

Analysis of Higgs production in the VBF-VH channel at the LHC

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Collaboration of . . .

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Introduction

⇒ **Tree-level Interference in VBF production of Vh** : [arXiv:2203.05729](https://arxiv.org/abs/2203.05729)
C. Paranjape, D. Stolarski, Y. Wu

- Propose to probe the Higgs couplings to vector bosons



- We only measure rates of the tree level processes $h \rightarrow ZZ^*$, $h \rightarrow WW^*$ without interference effects, which are proportional to square of couplings

$$|\mathcal{M}_{hZZ}|^2 \sim \kappa_Z^2$$

$$|\mathcal{M}_{hWW}|^2 \sim \kappa_W^2$$

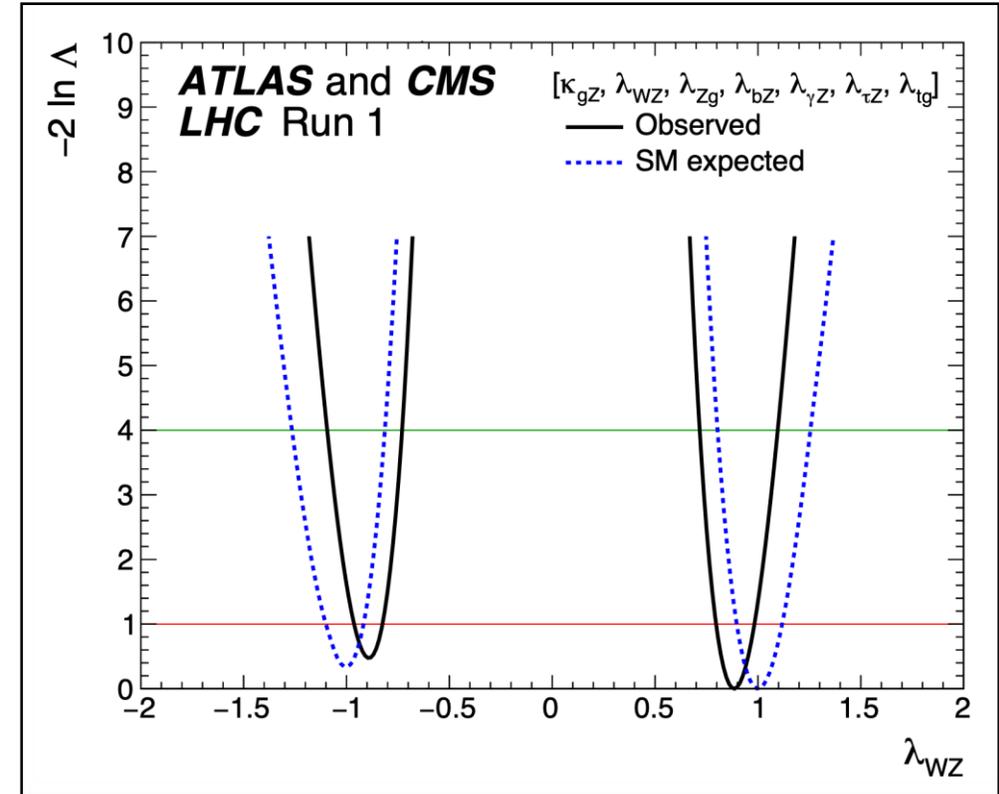
Introduction

- Thus, measuring λ_{WZ} with these couplings will have almost no discriminating power between positive and negative values of λ_{WZ} .

$$\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$$

$$\lambda_{WZ}^2 = \frac{\kappa_W^2}{\kappa_Z^2} \sim \frac{|\mathcal{M}_{hWW}|^2}{|\mathcal{M}_{hZZ}|^2}$$

- \implies Gives rise to the need of analysing processes with Interference effects
- \implies VBF-VH channel



ATLAS + CMS, arXiv:1606.02266.

D.Stolarski and Y. Wu, arXiv:2006.09374.

Signal Process

signal : $p p \rightarrow z h j j$ QCD=0, $h \rightarrow b b^{\sim}$, $z \rightarrow l^- l^+$

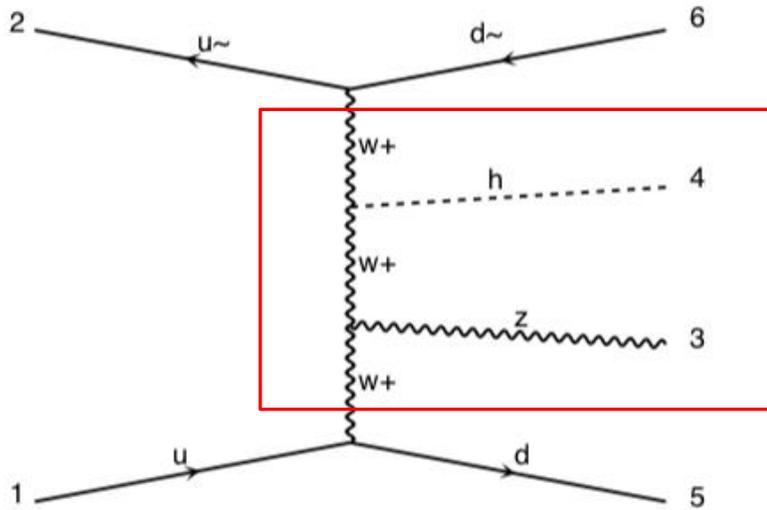


diagram 10 QCD=0, QED=4

$$\sim |\mathcal{M}_{hWW}|^2 \sim \kappa_W^2$$

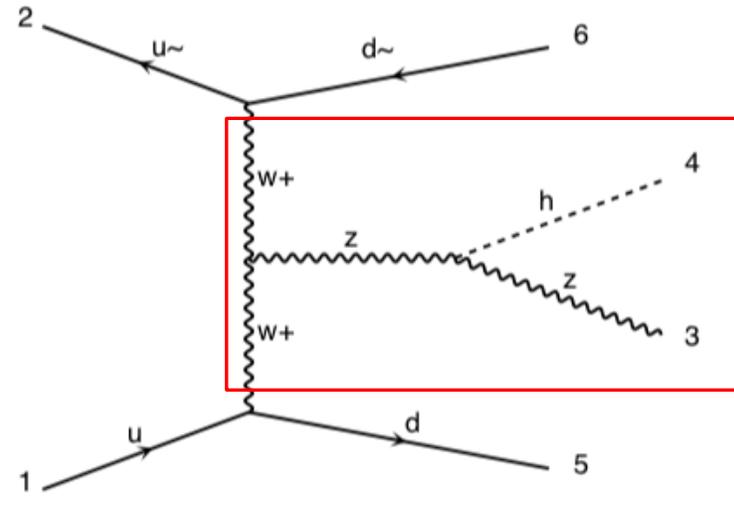


diagram 12 QCD=0, QED=4

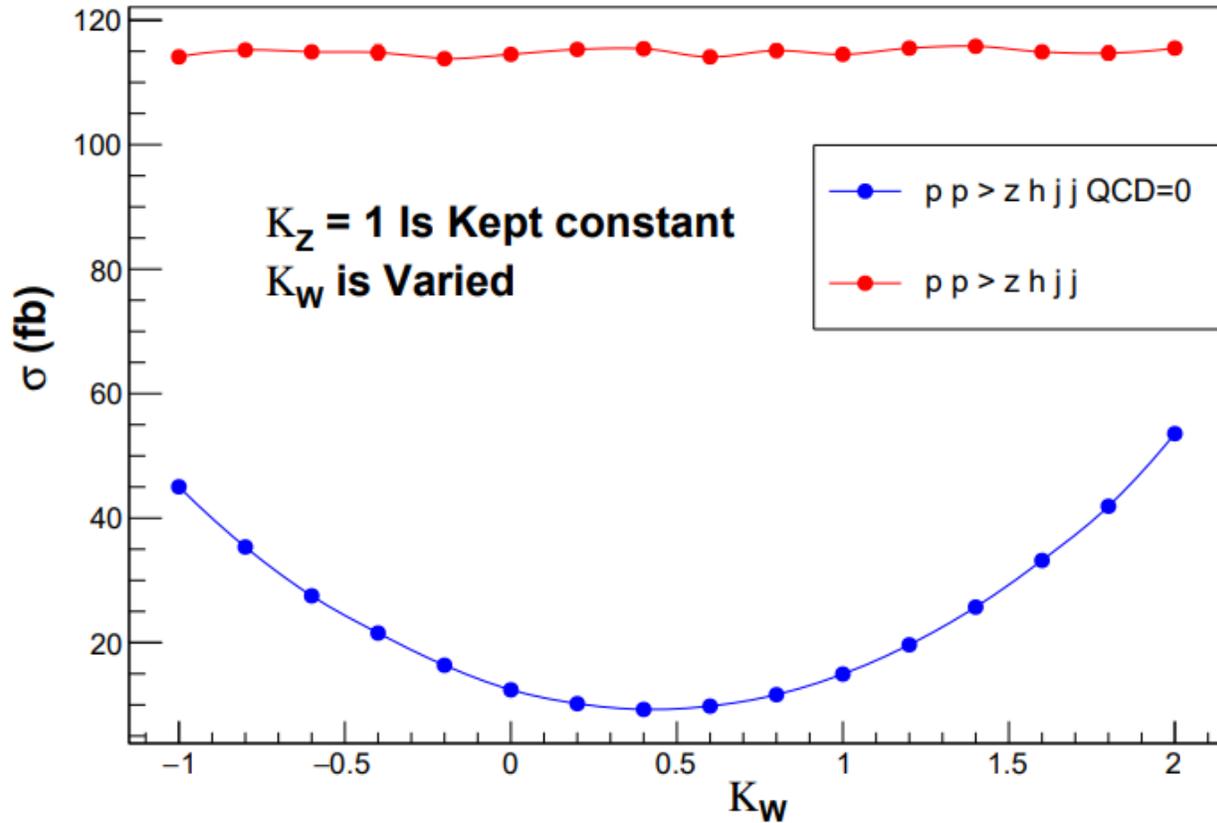
$$\sim |\mathcal{M}_{hZZ}|^2 \sim \kappa_Z^2$$

\implies Intefereance term $\sim \mathcal{M}_{hWZ}^2 \sim \kappa_W \cdot \kappa_Z$

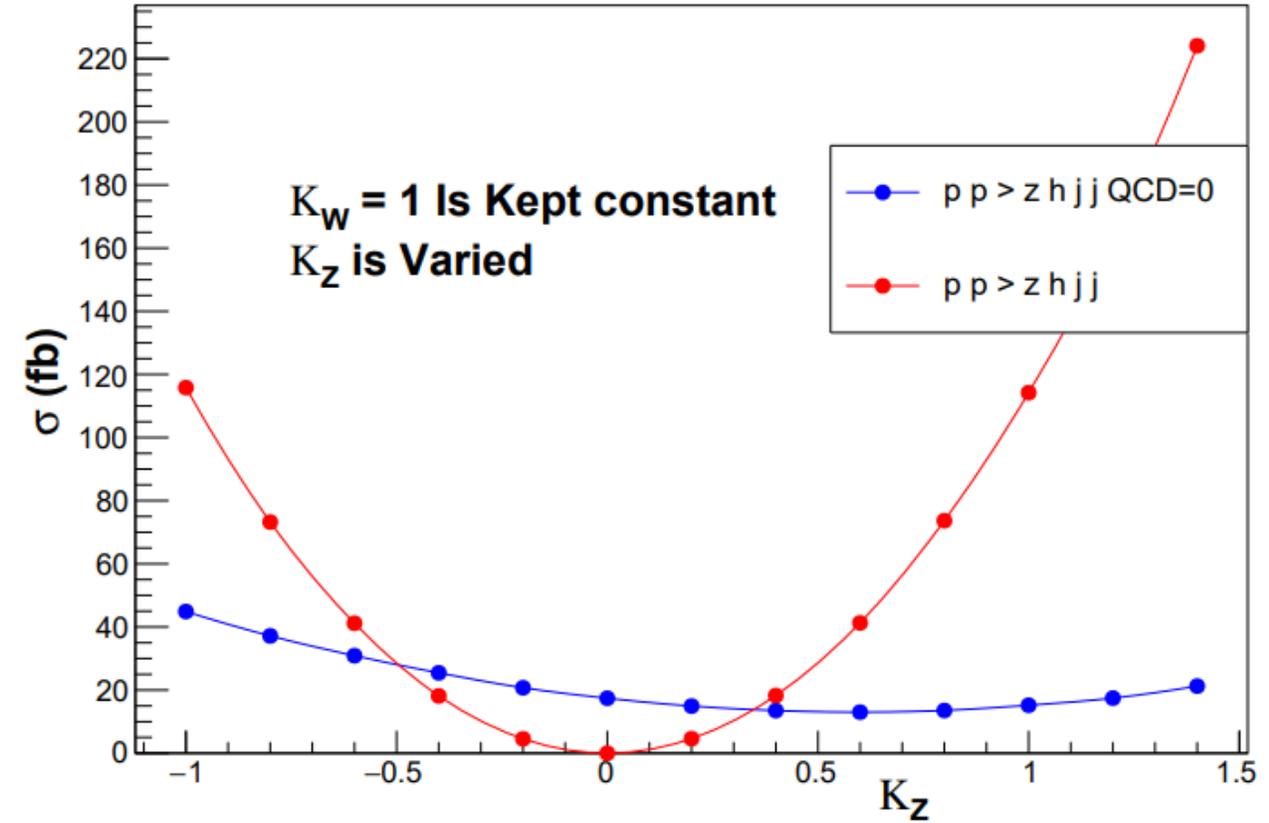
$$\implies |\mathcal{M}|^2 = \kappa_W^2 |\mathcal{M}_{hWW}|^2 + \kappa_W \kappa_Z \mathcal{M}_{hWZ}^2 + \kappa_Z^2 |\mathcal{M}_{hZZ}|^2$$

Variation with κ_W, κ_Z

Raw signal (Blue) VS Raw bcg1 (Red)



Raw signal (Blue) VS Raw bcg1 (Red)



- Cross-sections for the raw signal (C_1) and raw bcg1 (C_2) can be modeled as :

$$C_1 \sim (17.41 \text{ fb}) \cdot \kappa_W^2 - (14.755 \text{ fb}) \cdot \kappa_W \kappa_Z + (12.41 \text{ fb}) \cdot \kappa_Z^2 \quad C_2 \sim (114.2 \text{ fb}) \cdot \kappa_Z^2$$

All processes

Signal : $p p \rightarrow z h j j$ QCD=0, $h \rightarrow b b^{\sim}$, $z \rightarrow l^- l^+$ 0.9104 fb

QCD-VH : $p p \rightarrow z h j j$, $h \rightarrow b b^{\sim}$, $z \rightarrow l^- l^+$ 1.916 fb

$t \bar{t}$: $p p \rightarrow t t^{\sim}$, ($t \rightarrow w^+ b$, $w^+ \rightarrow e^+ \nu_l$) , ($t^{\sim} \rightarrow w^- b^{\sim}$, $w^- \rightarrow e^- \nu_l^{\sim}$) 5313.0 fb
 $p p \rightarrow t t^{\sim}$, ($t \rightarrow w^+ b$, $w^+ \rightarrow \mu^+ \nu_l$) , ($t^{\sim} \rightarrow w^- b^{\sim}$, $w^- \rightarrow \mu^- \nu_l^{\sim}$)

$Z b \bar{b}$: $p p \rightarrow z b b^{\sim} j j$, $z \rightarrow l^- l^+$ 1113.0 fb

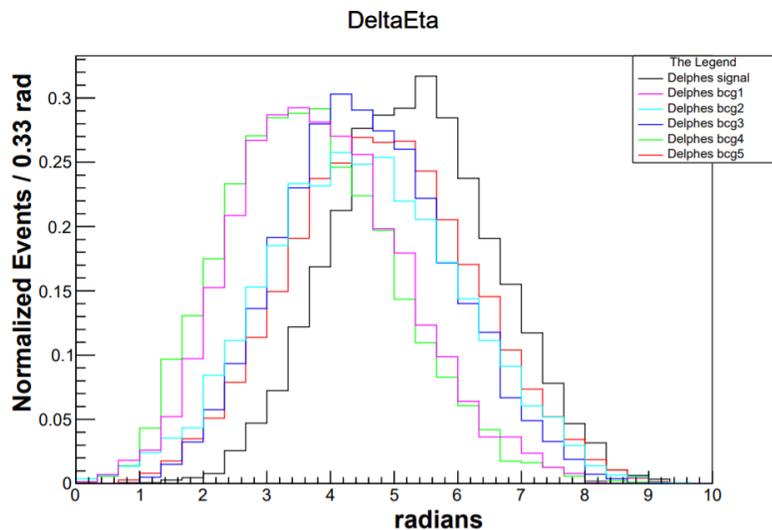
*Some event generation conditions are imposed

Initial cuts

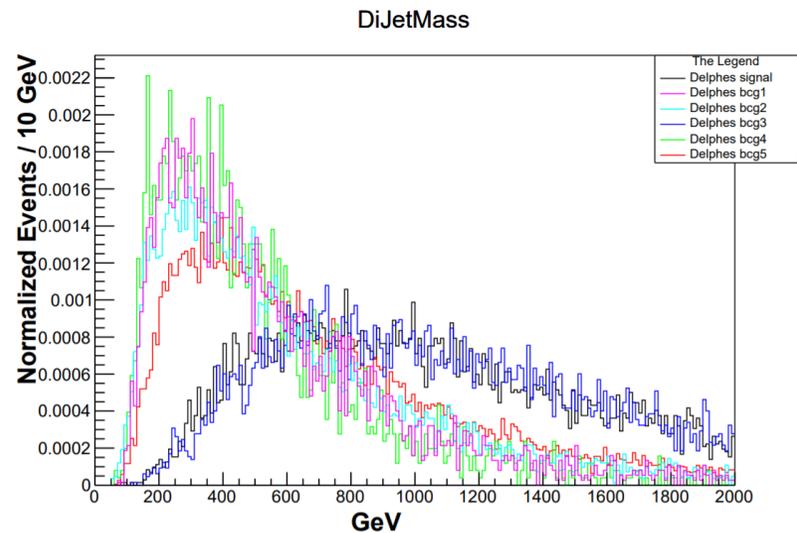
- At least one forward-backward jet pair must exist
- Number of MasterJets ≥ 4
- Number of Delphes B-tagged Jets ≥ 2
- Number of VBF-B-Jets $== 0$
- Invariant mass of the detected OSSF Lepton pair⁸ $\in (81\text{GeV}, 101\text{GeV})$

*VBF-Tagging Jet pair : a forward-backward jet pair with highest invariant mass of all such pairs

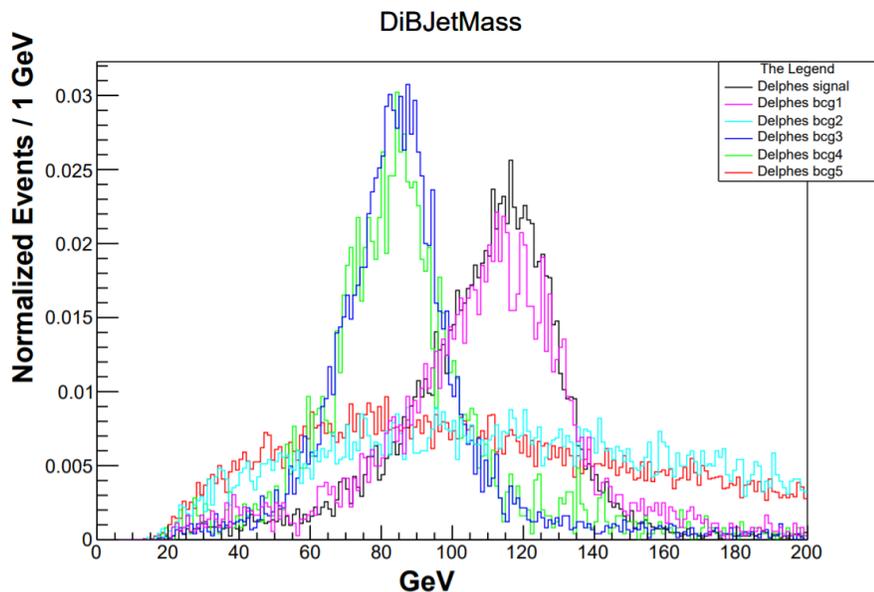
*MasterJet : A jet satisfying $p_T \geq 20 \text{ GeV}$ AND $|\eta| \leq 5$



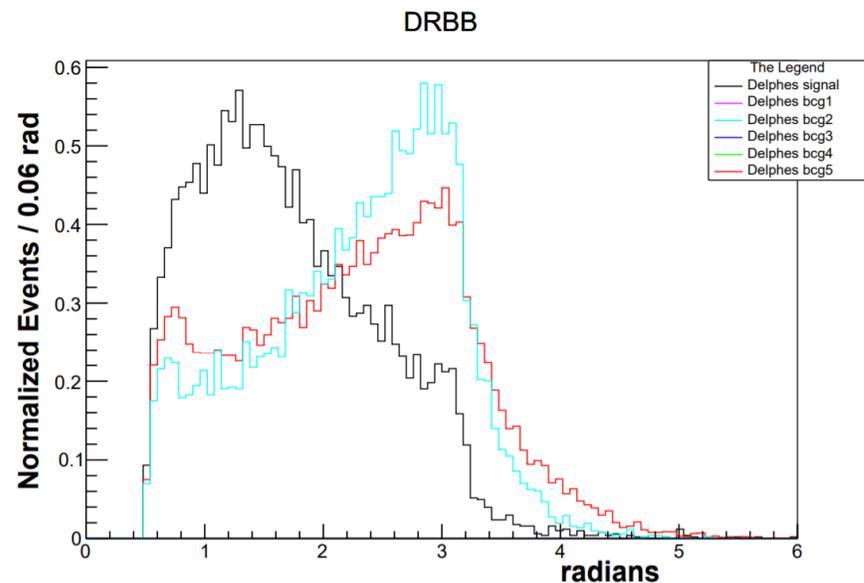
DeltaEta $|\eta_{\text{VBF}}|$: Absolute pseudo-rapidity difference between the two VBF-Tagging jets



DiJetMass : Invariant mass of the two VBF-Tagging jets



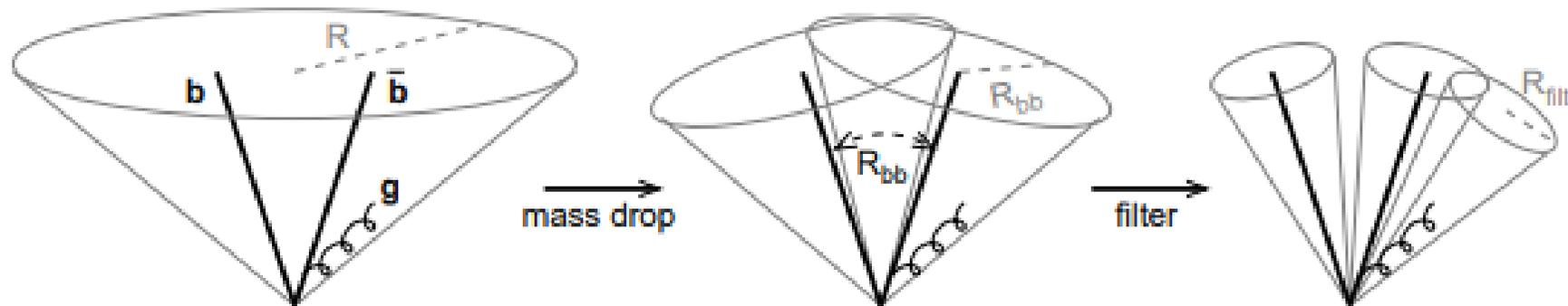
DiBJetMass : Invariant mass of the two Delphes B-Tagged jets



$$\Delta R_{b\bar{b}} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

Boosted-Higgs search

- We employ the *BDRS algorithm for boosted Higgs search
- Use FastJet analysis framework for this purpose, with (E, \vec{p}) data of detected particles from Delphes



*arXiv:0802.2470

Event yields

The event yield (Y) for any process is given by,

$$\mathcal{L} = 3000 \text{ fb}^{-1}$$

$$Y = \mathcal{L} \cdot C_X \cdot \frac{\text{Number of Events selected}}{\text{Total number of Events Simulated}}$$

$$\text{Yield-error} = \sqrt{\frac{Y^2}{\text{Number of Events selected}}}$$

Process	MC selection efficiency	# events (3,000 fb ⁻¹)
Signal	503 /100k	6.23 ± 0.28
$Zb\bar{b}jj$	9 /700k	42.93 ± 14.31
$t\bar{t}$	3 /5M	9.56 ± 5.52

TABLE I: Monte Carlo selection efficiency with the number of events generated in the denominator

Contour plots over (κ_W, κ_Z) plane

- We fix the analysis in the SM ($\kappa_W = \kappa_Z = 1$) with final cuts described as before.
- Proceed to run the analysis over multiple set of (κ_W, κ_Z) points and produce the contour plots for the deviation from the expected SM behaviour.

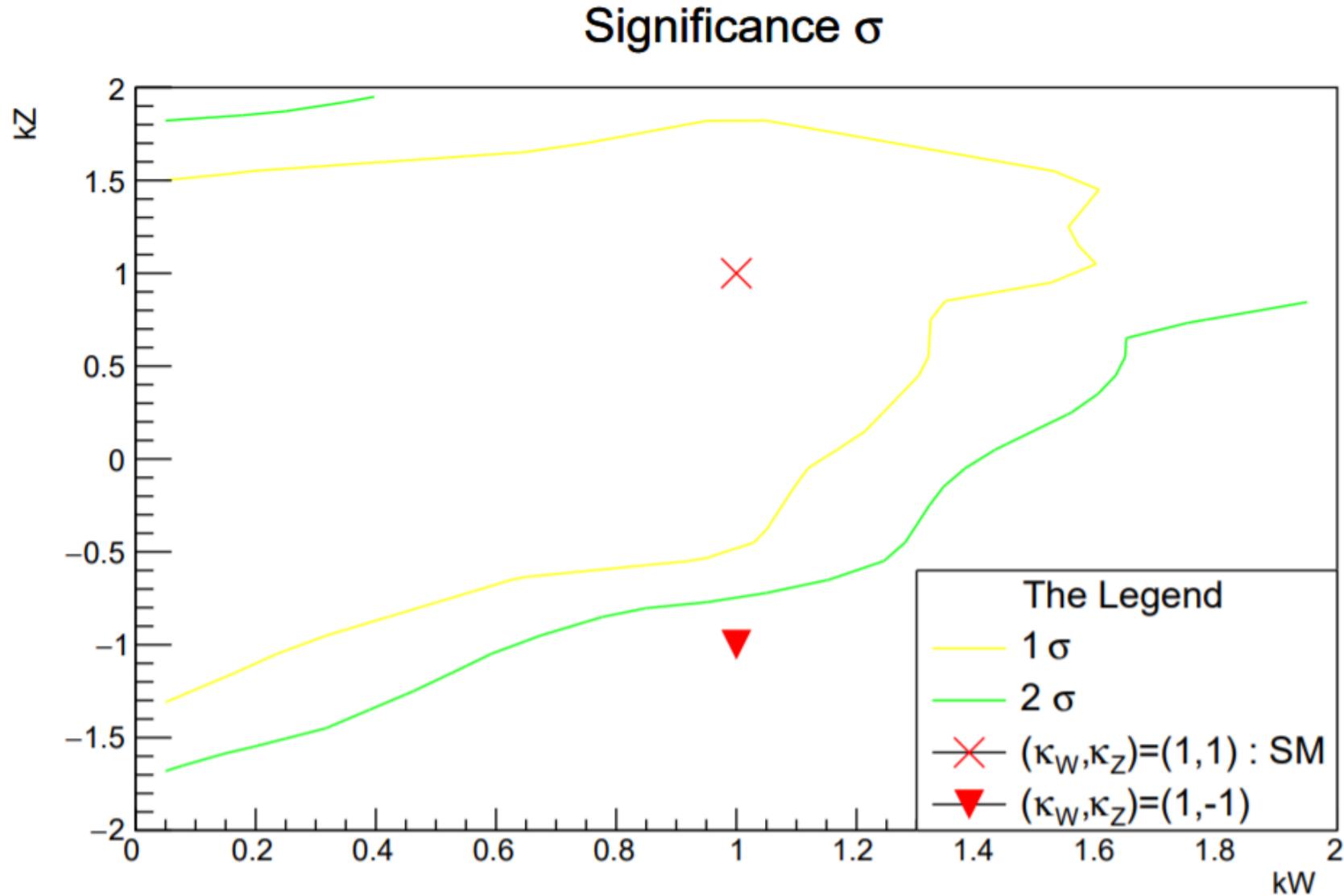
$$\sigma = \frac{|A(\kappa_W, \kappa_Z) - A_{SM}|}{\sqrt{A_{SM} + (\beta \cdot A_{SM})^2}}$$

Where $A = S + B$ is the total yield at the corresponding point.

Signal cross-section behaviour with $\sim \kappa_W, \kappa_Z$

$$C_s(\kappa_W, \kappa_Z) = (14.41 \text{ fb}) \cdot \kappa_W^2 - (12.147 \text{ fb}) \cdot \kappa_W \kappa_Z + (8.367 \text{ fb}) \cdot \kappa_Z^2$$

Contour plots over (κ_W, κ_Z) plane



Future high energy lepton collider

⇒ **Tree-level Interference in VBF production of Vh** : [arXiv:2006.09374](https://arxiv.org/abs/2006.09374)
D. Stolarski, Y. Wu

$$e^+ e^- \rightarrow \nu_e \bar{\nu}_e Z h,$$

$$e^+ e^- \rightarrow \nu_e e W h.$$

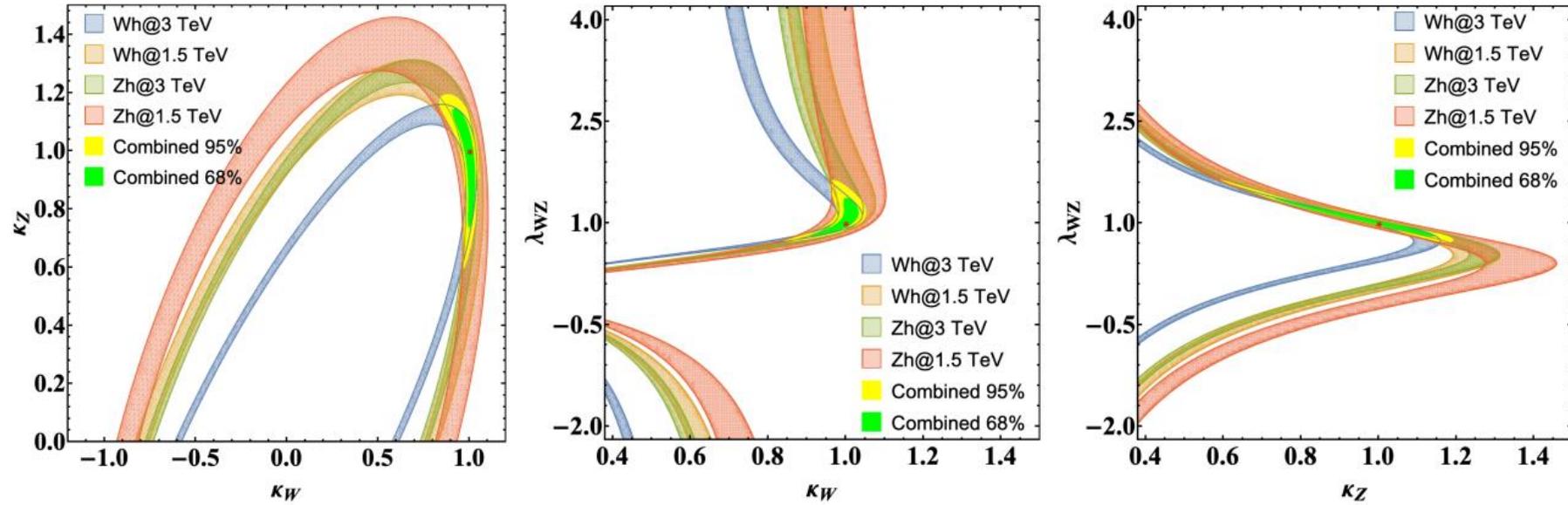
⇒ **Signal to background ratio is significantly higher than at the LHC**

- Analysis with the CLIC e^+e^- machine as a benchmark,
⇒ Applicable to high energy muon collider.

$$\sigma_{\text{total}} = \kappa_W^2 \sigma_W + \kappa_W \kappa_Z \sigma_{WZ} + \kappa_Z^2 \sigma_Z.$$

- Exploiting the strong destructive interference between W & Z mediated contributions σ_{WZ} dominating over σ_W, σ_Z

Future high energy lepton collider



Benchmark	$\sqrt{s} = 3.0 \text{ TeV}$	$\sqrt{s} = 1.5 \text{ TeV}$
$\kappa_W = \pm 1, \kappa_Z = \mp 1$	3.4 fb^{-1}	14.1 fb^{-1}
$\kappa_W = 1, \kappa_Z = 0$	29.3 fb^{-1}	243.3 fb^{-1}
$\kappa_W = 0, \kappa_Z = 1$	62.1 fb^{-1}	1772.4 fb^{-1}

Concluding remarks

- Possible to exclude the $(\kappa_W, \kappa_Z) = \pm(1, -1)$ point with more than 95% (2σ) CL limit at the HL-LHC, with the proposed VBF-ZH analysis.
- Analysis with the CLIC 3 TeV at 3.4 fb^{-1} or 1.5 TeV at 14.1 fb^{-1} can exclude the same point at 95% CL with respect to the SM case.
- \implies Provides a direction to measure the sensitivity of the relative sign between the Higgs couplings to vector bosons at the HL-LHC or a future high energy lepton collider.

Thank you for listening!

Questions?

Extra slides

Semi-final cuts

Initial cuts +

- $\Delta\eta \geq 4 : (|\eta_{\text{VBF}}| \geq 4)$
- $\text{DiJetMass} \geq 1000 \text{ GeV}$
- $\text{DiBJetMass} \in (110 \text{ GeV}, 130 \text{ GeV})$
- $\text{DRBB} \leq 2 : (\Delta R_{b\bar{b}} \leq 2)$
- $\text{missingET} < 50 \text{ GeV}$
- $\text{PT-Jet1}^{11} \geq 100 \text{ GeV}$
- $\text{PT-Jet2} \geq 70 \text{ GeV}$
- $\text{PT-Jet3} \geq 50 \text{ GeV}$
- $\text{PT-B-Jet1}^{12} \geq 55 \text{ GeV}$
- $\text{PT-B-Jet2} \geq 55 \text{ GeV}$

FastJet analysis

- Events selected with semi-final cuts are reconstructed again in FastJet with Anti-kt algorithm and $R = 0.5$ to remove the VBF-Jet constituents and isolated leptons.
- On the remaining particles, apply jet reconstruction with Cambridge-Aachen Algorithm with $R = 2.0$.
- Obtain the leading jet in p_T and apply Mass drop tagger with $\mu = 0.667$ & $y_{cut} = 0.09$
- Invariant mass of the two tagged pieces is the reconstructed Higgs mass : H_{mass}
- $H_{mass} \in (110 \text{ GeV}, 130 \text{ GeV})$

Final cuts

- At least one forward-backward jet pair must exist
- Number of MasterJets ≥ 4
- Number of Delphes B-tagged Jets ≥ 2
- Number of VBF-B-Jets == 0
- Invariant mass of the detected OSSF Lepton pair $\in (81\text{GeV}, 101\text{GeV})$
- DeltaEta $\geq 4 : (|\eta_{\text{VBF}}| \geq 4)$
- DiJetMass $\geq 1000 \text{ GeV}$
- DRBB $\leq 2 : (\Delta R_{b\bar{b}} \leq 2)$
- missingET $< 50 \text{ GeV}$
- PT-Jet1 $\geq 100 \text{ GeV}$
- PT-Jet2 $\geq 70 \text{ GeV}$
- PT-Jet3 $\geq 50 \text{ GeV}$
- PT-B-Jet1 $\geq 55 \text{ GeV}$
- PT-B-Jet2 $\geq 55 \text{ GeV}$
- DiBJetMass $\in (110 \text{ GeV}, 130 \text{ GeV})$
- Hmass $\in (110 \text{ GeV}, 130 \text{ GeV})$

Significance

- Significance compared with only Delphes analysis

Significance (σ)	Final analysis	Only Delphes analysis
$\frac{S}{\sqrt{B}}$	0.85	0.64
$\frac{S}{B}$	0.12	0.05
$\frac{S}{\sqrt{B+(\beta \cdot B)^2}}$	0.68	0.38

Table 4: Significance comparison between final analysis and only Delphes analysis.

we take $\beta = 0.1(10\%)$

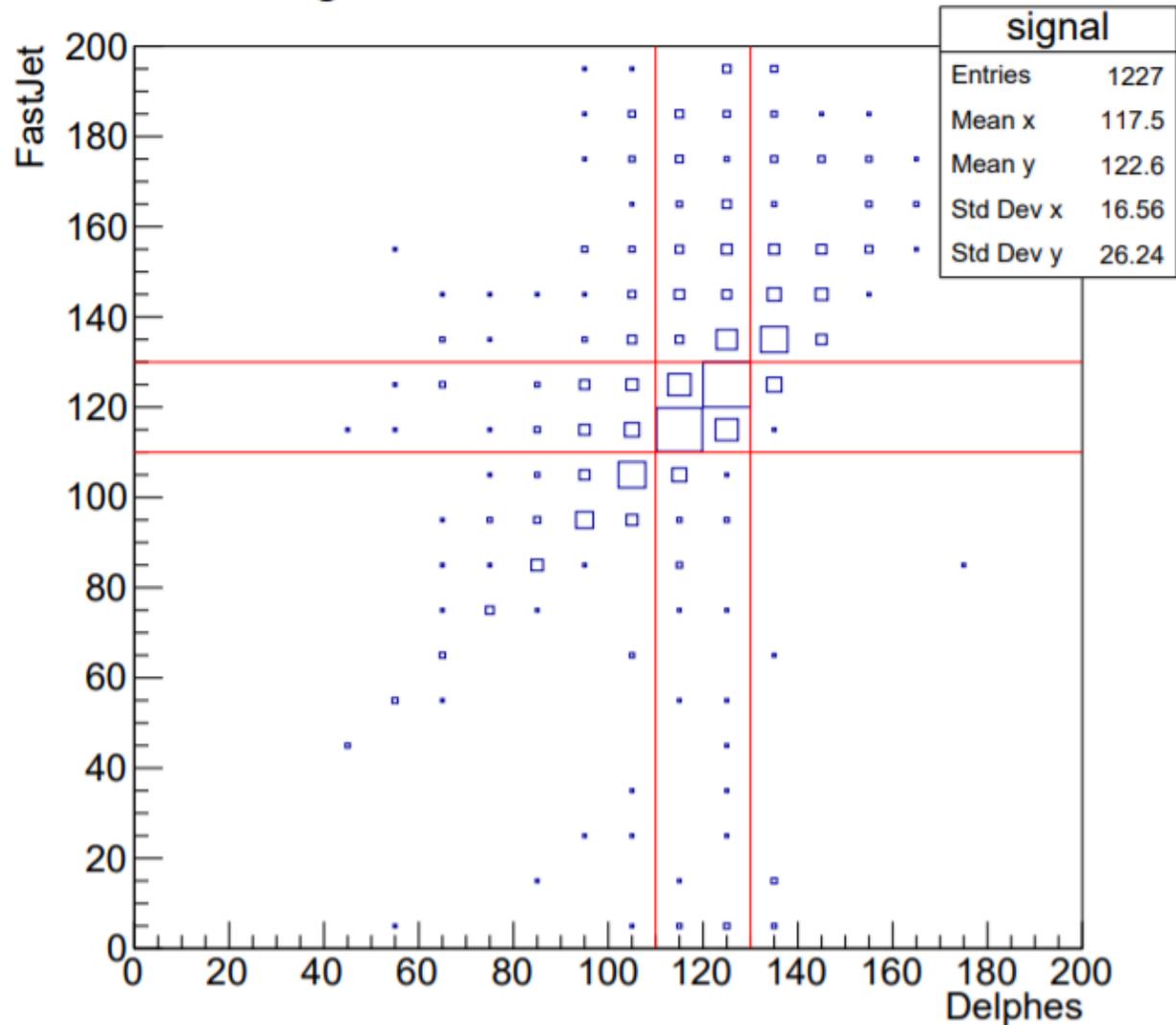
Process	Event selection	Yield
Signal (S)	698 /100k	8.65 ± 0.33
Bcg1 (b_1)	30 /100k	0.79 ± 0.14
Bcg2 (b_2)	4 /5M	12.75 ± 9.01
Bcg3 (b_3)	47 /100k	1.71 ± 0.25
Bcg4 (b_4)	2 /100k	0.52 ± 0.37
Bcg5 (b_5)	35 /700k	166.95 ± 28.22

Table 3: Event yields for all processes, if only Delphes had been employed.

Process	Event selection	Yield
Signal (S)	503 /100k	6.23 ± 0.28
Bcg1 (b_1)	12 /100k	0.32 ± 0.09
Bcg2 (b_2)	3 /5M	9.56 ± 5.52
Bcg3 (b_3)	23 /100k	0.84 ± 0.17
Bcg4 (b_4)	1 /100k	0.26 ± 0.26
Bcg5 (b_5)	9 /700k	42.93 ± 14.31

Table 2: Event yields for all processes, final analysis.

Signal Hmass~DiBJetMass



Bcg5 Hmass~DiBJetMass

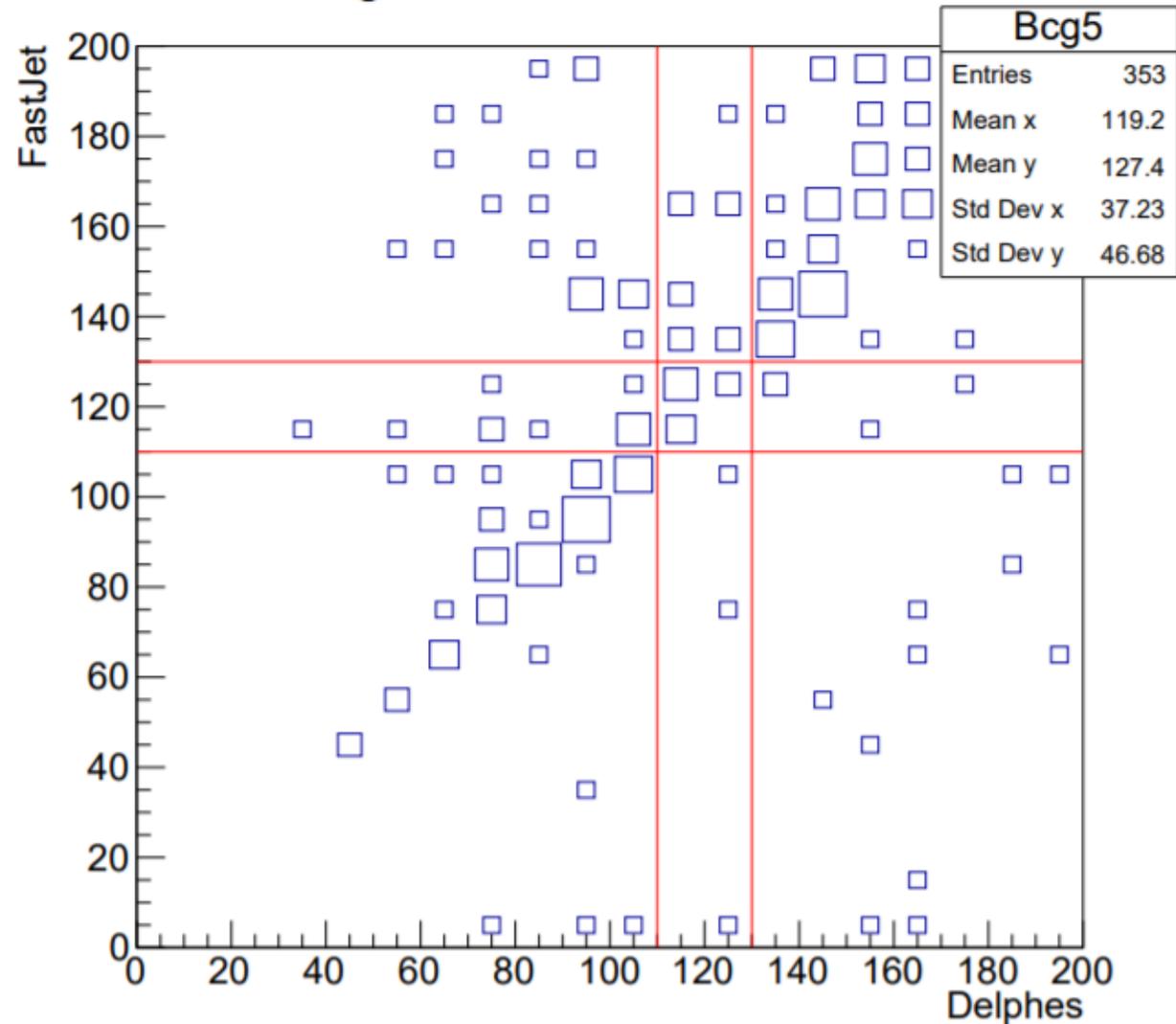


Figure 18: FastJet-Delphes characteristics for signal and bcg5 process : After all but the Hmass-DiBJetMass cuts

Future directions

Additional cuts to further improve the analysis :

- VETO events with an 'Extra' jet with $p_T \geq 30$ GeV AND $|\eta| \leq 2.5$
- Put limiting constraints on the p_T of Z boson.

\implies This was the analysis for VBF-ZH process.

Similarly, conduct an analysis of VBF-WH process for further insights.

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