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

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Collaboration of . . .

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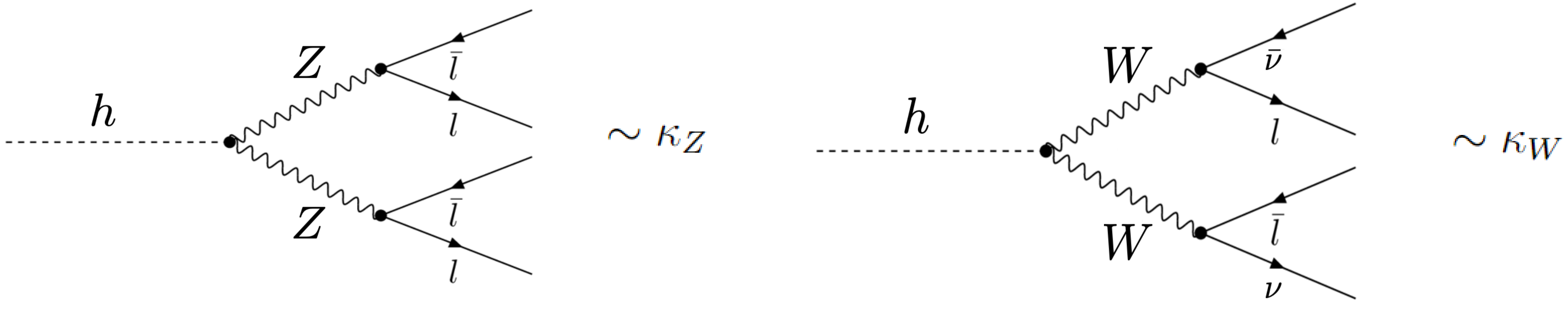
Introduction

- Propose to probe the Higgs couplings to vector bosons



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

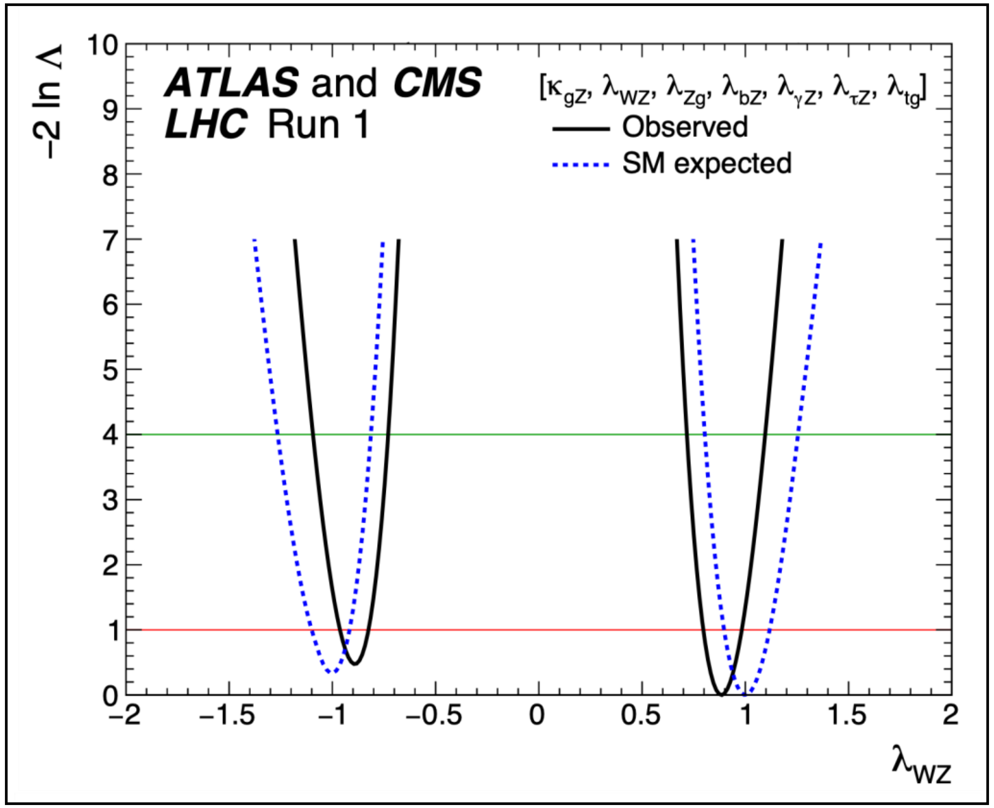
$$|\mathcal{M}_{hZZ}|^2 \sim \kappa_Z^2 \qquad |\mathcal{M}_{hWW}|^2 \sim \kappa_W^2$$

Introduction

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

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

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



- $\Longrightarrow$ Gives rise to the need of analysing processes with Interference effects

- $\Longrightarrow$ VBF-VH channel

ATLAS + CMS, arXiv:1606.02266.

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

Signal Process

- First we need to fix the 'signal' process suiting the VBF-VH channel

```
signal :  p p > z h j j QCD=0, h > b b~, z > l- l+
```

- $\Longrightarrow$ Quantum Interference between different diagrams, thus sensitive to both couplings κ_W & κ_Z

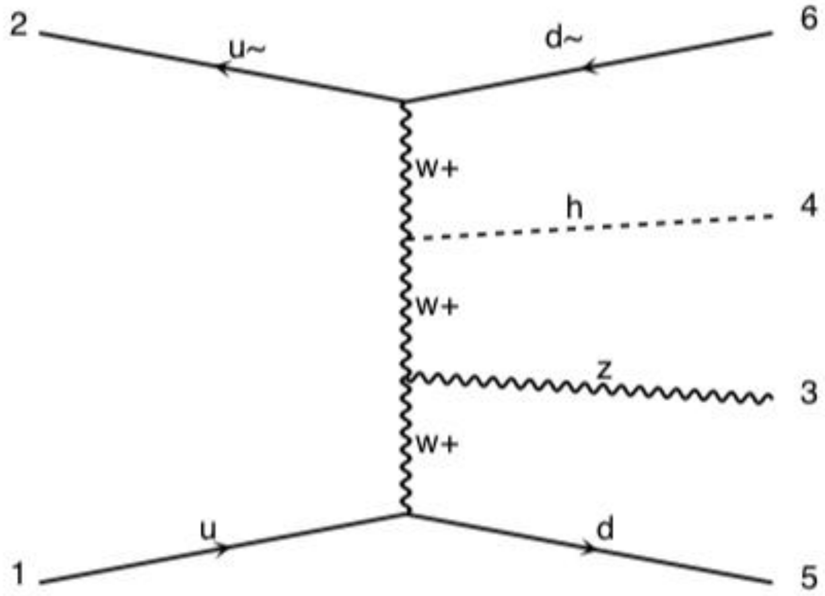


diagram 10 QCD=0, QED=4

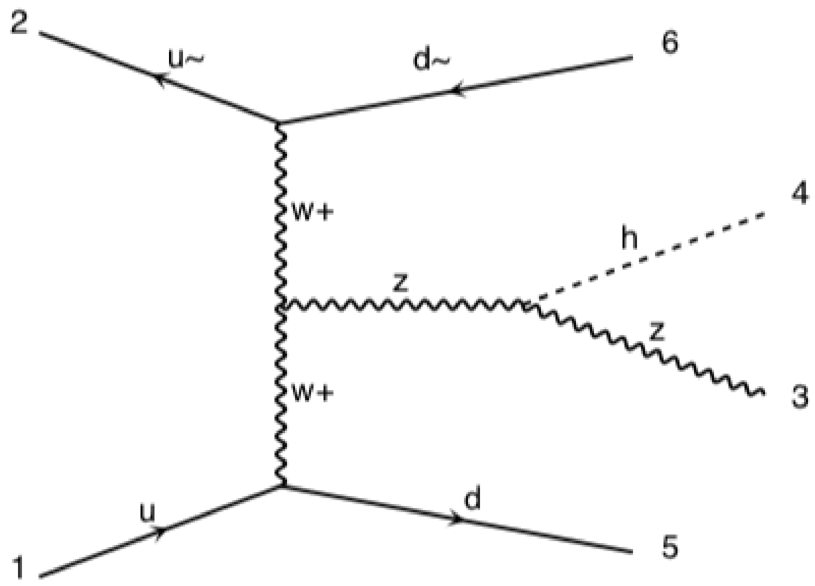


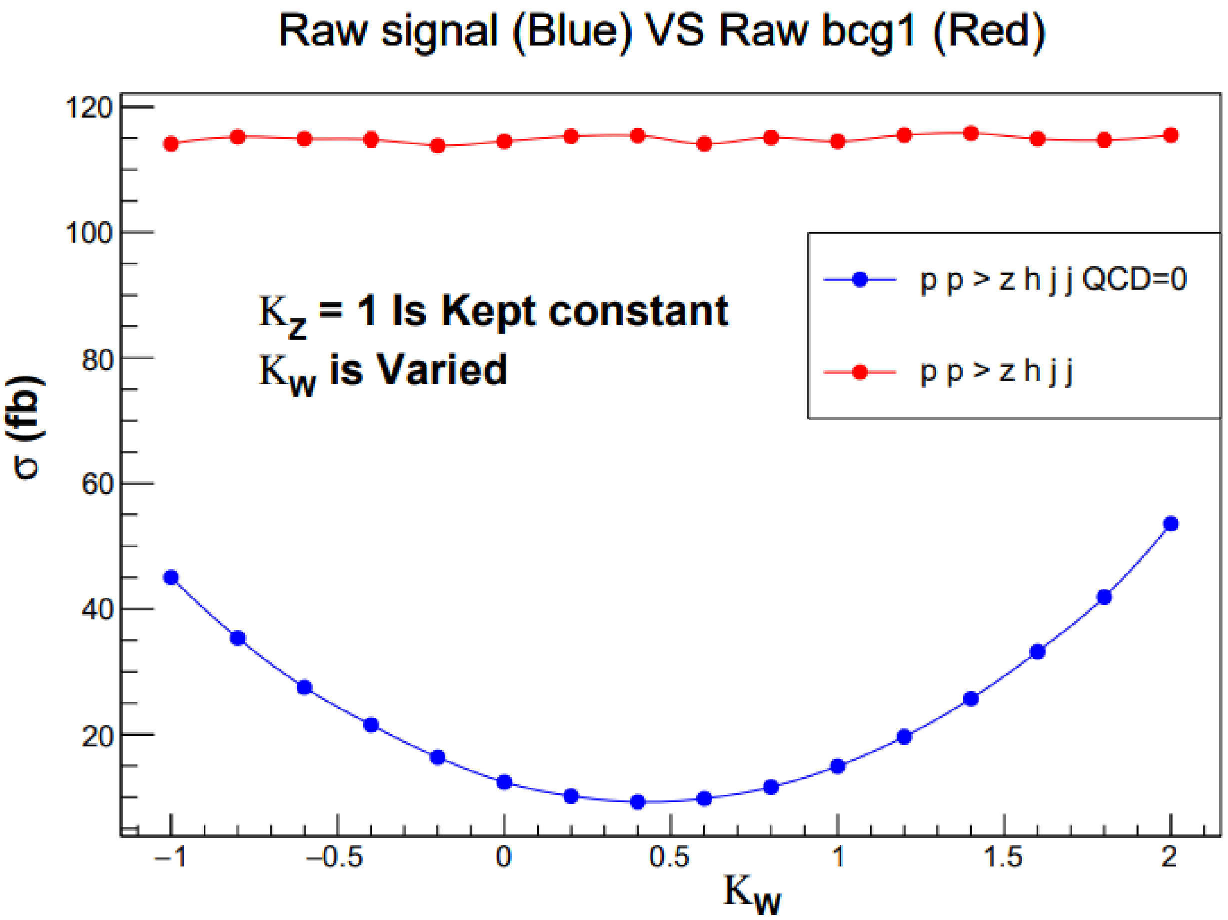
diagram 12 QCD=0, QED=4

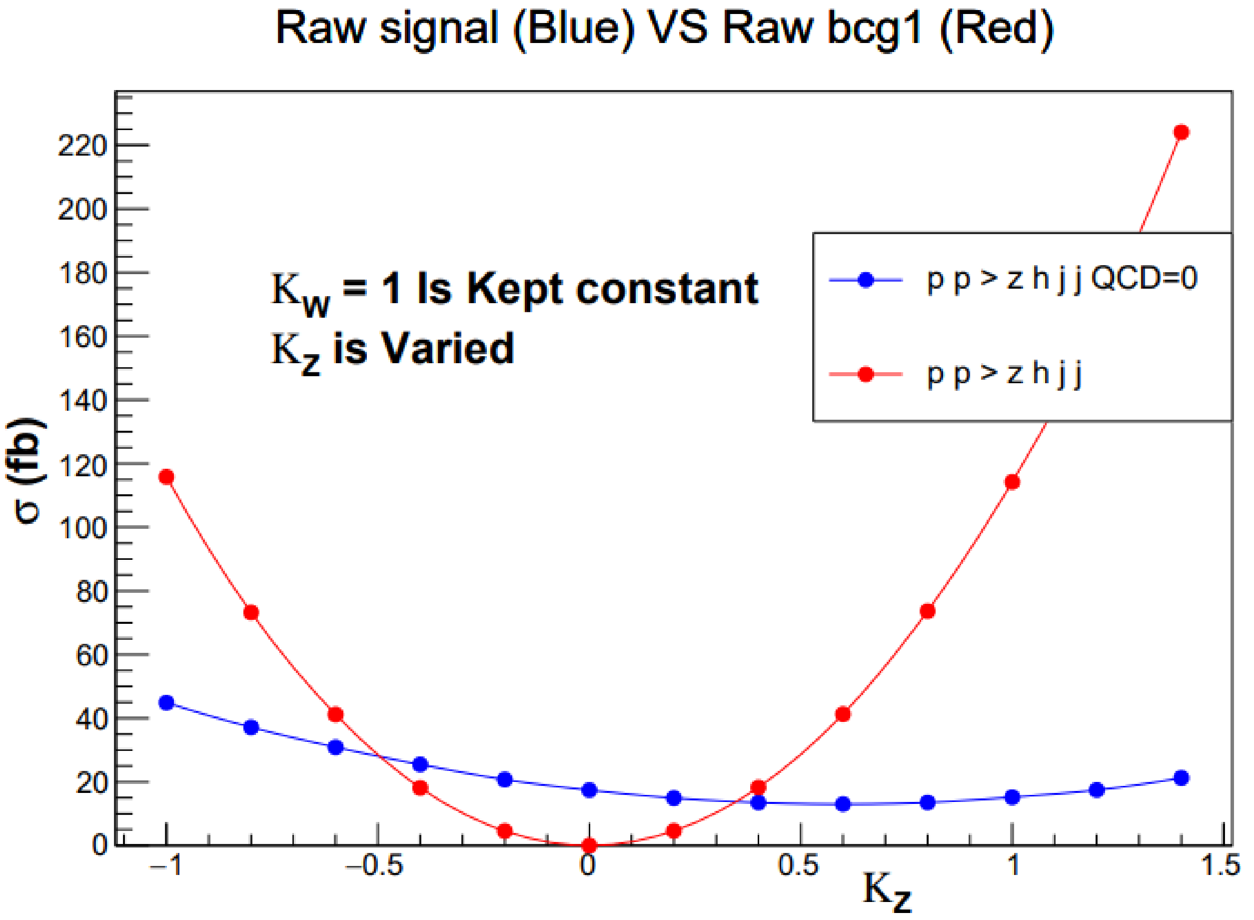
All processes

signal :	`p p > z h j j QCD=0, h > b b~, z > l- l+`	0.9104 fb
bcg1 :	`p p > z h j j , h > b b~, z > l- l+`	1.916 fb
bcg2 :	`p p > t t~ , (t > w+ b , w+ > e+ vl ) ,( t~ > w- b~ , w- > e- vl~)`	5313.0 fb
&&	`p p > t t~ , (t > w+ b , w+ > mu+ vl ) ,( t~ > w- b~ , w- > mu- vl~)`	
bcg3 :	`p p > z z j j QCD=0, z > b b~ , z > l- l+`	1.214 fb
bcg4 :	`p p > z z j j , z > b b~ , z > l- l+`	8.737 fb
bcg5 :	`p p > z b b~ j j , z > l- l+`	1113.0 fb

*Some event generation conditions are imposed

Variation with κ_W, κ_Z





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

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

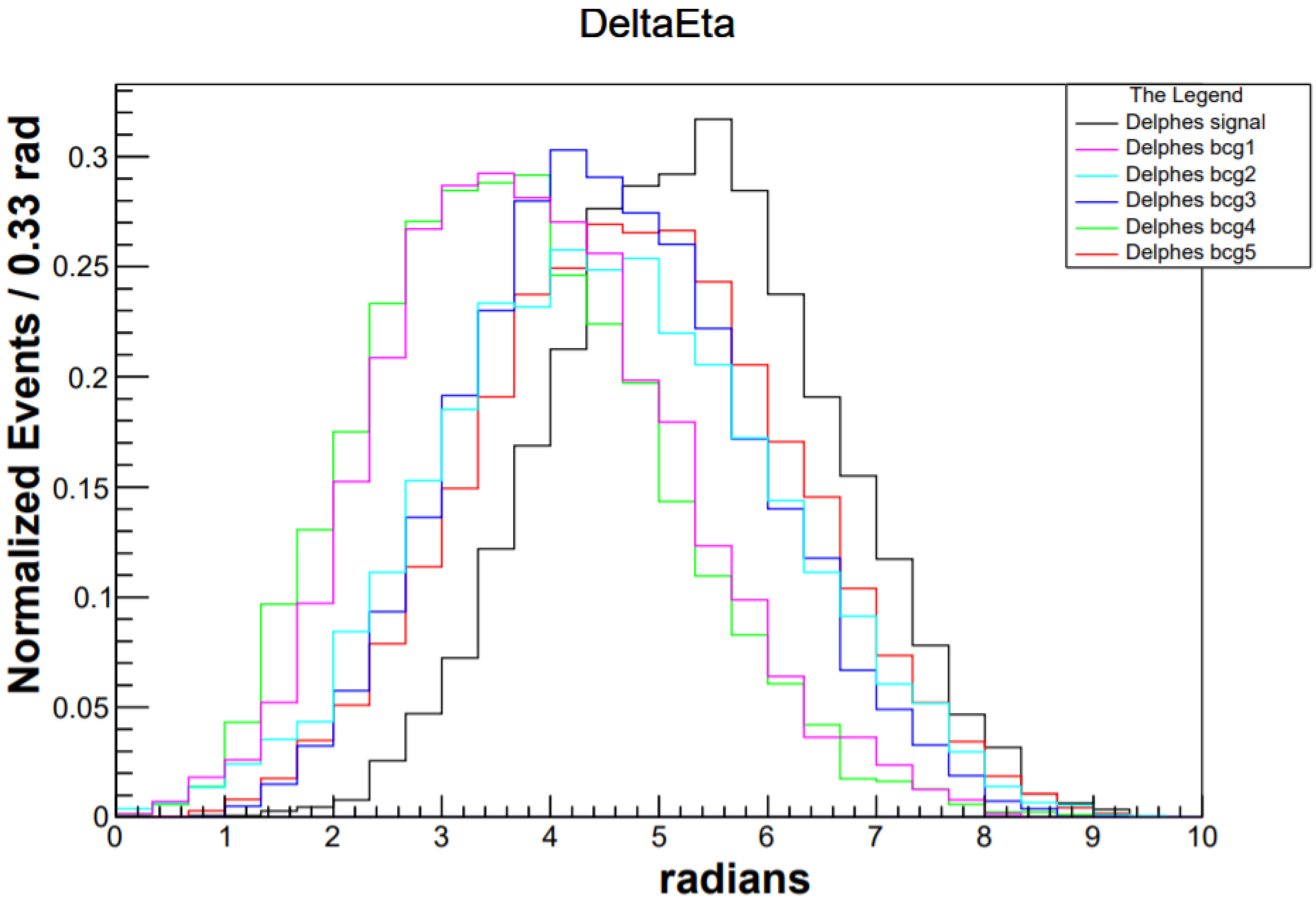
Initial cuts

- Atleast one forward-backward jet pair must exist
- Number of MasterJets $\geq\ 4$
- Number of Delphes B-tagged Jets $\geq\ 2$
- Number of VBF-B-Jets $==\ 0$
- Invariant mass of the detected OSSF Lepton pair[8] $\in\ (81\text{GeV}, 101\text{GeV})$

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

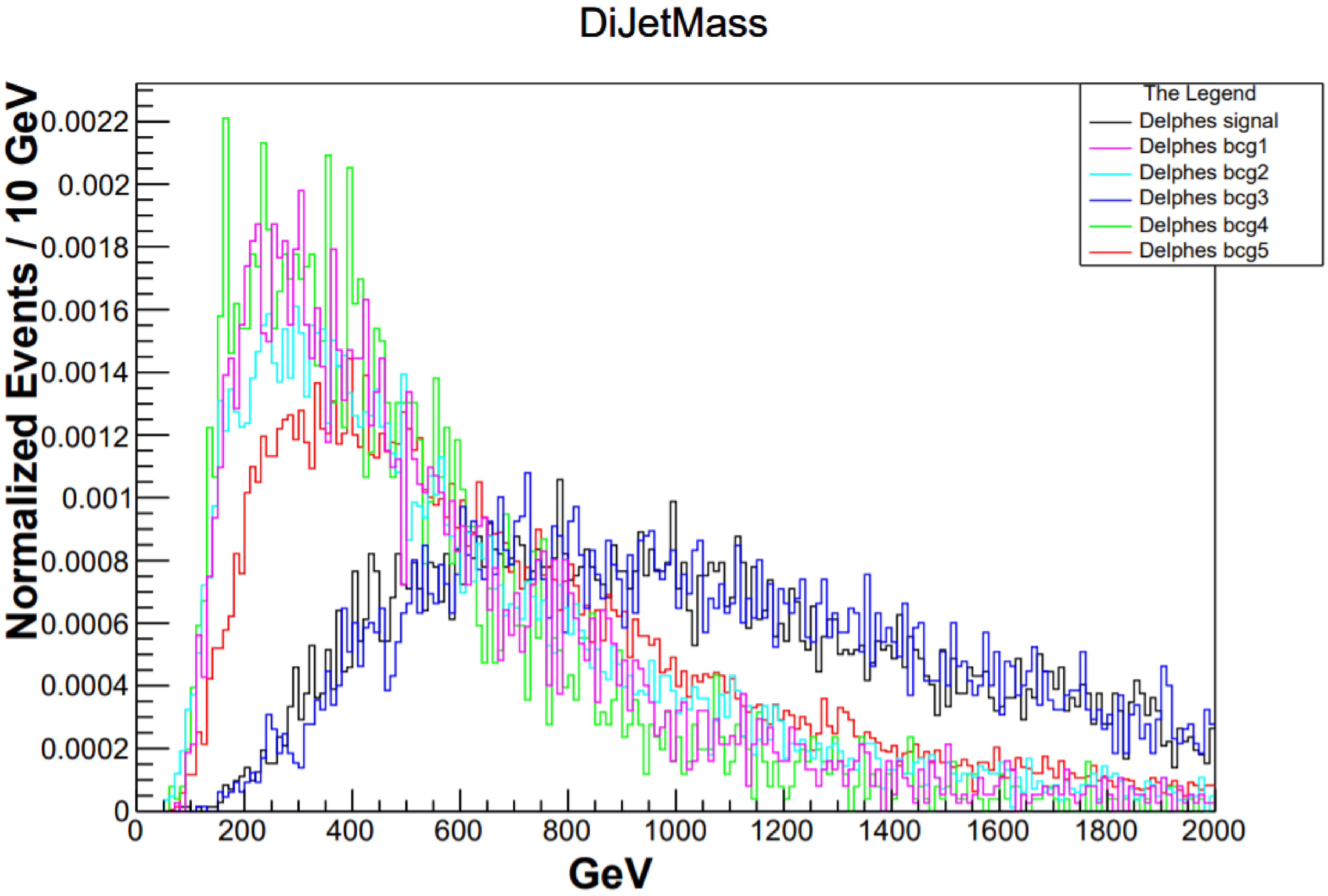
*`MasterJet` : A jet satisfying $p_T \geq 20$ GeV AND $|\eta| \leq 5$

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

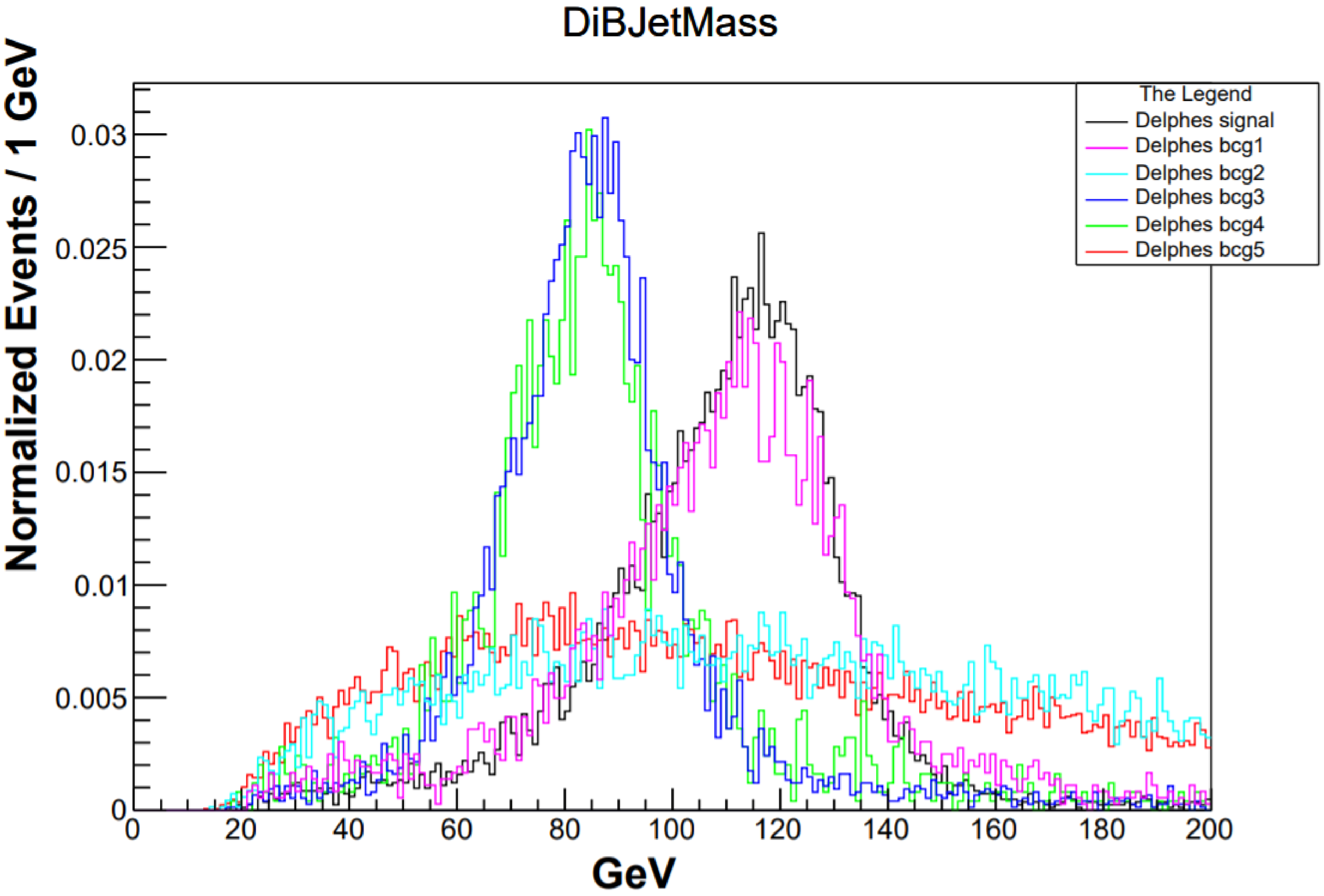


7.

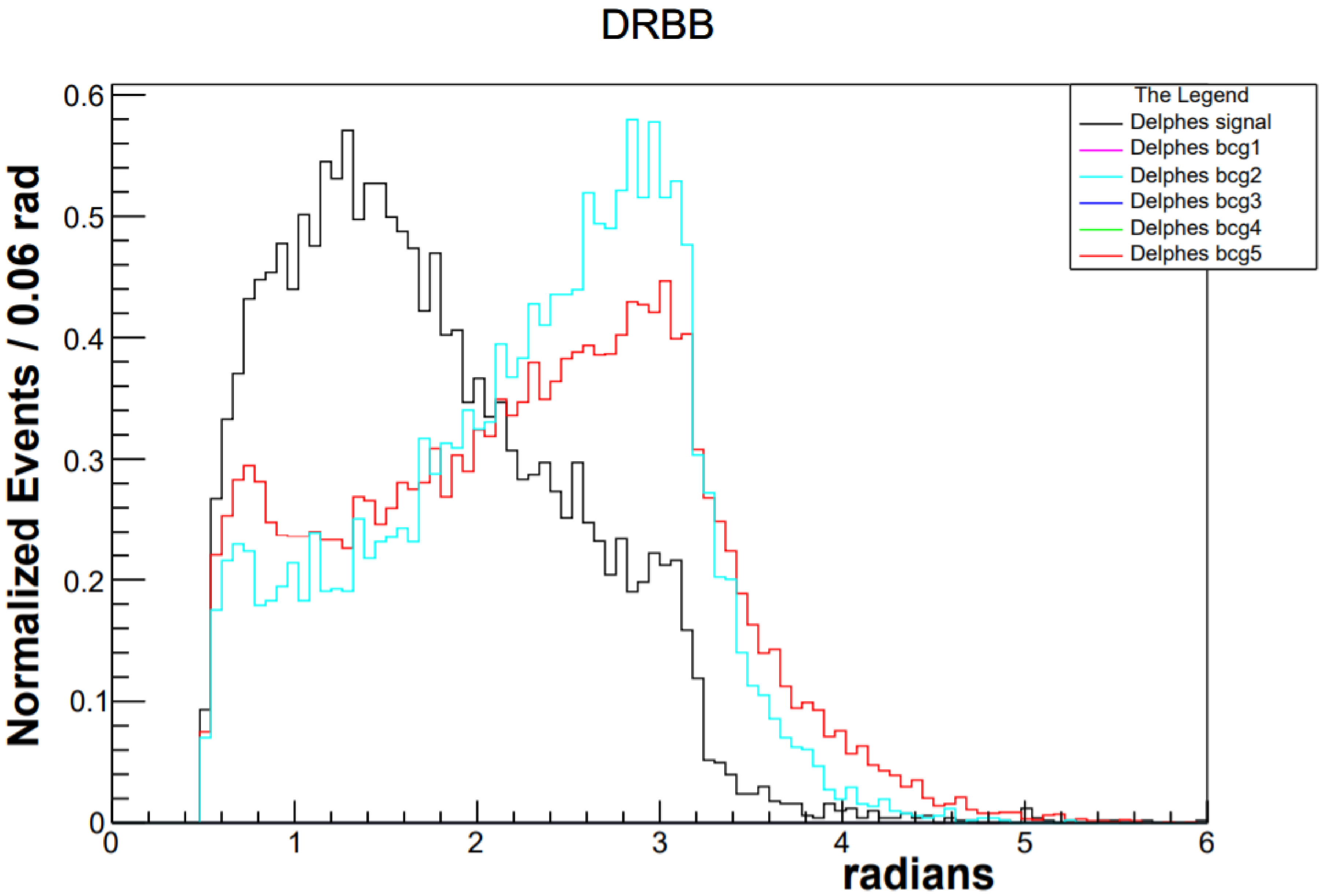
DiJetMass : Invariant mass of the two VBF-Tagging jets



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



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



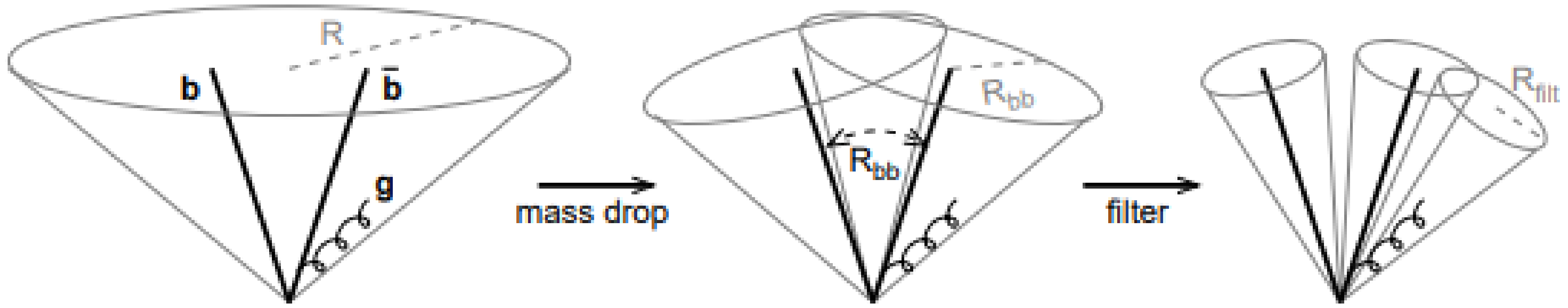
Semi-final cuts

Initial cuts +

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

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

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 constitutents 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 : `Hmass`
- `Hmass` $\in (110 \text{ GeV}, 130 \text{ GeV})$

Final cuts

- Atleast one forward-backward jet pair must exist
- Number of MasterJets $\geq$ 4
- Number of Delphes B-tagged Jets $\geq$ 2
- Number of VBF-B-Jets == 0
- Invariant mass of the detected OSSF Lepton pair $\in$ (81GeV, 101GeV)
- `DeltaEta` ≥ 4 : ($|\eta_{\text{VBF}}| \geq 4$)
- `DiJetMass` ≥ 1000 GeV
- `DRBB` ≤ 2 : ($\Delta R_{b\bar{b}} \leq 2$)

- `missingET` < 50 GeV
- `PT-Jet1` ≥ 100 GeV
- `PT-Jet2` ≥ 70 GeV
- `PT-Jet3` ≥ 50 GeV
- `PT-B-Jet1` ≥ 55 GeV
- `PT-B-Jet2` ≥ 55 GeV
- `DiBJetMass` $\in$ (110 GeV, 130 GeV)
- `Hmass` $\in$ (110 GeV, 130 GeV)

Event yields

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

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

$$Y = \mathcal{L} \cdot C_X \cdot \frac{\text{Number of Events selected}}{\text{Total number of Events Simulated}} \qquad \text{Yield-error} = \sqrt{\frac{Y^2}{\text{Number of Events selected}}}$$

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

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

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 $\beta = 0.1(10\%)$

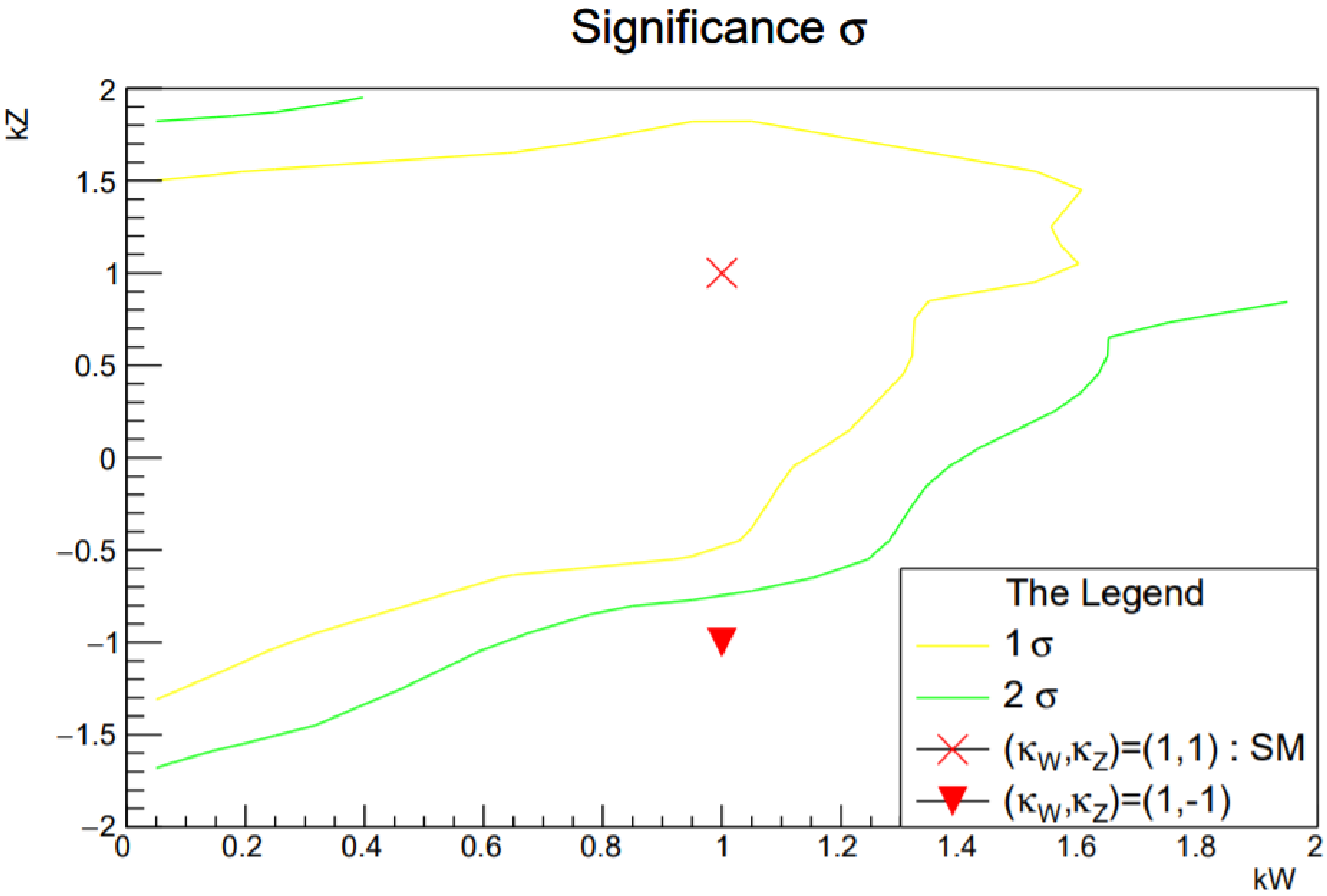
Contour plots over (κ_W, κ_Z) plane

- 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.

Contour plots over (κ_W, κ_Z) plane



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.
- $\Longrightarrow$ Provides a direction to measure the sensitivity of the relative sign between the Higgs couplings to vector bosons at the HL-LHC.

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.

$\Longrightarrow$ This was the analysis for VBF-ZH process.

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

Thank you for listening!

Questions?

Extra slides

Event generation

(This list is for all the processes except the bcg2)

```
set ptb 20.0        # minimum pt for the b
set drbb 0.4        # min distance between b's
set mmjj 100.0      # min invariant mass of a jet pair
set xetamin 0.5     # minimum rapidity for two jets in the WBF case
set deltaeta 1.0    # minimum rapidity difference for two jets in the WBF case
set ebeam1 6500     # Energy of beamline-1
set ebeam2 6500     # Energy of beamline-2
set kW 1.0          # κW value
set kZ 1.0          # κZ value
```

Event generation

Whereas, for the bcg2,

```
set missetmax 70.0  # maximum missing Et (sum of neutrino's momenta)
set mmll 70.0       # min invariant mass of l+l- (OSSF) lepton pair
set mmllmax 110.0   # max invariant mass of l+l- (OSSF) lepton pair
set ptb 20.0
set drbb 0.4
set mmjj 100.0
set xetamin 0.5
set deltaeta 1.0
set ebeam1 6500
set ebeam2 6500
set kW 1.0
set kZ 1.0
```

Process	Event selection	Yield
Signal (S)	698 $/100k$	8.65 $\pm$ 0.33
Bcg1 (b_1)	30 $/100k$	0.79 $\pm$ 0.14
Bcg2 (b_2)	4 $/5M$	12.75 $\pm$ 9.01
Bcg3 (b_3)	47 $/100k$	1.71 $\pm$ 0.25
Bcg4 (b_4)	2 $/100k$	0.52 $\pm$ 0.37
Bcg5 (b_5)	35 $/700k$	166.95 $\pm$ 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 $\pm$ 0.28
Bcg1 (b_1)	12 $/100k$	0.32 $\pm$ 0.09
Bcg2 (b_2)	3 $/5M$	9.56 $\pm$ 5.52
Bcg3 (b_3)	23 $/100k$	0.84 $\pm$ 0.17
Bcg4 (b_4)	1 $/100k$	0.26 $\pm$ 0.26
Bcg5 (b_5)	9 $/700k$	42.93 $\pm$ 14.31

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

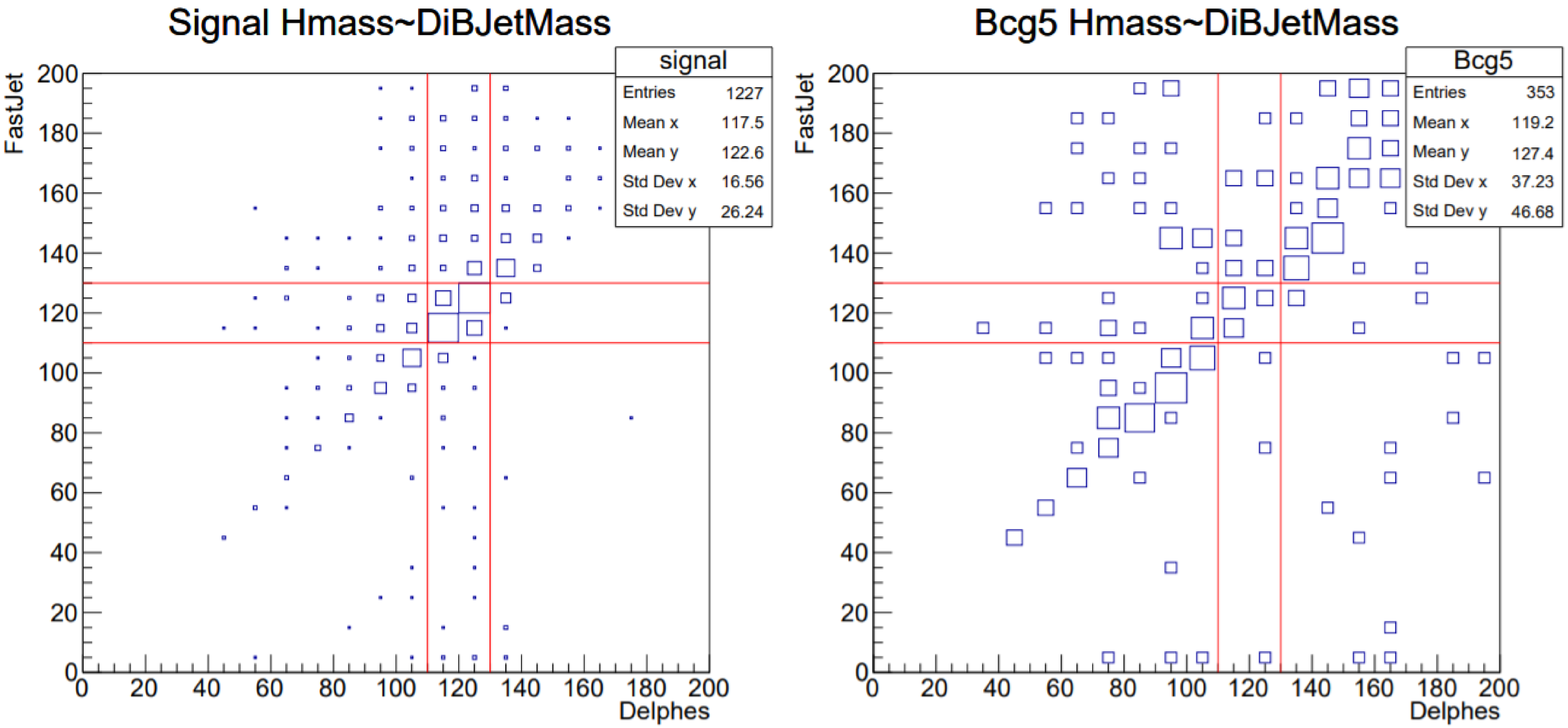


Figure 18: FastJet-Delphes characteristics for signal and bcg5 process : After all but the `Hmass-DiBJetMass` cuts

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