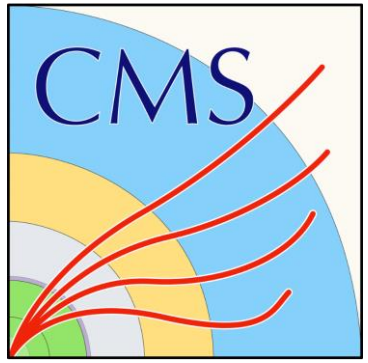


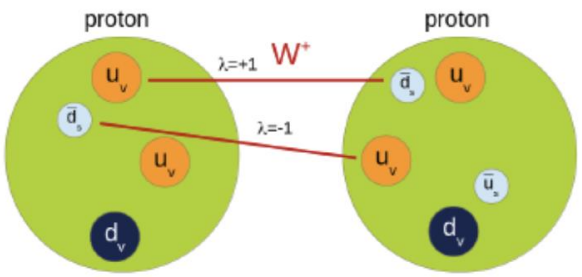
Electroweak measurements at CMS and ATLAS

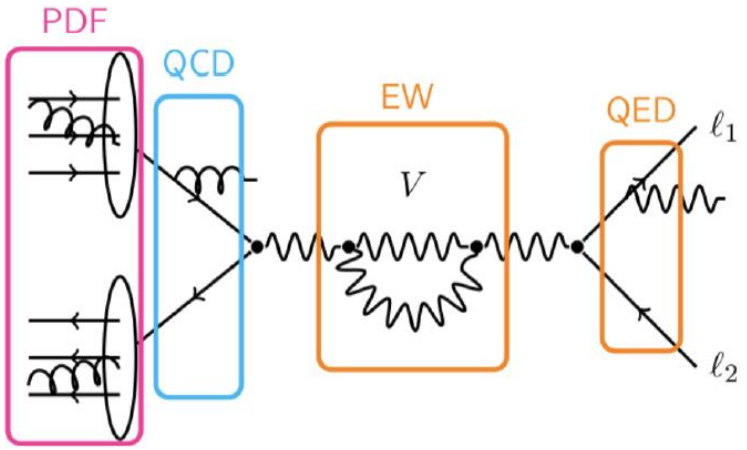
Tairan Xu

23.03.2023

Moriond EW 2023

W/Z measurements





Why the W/Z measurements?

- One of the best understood process in proton collider; cleanest final states
- The Extreme precision is achievable in LHC
  - EWK parameters measurements
  - Probing various QCD effects

ATLAS Wmass Strategy

$$\frac{d\sigma}{dp_1\,dp_2} = \left[\frac{d\sigma(m)}{dm}\right]\left[\frac{d\sigma(y)}{dy}\right]\left[\frac{d\sigma(p_T,y)}{dp_T\,dy}\left(\frac{d\sigma(y)}{dy}\right)^{-1}\right]\left[(1+\cos^2\theta)+\sum_{i=0}^{7}A_i(p_T,y)P_i(\cos\theta,\phi)\right]$$

Breit-Wigner

NNLO pQCD

Parton Shower

Z boson invisible width

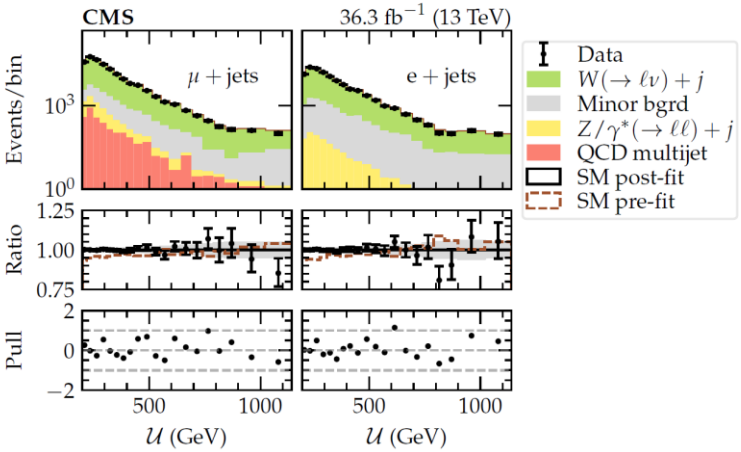
PLB accepted
arXiv:2206.07110

Precision measurement to Z invisible width at 13 TeV: **First Time at a hadron collider!**

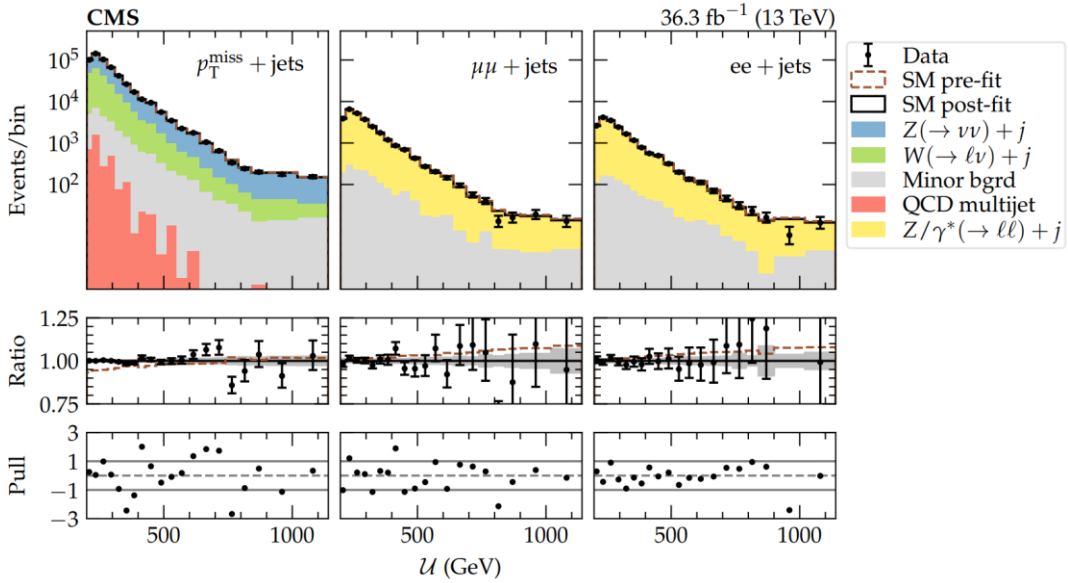
- Z boson decays to particles that are not detected
- constraint on the number of light neutrino species
- reveal non-SM contributions

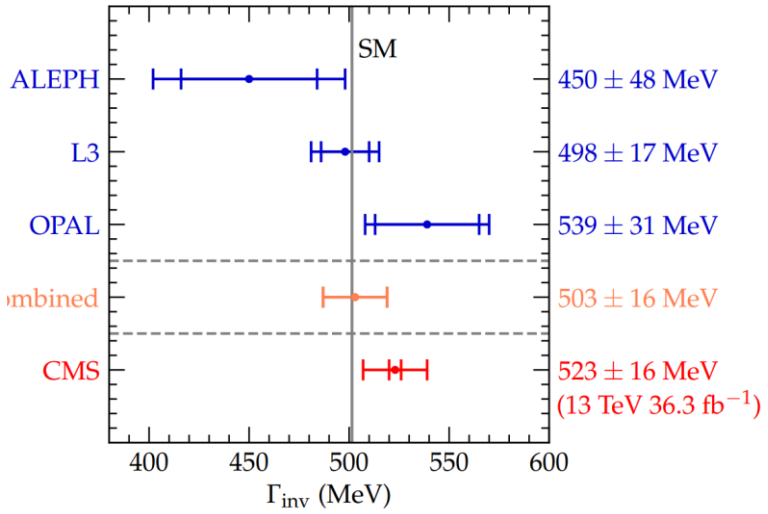
E_T^{miss} reconstructed from calibrated hadronic recoil $u \sim p_T^{W/Z}$

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



$\Gamma_{inv} = 523 \pm 3\,(stat) \pm 16\,(syst)\,MeV.$





τ lepton polarization in Z boson decays

SMP-18-010

$$P_\tau = \frac{1}{\sigma}[\sigma(h_\tau = +1) - \sigma(h_\tau = -1)] \qquad P_\tau = -A_\tau = -\frac{2v_\tau a_\tau}{v_\tau^2 + a_\tau^2} \approx -2 \cdot \frac{v_\tau}{a_\tau} = -2(1 - 4\sin^2\theta_W^{\text{eff}}).$$

Advanced MVA techniques exploited

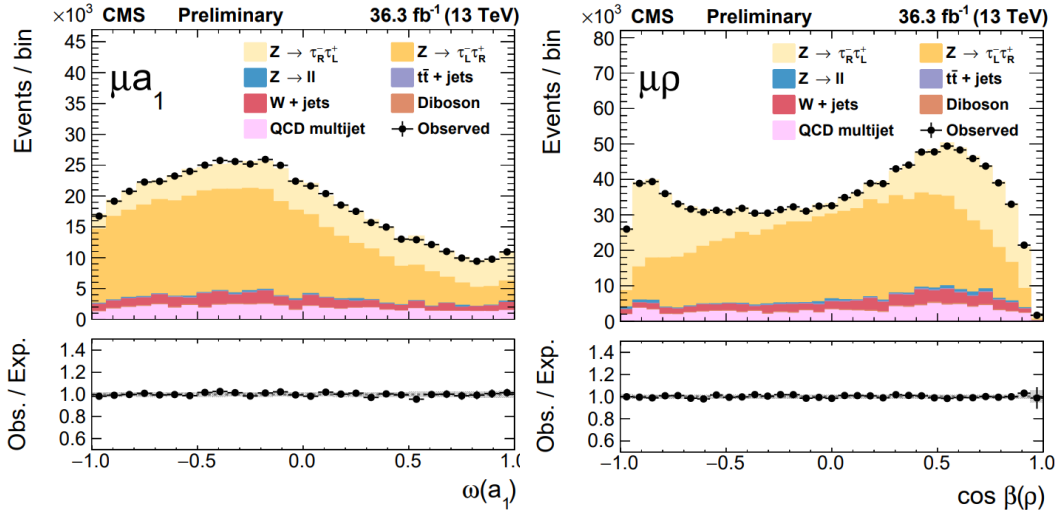
- The DeepTau discriminator for τ_h to reject fakes and improve decay mode purity

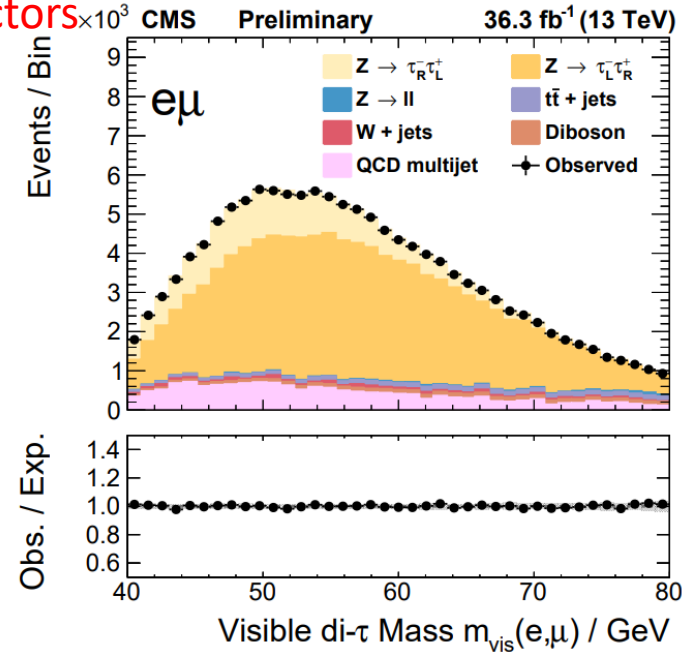
Optimal Observables from previous studies: $\omega_h = \cos\zeta_h$,

$$m_{\text{vis}} = \sqrt{2E_1E_2(1 - \cos\sphericalangle(\tau_1^{\text{vis}}, \tau_2^{\text{vis}}))},$$ polarimetric vectors

Final state	Trigger	Lepton selection	Additional selection
$\tau_h\tau_h$	τ_h (35 GeV)τ_h (35 GeV)	$p_T^{\tau_h} > 45(40)$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.1$	Med DeepTau iso
$\tau_\mu\tau_h$	μ(22 GeV)	$p_T^{\mu} > 23$ GeV, $\lvert\eta^{\mu}\rvert < 2.1$	$I_{rel}(\mu) < 0.15$ $m_T^{\mu} < 50$ GeV
	or μ(19 GeV)τ_h (20 GeV)	$p_T^{\mu} > 20$ GeV, $p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$	Med DeepTau iso
$\tau_e\tau_h$	e(25 GeV)	$p_T^{e} > 30$ GeV, $\lvert\eta^{e}\rvert < 2.1$	$I_{rel}(e) < 0.15$ $m_T^{e} < 50$ GeV
		$p_T^{\tau_h} > 30$ GeV, $\lvert\eta^{\tau_h}\rvert < 2.3$	Med DeepTau iso
$\tau_e\tau_\mu$	μ(8 GeV)e(23 GeV)	$p_T^{e} > 15$ GeV, $\lvert\eta^{e}\rvert < 2.4$	$I_{rel}(e) < 0.15$
	or μ(23 GeV)e(12 GeV)	$p_T^{\mu} > 15$ GeV, $\lvert\eta^{\mu}\rvert < 2.4$	$I_{rel}(\mu) < 0.20$
		$p_T^{\ell} > 24$ GeV for lead trigger leg	

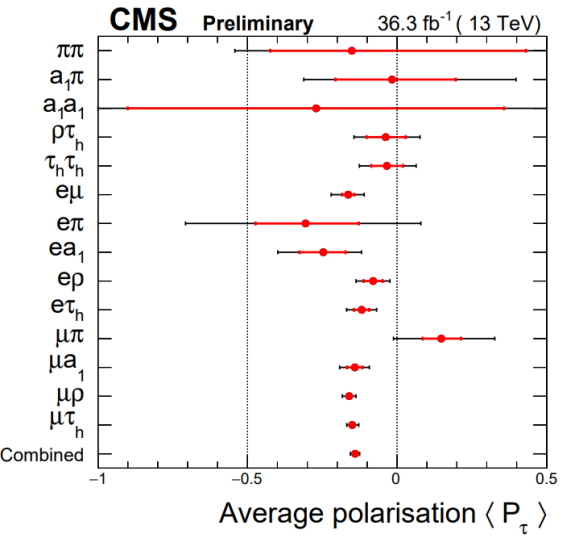
Best-fit templates for different channels

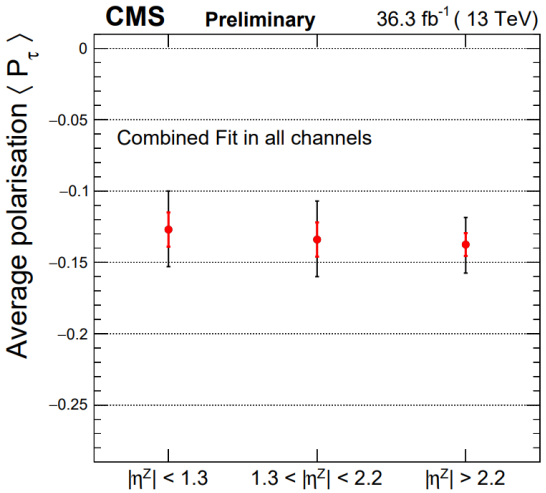


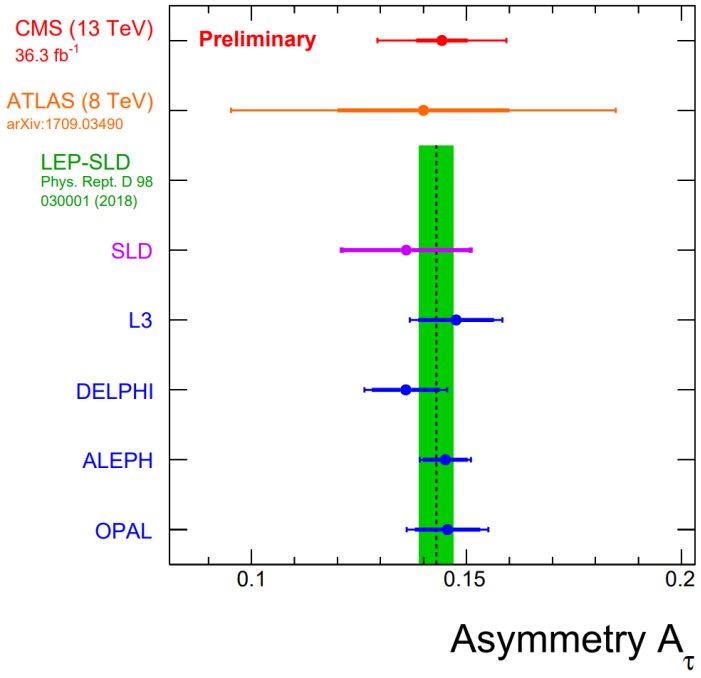


τ lepton polarization in Z boson decays

SMP-18-010







Systs:

- Modellings
- reconstruction
- background

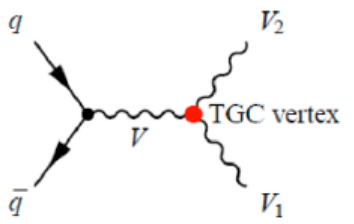
Agree with LEP+SLD results

$$\mathcal{P}_\tau(Z^0) = -0.144 \pm 0.015 = -0.144 \pm 0.006\,(\text{stat}) \pm 0.014\,(\text{syst}).$$

$$\sin^2\theta_W^{\text{eff}} = 0.2319 \pm 0.0019 = 0.2319 \pm 0.0008\,(\text{stat}) \pm 0.0018\,(\text{syst}).$$

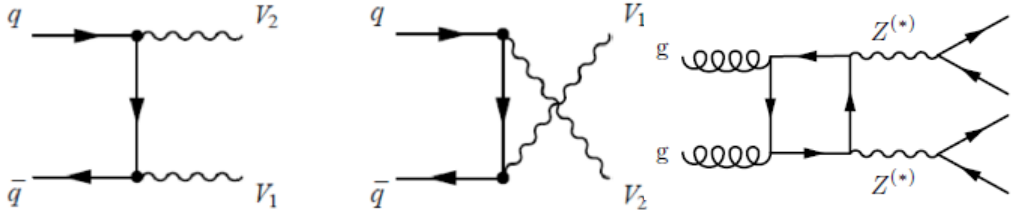
Spin of τ lepton and spin correlations of τ lepton pairs can be determined and used for BSM search regardless of complicated LHC environment: new window is open!

Multi-boson measurements

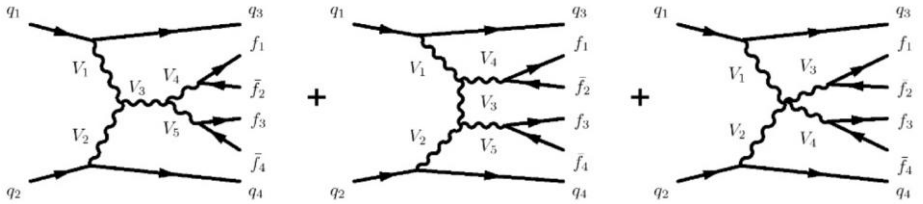


Test the standard model at TeV scale:

- Differential cross-section measurements in validation of current models



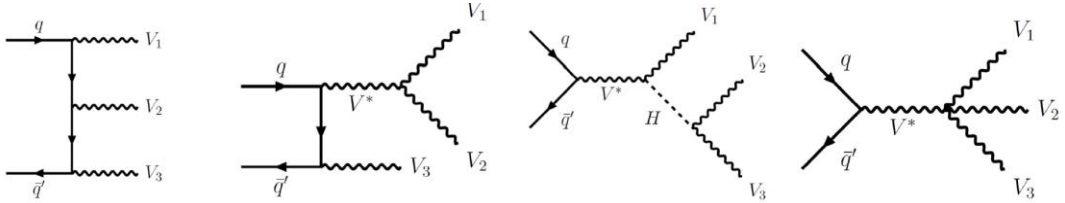
- Vector boson scattering/fusion (VBS/F) processes probe the mechanism of electroweak symmetry breaking



- Triple/Quartic Gauge Couplings (T/QGC):
  - Search for anomalous couplings
  - Probe new physics

- EFT interpretation:

$$\mathcal{L}_{\text{SMEFT}} \approx \mathcal{L}_{\text{SM}}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} O_j^{(8)}$$



$W^{\pm}Z$ polarization measurements

PLB accepted
arXiv:2211.09435

Observation of gauge boson joint-polarization states in W±Z production
- Measured in WZ rest frame: $W_L Z_L$ $(W_0 Z_0)$, $W_T Z_L$, $W_L Z_T$, $W_T Z_T$

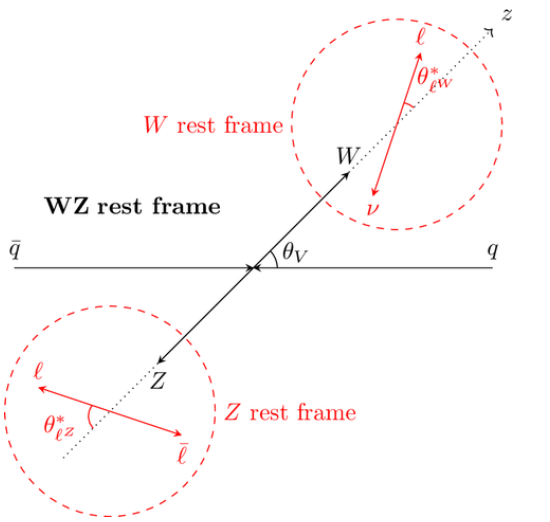
Signal:
- Polarized WZ with MadGraph @ LO → train the DNN model
- Inclusive WZ with Powheg @ NLO + reweighted to polarized states

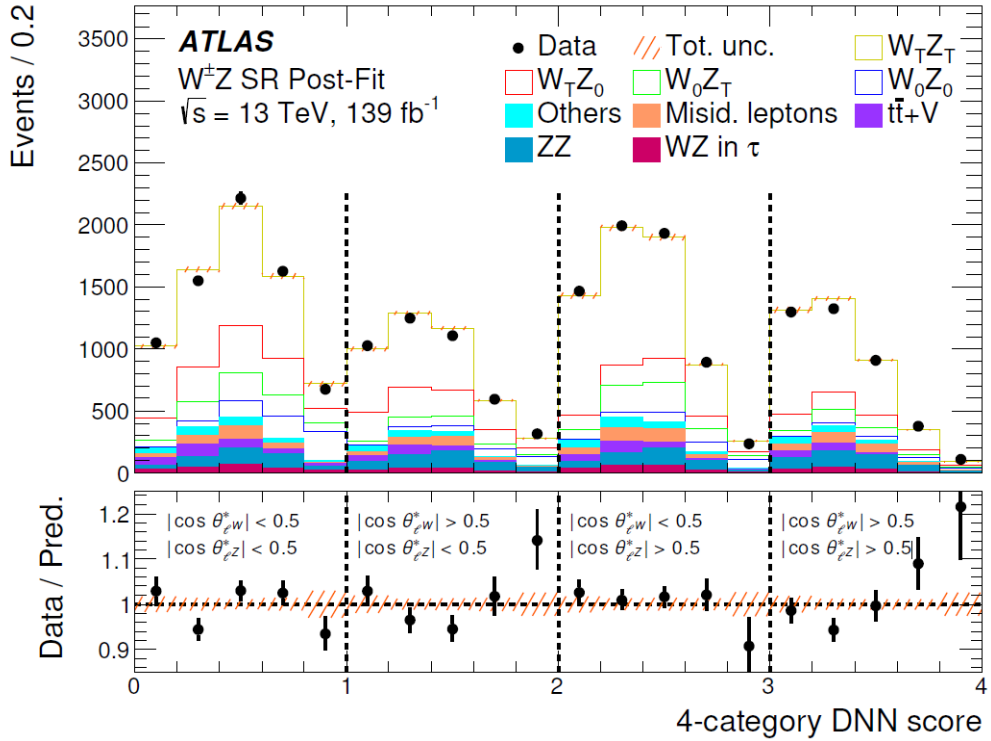
DNN score as discriminator to separate the polarization states:

CMS: WZ single boson polarization SMP-20-014

$$p_T^{WZ}, p_T^{l^W}, p_T^{l_1^Z}, p_T^{l_2^Z}, E_T^{Miss},$$

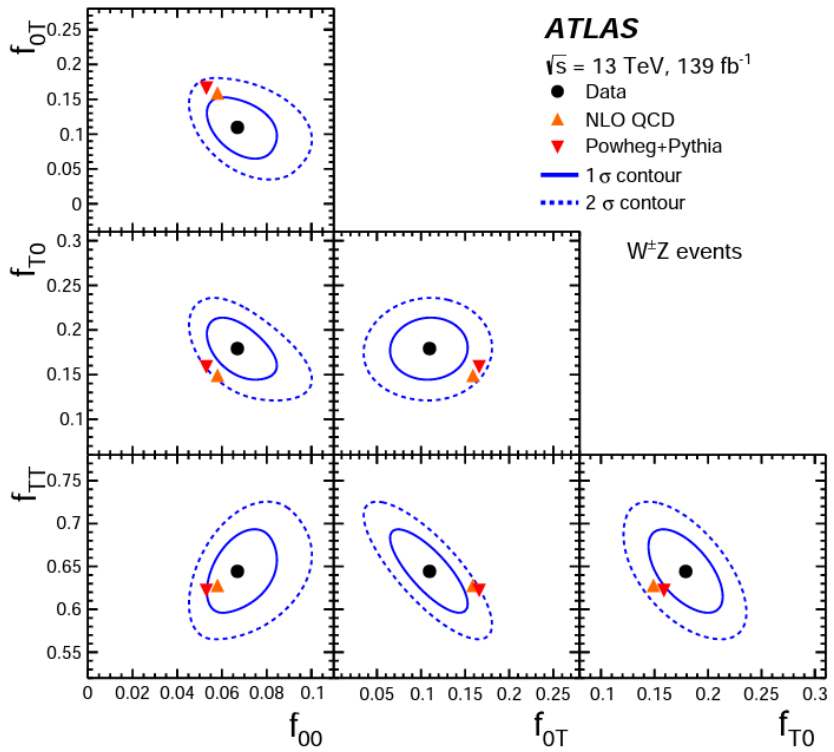
$$|y_Z - y_{\ell^W}|, \ \Delta\phi(\ell^W, \nu), \ \Delta\phi(\ell_1^Z, \ell_2^Z)$$

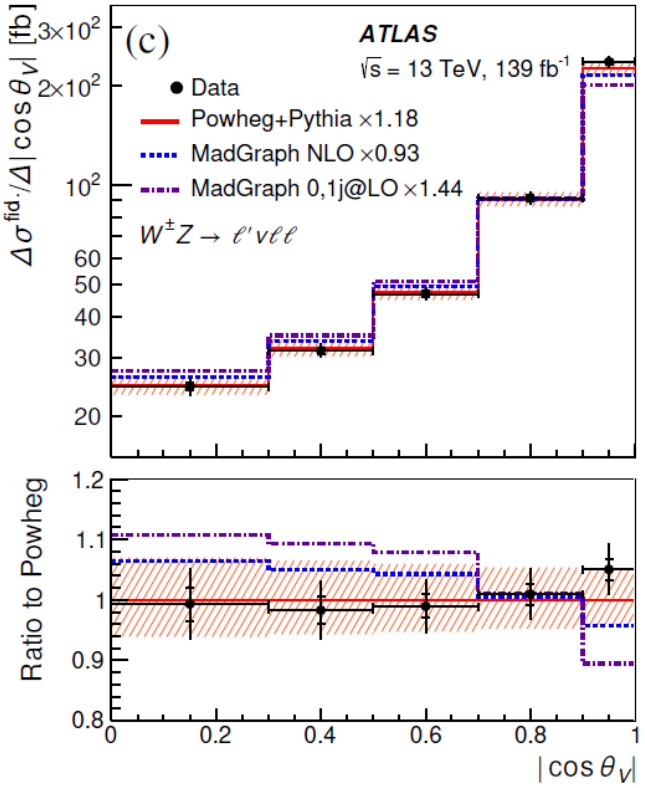




$W^{\pm}Z$ polarization measurements

arXiv:2211.09435



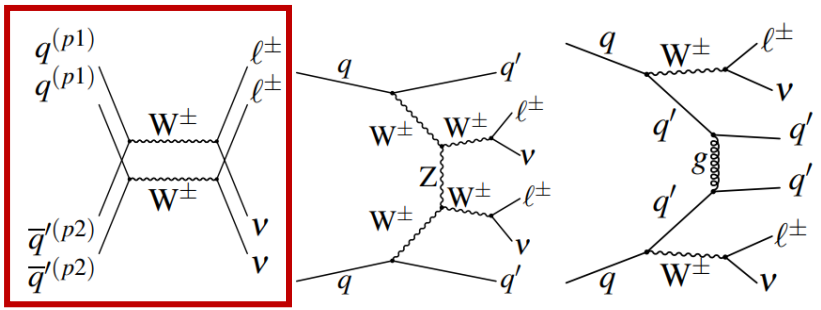


- First Observation of $W_L Z_L$ state: 7.1 (6.2)σ in observation (expectation)
- Different polarized states are measured and compared to prediction
- Differential cross sections are measured for polarization-sensitive variables.

f_{00}=0.067 $\pm$ 0.010, f_{0T} =0.110 $\pm$ 0.029, f_{T0} =0.179 $\pm$ 0.023 and f_{TT} =0.644 $\pm$ 0.032

$W^{\pm}W^{\pm}$ double parton scattering

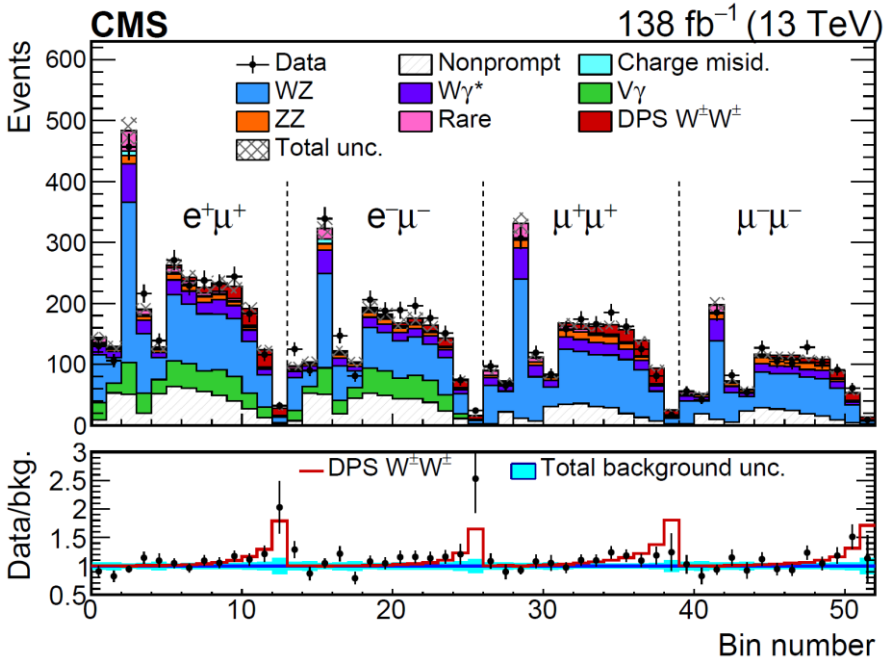
PRL accepted
arXiv:2206.02681



Double parton scattering:

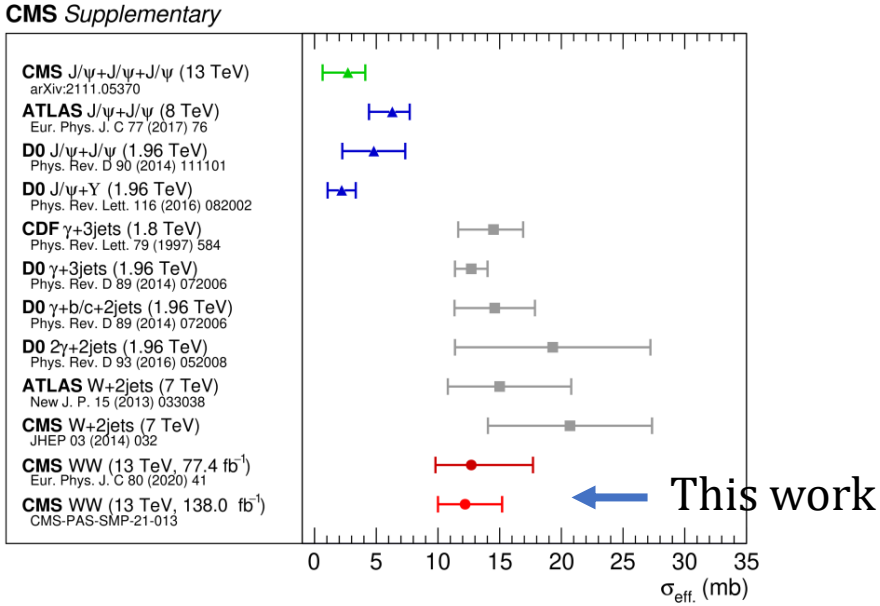
- provides information on the transverse profile of the proton and its energy evolution
- allow the study of correlations among the partons
- Indirect measurement to σ_{eff} $\quad \sigma_{\mathrm{AB}}^{\mathrm{DPS}} = \frac{n}{2}\frac{\sigma_{\mathrm{A}}\sigma_{\mathrm{B}}}{\sigma_{\mathrm{eff}}}$,

Distinguish backgrounds from signal with BDT



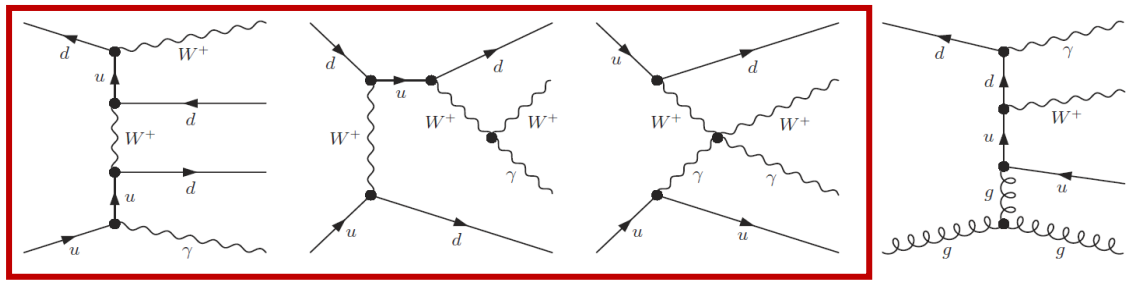
Inclusive Leptonic-decay Xs (6.2 σ observed):

$$80.7 \pm 11.2\,(\mathrm{stat})^{+9.5}_{-8.6}\,(\mathrm{syst}) \pm 12.1\,(\mathrm{model})\ \mathrm{fb}$$



EWK $W\gamma jj$ measurement

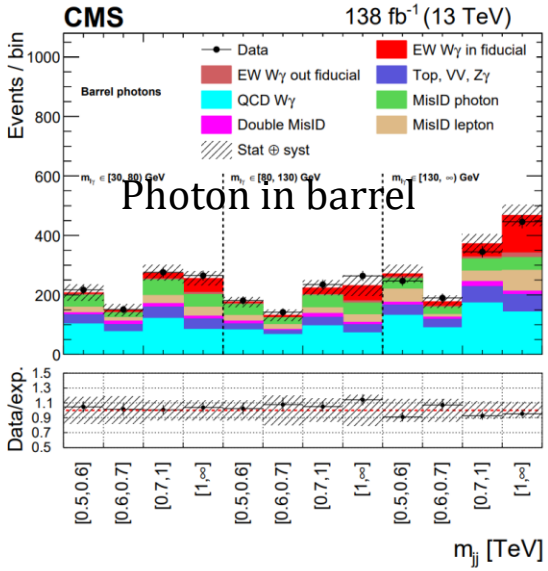
PRD accepted
arXiv:2212.12592



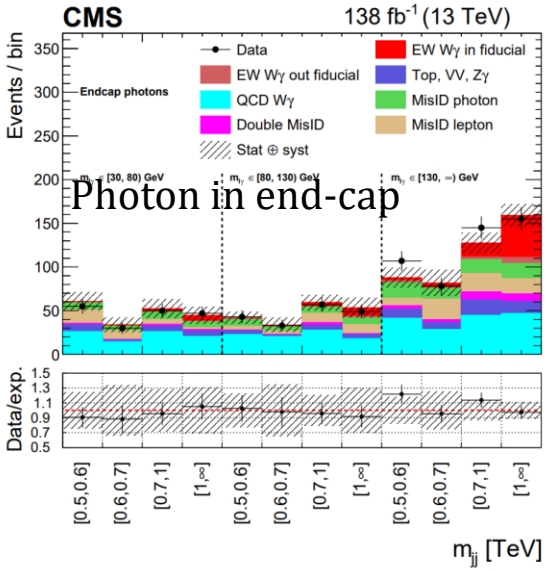
The EWK $W\gamma jj$ production is observed with 6.03 σ (6.79 σ expected).

Fiducial cross-section and differential cross-section are measured.

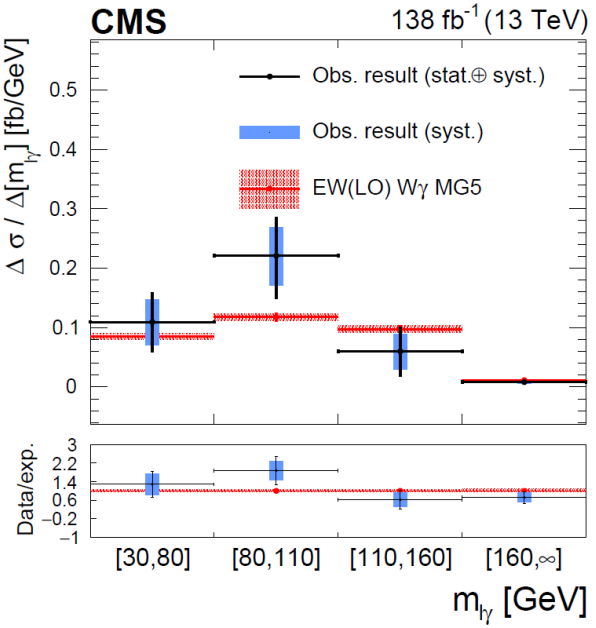
$mjj, m_{l\gamma}$ 2D-fit



Photon in barrel



Photon in end-cap



$$\sigma_{\mathrm{EW}}^{\mathrm{fid}} = 23.5 \pm 2.8\,(\mathrm{stat})^{+1.9}_{-1.7}\,(\mathrm{theo})^{+3.5}_{-3.4}\,(\mathrm{syst})\,\mathrm{fb} = 23.5^{+4.9}_{-4.7}\,\mathrm{fb}.$$

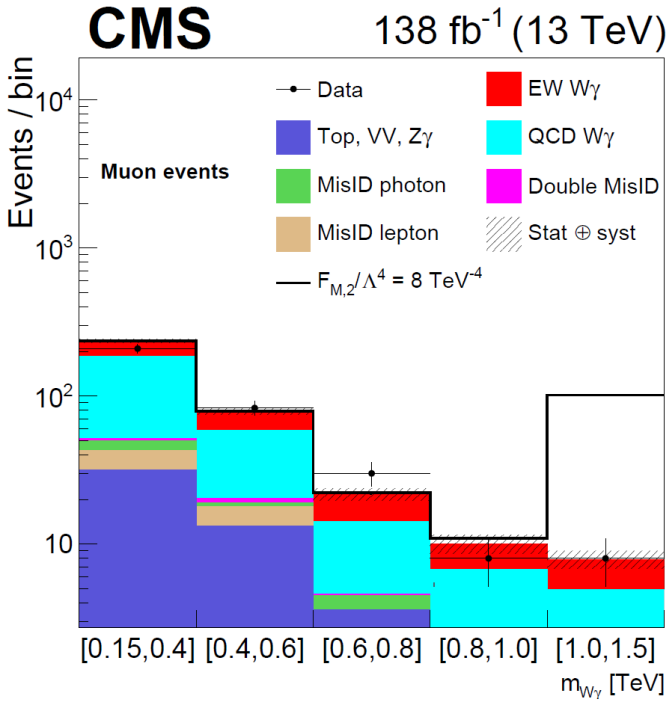
EWK $W\gamma jj$ measurement

PRD accepted
arXiv:2212.12592

The EWK $W\gamma jj$ production can probe the EFT model via anomalous quartic gauge coupling (aQGC) effect.

Strong constraints are set to EFT dim-8 parameters.
Red rectangle contains the most stringent limits.

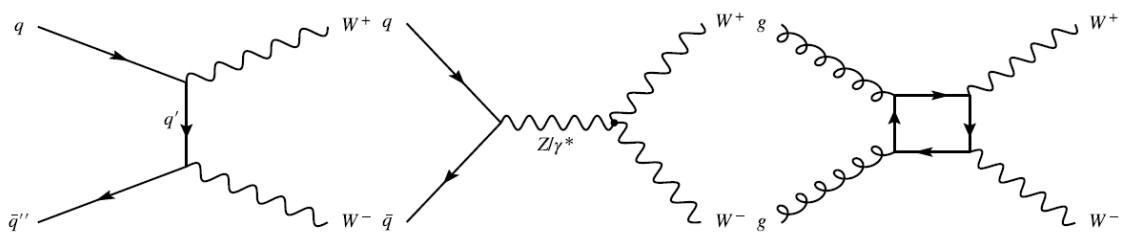
Operators:
- SU(2) strength
- U(1) strength
- Higgs doublet field covariant derivative

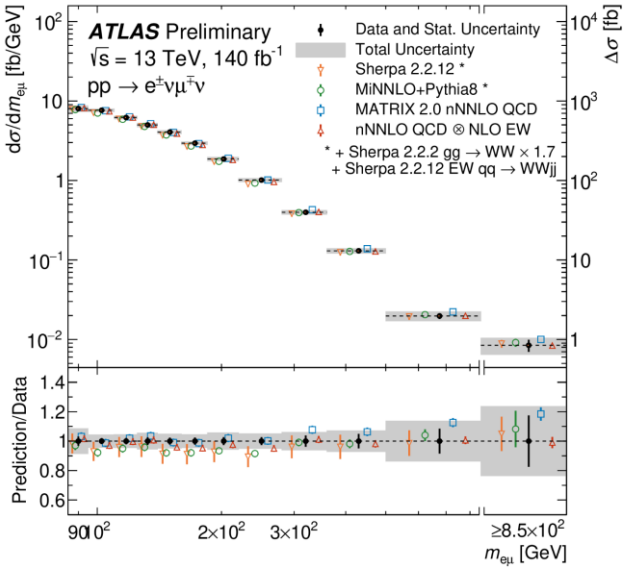


Expected limit	Observed limit	U_{bound}
$-5.1 < f_{M,0}/\Lambda^4 < 5.1$	$-5.6 < f_{M,0}/\Lambda^4 < 5.5$	1.7
$-7.1 < f_{M,1}/\Lambda^4 < 7.4$	$-7.8 < f_{M,1}/\Lambda^4 < 8.1$	2.1
$-1.8 < f_{M,2}/\Lambda^4 < 1.8$	$-1.9 < f_{M,2}/\Lambda^4 < 1.9$	2.0
$-2.5 < f_{M,3}/\Lambda^4 < 2.5$	$-2.7 < f_{M,3}/\Lambda^4 < 2.7$	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

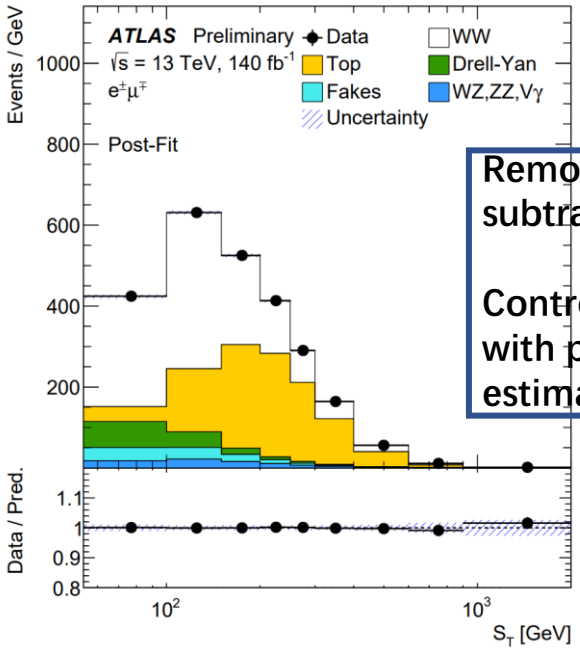
WW inclusive measurement

ATLAS-CONF-2023-012



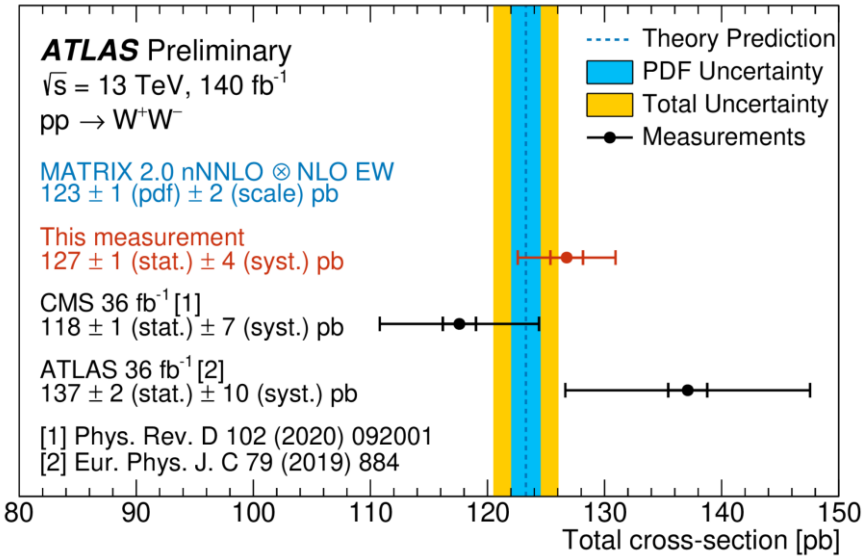


Incl & Diff cross-section measured.
Most precise result at 13 TeV.



Remove the jet veto to subtract uncertainty.

Control Top background with precise differential estimate of jet CRs.



$W\gamma\gamma/WZ\gamma$ observation

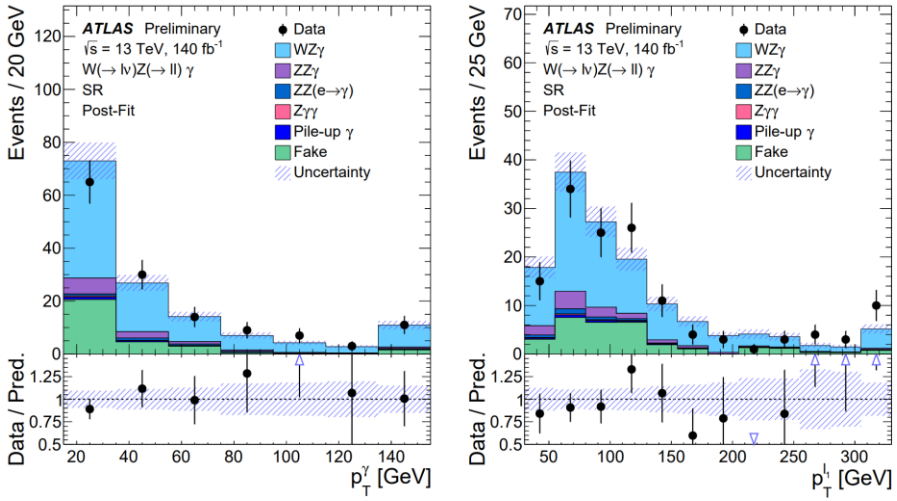
$WZ\gamma$: ATLAS-CONF-2023-014
$W\gamma\gamma$: ATLAS-CONF-2023-005

$WZ\gamma$ observation

Simultaneous fit with $\mu_{ZZ\gamma}, \mu_{ZZ}$;
$WZ\gamma$ observed with 6.3 σ

$$\sigma_{WZ\gamma} = 2.01 \pm 0.30\ (\text{stat.}) \pm 0.16\ (\text{syst.})\ \text{fb}$$

Process	SR	$ZZ\gamma$ CR	$ZZ(e \to \gamma)$ CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e \to \gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Fake background	30 ± 6	-	-
Pile-up γ	1.9 ± 0.7	-	-
Total predicted	139 ± 12	23 ± 5	33 ± 6
Data	139	23	33

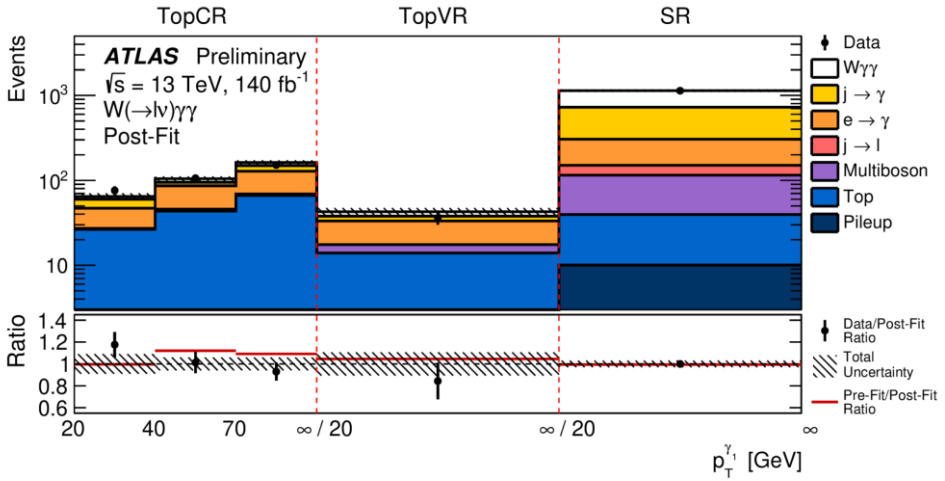


$W\gamma\gamma$ observation

data-driven Fake estimated in control regions
$WZ\gamma$ observed with 5.6 σ

$$\sigma_{fid} = 12.1^{+2.5}_{-2.2}\ \text{fb}^{-1}$$

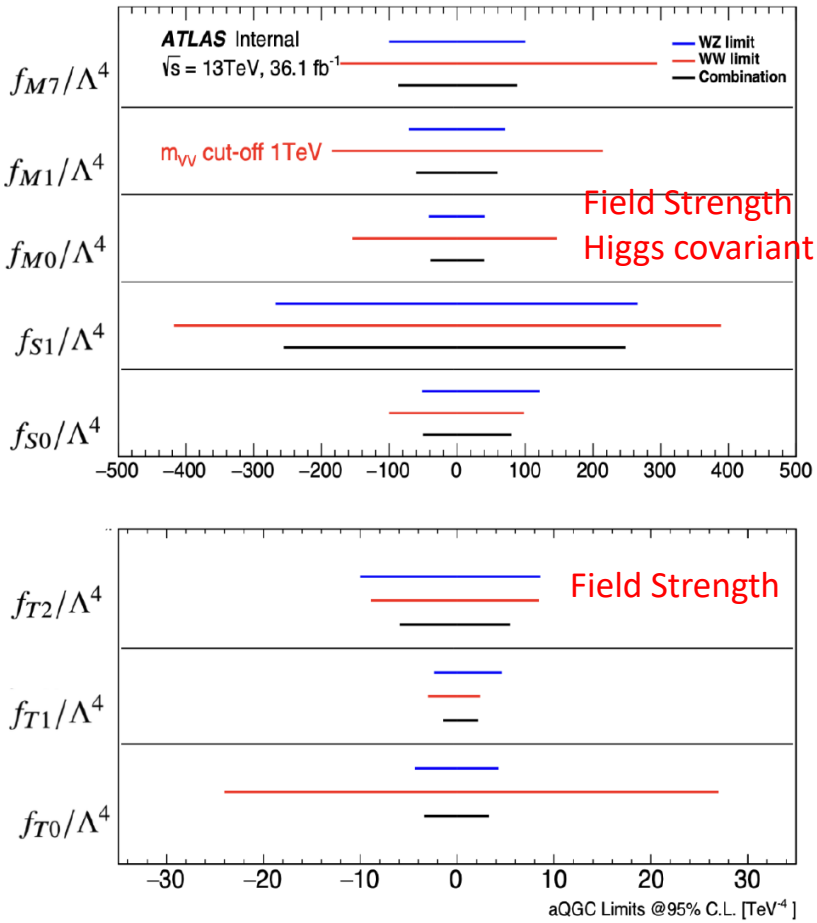
	SR	TopCR
$W\gamma\gamma$	410 ± 60	28 ± 5
Non-prompt $j \to \gamma$	420 ± 50	42 ± 20
Misidentified $e \to \gamma$	155 ± 11	120 ± 9
Multiboson ($WH(\gamma\gamma)$, $WW\gamma$, $Z\gamma\gamma$)	76 ± 13	5.2 ± 1.7
Non-prompt $j \to \ell$	35 ± 10	–
Top ($tt\gamma$, $tW\gamma$, $tq\gamma$)	30 ± 7	136 ± 32
Pileup	10 ± 5	–
Total	$1\,136 \pm 34$	332 ± 18
Data	1 136	333



EFT interpretation

$WZjj$ and $W^{\pm}W^{\pm}jj$ combination using 2015+2016 data: ATL-PHYS-PUB-2023-002

- Dim-8 EFT operators are constrained



First ATLAS EFT global Fit:
ATL-PHYS-PUB-2022-037

SMEFT interpretation constraining dim-6 operators with :

- ATLAS Higgs boson data
- ATLAS electroweak data: di-boson, Z boson
- EW precision observables (EWPO) at LEP and SLC.

Decay channel	Target Production Modes	$\mathcal{L}$ [fb^{-1}]
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139
$H \to WW^*$	ggF, VBF	139
$H \to \tau\tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$	139
$H \to b\bar{b}$	WH, ZH	139
	VBF	126
	$t\bar{t}H$	139

Process	Important phase space requirements	Observable	$\mathcal{L}$ [fb^{-1}]
$pp \to e^{\pm}\nu\mu^{\mp}\nu$	$m_{\ell\ell} > 55$ GeV, $p_{\text{T}}^{\text{jet}} < 35$ GeV	$p_{\text{T}}^{\text{lead. lep.}}$	36
$pp \to \ell^{\pm}\nu\ell^{+}\ell^{-}$	$m_{\ell\ell} \in (81, 101)$ GeV	m_{T}^{WZ}	36
$pp \to \ell^{+}\ell^{-}\ell^{+}\ell^{-}$	$m_{4\ell} > 180$ GeV	m_{Z2}	139
$pp \to \ell^{+}\ell^{-}jj$	$m_{jj} > 1000$ GeV, $m_{\ell\ell} \in (81, 101)$ GeV	$\Delta\phi_{jj}$	139

$$\Gamma_Z,\ \sigma_{\text{had}}^0,\ R_\ell^0,\ A_{\text{FB}}^{0,\ell},\ R_b^0,\ R_c^0,\ A_{\text{FB}}^{0,b},\ \text{and}\ A_{\text{FB}}^{0,c}$$

Global EFT

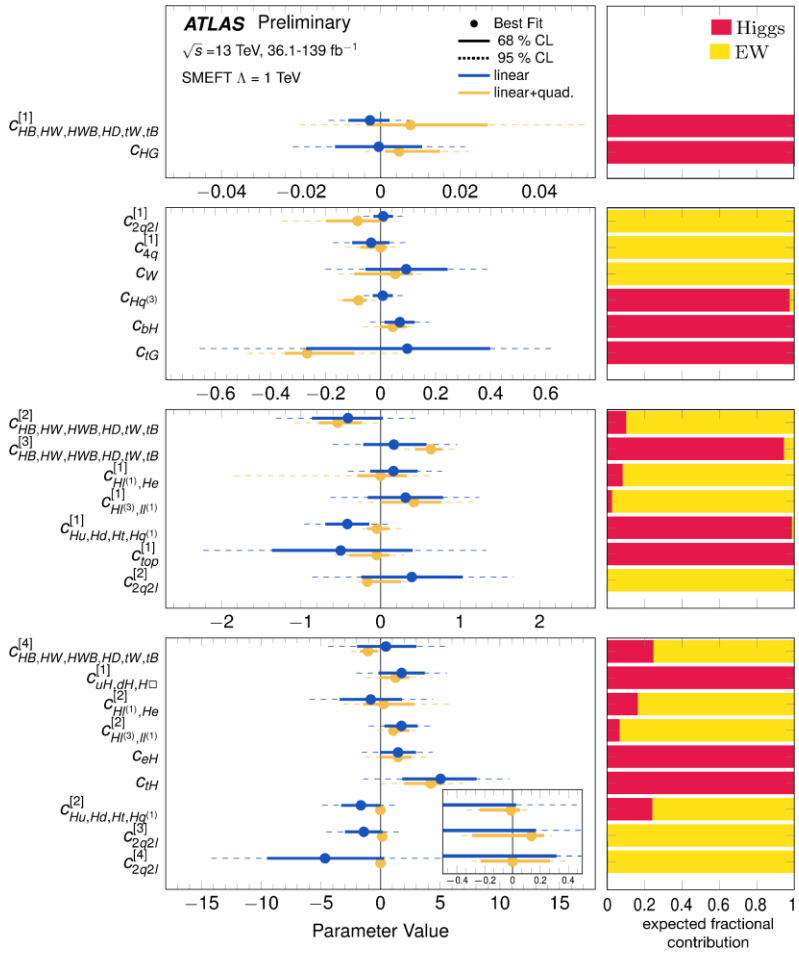
ATL-PHYS-PUB-2022-037

No New Deviations from SM observed

ATLAS only

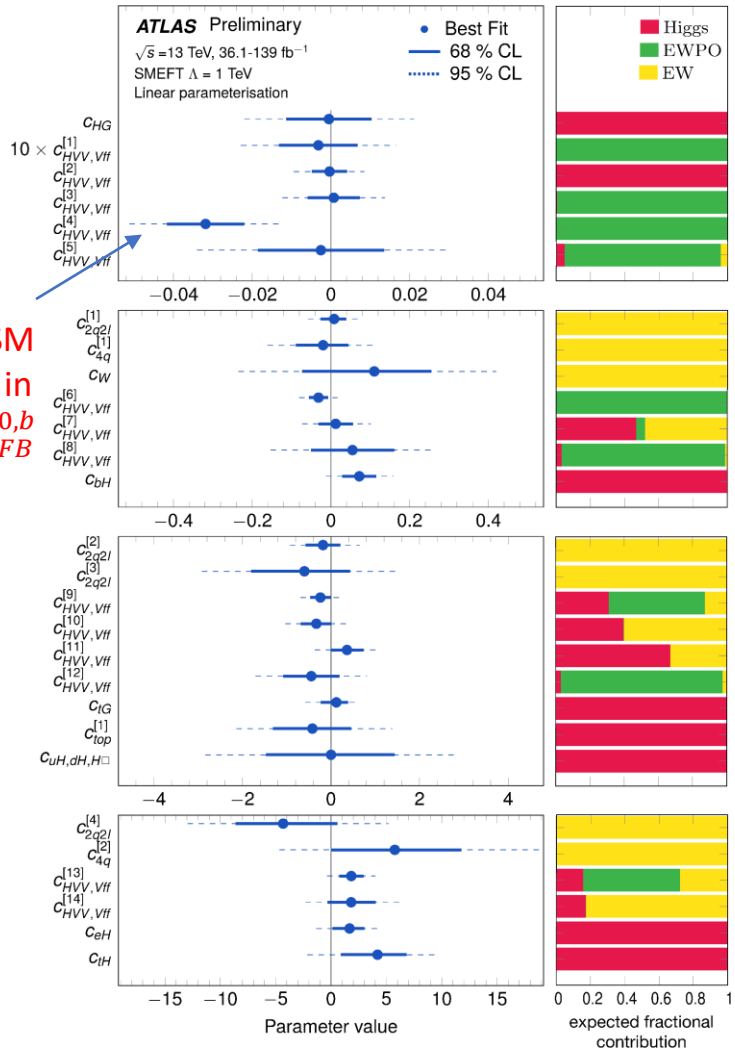
linear combinations of wilson coefficients

ATLAS + EWPO



linear+quad provided as an insight of the impact of higher order terms

From SM excess in $A_{FB}^{0,c}, A_{FB}^{0,b}$



A SMEFT framework is built to include additional results straightforward.

Summary

- New single- and multi-boson measurements at the LHC
  - Precision measurement of the Z boson invisible width
  - Measurement of the τ lepton polarization in Z boson decays
  - Polarization measurements in EWK WZ process
  - Azimuthal correlations in Z+jets events (backup)

- Observation of several rare multi-boson production processes:
  - $W^{\pm}W^{\pm}$double parton scattering at CMS
  - $W^{+}W^{-}jj$ process at CMS
  - $W^{+}W^{-}jj$ at CMS (backup)
  - $W\gamma\gamma$ at ATLAS
  - $WZ\gamma$ at ATLAS
  - EW $Z(\rightarrow \nu\nu)\gamma jj$ with high p_T^{γ} process in at ATLAS (backup)

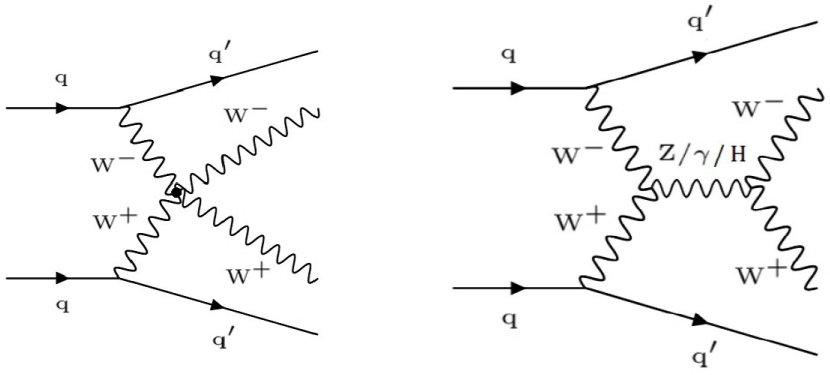
- New & Strong constraints on New Physics (EFT):
  - Including new rare processes;
  - Combinations

Challenges and opportunities ahead with more data and higher quality !

Backup

Observation of W^+W^-jj production

Phys.Lett.B accepted
arXiv:2205.05711



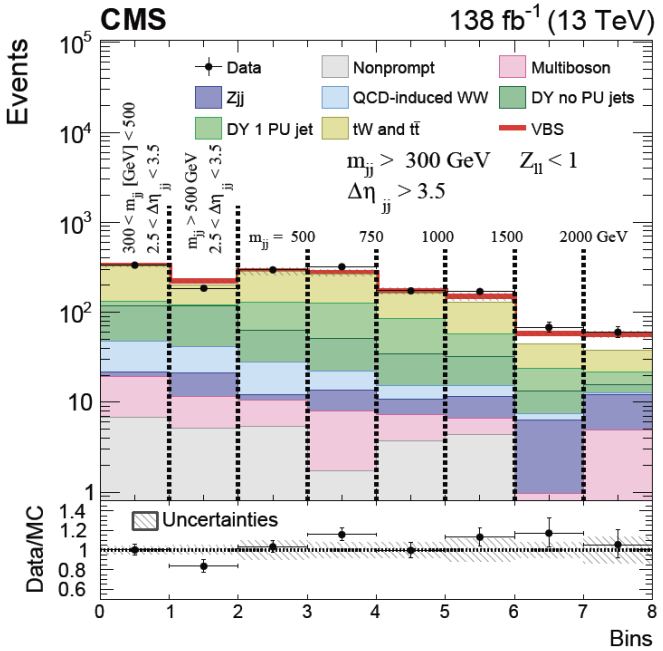
Vector boson scattering measurement:

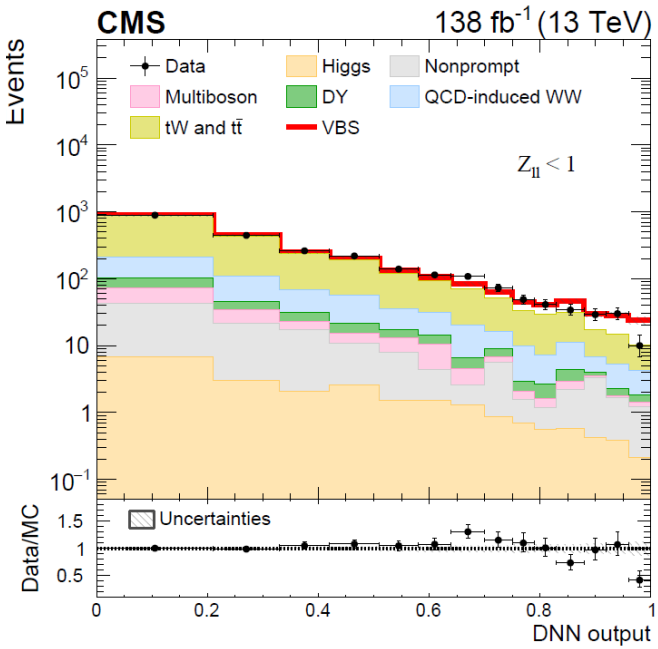
- Probe the nature of Higgs sector
- Search for BSM effects

DNN exploited to increase the sensitivity

- Large $\Delta\eta_{jj}$, m_{jj}, small Zeppenfeld

$$Z_{l1l2} = \frac{1}{2}\left|\left(\eta_{l1} - \frac{1}{2}(\eta_{j1}+\eta_{j1})\right) + \left(\eta_{l1} - \frac{1}{2}(\eta_{j1}+\eta_{j1})\right)\right|$$





Results:

- **Observed (expected) with 5.6 (5.2) σ**
- **Fiducial cross-section measured 10.2 $\pm$2.0 fb (9.1 $\pm$0.6 fb expected)**

Azimuthal correlations in Z+jets

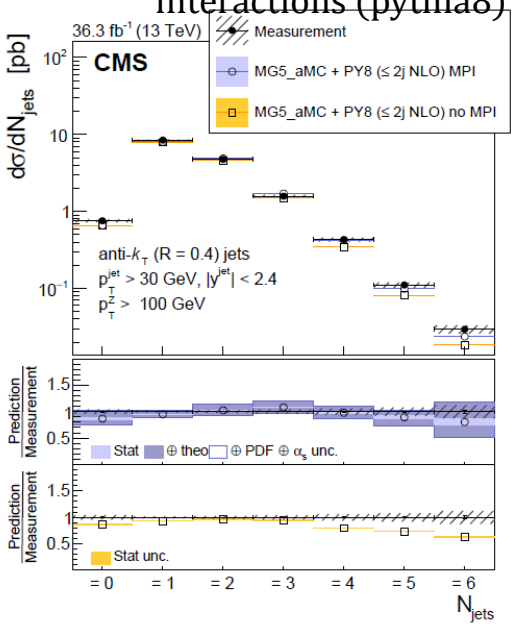
EPJC accepted
arXiv:2210.16139

Measurement to the azimuthal correlation $\Delta\phi$ between Z and leading jet, and two leading jets in p_T^Z categories; compared to various theoretical predictions.

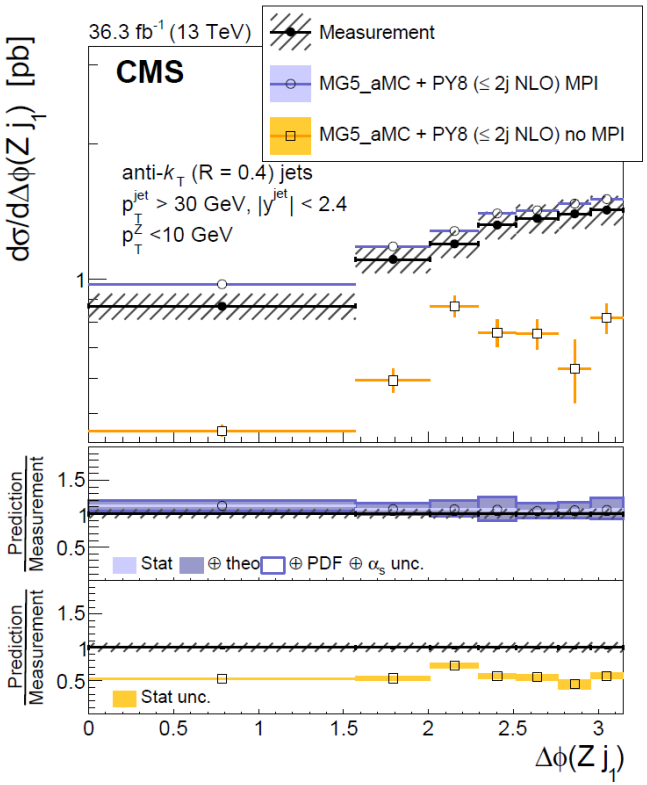
- Hard partonic radiation increases in high p_T^Z : probe QCD effects
- To study the NLO production with PS and hadronization as well as jet multiplicity

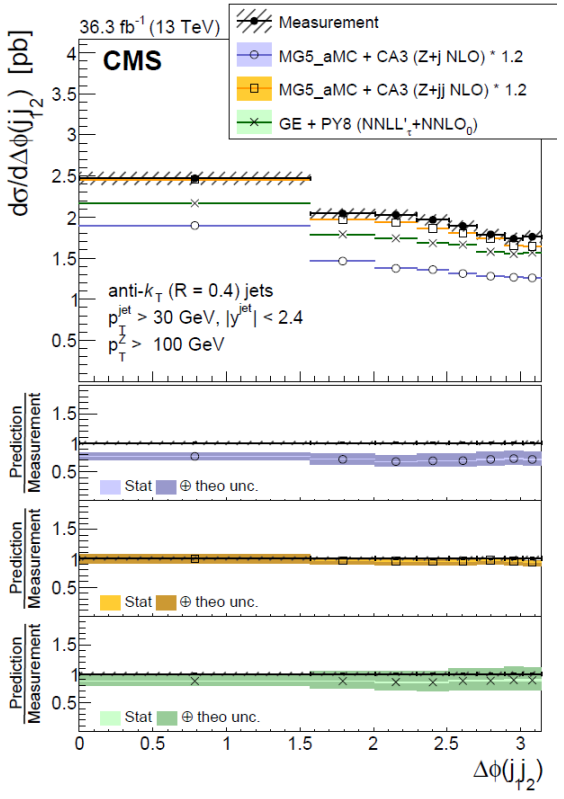
Generator	PDF	Matrix element	Tune
MG5_aMC+Py8 (≤ 2*j* NLO) [37]	NNPDF3.0 (NLO) [43]	NLO (2 → Z+0,1,2)	CUETP8M1 [44]
MG5_aMC+Py8 (≤ 4*j* LO) [37,53]	NNPDF2.3 (LO) [48]	LO (2 → Z+0,1,2,3,4)	CUETP8M1 [44]
MG5_aMC+CA3 (Z+1 NLO) [37]	PB NLO set2 (NLO) [20]	NLO (2 → Z+1)	—
MG5_aMC+CA3 (Z+2 NLO) [37]	PB NLO set2 (NLO) [20]	NLO (2 → Z+2)	—
MG5_aMC+CA3 (Z≤ 3*j* LO) [37,51]	PB NLO set2 (NLO) [20]	LO (2 → Z+0,1,2,3)	—
GENEVA (Z+0 NNLO) [22–25]	NNPDF3.1 (NLO) [54]	NNLO (2 → Z)	CUETP8M

Multiparton interactions (pythia8)



Measured in p_T^Z [0, 10],[30,50],[100,] categories



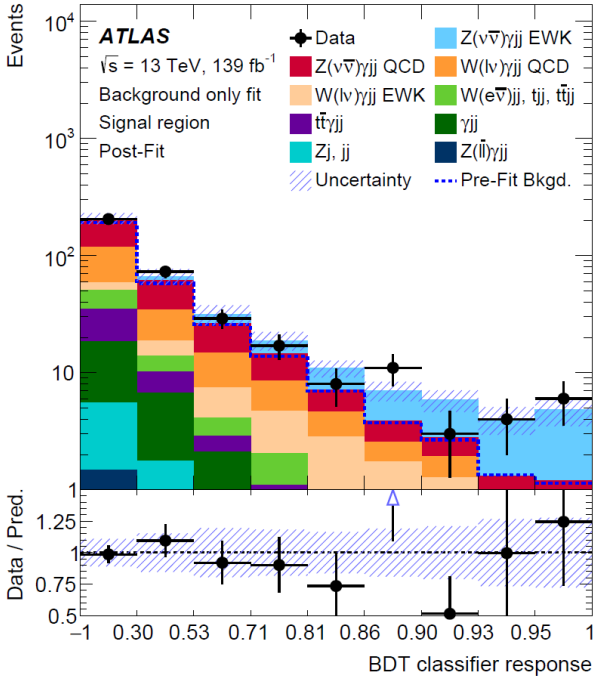


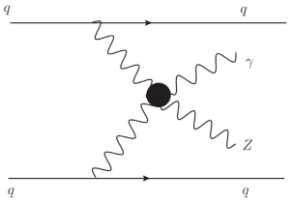
EW $Z(\rightarrow \nu\nu)\gamma jj$

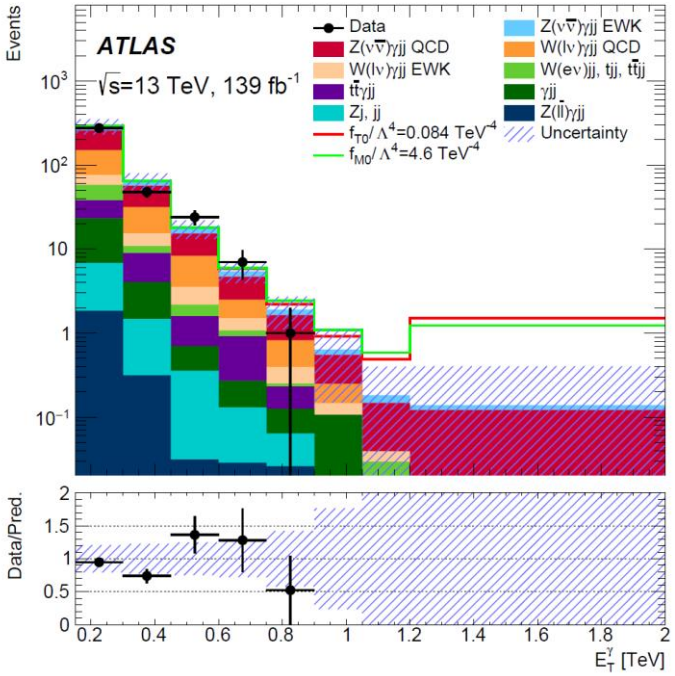
JHEP accepted
arXiv:2208.12741

- Previous observation at 5.2 σ in ATLAS: Eur. Phys. J. C 82 (2022) 105
- New measurement with extra $p_T^\gamma > 150\ GeV$ requirement to enrich the QGC events:
  - observed (expected): 3.2σ (3.7σ)

BDT to separate signal from backgrounds







Coefficient	E_c [TeV]	Observed limit [TeV^{-4}]	Expected limit [TeV^{-4}]
f_{T0}/Λ^4	1.7	$[-8.7, 7.1] \times 10^{-1}$	$[-8.9, 7.3] \times 10^{-1}$
f_{T5}/Λ^4	2.4	$[-3.4, 4.2] \times 10^{-1}$	$[-3.5, 4.3] \times 10^{-1}$
f_{T8}/Λ^4	1.7	$[-5.2, 5.2] \times 10^{-1}$	$[-5.3, 5.3] \times 10^{-1}$
f_{T9}/Λ^4	1.9	$[-7.9, 7.9] \times 10^{-1}$	$[-8.1, 8.1] \times 10^{-1}$
f_{M0}/Λ^4	0.7	$[-1.6, 1.6] \times 10^{2}$	$[-1.5, 1.5] \times 10^{2}$
f_{M1}/Λ^4	1.0	$[-1.6, 1.5] \times 10^{2}$	$[-1.4, 1.4] \times 10^{2}$
f_{M2}/Λ^4	1.0	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$