

New methods of distinguishing the associated $Z\gamma$ production

N.L.Belyaev, [E.Yu.Soldatov](#)

National Research Nuclear University "MEPhI"



QFTHEP Conference, Sochi, Russia
22-29 September 2019

The new physics searches

Two main methods of beyond Standard Model “new physics” search at the collider experiments:

- Direct search – the search for new particles in the collision data (“unknown unknowns”)
- Indirect search – the precision measurement of the known processes, which can be slightly changed by new physics beyond SM of the unachieved energy scale (“unknown knowns”)

Current direct search results:

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2019

ATLAS Preliminary

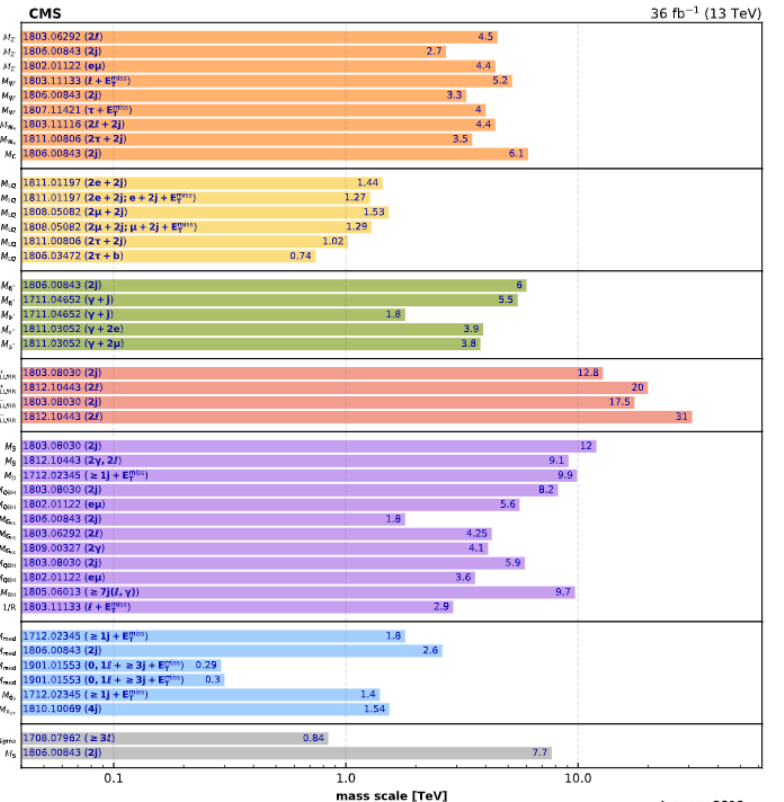
$\int \mathcal{L} dt = (3.2 - 139) \text{ fb}^{-1}$ $\sqrt{s} = 8, 13 \text{ TeV}$

Model	ℓ, γ	Jets†	E^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	$0 e, \mu$	1-4	Yes	36.1	M_{D} 7.7 TeV
	ADD non-resonant $\gamma\gamma$	2γ	-	-	36.7	M_{D} 8.6 TeV
	ADD QBH	e, μ	2j	-	37.0	M_{D} 6.9 TeV
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2j$	-	3.2	M_{D} 8.2 TeV
	ADD BH multijet	-	$\geq 3j$	-	3.6	M_{D} 9.55 TeV
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2γ	-	-	36.7	$G_{KK} \text{ mass}$ 4.1 TeV
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$G_{KK} \text{ mass}$ 2.3 TeV
	Bulk RS $G_{KK} \rightarrow WW \rightarrow qqqq$	$0 e, \mu$	2j	-	139	$G_{KK} \text{ mass}$ 1.6 TeV
	Bulk RS $G_{KK} \rightarrow tt$	$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	$G_{KK} \text{ mass}$ 3.8 TeV
	2UED / RPP	$1 e, \mu$	$\geq 2b, \geq 3j$	Yes	36.1	$KK \text{ mass}$ 1.8 TeV
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	$2 e, \mu$	-	-	139	$Z' \text{ mass}$ 5.1 TeV
	SSM $Z' \rightarrow \tau\tau$	2τ	-	-	36.1	$Z' \text{ mass}$ 2.42 TeV
	Leptophobic $Z' \rightarrow bb$	-	2b	-	36.1	$Z' \text{ mass}$ 2.1 TeV
	Leptophobic $Z' \rightarrow \tau\tau$	$1 e, \mu$	$\geq 1 b, \geq 1J/2j$	Yes	36.1	$Z' \text{ mass}$ 3.0 TeV
	SSM $W' \rightarrow \ell\nu$	$1 e, \mu$	-	-	139	$W' \text{ mass}$ 6.0 TeV
	SSM $W' \rightarrow \tau\nu$	1τ	-	-	36.1	$W' \text{ mass}$ 3.7 TeV
	HVT $V' \rightarrow WZ$ model B	$0 e, \mu$	2j	-	139	$V' \text{ mass}$ 3.8 TeV
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	$V' \text{ mass}$ 2.83 TeV
	LRSM $W_R \rightarrow tb$	multi-channel	-	-	36.1	$W_R \text{ mass}$ 3.25 TeV
	LRSM $W_R \rightarrow \mu N_k$	2μ	1j	-	80	$W_R \text{ mass}$ 5.0 TeV
CI	CI $qqqq$	-	2j	-	37.0	A 21.8 TeV η_{LL}
	CI $\ell\ell qq$	$2 e, \mu$	-	-	36.1	A 40.0 TeV η_{LL}
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	A 2.57 TeV
DM	Axial-vector mediator (Dirac DM)	$0 e, \mu$	1-4j	Yes	36.1	M_{DM} 1.55 TeV
	Colored scalar mediator (Dirac DM)	$0 e, \mu$	1-4j	Yes	36.1	M_{DM} 1.67 TeV
	VV _{UV} EFT (Dirac DM)	$0 e, \mu$	1j, $\leq 1j$	Yes	3.2	M 700 GeV
	Scalar reson. $\phi \rightarrow \chi\chi$ (Dirac DM)	$0-1 e, \mu$	1b, 0-1j	Yes	36.1	M 3.4 TeV
LO	Scalar LQ 1 st gen	$1, 2 e$	$\geq 2j$	Yes	36.1	LQ mass 1.4 TeV
	Scalar LQ 2 nd gen	$1, 2 e$	$\geq 2j$	Yes	36.1	LQ mass 1.56 TeV
	Scalar LQ 3 rd gen	2τ	2b	-	36.1	LQ mass 1.83 TeV
	Scalar LQ 3 rd gen	$0-1 e, \mu$	2b	Yes	36.1	LQ mass 870 GeV
Heavy quarks	VLO $TT \rightarrow H\gamma/Z\gamma/Wb + X$	multi-channel	-	-	36.1	T mass 1.37 TeV
	VLO $BB \rightarrow W\gamma/Zb + X$	multi-channel	-	-	36.1	T mass 1.34 TeV
	VLO $T\tau_{12} T\tau_{12} \rightarrow W\tau + X$	$2(S\bar{S})/\geq 3 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	T mass 1.64 TeV
	VLO $Y \rightarrow Wb + X$	$1 e, \mu$	$\geq 1 b, \geq 1j$	Yes	36.1	Y mass 1.85 TeV
	VLO $Q \rightarrow Hb + X$	$0 e, \mu, 2 \gamma$	$\geq 1 b, \geq 1j$	Yes	79.8	Q mass 1.21 TeV
VLO $QQ \rightarrow W\gamma/W\gamma$	$1 e, \mu$	$\geq 4j$	Yes	20.3	Q mass 650 GeV	
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2j	-	139	$q^* \text{ mass}$ 6.7 TeV
	Excited quark $q^* \rightarrow q\gamma$	1γ	1j	-	36.7	$q^* \text{ mass}$ 5.3 TeV
	Excited quark $b^* \rightarrow bg$	-	1b, 1j	-	36.1	$b^* \text{ mass}$ 2.6 TeV
	Excited lepton ℓ^*	$3 e, \mu$	-	-	20.3	$\ell^* \text{ mass}$ 3.0 TeV
Excited lepton ν^*	$3 e, \mu, \tau$	-	-	20.3	$\nu^* \text{ mass}$ 1.6 TeV	
Other	Type III Seesaw	$1 e, \mu$	$\geq 2j$	Yes	79.8	N^{R} mass 560 GeV
	LRSM Majorana ν	$2 e, \mu$	2j	-	36.1	N^{R} mass 1.34 TeV
	Higgs triplet H^{H} $\rightarrow \ell\ell$	$2, 3, 4 e, \mu$ (SS)	-	-	36.1	H^{H} mass 870 GeV
	Higgs triplet H^{H} $\rightarrow \ell\tau$	$3 e, \mu, \tau$	-	-	20.3	H^{H} mass 406 GeV
	Multi-charged particles	-	-	-	36.1	multi-charged particle mass
	Magnetic monopoles	-	-	-	34.4	monopole mass 1.22 TeV, 2.37 TeV

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small radius (large-radius) jets are denoted by the letter (L)(R).

Overview of CMS EXO results

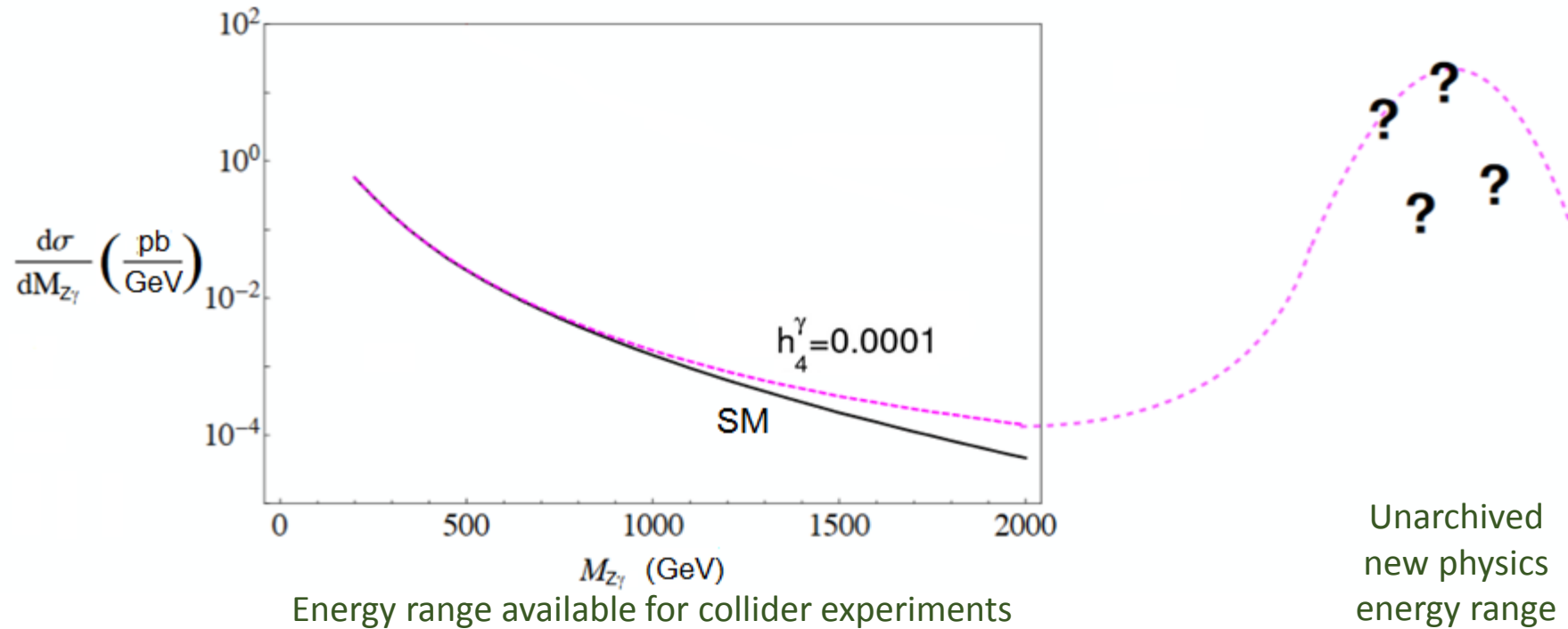


Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).

January 2019

No new particles found so far... And the limits for most of the states are at the level of 3-5 TeV, which can not be significantly improved without the increase of collision energy.

Indirect new physics searches



Indirect searches are also ongoing. These searches will have significant profit from the increase of luminosity w/o increase of collision energy.

The hottest topics are:

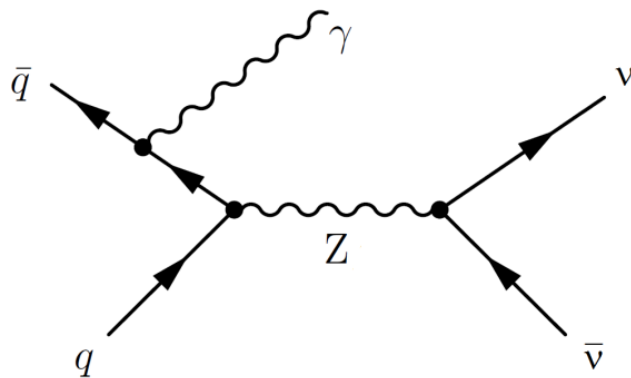
- Flavor physics (especially B physics) – some deviations from SM already reported
- Studies of electroweak boson interactions (VBF, VBS, multibosons)
- Top physics

These measurements increase the precision of SM tests. Theory predictions also can be very accurate: NLO, NNLO, ...

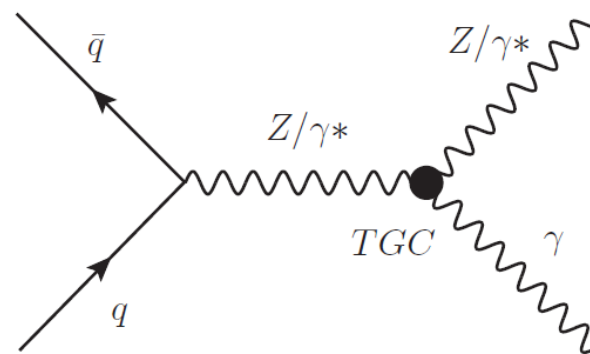
Why $Z\gamma$?

- Associated $Z\gamma$ production can be used for the study of anomalous triple gauge couplings (aTGC)
- Neutral vertices $Z\gamma\gamma$ and $ZZ\gamma$ are forbidden in SM at tree level, so its possible existence is the clear sign of new physics
- Neutrino channel of Z boson decay provides significantly bigger branching than charged lepton channels ($\nu\nu/ee \sim 6$) and much better background control than hadronic channel (dijet final state has huge background contamination at hadron collider experiments)

SM $Z\gamma$ production:



Beyond SM $Z\gamma$ production:



Why Z γ : anomalous couplings formalism and public results

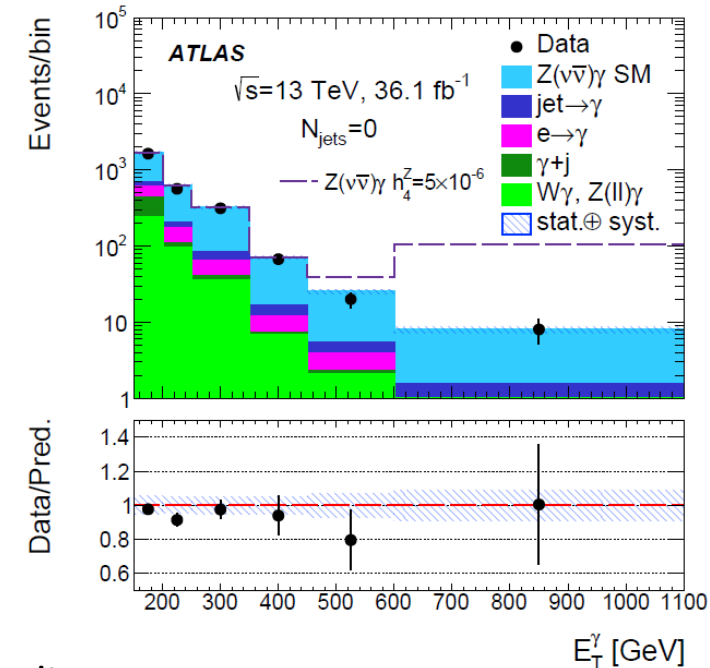
➤ Vertex functions formalism (e.g. for ZZ γ vertex):

$$\Gamma_{Z\gamma Z}^{\alpha\beta\mu}(q_1, q_2, P) = \frac{P^2 - q_1^2}{M_Z^2} \left[h_1^Z (q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \frac{h_2^Z}{M_Z^2} P^\alpha (P \cdot q_2 g^{\mu\beta} - q_2^\mu P^\beta) + h_3^Z \varepsilon^{\mu\alpha\beta\rho} q_{2\rho} + \frac{h_4^Z}{M_Z^2} P^\alpha \varepsilon^{\mu\beta\rho\sigma} P_\rho q_{2\sigma} \right]$$

Coupling is described by eight parameters:
 $h_1^V - h_4^V$, where $V = \gamma, Z$

- CP-conserving: h_3^V, h_4^V
 (correspond to electric dipole, magnetic quadrupole vertex transition moments)
- CP-violating: h_1^V, h_2^V
 (correspond to magnetic dipole, electric quadrupole vertex transition moments)

Non-zero (anomalous) values of the h_i^V couplings lead to increase of the Z γ cross section, especially for large photon transverse energies (or big s).



➤ Sensitivity of experiments for the Z $\gamma\gamma$ /ZZ γ vertex functions parameters ($h_3[Z]$ or “electric dipole transition moment” of Z boson) is close to the order of SM loop corrections ($\sim 10^{-4} - 10^{-5}$): [Z. Phys. C - Particles and Fields 28, 149-154 (1985)].

This can lead also to constrain BSM models, such as SUSY.

Best world limit

Parameter	Limit 95% CL
	Measured
h_3^Z	$(-3.2 \times 10^{-4}, 3.3 \times 10^{-4})$

Backgrounds and current selection

ATLAS selection:

Photons	Leptons	Jets
$E_T > 150 \text{ GeV}$	$p_T > 7 \text{ GeV}$	$p_T > 50 \text{ GeV}$
$ \eta < 2.37,$ excluding $1.37 < \eta < 1.52$	$ \eta < 2.47(2.7)$ for $e(\mu),$ excluding $1.37 < \eta^e < 1.52$	$ \eta < 4.5$ $\Delta R(\text{jet}, \gamma) > 0.3$
Event selection		
$N^\gamma = 1, N^{e,\mu} = 0, E_T^{\text{miss}} > 150 \text{ GeV}, E_T^{\text{miss}} \text{ signif.} > 10.5 \text{ GeV}^{1/2}, \Delta\phi(\vec{E}_T^{\text{miss}}, \gamma) > \pi/2$		
Inclusive : $N_{\text{jet}} \geq 0,$ Exclusive : $N_{\text{jet}} = 0$		

CMS selection:

$E_T[\gamma] > 175 \text{ GeV}$ and $|\eta[\gamma]| < 1.44$
 $E_T[\text{miss}] > 170 \text{ GeV}$
 $\Delta\phi(\gamma, p_T[\text{miss}]) > 2$
 Lepton veto ($p_T > 10 \text{ GeV}$)
 $\Delta\phi(\text{jet}, p_T[\text{miss}]) > 0.5$ ($p_T[\text{jet}] > 30 \text{ GeV}$)

➤ Base selection is similar. ATLAS one is more advanced.

	$N_{\text{jets}} \geq 0$	$N_{\text{jets}} = 0$
$N^{W\gamma}$	$650 \pm 40 \pm 60$	$360 \pm 20 \pm 30$
$N^{\gamma+\text{jet}}$	$409 \pm 18 \pm 108$	$219 \pm 10 \pm 58$
$N^{e \rightarrow \gamma}$	$320 \pm 15 \pm 45$	$254 \pm 12 \pm 35$
$N^{\text{jet} \rightarrow \gamma}$	$170 \pm 30 \pm 50$	$140 \pm 20 \pm 40$
$N^{Z(\ell\ell)\gamma}$	$40 \pm 3 \pm 3$	$26 \pm 3 \pm 2$
$N_{\text{total}}^{\text{bkg}}$	$1580 \pm 50 \pm 140$	$1000 \pm 40 \pm 90$
$N^{\text{sig}}(\text{exp})$	$2328 \pm 4 \pm 135$	$1710 \pm 4 \pm 91$
$N_{\text{total}}^{\text{sig+bkg}}$	$3910 \pm 50 \pm 190$	$2710 \pm 40 \pm 130$
$N^{\text{data}}(\text{obs})$	3812	2599

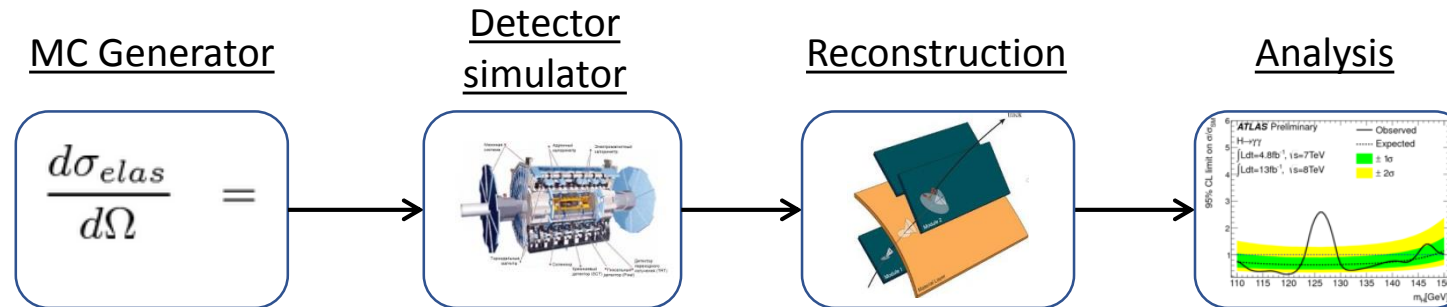
Process	Estimate
$Z\gamma \rightarrow \nu\bar{\nu}\gamma$	41.74 ± 6.67
$W\gamma \rightarrow \ell\nu\gamma$	10.60 ± 1.58
$W \rightarrow e\nu$	7.80 ± 1.78
Jet $\rightarrow \gamma$ misidentified	1.75 ± 0.61
Beam halo	5.90 ± 4.70
Spurious ECAL signals	5.63 ± 2.20
Rare backgrounds	3.03 ± 0.69
Total Expectation	76.45 ± 8.82
Data	77

➤ $W\gamma$ is the biggest background for that study for both of experiments.

It has two sources: a) lepton is not reconstructed/identified/out of acceptance; b) hadronic τ lepton decay.

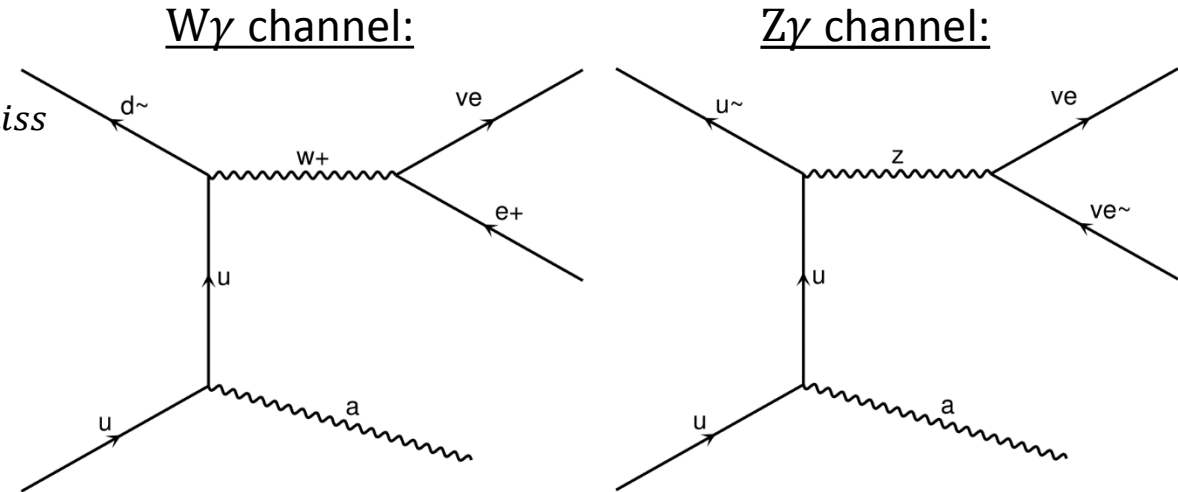
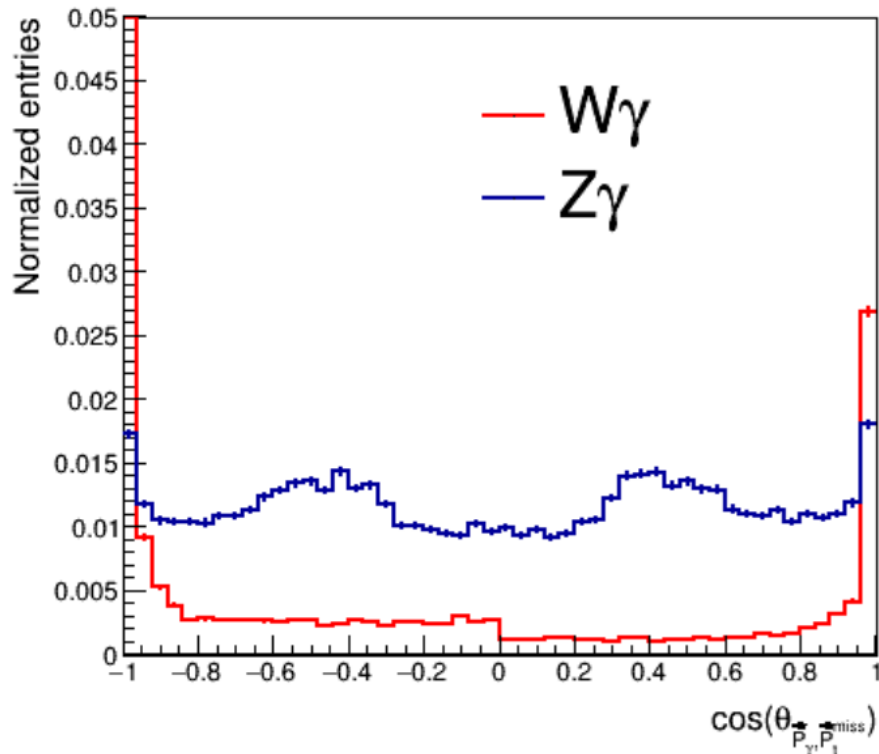
Setup for the study

- [MG5_aMC](#) samples were generated for this study (100k each)
- [Pythia8](#) was used for parton showering, hadronization and underlying event
- [Delphes framework](#) was used for detector simulation (ATLAS geometry card) and particles reconstruction



New ideas for backgrounds suppression: Angle

- $W\gamma$ and $Z\gamma$ channels are similar in terms of analysis.
- In the SR, two momentum vectors can be measured: \vec{P}_T^{miss} and \vec{P}_γ .
- Seeking for some separation potential.



- The simplest angular variable that can be constructed is $\cos(\theta_{\vec{P}_\gamma, \vec{P}_T^{miss}})$.
- First LO Monte Carlo studies with the MadGraph5 revealed the separation potential of $\cos(\theta_{\vec{P}_\gamma, \vec{P}_T^{miss}})$.
- The distribution shown in the \vec{P}_T^{miss} rest frame.
- In case of $W\gamma$ channel the angle $\theta_{\vec{P}_\gamma, \vec{P}_T^{miss}}$ is mostly 0 or π .

It is the development of $\Delta\phi(\gamma, p_T[\text{miss}])$ cut to maximize the separation power.

New ideas for backgrounds suppression: missing P_T

- Missing energy is calculated in the following way:

$$\vec{E}_T^{\text{miss}} = - \sum \vec{p}_T(i)$$

where i – photons, leptons and jets.

- For $Z\gamma$, full momentum of Z is genuine missing P_T . It will be not added to this formula.
- For $W\gamma$, only part of W momentum is genuine missing P_T . Lepton will leave a trace.

The cause to be in lepton veto region: Either lepton not reconstructed/out of acceptance or it is hadronic τ decay.

In any case it will be calculated in missing P_T : acceptance of calorimeter is much bigger (up to $|\eta|=4.9$), soft jets will be also taken into account

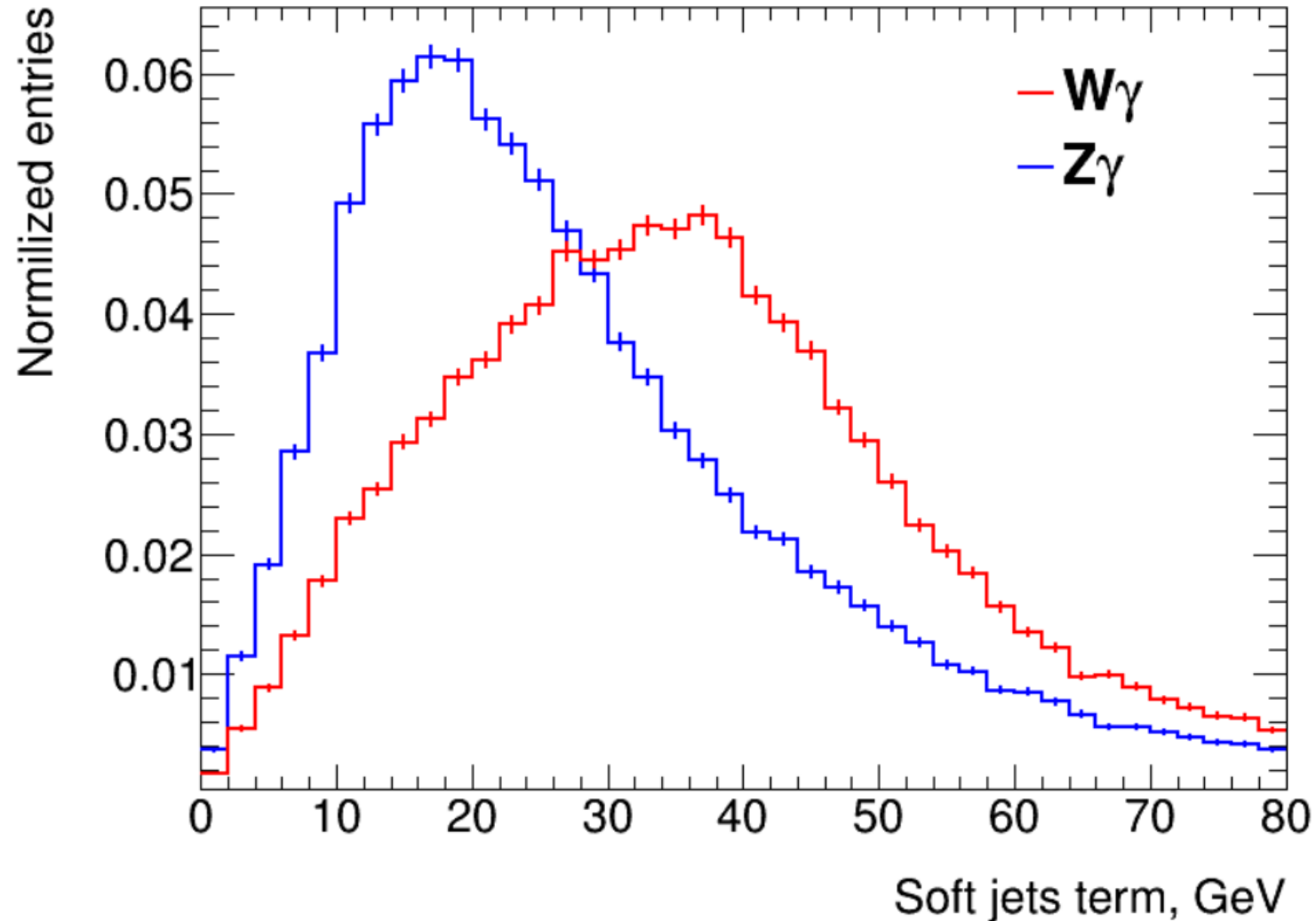
Missing P_T will be slightly different for $Z\gamma$. However, the best separation power will give the soft jets term:

$$\text{Softjets} = |\vec{E}_T^{\text{miss}}| - \sum \vec{p}_T^{\text{hard}}(i)$$

where i – hard objects: identified photons, leptons and jets with $p_T > 10$ GeV.

New ideas for backgrounds suppression: missing P_T

Soft jets term for these two processes:



This observable has obvious separation power. Can be used in experimental fiducial volume definition or as a Machine Learning (ML) discriminant.

Summary

- Indirect “new physics” searches start play the leading role.
- Anomalous couplings search is one of the most perspective topics.
- $Z\gamma$ final state (with Z decay to neutrino) is very sensitive to neutral anomalous couplings.
- The phase space for its measurement can be optimized further.
- Couple of new observables with good separation potential from the dominant $W\gamma$ background were found:
 - $\cos\left(\theta_{\vec{P}_\gamma, \vec{P}_t^{miss}}\right)$
 - Softjets term p_T
- The optimization is continuing. Results can be used in the experimental studies (fiducial volume definition, additional ML discriminants).

The reported study was funded by RFBR according to the research project № 18-32-20160.