Title: Observation of 152 GeV charged scalar at future lepton colliders

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Overview:

- Motivation
- Model Description
- Analysis
- Results

Motivation

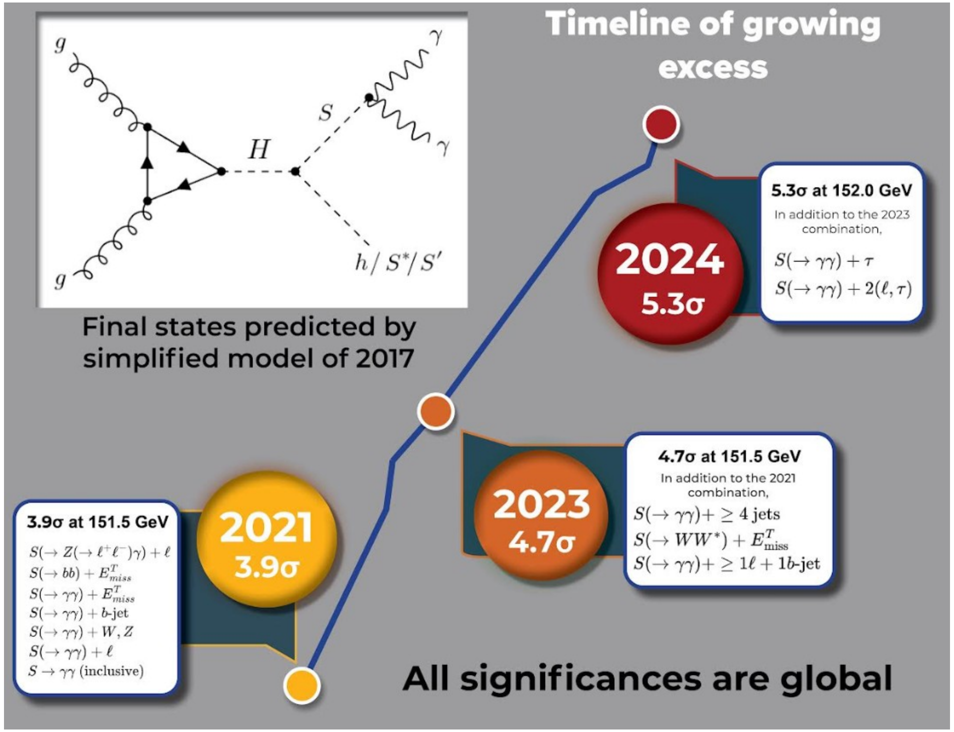
- The "multi-lepton anomalies": inconsistencies in the channels with multiple leptons, missing energy, and possibly (b)jets in the final states with the SM prediction, suggests a new scalar with a mass between 145 GeV and 155 GeV [J. Phys. G 46 (2019) no.11, 115001, JHEP10(2019)157, Chin.Phys.C 44 (2020) 6 063103, PLB 811 (2020) 135964, EPJC 81 (2021) 365, PRD 108 115031 (2023), PRD 108 (2023) 3 035026, Nature Review. Phys. 6 294–309 (2024)]

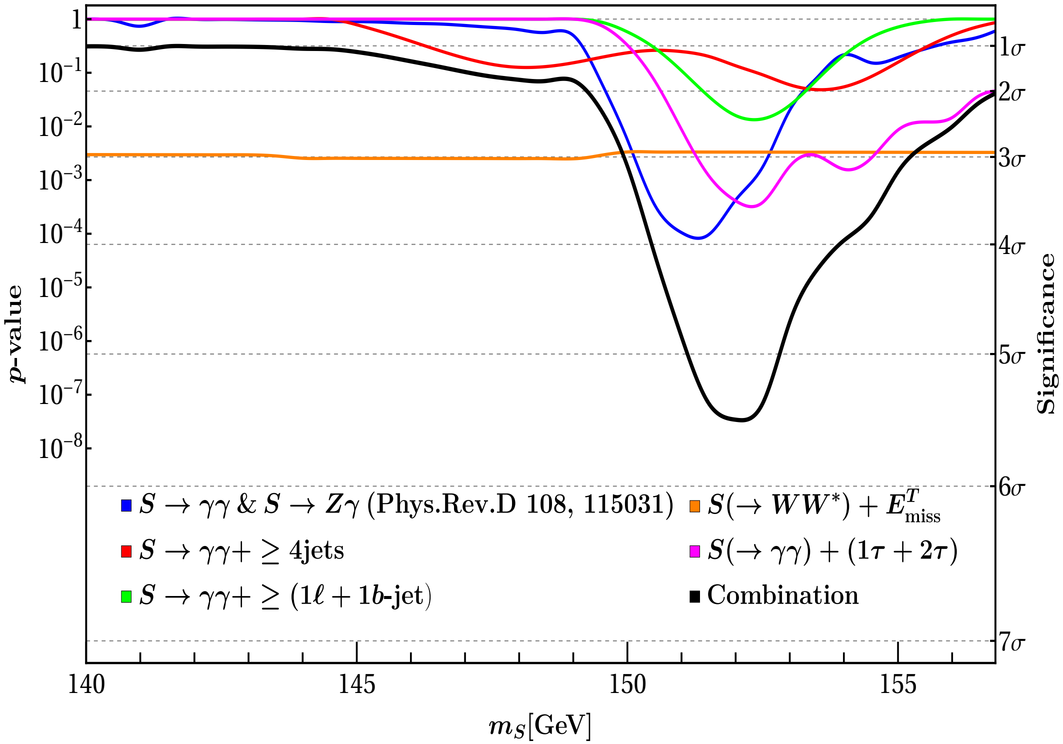
- Sidebands of SM Higgs searches refer to the associated production of a narrow scalar resonance of mass ≈ 152 GeV, in the $\gamma\gamma$ and $Z\gamma$ invariant mass spectrum [EPJC 81 no. 2 (2021) 178]

- Requirement of dominantly decaying to WW and not to ZZ, suggests the new scalar to be a part of Y=0 scalar triplet

- Analysis is done in lepton collider because of its low hadronic activity

Motivation





- Combining the latest ATLAS results, global significance of 5.3σ for $m_S \approx 152$ GeV is obtained. [2503.16245]

Model Description

Scalar spectrum of ΔSM:

[PLB 862 (2025) 139298]

$$\Phi = \begin{pmatrix} h_\Phi^+ \\ \frac{1}{\sqrt{2}}(v_\Phi + h_\Phi^0 + iG^0) \end{pmatrix},$$ SM like doublet

$$\Delta = \frac{1}{2}\begin{pmatrix} v_\Delta + h_\Delta^0 & \sqrt{2}h_\Delta^+ \\ \sqrt{2}h_\Delta^- & -(v_\Delta + h_\Delta^0) \end{pmatrix},$$ Hypercharge Y=0 triplet

Scalar potential:

$$V = -\mu_\Phi^2 \Phi^\dagger\Phi + \frac{\lambda_\Phi}{4}\left(\Phi^\dagger\Phi\right)^2 - \mu_\Delta^2 \mathrm{Tr}\left(\Delta^\dagger\Delta\right) + \frac{\lambda_\Delta}{4}\left[\mathrm{Tr}\left(\Delta^\dagger\Delta\right)\right]^2 + A\Phi^\dagger\Delta\Phi + \lambda_{\Phi\Delta}\Phi^\dagger\Phi\mathrm{Tr}\left(\Delta^\dagger\Delta\right),$$

Free parameter of the model: $m_\Delta^0, m_\Delta^\pm, \alpha, v_\Delta$

experimental limit on the ρ parameter restricts the mass-splitting to at most a few GeV, we have considered degenerate spectrum for our analysis

Model Description

Decay Rates:

$$\Gamma(\Delta^\pm \to f f') = \frac{N_c m^3_{\Delta^\pm} \sin^2\beta}{8\pi v^2_\Phi} \beta_{ff'} \left(\frac{m_f^2}{m^2_{\Delta^\pm}}, \frac{m^2_{f'}}{m^2_{\Delta^\pm}} \right),$$

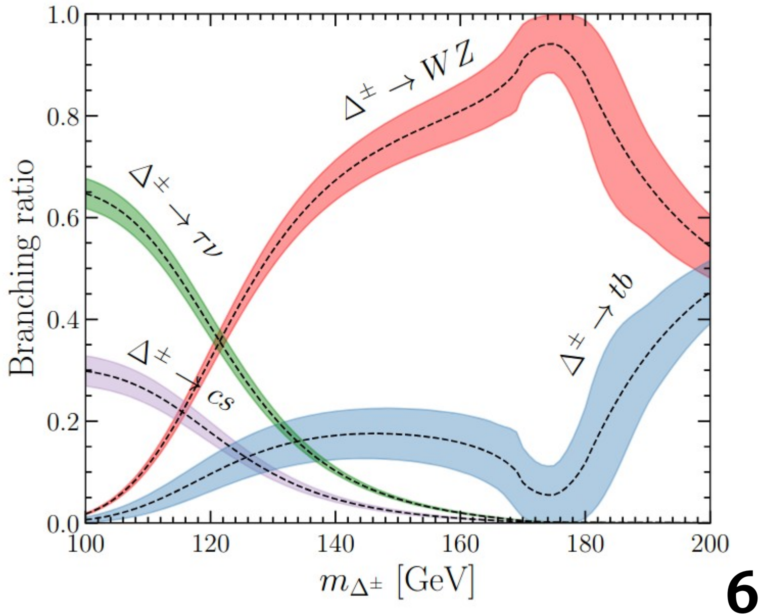
$$\Gamma(\Delta^\pm \to t^*\bar{b}/\bar{t}^*b \to W^\pm b\bar{b}) = \frac{3 m_t^4 m_{\Delta^\pm} \sin^2\beta}{128\pi^3 v^4_\Phi} \beta_t \left(\frac{m_t^2}{m^2_{\Delta^\pm}}, \frac{m_W^2}{m^2_{\Delta^\pm}} \right)$$

$$\Gamma(\Delta^\pm \to W^\pm Z^*) = \frac{9 g^2 \lambda^2_{\Delta^\pm W^\mp Z}}{128\pi^3 \cos^2\theta_w m_{\Delta^\pm}} \left(\frac{7}{12} - \frac{10}{9}\sin^2\theta_W + \frac{40}{27}\sin^4\theta_W \right) H \left(\frac{m_W^2}{m^2_{\Delta^\pm}}, \frac{m_Z^2}{m^2_{\Delta^\pm}} \right)$$

$$\Gamma(\Delta^\pm \to W^{\pm *} Z) = \frac{9 g^2 \lambda^2_{\Delta^\pm W^\mp Z}}{256\pi^3 m_{\Delta^\pm}} H \left(\frac{m_Z^2}{m^2_{\Delta^\pm}}, \frac{m_W^2}{m^2_{\Delta^\pm}} \right),$$

$$\Gamma(\Delta^\pm \to h W^{\pm *}) = \frac{9 g^2 m_{\Delta^\pm}}{128\pi^3} \lambda^2_{\Delta^\pm h W^\mp} G \left(\frac{m_h^2}{m^2_{\Delta^\pm}}, \frac{m_W^2}{m^2_{\Delta^\pm}} \right),$$

- The uncertainties in the BRs are obtained from CERN Yellow report [arXiv:1307.1347]



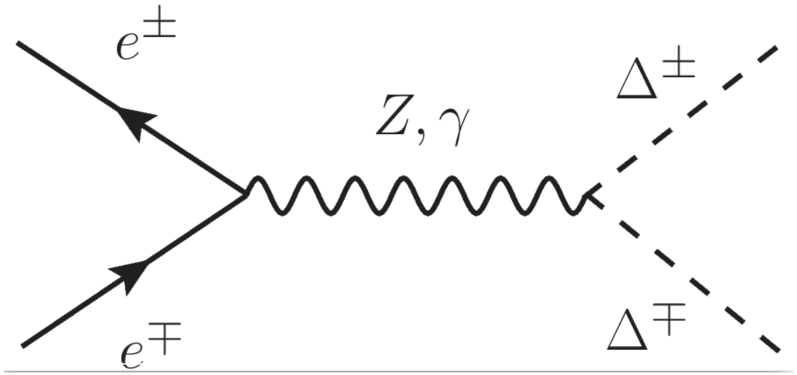
Lepton Colliders

- Serves as Higgs factories, a focused study of the Higgs boson can be done within a relatively pristine environment because of the lesser SM background

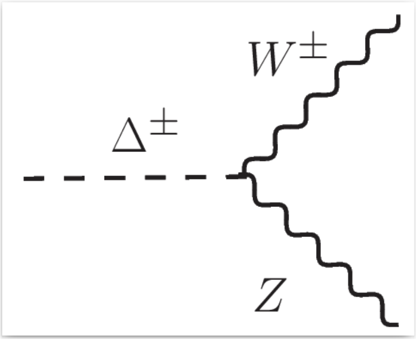
- In case of Lepton collider the collision is free from any pile-up events

- There are various Future proposed lepton colliders, like Circular Electron-Positron Collider (CEPC) [arXiv:2312.14363], Future ee Circular Collider (FCC-ee) [Eur. Phys. J. ST 228, 261 (2019)], International Linear Collider (ILC) [arXiv:2203.07622], the Compact LInear Collider (CLIC) [arXiv:2503.24168]

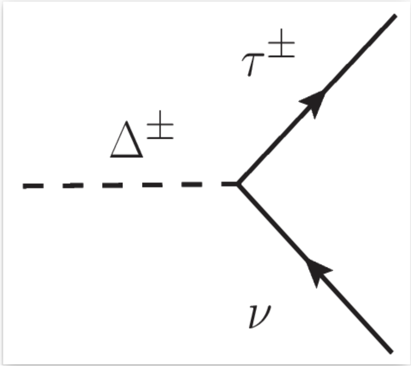
Analysis



Production of charged scalar



Further the W, Z decays to leptons or jets



$\tau^{\pm}$ can be detected as leptonic as well as hadronic

Depending upon the above important decay modes we grouped our analysis in 3 SRs

Analysis

- We consider the pair production of $\Delta^+\Delta^-$ at e^+e^- collider at COM 350 GeV

- Considering various decay modes of $\Delta^\pm$, the analysis is defined in 3 Signal regions.

1) SR1: $\geq 3j + 1\ell$
2) SR2: $\geq 3\ell + \tau_{had}$
3) SR3: $\geq 4j + \tau_{had}$

$$p_T^j > 20 \text{ GeV}, \ |\eta^j| < 2.5, \ E^j > 5 \text{ GeV}$$

$$p_T^\ell > 10 \text{ GeV}, \ |\eta^\ell| < 2.5, \ E^\ell > 5 \text{ GeV}$$

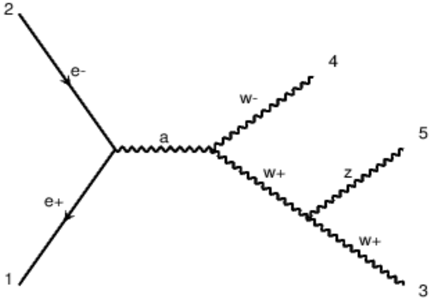
Basic physics object selection requirement

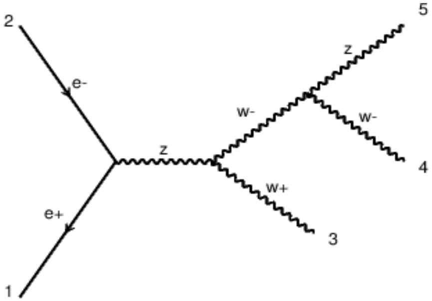
- We consider Madgraph for event generation, Pythia for showering and hadronisation and Delphes for detector effect.

SM Backgrounds

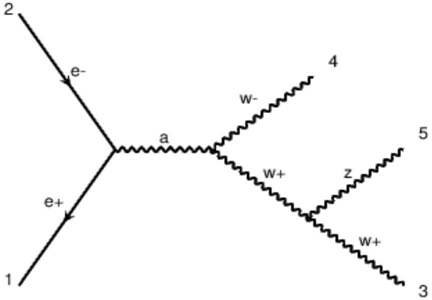
Feynman diagrams for different SRs

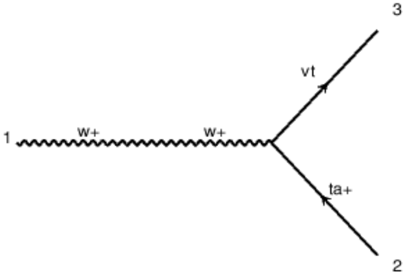
BG for SR1





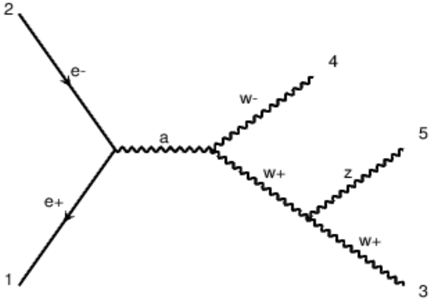
BG for SR2

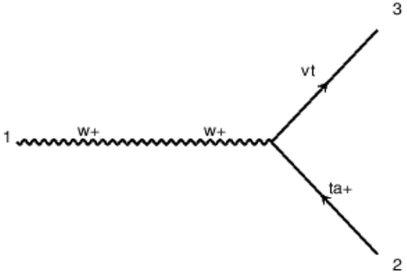




Other W,Z decay to 3 leptons

BG for SR3

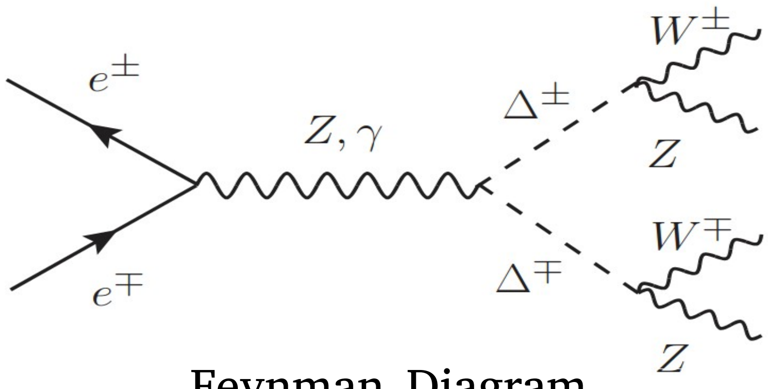




Other W,Z decay 4 jets

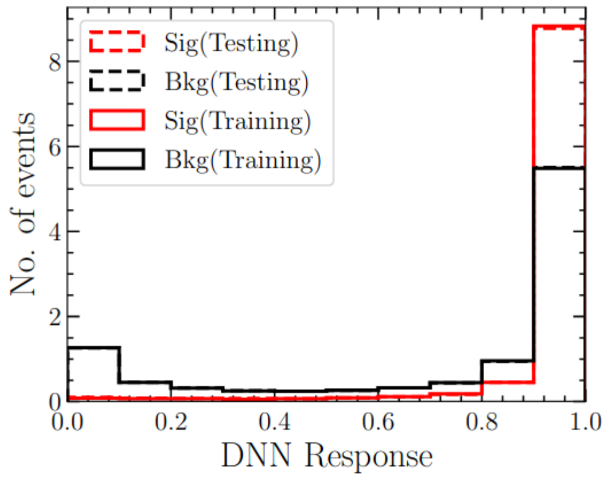
SR1:

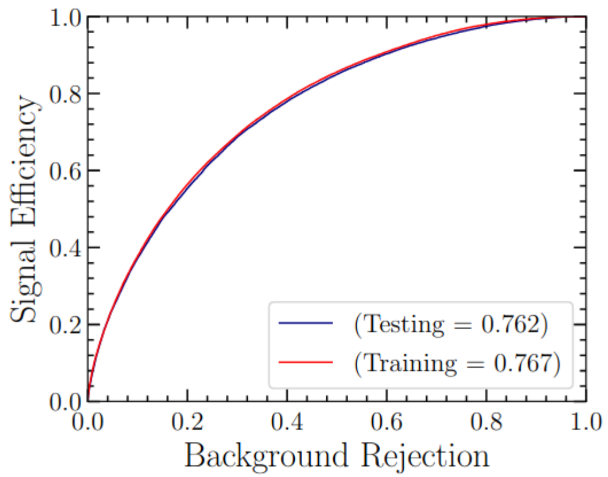
- Considered all possible final state from the produced W and Z.
- To maximize the signal over background ratio, we focus on the final state with at least 3j and 1ℓ



Feynman Diagram

- Dominant background: VV and VVV where V = W, Z and h



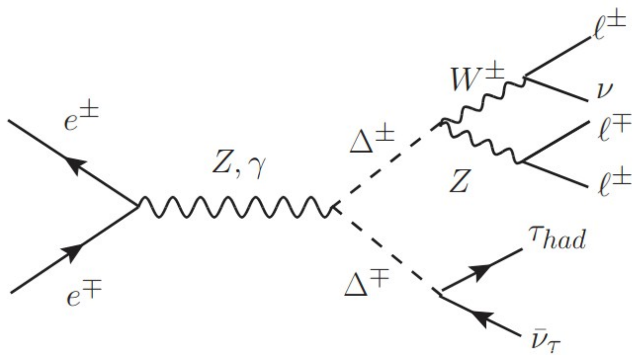


Cut-flow

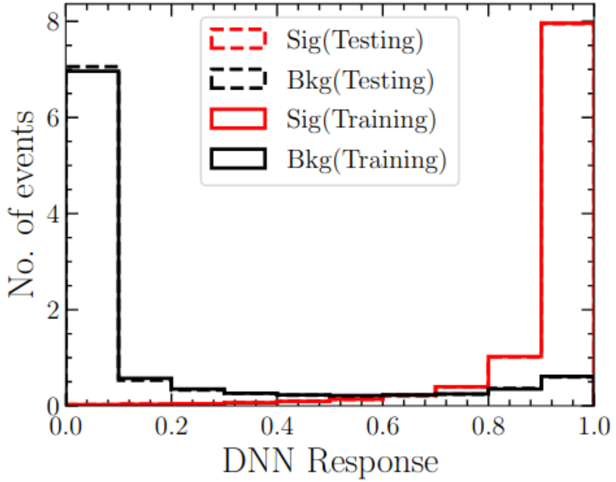
Process	$\geq 3j + 1\ell$	DNN Response > 0.6
Signal	29.193 fb	5.65 fb
VV	17.579 fb	0.279 fb
VVV	0.5068 fb	0.0823 fb

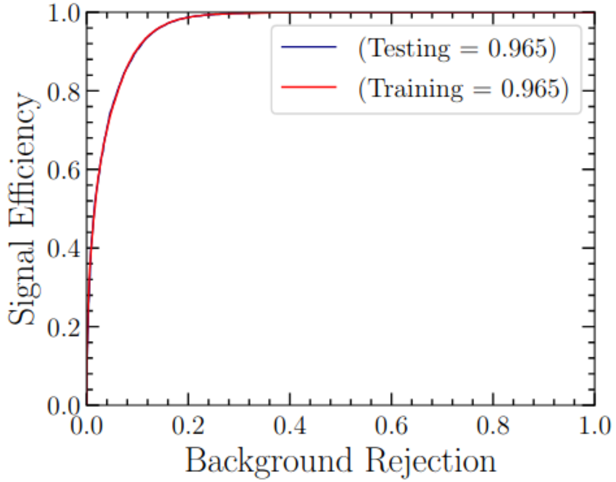
SR2:

- In this SR one of the $\Delta^{\pm}$ decays to WZ and further leptonically, and the other $\Delta^{\mp}$ decays to $\tau\nu$ final state.
- Since we tag the hadronic tau, the SR is named as $3\ell + \tau_{had}$



Feynman Diagram



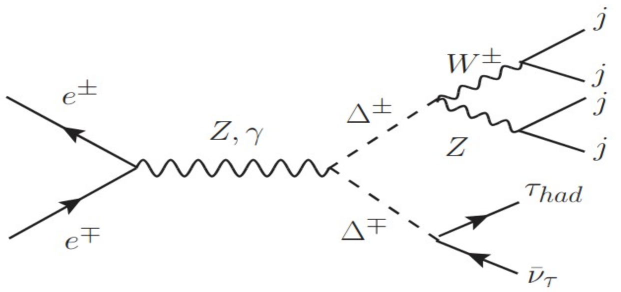


<u>Cut-flow</u>

Process	$\geq 3\ell + \tau_{\rm had}$	DNN Response > 0.7
Signal	0.0154 fb	0.0036 fb
VV $\tau\nu$	0.006 fb	0.0002 fb

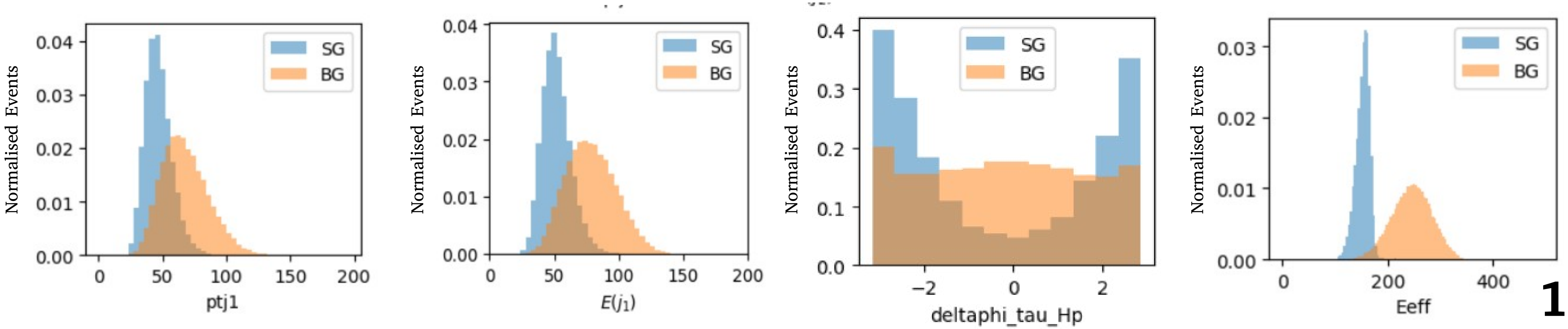
SR3:

- In this SR one of the $\Delta^{\pm}$ decays to WZ and further hadronically, and the other $\Delta^{\mp}$ decays to $\tau\nu$ final state.
- Since we tag the hadronic tau, the SR is named as 4j$+\tau_{had}$



Feynman Diagram

- For this SR we have not performed any DNN analysis since in this SR the charged higgs can be reconstructed and has a significant discrimination from BG.



SR3:

Cut-flow

Cuts	Signal [fb]	Background [fb]
$p_T(j_1) > 80$ GeV	0.2654	1.0146
$p_T(j_2) > 70$ GeV	0.2654	0.9928
$p_T(j_3) > 60$ GeV	0.2654	0.9855
110 GeV $> m_{H^\pm} >$ 170 GeV	0.2384	0.2931
$\lvert\Delta\phi(\tau_j, H^\pm)\rvert < 1.0$ rad	0.2141	0.1895
$\lvert\Delta\phi(W \text{ or } Z, H^\pm)\rvert > 2.0$ rad	0.2107	0.1737
$E_{eff} > 180$ GeV	0.2102	0.0275

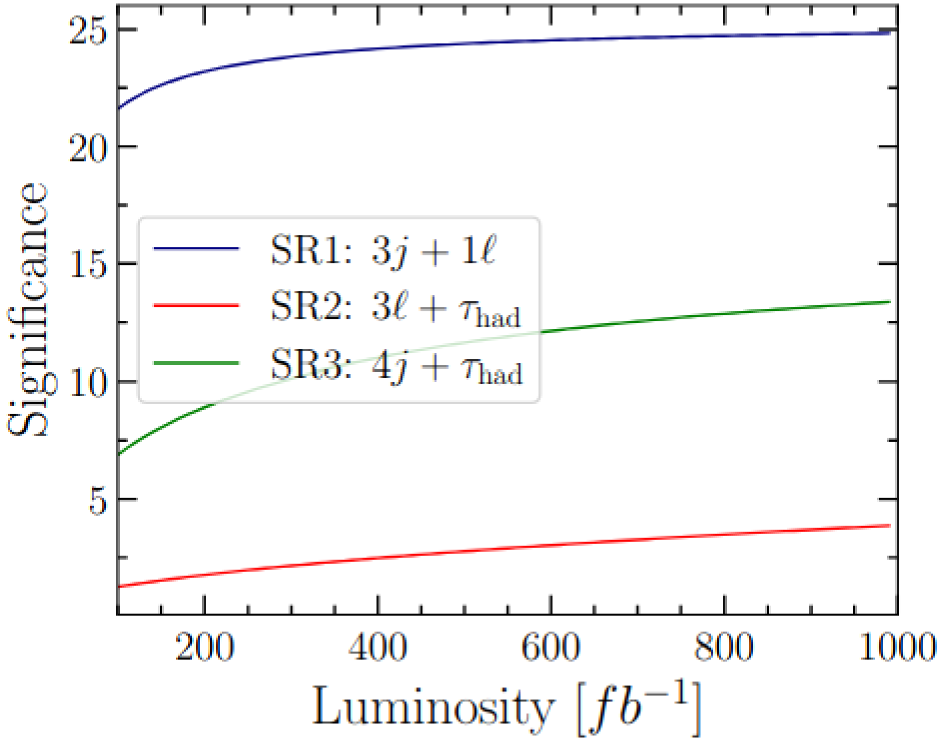
$$Z_{\rm dis} = \left[2\left((s+b)\ln\left[\frac{(s+b)(b+\delta_b^2)}{b^2+(s+b)\delta_b^2}\right] - \frac{b^2}{\delta_b^2}\ln\left[1+\frac{\delta_b^2 s}{b(b+\delta_b^2)}\right]\right)\right]^{1/2},$$

Results:

- Using the mentioned significance formula, obtained the discovery significance of all the Srs

- We found that SR1 is the most sigificant channel to look for the $\Delta^{\pm}$ in the proposed lepton collider.

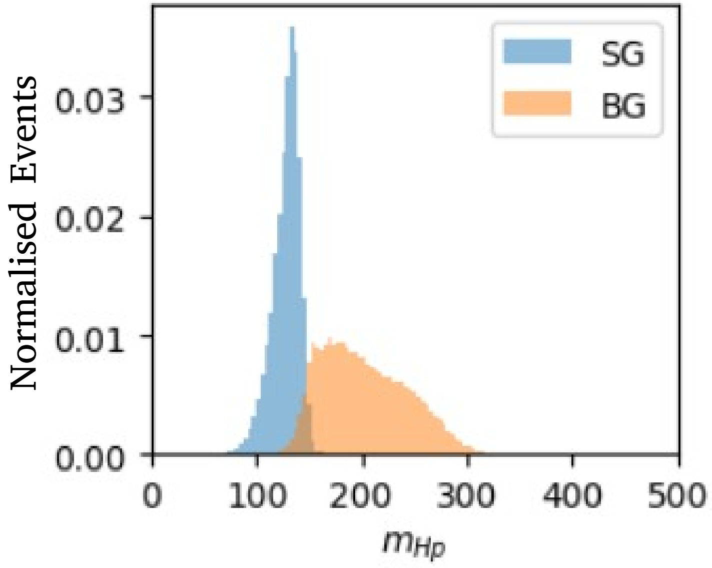
- Since in SR3, we can reconstruct one of $\Delta^{\pm}$, without performing any DNN we are still getting good result.



Significance vs Luminosity

Conclusion

- We conclude that the proposed lepton collider can be a usefull place to look for the expected 152 GeV scalar.
- SR1 is the most significant channel to look for the BSM scalar
- SR3 will be the most important channel to discover the BSM scalar, since in this signal region we can reconstruct the scalar.



Thanks for the Attention