Multi-boson Highlights and Electroweak Summary

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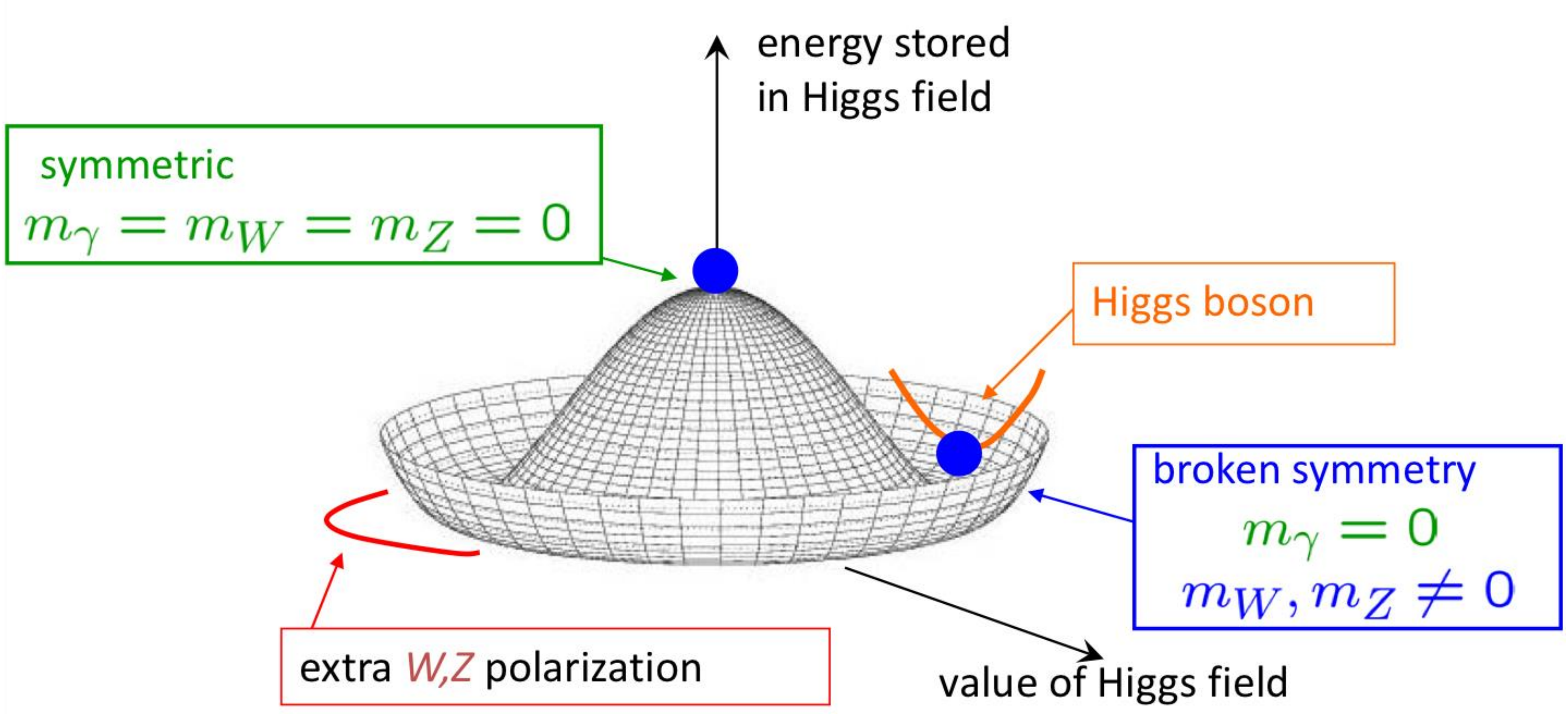
Introduction

- Gauge boson interactions are direct consequence of the Electroweak Symmetry Breaking
  - Masses of W/Z bosons acquired via the Higgs mechanism → this also gives the longitudinal polarization components to W/Z bosons



$$\epsilon^\mu_+ = \frac{1}{\sqrt{2}}(0, 1, i, 0),$$

$$\epsilon^\mu_- = \frac{1}{\sqrt{2}}(0, 1, -i, 0),$$

$$\epsilon^\mu_L = \frac{1}{M}(p_z, 0, 0, E).$$

Introduction

- Gauge boson interactions are direct consequence of the Electroweak Symmetry Breaking
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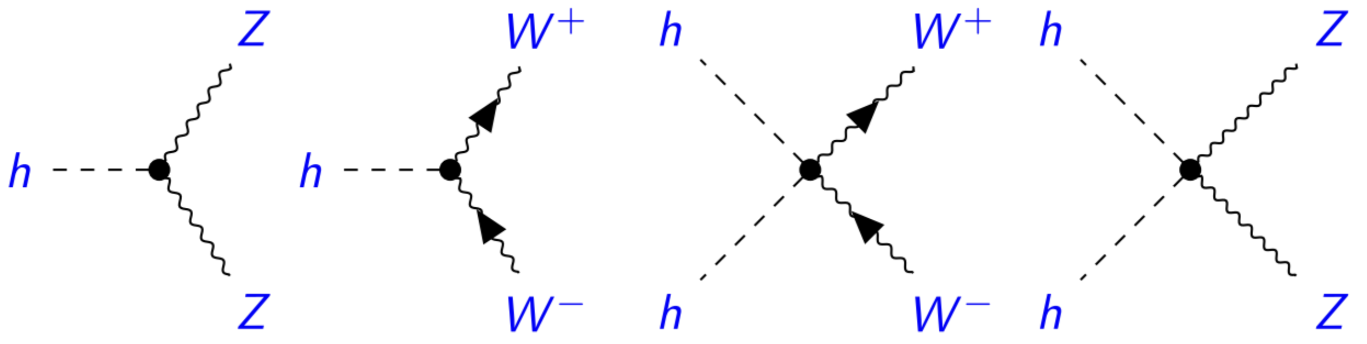
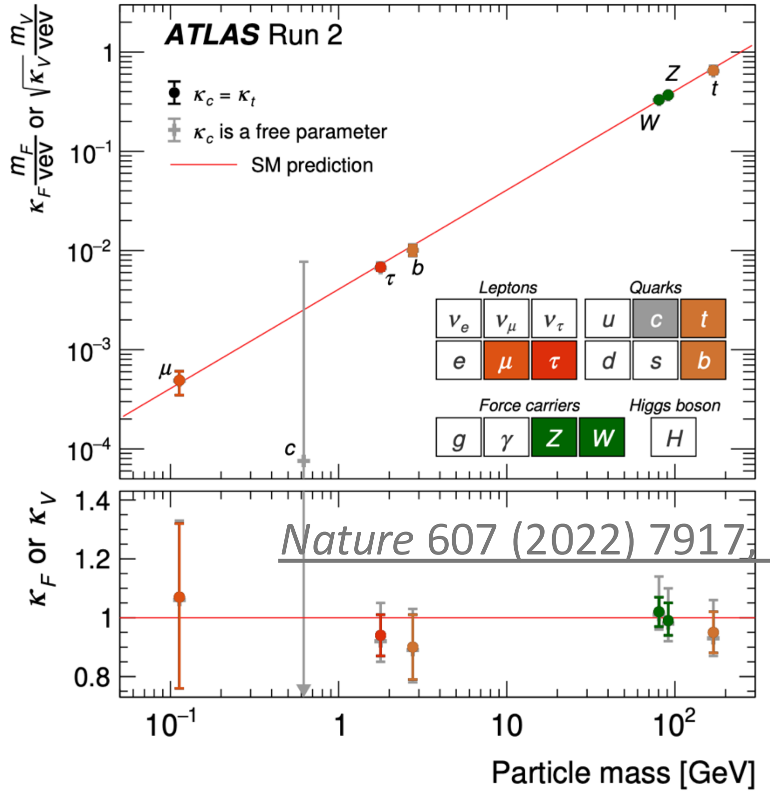
  - Couplings to the Higgs boson: pivotal to discover and characterize the Higgs boson





Nature 607 (2022) 7917, 52-59

Introduction

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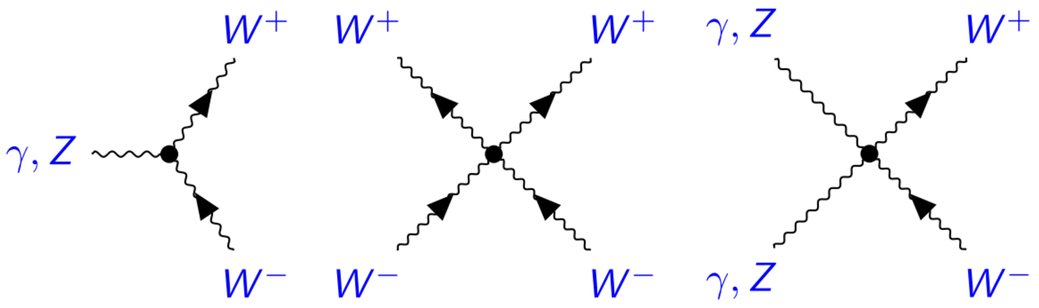
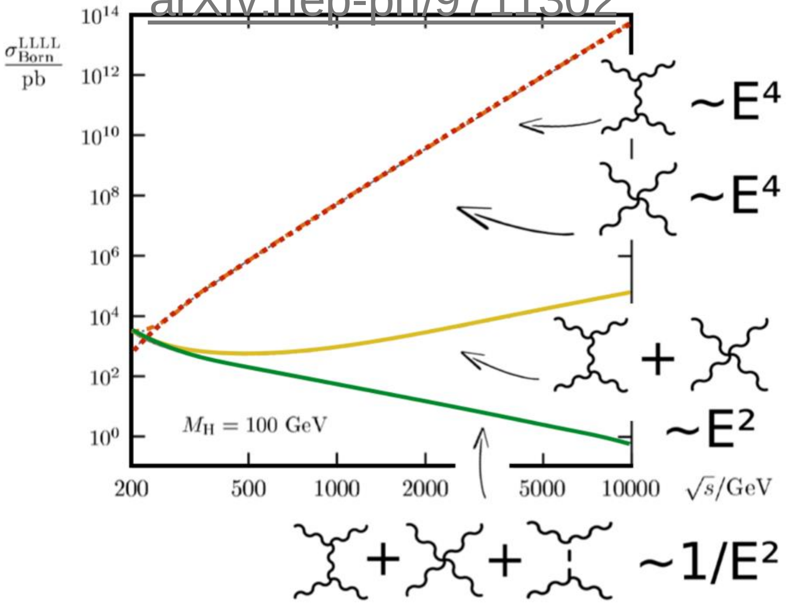
  - Couplings to the Higgs boson: pivotal to discover and characterize the Higgs boson
  - Gauge boson self-couplings: unique windows to new physics beyond the SM
    - Anomalous triple gauge couplings
    - Anomalous quartic gauge couplings
    - Unitarity violation in $V_L V_L \to V_L V_L$ scattering

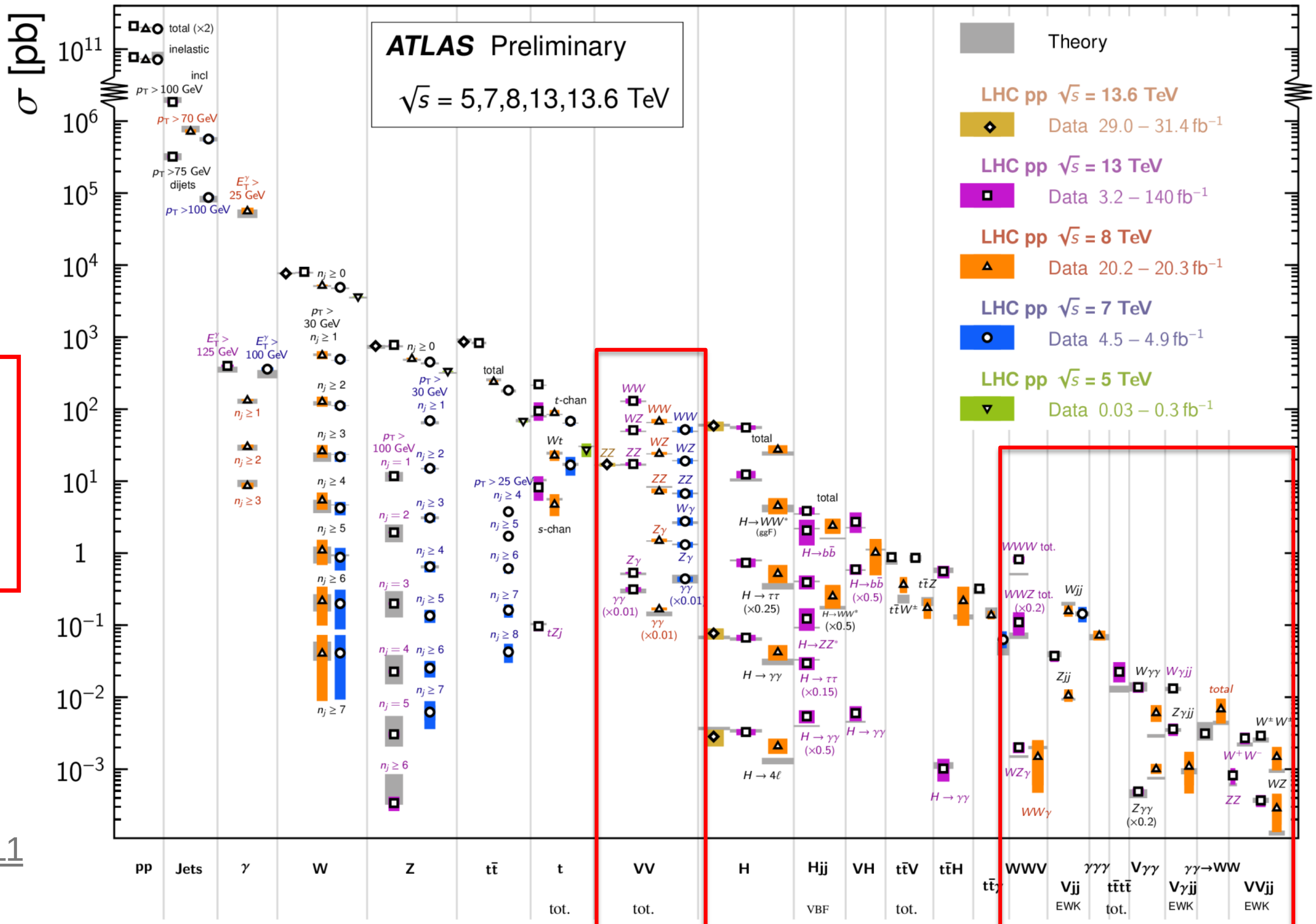


arXiv:hep-ph/9711302



Standard Model Production Cross Section Measurements

Status: June 2024



Multiboson: a flagship program of the SM precision measurements

ATL-PHYS-PUB-2024-011

Selected recent highlights

- Legacy measurement from Full Run2

Only show new results released after CLHCP 2023

13 TeV		
Diboson (VV)	WZ polarization	ATLAS, PRL133 (2024) 101802
	$Z(\nu\nu)\gamma$ and aTGC	CMS, SMP-22-009
Triboson(VVV)	$WZ\gamma$	CMS, SMP-22-018
VBS ($VVjj$)	$W^{\pm}W^{\mp}jj$ observation	ATLAS, JHEP 07 (2024) 254
	$W\gamma jj$ observation	ATLAS, EPJC 84 (2024) 1064
	$W^{\pm}W^{\pm}jj$ differential	ATLAS, JHEP 04 (2024) 026
	$W^{\pm}Zjj$ differential	ATLAS, JHEP 06 (2024) 192

- Fresh measurements from early Run3

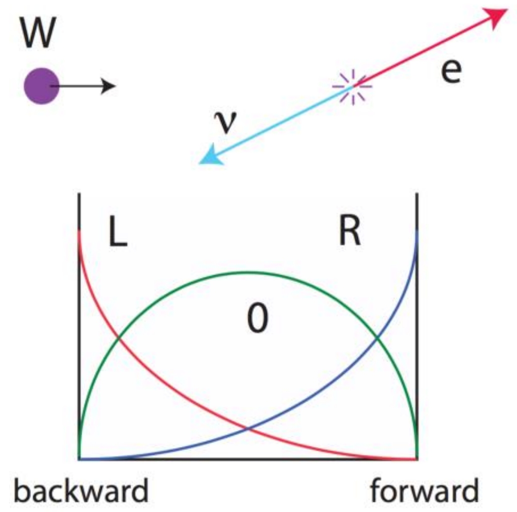
13.6 TeV		
Diboson (VV)	WW differential	CMS, arXiv:2406.05101
	WZ	CMS, SMP-24-005

Legacy measurements from Full Run2

Diboson polarization

- Diboson polarization measurements have gained increasing interest in both the theory and experiment community in recent years
  - Important probes of the EWK and Higgs sectors
  - Theory predictions already challenging beyond the Leading Order
  - Novel sensitivity to BSM
  - Closely connected to Quantum Entanglement

	SM	BSM
$q_{L,R}\bar{q}_{L,R} \to V_L V_L(h)$	~ 1	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_L(h)$	$\sim m_W/E$	$\sim m_W E/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\pm$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q_{L,R}\bar{q}_{L,R} \to V_\pm V_\mp$	~ 1	~ 1

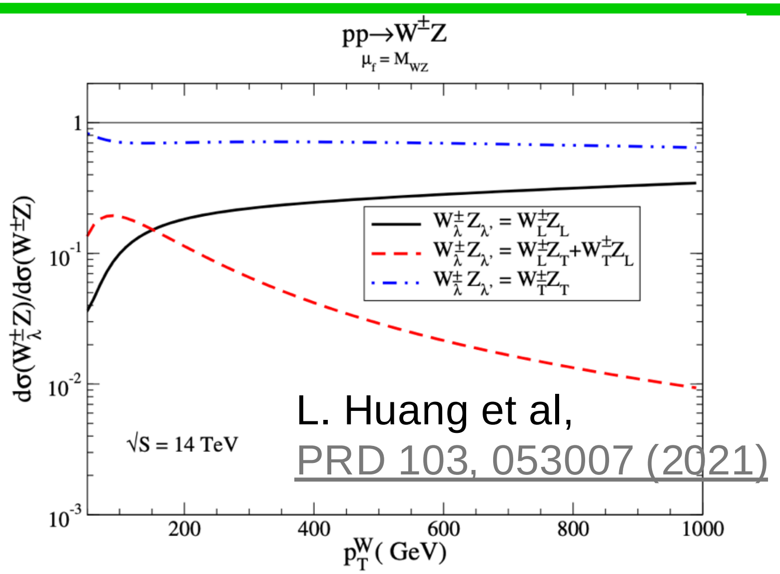


F. Riva et al, arXiv:1712.01310

- Recent measurements
  - $pp \to ZZ \to 4l$, ATLAS JHEP 12 (2023) 107 ($Z_L Z_L$ measured with 4.3σ)
  - $pp \to WZ \to l\nu ll$, ATLAS PLB 843 (2023) 137895 ($W_L Z_L$ observed with 7.1σ), CMS *JHEP 07 (2022) 032* ($W_L Z_L$ observed with 5.6σ)
  - $pp \to W^\pm W^\pm jj$ VBS, CMS *Phys. Lett. B 812 (2020) 136018* ($W_L W_X$ measured with 2.3σ)

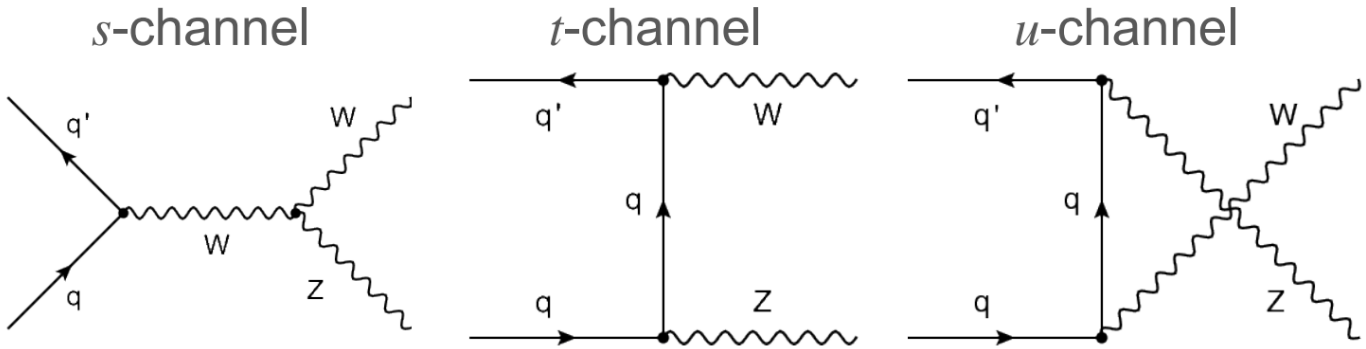
Energy Dependence and the Radiation Amplitude Zero Effect

- Polarization fraction is p_T dependent
- RAZ effect: at leading-order, the dominant helicity amplitude for TT vanishes when $\cos\theta_V \sim 0$
- RAZ **only** happens for WZ and $W\gamma$ processes and **not** for WW and ZZ processes
  - Observed in $W\gamma$ but not in WZ yet



L. Huang et al, PRD 103, 053007 (2021)

$$\frac{d^2\sigma_{WZ}^{LL}}{d^2\sigma_{WZ}^{TT}} \sim \frac{1}{8\cos^2\theta_V}\frac{1-\cos^2\theta_V}{1+\cos^2\theta_V}$$



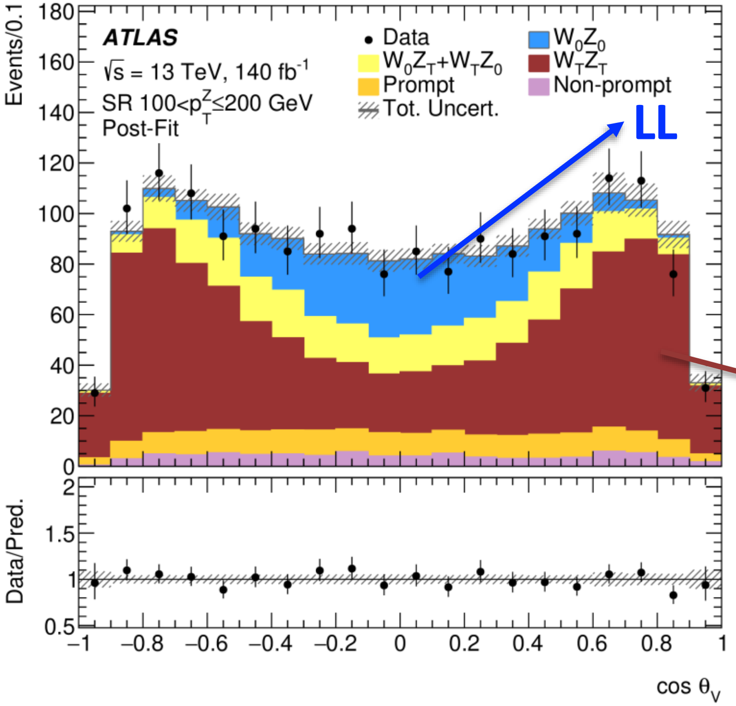
- High $p_T(Z)$ region enhances the LL fraction
- Low $p_T(WZ)$ region suppresses jet activity thus enhances the RAZ effect →also enhancing the LL fraction

f_{LL} increases from 5 − 7% in the inclusive region to 20 − 30% in the region with high $p_T(Z)$ and low $p_T(WZ)$

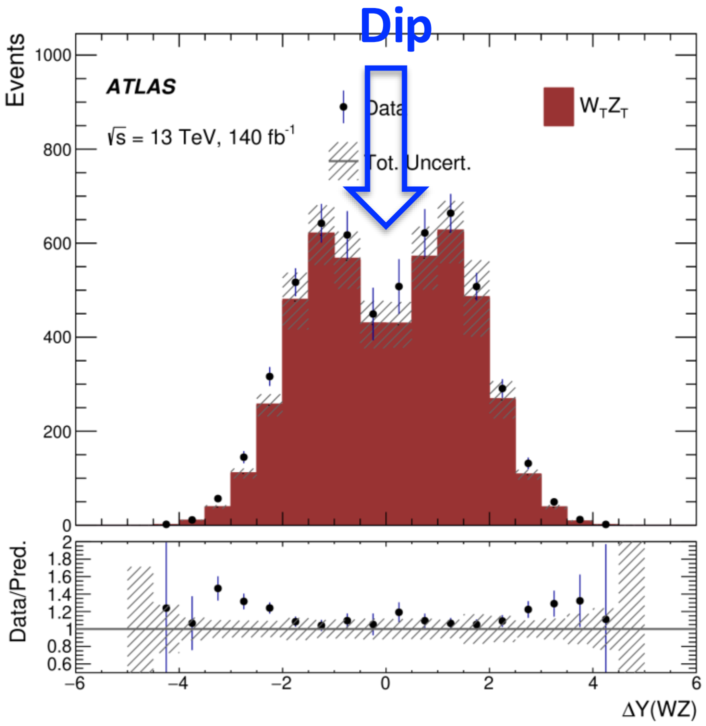
Observation of WZ pol. and the Radiation Amplitude Zero effect

	Measurement	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ

ATLAS, PRL133 (2024) 101802



First measurement of energy dependence of diboson polarization



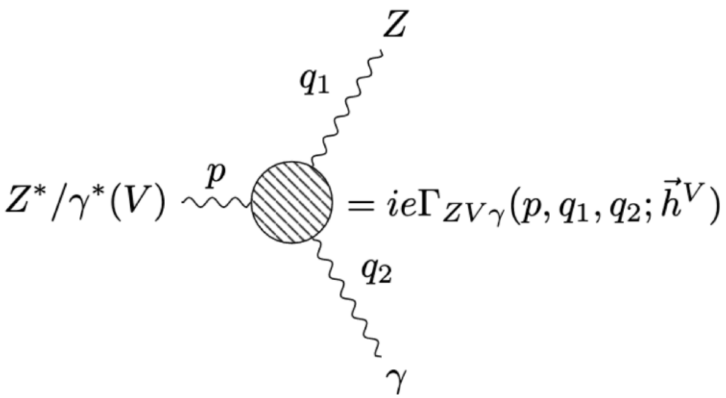
See more details in Zhenyu Zhao's talk (Friday afternoon)

- RAZ effect leads to a dip around 0 in the $\Delta Y(WZ)$ and $\Delta Y(l_W Z)$ distributions
- Significant dips are observed
- Unfolded distributions also measured

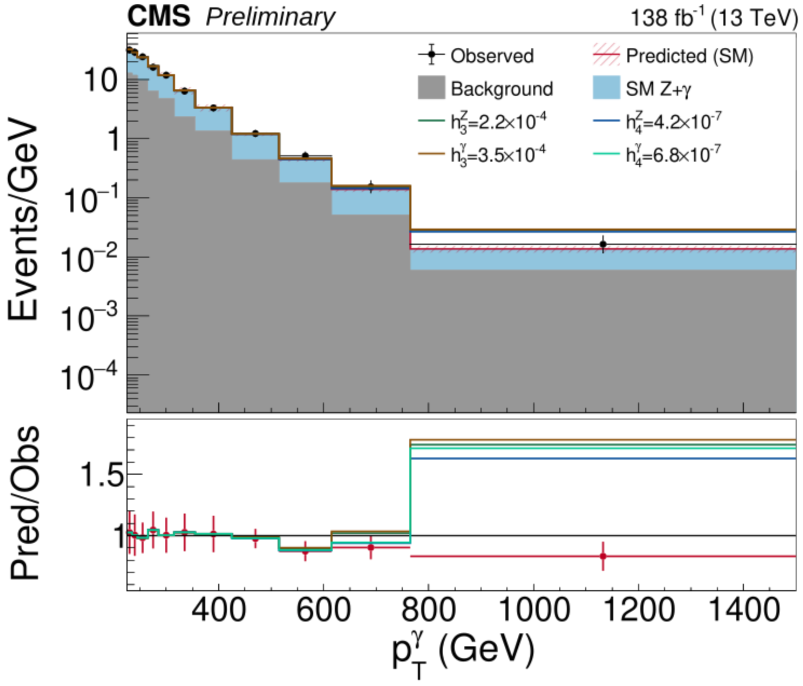
$Z(\nu\nu)\gamma$ measurement and aTGC

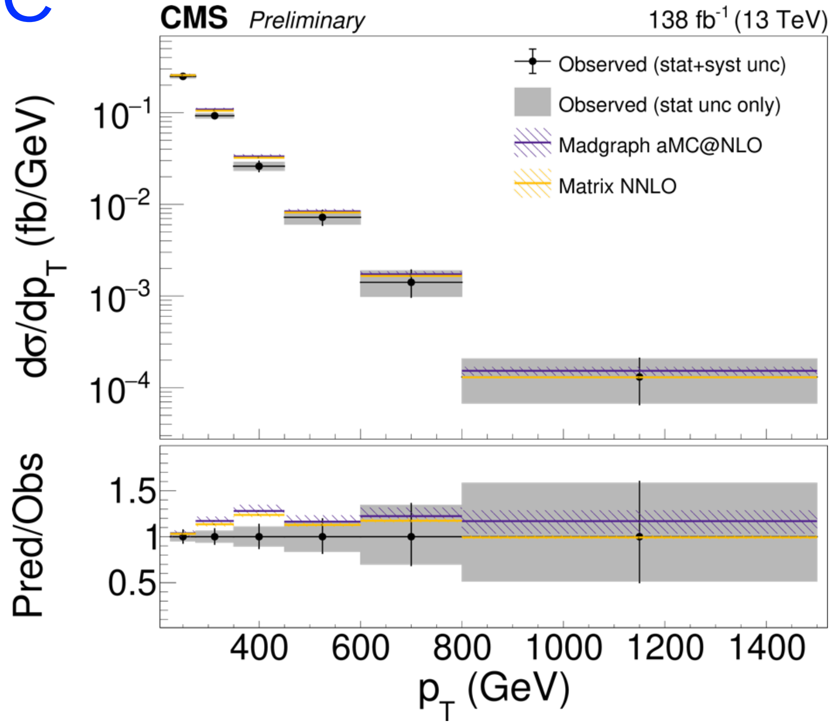
CMS, SMP-22-009

- $Z\gamma$ production sensitive to anomalous neutral TGC



Events selected with an energetic photon and large E_T^{miss}





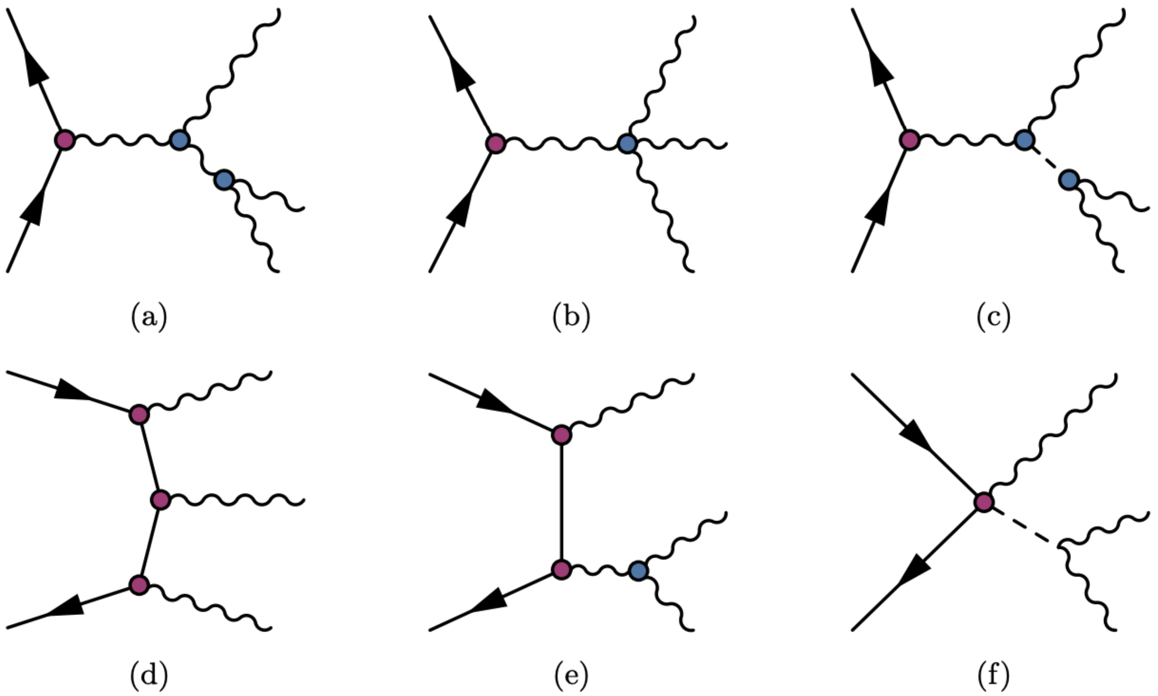
Parameter	Expected	Observed
$h_3^\gamma \times 10^4$	(-2.8, 2.9)	(-3.4, 3.5)
$h_4^\gamma \times 10^7$	(-5.9, 6.0)	(-6.8, 6.8)
$h_3^Z \times 10^4$	(-1.8,1.9)	(-2.2, 2.2)
$h_4^Z \times 10^7$	(-3.7, 3.7)	(-4.1, 4.2)

Stringent constraints on nTGCs

Measured cross section is compatible with NNLO predictions

Triboson production

- Rare and complicated processes
- Probe the EWK sector from a new angle
- Direct probe of quartic gauge couplings (QGC)



Triboson observations

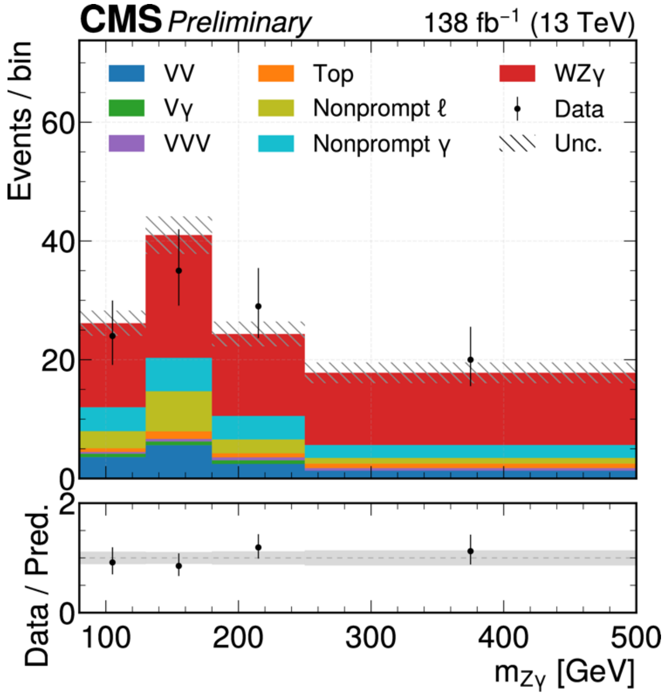
process	experiment	submission date	reference
VVV	CMS	Jun. 2020	[1]
WWW	ATLAS	Jan. 2022	[2, 3]
$WW\gamma$	CMS	Oct. 2023	[4]
$WZ\gamma$	ATLAS	May 2023	[5]
$V\gamma\gamma$	CMS	May 2021	[6]
$Z\gamma\gamma$	ATLAS	Nov. 2022	[7]
$W\gamma\gamma$	ATLAS	Aug. 2023	[8]

E. Celada et al, arXiv:2407.09600

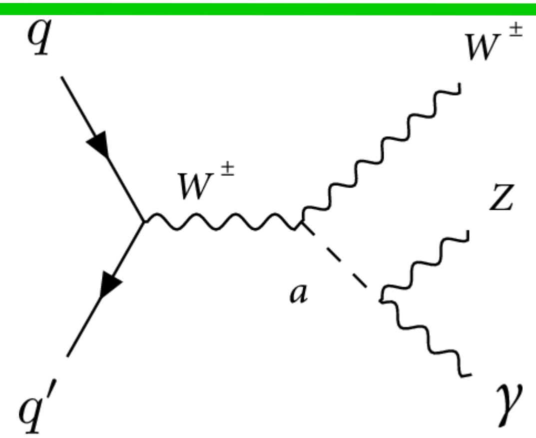
CMS $WZ\gamma$ observation

CMS, SMP-22-018

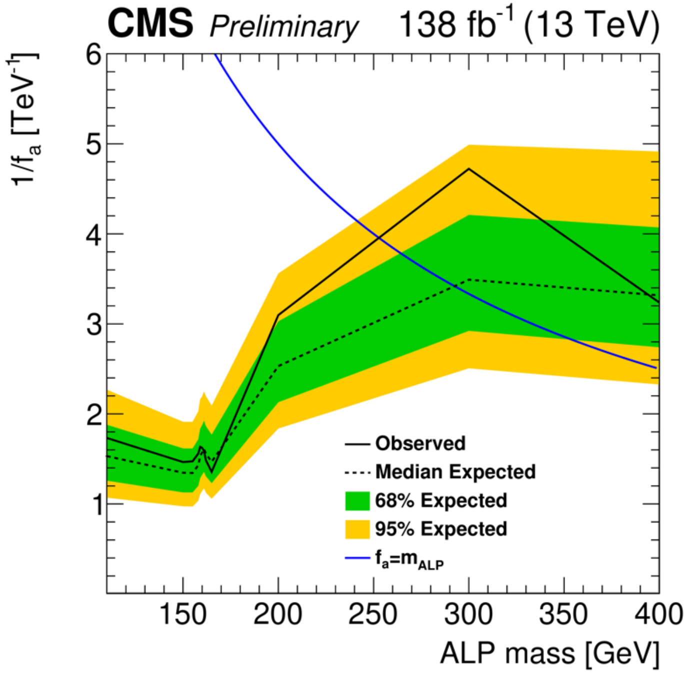
- Simultaneous production of three different gauge bosons



Observed (expected) significance: 5.4(3.8)σ



Search for axion-like particles (photophobic ALPs $a \rightarrow Z\gamma$)

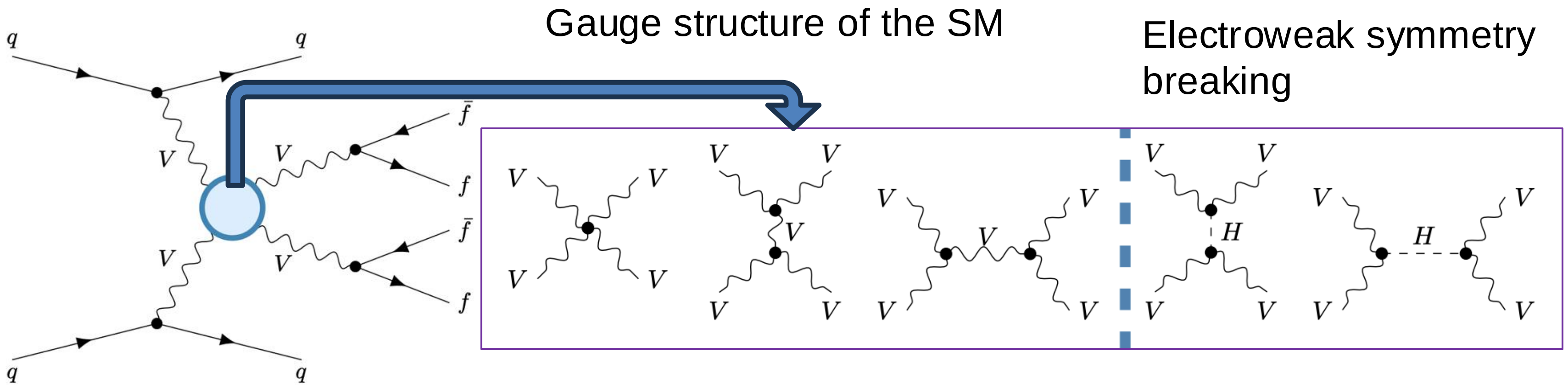


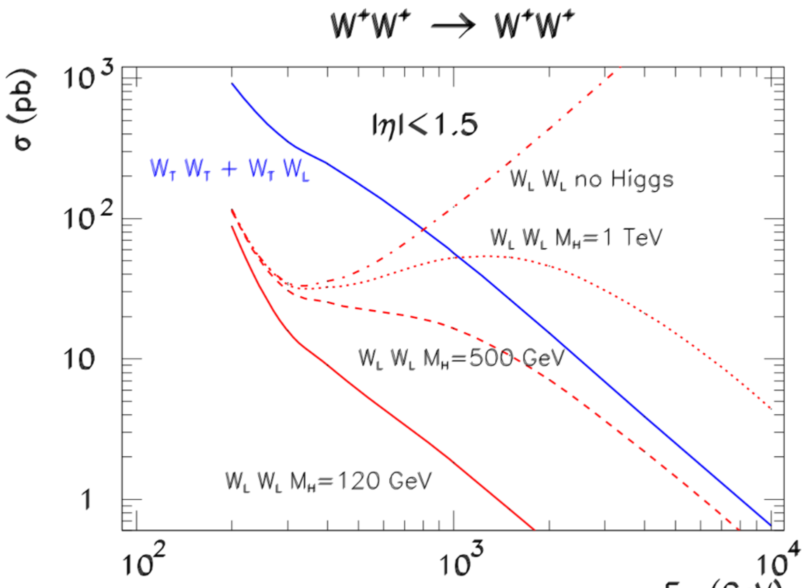
Constraints on aQGC

Operators	Observed limits [TeV $^{-4}$]	Expected limits [TeV $^{-4}$]	Unitarity bound [TeV]
$F_{T,0}/\Lambda^4$	[-2.60, 2.60]	[-2.52, 2.52]	1.32
$F_{T,1}/\Lambda^4$	[-3.28, 3.24]	[-3.18, 3.14]	1.48
$F_{T,2}/\Lambda^4$	[-7.15, 7.05]	[-6.95, 6.85]	1.35
$F_{T,5}/\Lambda^4$	[-2.54, 2.56]	[-2.46, 2.50]	1.55
$F_{T,6}/\Lambda^4$	[-3.18, 3.22]	[-3.08, 3.14]	1.61
$F_{T,7}/\Lambda^4$	[-6.85, 7.05]	[-6.65, 6.85]	1.71

LHC as a Vector Boson Collider

- VBS: a no-lose theorem program for the LHC
  - We would have either discovered the Higgs boson or New Physics
- Probing the interactions in VBS helps unveil the dynamics behind the Higgs mechanism
- A primary goal in VBS is to measure the scattering of $V_L V_L \rightarrow V_L V_L$
  - Strict cancellation required to unitarize the high energy behavior

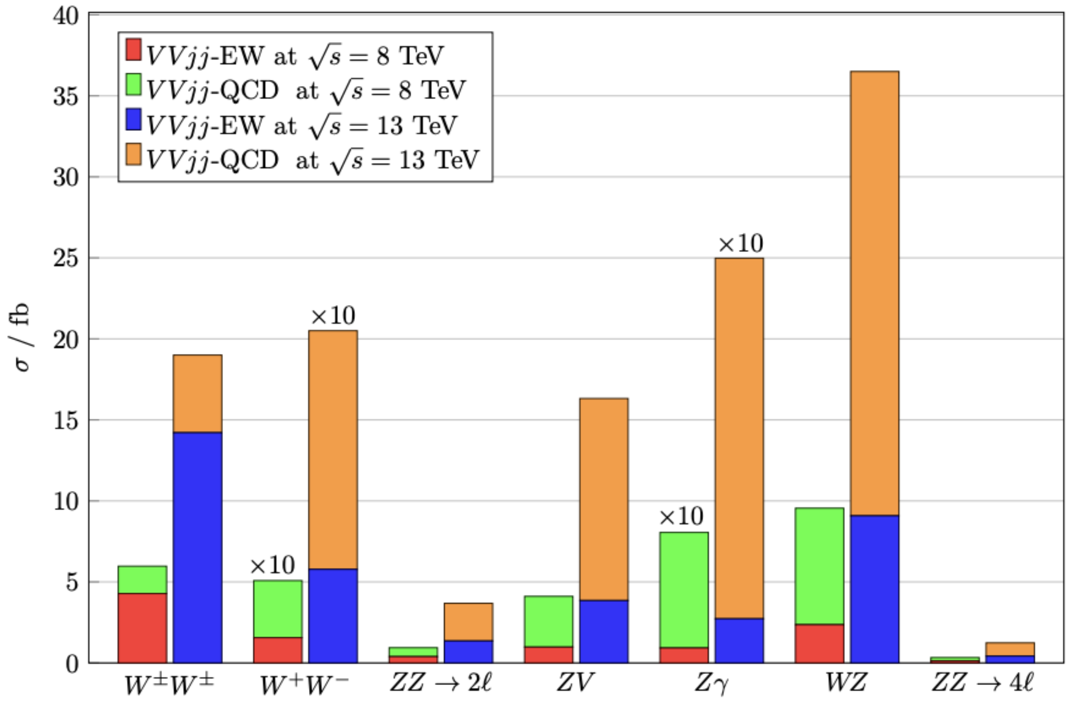




M. Szleper, arXiv:1412.8367

LHC as a Vector Boson Collider

Challenging to observe VBS at the LHC



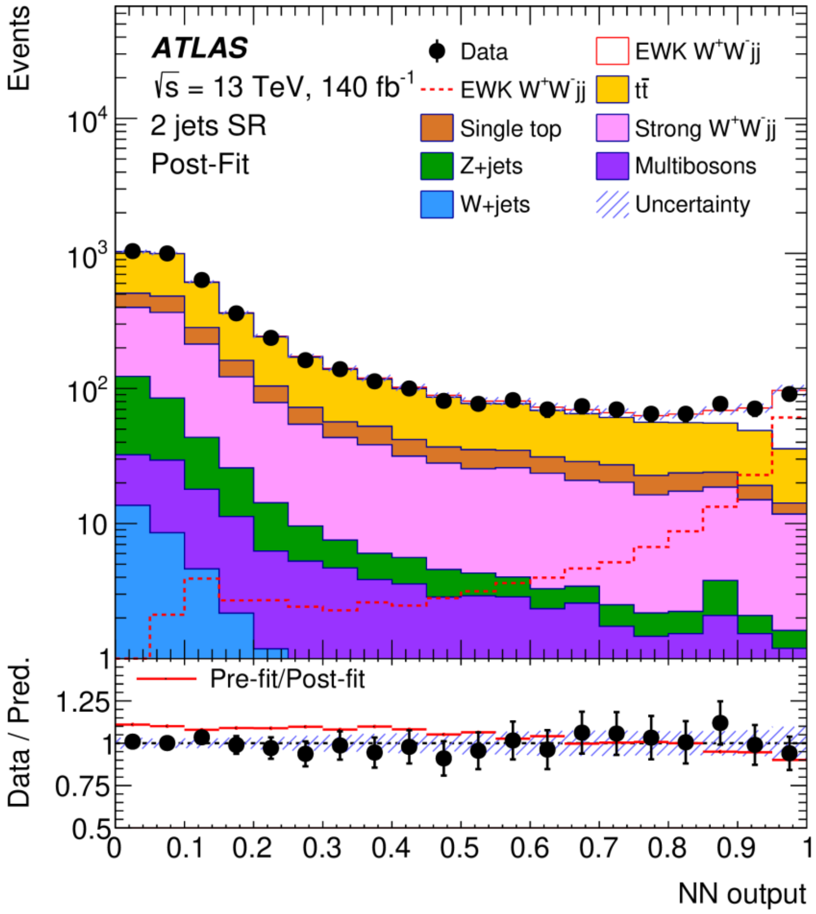
P. Anger, CERN-THESIS-2014-105

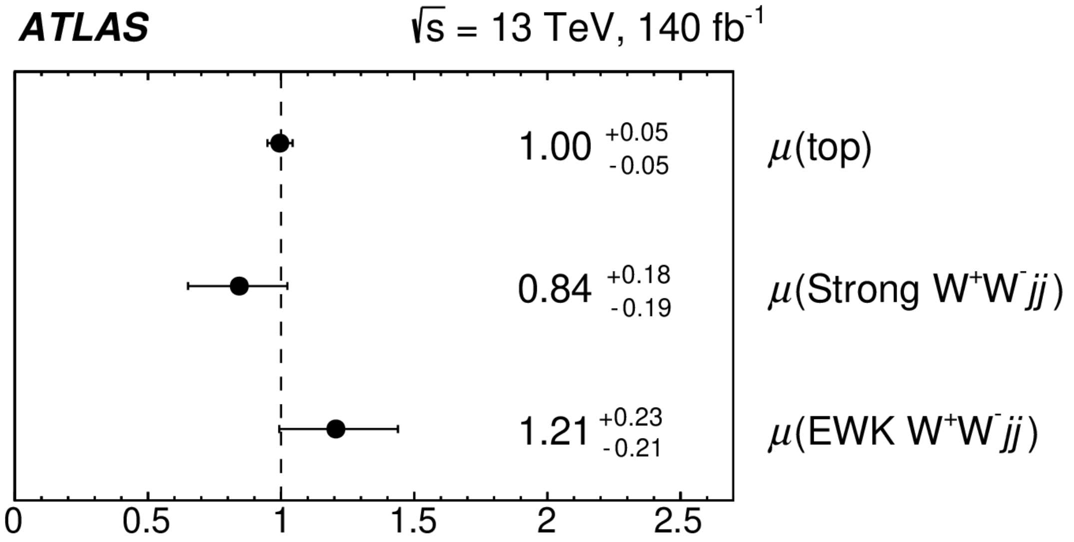
VBS observations	
$W^{\pm}W^{\pm}jj$ (same-sign)	CMS: PRL 120 (2018) 081801 ATLAS: PRL 123 (2019) 161801
$W^{\pm}W^{\mp}jj$ (opposite-sign)	CMS, PLB 841 (2023) 137495 ATLAS, JHEP 07 (2024) 254
$W^{\pm}Zjj$	ATLAS, PLB 793 (2019) 469 CMS, PLB 809 (2020) 135710
$W\gamma jj$	CMS, PLB 811 (2020) 135988 ATLAS, EPJC 84 (2024) 1064
$Z\gamma jj$	CMS, *PRD 104 (2021) 072001* ATLAS, PLB 846 (2023) 138222
$ZZjj$	ATLAS, Nature Phys. 19 (2023) 237

ATLAS $W^{\pm}W^{\mp}jj$ observation

JHEP 07 (2024) 254

- Observed by CMS(2023)
- Very challenging due to high background → a DNN discriminant used





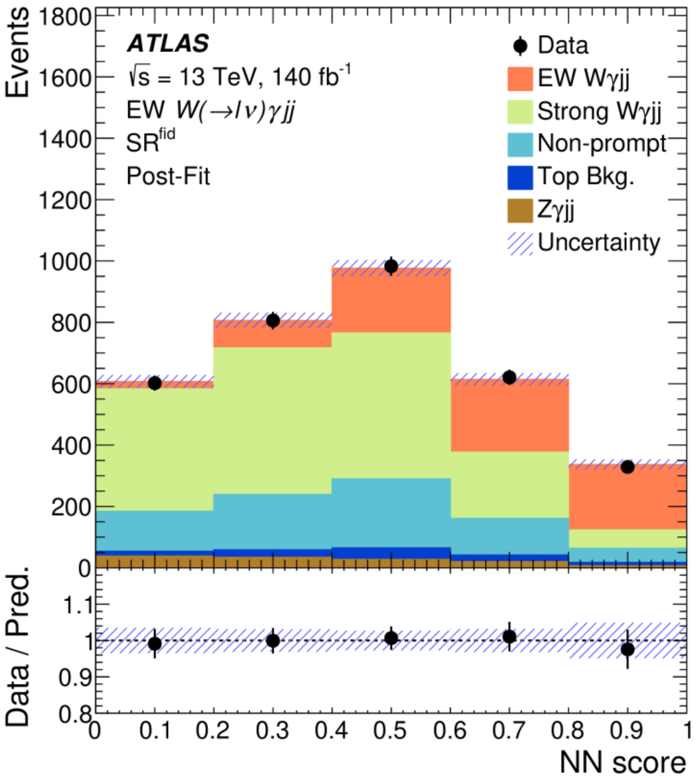
Observed (expected) significance: 7.1(6.2)σ

ATLAS $W\gamma jj$ observation

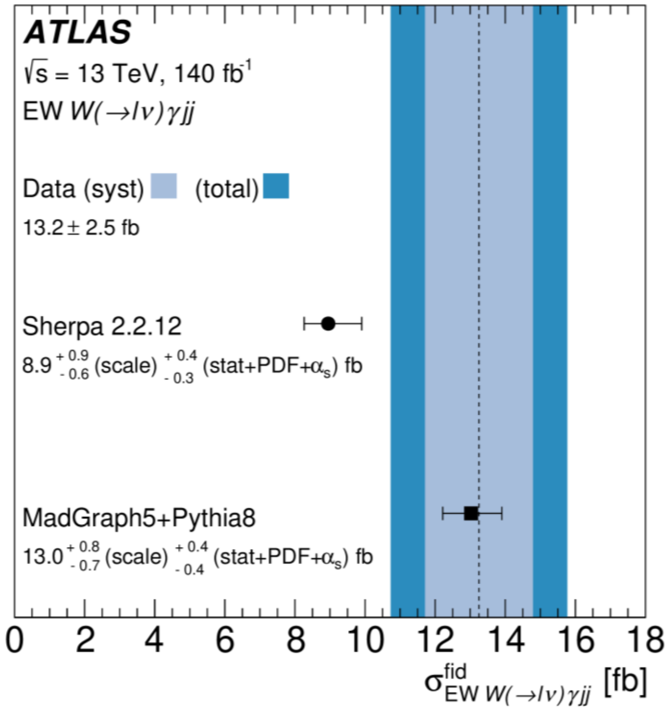
EPJC 84 (2024) 1064

- Observed by CMS(2020)
- Very challenging due to high background → a DNN discriminant used

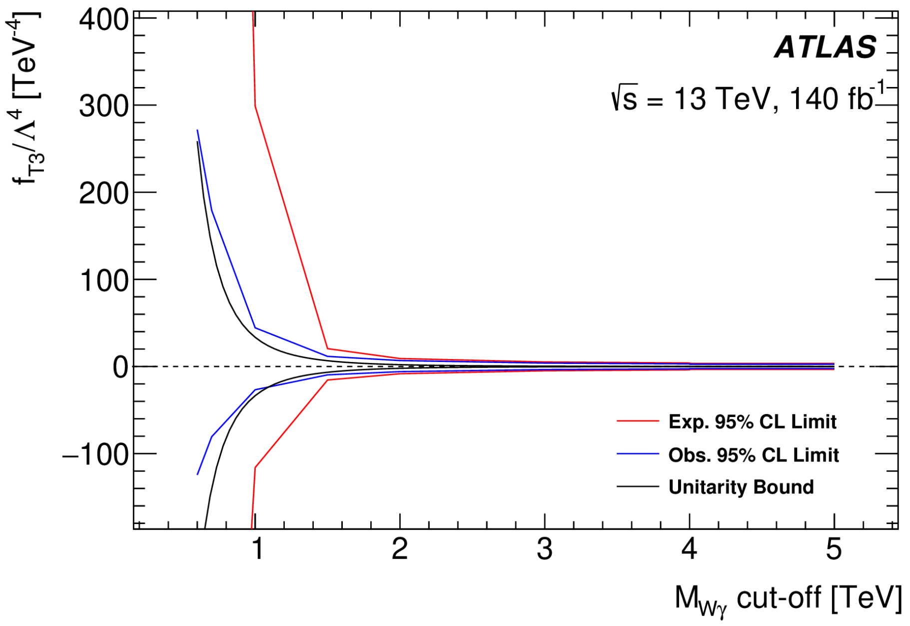
See more details in Jing Chen's talk (Friday afternoon)



Observed significance well above 6σ (expected 6.3σ)



Fiducial and differential cross-sections measured

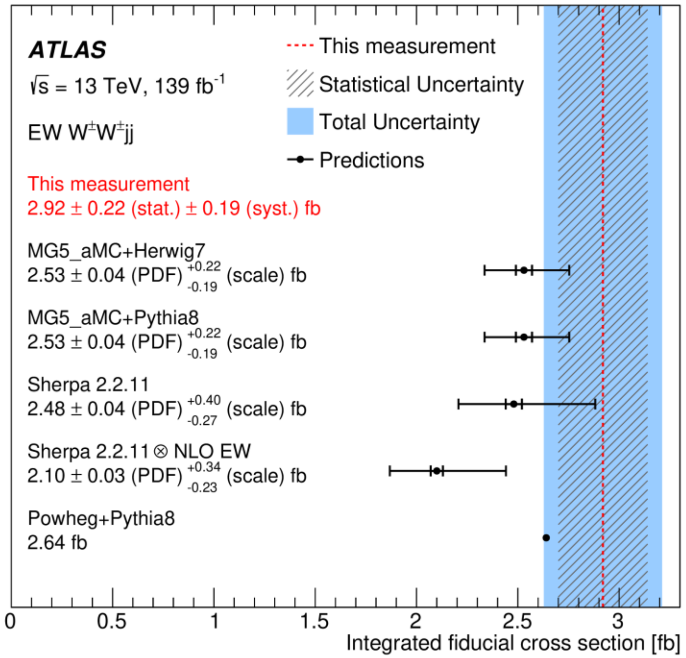


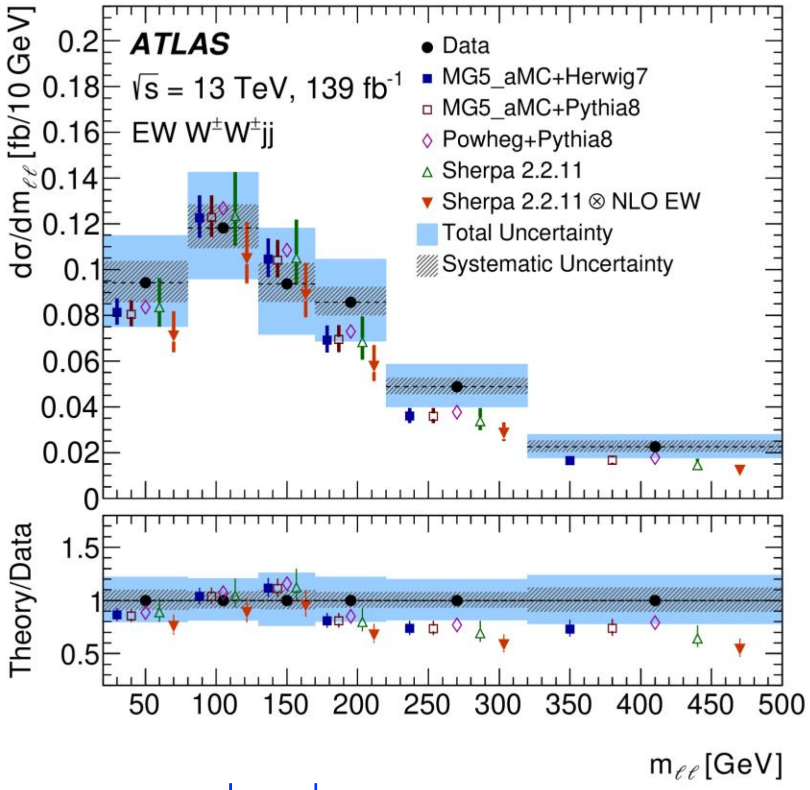
First LHC constraints on T_3, T_4 aQGC operators

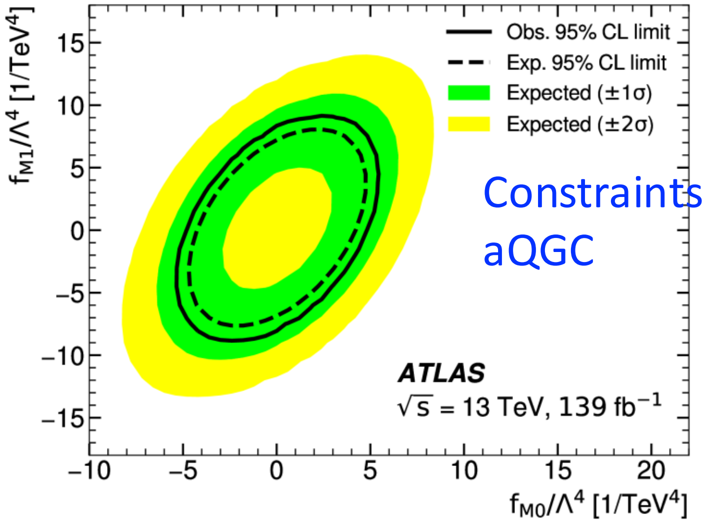
ATLAS $W^{\pm}W^{\pm}jj$ differential

JHEP 04 (2024) 026

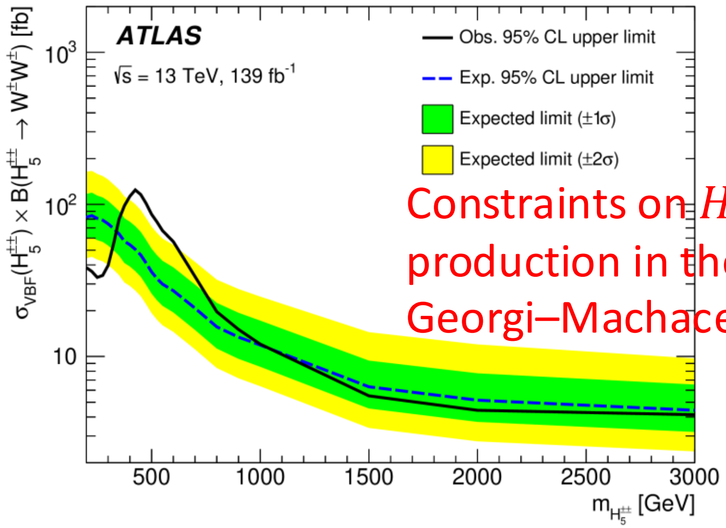
- Already observed by CMS(2018) and ATLAS(2019)
- Precise differential measurements of the EWK and QCD induced $W^{\pm}W^{\pm}jj$







Constraints on aQGC



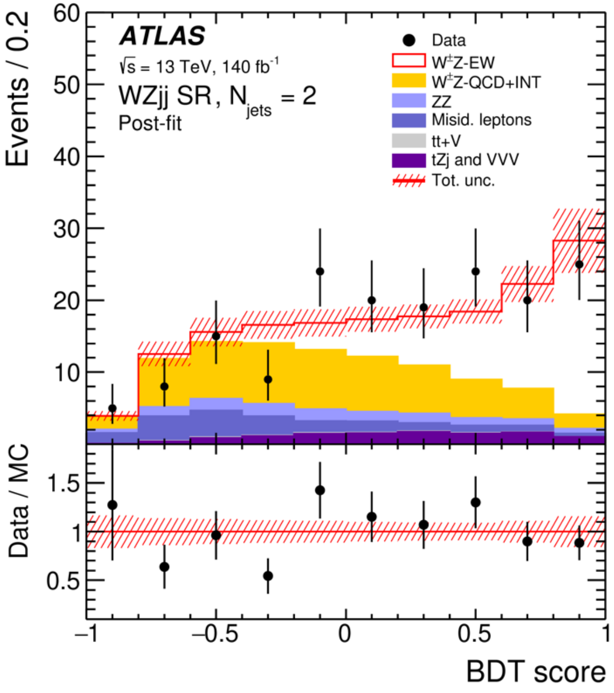
Constraints on $H^{\pm\pm}$ production in the Georgi–Machacek model

Most precise measurements of the EW $W^{\pm}W^{\pm}jj$ production

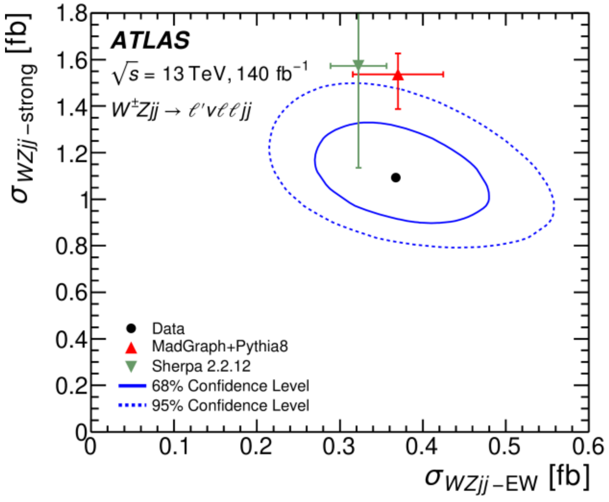
ATLAS $W^{\pm}Zjj$ differential

JHEP 06 (2024) 192

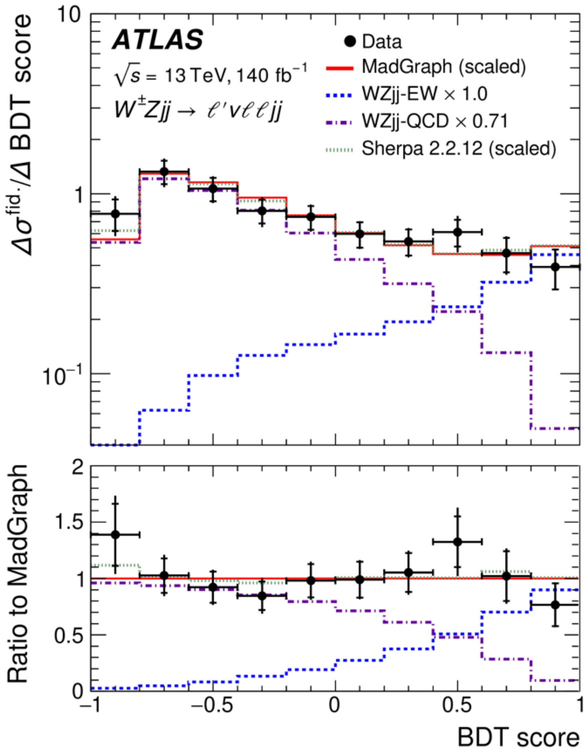
- Already observed by ATLAS(2019) and CMS(2020)
- First precise differential measurements of the EWK and QCD induced $W^{\pm}Zjj$



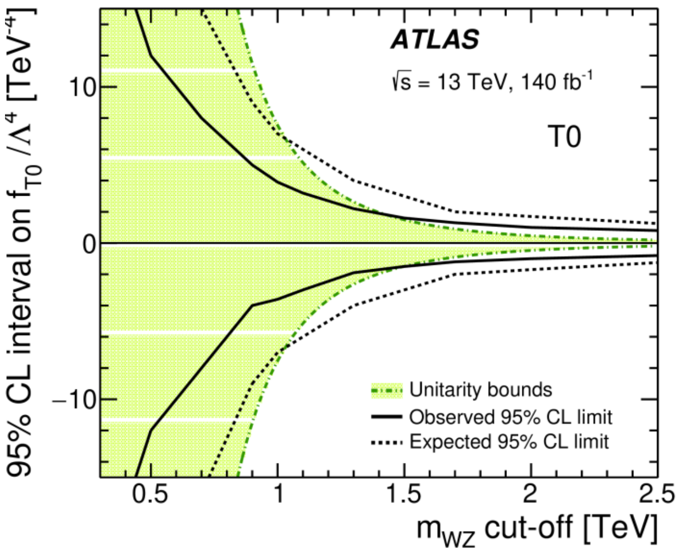
BDT trained to separate the QCD- and EWK- $W^{\pm}Zjj$



Deficit in the measured $W^{\pm}Zjj - QCD$ by a factor of 0.71 (1.8σ)



Unfolded differential cross-sections for various observables: BDT, $m_{jj}, \Delta\phi_{jj}, m_T(WZ)$, etc



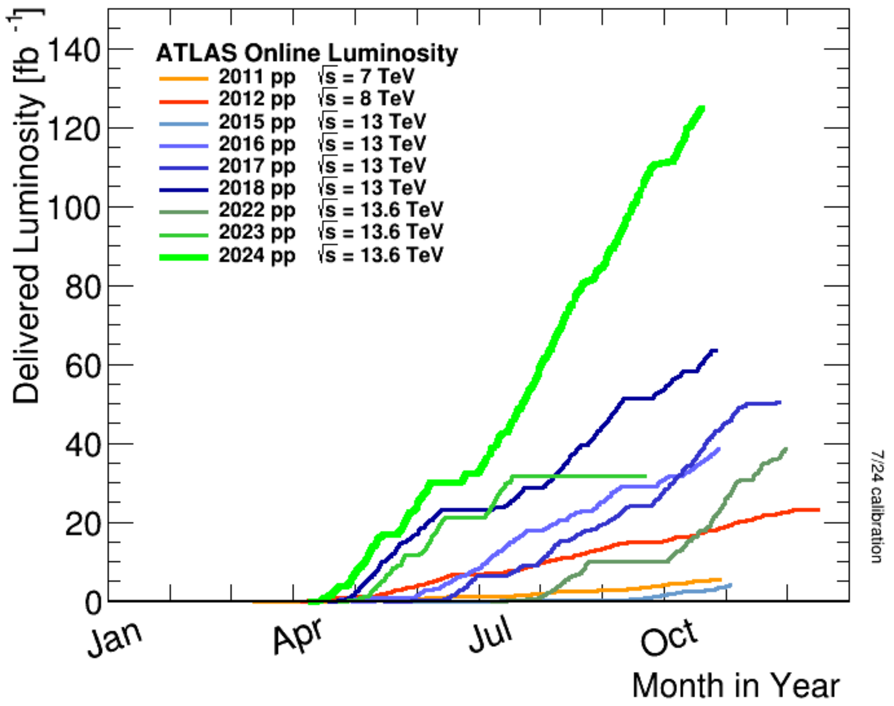
Constraints on aQGC

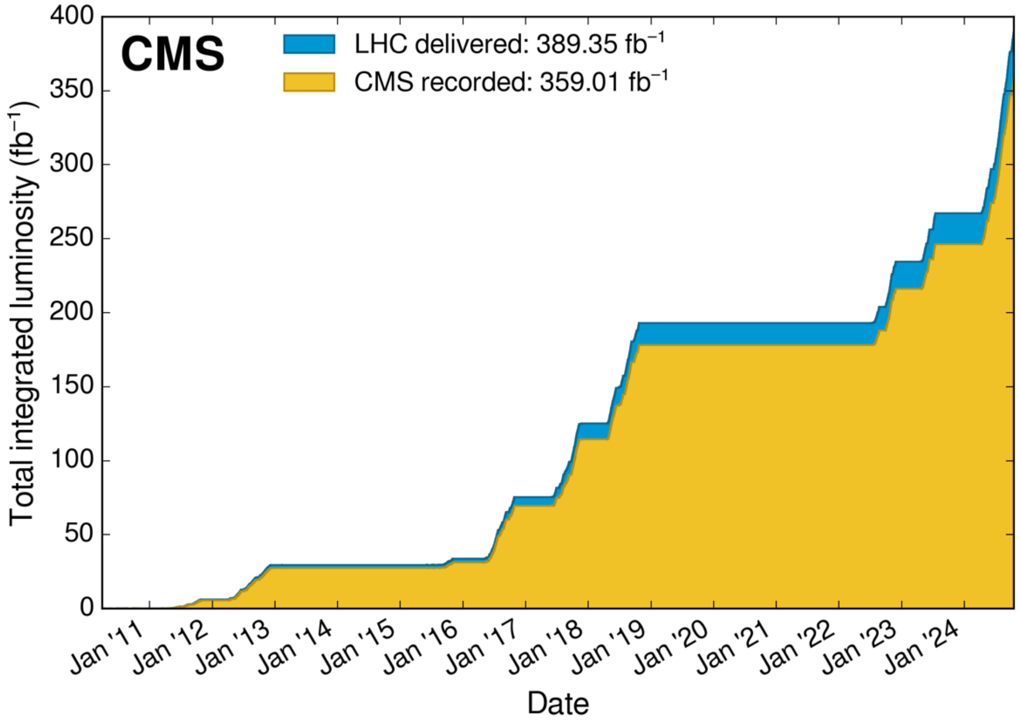
Pushing to the new energy fronter: fresh resutls from Run3

Run3 with 13.6 TeV

ATLAS
CMS

- Ongoing Run3 data taking already exceeds the Full Run2 luminosity



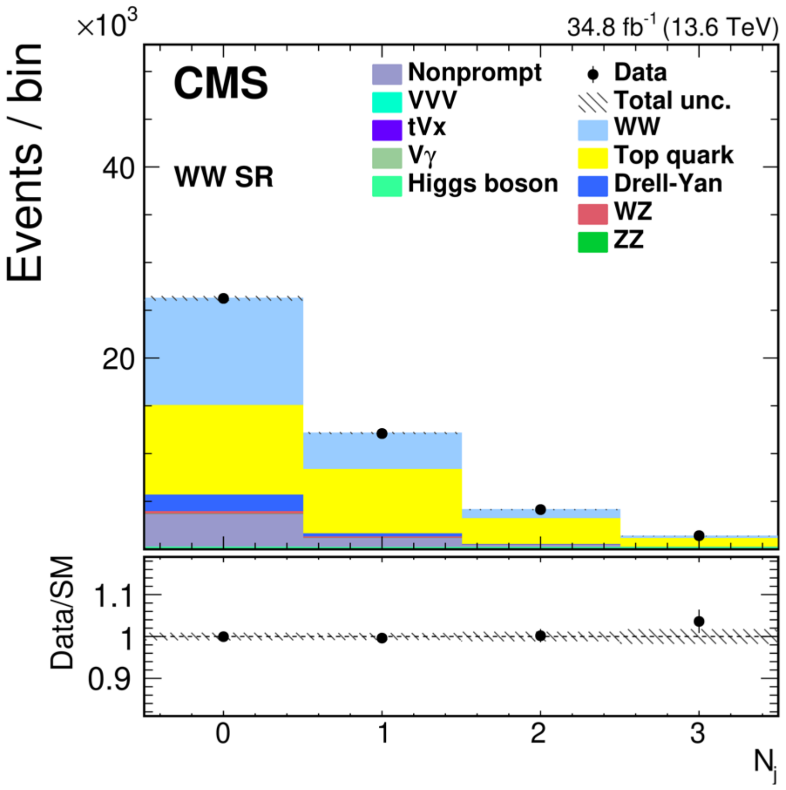


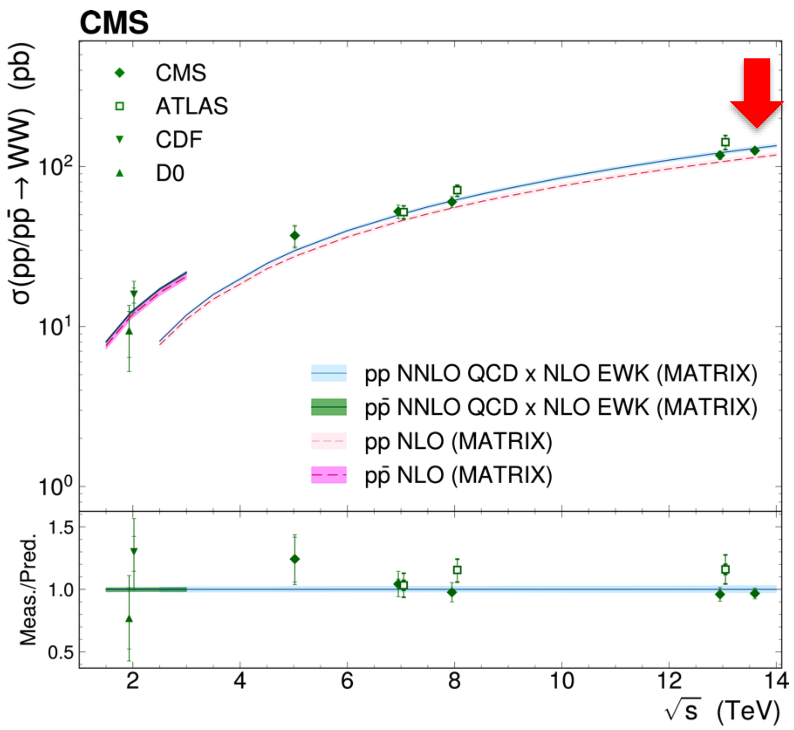
Fresh 13.6 TeV Multiboson Measurements	
ZZ	ATLAS, PLB 855 (2024) 138764
WW	CMS, arXiv:2406.05101
WZ	CMS, SMP-24-005

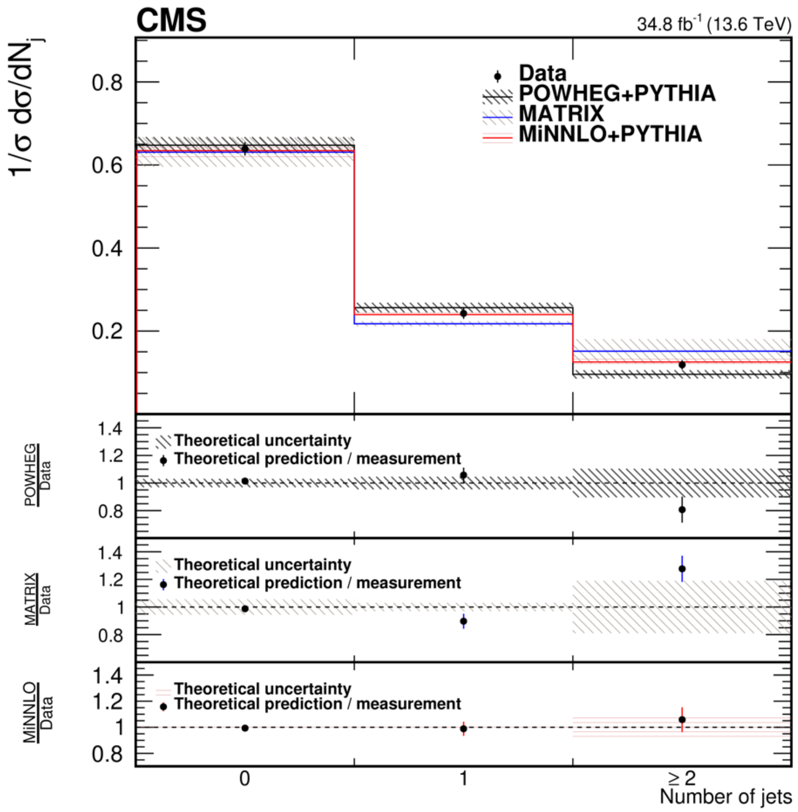
CMS WW production at 13.6 TeV

arXiv:2406.05101

- First Run-3 diboson measurement with the CMS detector using 2022 data(34.7 fb^{-1})
  - With $WW \rightarrow e\nu\mu\nu$ final state





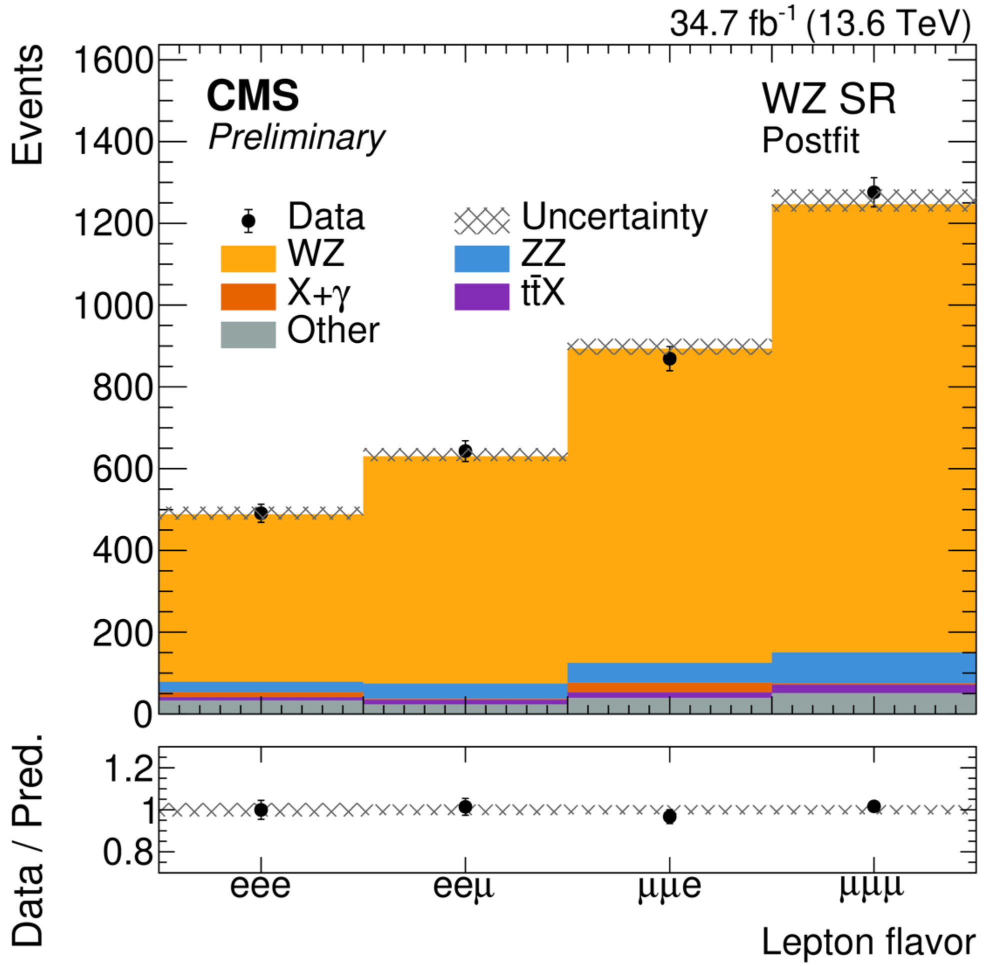


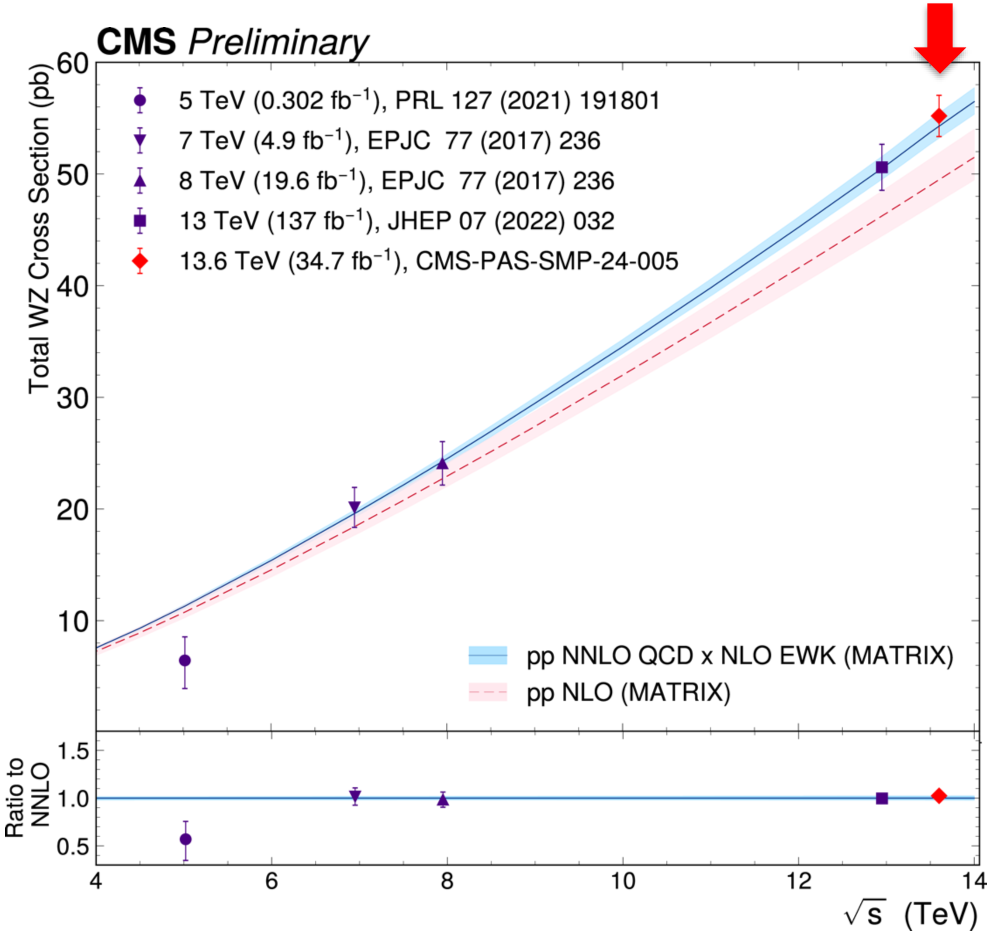
For first time $pp \rightarrow WW + \geq 2\text{jets}$ are studied and compared with the most precise theoretical predictions.

CMS WZ production at 13.6 TeV

SMP-24-005

- Using 2022 data(34.7 fb^{-1}) with $WZ \rightarrow l\nu ll$ final states

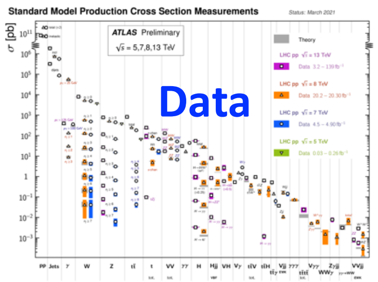




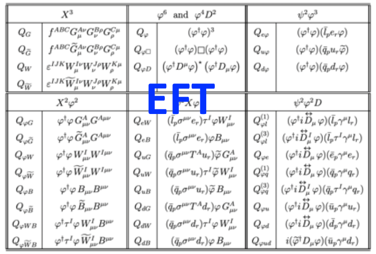
SMEFT Global Fit

SMEFT

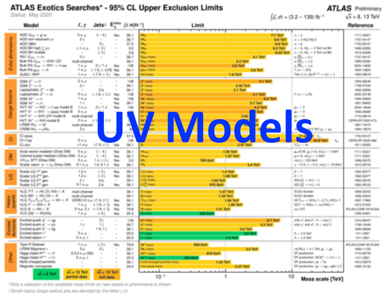
- Effective Field Theories: briedging precision measurements and BSM models



constraints



Interpretation



- SMEFT: SM as an EFT

$$L_{SMEFT} = L_{SM} + \frac{L_5}{\Lambda} + \frac{L_6}{\Lambda^2} + \frac{L_7}{\Lambda^3} + \frac{L_8}{\Lambda^4} + \ldots$$

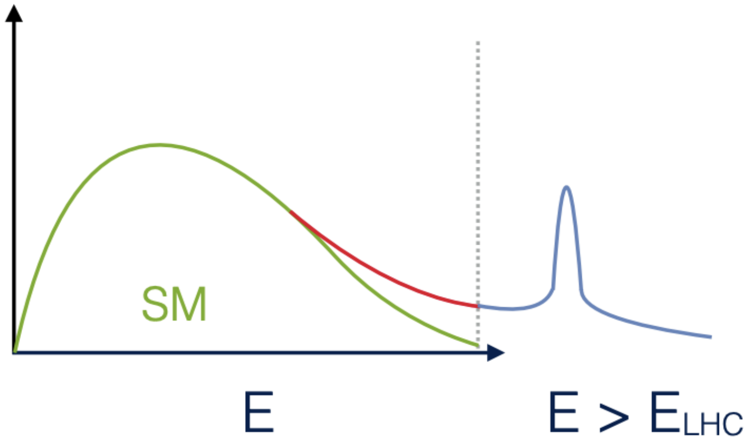
$$L_n = \sum_i C_i O_i^{d=n}$$

C_i free parameters (Wilson coefficients) → encode all UV information

O_i invariant operators that form a complete, non-redundant basis

→ describe the IR information

- ➢ The exact number of operators are known
- ➢ Complete operator bases available for L_5, L_6, L_7, L_8

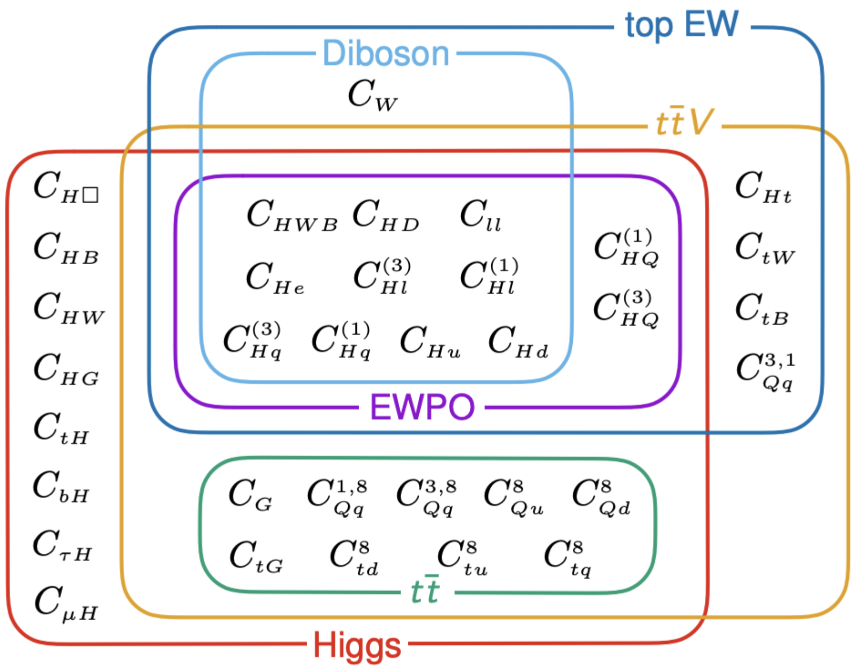


A model-independent way to probe BSM

SMEFT

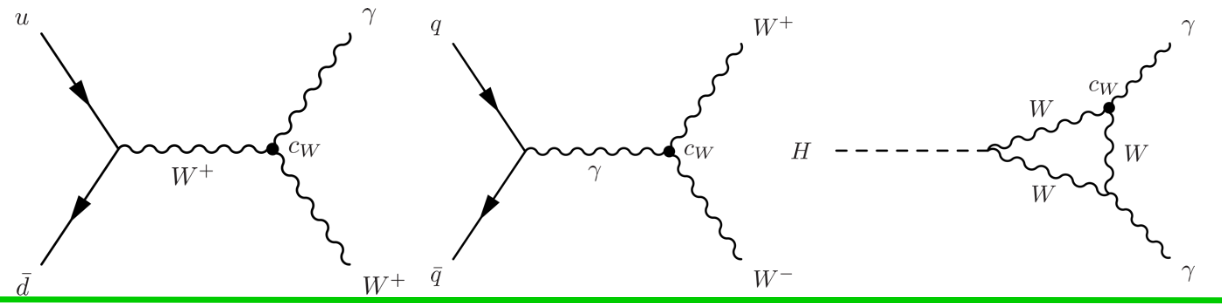
- Power of SMEFT is connection of data from different processes:
  - Higgs, EWK, Top, QCD Jets, etc
- Global EFT fits have been performed in both ATLAS and CMS

CMS-PAS-SMP-24-003
ATL-PHYS-PUB-2022-037



J. Ellis et al, arXiv:2012.02779

Analysis	Type of measurement	Observables used	Experimental likelihood
$H \to \gamma\gamma$	Diff. cross sections	STXS bins [41]	✓
$W\gamma$	Fid. diff. cross sections	$p_T^\gamma \times \lvert\phi_f\rvert$	✓
WW	Fid. diff. cross sections	$m_{\ell\ell}$	✓
$Z \to \nu\nu$	Fid. diff. cross sections	p_T^Z	✓
$t\bar{t}$	Fid. diff. cross sections	$M_{t\bar{t}}$	×
EWPO	Pseudo-observables	Γ_Z, σ^0_{had}, R_ℓ, R_c, R_b, $A^{0,\ell}_{FB}$, $A^{0,c}_{FB}$, $A^{0,b}_{FB}$	×
Inclusive jet	Fid. diff. cross sections	$p_T^{jet} \times \lvert y^{jet}\rvert$	×
$t\bar{t}X$	Direct EFT	Yields in regions of interest	✓

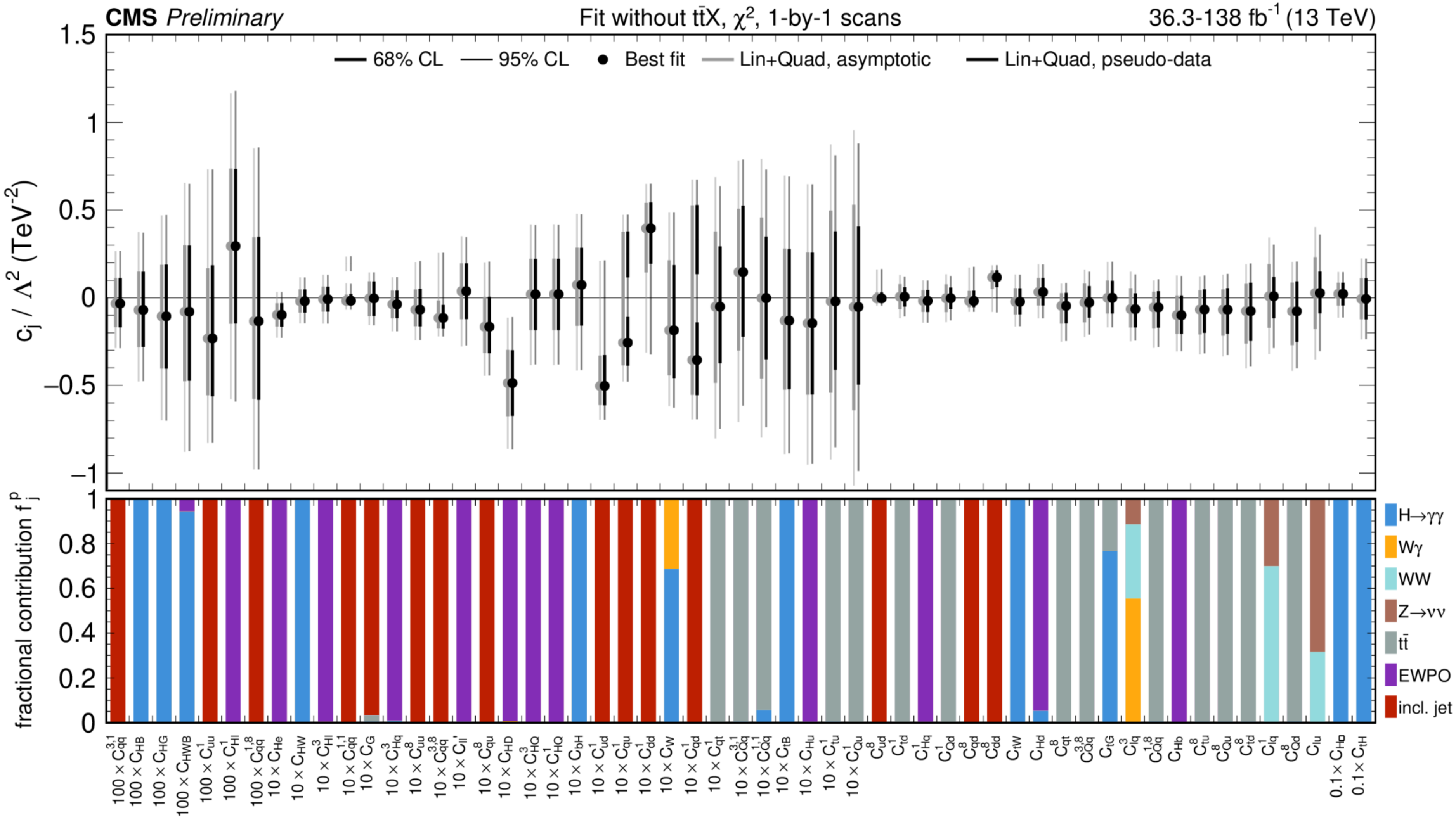


An example of c_W operator affecting $W\gamma, WW, H \to \gamma\gamma$

CMS global EFT fit

CMS-PAS-SMP-24-003

- SMEFT Warsaw basis
- Constraints on Wilson Coefficients
- Constraints also set on linear combinations of WCs (eigen-vectors from the Principal Component Analysis)



Summary

- Multiboson is a benchmark physics program at the LHC
  - Precision test of the SM EWK sector and unique window to New Physics
- Run 2 has been a very productive period for multiboson physics
  - Achieved first observations of several rare processes: triboson, vector boson scattering, polarized gauge bosons
  - Stringent constraints on anomalous triple and quartic gauge couplings
- Looking forward to Run 3 and beyond
  - 13.6 TeV multiboson program is just starting
  - Luminosity already surpassed that from full Run 2
  - Explore novel analysis techniques to deepen our understanding of the EWSB
- Efforts from the theory community essential
  - State-of-the-art predictions, new experimental probes, etc

To further unveil the mystery of EWSB?

https://indico.pnp.ustc.edu.cn/event/2009/

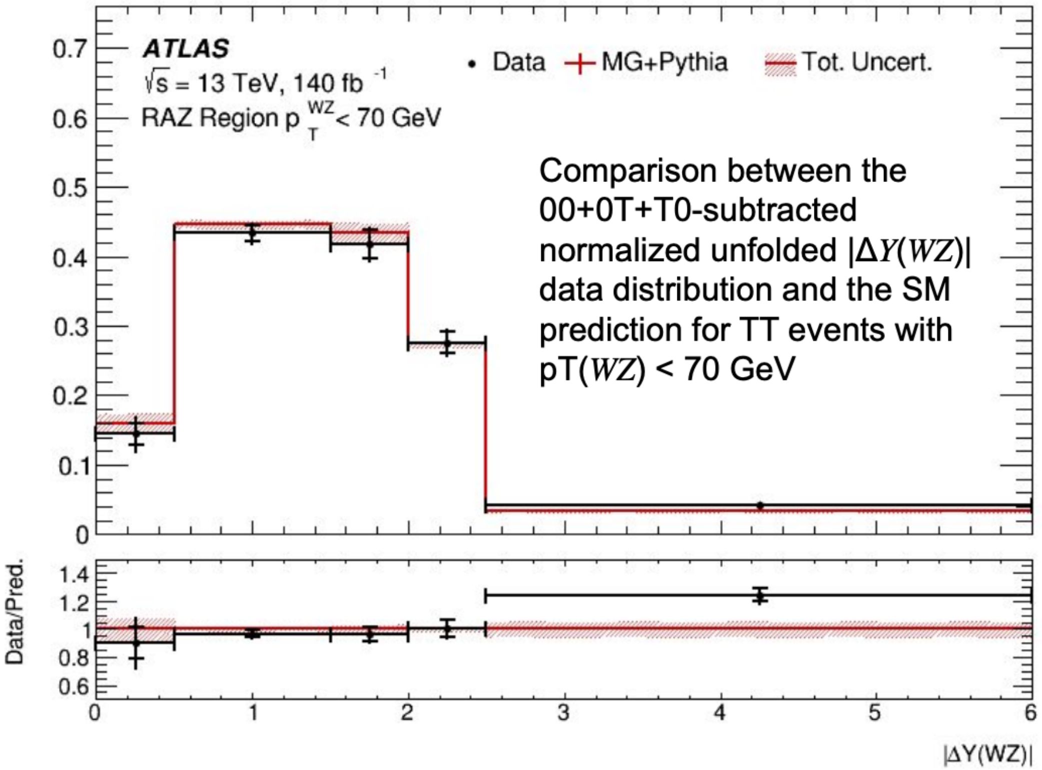
Backup

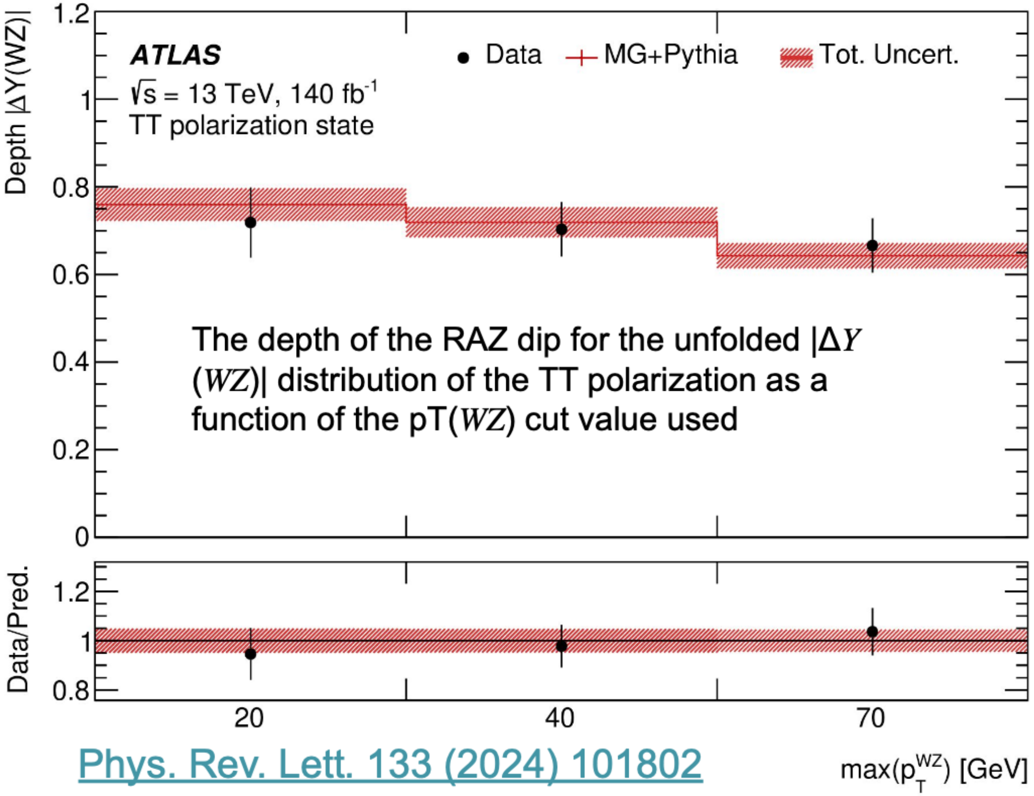
ATLAS WZ RAZ measurement

ATLAS, PRL133 (2024) 101802

The depth of the RAZ dip, represented by the variable $\mathcal{D} = 1 - 2 \times N^{\rm unf}_{\rm central} / N^{\rm unf}_{\rm sides}$

where $N^{\rm unf}{}_{\rm central}$ ($N^{\rm unf}{}_{\rm sides}$) indicates the number of events with $|\Delta Y(WZ)| < 0.5$ ($0.5 < |\Delta Y(\ell_W Z)| < 1.5$) after the unfolding. A positive value of $\mathcal{D}$ indicates the existence of a dip.





Phys. Rev. Lett. 133 (2024) 101802