New methods of distinguishing the associated Zγ production

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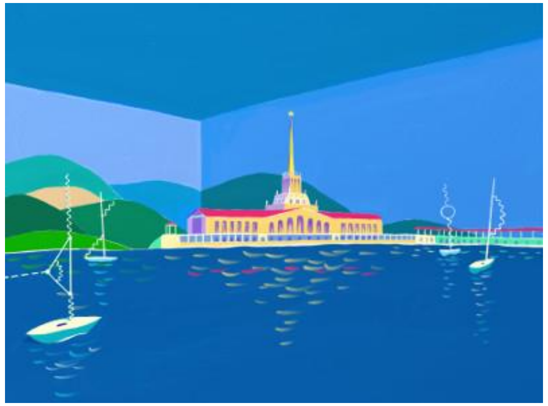

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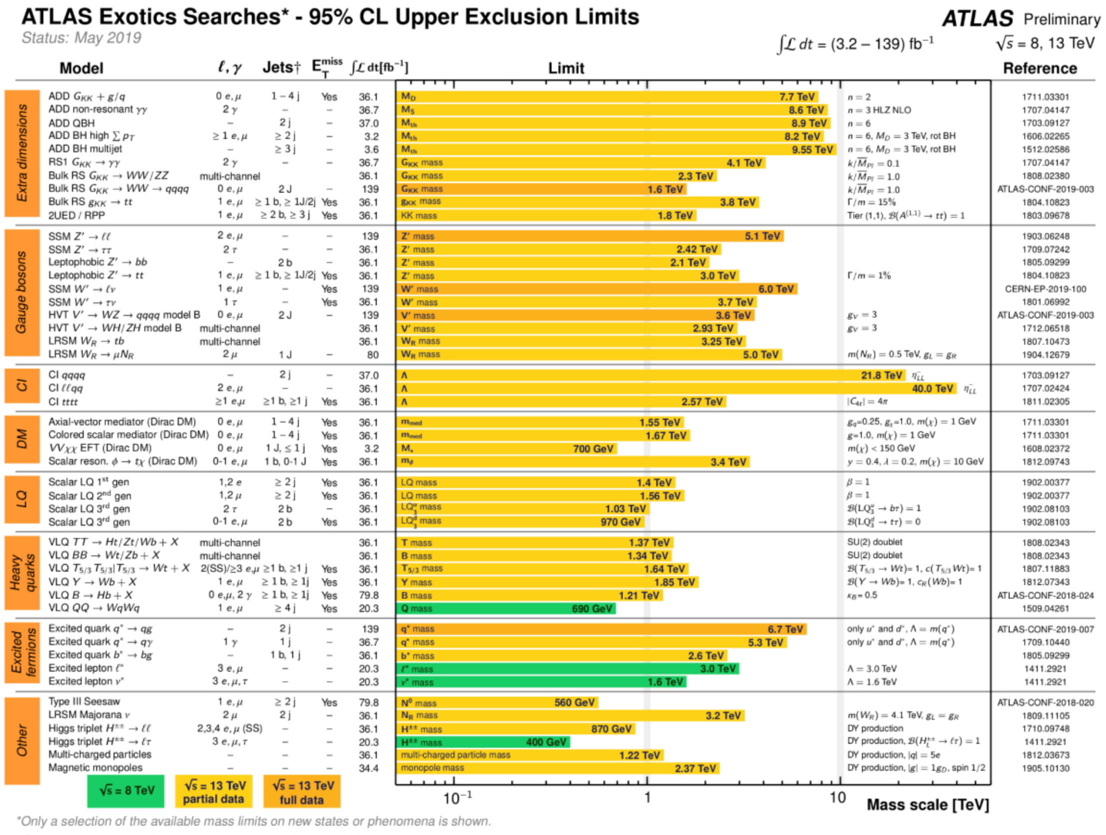
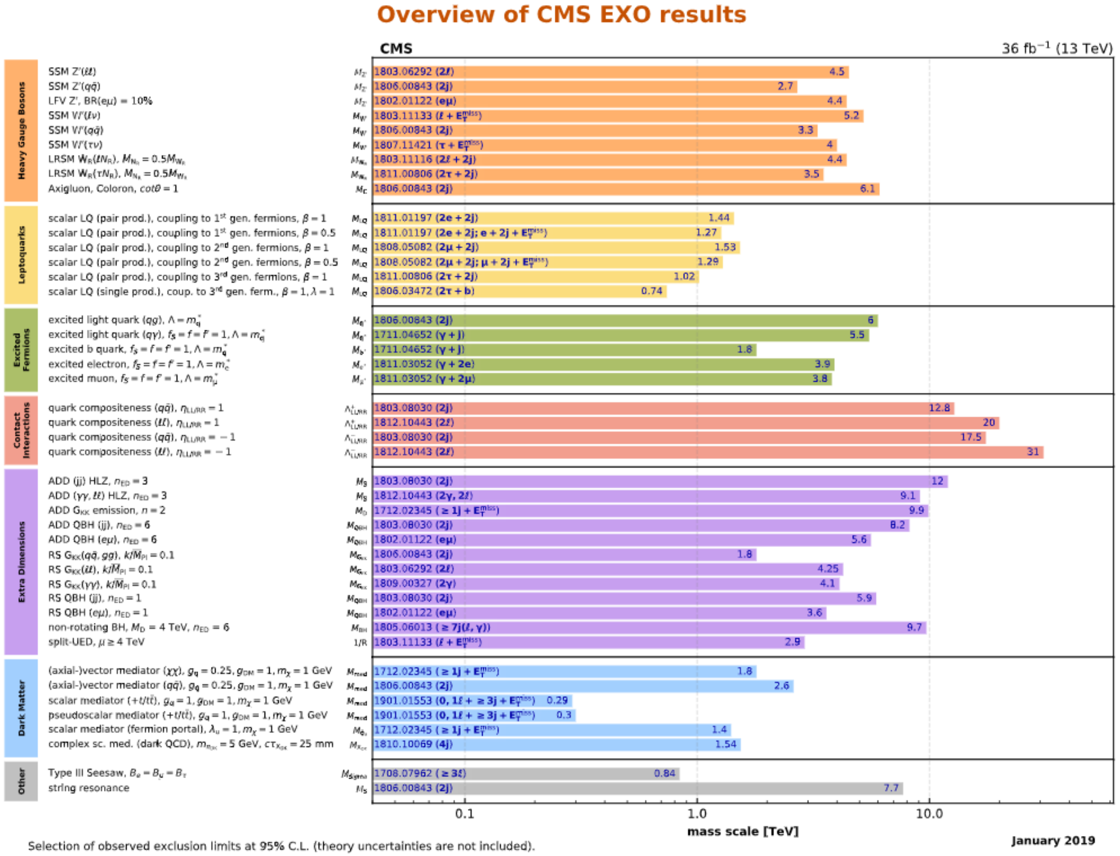
The new physics searches

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")

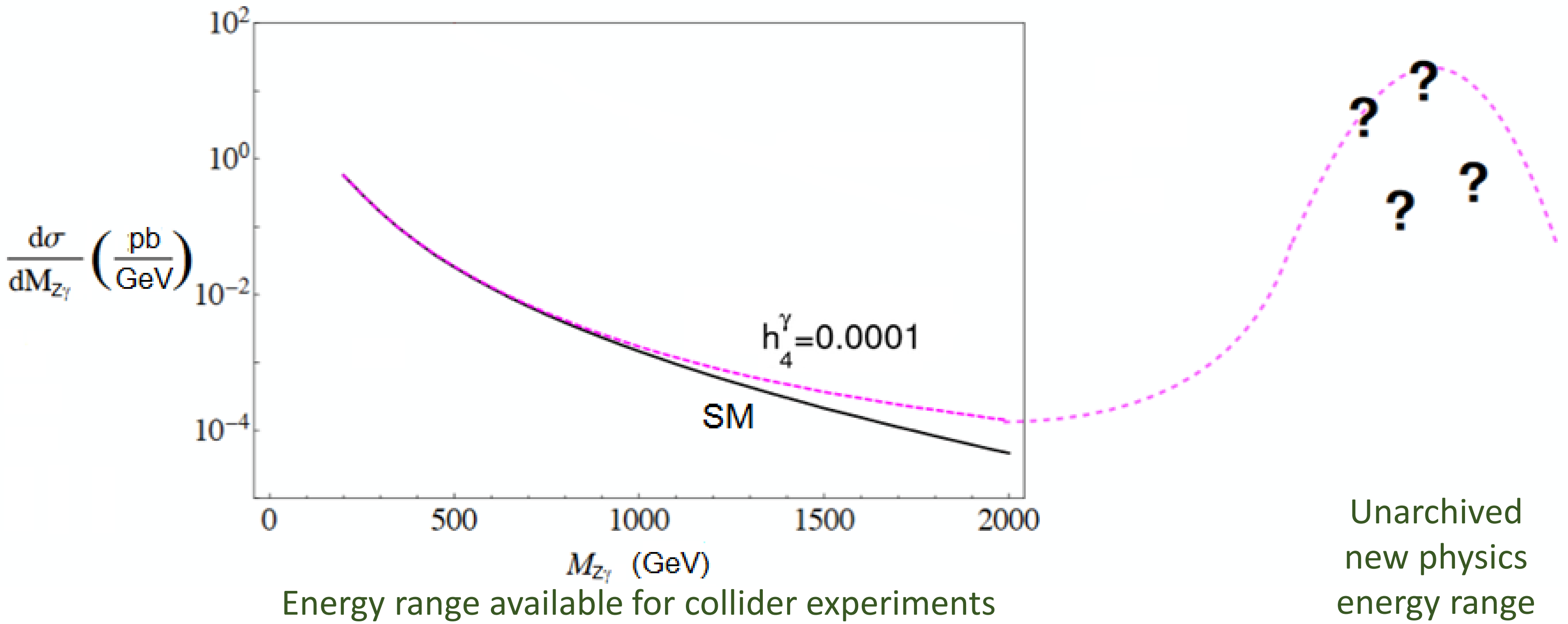
Current direct search results:





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:

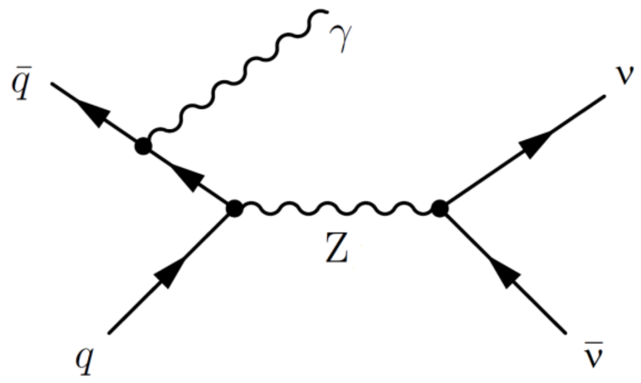
- Flavor physics (especially B physics) – some deviations from SM already reported
- Studies of electroweak boson interactions (VBF, VBS, multibosons)
- Top physics

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

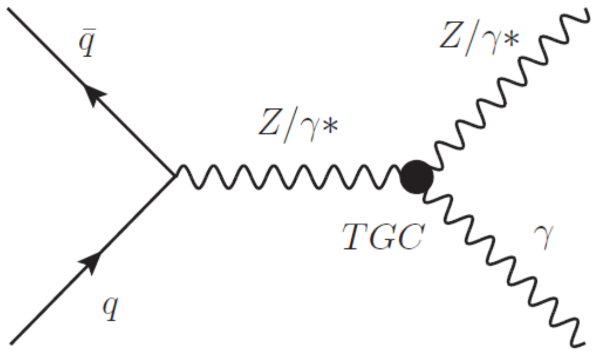
Why Zγ?

- Associated Zγ production can be used for the study of anomalous triple gauge couplings (aTGC)
- Neutral vertices Zγγ and ZZγ 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 (νν/ee ~ 6) and much better background control than hadronic channel (dijet final state has huge background contamination at hadron collider experiments)

SM Zγ production:



Beyond SM Zγ production:



Why Zγ: anomalous couplings formalism and public results

- Vertex functions formalism (e.g. for ZZγ vertex):

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

Coupling is described by eight parameters: $\mathbf{h_1^V}$ - $\mathbf{h_4^V}$, where V = γ, Z

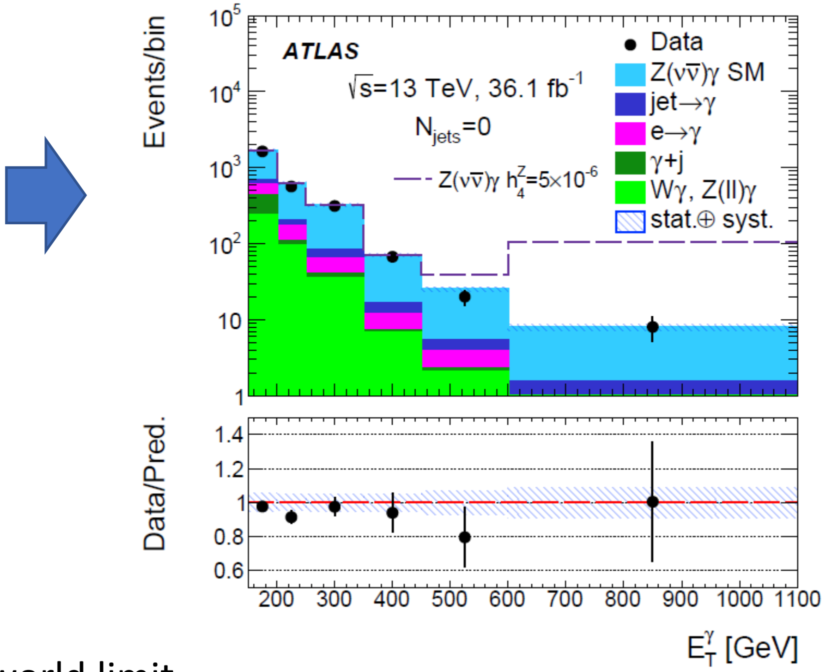
- CP-conserving: $\mathbf{h_3^V, h_4^V}$

(correspond to electric dipole, magnetic quadrupole vertex transition moments)

- CP-violating: $\mathbf{h_1^V, h_2^V}$

(correspond to magnetic dipole, electric quadrupole vertex transition moments)

Non-zero (anomalous) values of the $\mathbf{h_i^V}$ couplings lead to increase of the Zγ cross section, especially for large photon transverse energies (or big s).



- Sensitivity of experiments for the Zγγ/ZZγ vertex functions parameters (h_3[Z] or "electric dipole transition moment" of Z boson) is close to the order of SM loop corrections (~10^{-4}-10^{-5}): [Z. Phys. C - Particles and Fields 28, 149-154 (1985)].

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

Best world limit

Parameter	Limit 95% CL Measured
h_3^Z	$(-3.2\times10^{-4}, 3.3\times10^{-4})$

Backgrounds and current selection

ATLAS selection:

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

CMS selection:

$E_T[\gamma] > 175$ GeV and $|\eta[\gamma]| < 1.44$

$E_T[miss] > 170$ GeV

$\Delta\phi(\gamma, p_T[miss]) > 2$

Lepton veto (p_T>10 GeV)

$\Delta\phi(jet, p_T[miss]) > 0.5$ ($p_T[jet] > 30$ GeV)

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

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

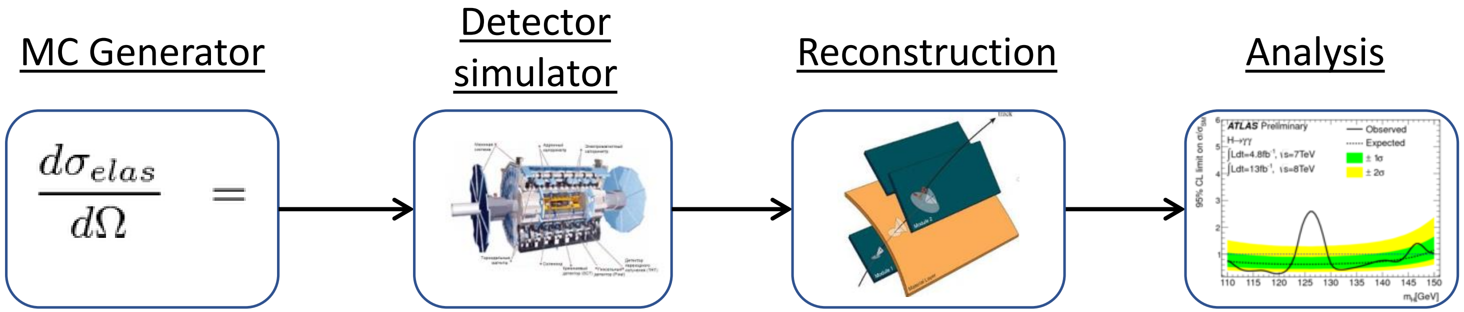
Process	Estimate
$Z\gamma \to \nu\bar{\nu}\gamma$	41.74 ± 6.67
$W\gamma \to \ell\nu\gamma$	10.60 ± 1.58
$W \to e\nu$	7.80 ± 1.78
Jet $\to \gamma$ misidentified	1.75 ± 0.61
Beam halo	5.90 ± 4.70
Spurious ECAL signals	5.63 ± 2.20
Rare backgrounds	3.03 ± 0.69
Total Expectation	76.45 ± 8.82
Data	77

- Wγ 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.

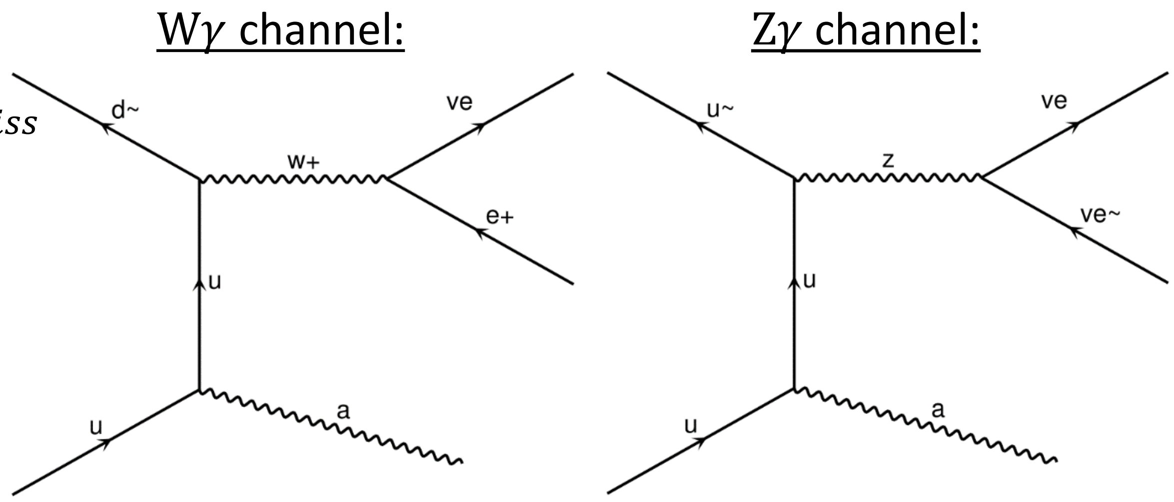
Setup for the study

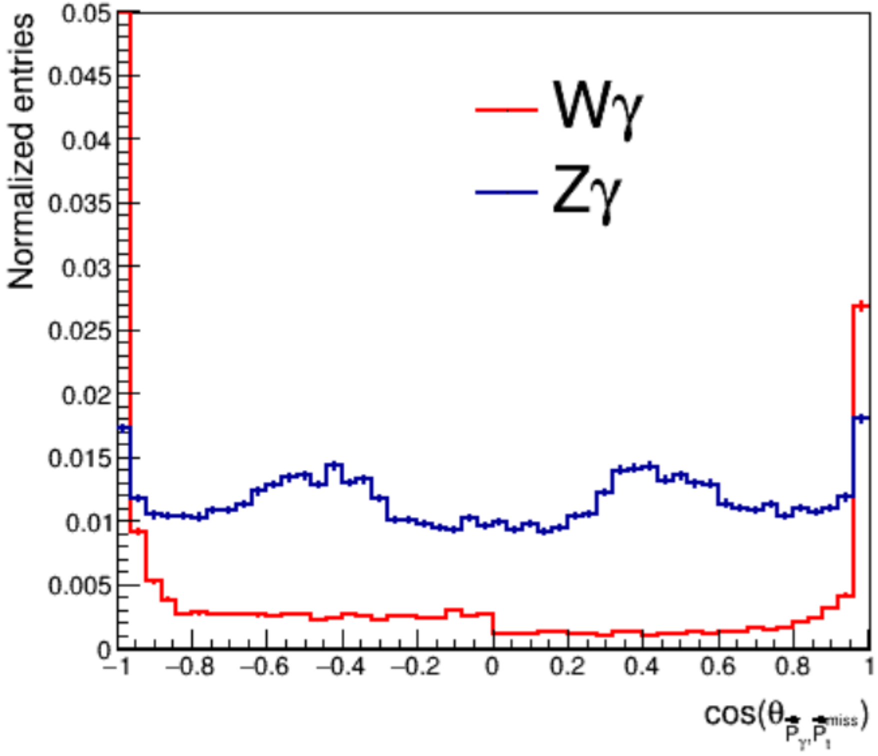
- MG5_aMC samples were generated for this study (100k each)
- Pythia8 was used for parton showering, hadronization and underlying event
- Delphes framework was used for detector simulation (ATLAS geometry card) and particles reconstruction



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 $\vec{P}_\gamma$.
- Seeking for some separation potential.





- The simplest angular variable that can be constructed is $cos\left(\theta_{\vec{P}_\gamma,\vec{P}_t^{miss}}\right)$.
- First LO Monte Carlo studies with the MadGraph5 revealed the separation potential of $cos\left(\theta_{\vec{P}_\gamma,\vec{P}_t^{miss}}\right)$.
- 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 $\Delta\phi(\gamma,p_T[miss])$ cut to maximize the separation power.

New ideas for backgrounds suppression: missing P_T

- Missing energy is calculated in the following way:

$$\overrightarrow{E_T}^{\text{miss}} = -\sum \overrightarrow{p_T}(i)$$

where i – photons, leptons and jets.

- For Zγ, full momentum of Z is genuine missing P_T. It will be not added to this formula.
- For Wγ, 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

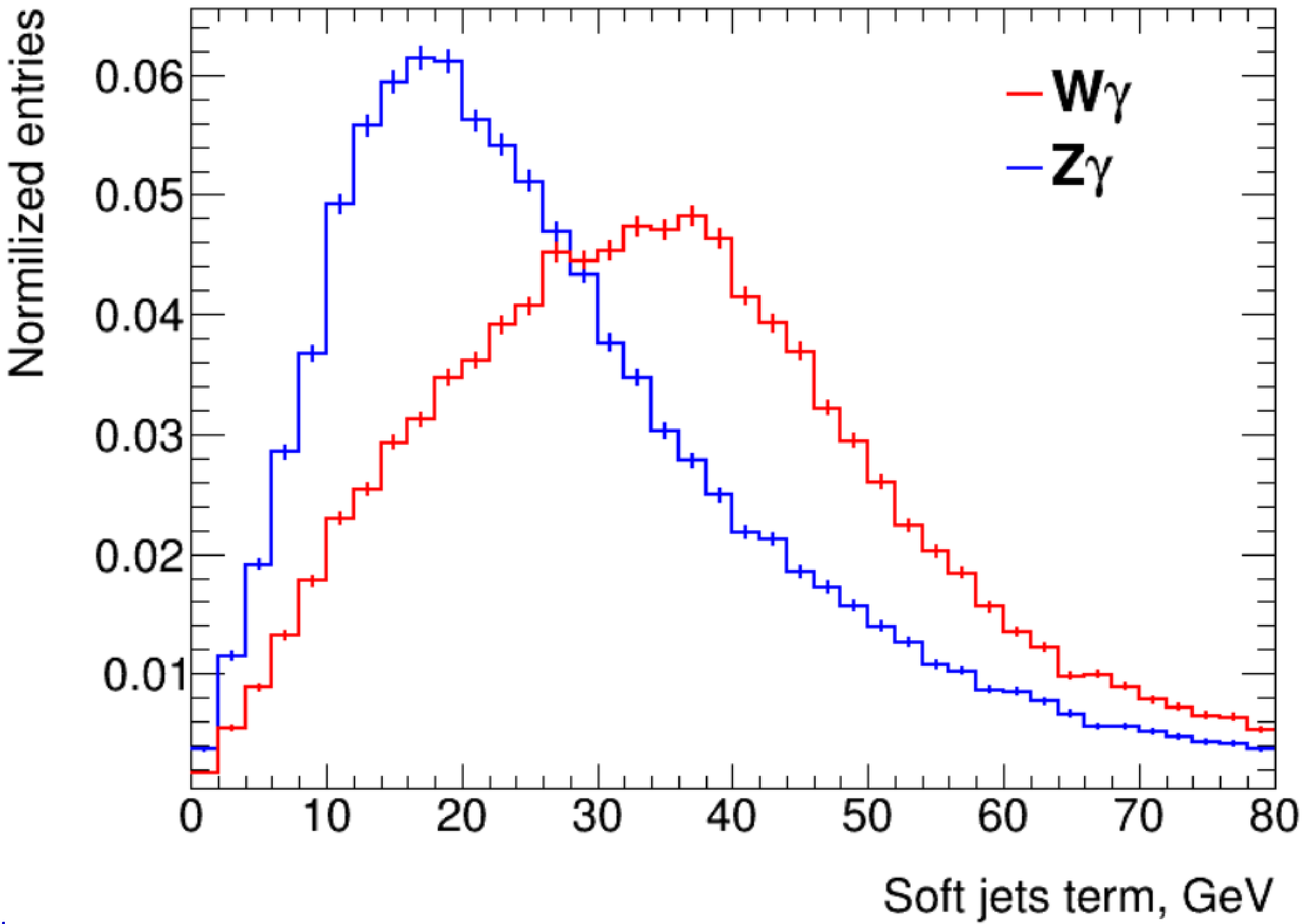
Missing P_T will be slightly different for Zγ. However, the best separation power will give the soft jets term:

$$\text{Softjets}=|\overrightarrow{E_T^{miss}}|-\sum \overrightarrow{p_T^{hard}(i)}$$

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.

- Zγ 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 Wγ 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).

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