Multiboson measurements

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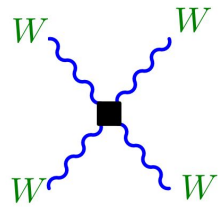
2023/05/26 LHCP2023

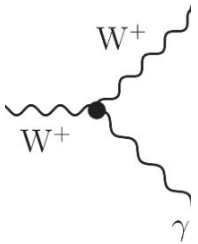
on behalf of the ATLAS & CMS collaborations

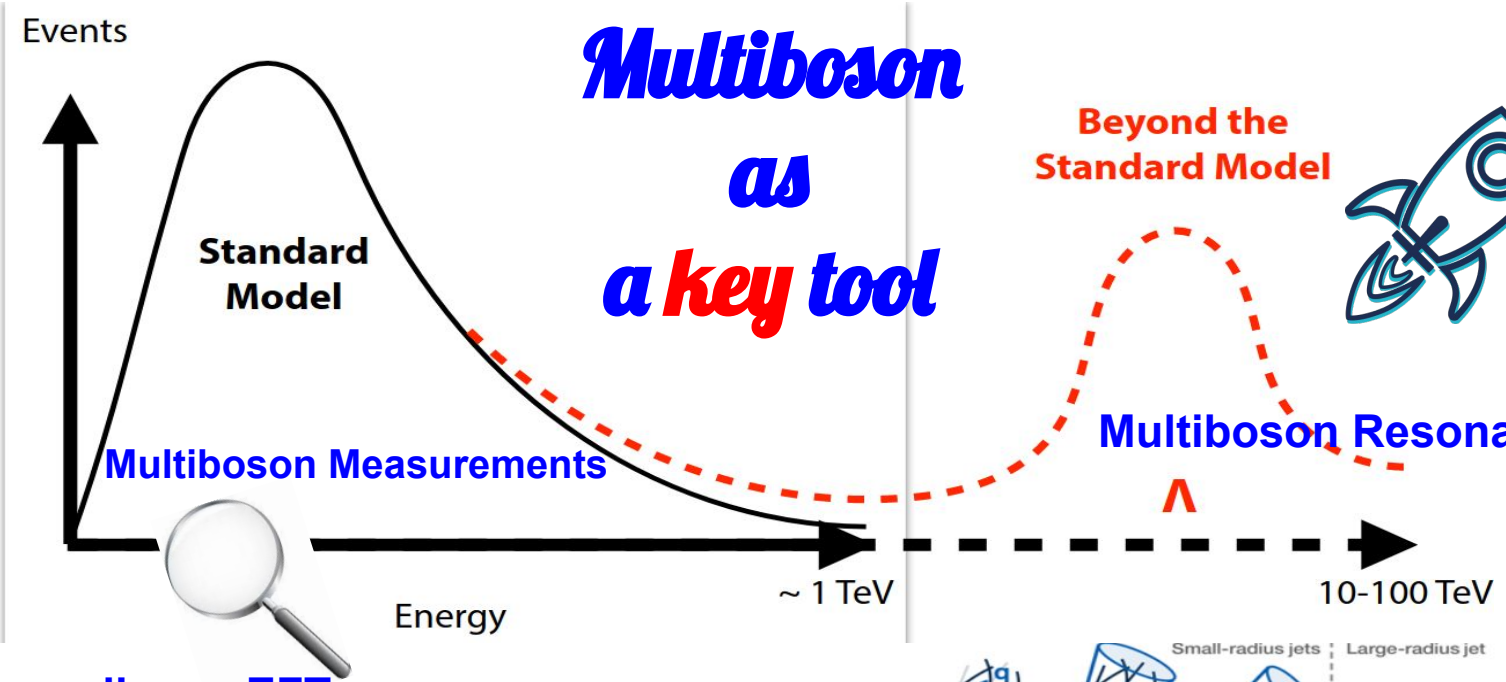
LHCPhysics

Belgrade, 22 - 26 May 2023

Direct and Indirect Searches for BSM



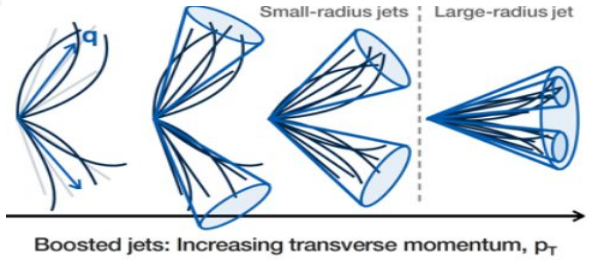




Multiboson as a key tool

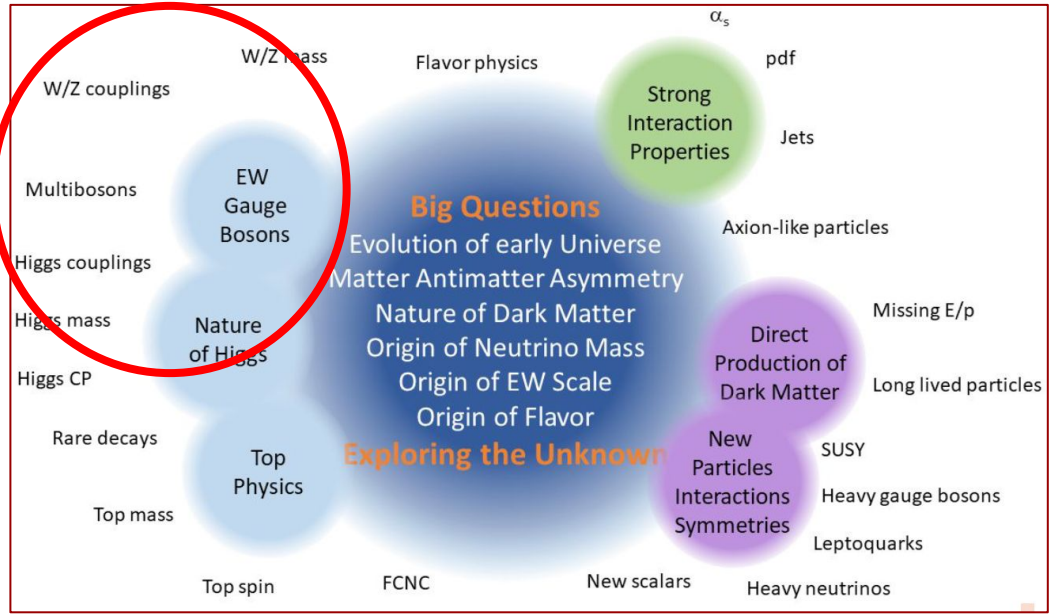
Anomalous couplings, EFT

$$L_{\mathrm{EFT}} = L_{\mathrm{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)} + \ldots$$



Great Potential to explore unknown

The large boson-boson collider



Symmetry

High energy.

High multiplicity.

High opportunities?

Brian Henning

$$|H|^2 \sim (v+h)^2 + \vec{\phi}^2$$

ops that modify HC will induce processes with longitudinal vectors

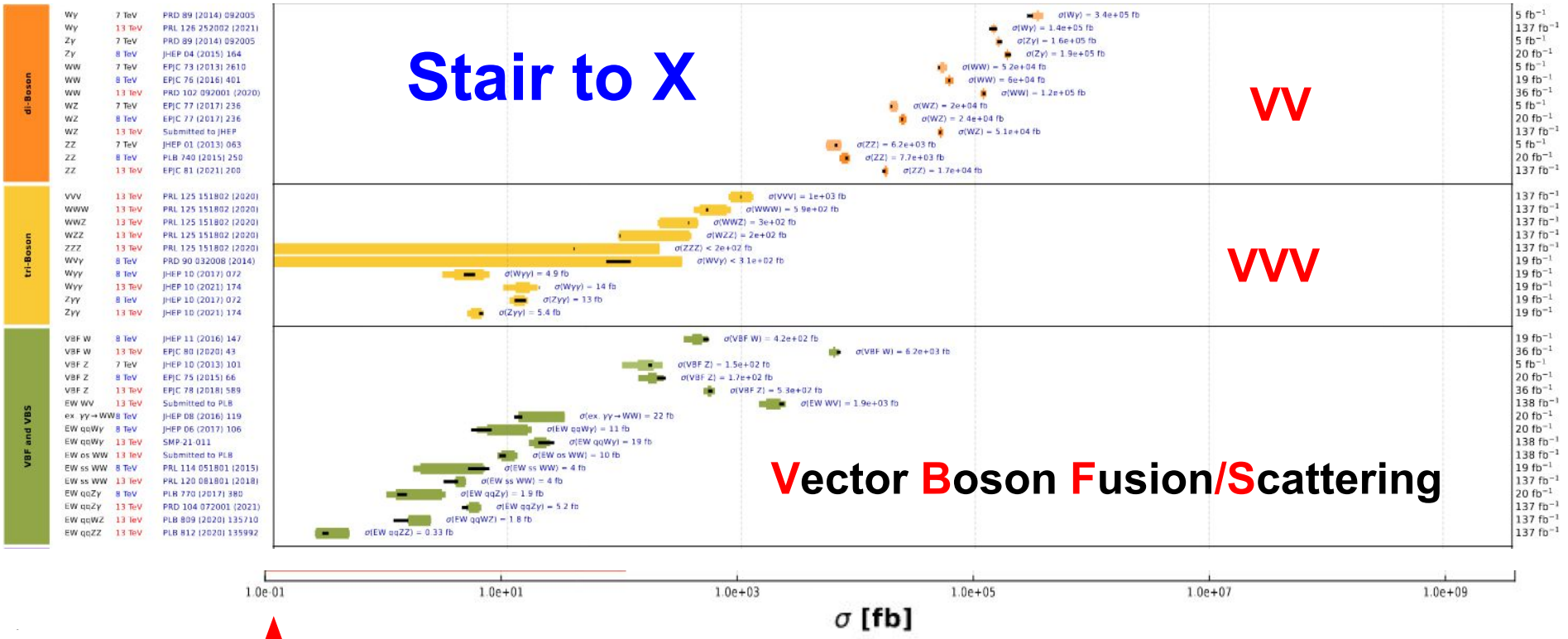
$$\text{HC:} \quad |H|^2 \mathcal{O}_{\rm SM} \supset vh\mathcal{O}_{\rm SM}$$

$$\text{HwH:} \quad |H|^2 \mathcal{O}_{\rm SM} \supset \vec{\phi}^2\mathcal{O}_{\rm SM}$$

Snowmass 2022

Higgs Couplings without the Higgs

Rich Results from Multiboson Measurements



0.1fb

CMS SM Summary Plot 2022/9 (see also ATLAS)

Boson Blossom from This Week: selected results today

VBS/VBF measurements (with photons) at ATLAS and CMS
Speaker: Ying An (Deutsches Elektronen-Synchrotron (DE))

VBS/VBF theory developments
Speakers: Dr Richard Ruiz, Richard Ruiz (University of Pittsburgh)

VBS/VBF measurements (without photons) at ATLAS
Speaker: Chilufya Mwewa (Brookhaven National Laboratory (US))

VBS/VBF measurements (without photons) at CMS
Speaker: Mr Giacomo Boldrini (Universita & INFN, Milano-Bicocca (IT))

Theory prediction and event generation for polarization measurements
Speakers: Giovanni Pelliccioli (Max-Planck-Institut für Physik), Giovanni Pelliccioli (Würzburg University)

Recent diboson and polarization measurements at ATLAS
Speaker: José Antonio Fernández Pretel (Albert Ludwigs Universitaet Freiburg (DE))

Recent diboson and polarization measurements at CMS
Speaker: Saptaparna Bhattacharya (Northwestern University (US))

Higher-order corrections in multiboson production
Speaker: Silvia Zanoli

Triboson measurements at ATLAS and CMS
Speaker: Alessandro Ambler (McGill University, (CA))

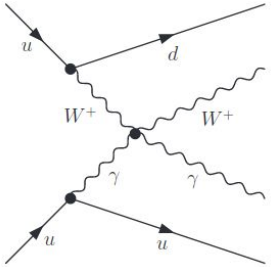
Vector boson modeling for precision physics
Speaker: Tobias Neumann

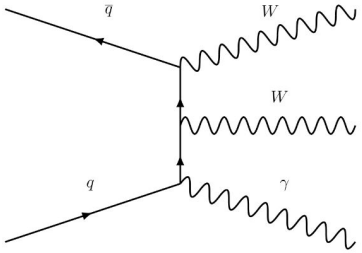
Recent EWK precision measurements in CMS
Speaker: Vladimir Cherepanov (University of Florida (US))

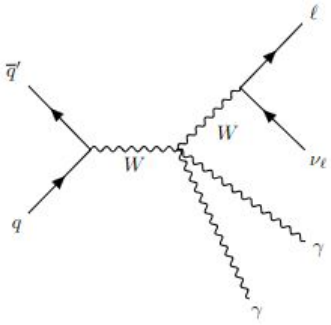
Recent EWK precision measurements in ATLAS
Speaker: Dr Xingguo Li (McGill University, (CA))

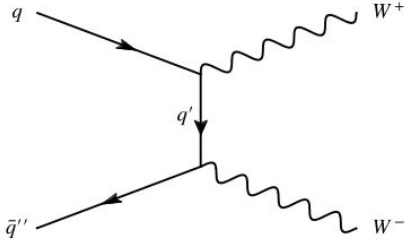
Recent EWK precision measurements in LHCb
Speaker: Jianqiao Deng (Central China Normal University CCNU (CN))

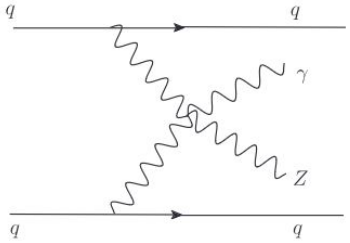
EFT theory outlook
Speaker: Dr Raquel Gomez Ambrosio (Milano Bicocca)

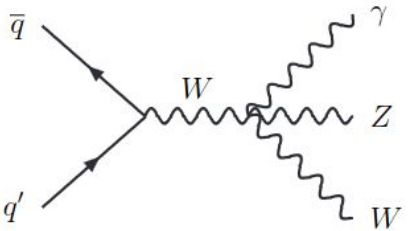


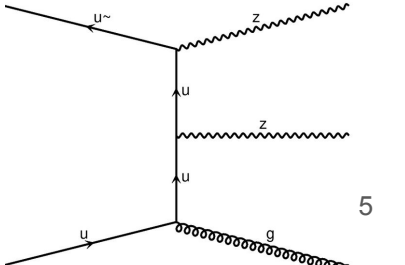








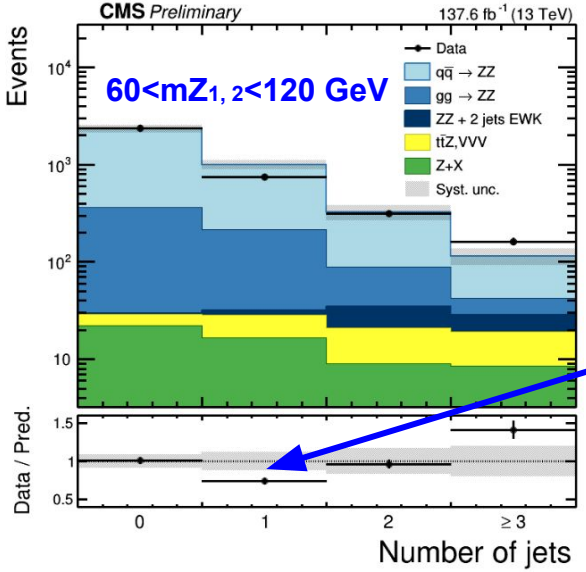




ZZ+jets CMS-PAS-SMP-22-001

NEW

- **ZZ production associated with jets in the fully leptonic final states**
- **Unfolding using the iterative D'Agostini's method** including correction for background contributions, with the `RooUnfold` toolkit.
- **Basic mZ requirement:** 40<mZ$_1$<120 GeV, 4<mZ$_2$<120 GeV
  - **On-shell requirement:** 60<mZ$_1$, mZ$_2$<120 GeV



Systematic source	Normalized
Trigger	-
Electron Efficiency	0.13 - 0.3 %
Muon Efficiency	0.02 - 0.08 %
Jet energy resolution	1.65 - 3.85 %
JES correction	0.93 - 5.32 %
Reducible background	0.05 - 0.43 %
Pileup	0.04 - 1.08 %
Luminosity	< 0.03 %
Monte Carlo choice	0.52 - 4.52 %
gg cross section	0.01 - 0.19 %
QCD Scales	0.16 - 0.82 %
PDF	0.05 - 0.12 %
α_S	0.01 - 0.1 %

Data in the 0 and 2 jet bins are well described by the predictions,

Significant discrepancy **In the 1 jet bin,**

The description of events with >=3 jets requires NNLO and even higher order corrections, thus **the discrepancy at high jets bin is expected.**

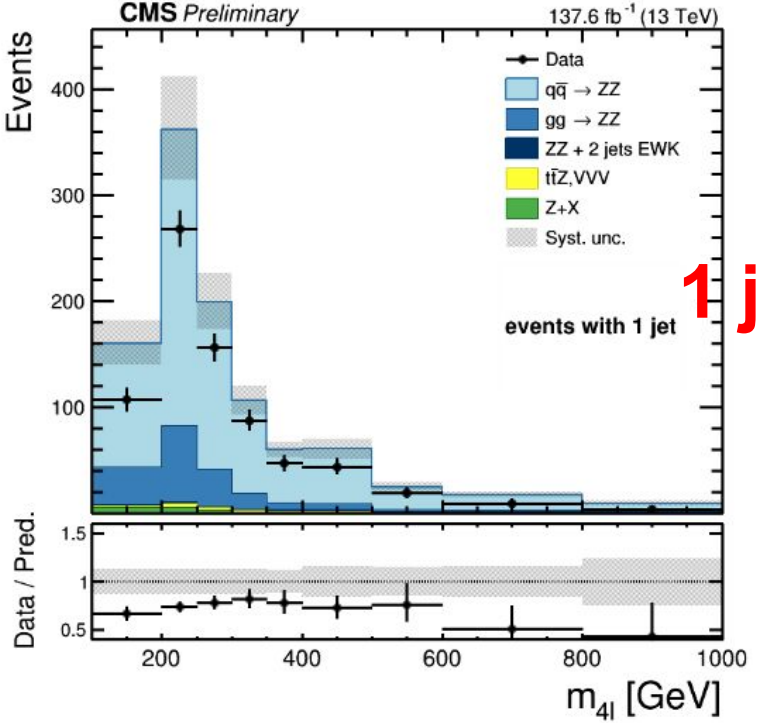
MadGraph ZZ+0/1jet@NLO FxFx, and Powheg ZZ NLO

ZZ+jets CMS-PAS-SMP-22-001

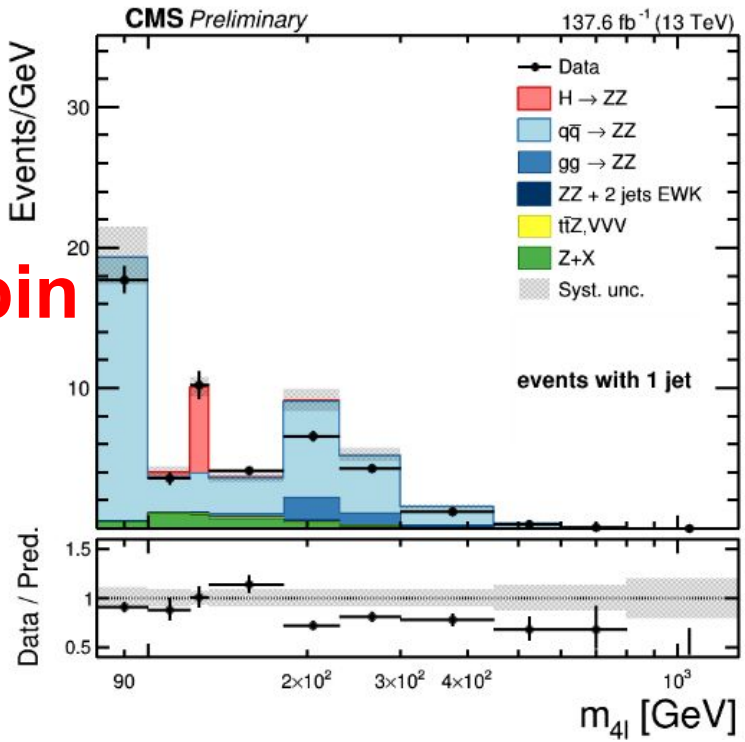
NEW

60<mZ1, 2<120 GeV

40<mZ1<120 GeV
4<mZ2<120 GeV

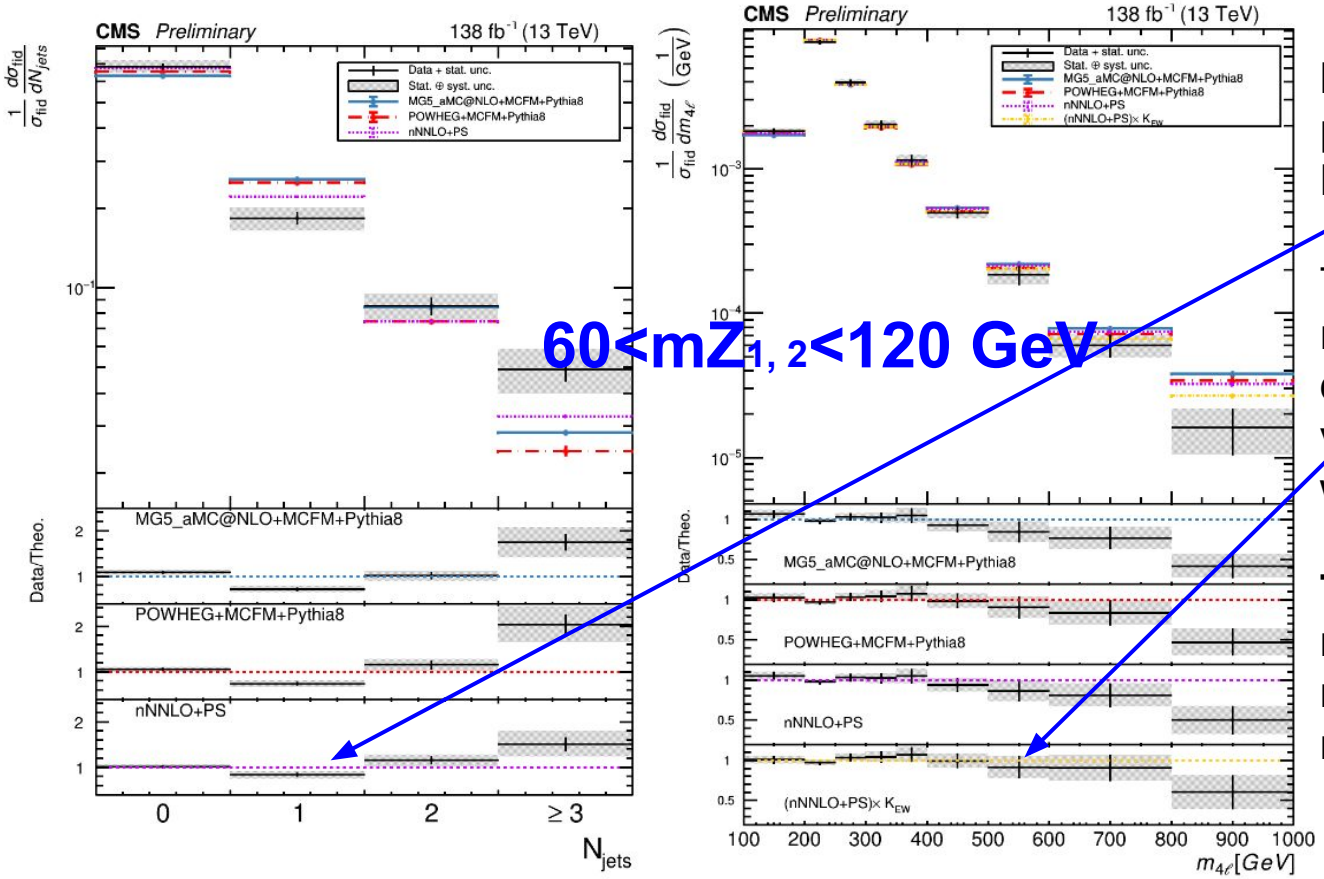


1 jet bin



ZZ+jets CMS-PAS-SMP-22-001

NEW



In general, the nNNLO+PS prediction describes the Njet distribution better.

The **EW corrected nNNLO+PS** predictions describe the measured values better than those without the EW corrections

The EW corrections have negligible effect on any other normalized distributions than m_{4l}.

Zγ+jets arXiv:2212.07184 accepted by JHEP

1D and 2D differential distributions

data-driven backgrounds

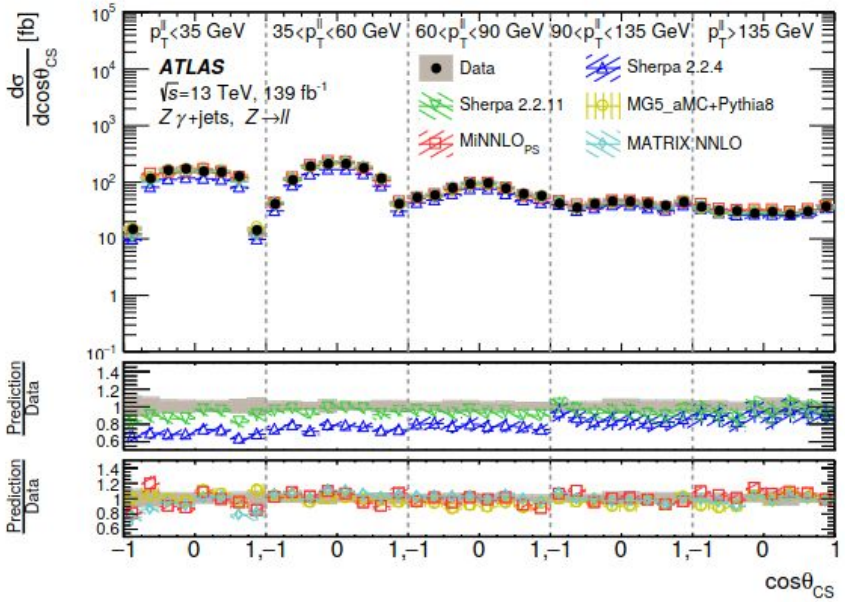
Z+Jets, Pile-up, ttγ

Uncertainties 4-10%

Jet energy scale, Bkg modelling

Data general well described

NLO 0,1p in Sherpa improves description wrt ME+PS @LO

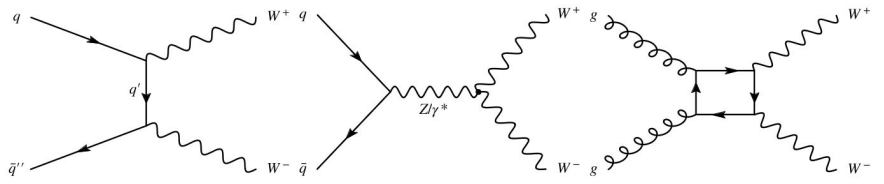


- N_{jet}, p_T^{j1}, p_T^{j2}, p_T^{j1}/p_T^{j2}, HT, $p_T(\gamma)$ and $p_T^{ll}/\sqrt{HT}$ $m_{ll\gamma j}$, m_{jj}, $\Delta R(ll), \Delta\phi(j,\gamma)$
- QCD sensitive 2D observables:
  - $P_T^{ll\gamma}/m^{ll\gamma}$ in bins of $m^{ll\gamma}$,
  - $P_T^{ll} - P_T^{\gamma}$ in bins of $P_T^{ll} + P_T^{\gamma}$,
  - $P_T^{ll\gamma j}$ in bins of $P_T^{ll\gamma}$
- Polarisation-sensitive 2D observables:
  - $\cos\theta_{CS}$ and ϕ_{CS} in bins of P_T^{ll}

Process	Generator	Order	PDF set	PS/UE/MPI
$Z\gamma$+jets	Sherpa 2.2.11	0,1j@NLO + 2,3,4j@LO	NNPDF3.0nnlo	Sherpa 2.2.11
$Z\gamma$+jets	Sherpa 2.2.4	0,1,2,3j@LO	NNPDF3.0nnlo	Sherpa 2.2.4
$Z\gamma$+jets	MadGraph5_aMC@NLO	0,1j@NLO	NNPDF3.0nlo_as_0118	Pythia 8.212
Purely EW $Z\gamma jj$	MadGraph5_aMC@NLO	LO	NNPDF3.0lo	Pythia 8.240
Z + jets	Powheg Box	0j@NLO	CT10nlo	Pythia 8.186
$t\bar{t}\gamma, tW\gamma$	MadGraph5_aMC@NLO	LO	NNPDF2.3lo	Pythia 8.212
$ZZ \to \ell\ell\ell\ell, W^{\pm}Z \to \ell\ell\ell\nu$	Sherpa 2.2.2	0,1j@NLO + 2,3j@LO	NNPDF3.0nnlo	Sherpa 2.2.2
$WZ\gamma, WW\gamma$	Sherpa 2.2.11	0j@NLO + 1,2j@LO	NNPDF3.0nnlo	Sherpa 2.2.11

WW

ATLAS-CONF-2023-012



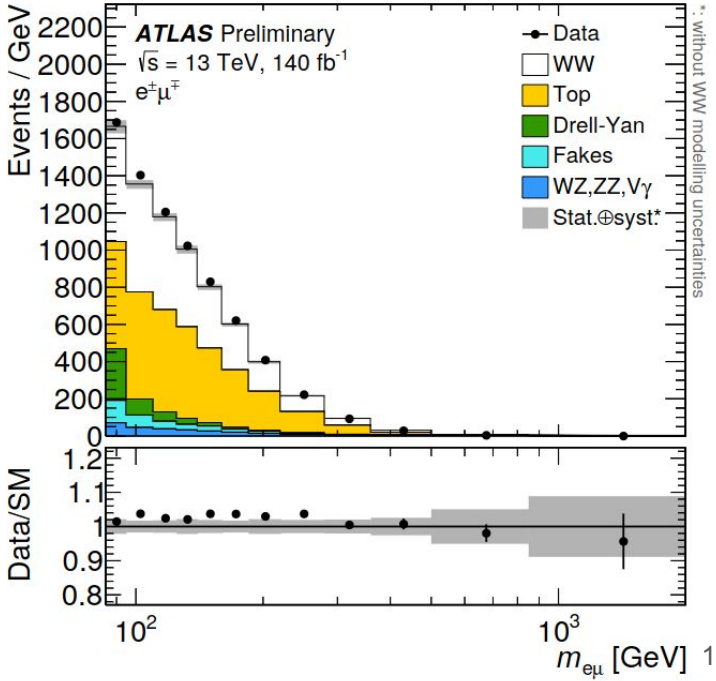
Lepton selection	1 electron and 1 muon of opposite charge, no additional lepton with $p_T > 10$ GeV, `Loose` isolation, and `LooseLH` (electron) / `Loose` (muon) identification
Number of b-jets	0
Dilepton invariant mass	> 85 GeV

- ***Jet-inclusive WW→eμ Measurements***
- ***Dominant bkg from top-related processes***

b-tag counting method

$$N_{2b}^{t\bar{t}} = N_{\geq 0b}^{t\bar{t}} \cdot C_b \varepsilon_b^2 \,,$$
$$N_{1b}^{t\bar{t}} = N_{\geq 0b}^{t\bar{t}} \cdot \left(2\varepsilon_b - C_b \varepsilon_b^2\right) \,,$$
$$N_{0b}^{t\bar{t}} = N_{\geq 0b}^{t\bar{t}} \cdot \left(1 - 2\varepsilon_b + C_b \varepsilon_b^2\right)$$

Process	Generator	Parton shower	Matrix element $O(\alpha_S)$	Normalization
$q\bar{q} \to WW$	MiNNLO	Pythia8	NNLO	Generator
$gg \to WW$	Sherpa2.2.2	Sherpa	LO (0–1 jet)	NLO
$t\bar{t}$	Powheg Boxv2	Pythia8	NLO	NNLO+NNLL
Wt	Powheg Boxv2	Pythia8	NLO	NLO+NNLL
Z+jets	Sherpa2.2.1	Sherpa	NLO (0–2 jets), LO (3–4 jets)	NNLO
WZ, ZZ	Sherpa2.2.2	Sherpa	NLO (0–1 jet), LO (2–3 jets)	Generator†
$W\gamma, Z\gamma$	Sherpa2.2.8	Sherpa	NLO (0–1 jet), LO (2–3 jets)	Generator†



WW ATLAS-CONF-2023-012

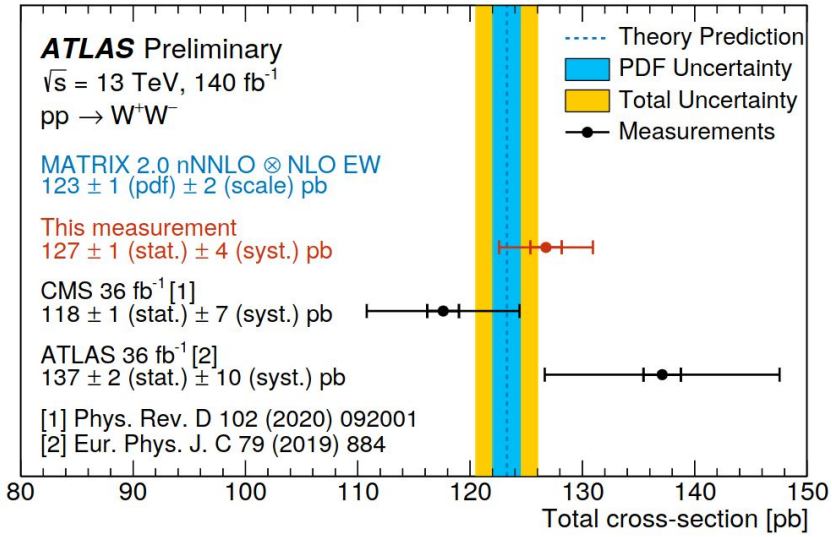
- The measured fiducial XS for WW production with $WW \to e\mu$ is

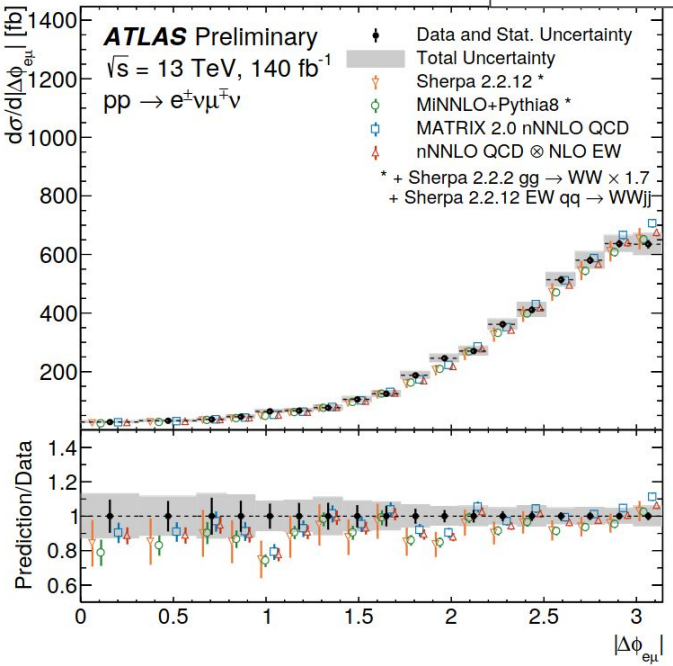
  $707 \pm 7(stat.) \pm 20(syst.)\ fb$

- The measurements is extrapolated to the full phase space of WW production

  $127 \pm 1(stat.) \pm 4(syst.)\ pb$

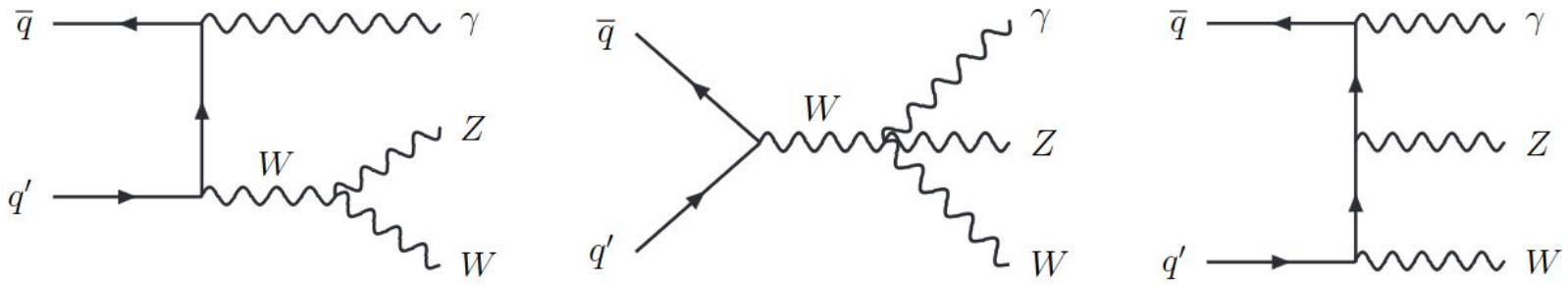
Uncertainty source	Effect
Total uncertainty	3.1%
Stat. uncertainty	1.1%
Top modelling	1.6%
Fake lepton background	1.5%
Flavour tagging	0.7%
Other background	0.9%
Signal modelling	1.0%
Jet calibration	0.6%
Luminosity	0.8%
Other systematic uncertainties	0.9%





WZγ observation

ATLAS-CONF-2023-014



- **Pure leptonic final state,**
- **Signal modelled by Sherpa 2.2.11** 0@NLO QCD+1,2@LO QCD Merged with Parton shower
- **FSR photon suppressed:** **mll>81GeV** (of the Z-lepton pair)
- **main backgrounds**: **Non-prompt photons or leptons**
- **WZγ, ZZγ and ZZ fitted simultaneously**

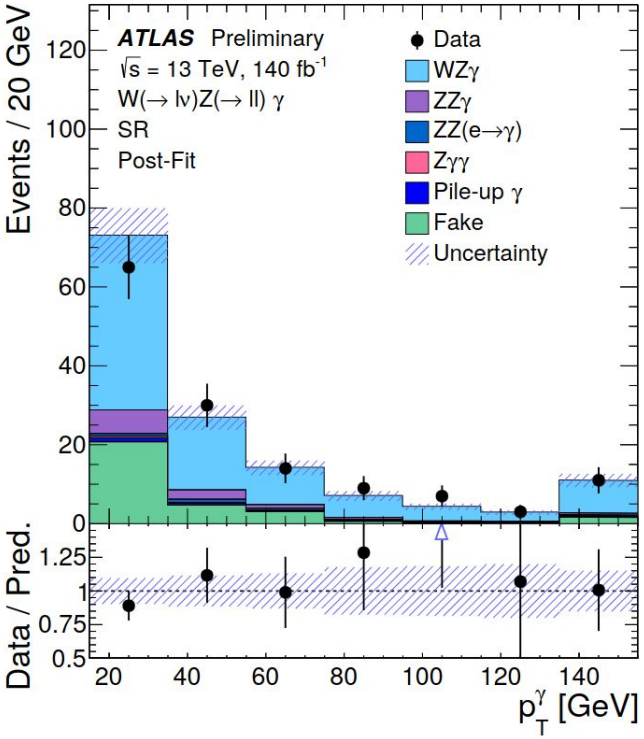
Process	SR	$ZZ\gamma$ CR	$ZZ(e \to \gamma)$ CR
$WZ\gamma$	92 ± 15	0.21 ± 0.07	0.56 ± 0.14
$ZZ\gamma$	10.7 ± 2.3	23 ± 5	1.8 ± 0.4
$ZZ(e \to \gamma)$	3.0 ± 0.6	0.028 ± 0.020	30 ± 6
$Z\gamma\gamma$	1.05 ± 0.32	0.15 ± 0.06	0.29 ± 0.10
Non-prompt background	30 ± 6	-	-
Pile-up γ	1.9 ± 0.7	-	-
Total prediction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

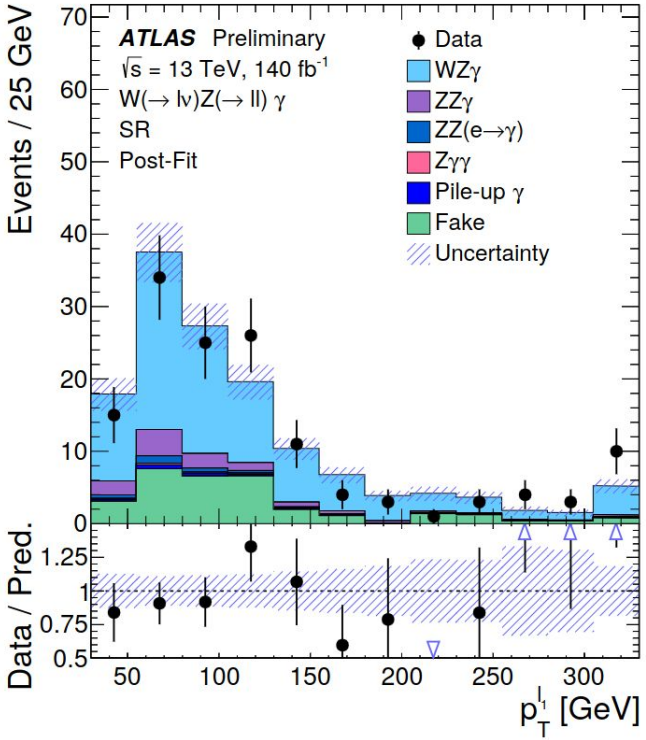
WZγ observation [ATLAS-CONF-2023-014]

(eμμ, μee, eee, μμμ) channels combined profile-likelihood fit in SR+2CRs

6.3 (5.0)σ obs.(exp.)

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



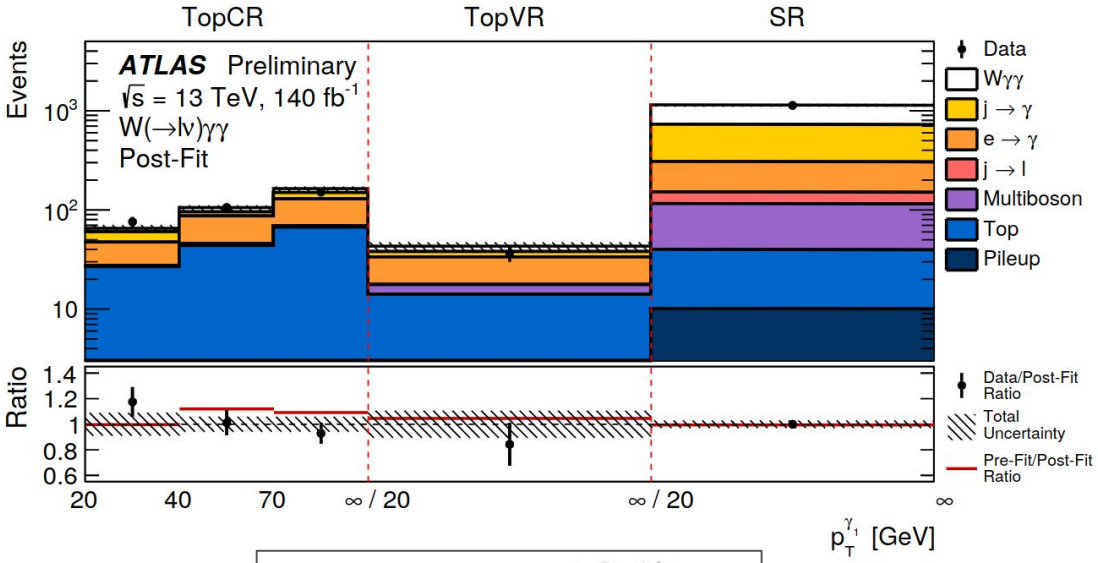


Wγγ observation [ATLAS-CONF-2023-005]

- Dominant background from non-prompt leptons and photons
- Main source of systematics due to data-driven bkg estimates

5.6 (5.6)σ obs.(exp.)

Source of uncertainty	Impact [%]
Data-driven background estimates	13
Photon efficiency	4.5
Signal MC theoretical modeling	3.5
Background MC theoretical modeling	3.0
Monte Carlo statistics	2.8
Jet efficiency and calibration	2.4
Top normalization	2.4
Pileup reweighting	1.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ calibration	1.4
Muon efficiency and calibration	1.4
Luminosity	1.0
Electron and photon calibration	0.7
Flavor tagging efficiency	0.6
Systematic	15
Statistical	8.3
Total	17

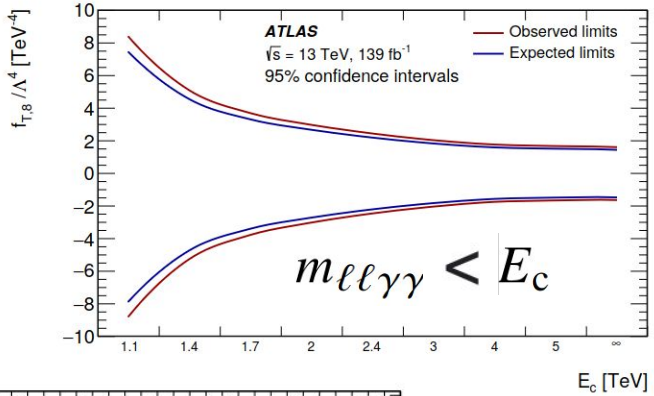


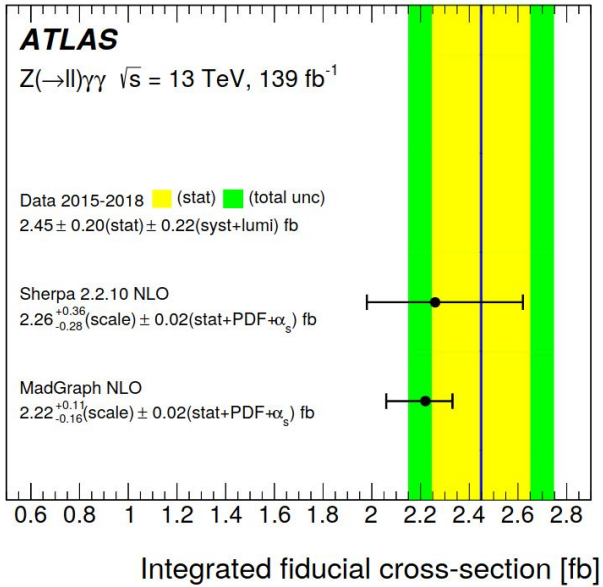
$$\mu_{\mathrm{obs}} = 1.01^{+0.17}_{-0.16}$$

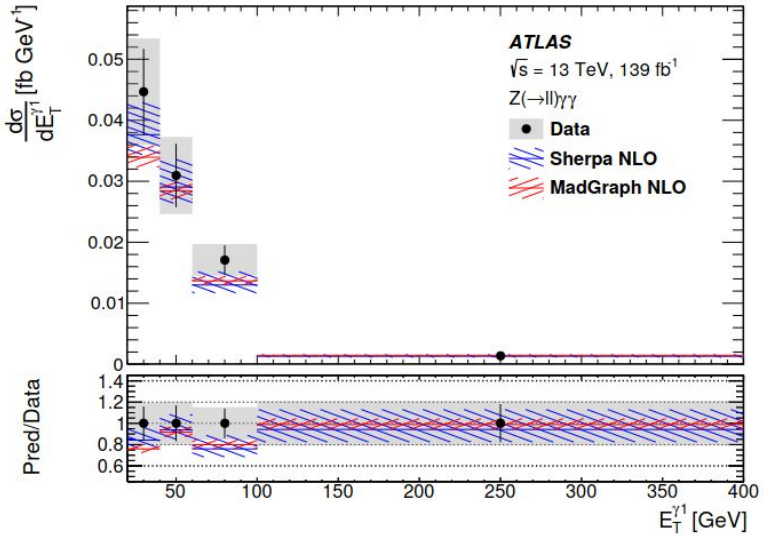
$$\sigma^{\mathrm{fid}}_{\mathrm{obs}} = 12.2^{+2.1}_{-2.0}\ \mathrm{fb}$$

$Z\gamma\gamma$ arXiv:2211.14171 accepted by EPJC

- Final-state radiation suppressed by the event selection
- Dominant background from non-prompt photons
- Statistically dominated
  - main syst. from non-prompt photons
- Unfolded differential distributions
- Limited on aQGC with (non-)unitarised treatment



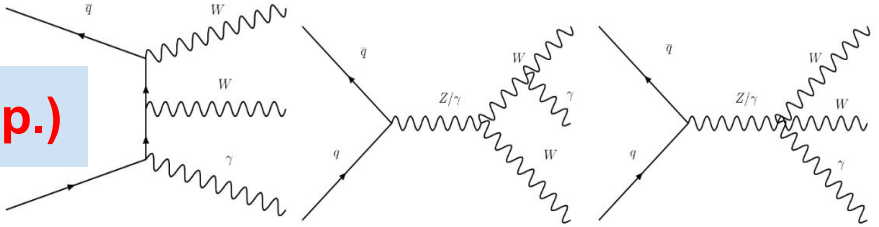




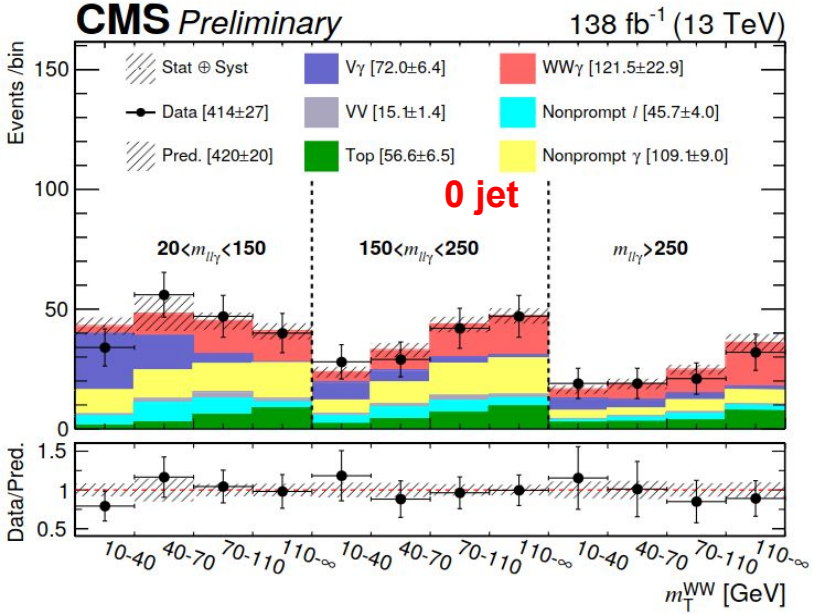
WWγ observation [CMS-PAS-SMP-22-006]

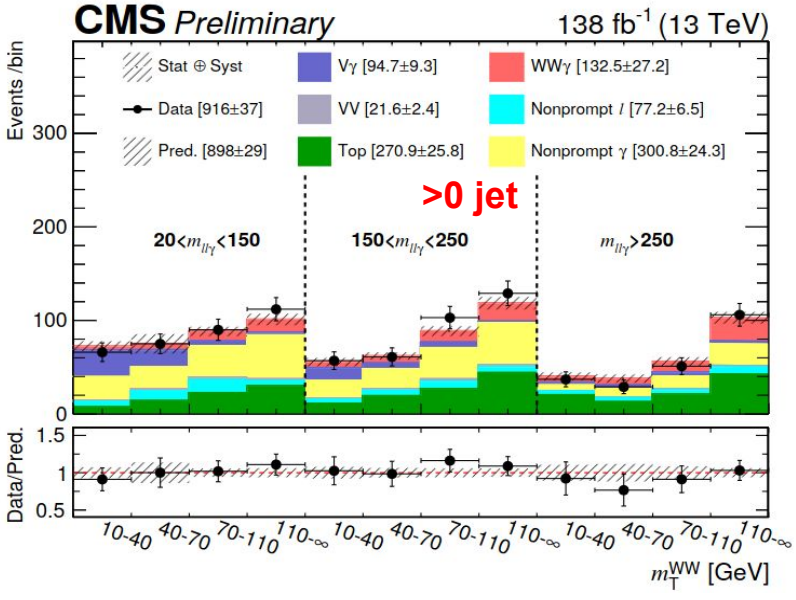
- Signal region categorized with **0 and >0 jet**,
- only **eμ channel**
- SSWWγ and TOPγ **CRs**,
- data-driven **non-prompt** backgrounds
- maximum likelihood fit of **2D binned distributions**.

5.6 (4.7)σ obs.(exp.)

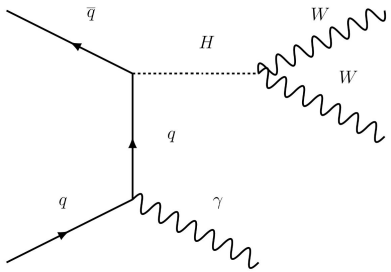


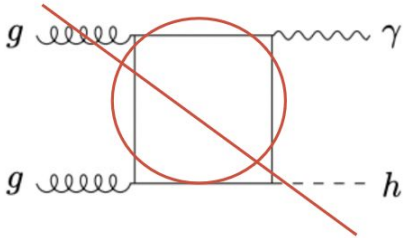
$$\mu^{\text{obs.}}_{\text{combined}} = 1.31 \pm 0.17\,(\text{stat}) \pm 0.21\,(\text{syst})$$





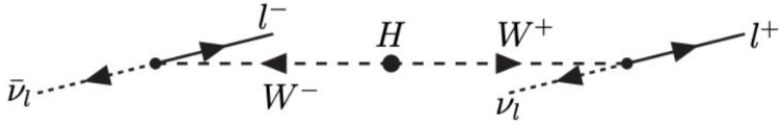
WWγ observation CMS-PAS-SMP-22-006





- Also sensitive to **Higgs couplings with light quarks**
  - no gluon fusion contribution due to Furry's theorem
- **Further optimization targeting the Higgs characteristics**

$$\Delta\phi_{\ell\ell} < 2.5,\ \Delta R_{\ell\ell} < 2.3,\ \text{and}\ \Delta R_{\ell\gamma} > 0.8$$

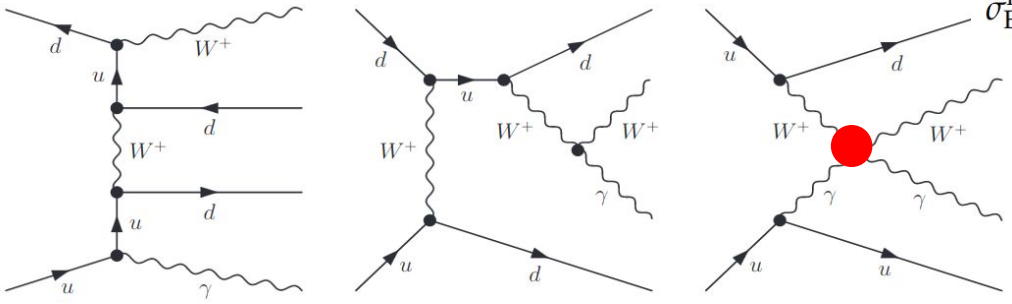


- **H Signal generated with MadGraph at LO**
  - Higgs effective Lagrangian for u, d and s;
  - Running mass effect included for c

Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq 13000\ (16000)$
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq 14000\ (17000)$
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq 1300\ (1700)$
$c\bar{c} \to H + \gamma \to e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq 110(200)$

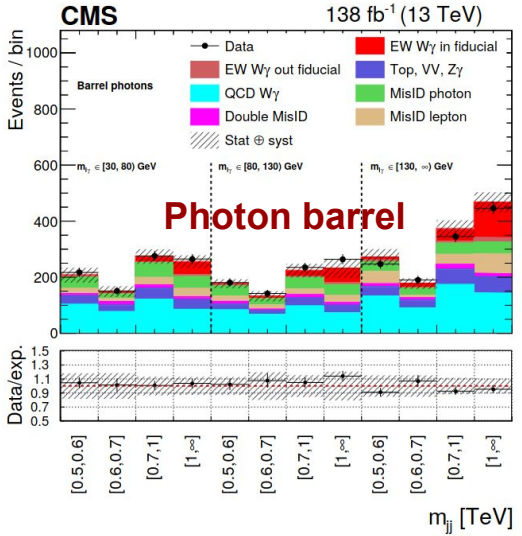
VBS Wγ

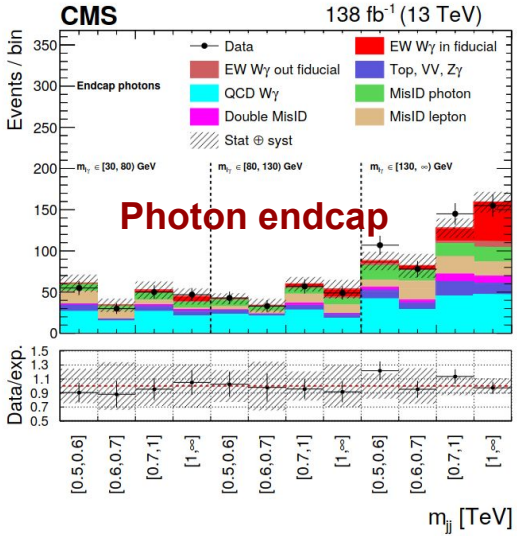
arXiv:2212.12592 accepted by PRD

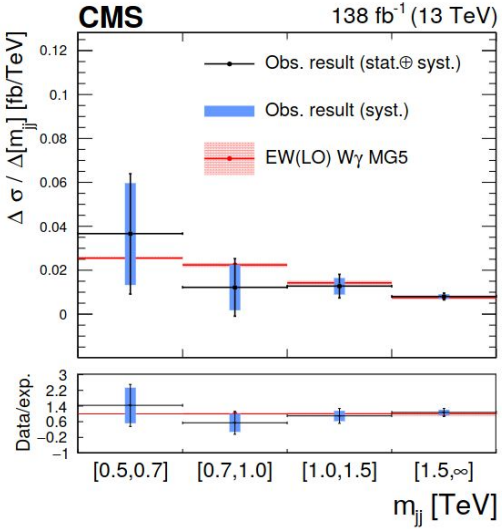


$$\sigma_{\mathrm{EW}}^{\mathrm{fid}} = 23.5 \pm 2.8\,(\mathrm{stat})^{+1.9}_{-1.7}\,(\mathrm{theo})^{+3.5}_{-3.4}\,(\mathrm{syst})\,\mathrm{fb} = 23.5^{+4.9}_{-4.7}\,\mathrm{fb}.$$

6.0 (6.8)σ observed (expected)







- **Fiducial and differential** cross sections;
- **Stringent limits on aQGCs:** fM,2-4 and fT6-7

VBS Zγ

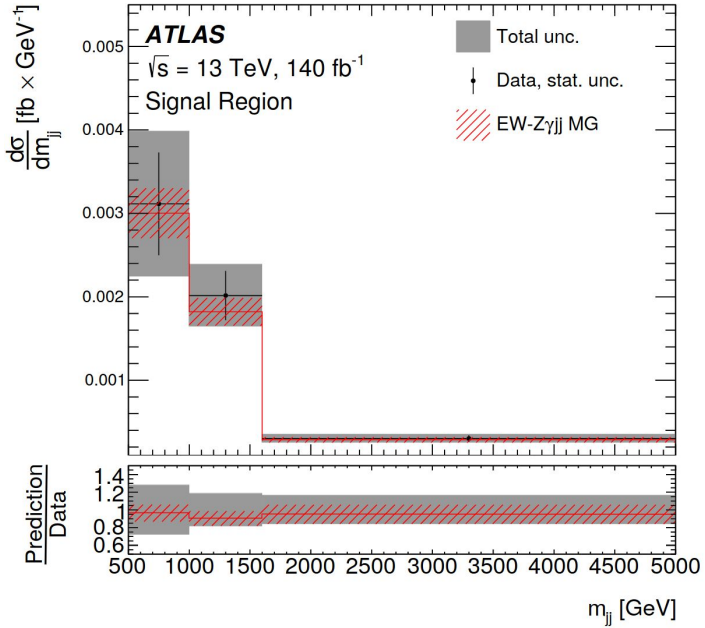
ATL-COM-PHYS-2023-282

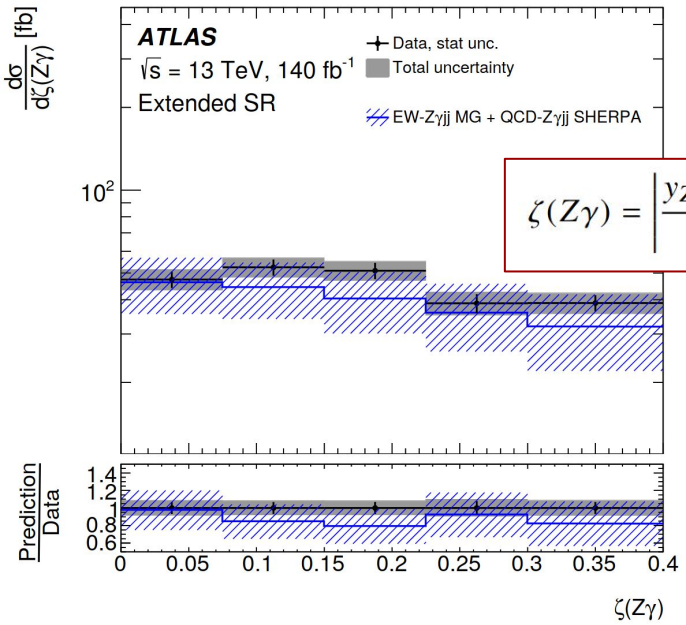
NEW

Electroweak production of Zγ (Z→ee, μμ) in association with two jets, Fiducial and differential cross-sections, for both EW and EW+QCD.

$$\mu_{EW} = 1.02 \pm 0.09\,(\text{stat}) \pm 0.09\,(\text{syst}) = 1.02^{+0.13}_{-0.12}.$$

	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	±9	±1	±1	±4	$^{+8}_{-6}$	±2	±13
$\Delta\sigma_{Z\gamma}/\sigma_{Z\gamma}$ [%]	±3	±1	±2	$^{+4}_{-3}$	$^{+7}_{-6}$	±9	$^{+12}_{-11}$





$$\zeta(Z\gamma) = \left| \frac{y_{Z\gamma} - (y_{j_1} + y_{j_2})/2}{y_{j_1} - y_{j_2}} \right|$$

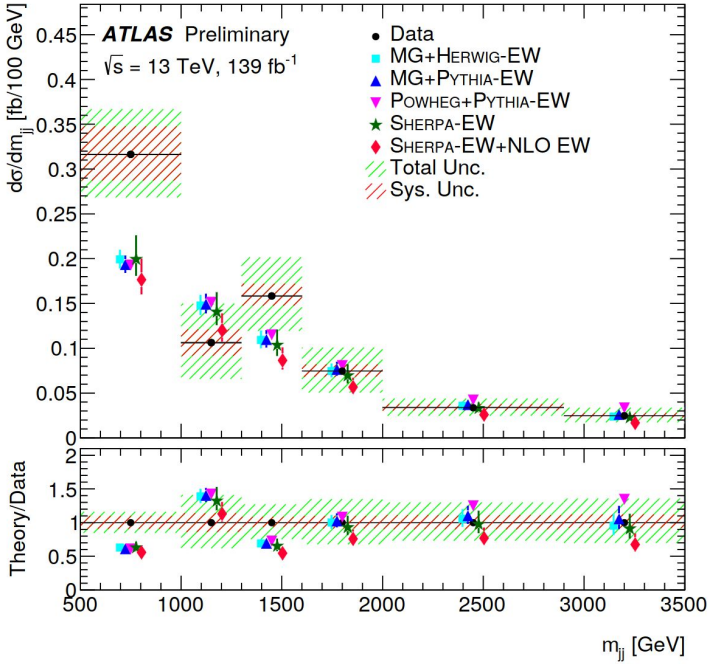
Same-Sign WW

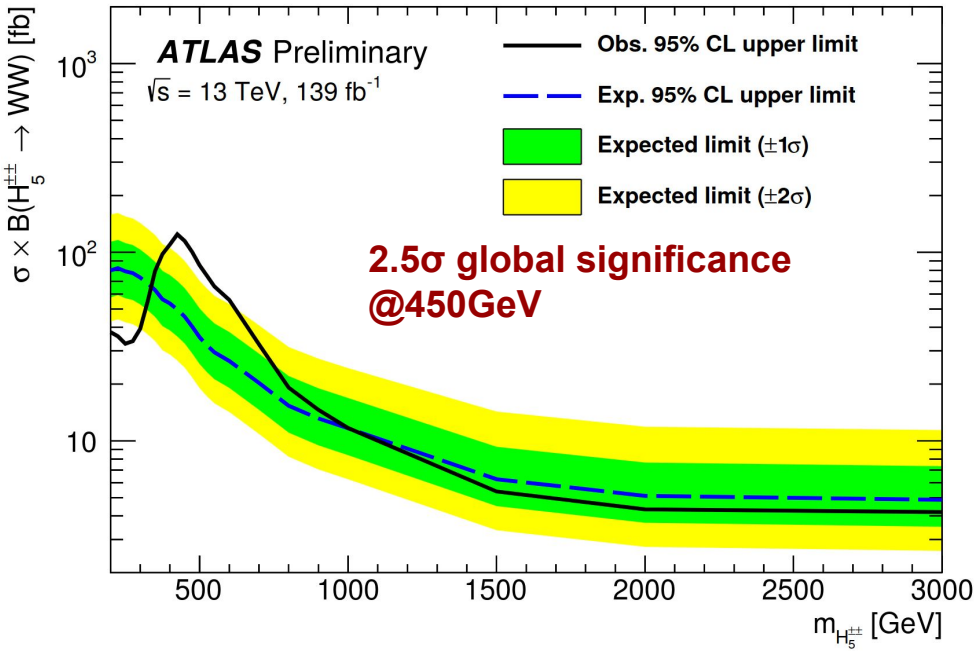
ATLAS-CONF-2023-023

NEW

- **Fiducial and differential cross sections**
- **Searches for aQGC, doubly charged Higgs**

Description	$\sigma_{\text{fid}}^{\text{EW}}$, fb	$\sigma_{\text{fid}}^{\text{EW+Int+QCD}}$, fb
Measured cross section	$2.88 \pm 0.21\,(\text{stat.}) \pm 0.19\,(\text{syst.})$	$3.35 \pm 0.22\,(\text{stat.}) \pm 0.20\,(\text{syst.})$
MG_aMC@NLO+Herwig	$2.53 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$	$2.93 \pm 0.05\,(\text{PDF}) \pm^{0.34}_{0.27}\,(\text{scale})$
MG_aMC@NLO+Pythia	$2.55 \pm 0.04\,(\text{PDF}) \pm^{0.22}_{0.19}\,(\text{scale})$	$2.94 \pm 0.05\,(\text{PDF}) \pm^{0.33}_{0.27}\,(\text{scale})$
Sherpa	$2.44 \pm 0.03\,(\text{PDF}) \pm^{0.40}_{0.27}\,(\text{scale})$	$2.80 \pm 0.03\,(\text{PDF}) \pm^{0.53}_{0.36}\,(\text{scale})$
Powheg Box +Pythia	2.67	–



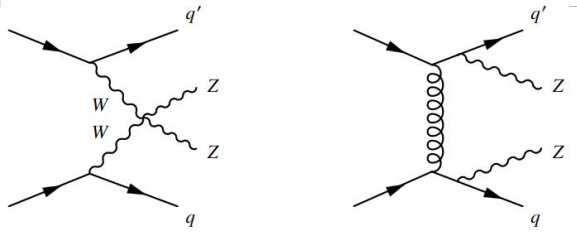


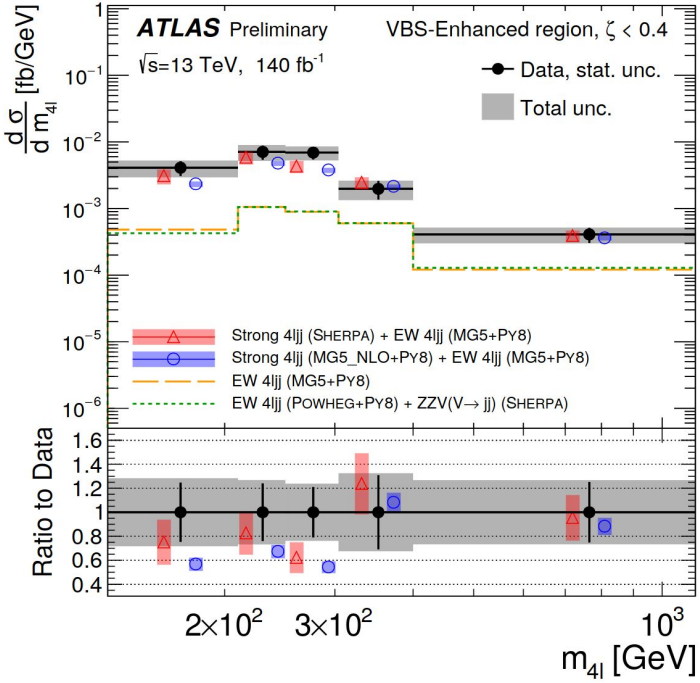
ZZ→4l + jets

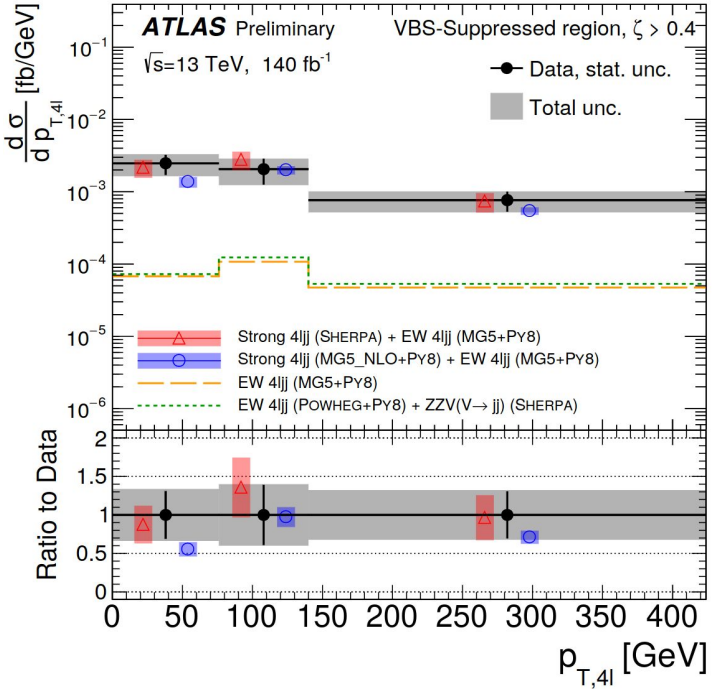
ATLAS-CONF-2023-024

NEW

- **Differential cross-section for both EW and Inclusive productions**
- **Searches for dim-6 and dim-8 EFTs**





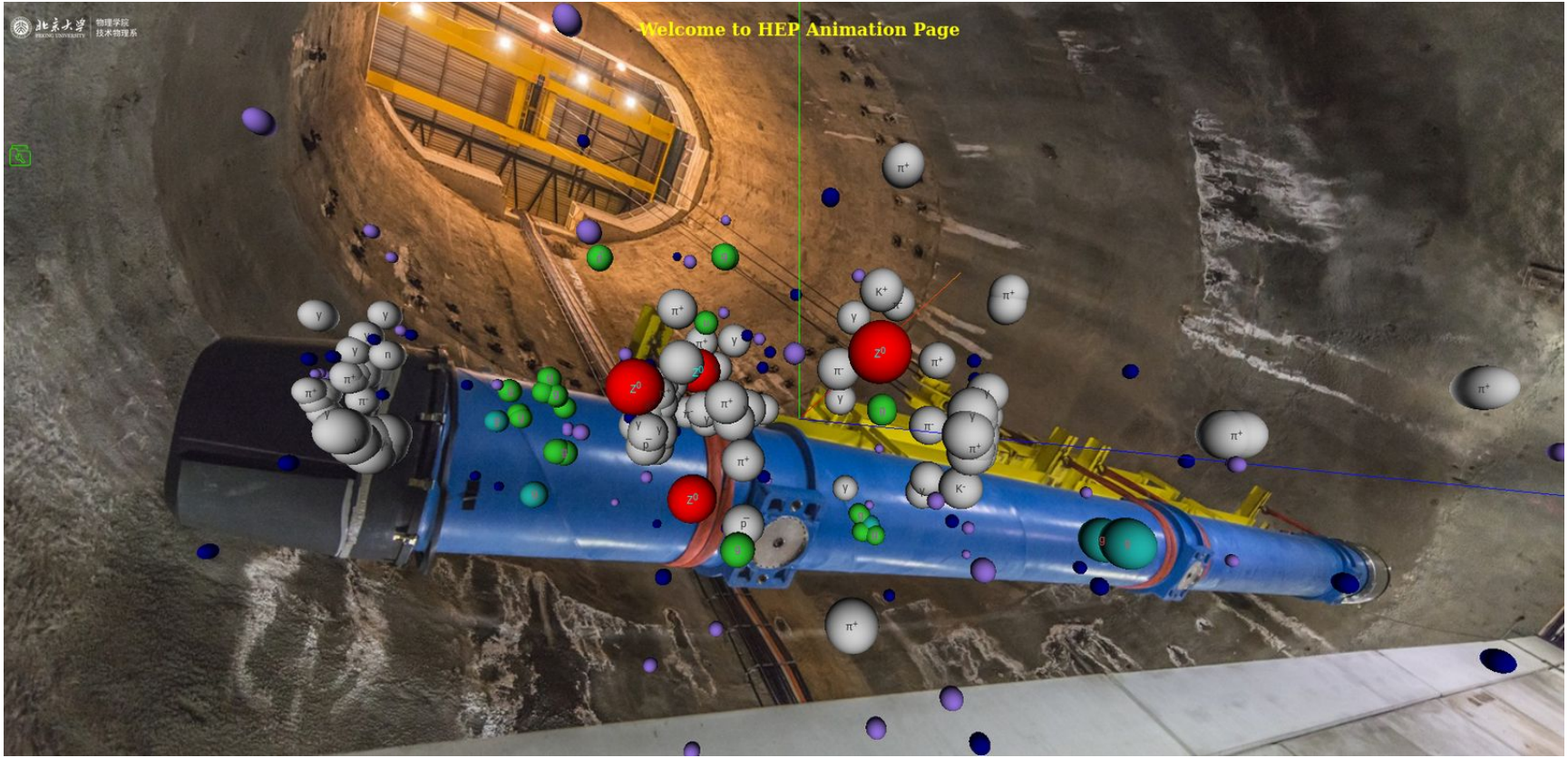


Summary and Outlook

- **Rich progress and potential from Multiboson Measurements/Probes**
  - Precise measurements on diboson+jets: ZZ, Zγ
  - First observations of several tri-boson processes: WZγ,WWγ,Wγγ,Zγγ
  - *Precise VBS measurements: W/Zγ, SSWW, ZZ*
  - Anomalous coupling, EFT, and even Higgs properties!
- **High energy, High Luminosity, High multiplicity, High opportunities!**
- **Run-3 data accumulating:** Keep tuned! More surprise (un)expected.

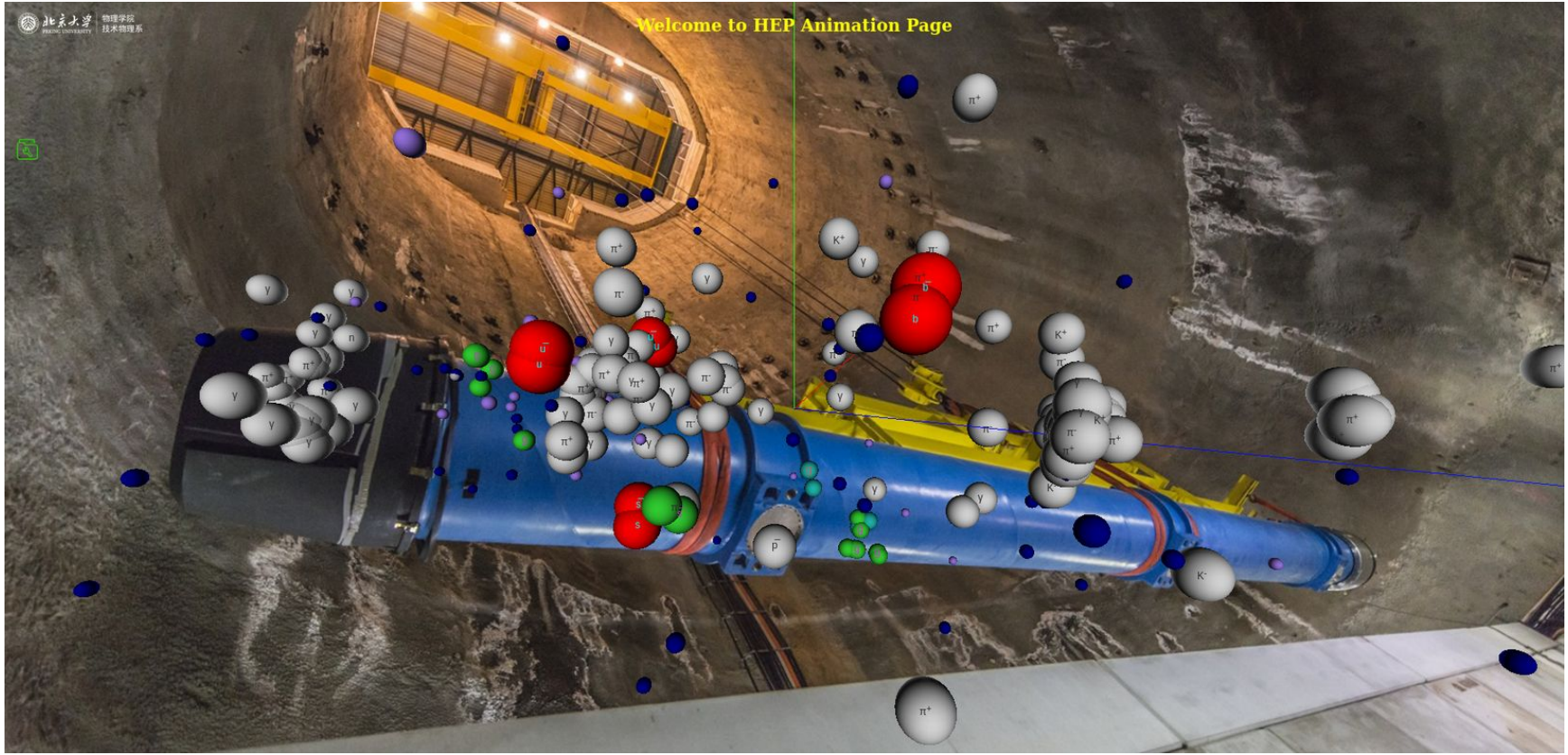
Backup

https://arxiv.org/abs/2109.14621 https://ppnp.pku.edu.cn/hepani/index.html

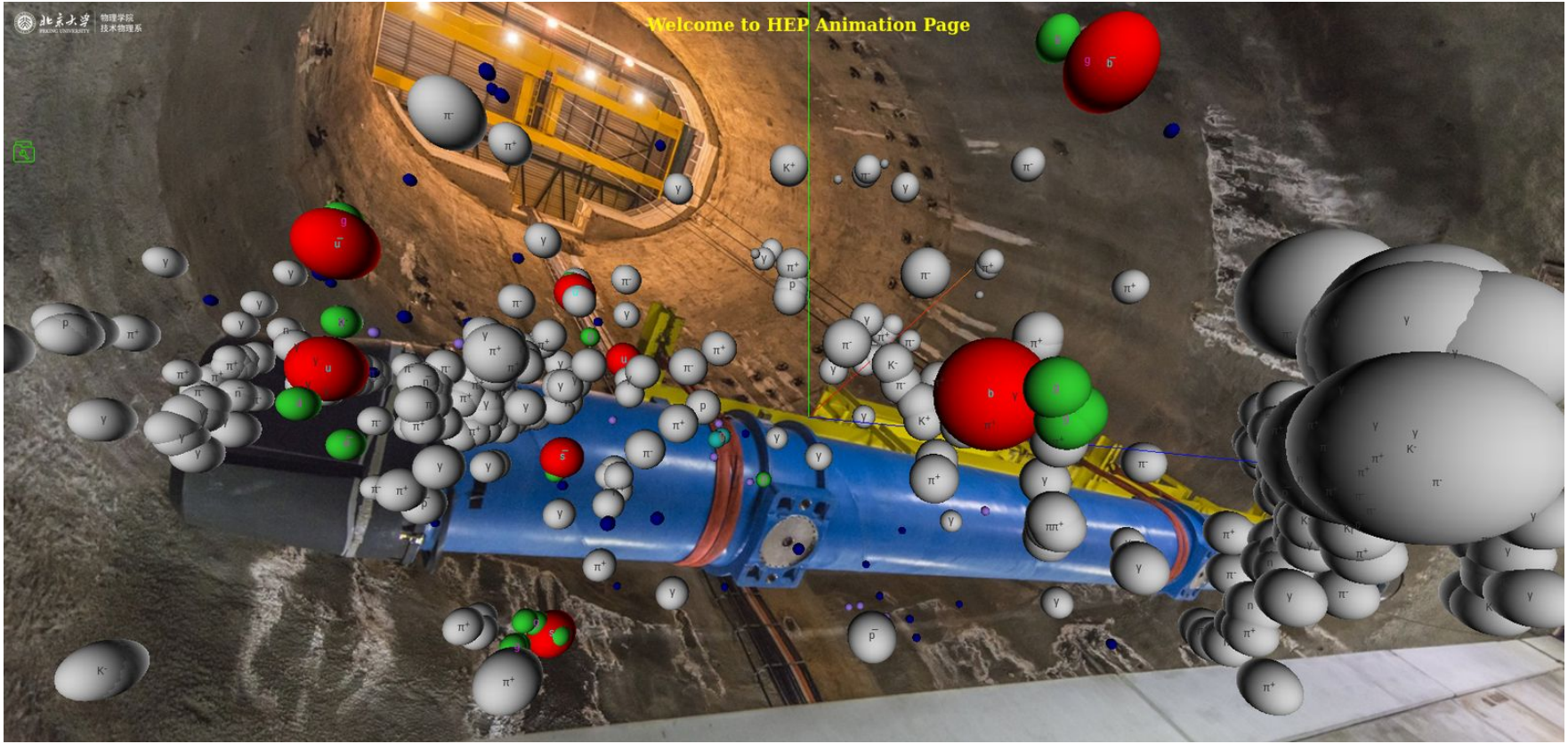


An animation cartoon for 4 Z boson event at the LHC

https://arxiv.org/abs/2109.14621 https://ppnp.pku.edu.cn/hepani/index.html



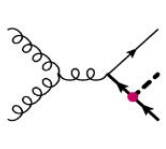
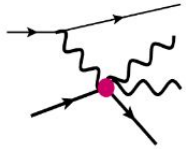
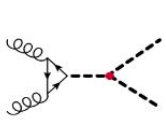
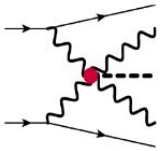
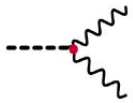
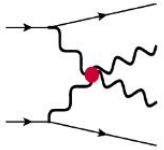
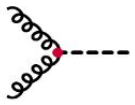
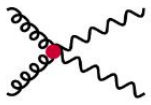
https://arxiv.org/abs/2109.14621 https://ppnp.pku.edu.cn/hepani/index.html



Higgs without Higgs

NEW

TABLE I. Each effect (left-hand column) can be measured as an on-shell Higgs coupling (diagram in the HC column) or in a high-energy process (diagram in the HwH column), where it grows with energy as indicated in the last column.

		HC	HwH	Growth
κ_t	$\mathcal{O}_{y_t}$			$\sim(E^2/\Lambda^2)$
κ_λ	$\mathcal{O}_6$			$\sim(vE/\Lambda^2)$
$\kappa_{Z\gamma}$ $\kappa_{\gamma\gamma}$ κ_V	$\mathcal{O}_{WW}$ $\mathcal{O}_{BB}$ $\mathcal{O}_r$			$\sim(E^2/\Lambda^2)$
κ_g	$\mathcal{O}_{gg}$			$\sim(E^2/\Lambda^2)$

HCs are associated with an EFT Lagrangian $\mathcal{L} = \sum_i c_i \mathcal{O}_i/\Lambda^2$, consisting in particular of the dimension-six operators [12,13],

$$\mathcal{O}_r = |H|^2 \partial_\mu H^\dagger \partial^\mu H, \qquad \mathcal{O}_{y_\psi} = Y_\psi |H|^2 \psi_L H \psi_R,$$
$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}, \qquad \mathcal{O}_{WW} = g^2 |H|^2 W^a_{\mu\nu} W^{a\mu\nu},$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^a_{\mu\nu} G^{a\mu\nu}, \qquad \mathcal{O}_6 = |H|^6, \qquad (1)$$

with Y_ψ the Yukawa coupling for the fermion ψ. [Note that the parameters in Eq. (3) can be put in correspondence with other parametrizations of HCs: via partial widths $\kappa_i^2 = \Gamma_{h\to ii}/\Gamma^{\rm SM}_{h\to ii}$ [14], via Lagrangian couplings in the unitary gauge g_{hii} [13,15], or via pseudo-observables [16].]

The operators of Eq. (1) have the form $|H|^2 \times \mathcal{O}^{\rm SM}$, with $\mathcal{O}^{\rm SM}$ a dimension-four SM operator (i.e., kinetic terms, Higgs potential, and Yukawa couplings) times

ZZ+jets CMS-PAS-SMP-22-001

NEW

The Monte Carlo (MC) simulation used for this analysis can be divided into signal and background samples. The ZZ signal production via quark-antiquark annihilation is simulated at next-to-leading order (NLO) with MadGraph5_aMC@NLO [19] and POWHEG 2.0 [20–23]. The $gg \to ZZ$ process is simulated at leading order (LO) with MCFM [24]. The cross sections of these samples are normalized to the cross sections calculated at NNLO for $q\bar{q} \to ZZ$ [15] (K factor of 1.1) and at NLO in QCD for $gg \to ZZ$ [25] (K factor of 1.7). The production via SM Higgs boson production and decay (in particular $gg \to H \to ZZ$) is simulated with POWHEG at NLO. Electroweak ZZ production in association with two jets is simulated with MadGraph [19] at LO. The nominal SM signal predictions in this analysis are derived from the MadGraph5_aMC@NLO $q\bar{q} \to ZZ$ sample, the MCFM $gg \to ZZ$ samples, and the MadGraph EW production sample, which includes vector boson fusion (VBF) Higgs events and their interference with non-Higgs EW production, and the POWHEG $H \to ZZ$ samples.

ZZ+jets CMS-PAS-SMP-22-001

NEW

Results in this note are also compared to the very recent nNNLO+PS predictions [26], which consist of NNLO predictions for quark-initiated channel combined with parton showers using the MiNNLO$_{PS}$ method, and NLO predictions for loop-induced gluon fusion channel matched to parton showers, with event generators for the two channels implemented in the POWHEG framework. Spin correlations, interferences and off-shell effects are included by calculating the full process $pp \to \ell^+\ell^-\ell'^+\ell'^-$ and considering all contributions to the four-lepton final state.

As part of the nNNLO+PS predictions, the NNLO+PS $q\bar{q} \to ZZ$ predictions from the MiNNLO$_{PS}$ method are NNLO accurate for inclusive production and NLO accurate for Z+1-jet production. The combination of the two jet multiplicities does not require any unphysical merging scale [27]. These predictions are expected to give better descriptions at high jet multiplicities than the POWHEG $q\bar{q} \to ZZ$ predictions, which are NLO accurate in inclusive production, and the MadGraph5_aMC@NLO predictions, which were simulated at NLO with the 0-jet and 1-jet processes, and merged using FxFx scheme [28].

data are unfolded for detector effects using the iterative D'Agostini's method [40] including correction for background contributions, with the RooUnfold toolkit as described in Ref. [41], and compared with the theoretical predictions from (MadGraph5_aMC@NLO $q\bar{q} \to ZZ$)+(MCFM $gg \to ZZ$)+(POWHEG $H \to ZZ$), and (POWHEG $q\bar{q} \to ZZ$)+(MCFM $gg \to ZZ$)+(POWHEG $H \to ZZ$), where MadGraph EW ZZ predictions are also added to these two sets of predictions. The unfolded results are also compared with the nNNLO+PS predictions. The truth-level distributions use generator-level leptons "dressed" by adding the momenta of generator-level photons within $\Delta R(\ell, \gamma) < 0.1$ from direction of the lepton.

ZZ+jets CMS-PAS-SMP-22-001

NEW

In constructing the response matrix, there are MC events that pass the reconstruction-level selections, but do not have corresponding events at truth level that pass the fiducial selections. In the `RooUnfold` toolkit's implementation of the D'Agostini's method, these out-of-fiducial events are treated equivalently as background events that propagate from an additional truth-level bin to the reconstruction-level bins. The size of contribution of these out-of-fiducial events can be up to 15% for events with at least 1 jet. In addition, instead of subtracting the non-prompt and VVV backgrounds from data, we added these background events to the out-of-fiducial events with the mentioned treatment to avoid problem of having negative signal bin contents in regions of low data statistics.

Most systematic uncertainties are propagated through unfolding by recomputing the response matrix with the sample used in building the matrix shifted or reweighted to reflect a 1σ shift in the quantity of interest. The uncertainty related to that quantity is taken as the resulting normalized shape difference in the final unfolded distribution.

$Z\gamma$+jets

arXiv:2212.07184 accepted by JHEP

Observable	Signal Region	$t\bar{t}\gamma$ Control Region
Number of signal leptons	≥ 2 opposite sign, same flavour	≥ 2 opposite sign, different flavour
Lepton	$p_{\mathrm{T}}(\ell_1) > 30$ GeV, $p_{\mathrm{T}}(\ell_2) > 25$ GeV	
Photon	≥ 1 photon with $p_{\mathrm{T}}^{\gamma} > 30$ GeV	
$m_{\ell\ell}$	> 40 GeV	
$m_{\ell\ell} + m_{\ell\ell\gamma}$	> 182 GeV	

Source	$ee + \mu\mu$
$Z\gamma$+jets signal	73 500 ± 50 (stat.) ± 2 600 (syst.)
Z + jets	9 800 ± 460 (stat.) ± 2 100 (syst.)
$t\bar{t}\gamma$	3 600 ± 10 (stat.) ± 540 (syst.)
Pile-up	2 500 ± 70 (stat.) ± 700 (syst.)
Multiboson	950 ± 5 (stat.) ± 280 (syst.)
$tW\gamma$	150 ± 1 (stat.) ± 45 (syst.)
Total prediction	90 500 ± 500 (stat.) ± 3 500 (syst.)
Data	96 410

The primary vertex position z_{vtx} has a Gaussian distribution with a measured width of $\sigma(z_{\mathrm{vtx}}) \sim 35$ mm [14], corresponding to the width of the luminous region. The fraction f_{PU} can then be written as:

$$f_{\mathrm{PU}} = \frac{1}{N_{\mathrm{data}}} \cdot \frac{N_{\mathrm{data}}^{\mathrm{PU}} - N_{\mathrm{MC}}^{\mathrm{PU}}}{P_{\mathrm{PU}}},$$

where $N_{\mathrm{data(MC)}}^{\mathrm{PU}}$ is the number of data (MC) events in a region dominated by pile-up, defined as the region with $|\Delta z| = |z_{\mathrm{vtx}} - z_{\gamma}| > 50$ mm. Since the pile-up events are Gaussian-distributed with a width $\sigma(z_{\mathrm{vtx}} - z_{\gamma}) = \sqrt{2}\sigma(z_{\mathrm{vtx}}) \sim 50$ mm, the probability of observing events with $|\Delta z| > 50$ mm is estimated to be $P_{\mathrm{PU}} = 0.32$. The term N_{MC} describes the MC events where the Z boson and the photon come from the same pp collision, and is taken from signal MC simulation. The MC sample is normalised to the data with $|\Delta z| < 5$ mm. The $|z_{\mathrm{vtx}} - z_{\gamma}|$ distribution is shown in Figure 3 of Ref. [14]. To have a better description of the pile-up events in the differential observables, f_{PU} is computed as a function of N_{jets} and p_{T}^{γ}. The estimated f_{PU} varies from 0.02 to 0.08.

Table 4: Definition of the fiducial region at particle level.

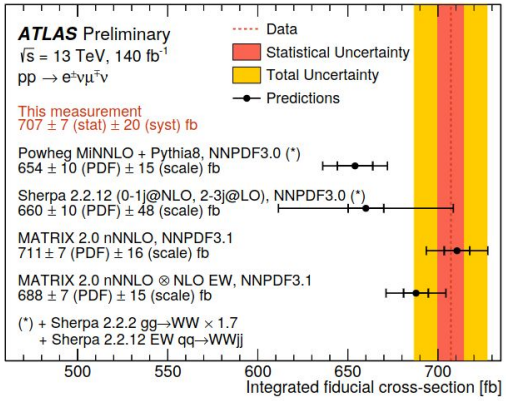
Quantity	Selection criteria
Lepton kinematics	$p_{\mathrm{T}}(\ell_1) > 30$ GeV, $p_{\mathrm{T}}(\ell_2) > 25$ GeV, $\|\eta\| < 2.47$
Photon kinematics	$p_{\mathrm{T}} > 30$ GeV, $\|\eta\| < 2.37$, $\Delta R(\gamma, \ell) > 0.4$
Photon isolation	$E_{\mathrm{T}}^{\mathrm{iso}}/E_{\mathrm{T}}^{\gamma} < 0.07$
Jet kinematics	($p_{\mathrm{T}} > 30$ GeV if $\|\eta\| < 2.5$) or ($p_{\mathrm{T}} > 50$ GeV if $2.5 < \|\eta\| < 4.5$), $\Delta R(\gamma, \mathrm{jet}) > 0.4$
Invariant mass	$m_{\ell\ell} > 40$ GeV, $m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV

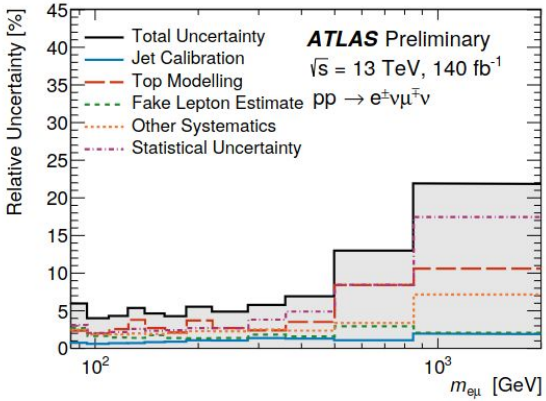
Leptons are required to pass the same p_{T} requirements as in the SR: $p_{\mathrm{T}}(\ell_1) > 30$ GeV, $p_{\mathrm{T}}(\ell_2) > 25$ GeV. However, the η requirements are different: for both electrons and muons $|\eta(\ell)| < 2.47$ is required, since at particle level the discontinuities in the detector are not present. A particle-level isolation requirement is applied to photons: the scalar sum of the E_{T} of all particles, except muons and neutrinos, within a cone of size $\Delta R = 0.2$ around the photon must be less than 7% of the transverse energy of the photon, E_{T}^{γ}. This selection is the same as in Ref. [14] and is optimised to achieve the same level of acceptance in both the detector-level and particle-level selections. Photons are rejected if they are within $\Delta R = 0.4$ of any lepton. Jets are obtained by clustering stable particles, excluding prompt leptons and using the anti-k_t algorithm

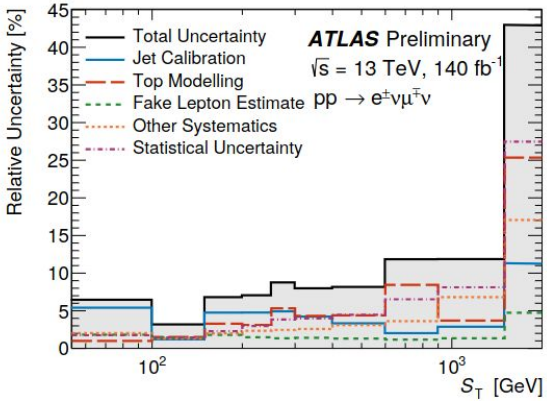
WW

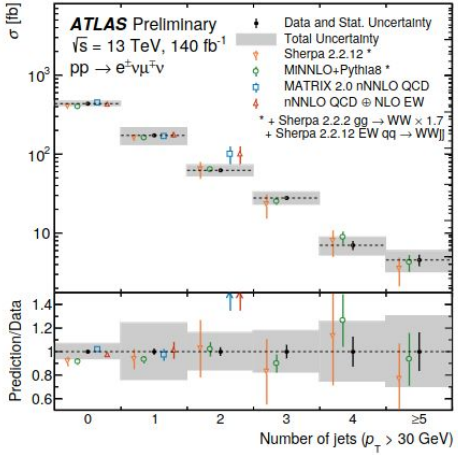
ATLAS-CONF-2023-012

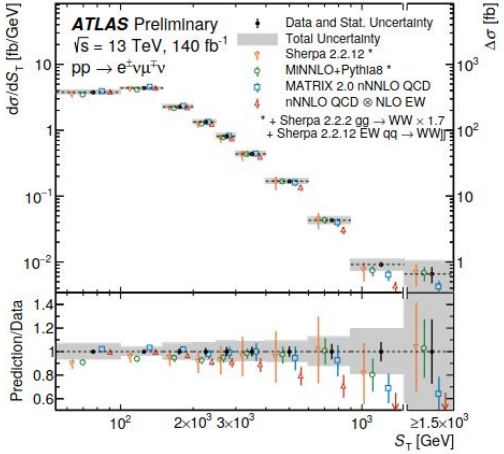
The differential cross-sections are determined using an iterative Bayesian unfolding method [92, 93]. In contrast to the integrated cross-section measurement, these results only weakly depend on the signal model,





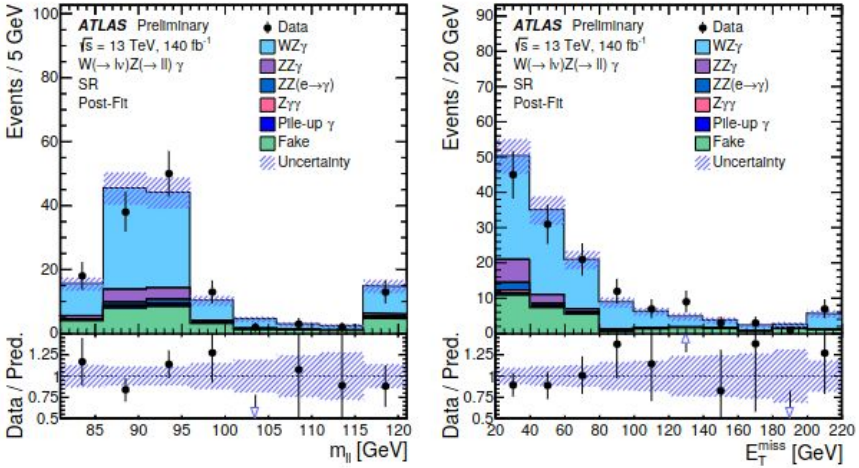






WZγ, Wγγ observation

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



Source	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

In order to obtain an unfolded production cross-section measurement, a fiducial phase space is defined to be as close as possible to the SR event sample selected at detector-level. Fiducial requirements are applied to dressed leptons, which are particle-level electrons and muons recombined with radiated photons within a cone of $\Delta R = 0.1$. Events are required to have a dressed electron or muon with $p_T > 25$ GeV and $|\eta| < 2.47$ while the two particle-level photons must satisfy $p_T > 20$ GeV, $|\eta| < 2.37$, and the isolation requirement ($E_T^{\text{cone40}} - 0.039 \times p_T$) < 6.2 GeV. Additionally, two separation requirements are applied to the two photons and between the lepton and each photon: $\Delta R_{\gamma\gamma} > 0.4$ and $\Delta R_{\ell\gamma} > 0.4$. Finally, fiducial events must satisfy $E_T^{\text{miss}} > 25$ GeV, $m_T^W > 40$ GeV, and a veto on b-jets with $p_T > 20$ GeV. Events from $W \to \tau\nu$ decays that pass these requirements are not considered as signal.

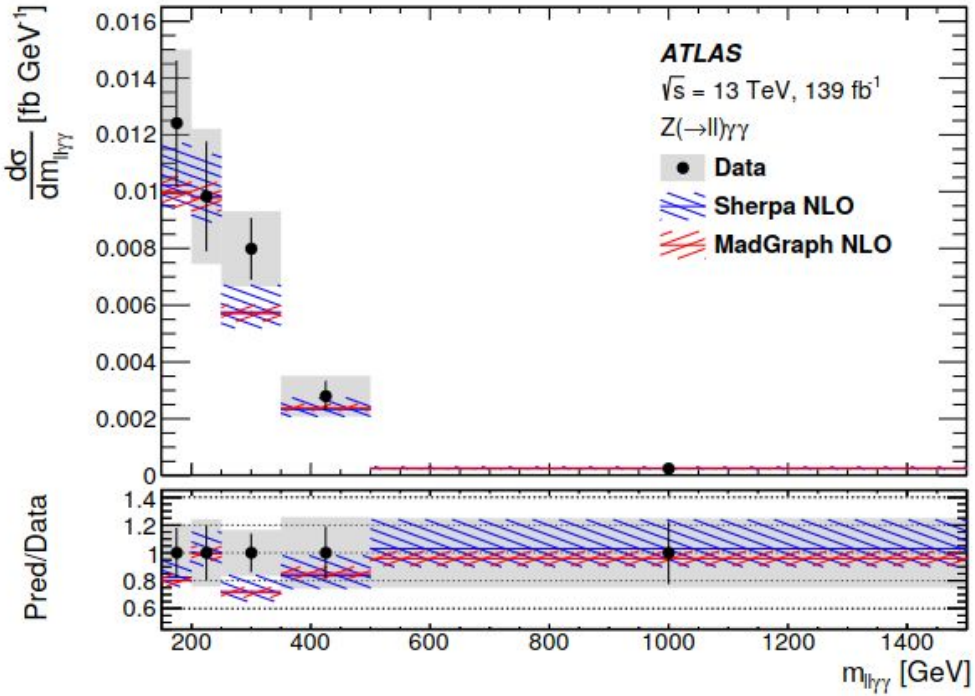
The SM predicted fiducial cross-section, $\sigma_{\text{fid.}}^{\text{SM}}$, obtained using the SHERPA 2.2.11 event generator is 1.50 ± 0.01 (stat.) ± 0.02 (PDF+α_s) ± 0.06 (scale) fb. This value does not include the effect of NLO EW corrections which have been found to be $k_{\text{EW}} = \sigma_{\text{fid.}}^{\text{NLO EW}} / \sigma_{\text{fid.}}^{\text{LO}} = 1.05$ [36] for the subprocess $pp \to WZ\gamma \to e^+\nu_e\mu^+\mu^-\gamma$. The measured cross section in the FR is $\sigma_{WZ\gamma} = 2.01 \pm 0.30$ (stat.) ± 0.16 (syst.) fb, which is consistent with the SM prediction within 1.5 standard deviations.

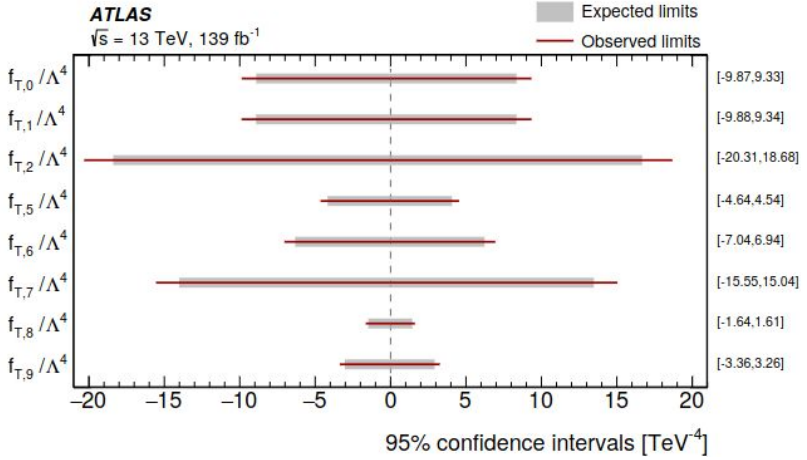
NLO electroweak and QCD corrections to the production of a photon with three charged lepton plus missing energy at the LHC

Huanfeng Cheng and Doreen Wackeroth
Phys. Rev. D **105**, 096009 – Published 11 May 2022

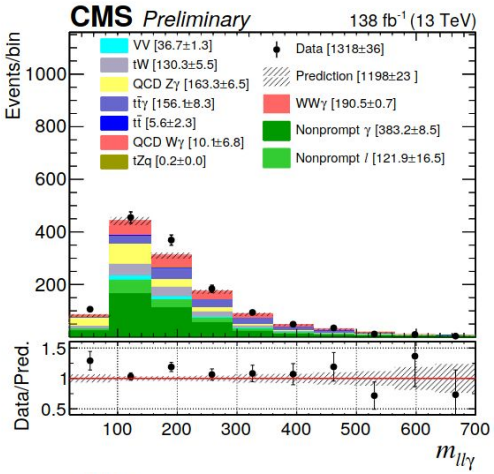
Zγγ

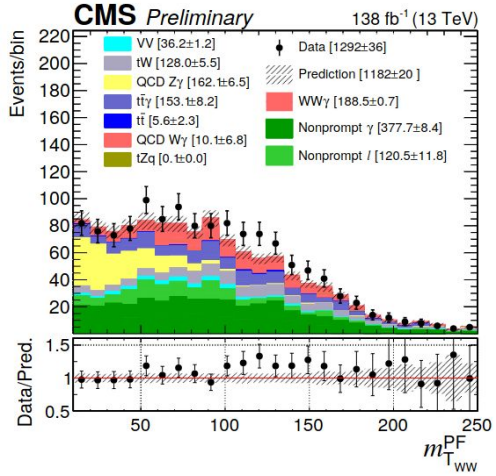
arXiv:2211.14171 accepted by EPJC

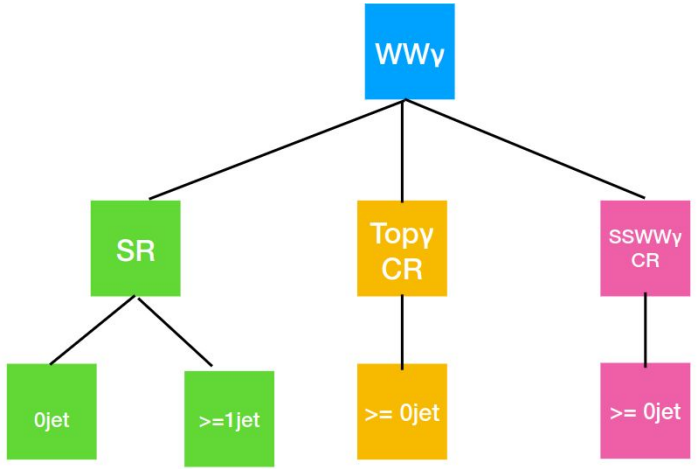




WWγ observation [CMS-PAS-SMP-22-006]







m_T^{WW}	[10,40,70,110,∞]	[10,40,70,110,∞]	[10,∞]	[10,40,70,110,∞]
$m_{ll\gamma}$	[20,150,250,∞]	[20,150,250,∞]	[20,∞]	[20,∞]

- Perform simultaneous fit for events
- Using the 2D variable (m_T^{WW} and $m_{ll\gamma}$) to build the likelihood function for SR

WWγ observation CMS-PAS-SMP-22-006

Flat Direction scenario:

production and decay rates at the LHC [57–59] (see also Ref. [14]), unless further assumptions are made. The effect of an enhanced Higgs Yukawa coupling y_q to a light quark $q = u, d, c, s$ on the Higgs branching fractions may be compensated by a related increase of the Higgs couplings to gauge bosons and third-generation fermions, leading to a "flat direction" in the fit along which the Higgs signal strengths remain unchanged. From the present good agreement between SM predictions and LHC Higgs measurements [22,60,61], this flat direction may be approximately described by a single generic κ_h enhancement factor for all Higgs couplings other than the light quark Yukawa y_q of interest [14]:

$$\kappa_h^2 \simeq \frac{1 - Br_{q\bar{q}}^{\mathrm{SM}}}{2} + \frac{\sqrt{(1 - Br_{q\bar{q}}^{\mathrm{SM}})^2 + 4Br_{q\bar{q}}^{\mathrm{SM}}\kappa_q^2}}{2}, \qquad (4)$$

with $Br_{q\bar{q}}^{\mathrm{SM}}$ being the branching fraction for $h \to q\bar{q}$ in the SM. While the combination of Higgs signal strengths with other measurements—e.g., with electroweak precision observables or an indirect measurement of the Higgs total width (model-dependent, see Ref. [62])—can help in lifting the flat direction [Eq. (4)], this discussion highlights the importance of complementary probes of Higgs couplings to light quarks.

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG2KAPPA?redirectedfrom=LHCPhysics.LHCHXSWG2KAPPA#1_gluon_gluon_Fusion_Process

$$\kappa_g^2 = 1.042\kappa_t^2 + 0.002\kappa_b^2 - 0.040\kappa_t\kappa_b - 0.005\kappa_t\kappa_c + 0.0005\kappa_b\kappa_c + 0.00002\kappa_c^2$$

WWγ observation CMS-PAS-SMP-22-006

PHYSICAL REVIEW D **101,** 115005 (2020)

Probing the Higgs–strange-quark coupling at e^+e^- colliders using light-jet flavor tagging

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(Received 29 April 2019; revised manuscri

[11] M. Aaboud *et al.* (ATLAS Collaboration), Phys. Rev. Lett. **119**, 051802 (2017).
[12] V. Khachatryan *et al.* (CMS Collaboration), Phys. Lett. B **744**, 184 (2015).
[13] G. Perez, Y. Soreq, E. Stamou, and K. Tobioka, Phys. Rev. D **92**, 033016 (2015).
[14] M. Aaboud *et al.* (ATLAS Collaboration), J. High Energy Phys. 07 (2018) 127.

However, it is important to note that the flavor puzzle is related to the mass hierarchy among all three generations of up-type quarks (u, c, t), down-type quarks (d, s, b), and charged leptons (e, μ, τ). Therefore, direct measurements of the smaller couplings of the Higgs to the first two generations of the different sectors are also necessary. So far, only upper bounds on the corresponding signal strengths have been obtained [11–14],

$$\mu_{\mu\mu} \lesssim 2.8, \qquad \mu_{ee} \lesssim 3.7 \times 10^5,$$
$$\mu_{cc} \lesssim 110, \qquad \mu_{ss} \lesssim 7.2 \times 10^8. \qquad (3)$$

Same-Sign WW

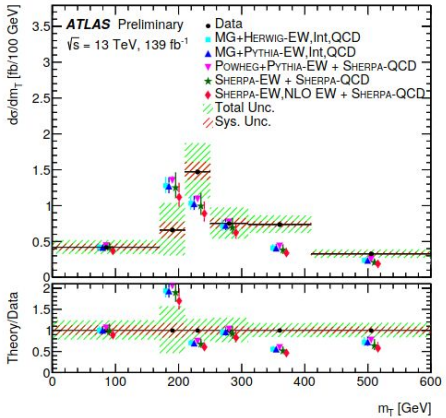
ATLAS-CONF-2023-023

NEW

Process, short description	ME Generator + parton shower	Order	Tune	PDF set in ME
EW, Int, QCD $W^{\pm}W^{\pm}jj$, nominal signal	MadGraph5_aMC@NLO2.6.7 + Herwig7.2	LO	default	NNPDF3.0NLO
EW, Int, QCD $W^{\pm}W^{\pm}jj$, alternative shower	MadGraph5_aMC@NLO2.6.7 + Pythia8.244	LO	A14	NNPDF3.0NLO
EW $W^{\pm}W^{\pm}jj$, NLO pQCD approx.	Sherpa2.2.11[2]	+0,1j@LO	Sherpa	NNPDF3.0NNLO
EW $W^{\pm}W^{\pm}jj$, NLO pQCD approx.	Powheg Boxv2 + Pythia8.230	NLO (VBS approx.)	AZNLO	NNPDF3.0NLO
QCD $W^{\pm}W^{\pm}jj$, NLO pQCD approx.	Sherpa2.2.2	+0,1j@LO	Sherpa	NNPDF3.0NNLO
QCD $VVjj$	Sherpa2.2.2	+0,1j@NLO; +2,3j@LO	Sherpa	NNPDF3.0NNLO
EW $W^{\pm}Zjj$	MadGraph5_aMC@NLO2.6.2+Pythia8.235	LO	A14	NNPDF3.0NLO
EW $ZZjj$	Sherpa2.2.2	LO	Sherpa	NNPDF3.0NNLO
QCD $V\gamma jj$	Sherpa2.2.11	+0,1j@NLO; +2,3j@LO	A14	NNPDF3.0NNLO
EW $V\gamma jj$	MadGraph5_aMC@NLO2.6.5+Pythia8.240	LO	A14	NNPDF3.0NLO
VVV	Sherpa2.2.1 (leptonic) & Sherpa2.2.2 (one $V \to jj$)	+0,1j@LO	Sherpa	NNPDF3.0NNLO
$t\bar{t}V$	MadGraph5_aMC@NLO2.3.3.p0 + Pythia8.210	NLO	A14	NNPDF3.0NLO

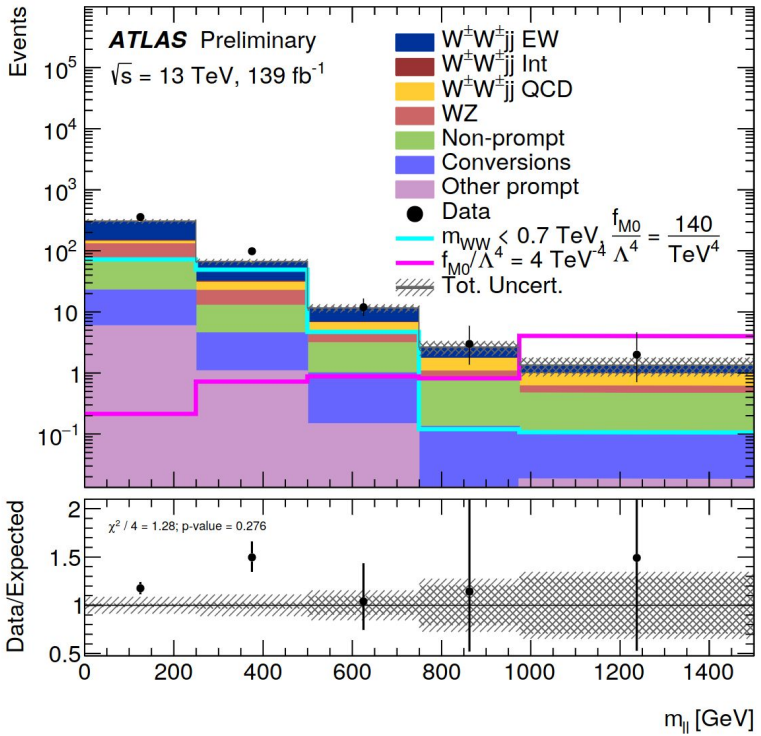
MG+Herwig

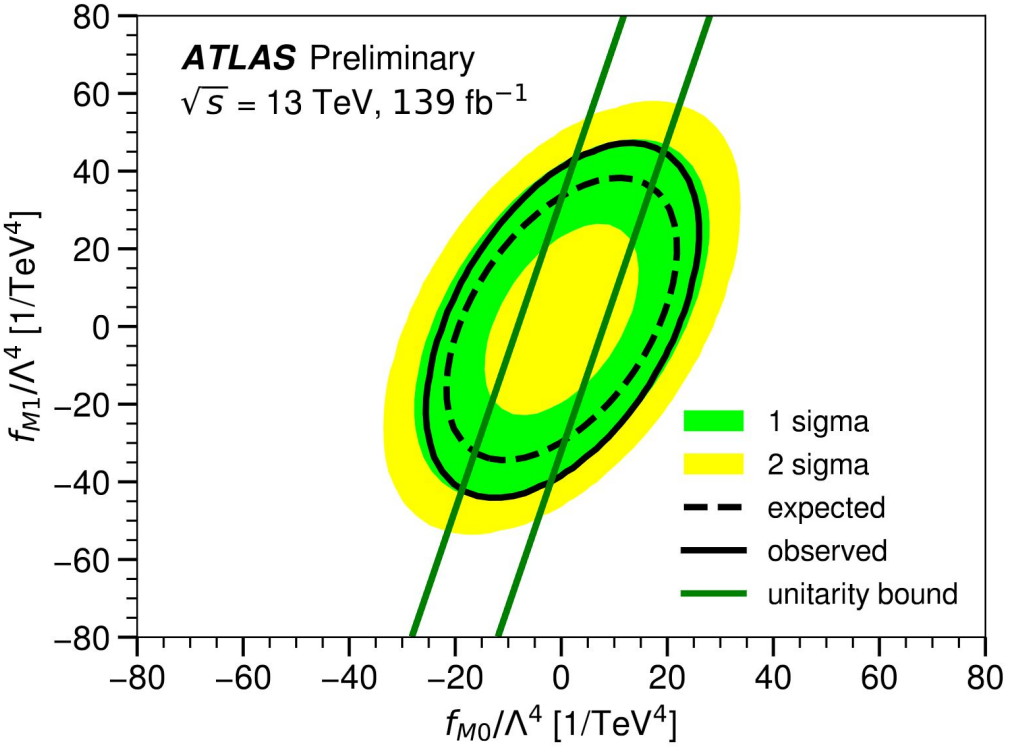
Variable	EW $W^{\pm}W^{\pm}jj$ χ^2/N_{dof}	EW $W^{\pm}W^{\pm}jj$ p-value	Inclusive $W^{\pm}W^{\pm}jj$ χ^2/N_{dof}	Inclusive $W^{\pm}W^{\pm}jj$ p-value
$m_{\ell\ell}$	4.4/6	0.623	7.0/6	0.322
m_{T}	12.9/6	0.045	15.9/6	0.014
m_{jj}	7.2/6	0.300	7.8/6	0.250
$N_{\text{gap jets}}$	2.3/2	0.316	2.3/2	0.316
ξ_{j3}	4.3/5	0.511	5.2/5	0.396



Same-Sign WW

ATLAS-COM-CONF-2023-031 EPJC 81 (2021) 723





ZZ→4l + jets

ATLAS-COM-CONF-2023-032

Source	Uncertainty (%)
Luminosity	0.8 – 1.3
Leptons	0.8 – 1.6
Jets	2.7 – 18
Pile-up	0.0 – 2.5
Backgrounds	0.9 – 9.0
Theory modelling	0.6 – 8.8
Unfolding method	0.9 – 12
Total systematic	5 – 22

Wilson coefficient	$\lvert\mathcal{M}_{d6}\rvert^2$ Included	95% confidence interval [TeV^{-2}] Expected	Observed
c_W/Λ^2	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-32, 32]	[-37, 28]
$c_{\widetilde{W}}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-17, 17]*	[0, 30]*
c_{HWB}/Λ^2	yes	[-16, 7]	[-16, 6]
	no	[-12, 12]	[-15, 10]
$c_{H\widetilde{W}B}/\Lambda^2$	yes	[-1.3, 1.3]	[-1.2, 1.2]
	no	[-67, 67]*	[-25, 130]*
c_{HB}/Λ^2	yes	[-13, 13]	[-12, 12]
	no	[-38, 38]	[-38, 38]
$c_{H\widetilde{B}}/\Lambda^2$	yes	[-13, 13]	[-12, 12]
	no	[-420, 420]*	[-200, 790]*