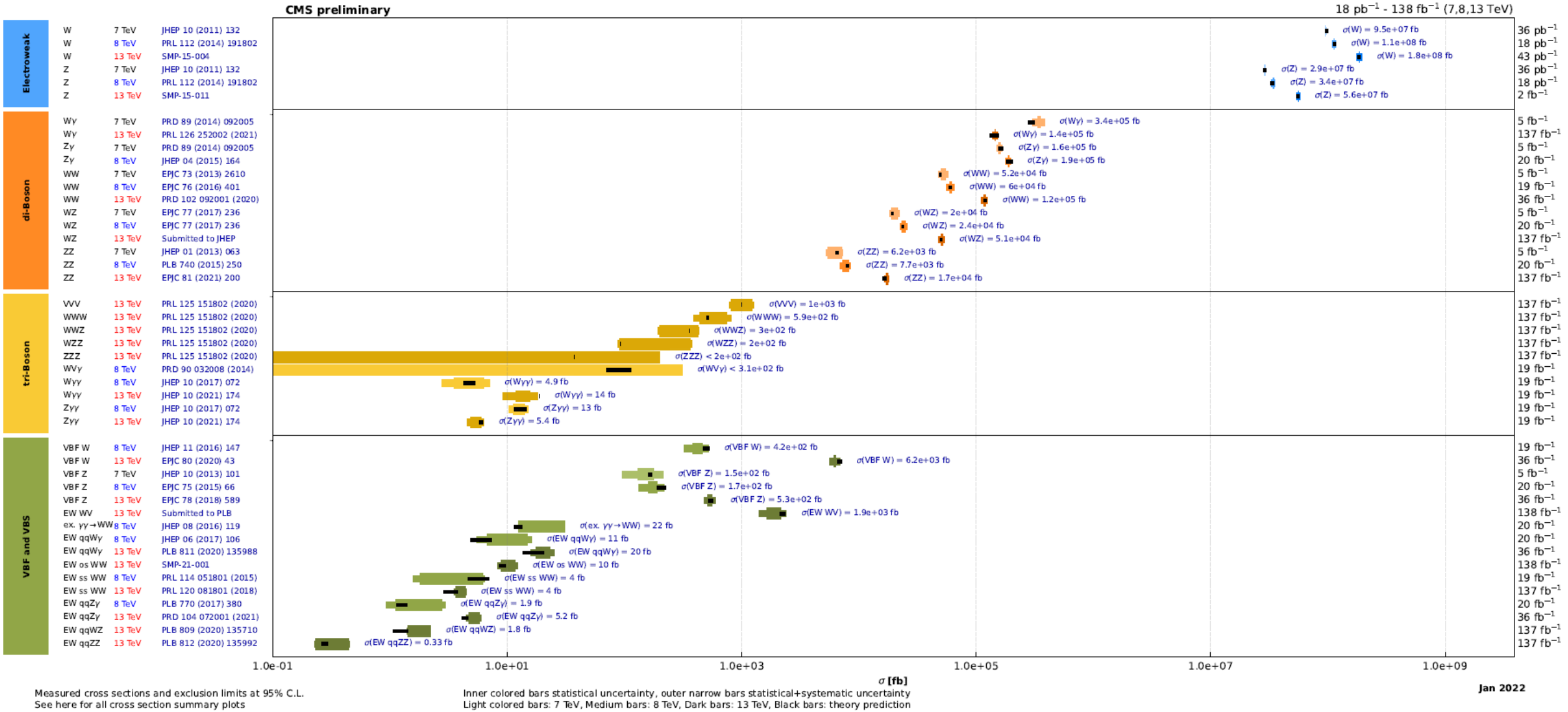
Grant PID2020-113341RB-100 funded by

Recent SM measurements with the CMS detector

Santiago Folgueras on behalf of the CMS collaboration

Overview of CMS cross section results



Measured cross sections and exclusion limits at 95% C.L.
See here for all cross section summary plots

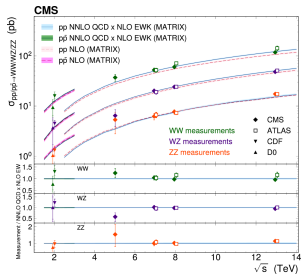
Inner colored bars statistical uncertainty, outer narrow bars statistical+systematic uncertainty
Light colored bars: 7 TeV, Medium bars: 8 TeV, Dark bars: 13 TeV, Black bars: theory prediction

Recent results in Standard Model measurements?

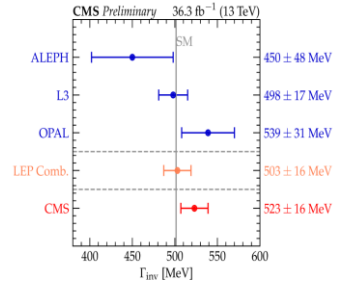
My personal choice for today

Talk is focused on EWK physics, some topics have already been covered by A. Piccinelli (VBS) and A. Mecca (Dibosons)

CMS-SMP-20-012



CMS-PAS-SMP-18-014



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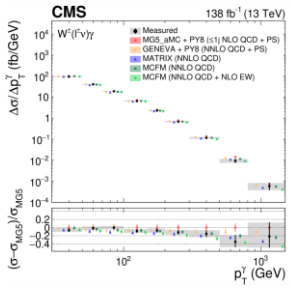

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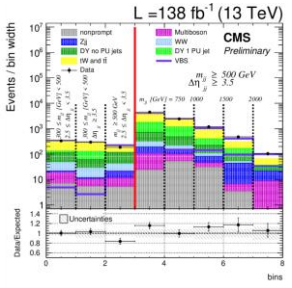

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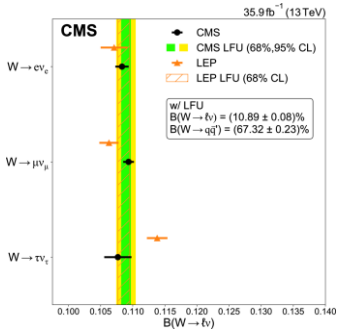
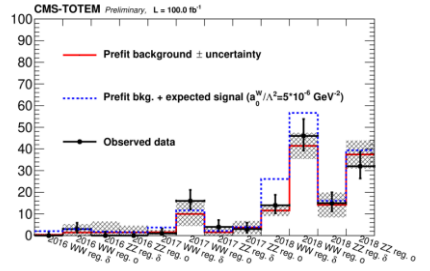
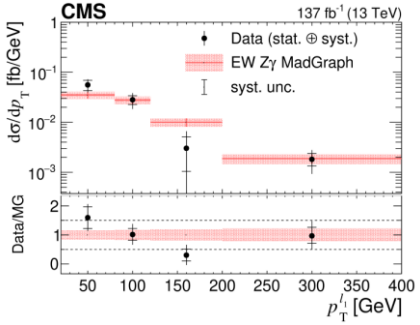


CMS-PAS-SMP-21-014



Jul 21 | Sep 21 | Nov 21 | Jan 22 | Mar 22

Jun 21



CMS-SMP-20-016

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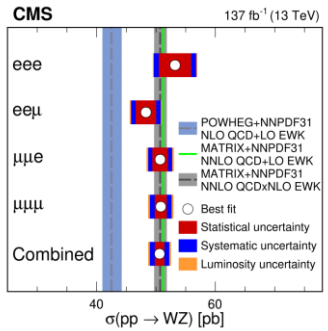
Oct 21



CMS-SMP-20-014

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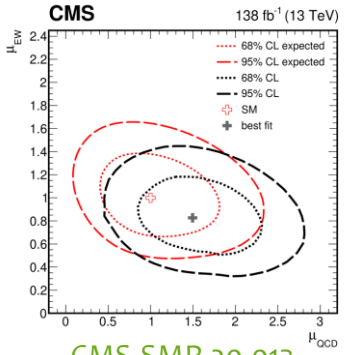
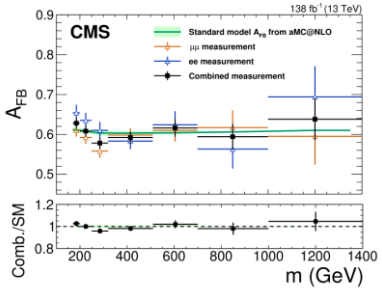


CMS-SMP-20-013

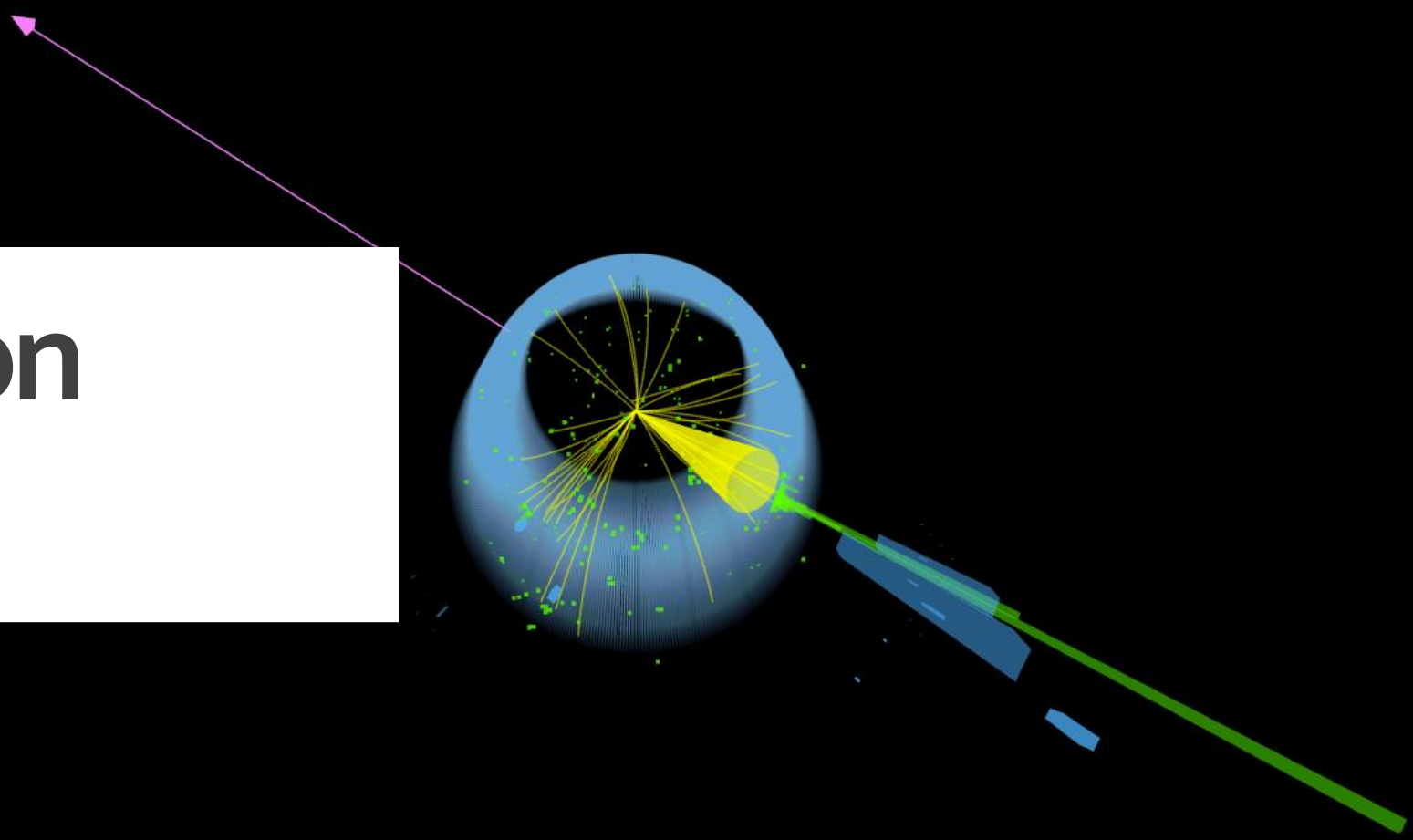
Feb 22



CMS-SMP-21-002

http://cms-results.web.cern.ch/cms-results/public-results/publications/SMP/index.html

W and Z boson properties



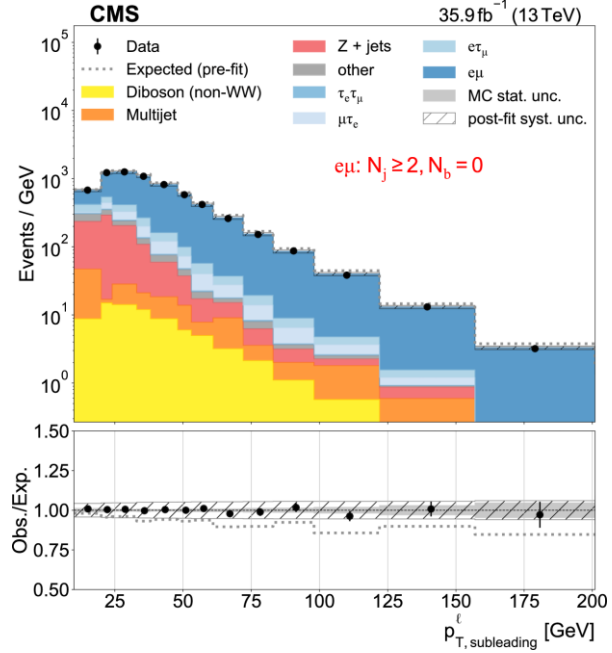
High precision measurements

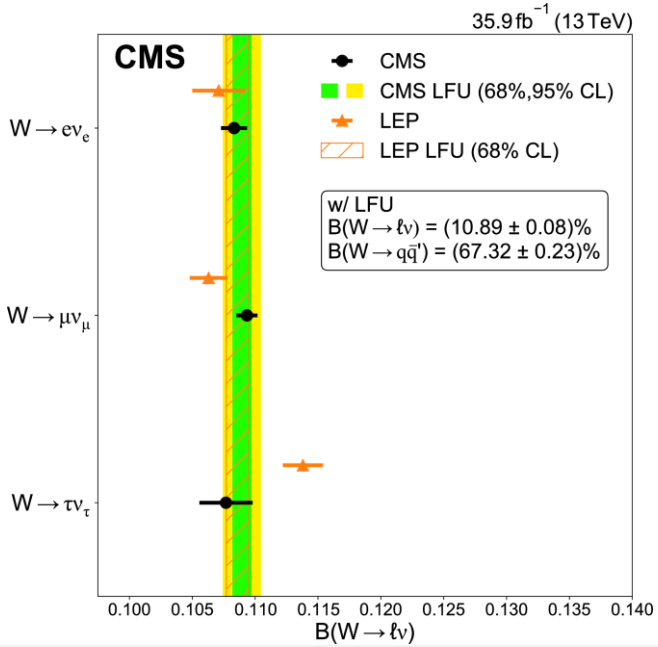
W decay branching fractions

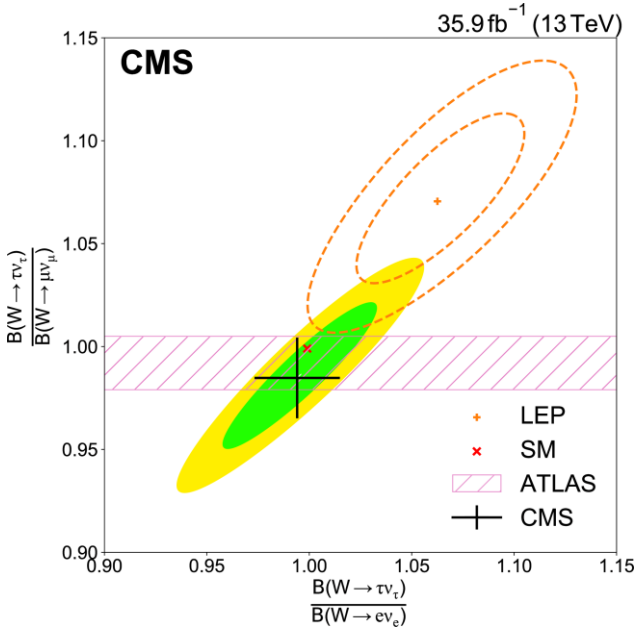
- All charged leptons (e, μ, τ) couple to W boson with identical branching ratio
- **LEP reported 2.6σ tension between τ and e/μ**
  - BR of W to electrons and muons agree well
- **Using $t\bar{t}$, tW, WW, W + jets to study W decay BR**
  - Trailing lepton p_T used to discriminate between prompt $W \to e/\mu$ decays and τ lepton in ee, $\mu\mu$, and $e\mu$
- **Measured BR of individual lepton flavours**
  - Systematic uncertainties comparable to LEP
  - Assuming lepton universality $(10.89 \pm 0.01 \pm 0.08)\%$

	CMS	LEP
$\mathcal{B}(W \to e\bar{\nu}_e)$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)$ %
$\mathcal{B}(W \to \mu\bar{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)$ %
$\mathcal{B}(W \to \tau\bar{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)$ %
$\mathcal{B}(W \to q\bar{q}')$	$(67.46 \pm 0.04 \pm 0.28)\%$	—

	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	—	—	—	—
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	—	—	—
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	—	—	—	—



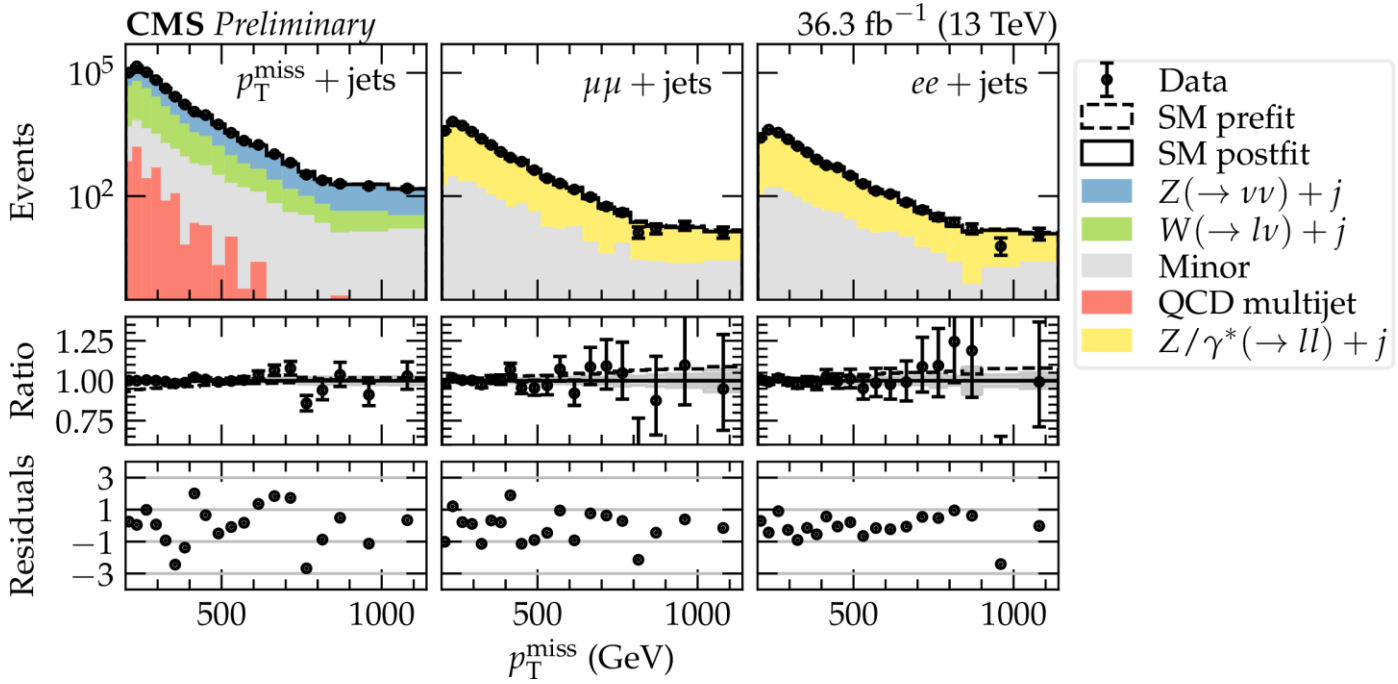


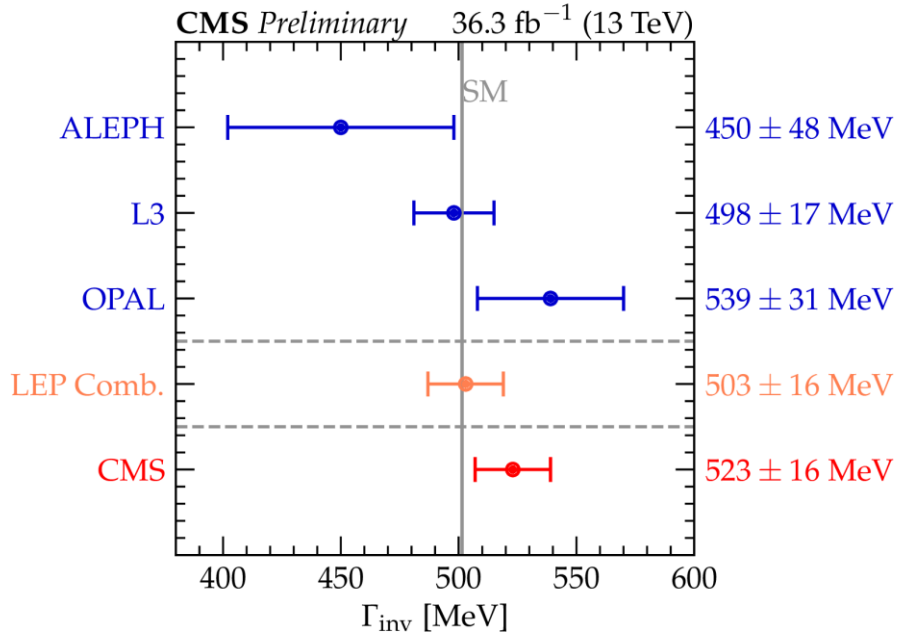


Precision measurement of the Z invisible width

- **First measurement of Z invisible width at a hadron collider**
  - Sensitivity to the number of neutrinos coupling to Z boson
  - Ratio $\sigma(Z \to \nu\nu)/\sigma(Z \to \ell\ell)$ interpreted as Γ_{inv}
- **Competitive precision with direct LEP measurements**

$$\frac{\sigma(Z \to \nu\nu)}{\sigma(Z \to \ell\ell)} = \frac{\Gamma(Z \to \nu\nu)}{\Gamma(Z \to \ell\ell)}$$

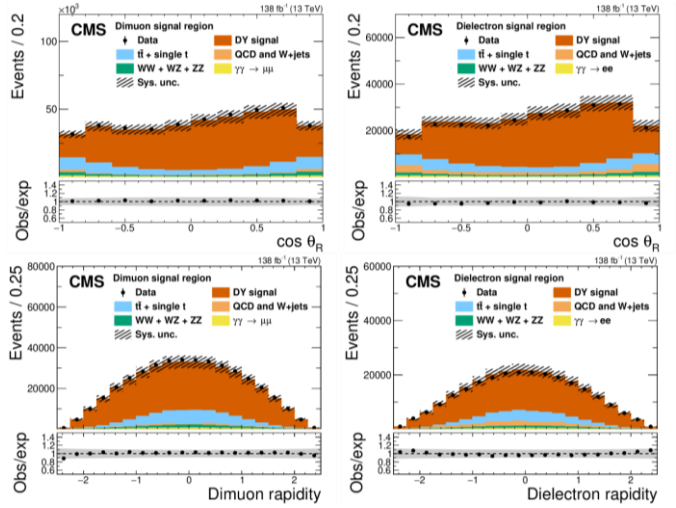


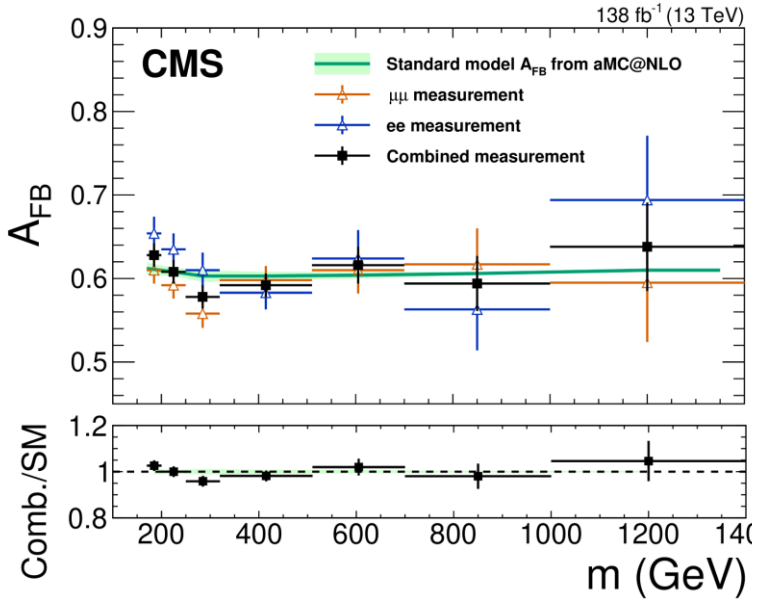


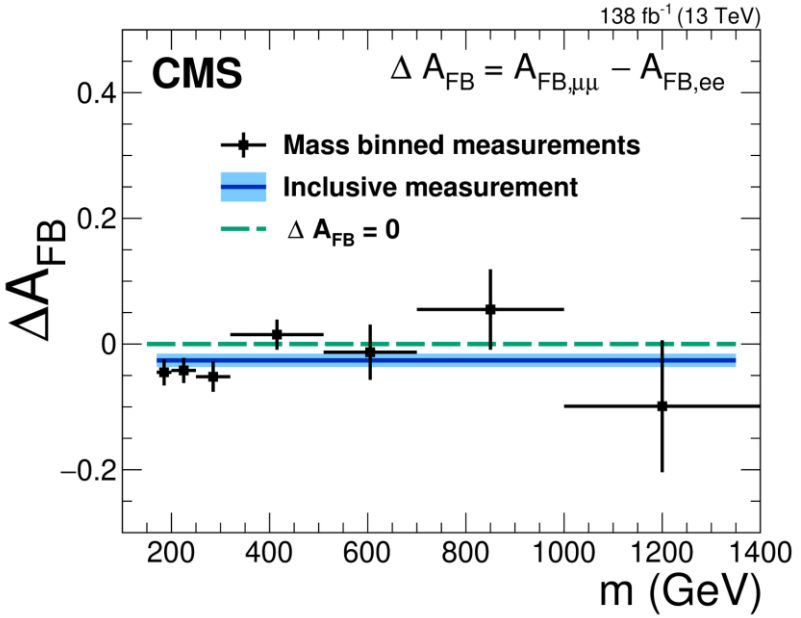
CMS-PAS-SMP-18-014 (*soon to be submitted*)

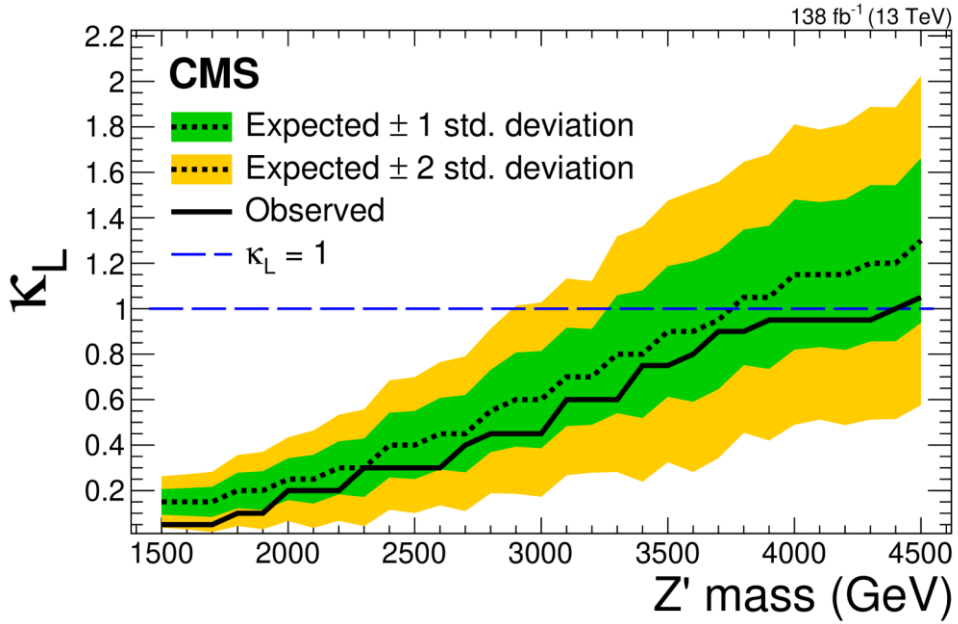
Measurement of Drell-Yan A_{FB} at high dilepton masses

- **CMS A_{FB} measurement for $m_{ll} > 170$ GeV**
  - A_{FB} non-zero and positive above Z-peak due to interference
  - Sensitive to BSM through interference with heavy vector boson
- **A_{FB} for ee and μμ allows to test lepton universality**
  - In the inclusive ΔA_{FB}, e/μ are found to deviate at 2.4σ

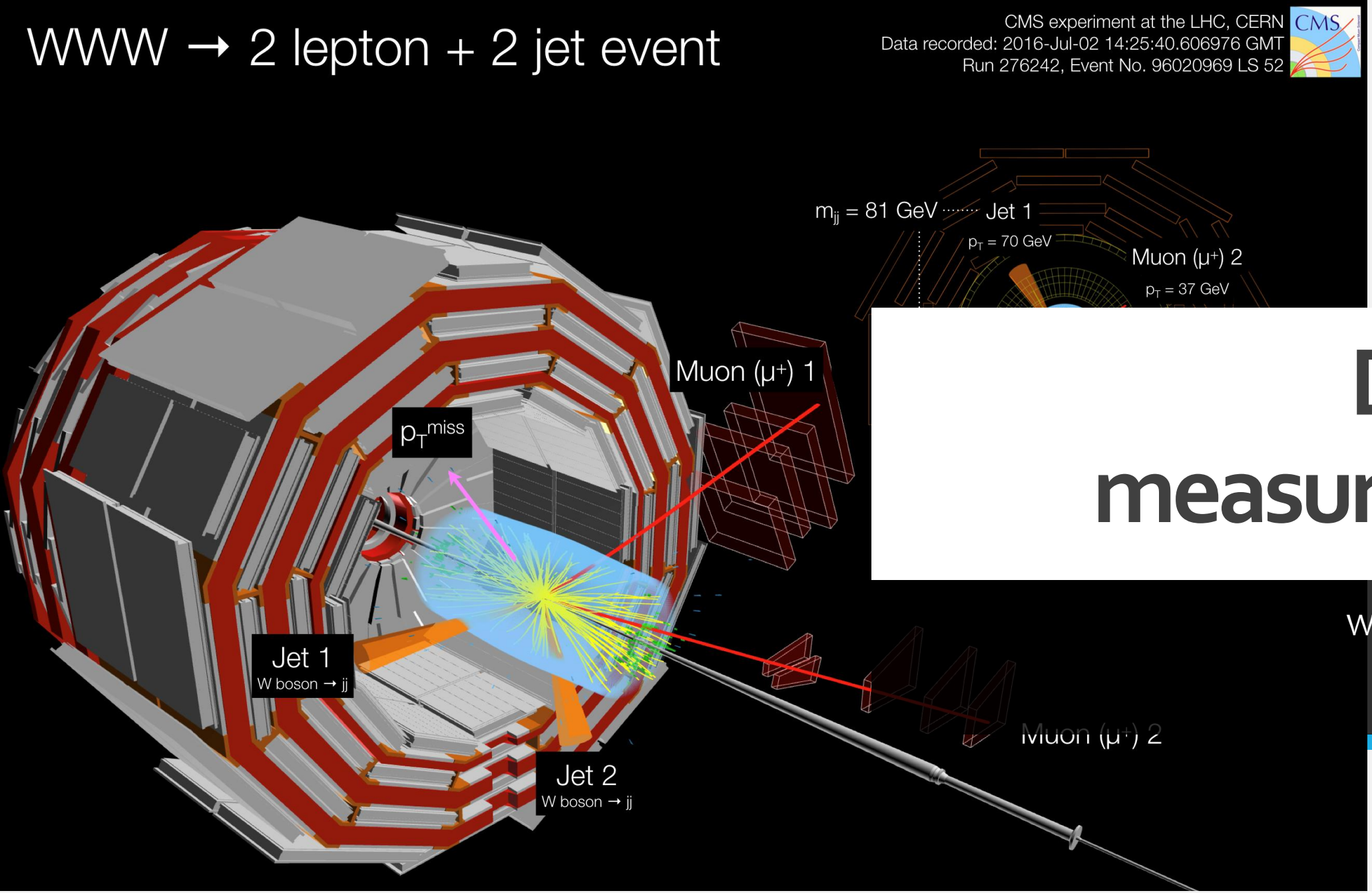








arXiv:2202.12327 submitted to JHEP



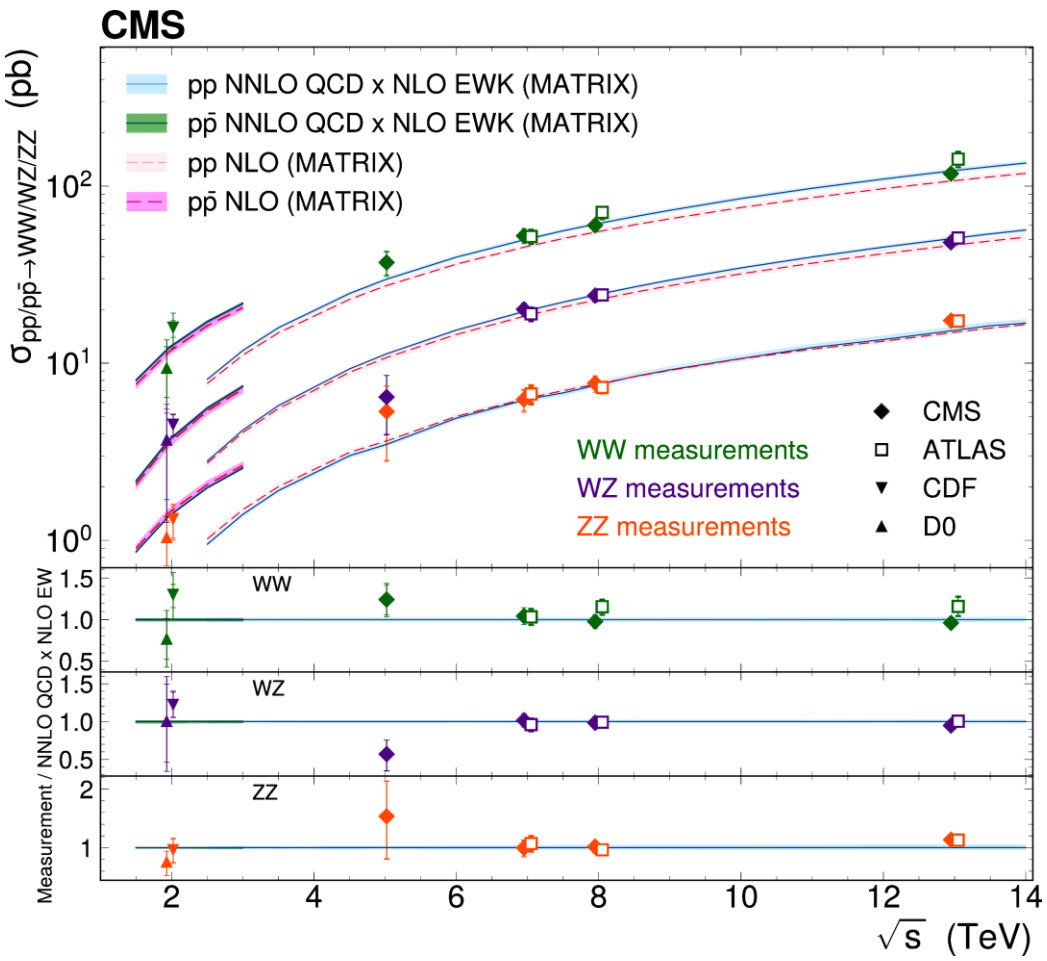
Diboson measurements

WW, WZ, ZZ, Wγ and Zγ

Diboson production cross sections in pp collisions at $\sqrt{s} = 5.02$ TeV

- Very Low pile-up run, important probe of the dependence of the cross section on the beam energy
- Dedicated signal regions for each diboson production:
  - WW: two opposite-charge different-flavour leptons
  - WZ: 3ℓ + two same-sign leptons
  - ZZ: 4ℓ + 2ℓ + 2ν
- **First measurement at 5.02 GeV**
  - Consistent with NNLO QCD + NLO EWK predictions

Process	Estimation	Total cross section [pb]
WW	MATRIX	$29.8^{+0.7}_{-0.6}(\text{scale})$
	Measured	$37.0^{+5.5}_{-5.2}\,(\text{stat})^{+2.7}_{-2.6}\,(\text{syst})$
WZ	MATRIX	$11.3^{+0.2}_{-0.2}(\text{scale})$
	Measured	$6.4^{+2.5}_{-2.1}\,(\text{stat})^{+0.5}_{-0.3}\,(\text{syst})$
ZZ	MATRIX	$3.9^{+0.1}_{-0.1}(\text{scale})$
	Measured	$5.3^{+2.5}_{-2.1}\,(\text{stat})^{+0.5}_{-0.4}\,(\text{syst})$



Phys. Rev. Lett. 127 (2021) 191801

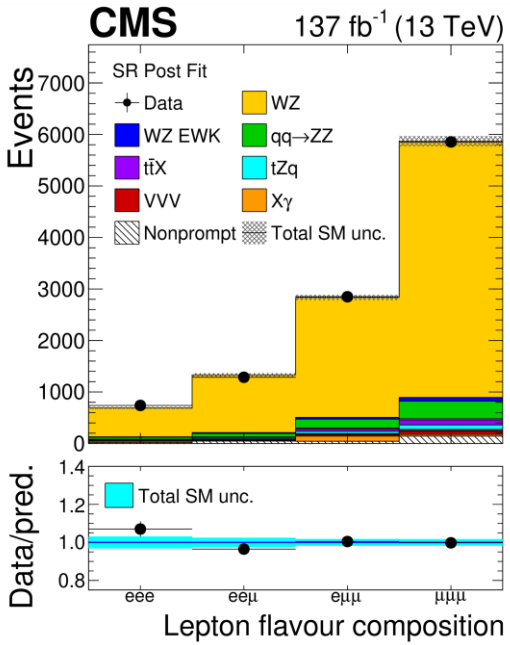
Leptonic WZ production (I)

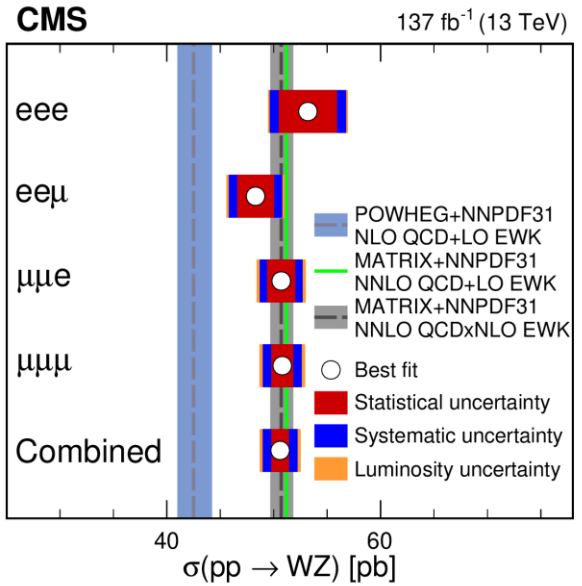
- **Very clean final state that allowed to perform several relevant SM measurements**
- **Cross-section measurement**
  - Fit to lepton flavour distribution performed in CRs + SR
  - Signal strength estimated both for each final state and inclusively
  - Cross-section measurement extrapolated from SR to a Fiducial (detector-independent) Region
  - Inclusive cross-section:

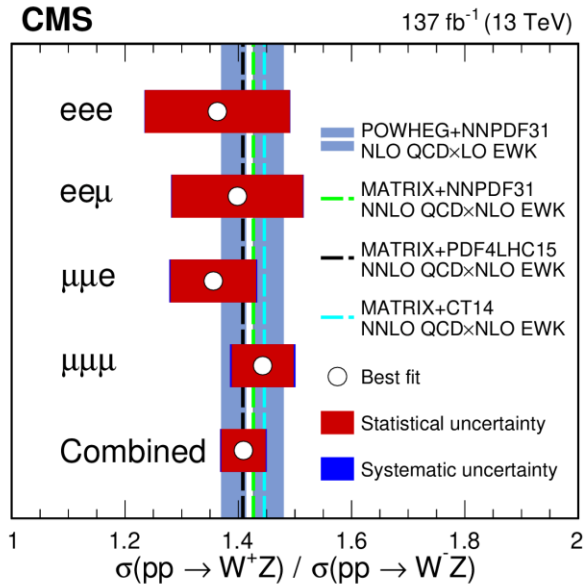
Category or source	Total cross section
POWHEG	$42.5\ ^{+1.6}_{-1.4}(\text{scale}) \pm 0.6(\text{PDF})$ pb
MATRIX, NNLO QCD	$51.2\ ^{+1.2}_{-1.0}(\text{scale})$ pb
MATRIX, NNLO QCD × NLO EWK	$50.7\ ^{+1.1}_{-1.0}(\text{scale})$ pb
eee (Measured)	$53.2 \pm 2.7\,(\text{stat}) \pm 2.3\,(\text{syst}) \pm 1.1\,(\text{lumi}) \pm 0.5\,(\text{theo})$ pb
eeμ (Measured)	$48.1 \pm 1.7\,(\text{stat}) \pm 1.8\,(\text{syst}) \pm 1.1\,(\text{lumi}) \pm 0.4\,(\text{theo})$ pb
$\mu\mu$e (Measured)	$50.6 \pm 1.3\,(\text{stat}) \pm 1.5\,(\text{syst}) \pm 1.1\,(\text{lumi}) \pm 0.5\,(\text{theo})$ pb
$\mu\mu\mu$ (Measured)	$50.8 \pm 1.0\,(\text{stat}) \pm 1.5\,(\text{syst}) \pm 1.1\,(\text{lumi}) \pm 0.5\,(\text{theo})$ pb
Combined (Measured)	$50.6 \pm 0.8\,(\text{stat}) \pm 1.5\,(\text{syst}) \pm 1.1\,(\text{lumi}) \pm 0.5\,(\text{theo})$ pb

- **Charge asymmetry:**
  - Distributions divided upon final state total charge
  - Consistency with PDF uncertainties verified with Bayesian reweighting techniques with a p-value = 0.747
  - Measured charge asymmetry:

$$A_{WZ}^{\pm} = 1.41 \pm 0.04\ (\text{stat}) \pm 0.01\ (\text{syst}) \pm 0.01\ (\text{lumi})$$



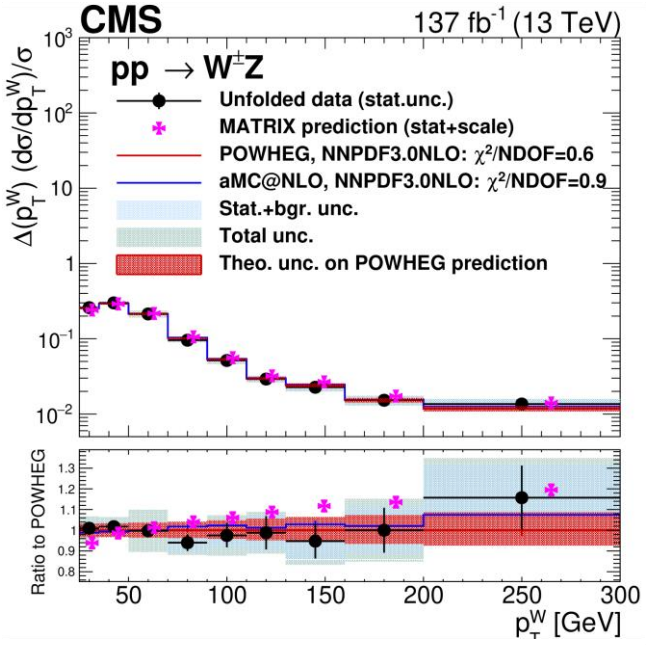


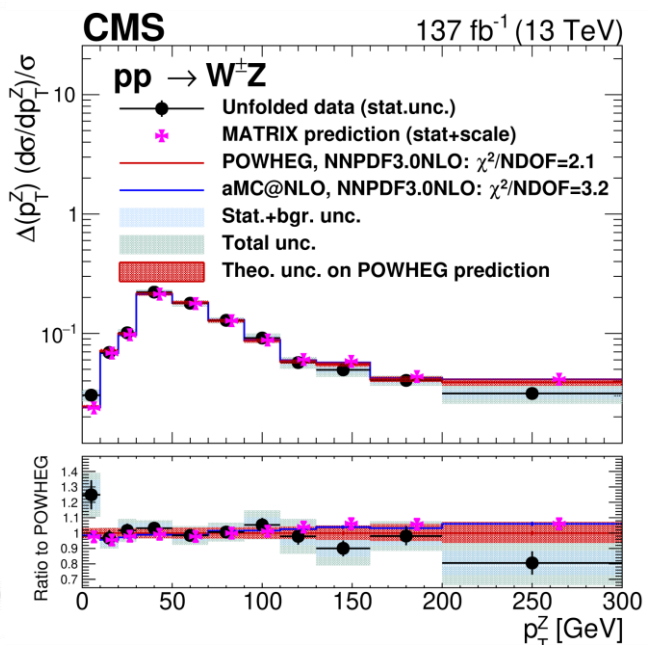


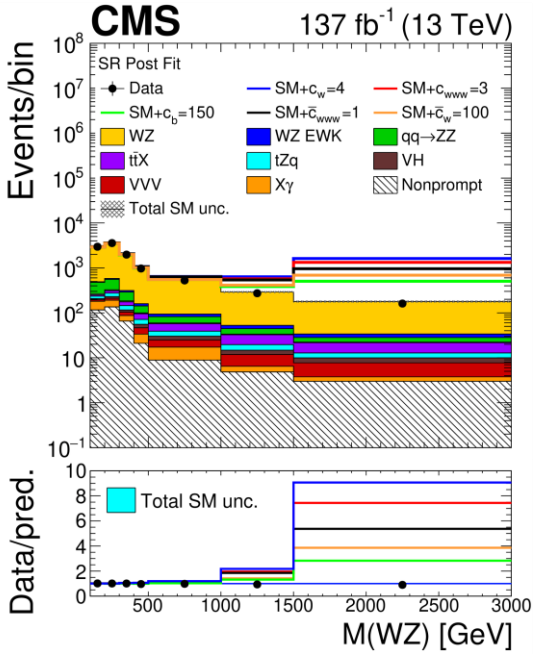
arXiv:2110.11231 (submitted to JHEP) more details in A.Piccinelli's and A. Mecca's talks

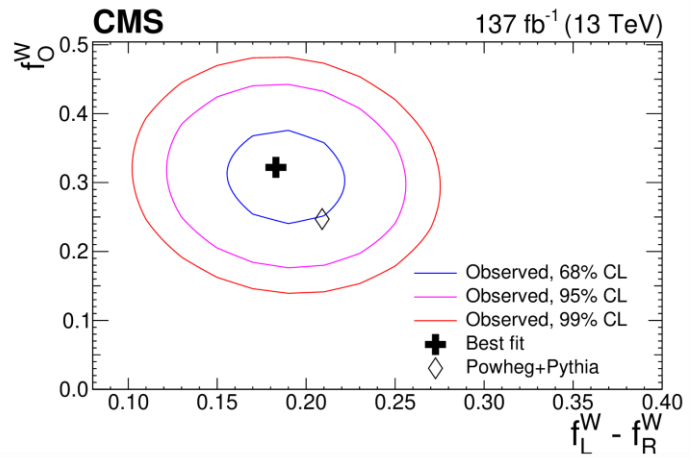
Leptonic WZ production (II)

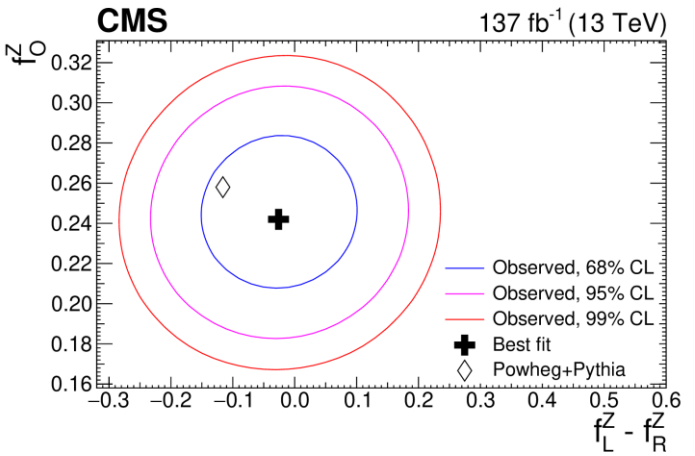
- **First W/Z polarization measured** in the helicity frame
  - Search for BSM-originated anomalies in the spin correlation between the massive boson and its decay products.
  - Simultaneous fit with every polarization: observation of longitudinally polarized W and Z significance 5.6σ and $\gg 5.0\sigma$
- **Differential cross section** in several observables and compared to NLO estimates
  - Separated by charge and inclusive







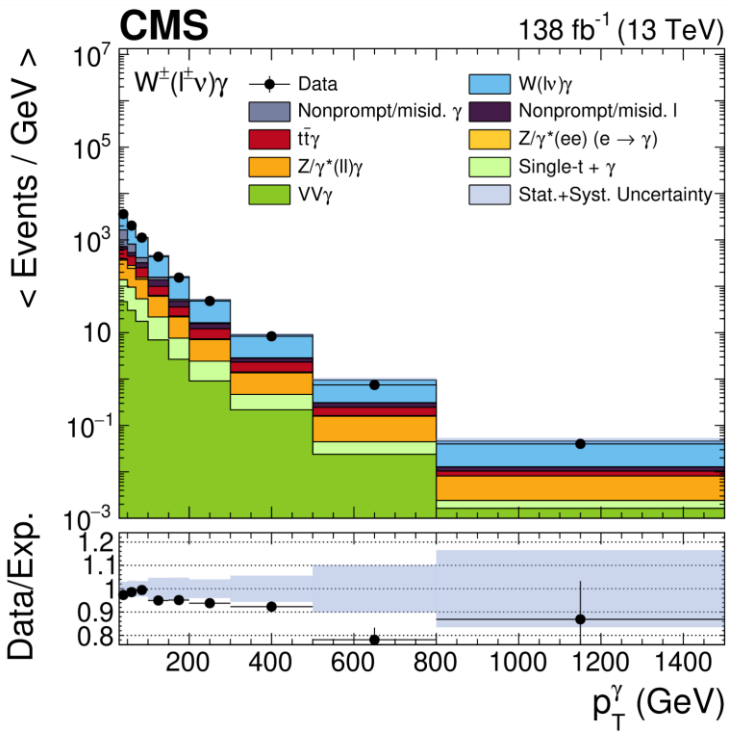


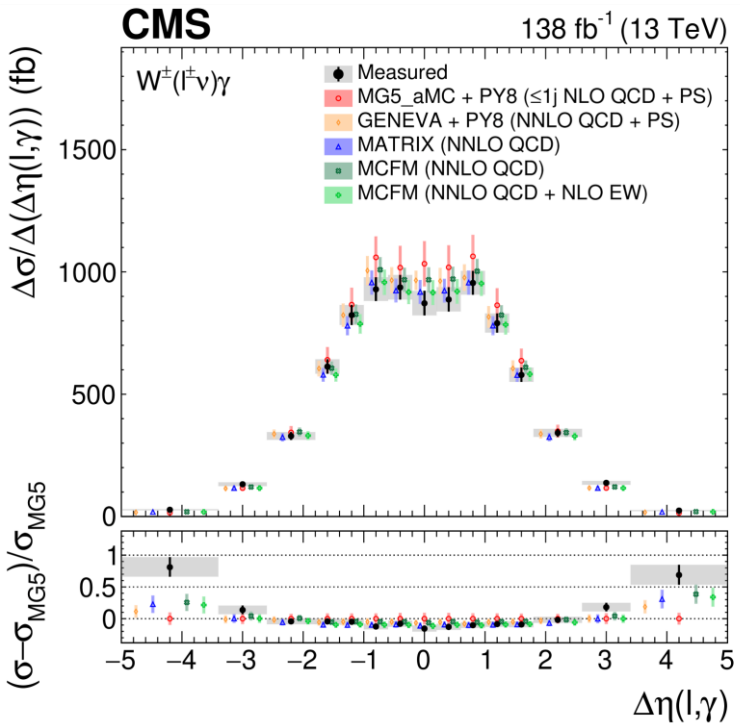


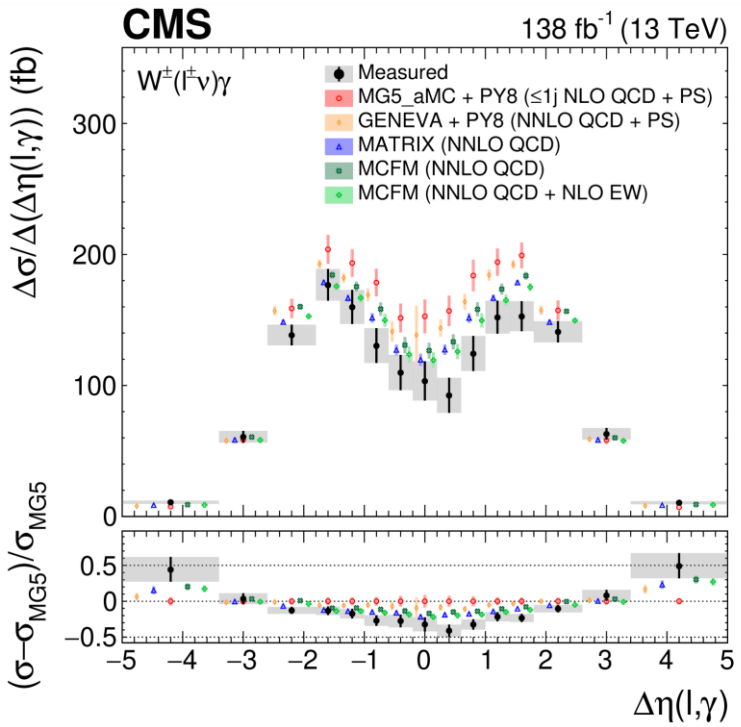
- **Constrains on aTGCs have been also set**
  - Fit to m_{WZ} performed with a joint likelihood function

Wγ differential cross section

- **Full Run 2 measurement** of differential cross-section, compared to NNLO.
- Explore Radiation-zero (RAZ) due to W/γ destructive interference observed in rapidity difference between lepton/γ to test BSM manifestations.
- Good agreement with simulation, more signal in high Δη regions compared to predictions
- Tighter selection to observe the RAZ effect: bigger dip at $\Delta\eta(\ell,\gamma) = 0$ than in NNLO predictions







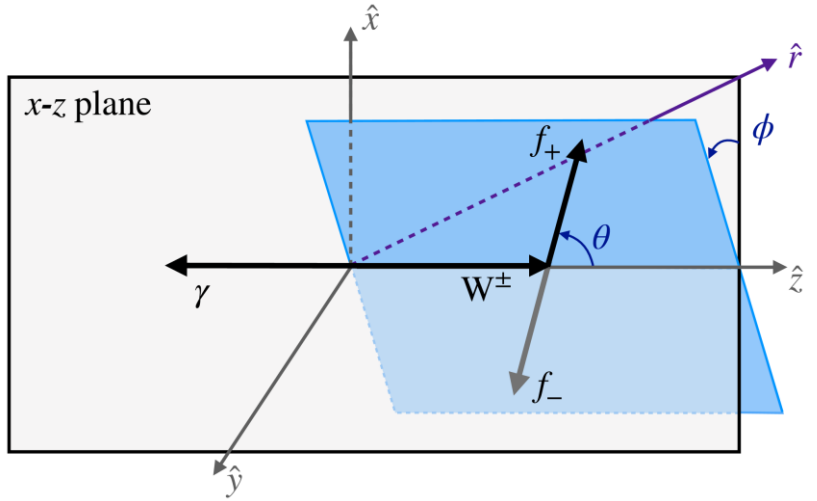
[Phys. Rev. D 105 (2022) 052003]

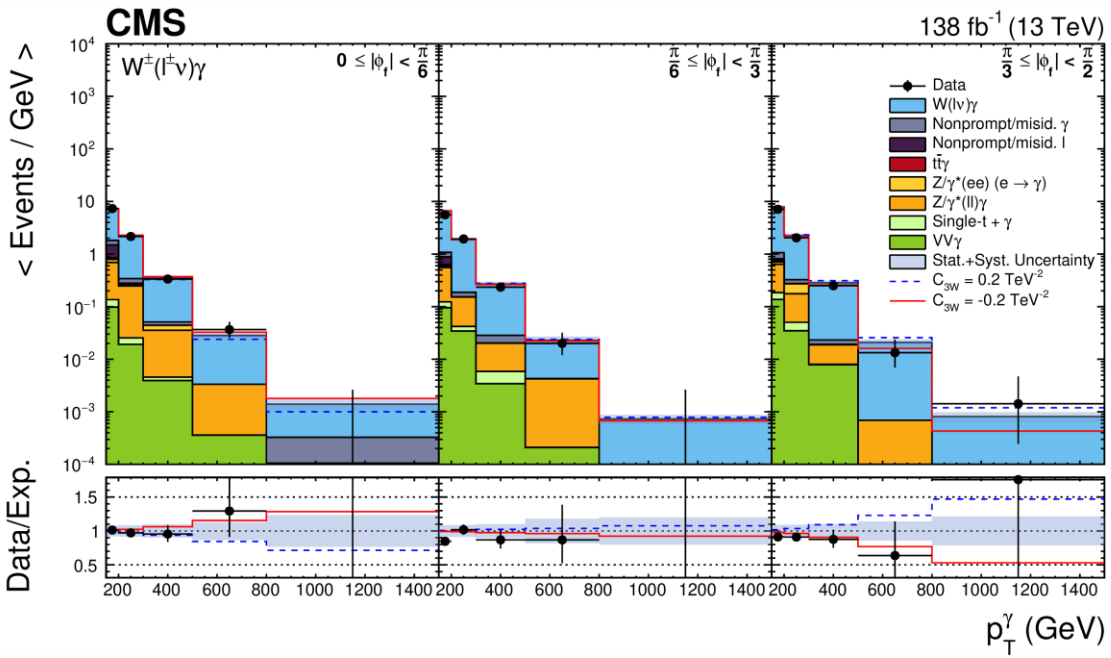
Wγ differential cross section (II): anomalous TGCs

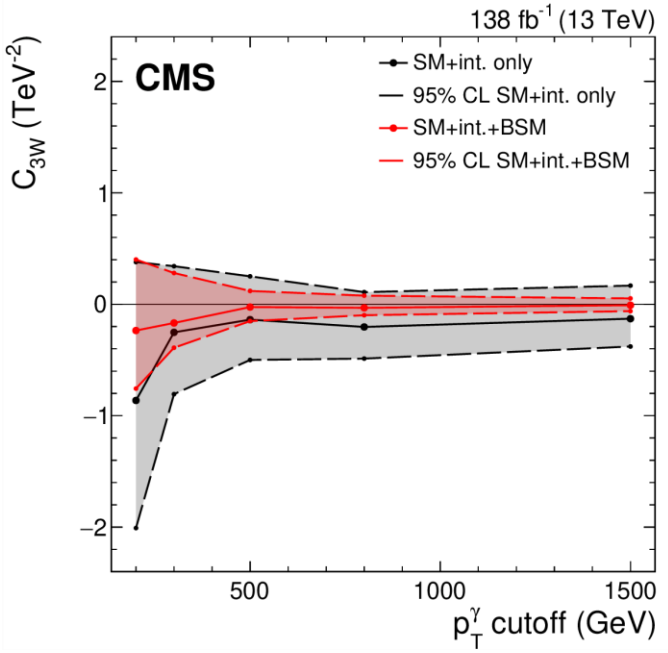
- ϕ variable defined in the Wγ rest frame increases sensitivity (x10) for EFT constraints on dim-6 operators, using **interference resurrection**

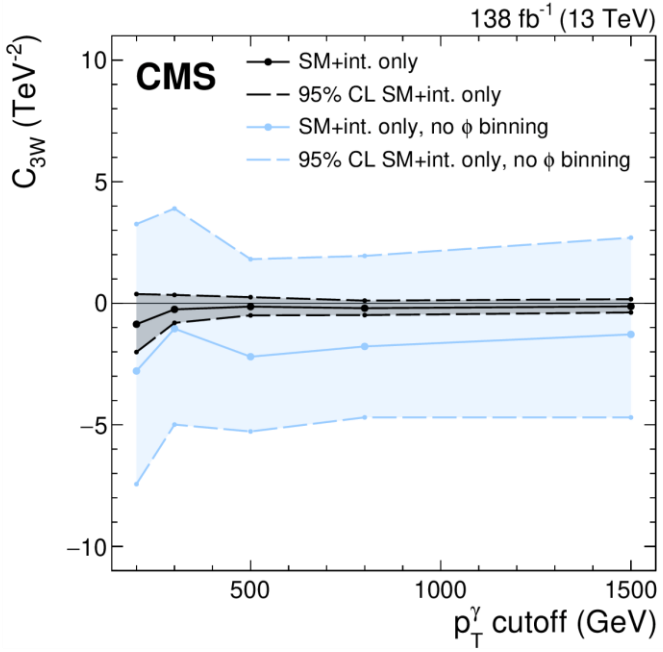
$$\sigma^{tot} = \sigma_{SM} + C_{3W}\sigma_{int} + C_{3W}^2\sigma_{BSM}$$

- At $E > m_W$, SM and BSM have different helicity configurations for angle-inclusive variables insensitive to σ_{int}
  - search in 2D space of $|\phi_f|$ and p_T^γ





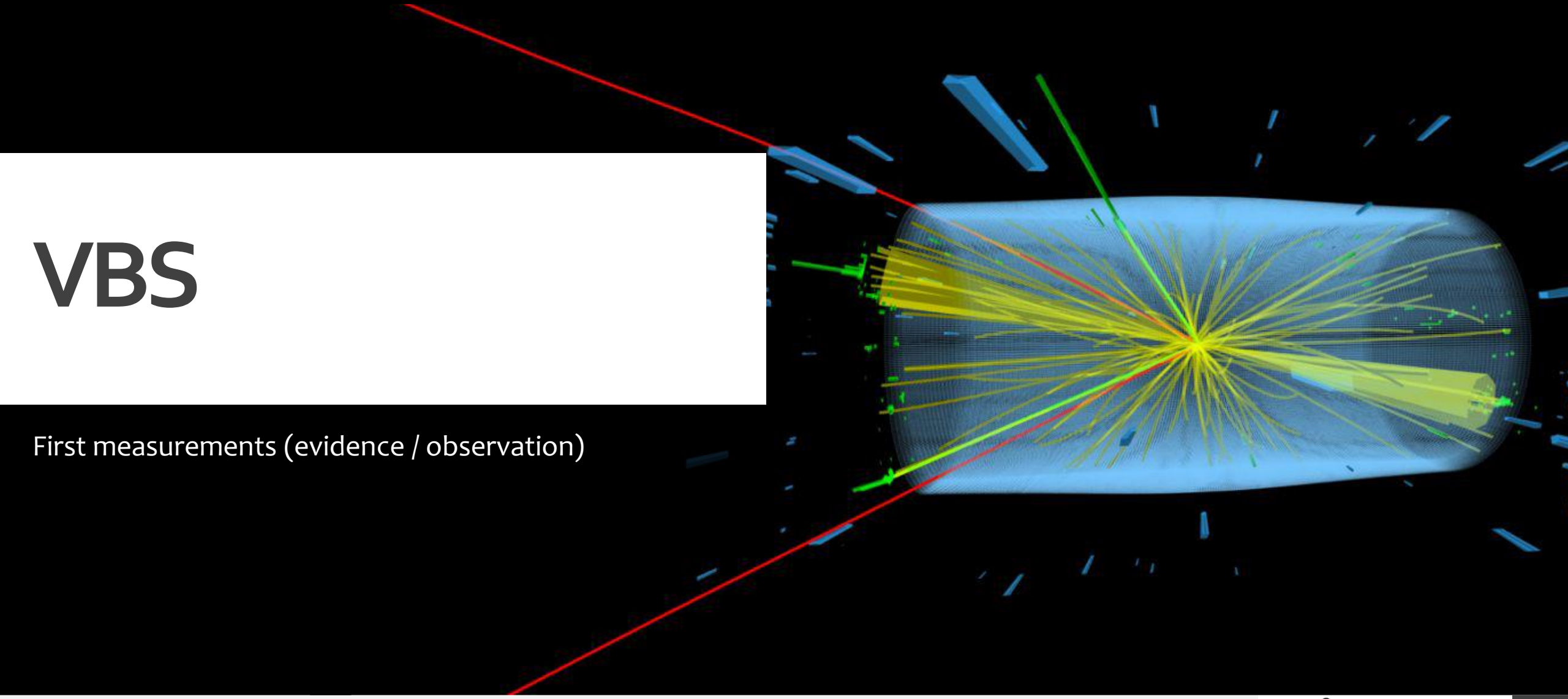




[Phys. Rev. D 105 (2022) 052003]

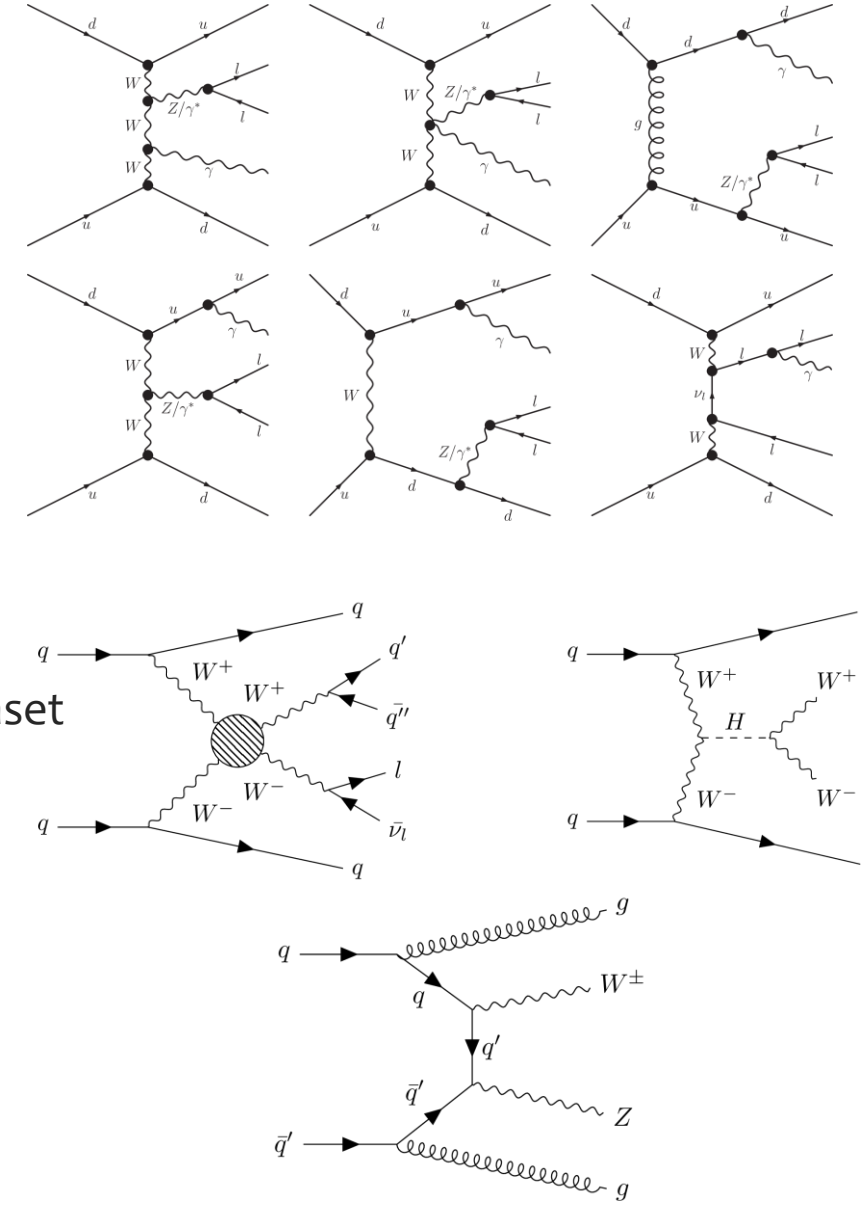
VBS

First measurements (evidence / observation)



VBS production in CMS

- Purely electroweak process with unique topology
  - two very forward jets, with large η separation and invariant mass
- Very rare process (~fb-1) with high irreducible background (from QCD)
  - only accessible with LHC run II
  - sophisticated signal extraction and data driven bkg estimation
- Longitudinal polarized part of V connected to Higgs mechanism
- SM extension with dim-8 operators standing for anomalous couplings
- Big experimental effort to investigate VBS processes with full Run-II dataset
  - Fiducial cross-section measurements
  - Differential cross-section wrt different variables
  - Indirect search for New Physics within the EFT framework
- Different channels depending on decay modes
  - fully leptonic
  - semi leptonic (one V decay leptonically, the other hadronicaly)
  - full hadronic



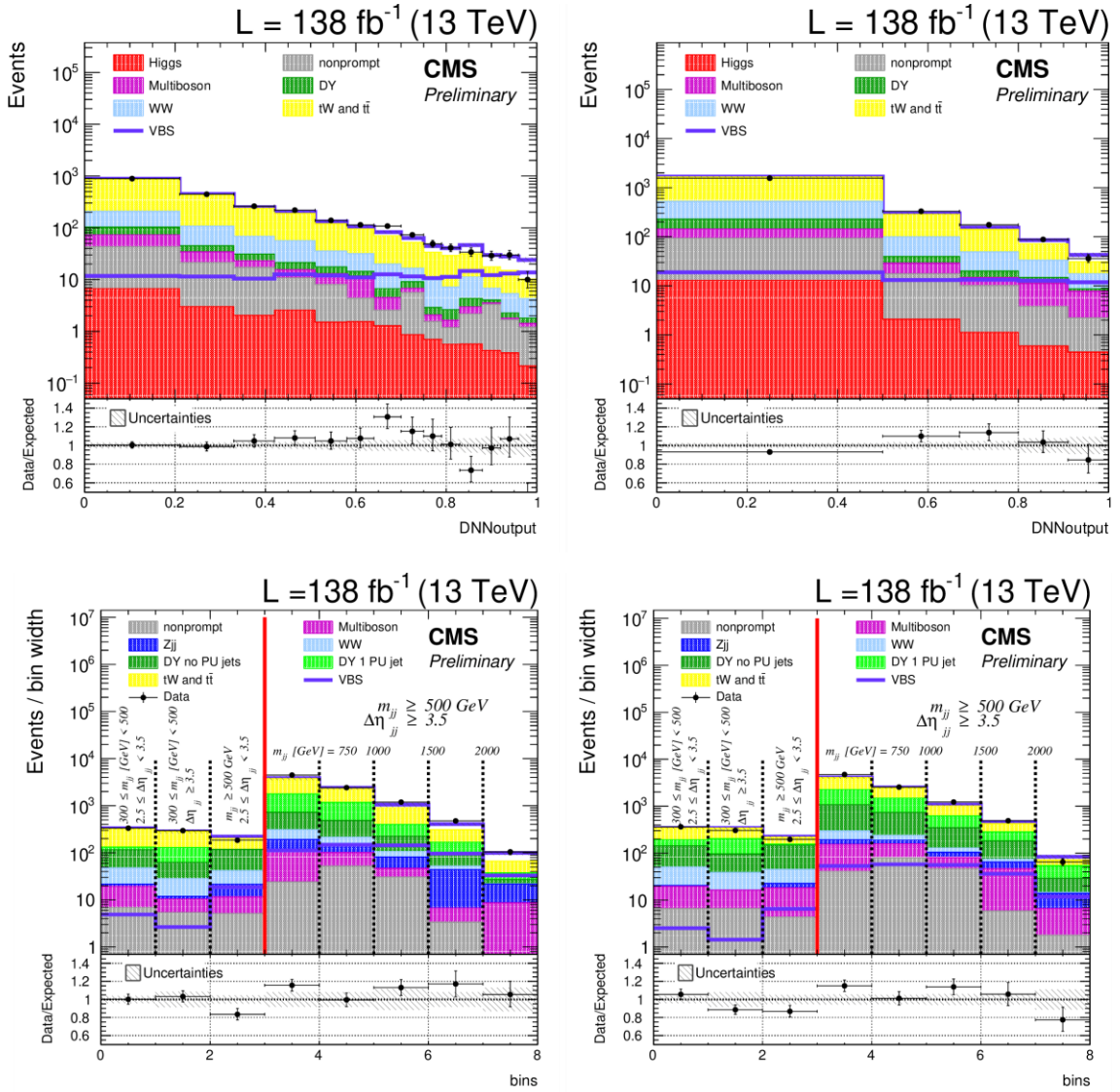
Leptonic W^+W^- scattering

- Events are selected by requiring two leptons (e, μ), two jets with large pseudorapidity separation and high invariant mass.
  - Categorization based on lepton flavour pair and on the centrality of the dilepton system with respect to the tagging jets:

$$Z_{\ell\ell} = \frac{1}{2}\left|Z_{\ell_1} + Z_{\ell_2}\right|, \text{with } Z_\ell = \eta_\ell - \frac{1}{2}(\eta_{j_1} + \eta_{j_2})$$

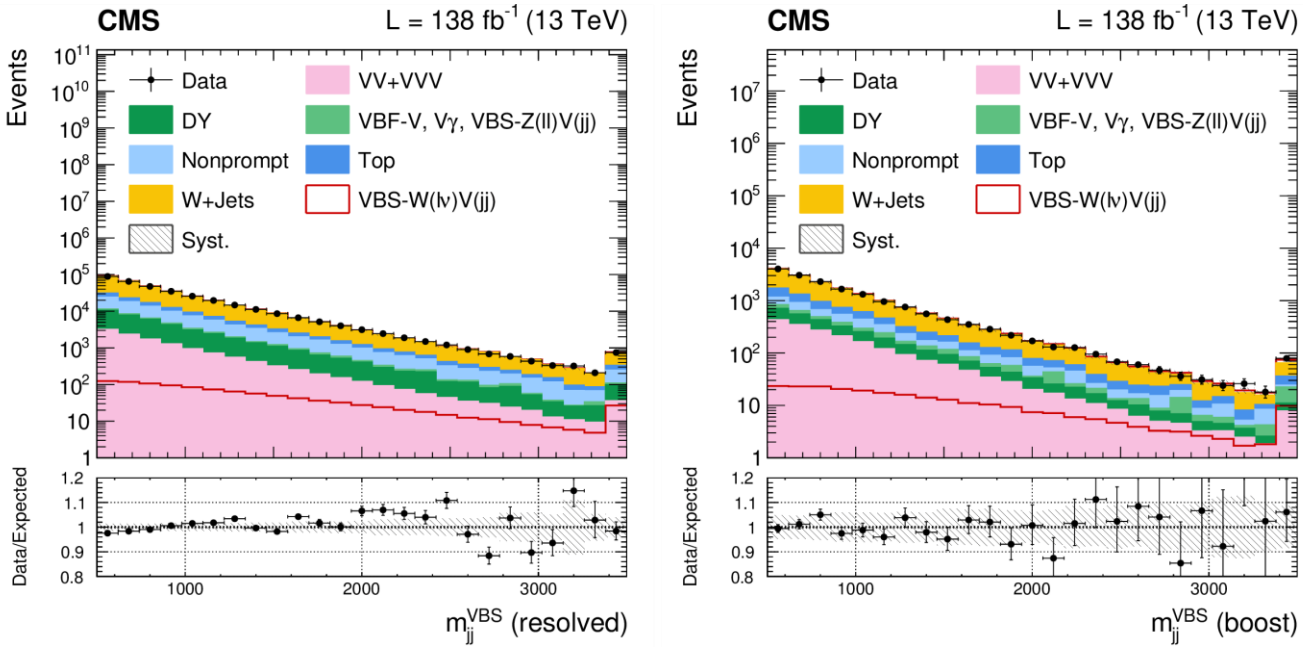
  - Fit to the most discriminating variable in SR: DNN (DF), Number of events or m_{jj} distribution (SF)
- **First observation** of the electroweak production of a leptonically decaying W^+W^- pair in association with two jets (5.6σ)
- **Signal strength in SR:**
  - $1.12 \pm 0.17\ (\text{stat}) \pm 0.14\ (\text{syst}) \pm 0.07(\text{theo})$
- **Measured cross-section** extrapolated to Fiducial Region
  - in SR-like Fiducial Region: 10.2 ± 2.0 fb (LO prediction: 9.1 ± 0.6 fb)

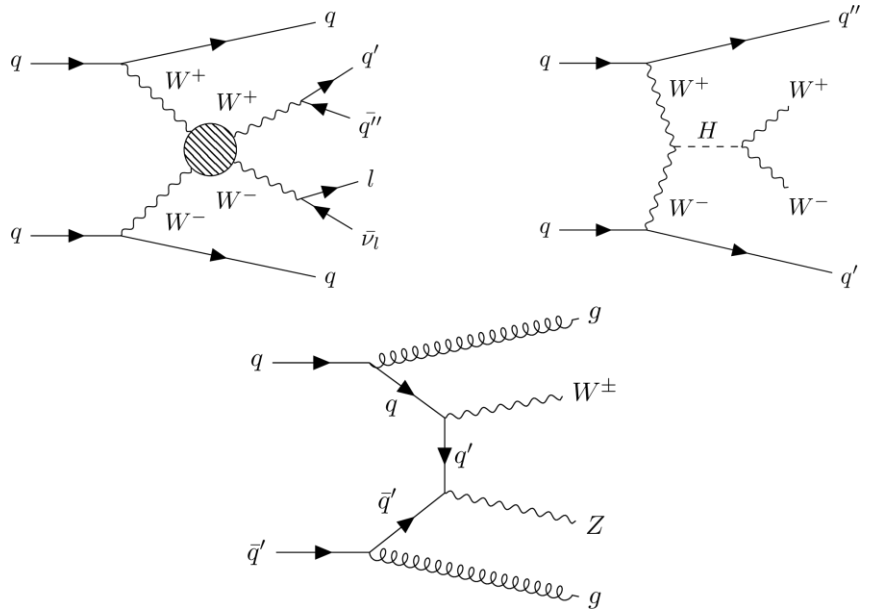
$Z_{\ell\ell} < 1$ | $Z_{\ell\ell} > 1$



Evidence for semileptonic WW/WZ scattering

- Measurement in semi-leptonic WV decays, WV(→lνjj)jj
  - Previous results by ATLAS/CMS using 2015+2016 data,
- Large backgrounds from W+jet and top quark, estimated from data-driven techniques
- Separated using DNN classifier, resolved and boosted categories





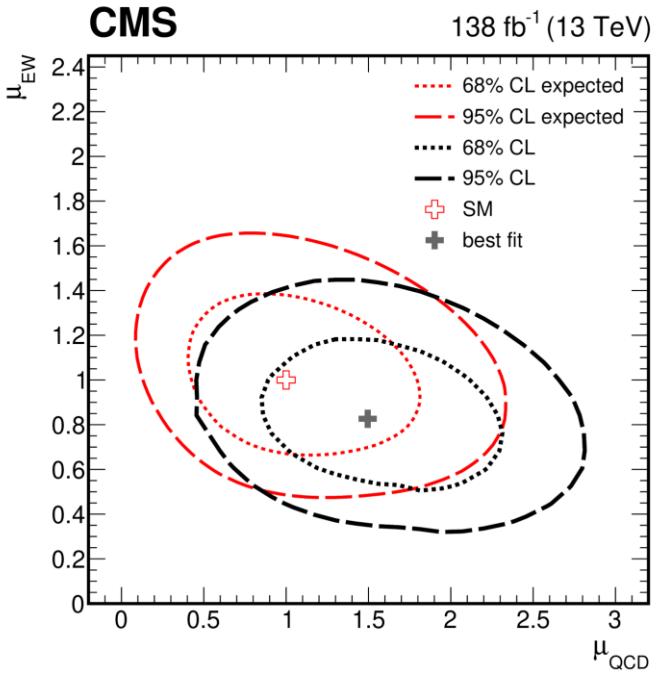
arXiv:2112.05259 (submitted to PLB)

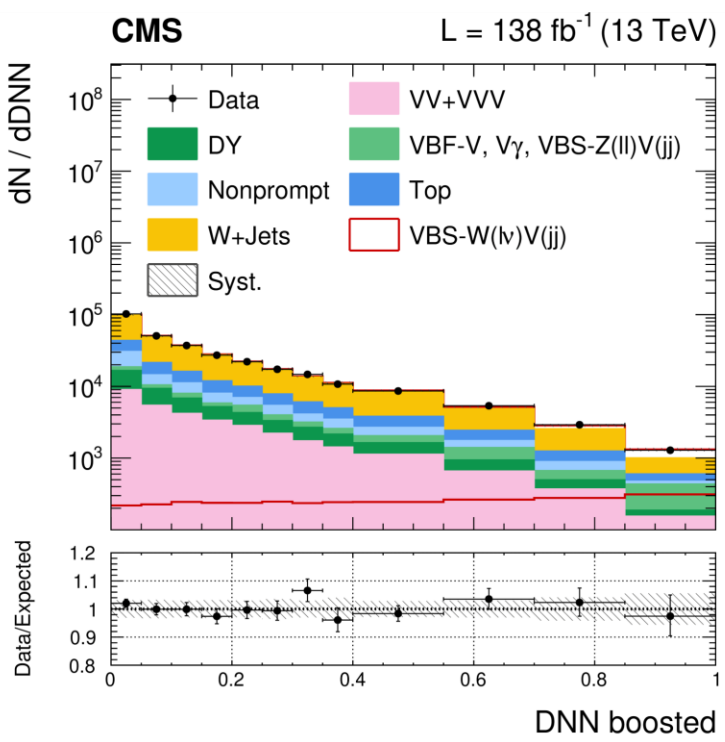
Evidence for semileptonic WW/WZ scattering (II)

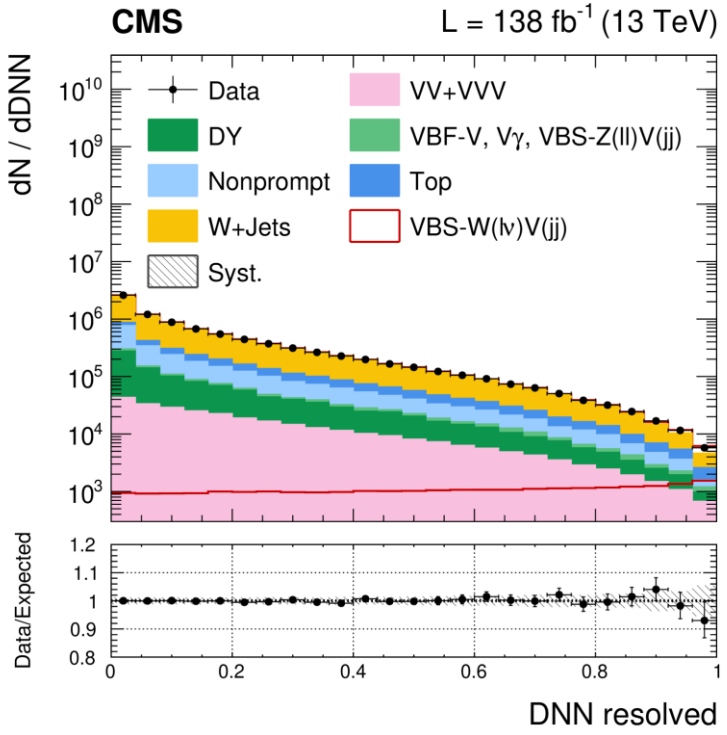
- 3 ML fits is performed to extract signal strengths
- First evidence observed (expected) significance of $4.4\sigma(5.1\sigma)$

$$\mu_{EW} = 0.85 \pm 0.12\ (stat)^{+0.19}_{-0.17}\ (syst)$$
$$\mu_{EW+QCD} = 0.97 \pm 0.06\ (stat)^{+0.19}_{-0.21}(syst)$$

- Simultaneous fit to QCD and EWK signal strengths



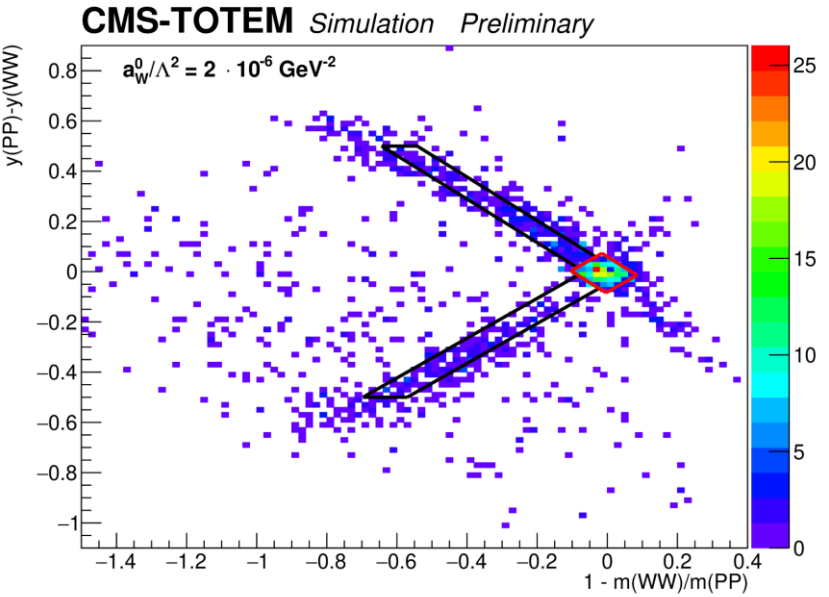


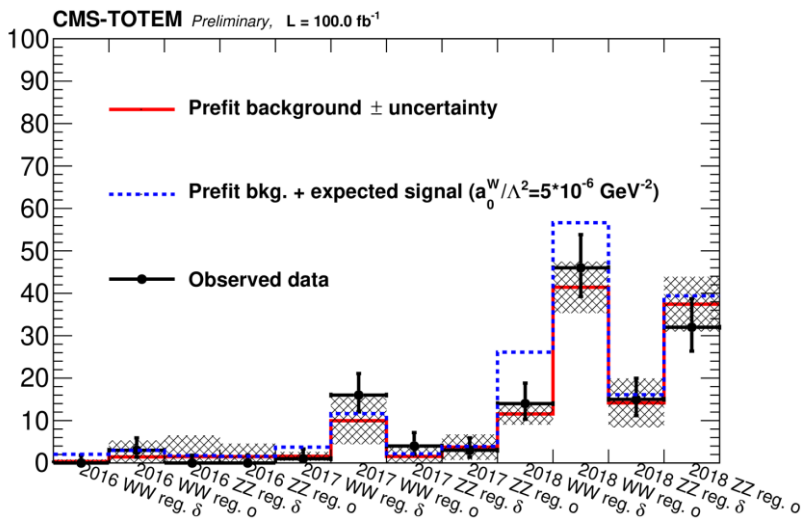


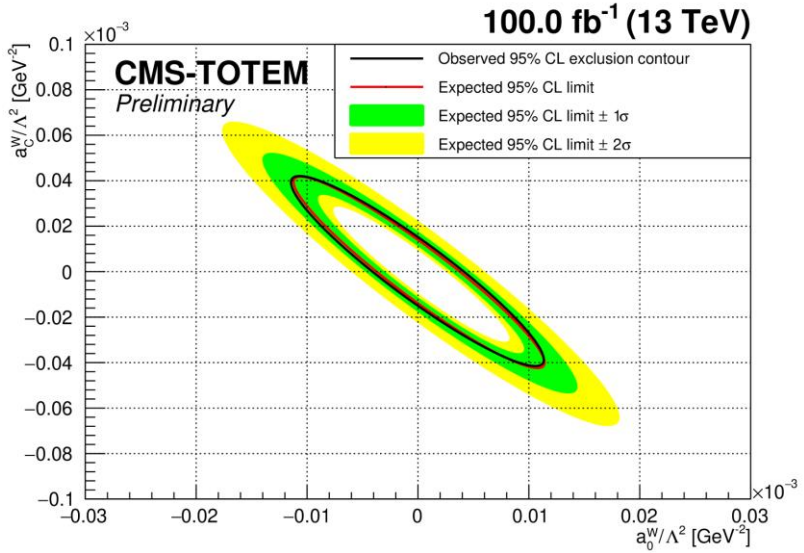
arXiv:2112.05259 (submitted to PLB)

Exclusive WW, ZZ production

- Fully hadronic final state, each boson reconstructed as a single "fat" jet and forward proton reconstruction using the PPS detector.
- Fit to 12 signal regions (data-driven background estimate), categorized by year, and by quality of the reconstruction:
  - both protons matched to jets (signal region δ)
  - One proton matched only (signal region “o”)
- **Limits set on dim-6 aQGC operators: 15-20x more stringent than Run 1 γγ→WW/ZZ**







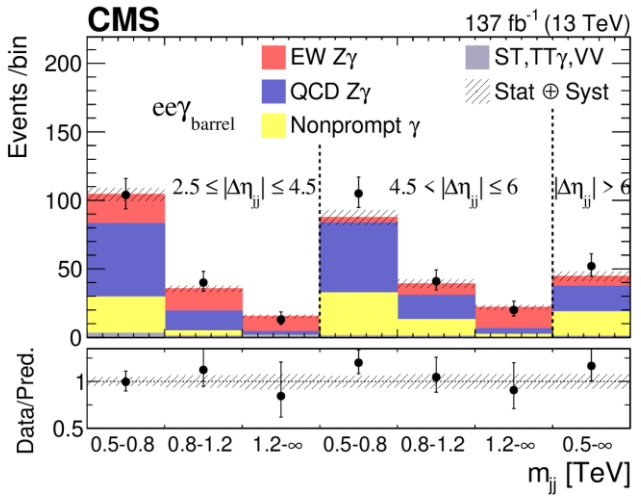
CMS-PAS-SMP-21-014 (soon to be submitted)

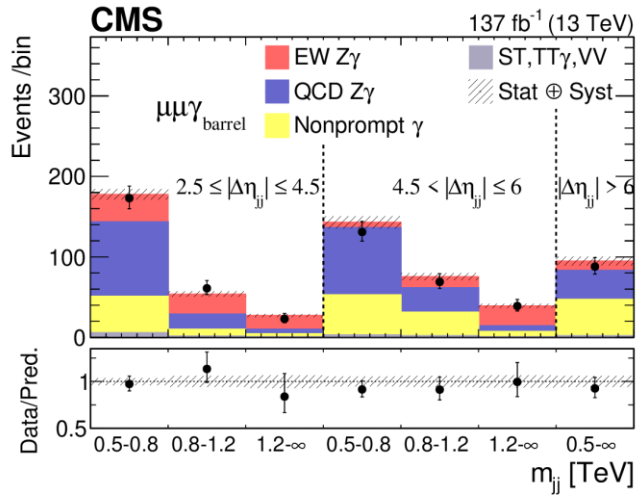
Observation of electroweak production of Zγ

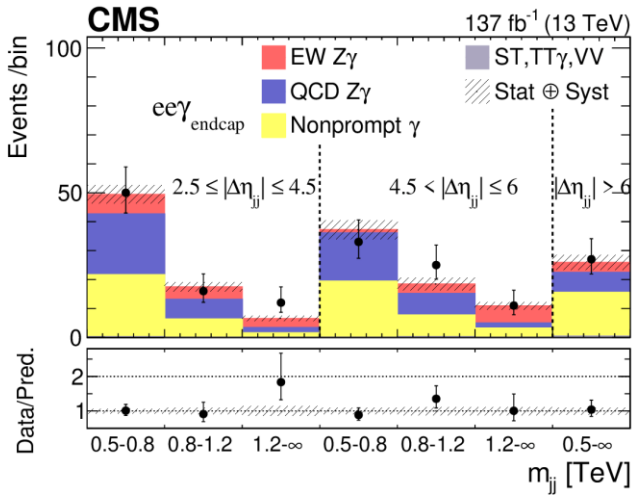
- No photon coupling to Higgs: sensitivity to neutral (a)QGC and (a)TGC
- Main backgrounds:
  - QCD Zγ : estimated from MC, constrained in simultaneous fit
  - Non-prompt photon: data-driven estimate through photon shape fit
- Signal extracted with m_{jj} and $\Delta\eta_{jj}$
- **First** observed (expected) **observation at 9.4σ** (8.5σ)

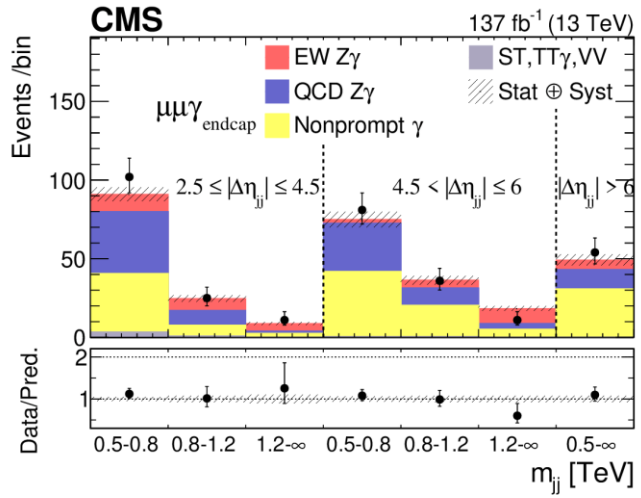
$$\sigma^{\text{fid}}_{\text{EW}} = 5.21 \pm 0.52\ (\text{stat}) \pm 0.56\ (\text{syst})\ \text{fb}$$
$$\sigma^{\text{fid}}_{\text{EW+QCD}} = 14.7 \pm 0.80\ (\text{stat}) \pm 1.26\ (\text{syst})\ \text{fb}$$

- In good agreement with SM expectations









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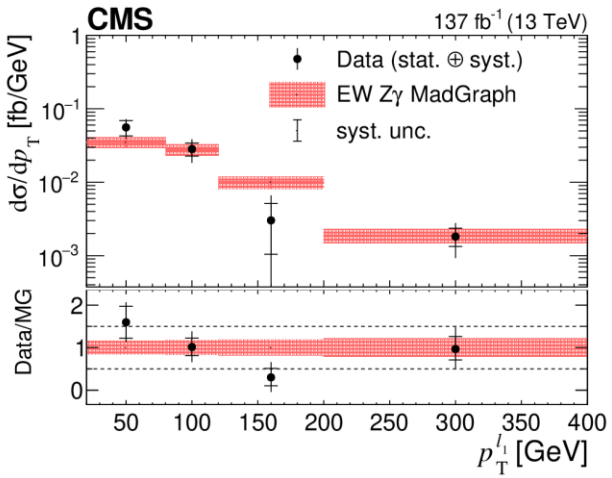
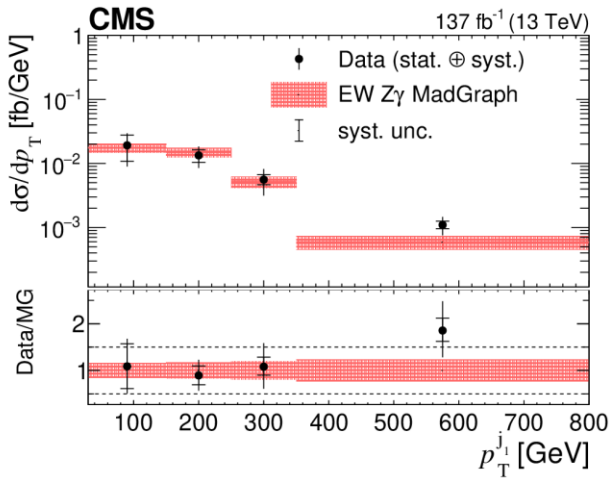
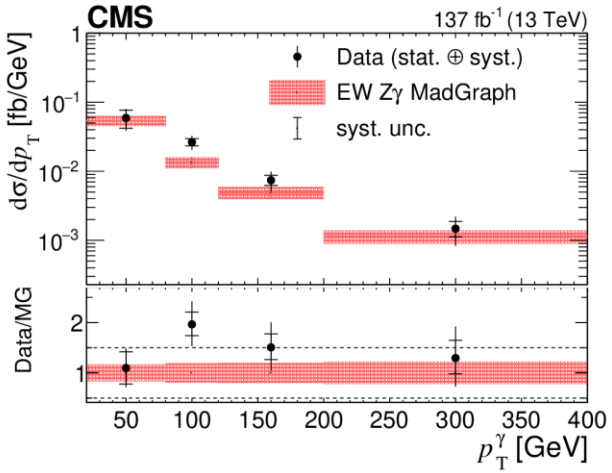
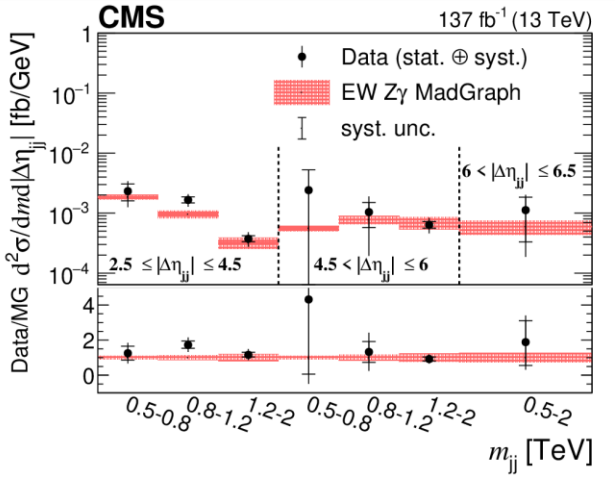
Observation of electroweak production of Zγ (II)

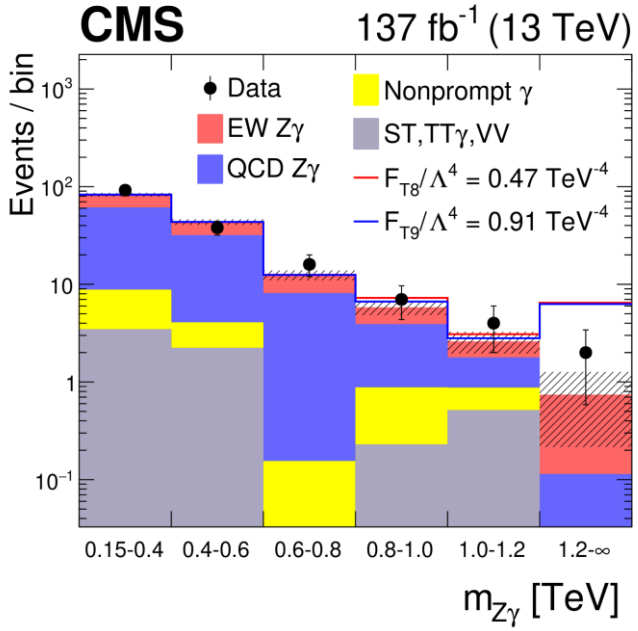








- **Differential cross sections** for EW and EW+QCD are measured for several observables and in agreement to SM predictions computed at leading order (within uncertainties)
- **Constraints** are set on the effective field theory **dimension-8 operators** giving rise to aQGCs



Summary

- CMS counts with a **sound SM physics program** with several **high precision results** that allow to put the SM in question.
  - EW precision parameters with full Run 2 data still to come.
- **Diboson cross section** all measured and in good agreement with state-of-the art predictions
  - Precision measurements and improvements in the tails
- **Many VBS/VBF processes observed**
  - More precise measurement will benefit from Run 3 dataset and HL-LHC
- **No significant deviation from Standard Model observed**
- **Run 3 is starting** (beams reached CMS last week) at a new centre of mass energy that will require to re-measure all of the cross-sections with the first data.

Thanks you for listening!