The production of a singlet scalar at future $e^+ e^-$ colliders

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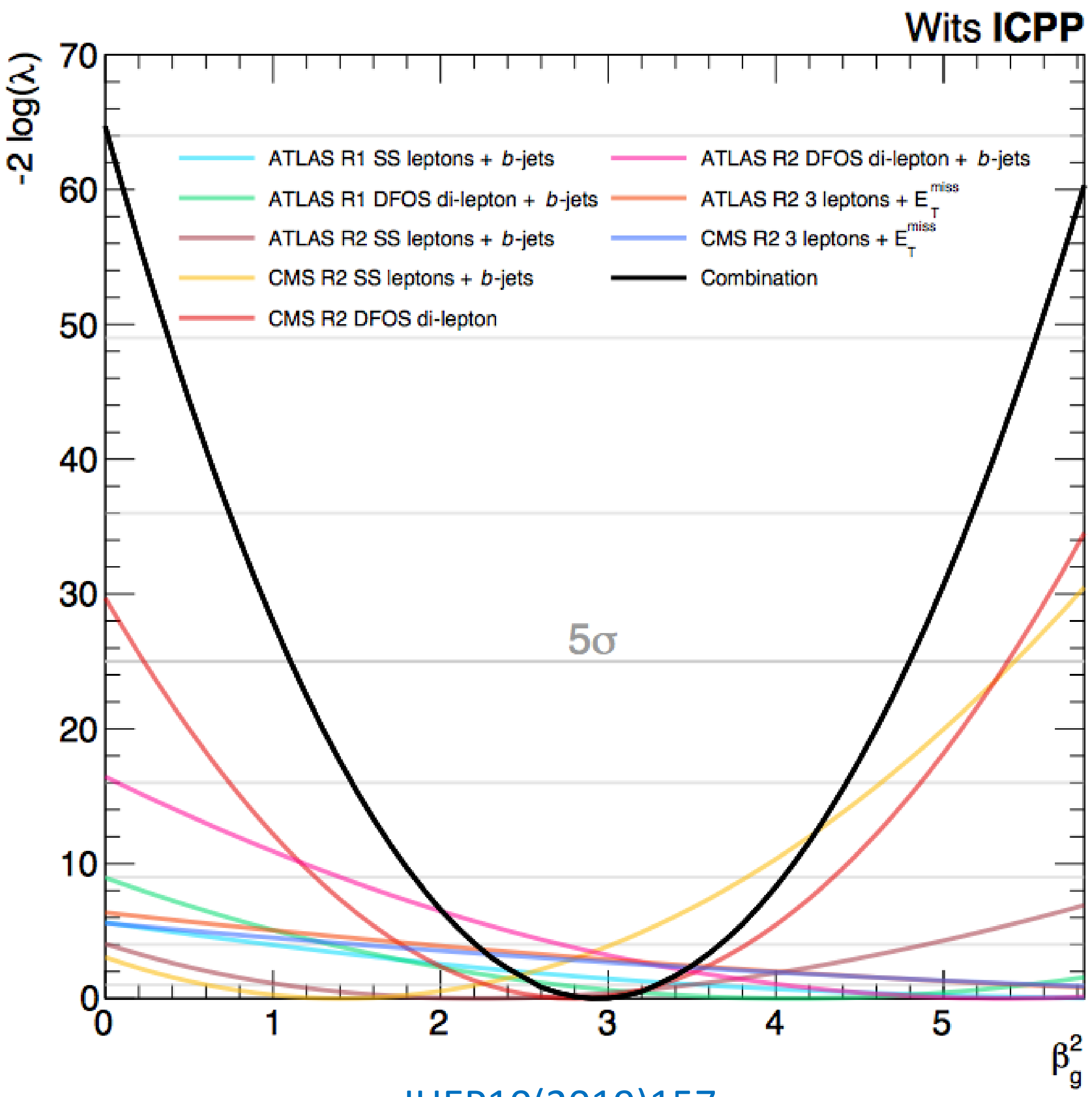
Multi-lepton anomalies at the LHC



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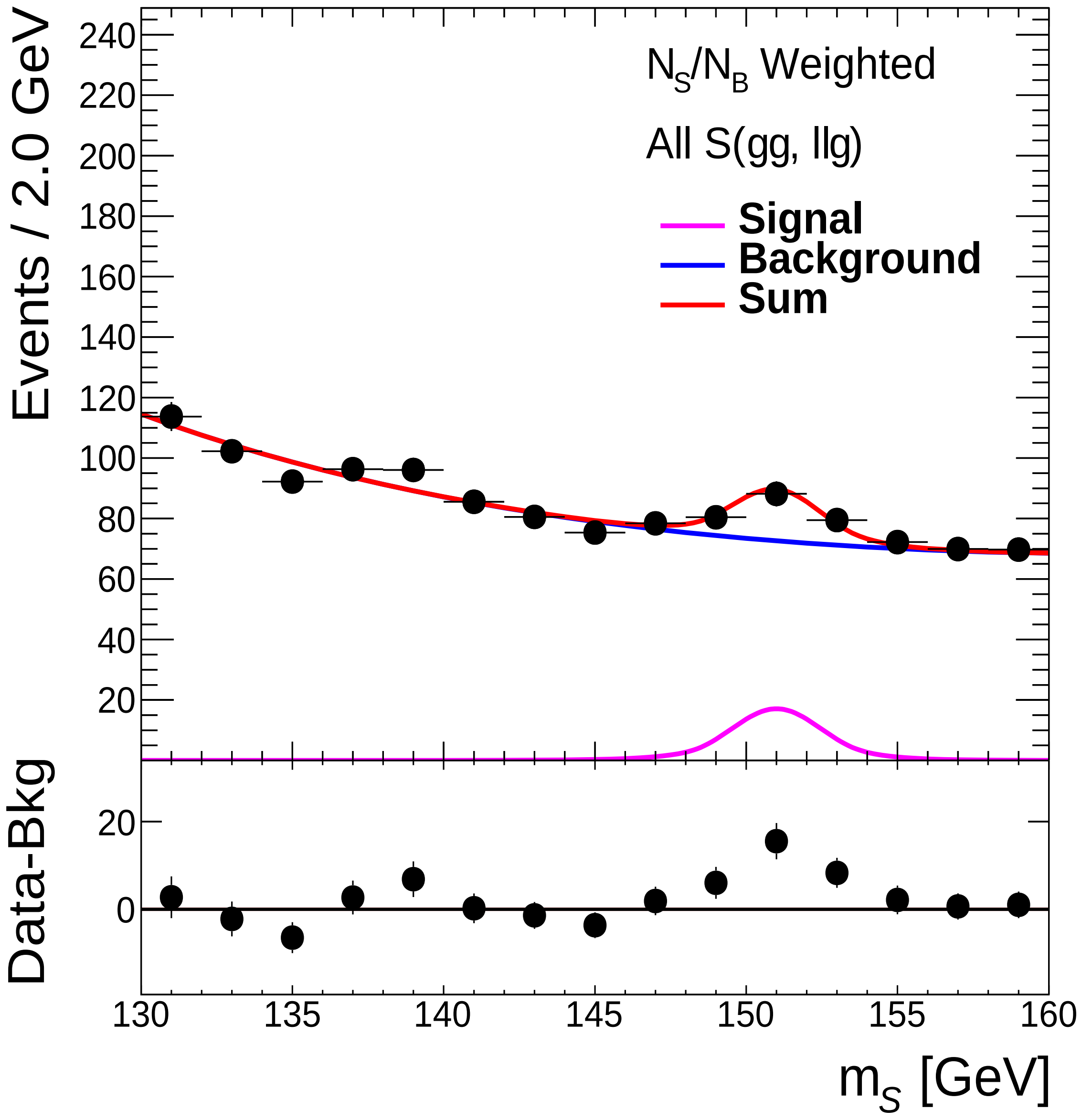
- The multi-lepton anomalies at the LHC are explained by the production of $H \rightarrow SS$ where H and S are new scalar bosons. It turns out that S has been found in association with DM, indicating that $H \rightarrow S(\rightarrow \gamma\gamma, Z\gamma) S \rightarrow \chi\chi$ where χ is the DM particle.
- The combined results correspond to a **8.04σ** significance.
- Significance of the anomalies has been growing further in the past two year.
- Data consistent with new bosons: one with a mass around 270 GeV and another around 151 GeV.

Candidate of the new boson at $m_S = 151$ GeV



arXiv:2109.02650

- ❑ Candidate for a new boson with a mass of 151 GeV has been reported by Wits and collaborators in September.
- ❑ This candidate appears with missing energy, which is a signature of Dark Matter.
- ❑ Here we investigate a new approach to detect Dark Matter in future $e^+ e^-$ colliders in light of these observations.

Electroweak properties of the new scalar resonance:

- The Lagrangian for the 2HDM+S is

$$\mathcal{L}_{HhS} = -\frac{1}{2} v[\lambda_{hhS} hhS + \lambda_{hSS} hSS + \lambda_{HHS} HHS + \lambda_{HSS} HSS + \lambda_{HhS} HhS]$$

$$V(\Phi_1, \Phi_2, \Phi_3) = m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] + \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_1^\dagger\Phi_2(\Phi_2^\dagger\Phi_2)\Phi_S^2$$

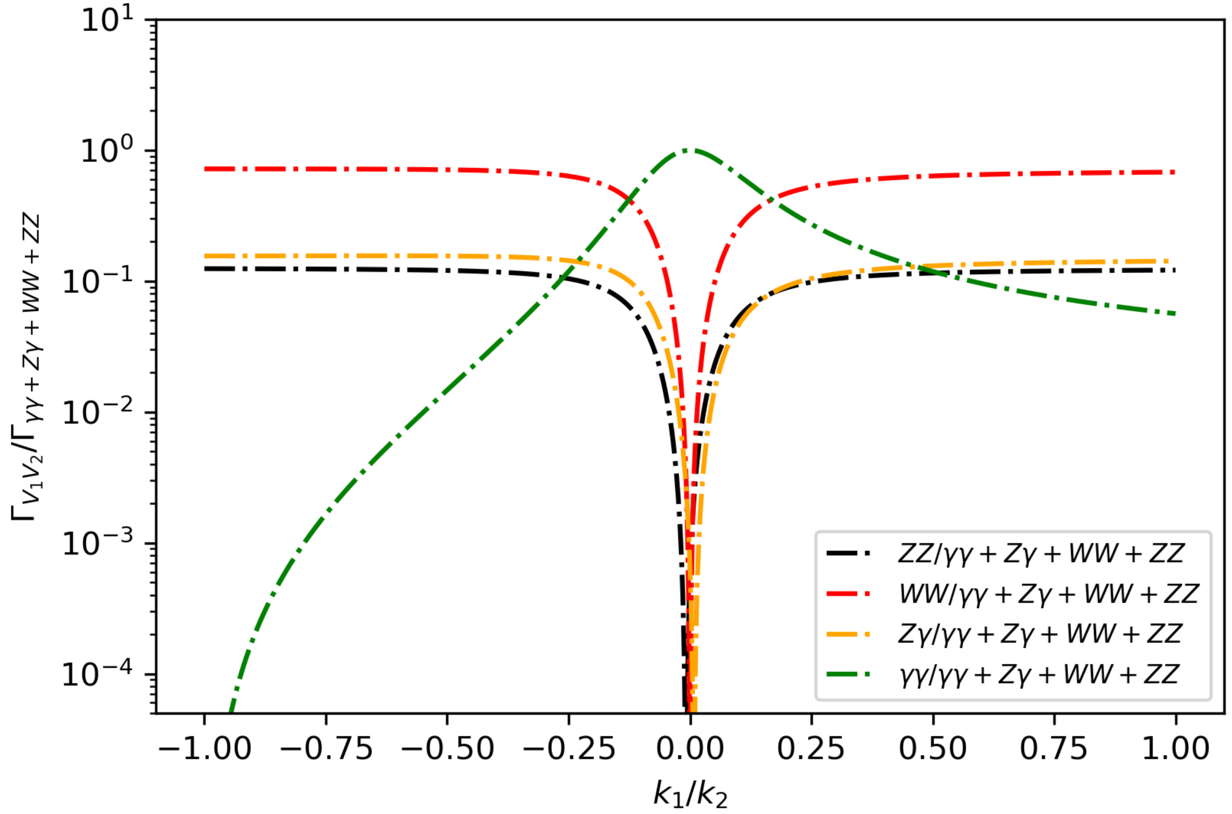
- The couplings of $S \to V_1 V_2$ are defined as:

$$g_{sZZ} = (\kappa_2 c_w^2 + \kappa_1 s_w^2),$$
$$g_{sZ\gamma} = c_w s_w (k_2 - k_1),$$
$$g_{s\gamma\gamma} = (\kappa_2 s_w^2 + \kappa_1 c_w^2)$$

- The electroweak singlet will have the following partial decay widths into two on-shell electroweak bosons ($m_S = 151\ GeV$):

$$\Gamma(s \to WW) = \frac{1}{32\pi} g_{sWW}^2 m_s \sqrt{1-4x}(1 - 4x + 6x^2)$$
$$\Gamma(s \to ZZ) = \frac{1}{64\pi} g_{sZZ}^2 m_s \sqrt{1-4x}(1 - 4x + 6x^2)$$
$$\Gamma(s \to Z\gamma) = \frac{1}{32\pi} g_{sZ\gamma}^2 m_s (1 - x^2)^3$$
$$\Gamma(s \to \gamma\gamma) = \frac{1}{64\pi} g_{s\gamma\gamma}^2 m_s$$

where $x = \frac{m_Z^2}{m_s^2}$.



Background and signal Processes

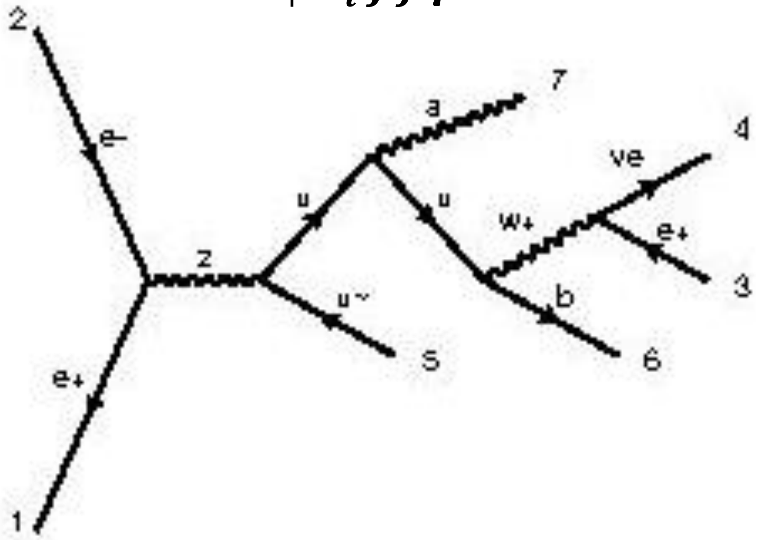
Background	
1.	$e^+ e^- \rightarrow l_+ \nu_l\, j\, j\, \gamma$
2.	$e^+ e^- \rightarrow l_- \tilde{\nu}_l\, j\, j\, \gamma$
3.	$e^+ e^- \rightarrow j\, j\, j\, j\, \gamma$
Signal	
1.	$e^+ e^- \rightarrow Z^* \rightarrow S\gamma \rightarrow l_+ \nu_l\, j\, j\, \gamma$
2.	$e^+ e^- \rightarrow Z^* \rightarrow S\gamma \rightarrow l_- \tilde{\nu}_l\, j\, j\, \gamma$
3.	$e^+ e^- \rightarrow Z^* \rightarrow S\gamma \rightarrow j\, j\, j\, j\, \gamma$

- 500 000 simulated events
- Centre-of-mass energy 250 GeV
- Cuts:

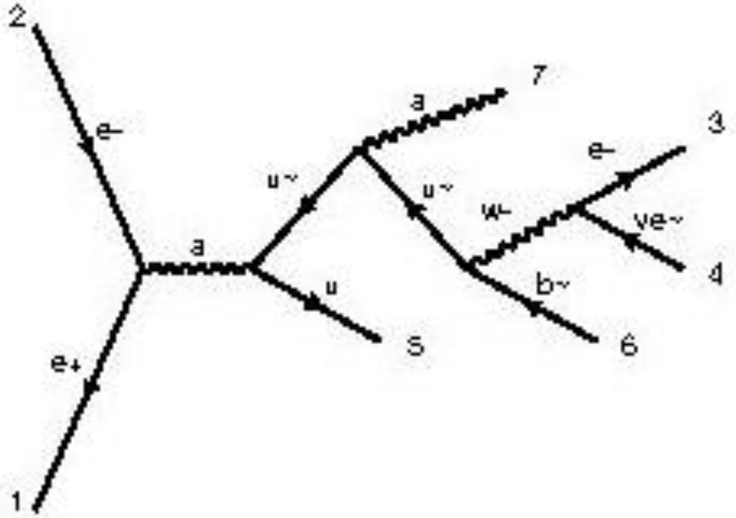
$$|\eta| < 2.6$$
$$70\ GeV < E_\gamma < 90\ GeV$$

Feynman diagrams

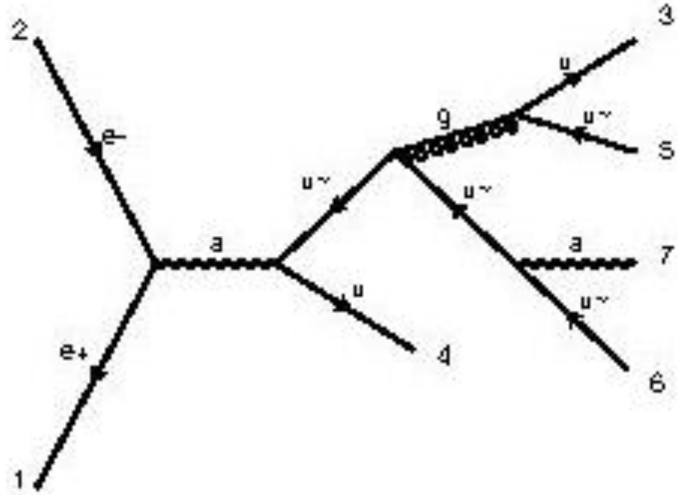
$l_+ \, \nu_l \, j \, j \, \gamma$



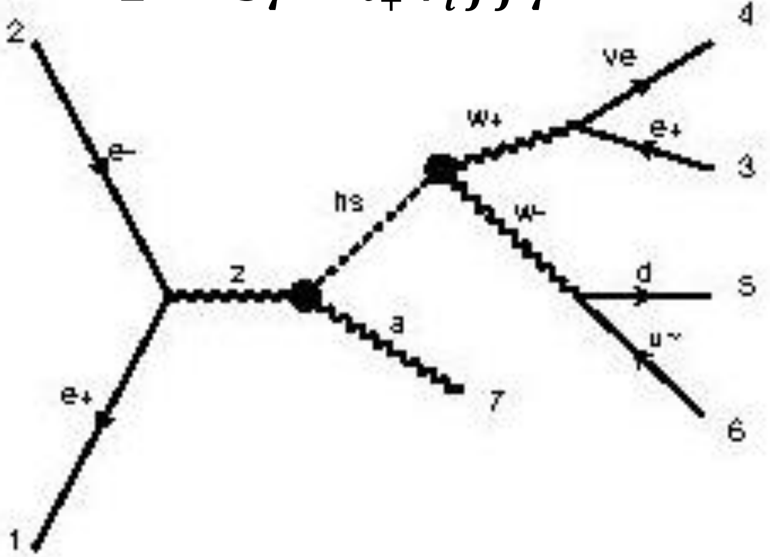
$l_- \, \tilde{\nu}_l \, j \, j \, \gamma$



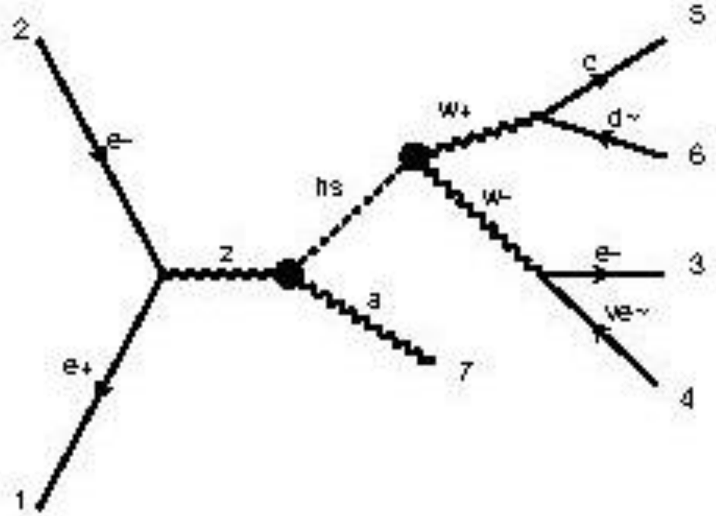
$j \, j \, j \, j \, \gamma$



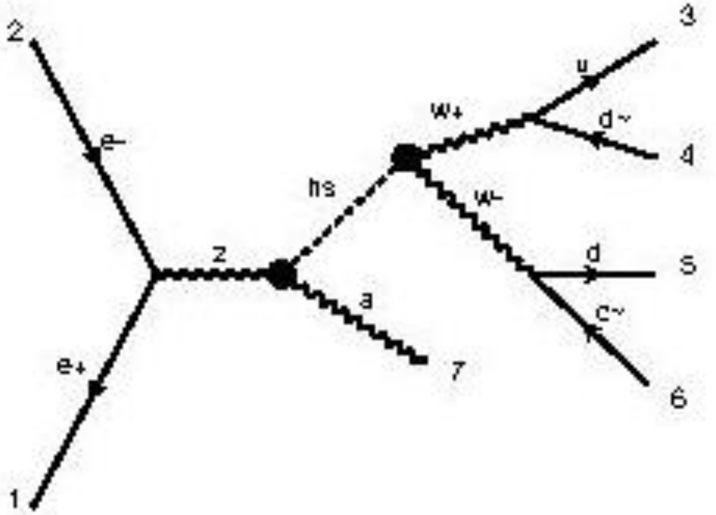
$Z^* \rightarrow S\gamma \rightarrow l_+ \, \nu_l \, j \, j \, \gamma$



$Z^* \rightarrow S\gamma \rightarrow l_- \, \tilde{\nu}_l \, j \, j \, \gamma$



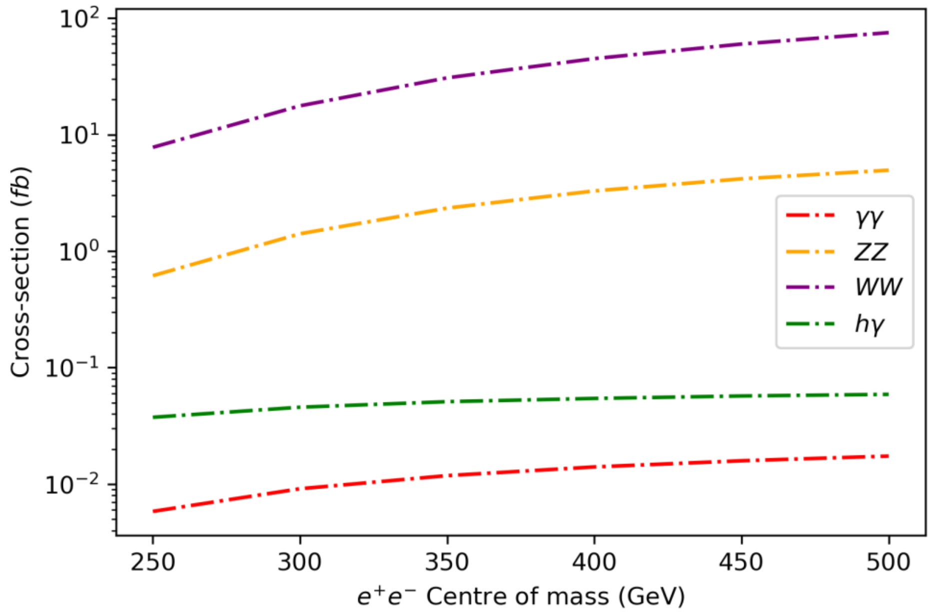
$Z^* \rightarrow S\gamma \rightarrow j \, j \, j \, j \, \gamma$



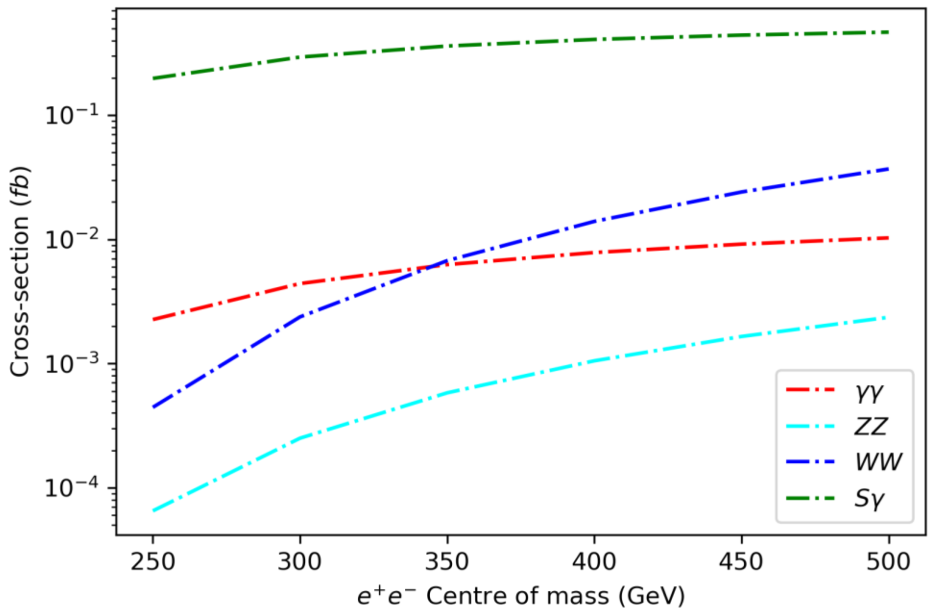
Cross-sections

Background processes	$\sigma\ (fb)$
$e^+ e^- \to l_+ \nu_l\, j\, j\, \gamma$	1.801
$e^+ e^- \to l_- \tilde{\nu}_l\, j\, j\, \gamma$	1.803
$e^+ e^- \to j\, j\, j\, j\, \gamma$	13.07
Signal processes	$\sigma\ (fb)$
$e^+ e^- \to Z^* \to S\gamma \to l_+ \nu_l\, j\, j\, \gamma$	0.028
$e^+ e^- \to Z^* \to S\gamma \to l_- \tilde{\nu}_l\, j\, j\, \gamma$	0.028
$e^+ e^- \to Z^* \to S\gamma \to j\, j\, j\, j\, \gamma$	0.098

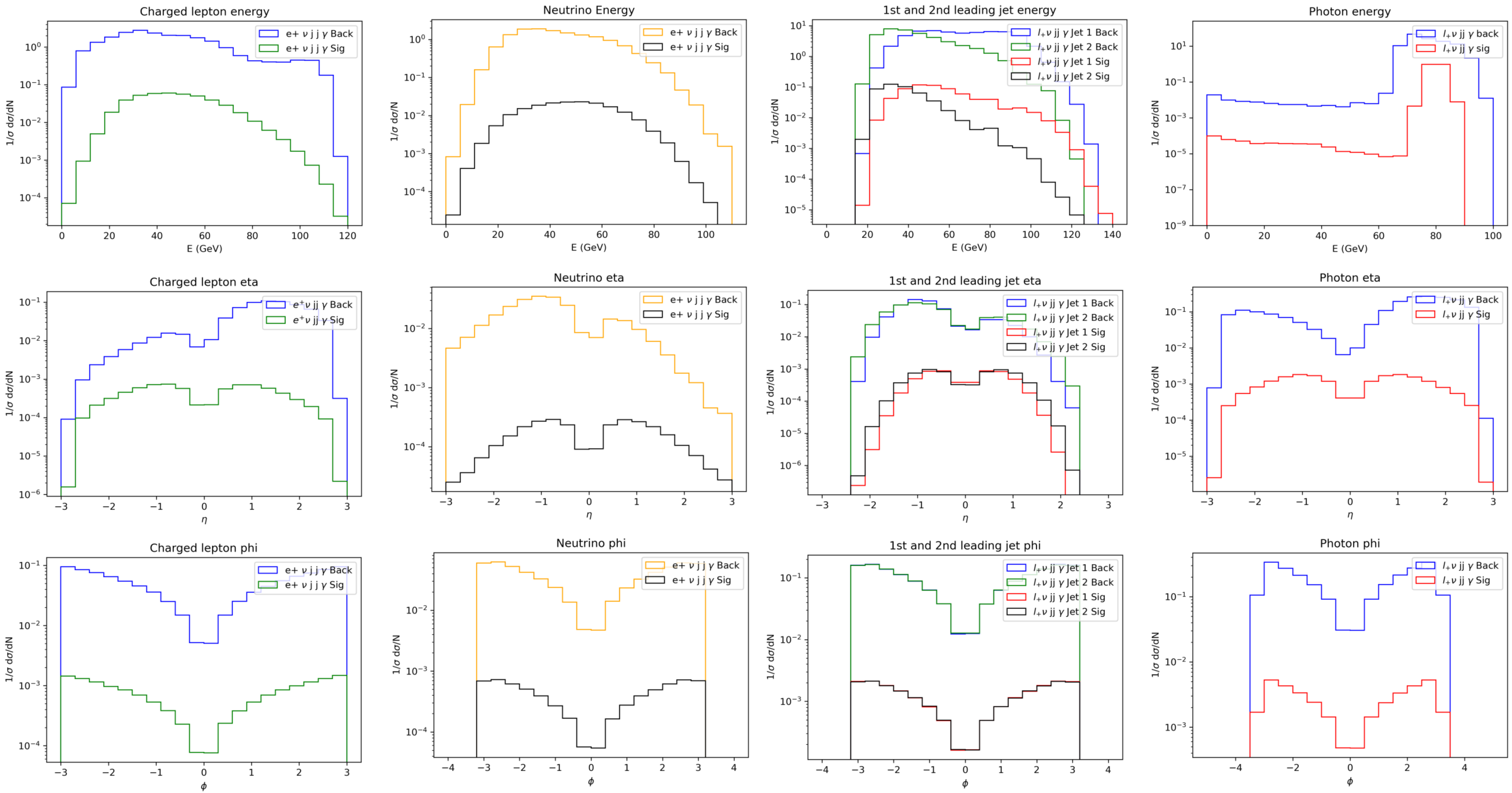
SM Higgs



Scalar

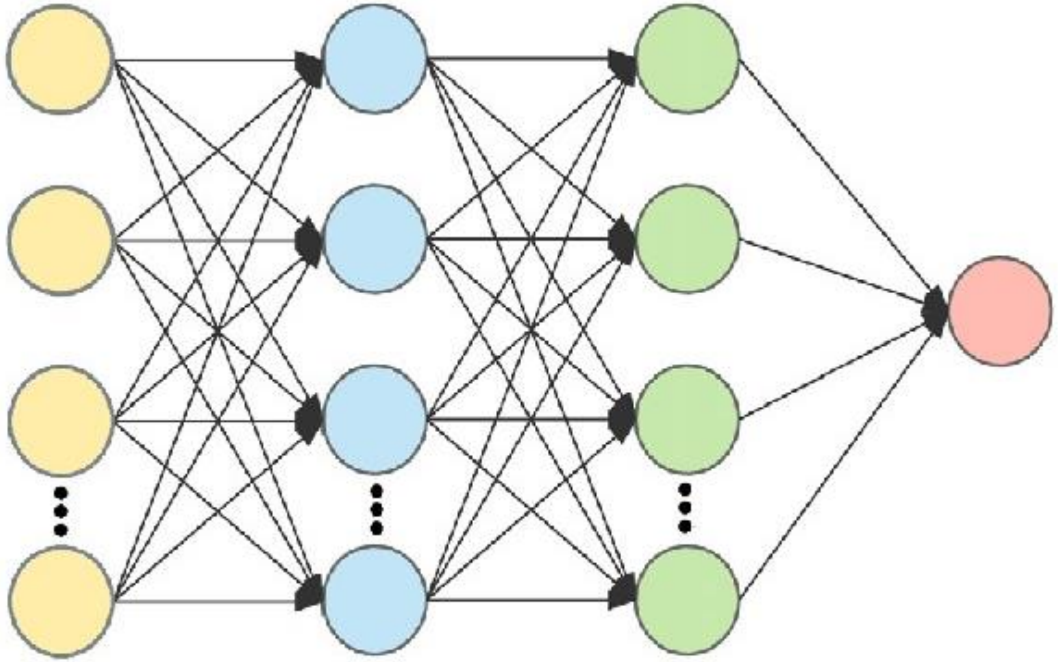


Kinematic distributions: $l_+ \, \nu_l \, j \, j \, \gamma$ final state



Inclusion of machine learning

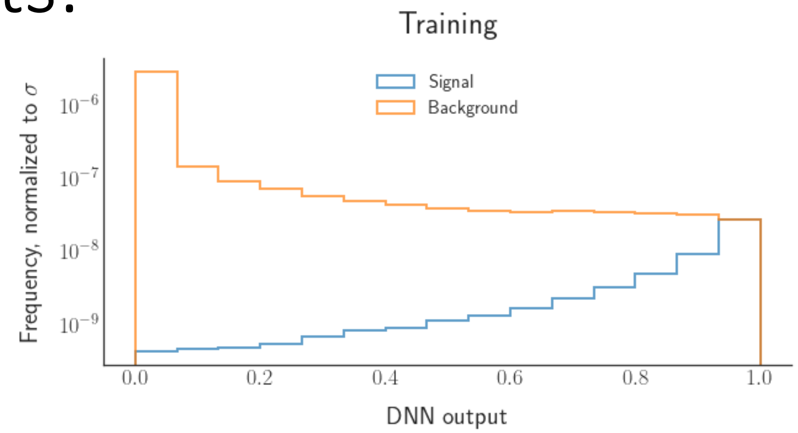
- ❑ This is used to distinguish between the signal and the background processes.
- ❑ The classification model that was used is Sequential with "Adam" used as the optimizer.
- ❑ Hyperparameter optimisation is implemented to tune the hyperparameters and achieve the most accurate results.

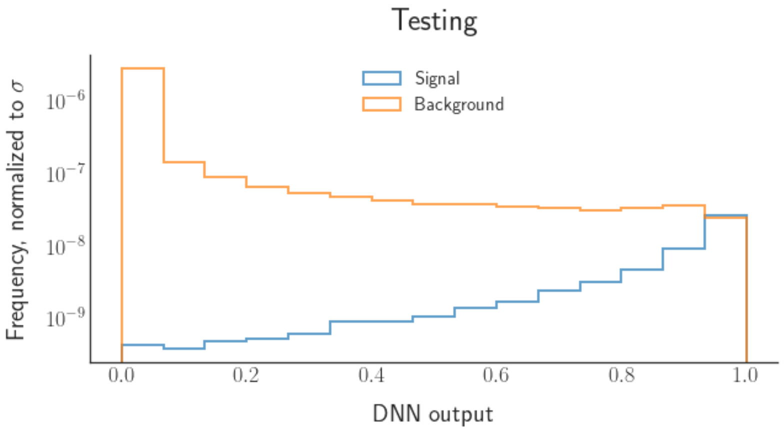


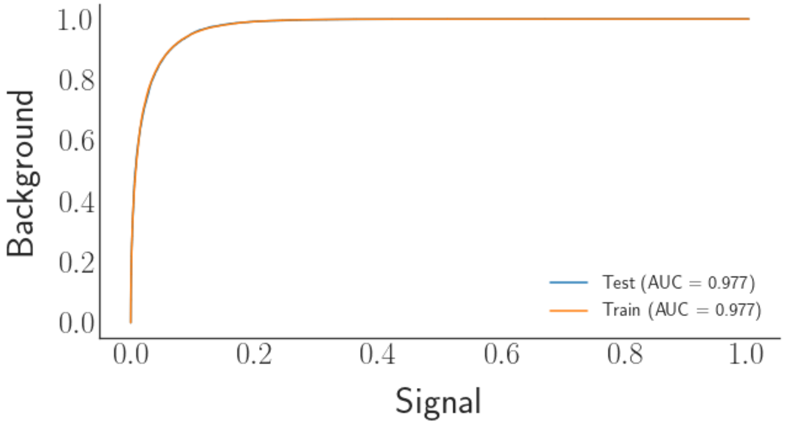
$l_{\pm}\,\nu_l\,j\,j\,\gamma$ DNN results:

- The hyperparameters that are used are:
- Number of inputs
- Hidden layers
- Epochs
- Batch size
- Learning rate

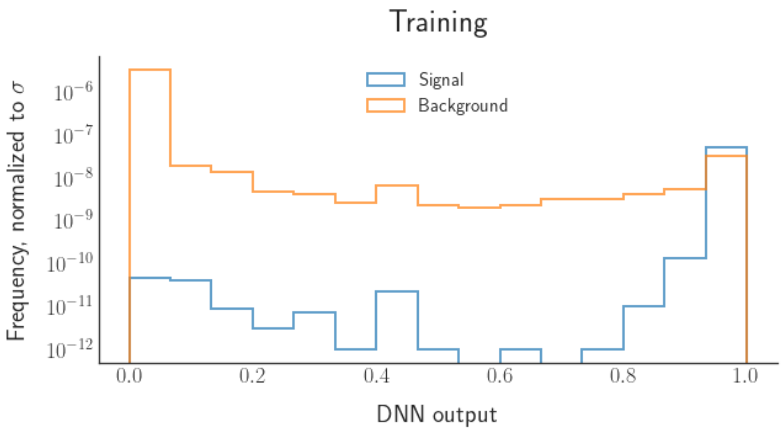
$l_{+}\,\nu_l\,j\,j\,\gamma$

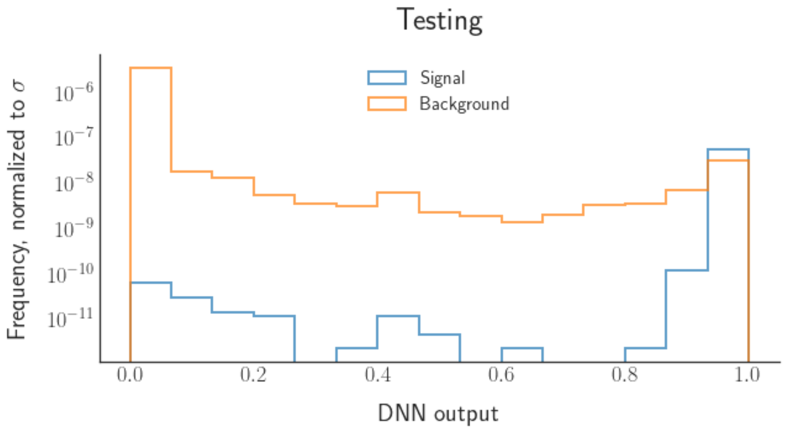


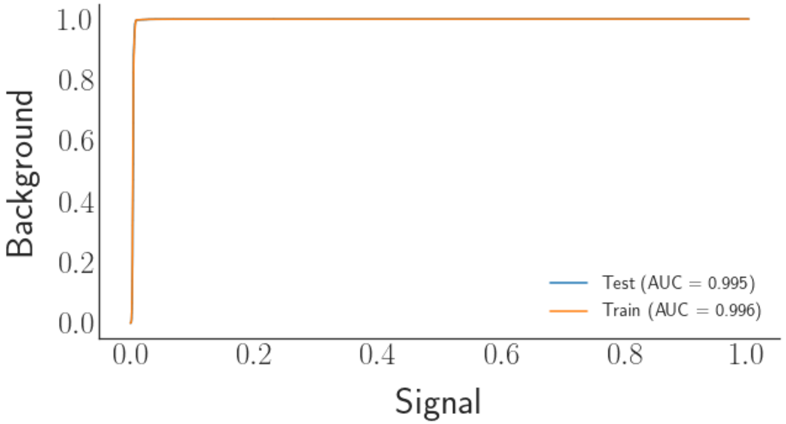




$l_{-}\,\tilde{\nu}_l\,j\,j\,\gamma$







Summary and Conclusion:

- The multi-lepton anomalies at the LHC are explained by the production of $H \rightarrow SS$ where H and S are new scalar bosons. It turns out that S has been found in association with DM, indicating that $H \rightarrow S(\rightarrow \gamma\gamma,\ Z\gamma)S \rightarrow \chi\chi$ where $\chi\chi$ is the DM particle.

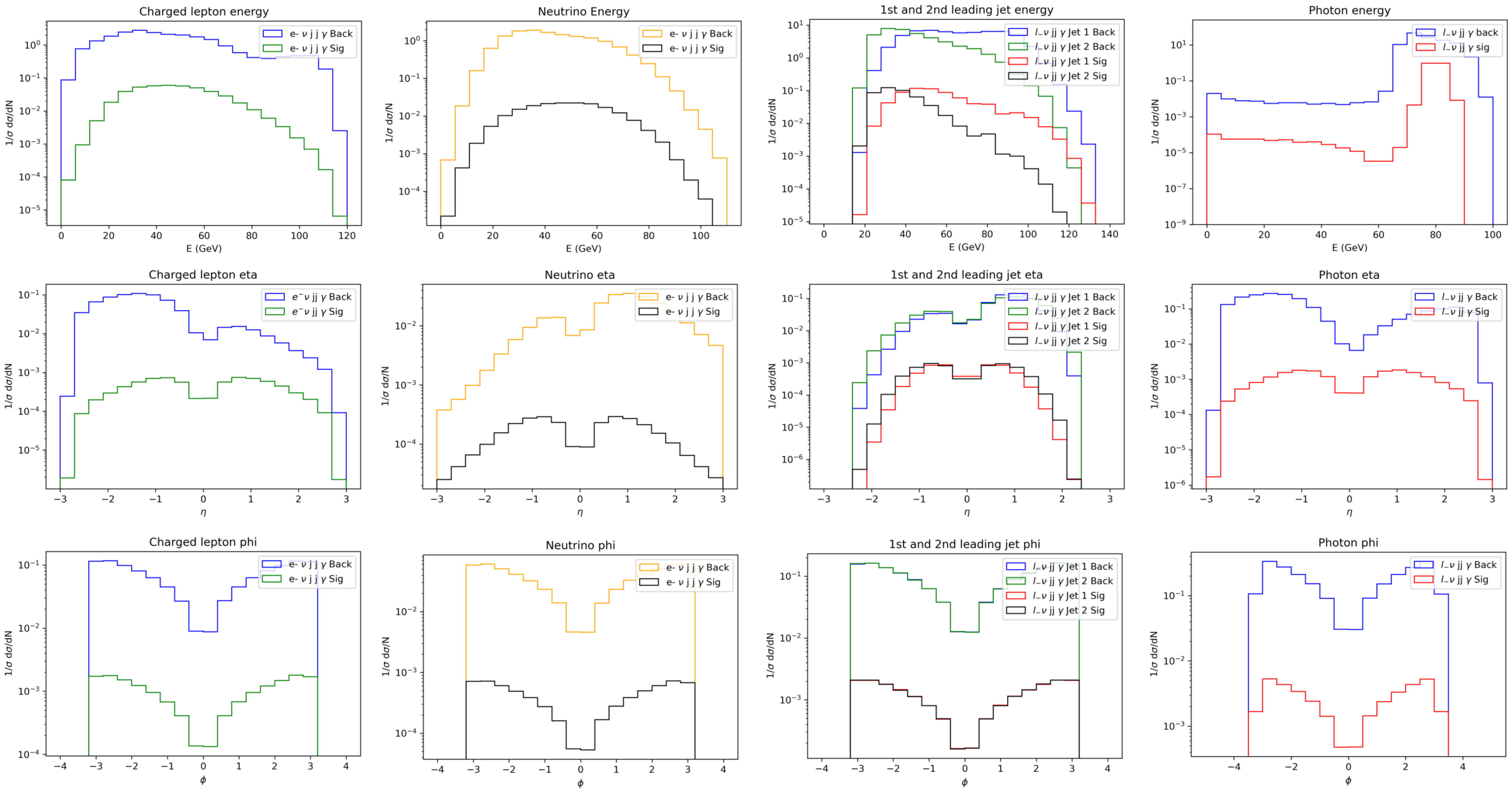
- The results show that the cross-section of this scalar resonances are large enough to be detected at future $e^+ e^-$ colliders.

- The hyperparameters of the machine learning model can be optimised in order to achieve more accurate results of the DNN outputs for each of the final state. However, the obtained results are sufficient enough to probe the search for the scalar resonances at future $e^+ e^-$ colliders.

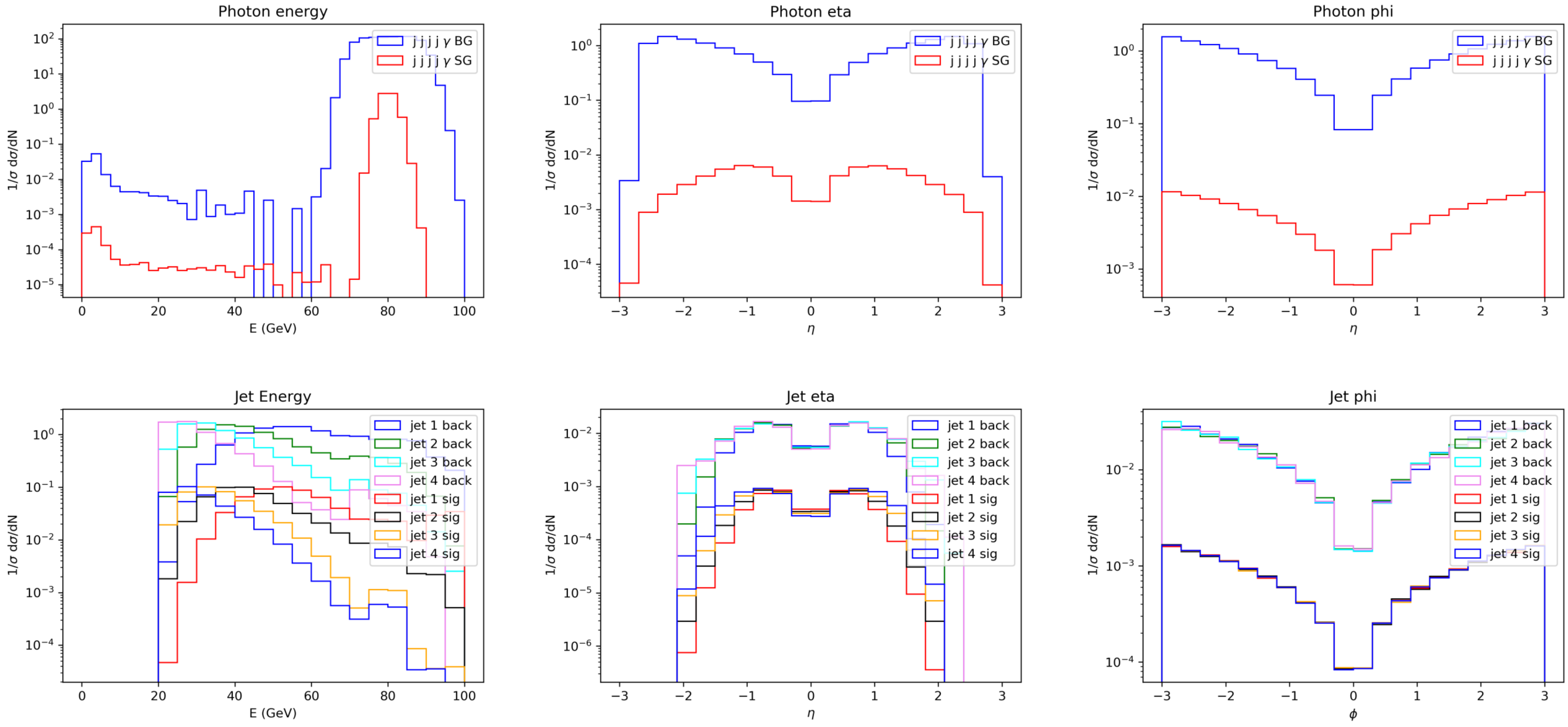
Thank you!

Additional slides

Kinematic distributions: $l\_ \, \tilde{\nu}_l \, j \, j \, \gamma$ final state



Kinematic distributions: $j\,j\,j\,j\,\gamma$ final state



$jjjj\gamma$ final state DNN results