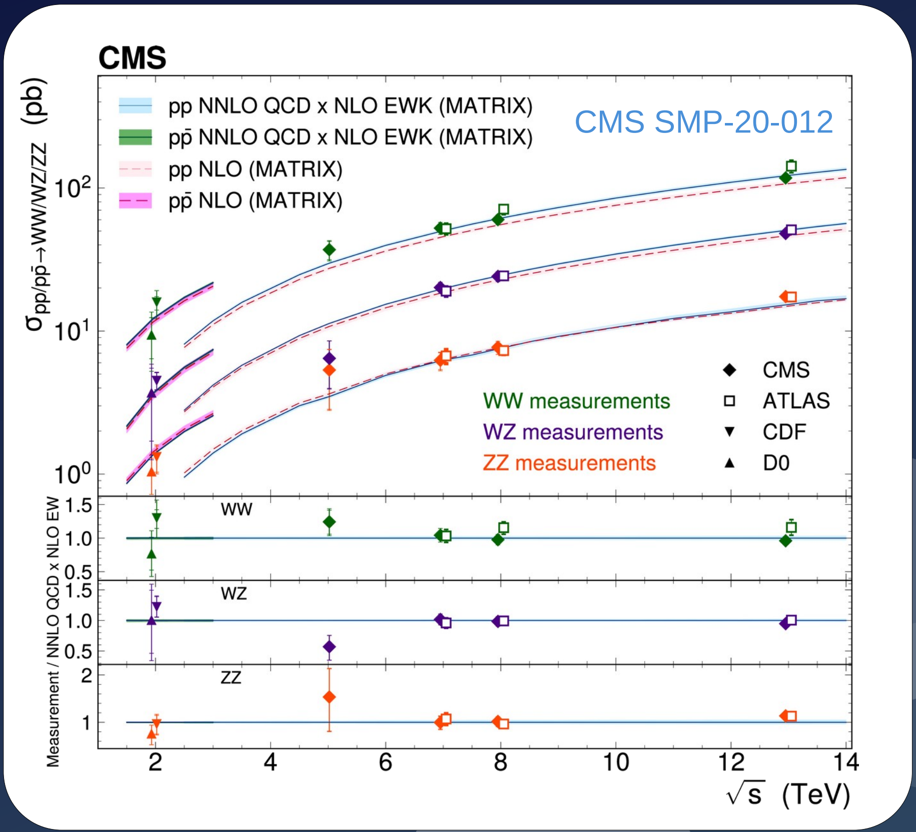


Image: João Guimarães da Costa Lepton Photon 2023



New results with full LHC Run 2 integrated luminosity ~ 140 fb^{-1}

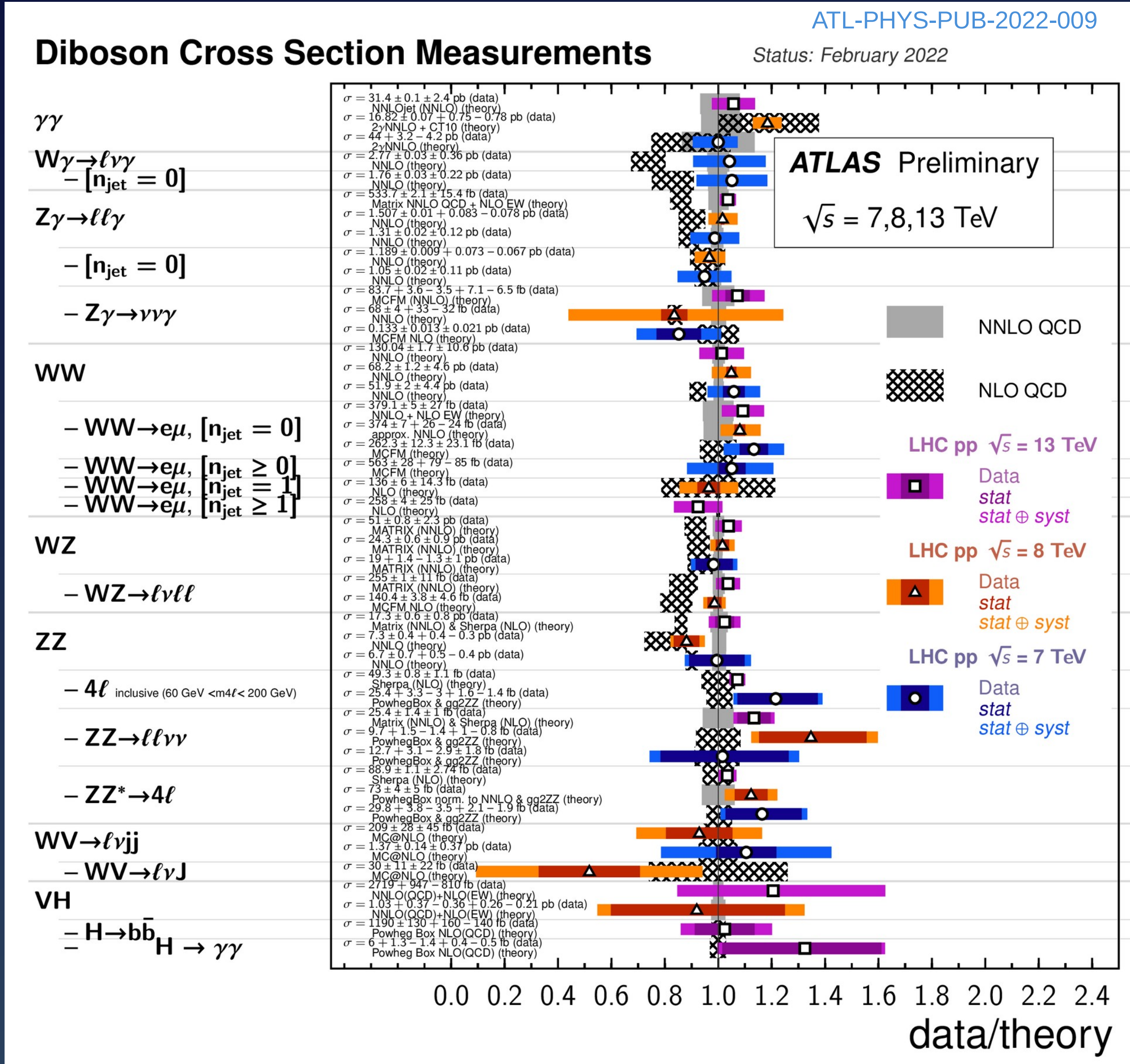
- Better statistical precision, plus more differential distributions
- Observations of rare processes, understand backgrounds to even more rare processes
- Stringent tests of EW sector of SM and search for new physics at the TeV scale

Diboson production at the LHC

See also CMS summary plots

Exceptionally active area of research on ATLAS and CMS

Experimental results have been pushing for the development of higher precision theoretical calculations.



Diboson production at the LHC

Exceptionally active area of research on ATLAS and CMS

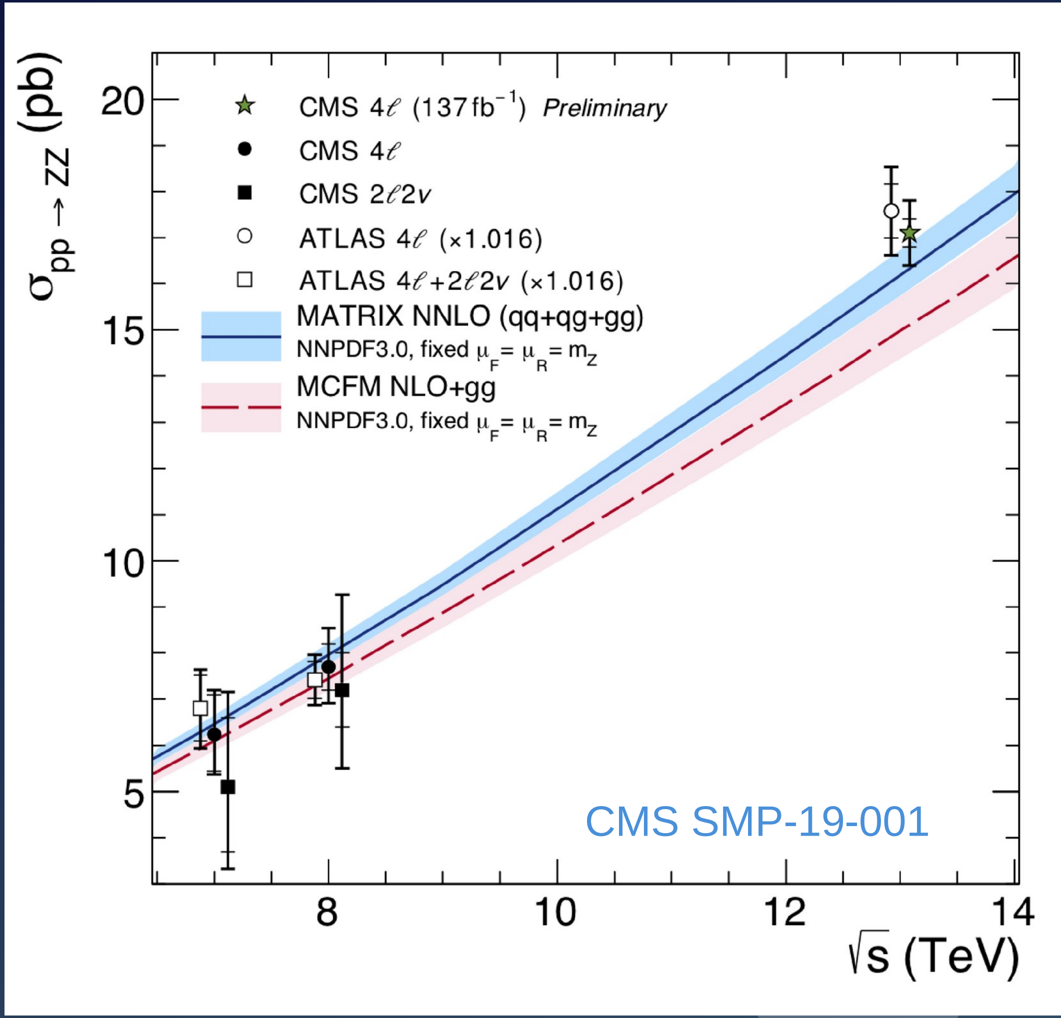
Experimental results have been pushing the development of higher precision theoretical calculations,

Eg, NNLO QCD calculations have removed earlier excesses.

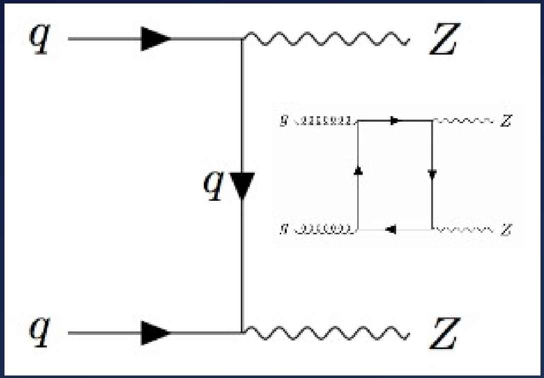
New differential results further challenge predictions.

Selected results follow.

See also CMS summary plots



Measurement of the ZZ(4ℓ) + jets

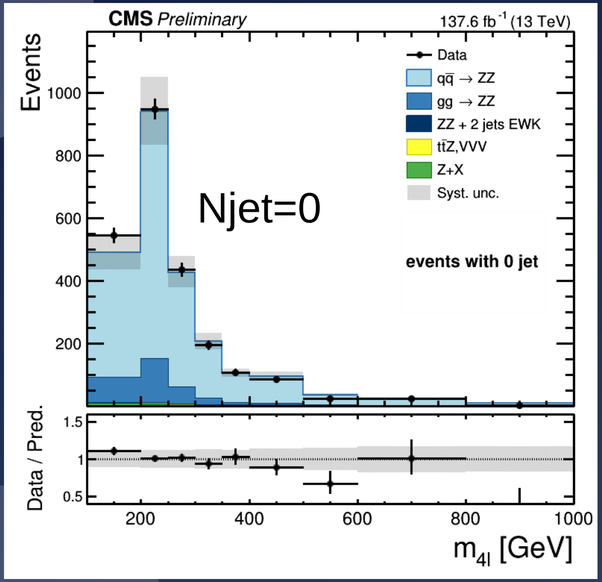


ZZ production in 4 lepton final state
- s-channel production forbidden in the SM
- Up to 10% contribution from loop effects

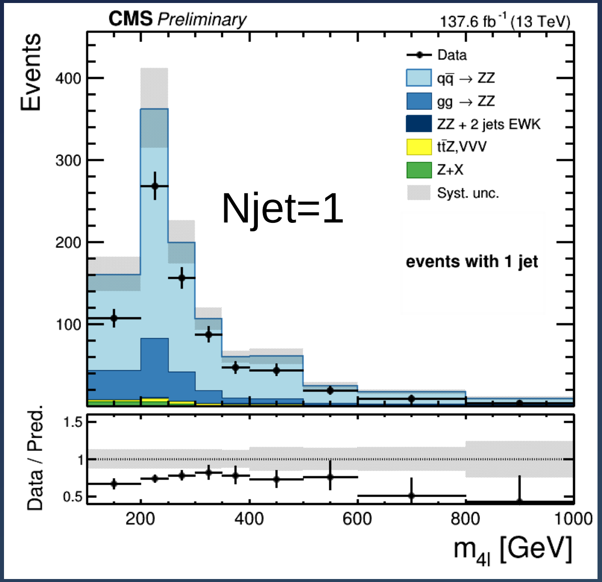
New result presents 1st differential cross sections in many observables
- Njet, jet p_T and |η|, $m(j_1,j_2)$, $\Delta\eta(j_1,j_2)$, m4ℓ vs njet

Compared with the state-of-the-art NNLO and parton shower predictions using MiNNLOPS
- Unfolded distributions

agree

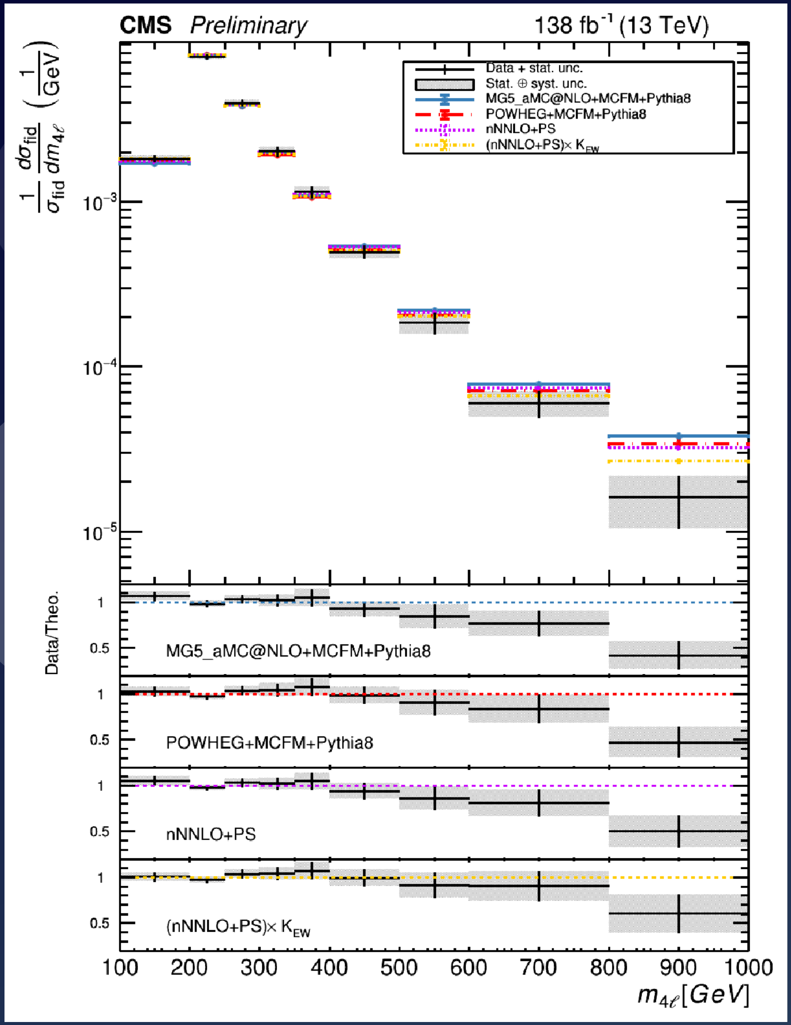


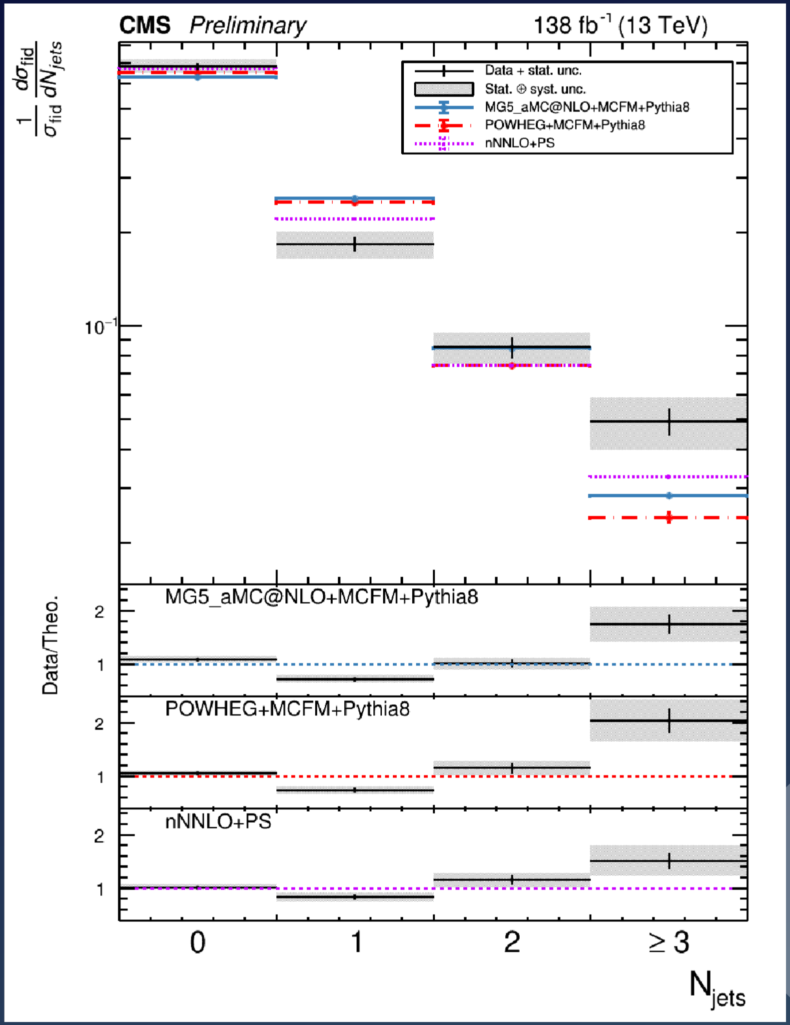
disagree



Predictions in general agree with the data, but in some regions significant discrepancies between predicted and measured values are observed.

Measurement of the ZZ(4l) + jets



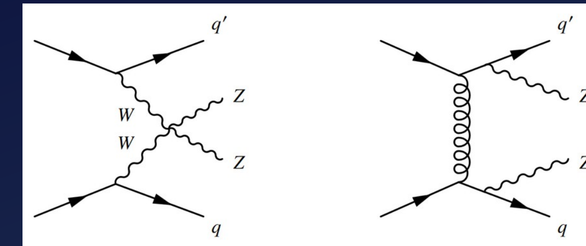


- nNNLO+PS prediction describes the distribution of jet multiplicities better than MadGraph5 aMC@NLO and POWHEG

- Inclusion of EW corrections improves the description of the m4ℓ distribution.

ATLAS-CONF-2023-024

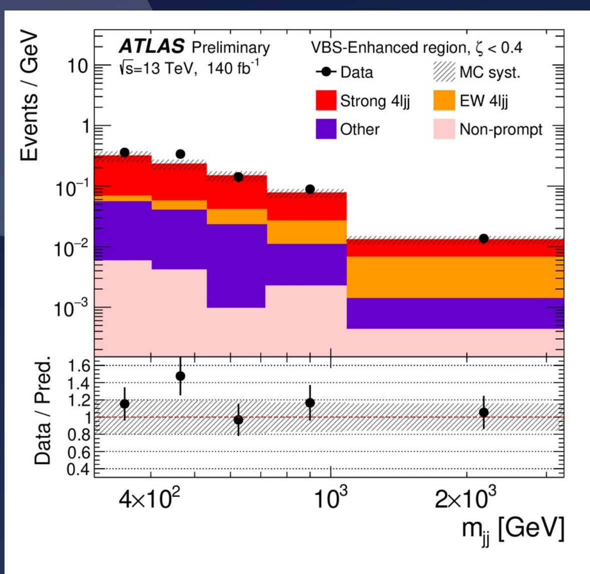
ATLAS ZZjj

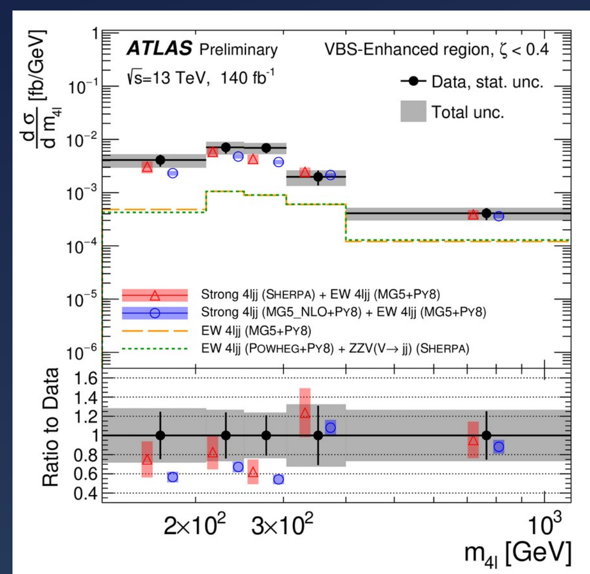


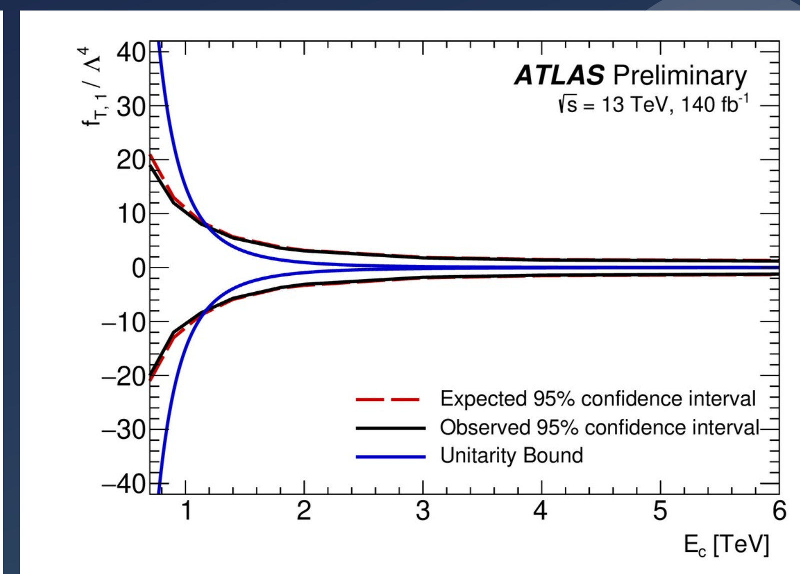
Examine EWK production of 4 leptons in association with two jets

- VBS enhanced and suppressed regions based on 4ℓ system centrality
- Differential (unfolded) measurements of ZZjj with full Run 2 data set
- Sherpa prediction for the strong 4ℓ process generally agrees with data better than MG5_NLO+Py8 in the VBS-enhanced region
- Expected and observed limits D-8(6) operators on aQGC from 2D fit in $m_{4\ell}$ and m_{jj}, as a function of $m_{4\ell}$ < cut-off energy

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{f_{\mathrm{T},i}}{\Lambda^4} O_{\mathrm{T},i}$$







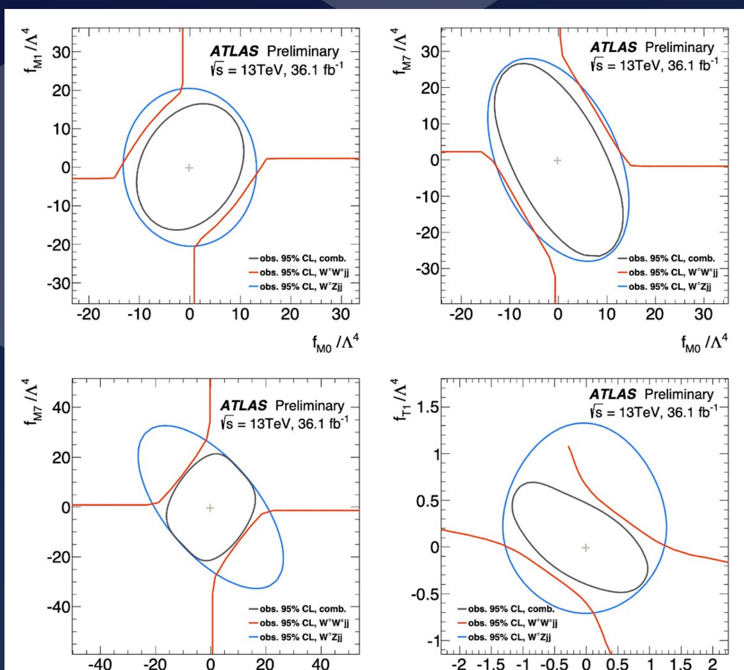
See also new result on first evidence of EW production of Zγjj ATLAS-STDM-2018-36

ATLAS PUB-2023-002

ATLAS ssWW+WZ

Combined interpretation of ssWW and WZjj with partial Run2 dataset

Discriminating distributions:
- ssWW: Reco-level $m_{\ell\ell}$
- WZjj: Differential distribution of mT_{WZ}



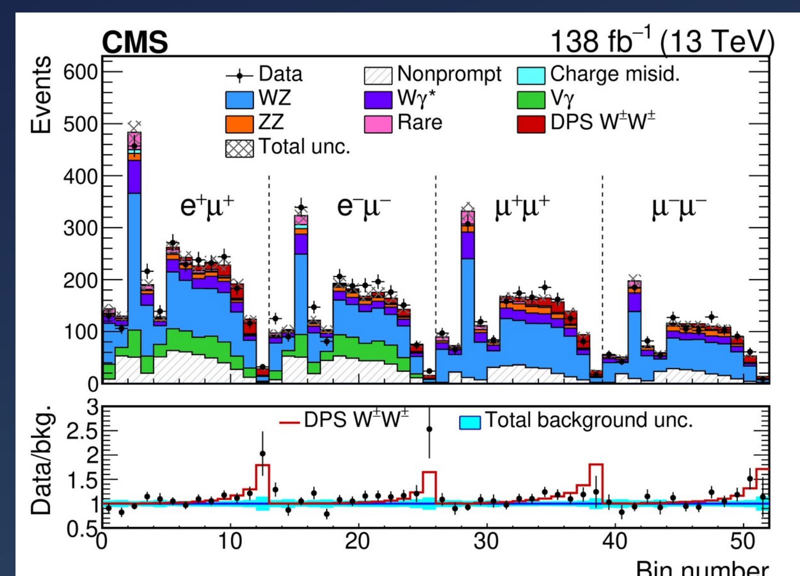
See also: first ATLAS EFT global Fit: ATL-PHYS-PUB-2022-037

1 and 2D limits limits on D-8 operators in aQGC, experimental systematic uncertainty correlations included in combination

Unitarization: clipping method also used for limits as a function of Ec
- WZjj: Ec > mWZ at generator level
- ssWW: Ec > mWW at generator level

CMS SMP-21-013

CMS ssWW



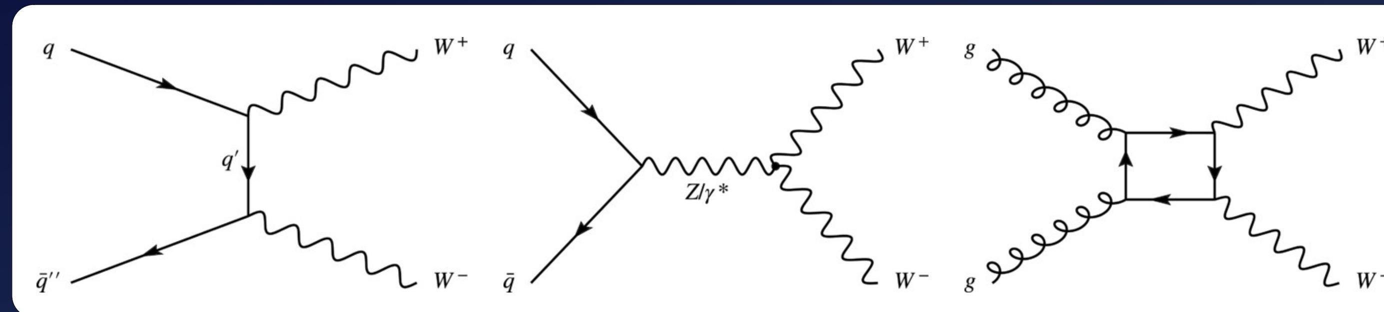
First Observation of ssWW in double parton scattering. Significance of 6.2 s.d.

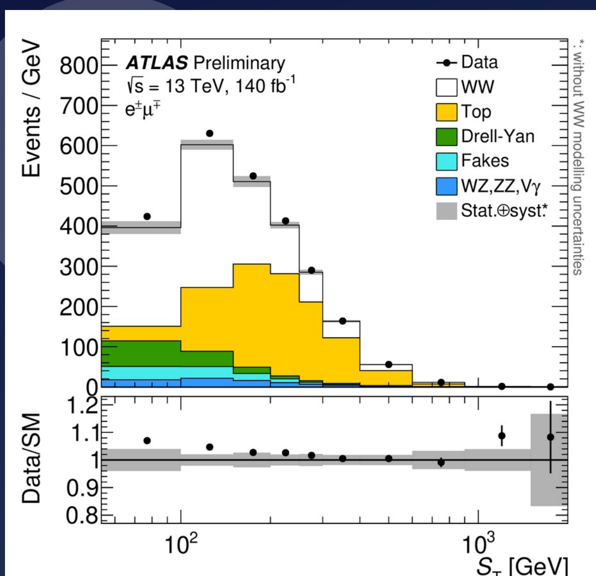
Inclusive WW production

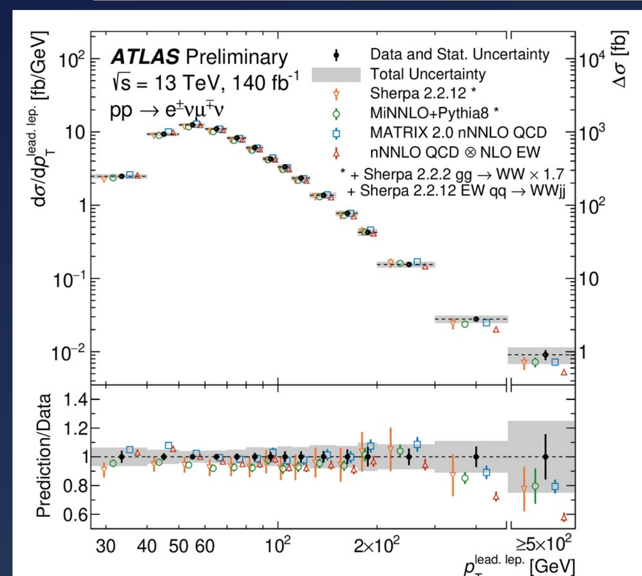
Most precise measurement of inclusive and differential cross sections at 13 TeV

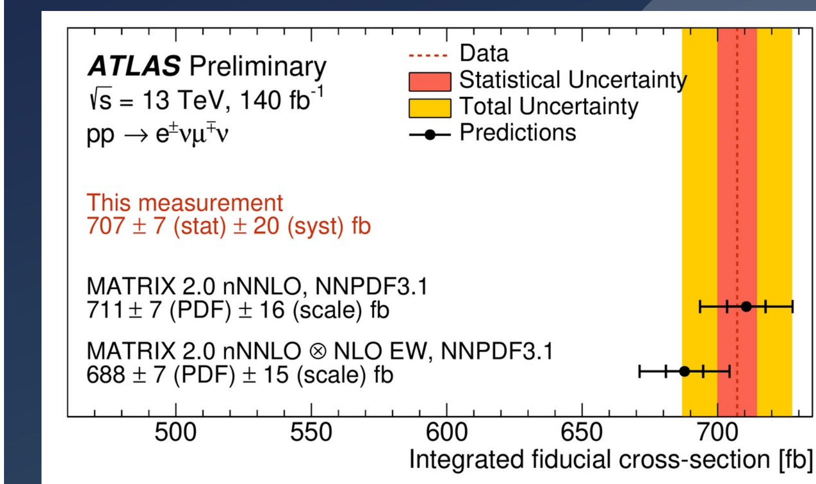
W+W− -> e± ν μ ∓ ν channel

Improved control on uncertainty in dominant background from $t\bar{t}$ production



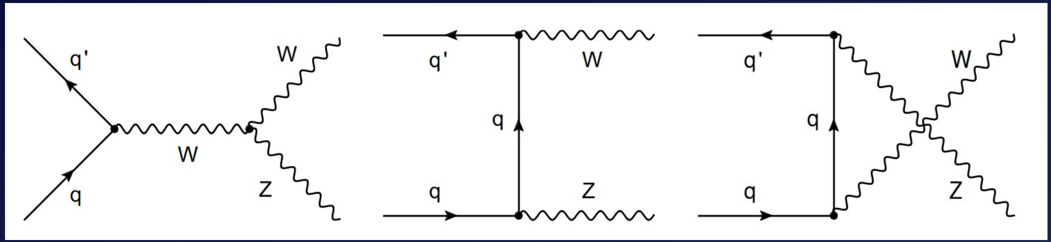




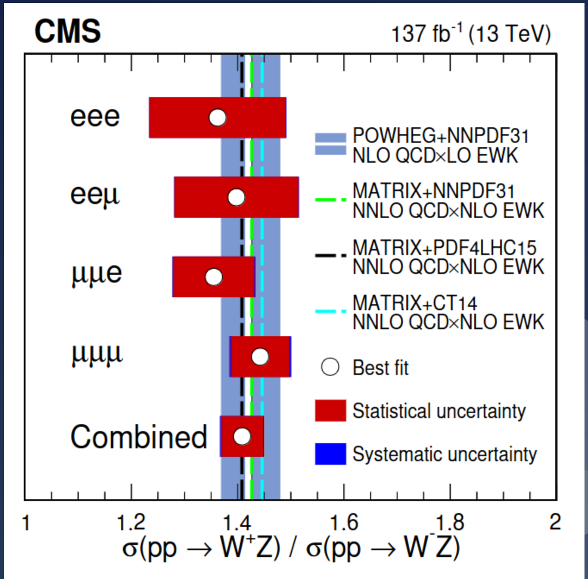


- Fixed-order nNNLO QCD in excellent agreement with the measured total cross-section
- PS matched predictions better describe regions with small p_T or high jet activity

$W^{\pm}Z$ process and (logitudinal) polarization

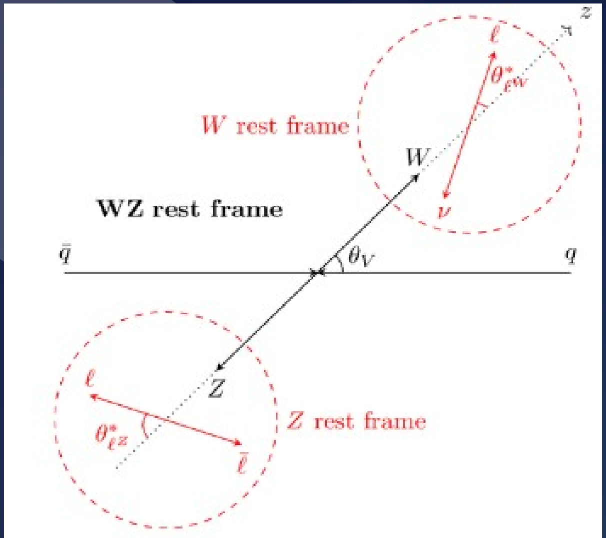


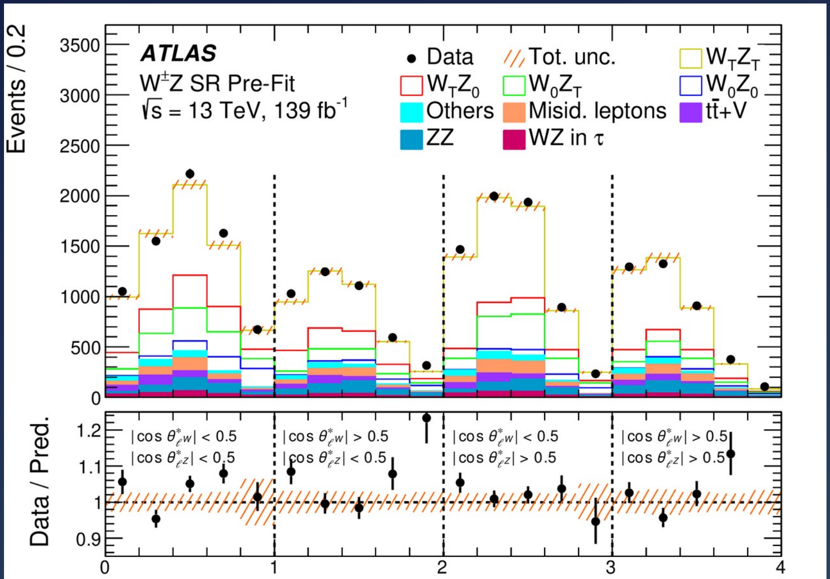
CMS JHEP 07 (2022) 032



EW process sensitive to the u,d PDFs, little dependence on gluon

- Another sensitive test of SM and anom, couplings
- High WZ cross section enables use of 3-lepton final states
- W^+Z/W^-Z xs ratio is precisely measurable
- First observations: W (CMS) and WZ polarizations (ATLAS) in WZ





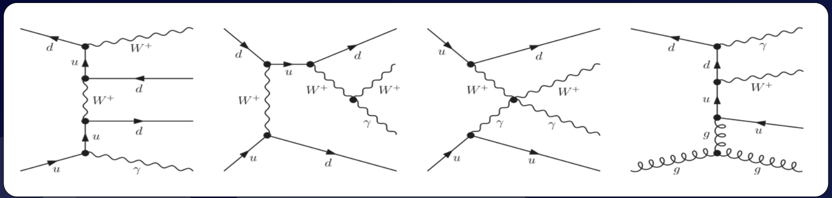
ATLAS STDM-2022-01

<= First Observation of $W_L Z_L$ state: 7.1 (6.2)σ in observation (expectation)

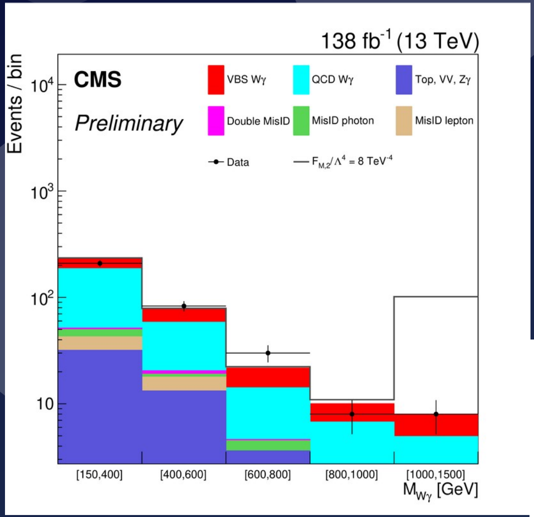
See also new result on evidence of longitudinal polarization in ZZ ATLAS-CONF-2023-038

CMS-SMP-21-011

EW Wγjj measurement



Fiducial and differential cross sections measured



The EW measurement provides stringent constraints on aQGC dim-8 parameters in EFT.

Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	2.7
$-3.3 < f_{M,4}/\Lambda^4 < 3.3$	$-3.7 < f_{M,4}/\Lambda^4 < 3.6$	2.3
$-3.4 < f_{M,5}/\Lambda^4 < 3.6$	$-3.9 < f_{M,5}/\Lambda^4 < 3.9$	2.7
$-13 < f_{M,7}/\Lambda^4 < 13$	$-14 < f_{M7}/\Lambda^4 < 14$	2.2
$-0.43 < f_{T,0}/\Lambda^4 < 0.51$	$-0.47 < f_{T,0}/\Lambda^4 < 0.51$	1.9
$-0.27 < f_{T,1}/\Lambda^4 < 0.31$	$-0.31 < f_{T,1}/\Lambda^4 < 0.34$	2.5
$-0.72 < f_{T,2}/\Lambda^4 < 0.92$	$-0.85 < f_{T,2}/\Lambda^4 < 1.0$	2.3
$-0.29 < f_{T,5}/\Lambda^4 < 0.31$	$-0.31 < f_{T,5}/\Lambda^4 < 0.33$	2.6
$-0.23 < f_{T,6}/\Lambda^4 < 0.25$	$-0.25 < f_{T,6}/\Lambda^4 < 0.27$	2.9
$-0.60 < f_{T,7}/\Lambda^4 < 0.68$	$-0.67 < f_{T,7}/\Lambda^4 < 0.73$	3.1

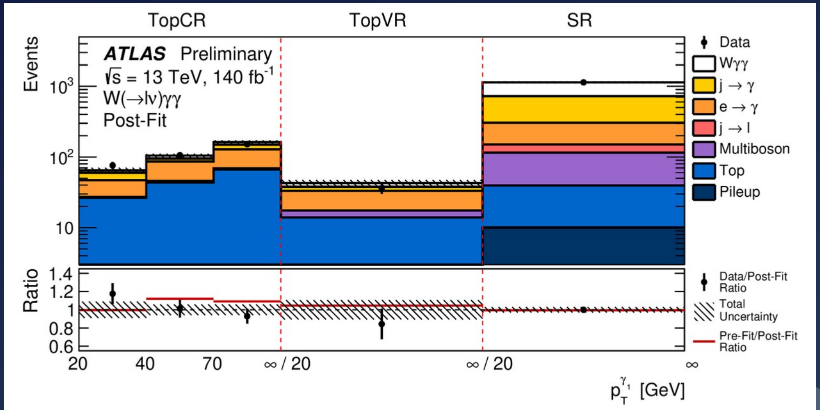
Red boxes show best overall limits.

ATLAS-CONF-2023-005 ATLAS-CONF-2023-014

Wγγ and WZγ first observations

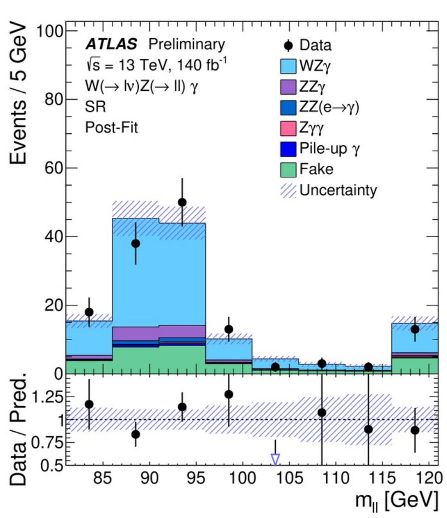
Wγγ observed with 5.6 σ

$\sigma_{fid}=12.1^{+2.5}_{-2.2}$ fb



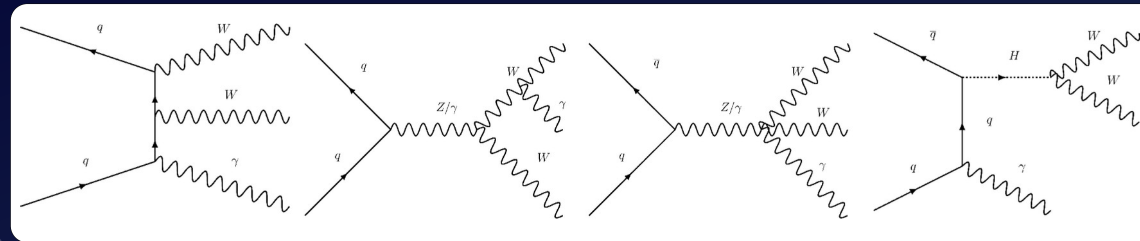
WZγ observed with 6.3 σ

$\sigma_{WZ\gamma}$ = 2.01 ± 0.30(st) ± 0.16(sys) fb



See parallel talks as well

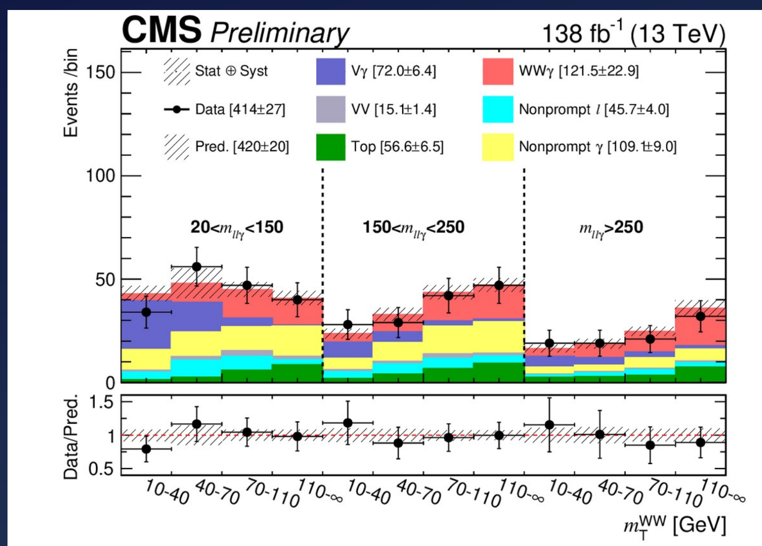
CMS WWγ



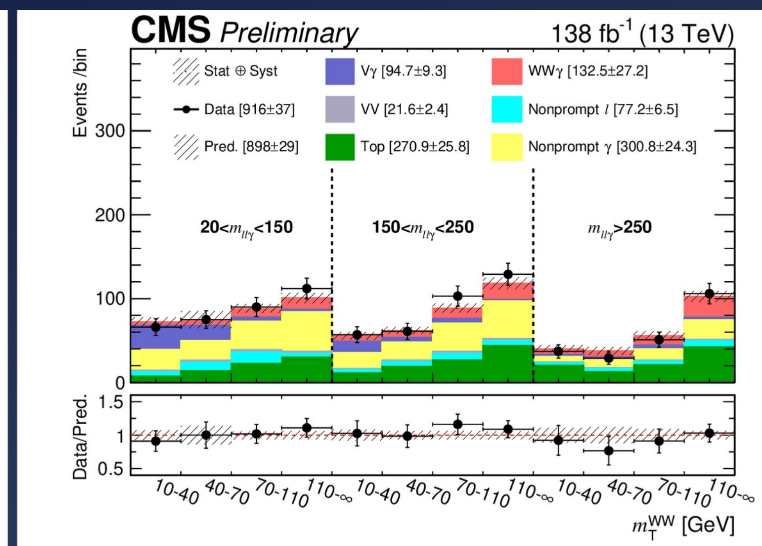
Triboson production sensitive to both triple and quartic gauge couplings (TGCs and QGCs)

Extract signal using 2D fit to m_T(WW) and m(ℓℓγ)
and control regions especially to constrain ssWWγ and topγ backgrounds

0 jet subsample



1 jet subsample



First observation of WWγ production at LHC, significance 5.6 (4.7) sigma
The measured σWWγ= is 6.0 ± 1.7 fb is in good agreement with NLO QCD
μobs.= 1.31 ± 0.17 (stat) ± 0.21 (syst)

Summary

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We are making first observations of many tri-boson processes, tightening limits on EFT extensions, and sailing on to ever more rare and multi-faceted observables

Many more results that could not be presented in the time allotted, see ATLAS and CMS public results pages for comprehensive lists

Every first observation is a new laboratory to test the self consistency of the SM and to search for (in)direct evidence of NP…

Whither these lead us, time will tell