Zγ VBS measurements with ATLAS full Run2

Qibin LIU

Tsung-Dao Lee Institute,
Shanghai Jiao Tong Univ.

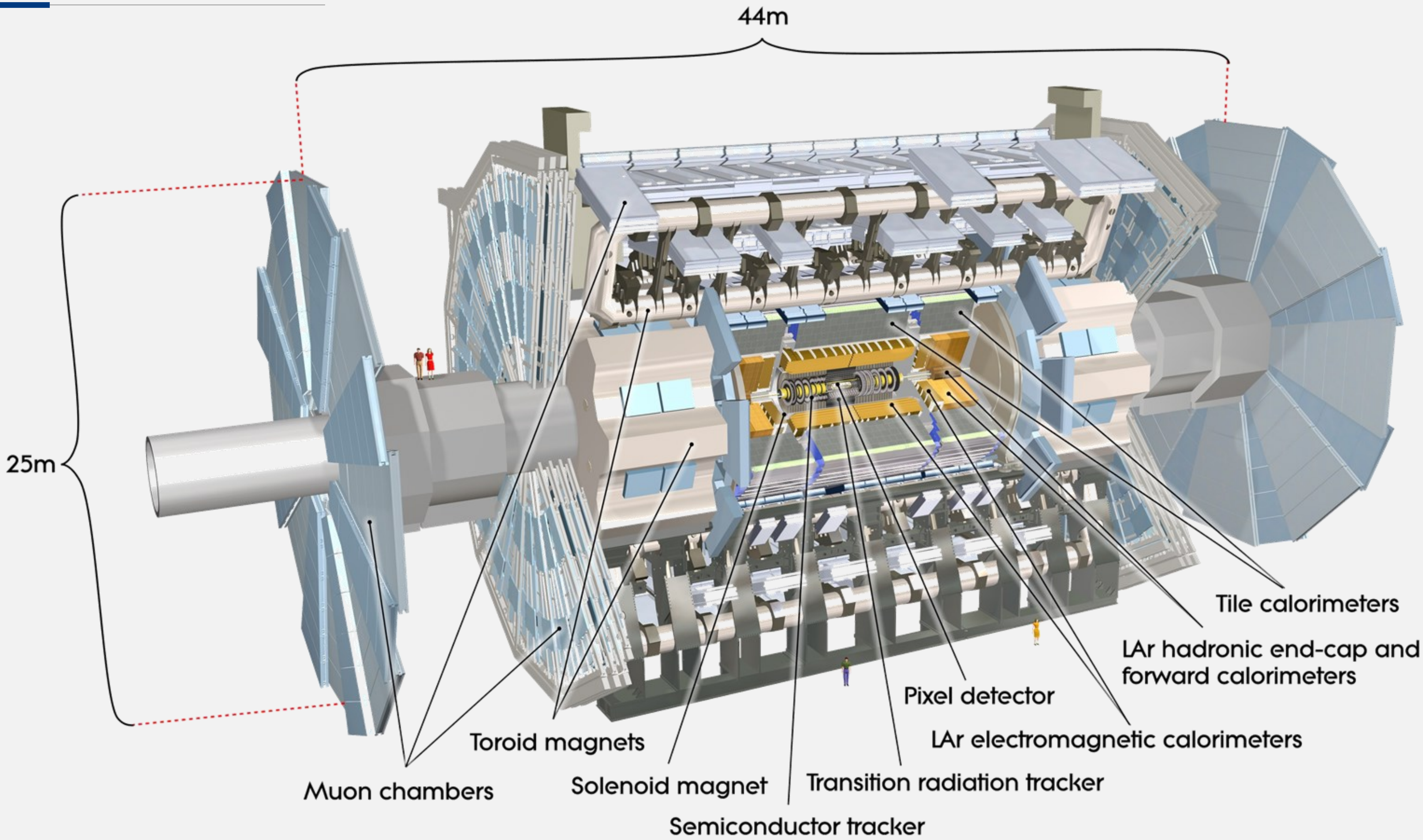
On behalf of the ATLAS collaboration

李政道研究所
TSUNG-DAO LEE INSTITUTE

MBI 2022

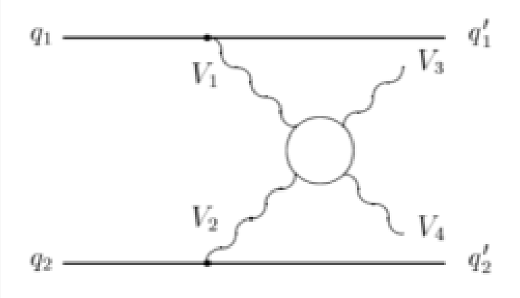
contents

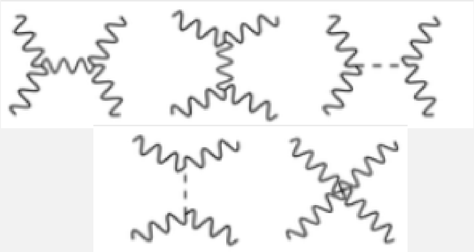
ATLAS detector



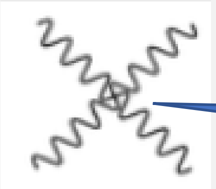
Vector Boson Scattering

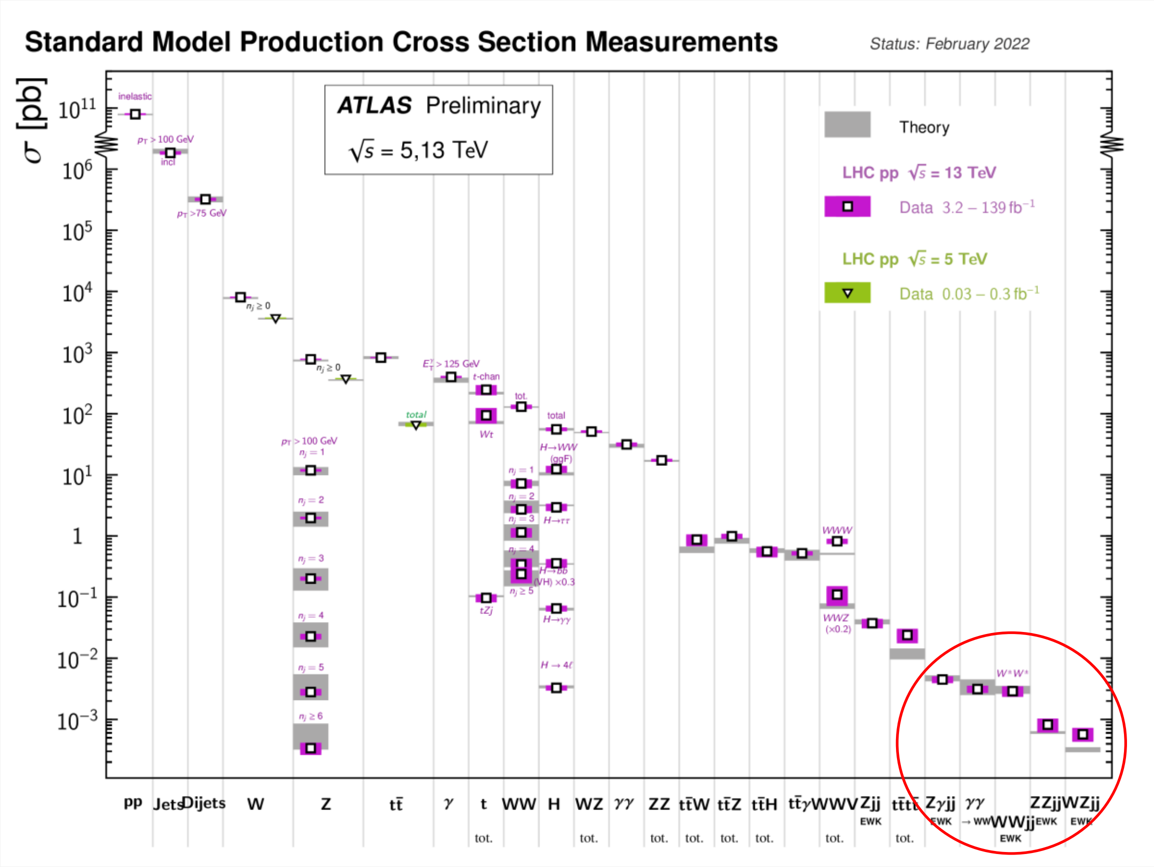
- **Rare but vital in both SM and BSM**
  - Cross-section ~fb : Challenging for analysis
  - Rich physics contents





  - Key process to probe the mechanism of electroweak symmetry breaking
  - Sensitive to many new physics scenarios
  - Crucial inputs for EFT study like aQGC





(anomalous) Quartic Gauge Coupling
Higgs can also be involved

ATLAS VBS Zγjj analysis with full Run2

- **Pure VBS and quartic coupling is not accessible (due to gauge invariance)**
  - Typical study of the EWK production of VVjj process
  - 2 energetic jets with large angle ($\Delta\eta$), high invariant mass (m_{jj})

    Little hadronic activity in the rapidity gap → distinctive feature of VBS VVjj
- **EWK Zγ process observed and measured with ATLAS full Run2 data**
  - Leptonic decay of Z:
    - EWK $Z(\rightarrow ll)\boldsymbol{\gamma jj}$: observed at 10σ
  - Invisible decay of Z:
    - EWK $Z(\rightarrow \nu\nu)\boldsymbol{\gamma jj}$ w/ photon pT ∈[15,110] GeV: observed at 5.2σ
    - EWK $Z(\rightarrow \nu\nu)\boldsymbol{\gamma jj}$ w/ photon pT >150 GeV : to be public
- **BSM topics discussed : aQGC, dark photon, invisible decay of Higgs and so on**

	Obs (Exp) sign.	Fid. XS of EW-Z$\boldsymbol{\gamma}$jj / fb	Ref
$Z(\rightarrow ll)\boldsymbol{\gamma jj}$ VBS analysis	10σ (11σ)	4.49±0.40 (stat.)±0.42 (syst.)	ATLAS-CONF-2021-038
VBF+MET+Photon (EW-Zνν$\boldsymbol{\gamma jj}$ w/ $p_T^\gamma \in [15{,}110 GeV]$)	5.2σ (5.1σ)	1.31±0.20 (stat.)±0.20 (syst.)	Eur. Phys. J. C 82 (2022) 105
$Z(\rightarrow \nu\nu)\boldsymbol{\gamma jj}$ VBS analysis ($p_T^\gamma > 150 GeV$)	(To be public)		

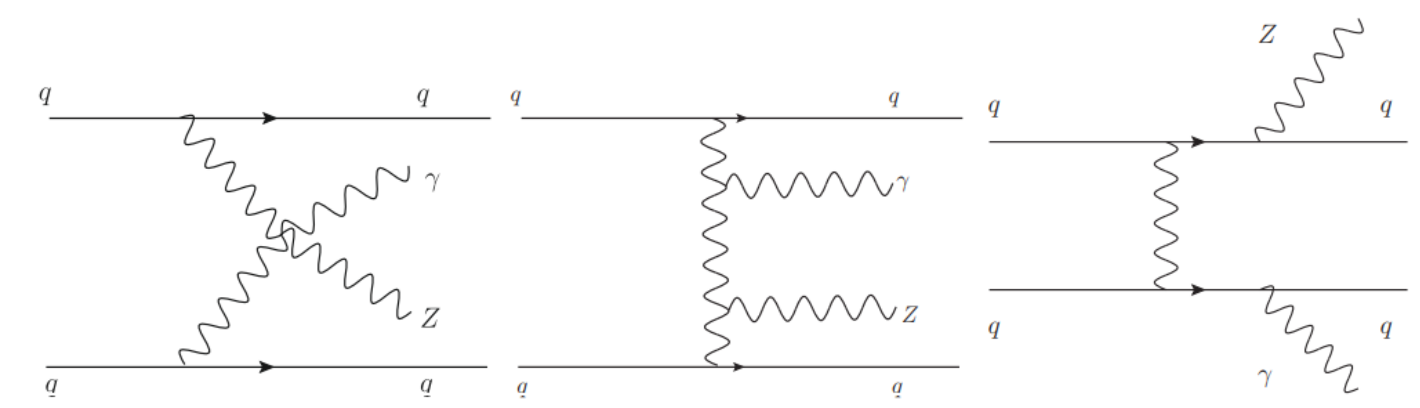
$Z(\rightarrow ll)\gamma jj$ VBS

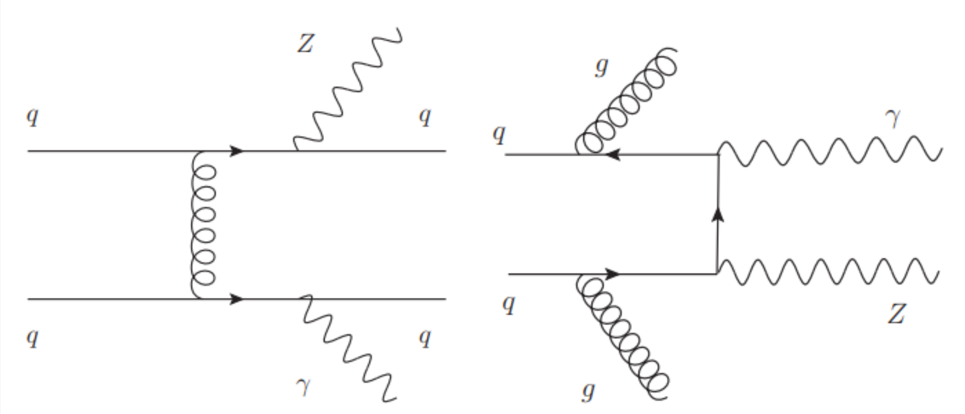
ATLAS-CONF-2021-038

$Z(\rightarrow ll)\gamma jj$ VBS analysis : Introduction

李政道研究所 TSUNG-DAO LEE INSTITUTE

- **EW production Zγjj studied in the eeγjj and μμγjj channels using 139/fb data**
- **Dominant background from QCD production Zγjj**





Quartic gauge coupling VBS signal | Triple gauge coupling | EWK non-VBS signal | Gluon exchange QCD background | Gluon radiation QCD background

EWK production Zγjj (Signal)

Madgraph LO

QCD production Zγjj (Dominant Background)

Madgraph NLO (Alt. Sherpa2.2.4/2.2.10)

$Z(\to ll)\gamma jj$ VBS analysis : Selection

Single and di-lepton trigger used in analysis

25GeV photon E_T requirement

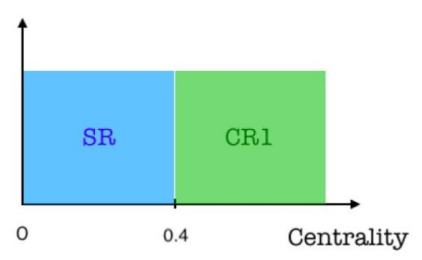
→ reduce significantly Z+jets and pile-up background

Remove low-mass resonance by requiring large m_{ll}

Remove the FSR photon by requiring large $m_{ll} + m_{ll\gamma}$

$Z\gamma$ centrality cut to separate EWK and QCD $Z\gamma jj$ process

$$\zeta(Z\gamma) = \left|\frac{y_{Z\gamma} - (y_{j1} + y_{j2})/2}{(y_{j1} - y_{j2})}\right|$$

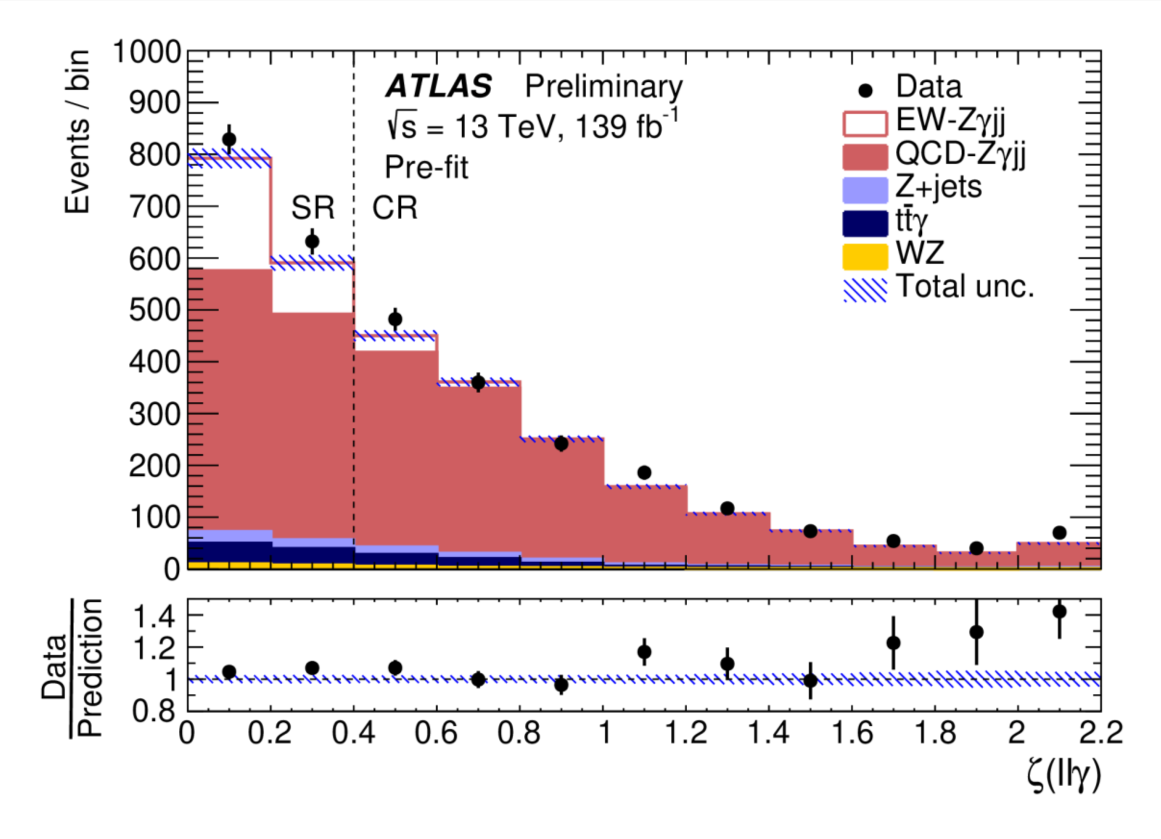


No jet in rapidity gap of two jets → increase S/B

Lepton	$p_T^\ell > 20, 30(\text{leading})$ GeV, $\lvert\eta_\ell\rvert < 2.47$ $N_\ell \geq 2$
Photon	$E_T^\gamma > 25$ GeV, $\lvert\eta_\gamma\rvert < 2.37$ $E_T^{cone20} < 0.07 E_T^\gamma$ $\Delta R(\ell, \gamma) > 0.4$
Jet	$p_T^{jet} > 50$ GeV, $\lvert y_{jet}\rvert < 4.4$ $\lvert\Delta y\rvert > 1.0$ $m_{jj} > 150$ GeV remove jets if $\Delta R(\gamma, j) < 0.4$ or if $\Delta R(\ell, j) < 0.3$
Event	$m_{\ell\ell} > 40$ GeV $m_{\ell\ell} + m_{\ell\ell\gamma} > 182$ GeV $\zeta(\ell\ell\gamma) < 0.4$ $N_{jets}^{gap} = 0$

$Z(\to ll)\gamma jj$ VBS analysis : Background

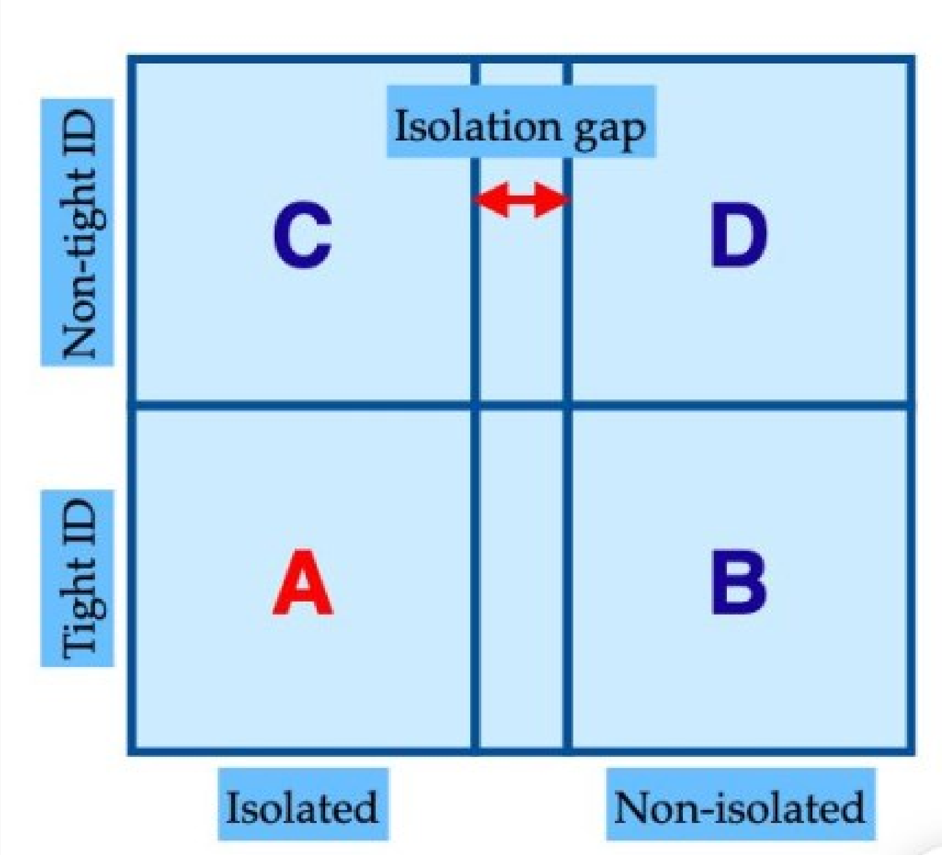
- **QCD Zγjj: Estimated from MC**
  - **Norm. fitted in SR and CR1 ($\zeta_{Z\gamma}$ cut inverted)**
- Z+jets : Data-driven
  - Normalization and shape extracted from data
  - 2D Sideband method : photon ID and isolation
- ttγ: Estimated from MC (Madgraph LO)
  - Scale factor of 1.44 and in agreement with [1]
  - Validated with data in standalone e$\mu\gamma$ CR
- WZjj: Estimated from MC (Sherpa/Madgraph)



[1] Eur. Phys. J. C 79 (2019) 382

$Z(\rightarrow ll)\gamma jj$ VBS analysis : Background

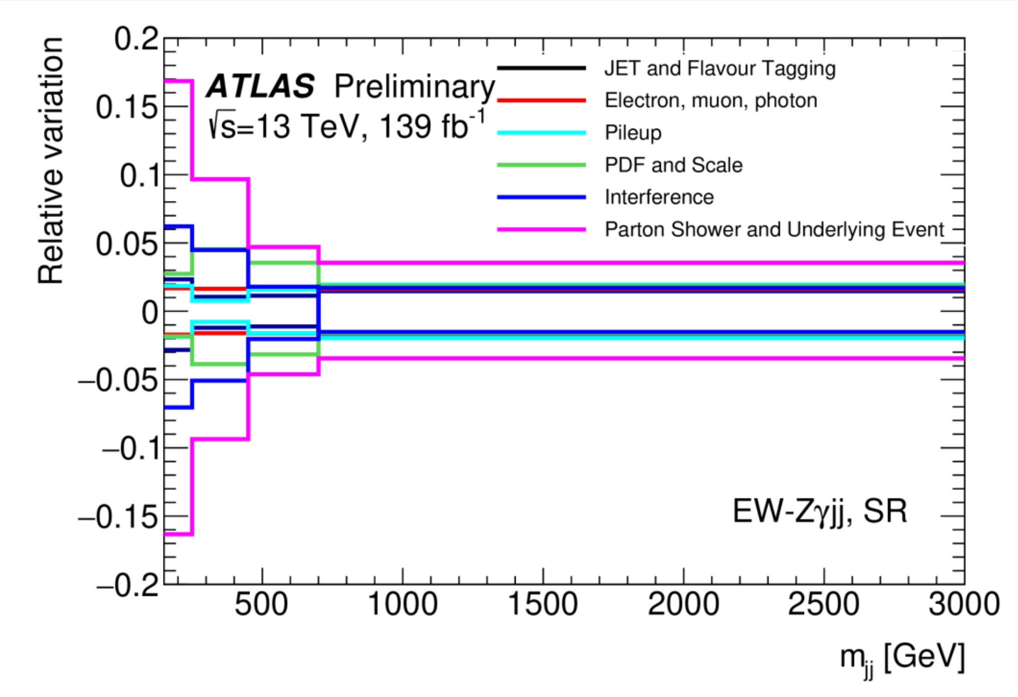
- QCD Zγjj: Estimated from MC
  - Norm. fitted in SR and CR1 ($\zeta_{Z\gamma}$ cut inverted)
- **Z+jets : Data-driven**
  - **Normalization and shape extracted from data**
  - **2D Sideband method : photon ID and isolation**
- ttγ: Estimated from MC (Madgraph LO)
  - Scale factor of 1.44 and in agreement with [1]
  - Validated with data in standalone e$\mu\gamma$ CR
- WZjj: Estimated from MC (Sherpa/Madgraph)

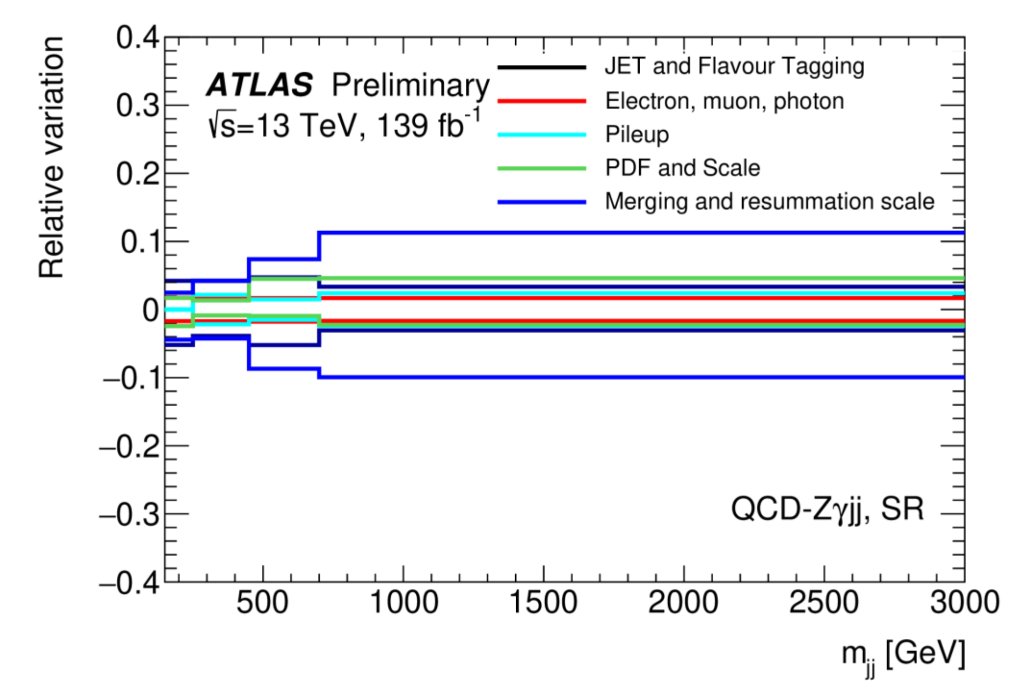


[1] Eur. Phys. J. C 79 (2019) 382

$Z(\rightarrow ll)\gamma jj$ VBS analysis : Systematics

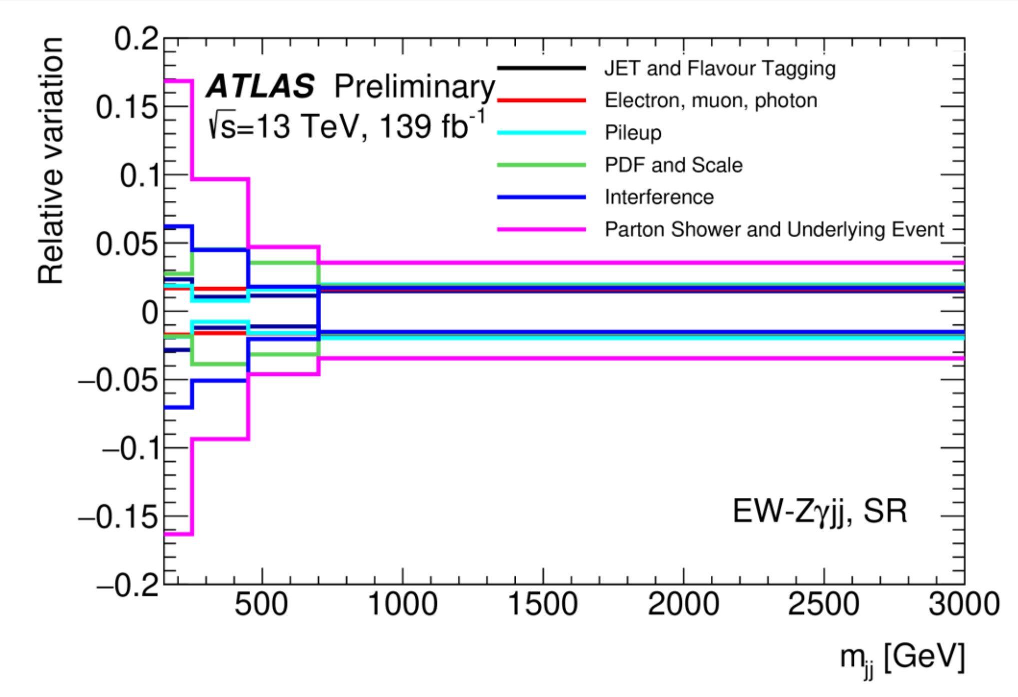
- **Experimental Systematics:**
  - Lepton, Photon, Jet and PRW
  - Typically <2% and largest from jet energy calibration and response
  - Correlated among all the regions and processes
- **Background Normalization:**
  - 35% uncertainty for Z+jets from Data-driven
  - 15% (20%) uncertainty for ttγ (WZ) estimated from QCD scale and PDF

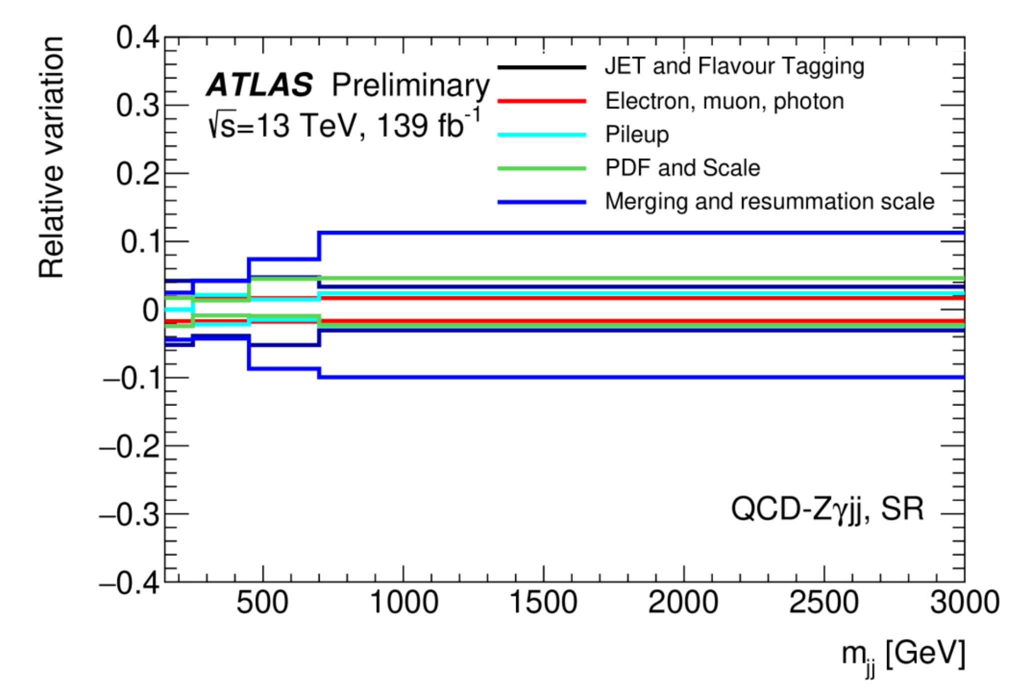




$Z(\rightarrow ll)\gamma jj$ VBS analysis : Systematics

- **Theoretical Systematics:**
  - Scale and PDF variation for both EW- and QCD- Zγjj
  - Parton showering and underlying event model variation of EW-Zγjj
    - Only shape difference considered
  - Merging (CKKW) and resummation (QSF) scale variation of QCD-Zγjj
    - Estimated based on Sherpa2.2.10 LO samples
  - Interference between EW- and QCD-Zγjj considered as an extra uncertainty





$Z(\rightarrow ll)\gamma jj$ VBS analysis : Signal Extraction

李政道研究所 TSUNG-DAO LEE INSTITUTE

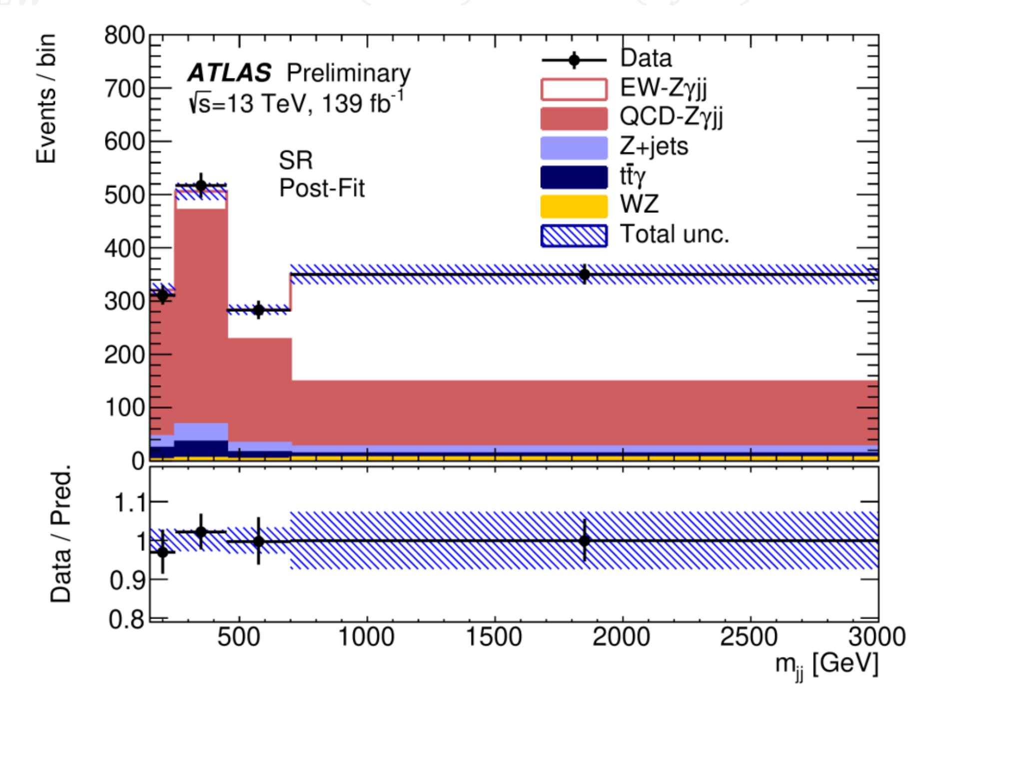
- **Maximum likelihood fit of m_{jj} on SR and CR simultaneously to extract**
  - Signal strength for EW-Zγjj : $\boldsymbol{\mu_{EW}} \equiv \frac{\sigma_{EW}^{meas.}}{\sigma_{EW}^{exp.}}$ correlated between SR and CR
  - Two norm. factors for QCD-Zγjj : decorrelated between SR and CR
    → CR only used to validate the shape and constrain the systematics

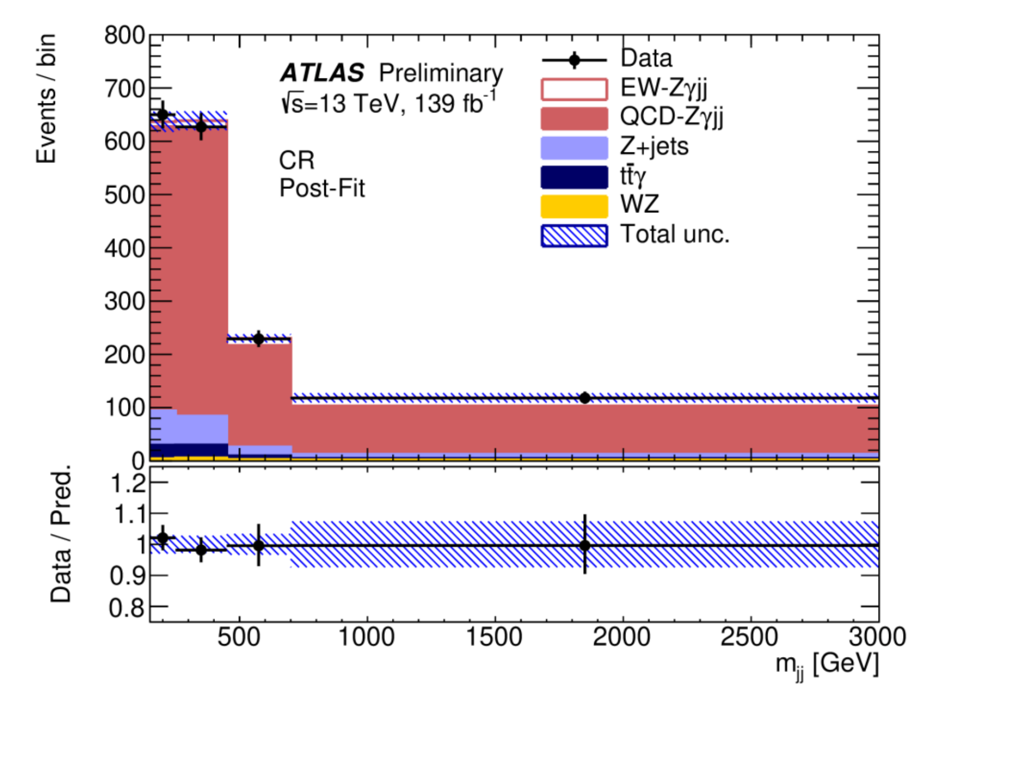
	SR	CR1
μ_{EWK}	√	√
μ_{QCD}^{SR}	√	
μ_{QCD}^{CR1}		√

$Z(\rightarrow ll)\gamma jj$ VBS analysis : Signal Extraction

Sample	SR	CR
$N_{EW-Z\gamma jj}$	300 ± 36	55 ± 7
$N_{QCD-Z\gamma jj}$	987 ± 55	1352 ± 60
$N_{t\bar{t}\gamma}$	72 ± 11	59 ± 9
N_{WZ}	17 ± 3	14 ± 3
N_{Z+jets}	85 ± 30	143 ± 43
Total	1461 ± 38	1624 ± 40
N_{obs}	1461	1624

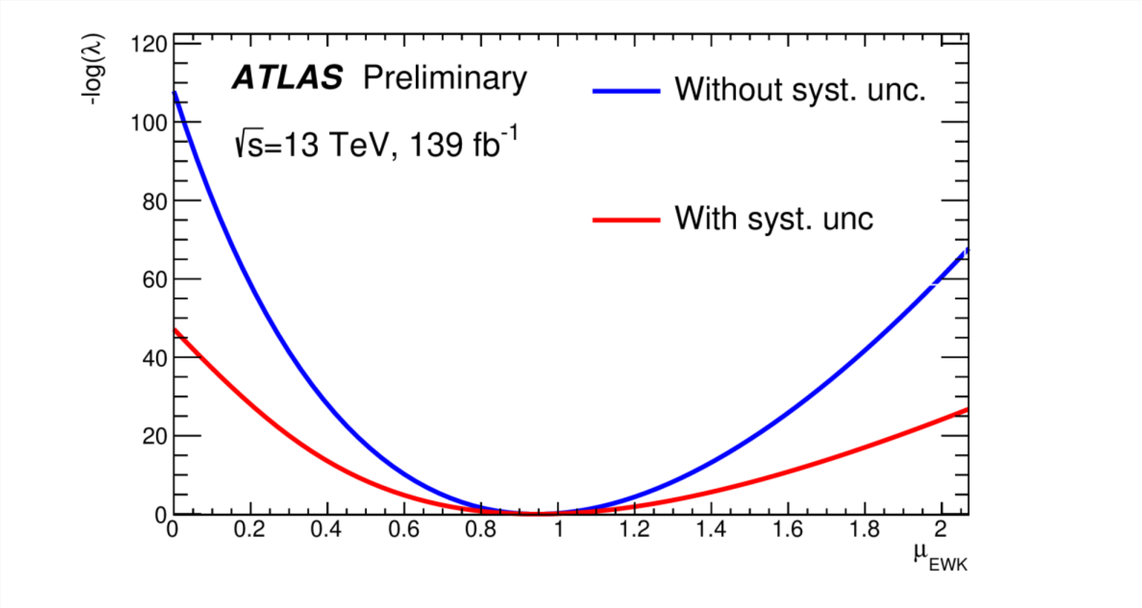
- **Maximum likelihood fit of m_{jj} on SR and CR simultaneously to extract**
  - Signal strength for EW-Zγjj : $\mu_{EW} \equiv \frac{\sigma_{EW}^{meas.}}{\sigma_{EW}^{exp.}}$ correlated between SR and CR
  - Two norm. factors for QCD-Zγjj : decorrelated between SR and CR
    → CR only used to validate the shape and constrain the systematics
- **The post-fit distribution shows good data/MC agreement**





$Z(\rightarrow ll)\gamma jj$ VBS analysis : Signal Extraction

- **Maximum likelihood fit of m_{jj} on SR and CR simultaneously to extract**
  - Signal strength for EW-Zγjj : $\mu_{EW} \equiv \frac{\sigma_{EW}^{meas.}}{\sigma_{EW}^{exp.}}$ correlated between SR and CR
  - Two norm. factors for QCD-Zγjj : decorrelated between SR and CR
    → CR only used to validate the shape and constrain the systematics
- **The post-fit distribution shows good data/MC agreement**
- $\mu_{EW} = 0.95 \pm 0.08\ (stat) \pm 0.11\ (syst)$



EW- $Z(\rightarrow ll)\gamma jj$ observed with more than 10σ (11σ expected)

$Z(\to ll)\gamma jj$ VBS analysis : Measurement of Cross-section

李政道研究所 TSUNG-DAO LEE INSTITUTE

- **Fiducial cross-section of EW-Zγjj measured from μ_{EW} :**
  - $\sigma_{EW} = 4.49 \pm 0.40\ (stat) \pm 0.42\ (syst)\ fb$
  - $\sigma_{EW}^{pred} = 4.73 \pm 0.01\ (stat) \pm 0.15\ (PDF)^{+0.23}_{-0.22}\ (scale) fb$

	Data stat.	MC stat.	Background	Reco	EW mod.	QCD mod.	Total
$\Delta\sigma_{EW}/\sigma_{EW}$ [%]	± 9	± 1	± 1	± 5	$^{+6}_{-5}$	$^{+5}_{-4}$	± 13

Source	Size [%]
Electron/photon calibration	$\pm$ 0.3
Photon	$\pm$ 0.3
Backgrounds	$\pm$ 1.0
Electron	$\pm$ 1.1
Flavour tagging	$\pm$ 1.1
Muon	$\pm$ 1.1
MC stat.	$\pm$ 1.4
Pileup	$\pm$ 2.6
Jets	$\pm$ 4.7
QCD-Zγjj modelling	$^{+4.8}_{-4.3}$
EW-Zγjj modelling	$^{+5.7}_{-4.6}$
Data stat.	$\pm$ 8.8
Total	$^{+13.4}_{-12.6}$

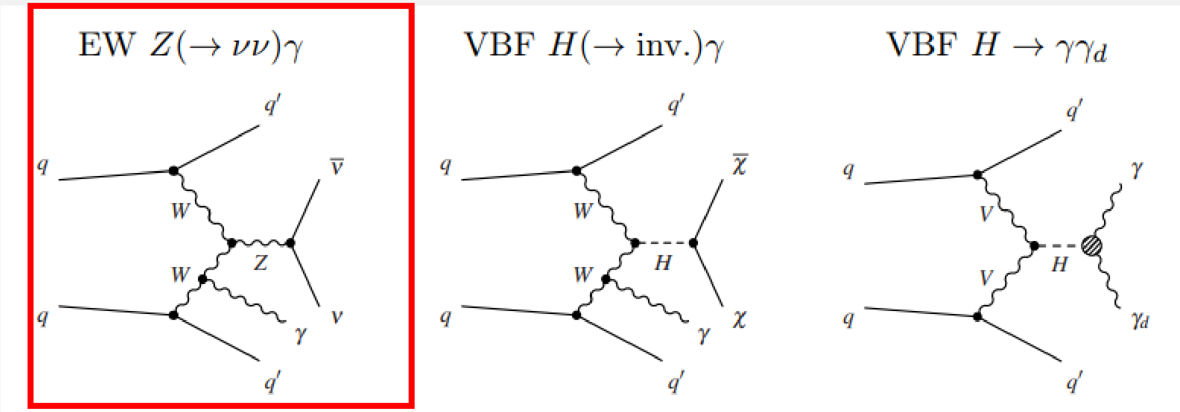
- **Fid. cross-section of EW+QCD Zγjj measured in SR-only:**
  - $\sigma_{EW+QCD} = 20.6 \pm 0.6\ (stat)^{+1.2}_{-1.0}\ (syst)\ fb$
  - $\sigma_{EW+QCD}^{pred} = 20.4 \pm 0.1\ (stat) \pm 0.2\ (PDF)^{+2.6}_{-2.0}\ (scale) fb$

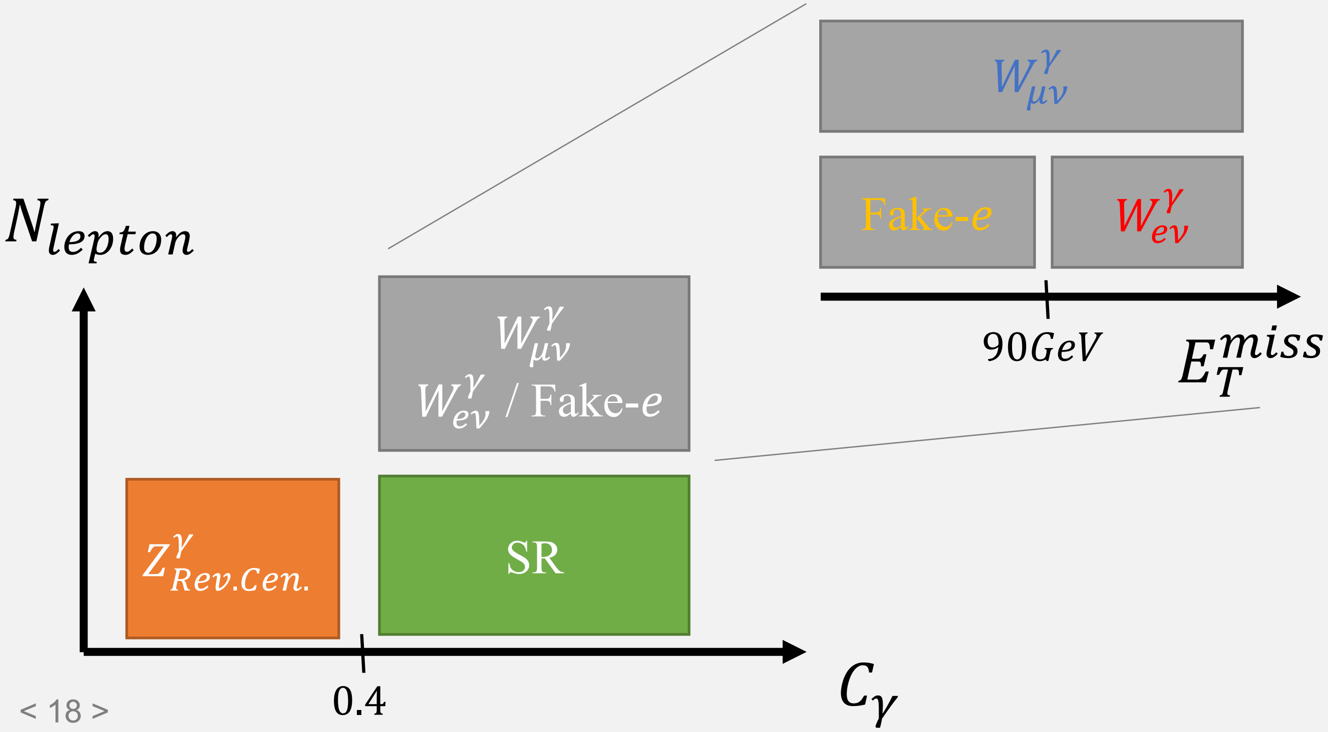
EW $Z(\rightarrow\nu\nu)\gamma jj$

Eur. Phys. J. C 82 (2022) 105

Observation of EW $Z(\to \nu\nu)\gamma jj$: Overview

- **Analysis originally designed to search for H(→inv)γ with VBF+MET+Photon signature**
- **EW-production of Z(→νν)γjj studied for $p_T^\gamma \in [15, 110]$ GeV with dedicated regions**
- **Dominant background from QCD-Zγjj and W(lν)γ+jets and controlled with CRs**
  - $W_{\mu\nu}^{\gamma}$, $W_{e\nu}^{\gamma}$ and Fake-e region: allowing one lepton (or jet fake electron)
  - $Z_{Rev.Cen.}^{\gamma}$ CR: low photon centrality (reversed) where QCD-Zγjj enriched
- **Signal extracted from simultaneous fitting across all the regions**





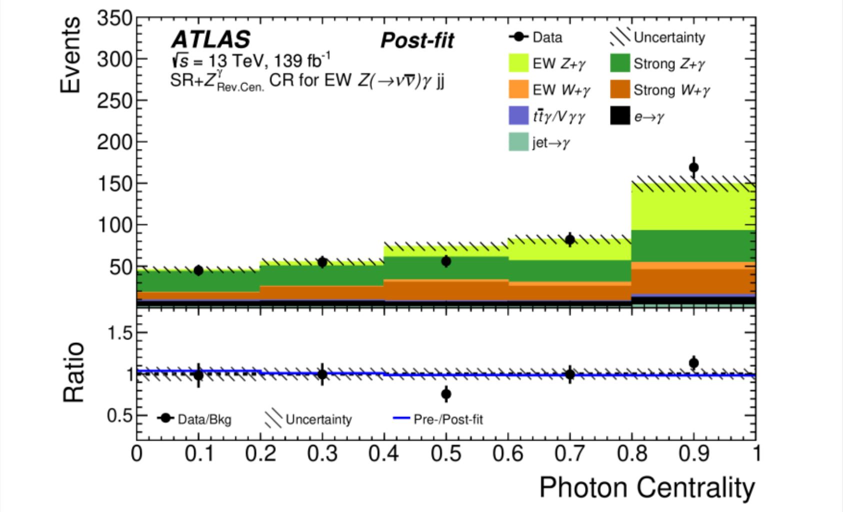
Observation of EW $Z(\to \nu\nu)\gamma jj$: Selection

- **Centrality Cut**
  - ➢ Photon centrality: C_γ
  - ➢ 3rd jet centrality: C_3

Observable	Requirements
N_{jet} with $p_{\text{T}} > 25$ GeV	≥ 2
$\lvert\eta(j_{1,2})\rvert$	< 4.5
$p_{\text{T}}(j_1)$ [GeV]	> 60
$p_{\text{T}}(j_2)$ [GeV]	> 50
$\Delta R(j, \ell)$	> 0.4
$\lvert\Delta\eta_{\text{jj}}\rvert$	> 3.0
C_3	< 0.7
m_{jj} [TeV]	> 0.5
truth-$E_{\text{T}}^{\text{miss}}$ [GeV]	> 150
$\Delta\phi(\text{truth-}\vec{E}_{\text{T}}^{\text{miss}}, j_i)$	> 1.0
$p_{\text{T}}(\gamma)$ [GeV]	$> 15, < 110$
$\lvert\eta(\gamma)\rvert$	< 2.37
$E_{\text{T}}^{\text{cone20}}/E_{\text{T}}^{\gamma}$	< 0.07
$\Delta R(\gamma, \text{jet-or-}\ell)$	> 0.4
C_γ	> 0.4
$\Delta\phi(\text{truth-}\vec{E}_{\text{T}}^{\text{miss}}, \gamma)$	> 1.8
N_ℓ with $p_{\text{T}} > 4$ GeV and $\lvert\eta\rvert < 2.47$	0

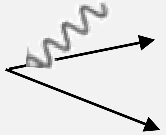
$$C_\gamma = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_\gamma - \frac{\eta_1+\eta_2}{2}\right)^2\right]$$

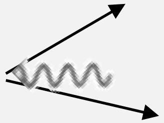
$$C_3 = \exp\left[-\frac{4}{(\eta_1-\eta_2)^2}\left(\eta_3 - \frac{\eta_1+\eta_2}{2}\right)^2\right]$$



Forward
QCD-Zγjj

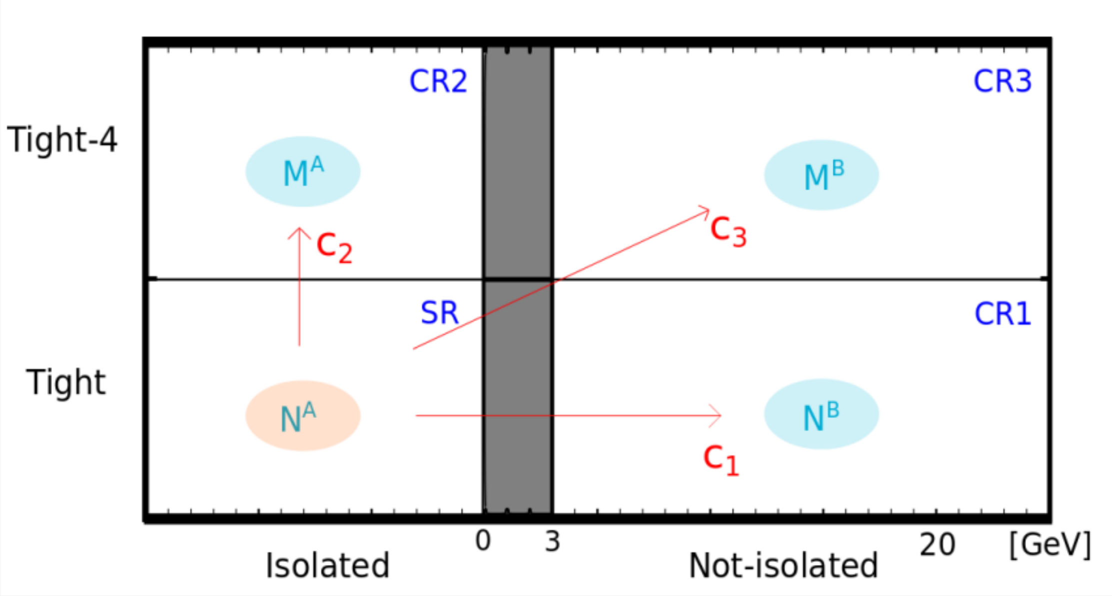
Central
EW-Zγjj

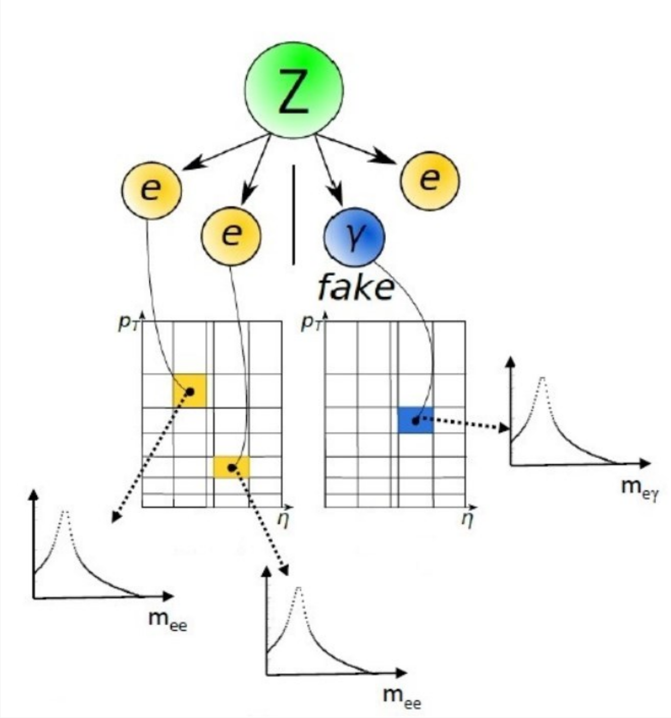




Observation of EW $Z(\rightarrow \nu\nu)\gamma jj$: Fake Photon Background

- **Jet fakes photon enter SR e.g. from Z(νν)+jets**
  - Estimated using data-driven method based on isolation and tight ID
  - ~ 1% of SR and 50% uncertainty assigned mainly due to MC statistics
- **Electron fakes photon from e.g. W(eν)+jets:**
  - measured by comparing *ee* and *eγ* rates in Z peak
  - ~ 6% in EW $Z(\rightarrow \nu\nu)\gamma$ signal region and uncertainty ranging from 15-30%





Observation of EW $Z(\rightarrow \nu\nu)\gamma jj$: Uncertainties

- **Dominated by statistical unc. in all channels**
- **Large systematic variation from modelling:**
  - Scale var. 25%~56% (3%~11%) for QCD (EW)-Vγjj
  - Madgraph v.s. Sherpa up to 20% for QCD-Vγjj
  - Parton showering model: 4-15% for EW-Vγjj
  - Interference between EW- and QCD-Vγjj up to -22%
- **Post-fit impact of each systematics term →**
  - Largest exp. systematic impact from jet related

Source	1σ Uncertainty on $\mu_{Z\gamma_{\mathrm{EW}}}$
Jet scale and resolution	0.076
$V\gamma$ + jets theory	0.067
pile-up	0.040
Photon	0.035
$e \rightarrow \gamma$, jet$\rightarrow e, \gamma$ Bkg.	0.035
Lepton	0.027
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.023
Signal theory shape	0.020
Signal theory acceptance	0.12
Data stats.	0.16
$W\gamma$ + jets/$Z\gamma$ + jets Norm.	0.073
MC stats.	0.063
Total	0.25

Observation of EW $Z(\rightarrow \nu\nu)\gamma jj$: Signal Extraction & Meas.

李政道研究所 TSUNG-DAO LEE INSTITUTE

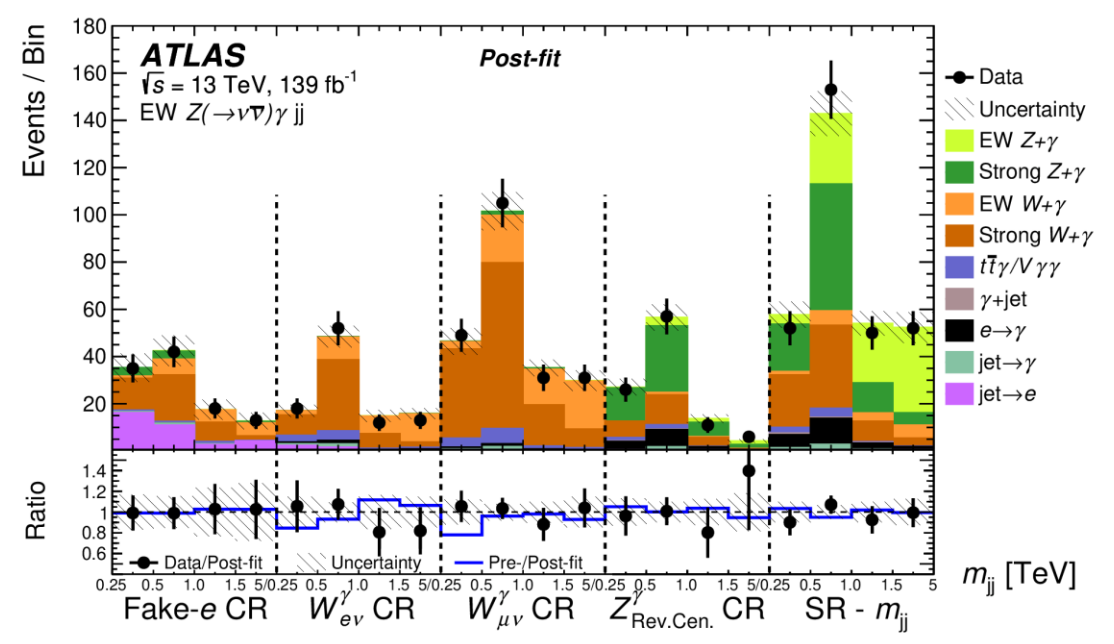
- **Maximum likelihood fit performed :**
  signal strength and normalization of dominant background determined simultaneously
- **4 m_{jj} bins for each region and totally 4+16 bins**
- **5.2σ (5.1σ expected) observed of EW-Zγjj process**
- $\sigma_{EW} = 1.31 \pm 0.20\ (stat) \pm 0.20\ (syst)\ fb$
- **In agreement with prediction:**

$$\sigma_{EW}^{pred} = 1.27 \pm 0.01\ (stat)$$
$$\pm 0.17\ (LO\ QCD\ scale)$$
$$\pm 0.03\ (PDF)\ fb$$

(0.3% NLO QCD k-factor correction from VBFNLO applied)

	SR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	$W^{\gamma}_{\ell\nu}$ CRs
$\mu_{Z\gamma\text{EWK}}$	✓	✓	
$\mu_{Z\gamma\text{QCD}}$	✓	✓	
$\mu_{W\gamma}$	✓	✓	✓

$\mu_{Z\gamma_{\text{EW}}}$	$\beta_{Z\gamma_{\text{strong}}}$	$\beta_{W\gamma}$
1.03 ± 0.25	1.02 ± 0.41	1.01 ± 0.20



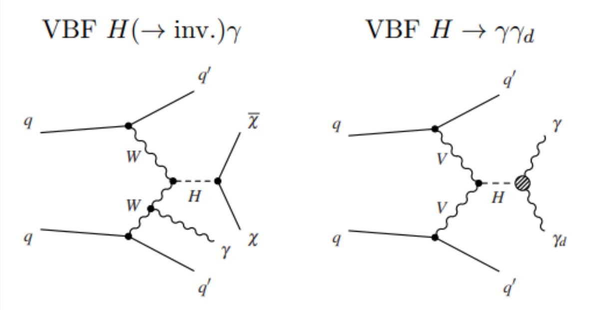
Observation of EW $Z(\to \nu\nu)\gamma jj$: BSM interpretation

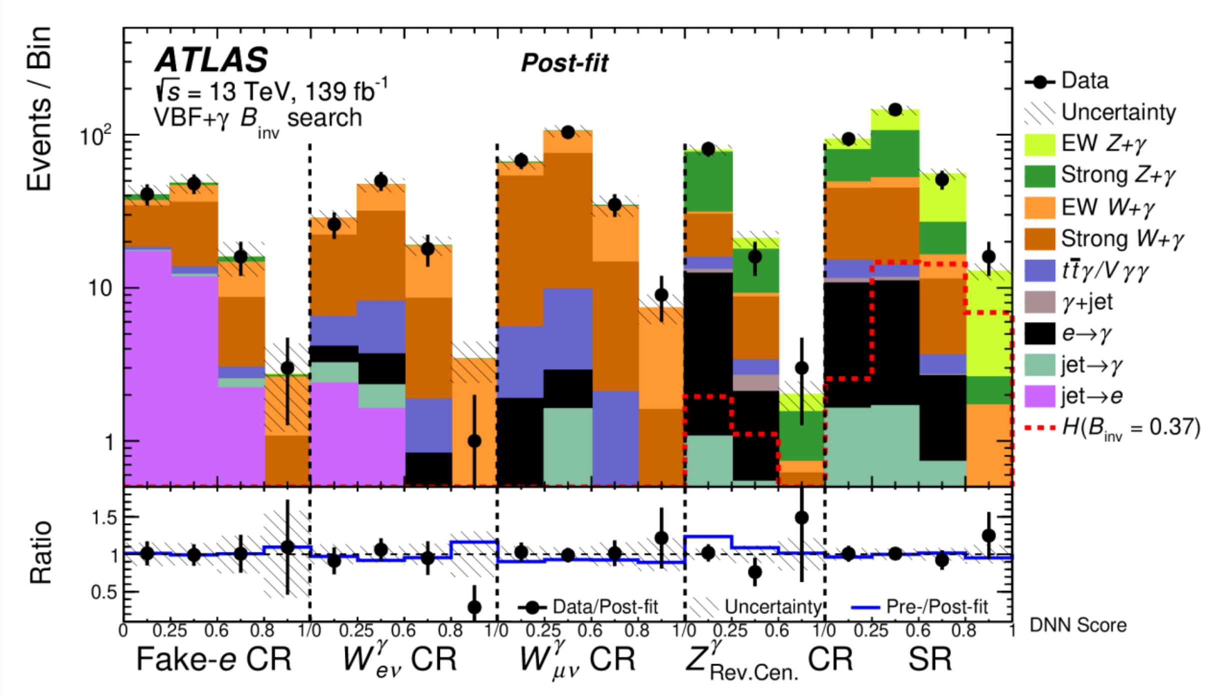
李政道研究所
TSUNG-DAO LEE INSTITUTE

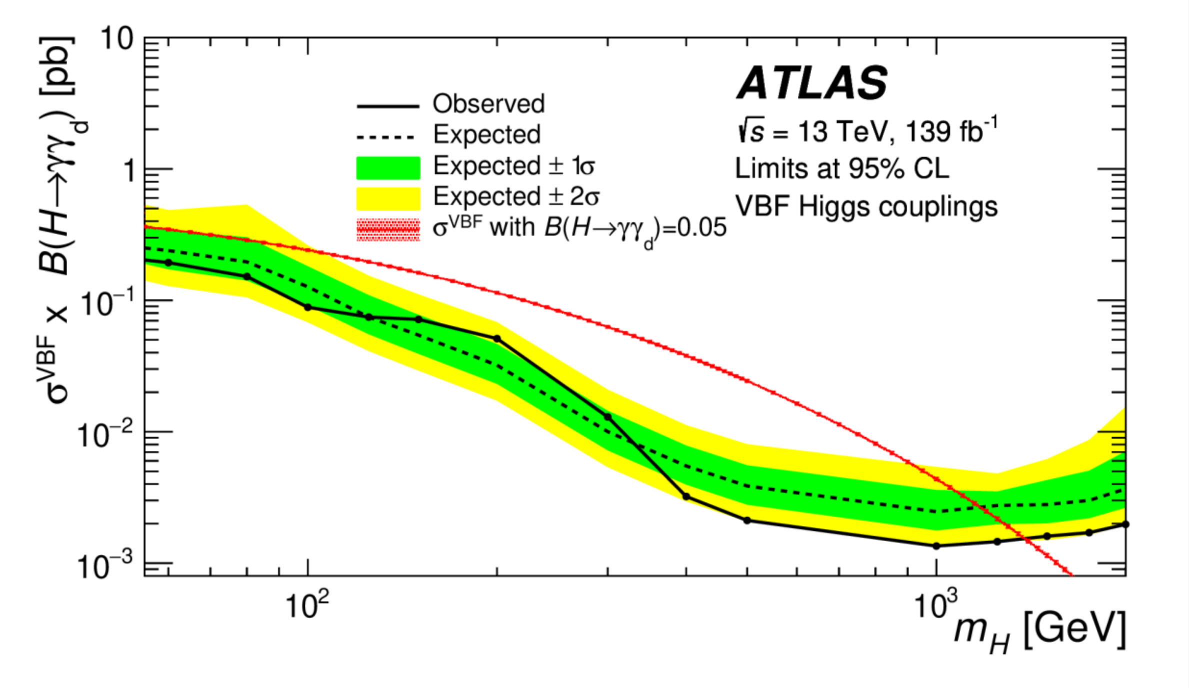
- Same VBF+MET+Photon signature also used to search for $H \to inv.$ and $H \to \gamma\gamma_d$
- Dense Neural Network (DNN) used as fitting discriminant

  Highly suppress the QCD production Zγjj events
- No significant excess observed

  95% CL upper limit of 0.37 ($0.34^{+0.15}_{-0.10}$ exp.) set on observed branching ratio

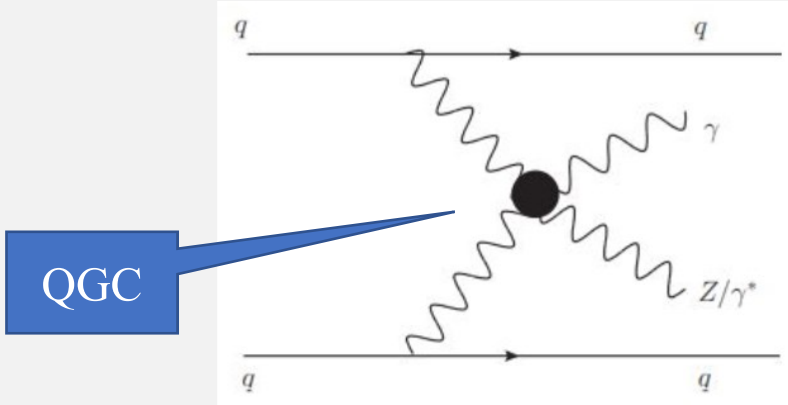






$Z(\to \nu\nu)\gamma jj$ VBS analysis : Overview

- **Dedicated measurement of SM EWK Z(→$\nu\nu$)γjj process with full Run2 data**
- **High p_T^{γ} > 150GeV and combined with orthogonal low p_T^{γ} $(15-110GeV)$ observation from VBF+MET+Photon analysis**
- **Dominant background from QCD Z(→$\nu\nu$)γ [36%] and W(lν)γ/ttγ [32%/6%] controlled by:**
  - QCD-Zγjj enriched regions : low mjj and reversed centrality requirement
  - Wγ region : ≥1 lepton
  - ➢ Normalization simultaneously extracted together with signal strength in fit
- **Fake photon and MET background estimated with data-driven and ~13% in total**
- **Boosted decision tree developed to increase S/B and used as fitting discriminant in SR, fit together with m_{jj} in CRs**
- **Sensitive final states to SM/anomalous QGC and limit set using EFT formalism**

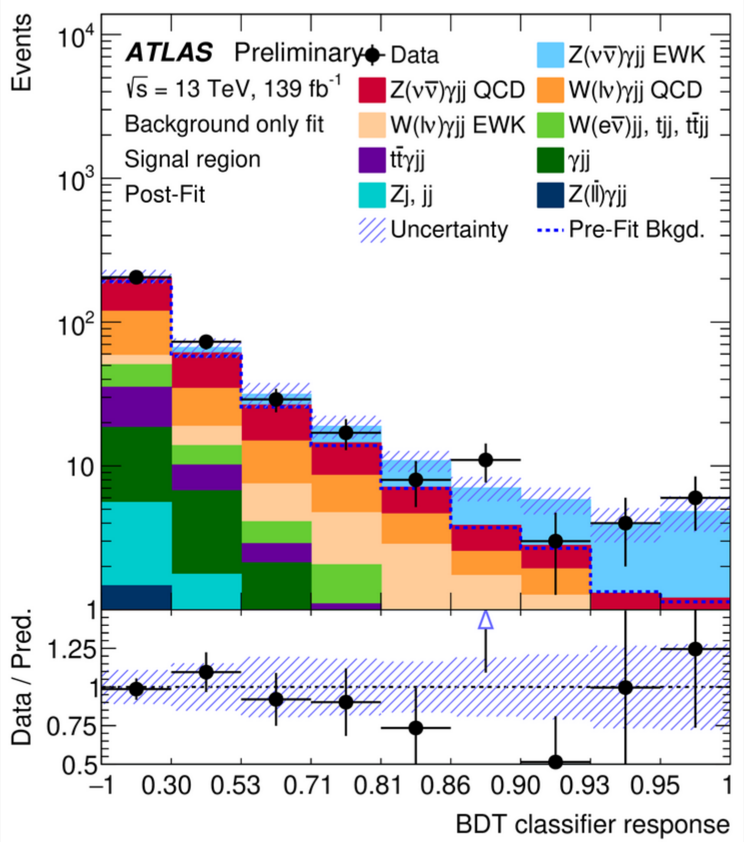


Dimension 8 operators (SM: WWAZ; Beyond SM: ZZZA, ZZAA, ZAAA)

	WWWW	WWZZ	ZZZZ	WWAZ	WWAA	ZZZA	ZZAA	ZAAA	AAAA
$\mathcal{O}_{S,0/1}$	✓	✓	✓						
$\mathcal{O}_{M,0/1/6/7}$	✓	✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{M,2/3/4/5}$		✓	✓	✓	✓	✓	✓		
$\mathcal{O}_{T,0/1/2}$	✓	✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,5/6/7}$		✓	✓	✓	✓	✓	✓	✓	✓
$\mathcal{O}_{T,8/9}$			✓			✓	✓	✓	✓

$Z(\rightarrow \nu\nu)\gamma jj$ VBS analysis : Results

- Evidence of EW $Z(\rightarrow \nu\nu)\gamma jj$ with high p_T^γ >150GeV
- Combination with observation of EW $Z(\rightarrow \nu\nu)\gamma jj$ at low p_T^γ from VBF+MET+γ analysis : better significance
- No significant deviation from SM prediction and limit set on EFT dim-8 operator, competitive with or better than previous analyses, in particular f_{T5}/Λ^4, f_{T8}/Λ^4 and f_{T9}/Λ^4 (best up to now)

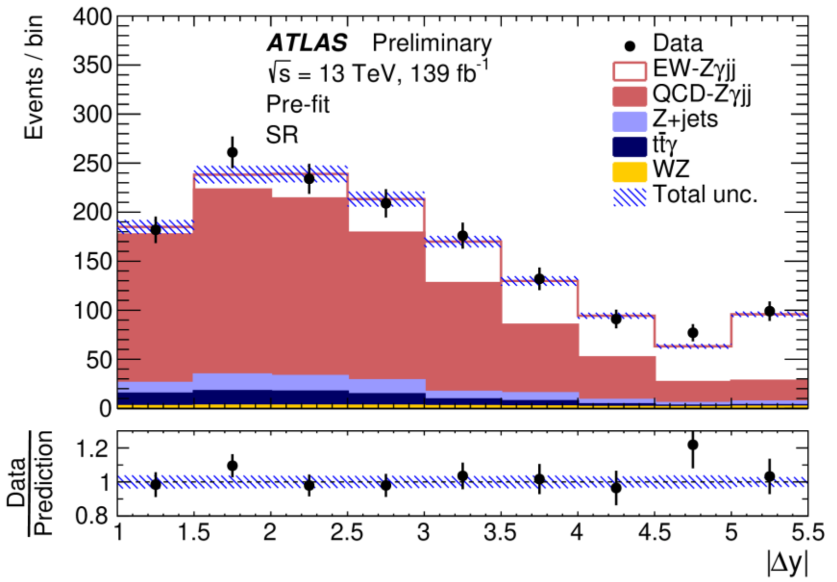


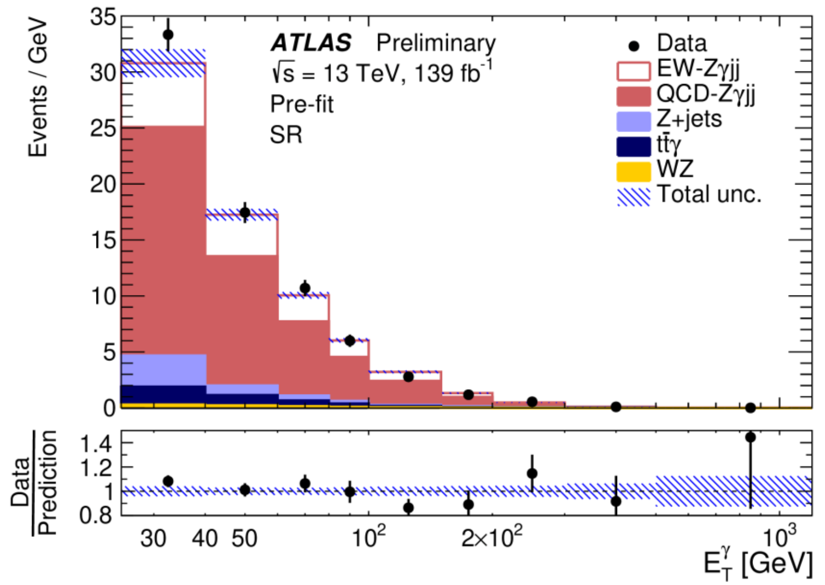
Coefficient	Observed limit, TeV^{-4}	Expected limit, TeV^{-4}
f_{T0}/Λ^4	$[-9.4, 8.4] \times 10^{-2}$	$[-1.3, 1.2] \times 10^{-1}$
f_{T5}/Λ^4	$[-8.8, 9.9] \times 10^{-2}$	$[-1.2, 1.3] \times 10^{-1}$
f_{T8}/Λ^4	$[-5.9, 5.9] \times 10^{-2}$	$[-8.1, 8.0] \times 10^{-2}$
f_{T9}/Λ^4	$[-1.3, 1.3] \times 10^{-1}$	$[-1.7, 1.7] \times 10^{-1}$
f_{M0}/Λ^4	$[-4.6, 4.6]$	$[-6.2, 6.2]$
f_{M1}/Λ^4	$[-7.7, 7.7]$	$[-1.0, 1.0] \times 10^{1}$
f_{M2}/Λ^4	$[-1.9, 1.9]$	$[-2.6, 2.6]$

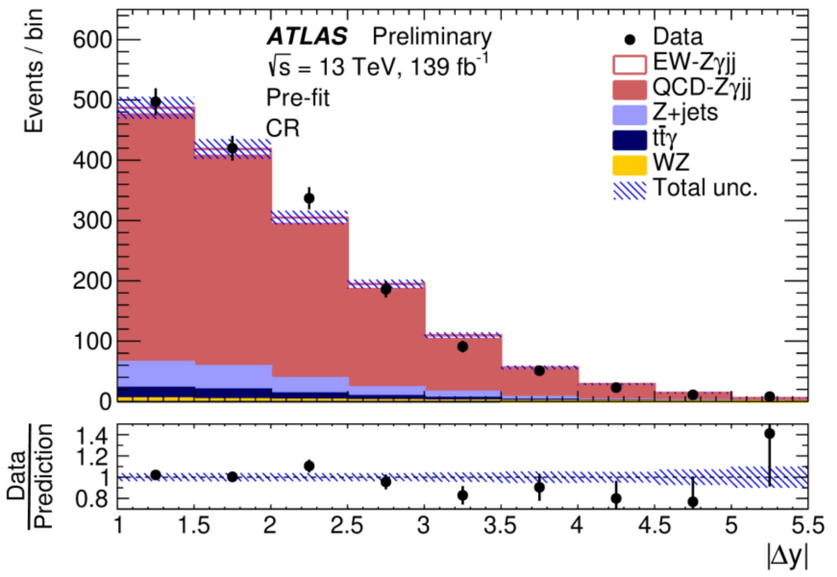
Summary

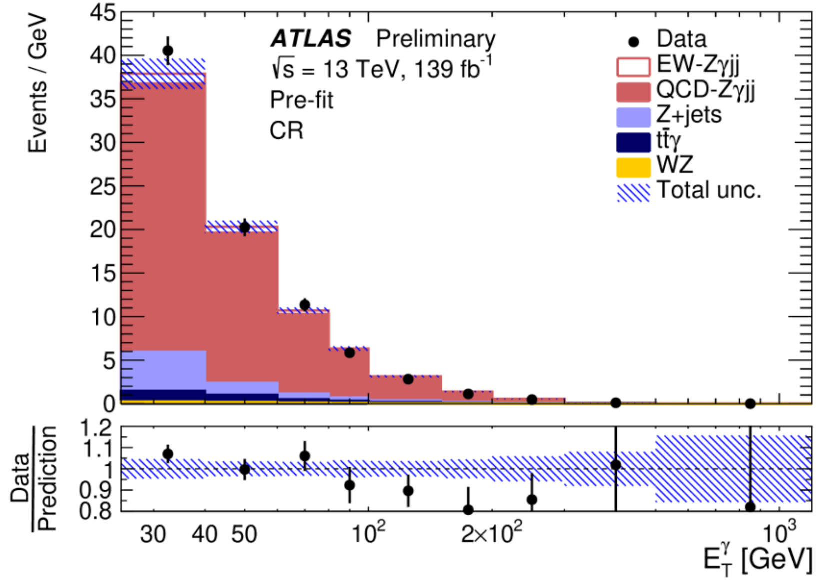
- **VBS process has rich physics interest and widely studied in ATLAS**
  - Important test of SM like EWSB and Higgs mechanism
  - Sensitive to new physics including invisible Higgs decay and dark matter
  - Crucial input for EFT study like aQGC
- **Zy VBS process observed and measured with ATLAS full Run2 data**
  - ➢ EWK production of Z(→$\boldsymbol{ll}$)$\boldsymbol{\gamma}$jj observed with 10σ
  - ➢ EWK production of Z(→$\boldsymbol{\nu\nu}$)$\boldsymbol{\gamma}$jj observed with 5.2σ
  - Measurement of SM Z(→$\boldsymbol{\nu\nu}$)$\boldsymbol{\gamma}$jj VBS analysis with high photon p_T :
    - Combination with low photon p_T observation from VBF+MET+Photon analysis
    - Sensitive limit set on EFT dimension-8 operator and best result of $\boldsymbol{f_{T5}/\Lambda^4}$, $\boldsymbol{f_{T8}/\Lambda^4}$ and $\boldsymbol{f_{T9}/\Lambda^4}$

Backups: $Z(\to ll)\gamma jj$ VBS

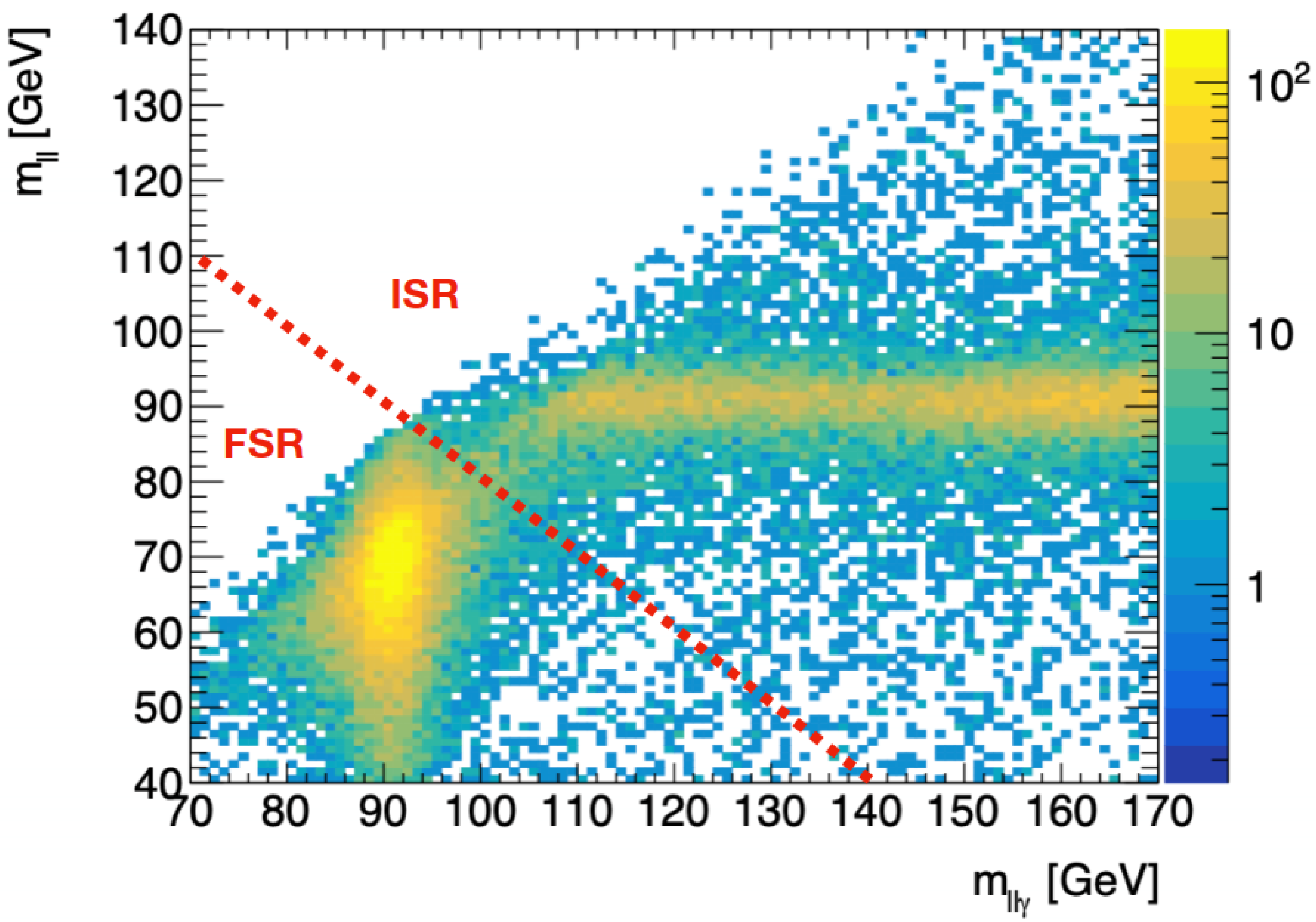




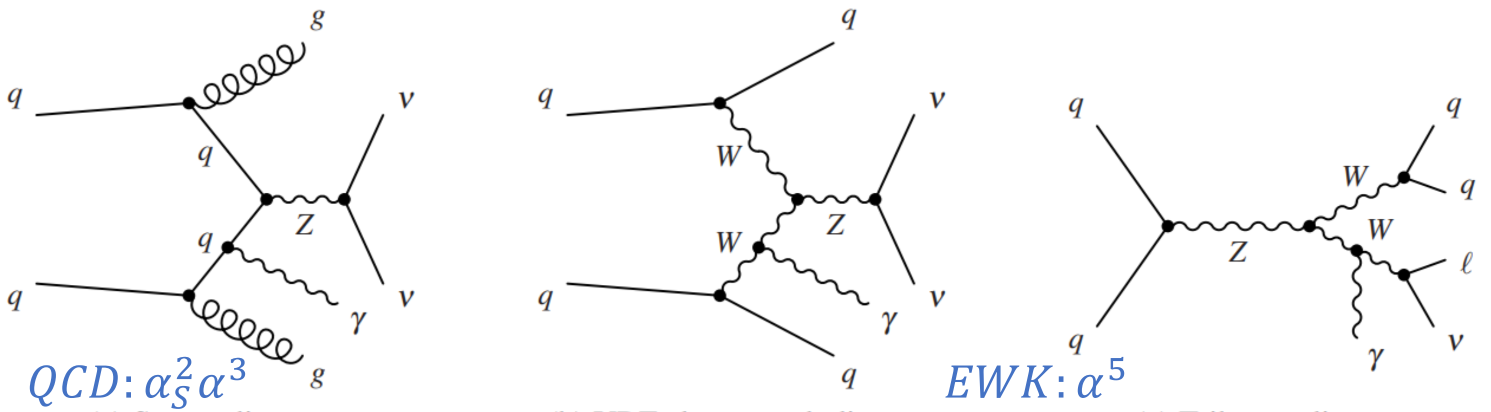




Backups: $Z(\to ll)\gamma jj$ VBS



Backups: EW $Z(\to \nu\nu)\gamma jj$



(a) Strong diagram (b) VBF electroweak diagram (c) Triboson diagram

Process	Fake-e CR	$W^{\gamma}_{e\nu}$ CR	$W^{\gamma}_{\mu\nu}$ CR	$Z^{\gamma}_{\text{Rev.Cen.}}$ CR	SR - m_{jj} [TeV] 0.25-0.5	0.5-1.0	1.0-1.5	≥ 1.5
Strong $Z\gamma$ + jets	8 ± 8	0 ± 1	3 ± 2	50 ± 12	20 ± 6	54 ± 12	13 ± 5	5 ± 2
EW $Z\gamma$ + jets	0.6 ± 0.2	0.3 ± 0.2	0.4 ± 0.2	7 ± 2	4 ± 1	30 ± 7	25 ± 5	36 ± 7
Strong $W\gamma$ + jets	43 ± 9	47 ± 9	133 ± 21	24 ± 6	22 ± 6	35 ± 10	9 ± 3	3 ± 1
EW $W\gamma$ + jets	19 ± 6	31 ± 7	59 ± 13	1.4 ± 0.5	2 ± 1	6 ± 1	4 ± 1	5 ± 1
jet$\to \gamma$	1 ± 1	2 ± 2	3 ± 2	2 ± 2	1 ± 1	2 ± 2	1 ± 1	0.4 ± 0.3
jet$\to e$	34 ± 17	5 ± 3	–	–	–	–	–	–
$e \to \gamma$	–	2.7 ± 0.4	2.9 ± 0.4	13 ± 1	6 ± 1	11 ± 1	2.6 ± 0.4	1.4 ± 0.3
γ + jet	–	–	–	0.7 ± 0.5	0.7 ± 0.5	0.4 ± 0.3	0.1 ± 0.1	0.1 ± 0.1
$t\bar{t}\gamma/V\gamma\gamma$	3 ± 1	9 ± 2	13 ± 2	3 ± 1	2 ± 1	4 ± 1	0.4 ± 0.2	0.1 ± 0.1
Fitted Yields	108 ± 10	96 ± 8	213 ± 14	102 ± 9	58 ± 6	143 ± 12	54 ± 5	52 ± 6
Data	108	95	216	100	52	153	50	52
Data/Fit	1.00 ± 0.14	0.99 ± 0.12	1.01 ± 0.09	0.98 ± 0.13	0.90 ± 0.15	1.07 ± 0.11	0.93 ± 0.16	0.99 ± 0.18

Backups: EW $Z(\to \nu\nu)\gamma jj$

Process	Generator	ME Order	PDF	Parton Shower	Tune
		SM process samples			
Strong $V\gamma$ + jets	SHERPA 2.2.8	NLO (up to 1-jet), LO (up to 3-jets)	NNPDF3.0NNLO	SHERPA MEPS@NLO	SHERPA
EW $V\gamma$ + jets	MADGRAPH5_AMC@NLO 2.6.5	LO	NNPDF3.1LO	PYTHIA 8.240	A14
EW VV+jets	SHERPA 2.2.1 or SHERPA v2.2.2	LO	NNPDF3.0NNLO	SHERPA MEPS@NLO	SHERPA
VV+jets	SHERPA 2.2.1 or SHERPA 2.2.2	NLO (up to 1-jet), LO (up to 3-jets)	NNPDF3.0NNLO	SHERPA MEPS@NLO	SHERPA
EW V+jets	HERWIG 7.1.3 or HERWIG 7.2.0	NLO	MMHT2014NLO68CL	HERWIG 7.1.3	HERWIG 7
Strong $W(\to \mu\nu)$ + jets/ $W(\to \tau\nu)$ + jets	SHERPA 2.2.7	NLO (up to 2-jets), LO (up to 4-jets)	NNPDF3.0NNLO	SHERPA MEPS@NLO	SHERPA
$t\bar{t}\gamma$	MADGRAPH5_AMC@NLO 2.2.3	NLO	NNPDF2.3LO	PYTHIA 8.186	A14
$t\bar{t}/Wt$	POWHEG BOX v2	NLO	NNPDF3.0NLO	PYTHIA 8.230	A14
$V\gamma\gamma$	SHERPA 2.2.2 (at 0-jet), LO (up to 2-jets)	NLO	NNPDF3.0NNLO	SHERPA MEPS@NLO	SHERPA
γ + jet	SHERPA 2.2.2	NLO (up to 2-jets), LO (up to 4-jets)	NNPDF3.0NNLO	SHERPA MEPS@NLO	SHERPA
		Higgs-related samples			
ggF Higgs	POWHEG v2 NNLOPS	NNLO	PDF4LHC15	PYTHIA 8.230	AZNLO
Higgs + γ	MADGRAPH5_AMC@NLO 2.6.2	NLO	PDF4LHC15	HERWIG 7.1.3p1	A14
ggF Higgs$\to \gamma\gamma_{\mathrm{d}}$	POWHEG v2 NNLOPS	NNLO	PDF4LHC15	PYTHIA 8.244p3	AZNLO
VBF Higgs$\to \gamma\gamma_{\mathrm{d}}$	POWHEG v2	NLO	CTEQ6L1	PYTHIA 8.244p3	AZNLO
		Systematic variation samples			
$V\gamma$ + jets α^4 interference	MADGRAPH5_AMC@NLO 2.6.2	LO	NNPDF3.1LO	PYTHIA 8.240	AZNLO

EFT results for $Z(\rightarrow \nu\nu)\gamma jj$ VBS

Unitarity is not preserved

Coefficient	Observed limit, TeV^{-4}	Expected limit, TeV^{-4}
f_{T0}/Λ^4	$[-9.4, 8.4] \times 10^{-2}$	$[-1.3, 1.2] \times 10^{-1}$
f_{T5}/Λ^4	$[-8.8, 9.9] \times 10^{-2}$	$[-1.2, 1.3] \times 10^{-1}$
f_{T8}/Λ^4	$[-5.9, 5.9] \times 10^{-2}$	$[-8.1, 8.0] \times 10^{-2}$
f_{T9}/Λ^4	$[-1.3, 1.3] \times 10^{-1}$	$[-1.7, 1.7] \times 10^{-1}$
f_{M0}/Λ^4	$[-4.6, 4.6]$	$[-6.2, 6.2]$
f_{M1}/Λ^4	$[-7.7, 7.7]$	$[-1.0, 1.0] \times 10^{1}$
f_{M2}/Λ^4	$[-1.9, 1.9]$	$[-2.6, 2.6]$

Clipping at E_c
Unitarity is preserved

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	$[-3.3, 3.2] \times 10^{1}$	$[-3.0, 3.0] \times 10^{1}$

$E_T^{\gamma} > 600GeV\ for\ E_c < 4TeV;\ E_T^{\gamma} > 900GeV\ for E_c > 4TeV$