$e^+e^- \rightarrow$ ZH Recoil mass

FCCee Jamboree--Case studies 25th June 2021

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Plans

- Short introduction of Higgs recoil mass
- Signal and background samples
- Background rejection, Final Selection
- Signal Only fit and Signal + Background fit

FUTURE CIRCULAR Higgs recoil mass at Future Circular Collider (FCC)

- Goal: Measurement of the ZH total cross section
- Signal: $e^+e^- \rightarrow ZH \rightarrow l\bar{l} + X$ ZH is the dominant Higgs production process @ 240 GeV e^+e^- machine
- Use events with a Z decaying leptonically, and reconstruct M_{recoil} from the Z production without measuring the Higgs production final state

$$M_{recoil}^{2} = (\sqrt{s} - E_{l\bar{l}})^{2} - p_{l\bar{l}}^{2} = s - 2E_{l\bar{l}}\sqrt{s} + m_{l\bar{l}}^{2}$$

- The reconstructed *M_{recoil}* is sensitive to the precise knowledge of the centre-of-mass energy
- Physic independent study
- WW & ZZ Background @ 240 GeV 25/06/2021





Signals, Backgrounds and Selections

• Signals:

- 1. $Z(\mu^+\mu^-)H$ (Whizard)
- 2. $Z(\tau^+\tau^-)H$ (Whizard)
- 3. $Z(q\bar{q})H$ (Whizard)
- Or ZH inclusive (Pythia)
- 4. $Z(\nu\bar{\nu})H$ (Whizard)
- 5. $Z(e^+e^-)H$ (Whizard)

Backgrounds:

- 1. ZZ(inclusive), (Pythia)
- 2. $W^+(\nu\mu^+)W^-(\bar{\nu}\mu^-)$, (Pythia)
- $7 \rightarrow l^+ l^-$ (Dythia) 3
- 4
- 5
- 6

- $\sqrt{s} = 240 \text{ GeV}$
- **ISR and FSR on**
- **Beam Energy Spread**
- Luminosity: $L = 5 a b^{-1}$
- **IDEA detector**
- Spring2021 samples

Pre-Selection:

- 1. At least one Z boson from a $\mu^+\mu^-$ pair
- 2. $m_{\mu^+\mu^-} \in [80, 100]$ GeV

).	$Z \rightarrow l^{+}l^{-}$, (Pythia)					77/inclusiva)	711
L.	$Z \rightarrow a \overline{a}$. (Pythia)			mumun	ww_mumu	ZZ(Inclusive)	211
).	eeZ, (Whizard)	$\sigma \cdot L$	1006580	33822	1289600	6794950	68893500
5.	$\gamma \gamma \rightarrow \mu^+ \mu^-$, (Whizard)	NEVENTS	10 ⁷	10 ⁶	107	10 ⁷	$0.99 \cdot 10^7$
7.	$\gamma \gamma \rightarrow \tau^+ \tau^-$ (Whizard)	NEVENTS/ $\sigma \cdot L$	9.93	29.57	7.75	1.47	0.14

M_{recoil} and $M_{\mu^+\mu^-}$ distribution



2. $m_{\mu^+\mu^-} \in [80, 100]$ GeV

\Box For $m_{\mu^+\mu^-}$

- Large Zll evnets
- \succ Two peaks for $m_{\mu^+\mu^-}$
 - 1. ~ 90 GeV (Z mass)
 - 2. ~ 240 GeV (\sqrt{S})
- \succ Cuts for $\gamma\gamma$ events

Given Set up For M_{recoil}

 \blacktriangleright ZII concentrate on low M_{recoil}

$p_T^{\mu^+\mu^-}$ and $\cos \theta_{missing}$ distribution



After Pre-Selection:

1. At least one Z boson from

a
$$\mu^+\mu^-$$
 pair

2. $m_{\mu^+\mu^-} \in [80, 100] \text{ GeV}$

Log Scale
For
$$p_T^{\mu^+\mu^-}$$

- > No signal above $p_T^{\mu^+\mu^-} > 70$ GeV and large background below $p_T^{\mu^+\mu^-} < 70$ GeV
- So, we require $p_T^{\mu^+\mu^-} \in [20, 70]$ GeV
- > Low $p_T^{\mu^+\mu^-}$ cuts back-to-back events For $\cos \theta_{missing}$
 - polar angle of the missing momentum
 - ➤ $\cos \theta_{missing}$ is calculated using the missing information p_x , p_y , p_z and E
- \succ Reduce $\gamma\gamma$ processes
- ISR emitted approximately collinear with the incoming beams escapes detection in the beam pipe

Evaluation of M_{recoil} distribution



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Evaluation of $m_{\mu^+\mu^-}$ distribution



#Events, error and #Entries

		Pre-Selection			APC-FCC-2-Selection			
	Sample	#Events	Error	#Entries	#Events	Error	#Entries	
	ZH inclusive P8	25632.6	50.9	253954	18150.6	42.8	179826	
	$Z(\mu^+\mu^-)H$	24178.8	28.6	714893	18181.1	24.8	537560	
	$Z(\tau^+\tau^-)H$	32.7	1.1	873	12.4	0.7	330	
	$Z(q\bar{q})H$	425.5	5.4	6179	171.5	3.4	2491	
	Total Signal	24637.0	35.1	721945	18365.0	28.9	540381	
Ŵ	$W^{+}(\nu\mu^{+})W^{-}(\bar{\nu}\mu^{-})$	133530.9	131.2	1035444	16927.3	46.7	131260	
	ZZ(inclusive)	315780.4	463.2	464728	11219.8	87.3	16512	
	$Z \rightarrow l\bar{l}$	7846308.6	7389.3	1127515	9471.1	256.7	1361	
	Total Main Bkgs.	8295619.8	7983.8	2627687	37618.2	390.8	149133	
	γγμμ	384090.8	315.2	1484600	4.7	1.1	18	
	γγττ	304.3	8.0	1456	6.3	1.1	30	
	eeZ	793603.7	286.8	7654357	24.0	1.6	231	
	$\mathrm{Z} ightarrow q \overline{q}$	0.0	0.0	0	0.0	0.0	0	
	$Z(\nu\bar{\nu})H$	173.8	3.7	2257	69.3	2.3	900	
	$Z(e^+e^-)H$	23.4	1.0	587	9.3	0.6	234	
	Additional Bkgs	1178195.9	614.7	9143257	113.5	6.7	1413	

APC-2-Selection

- 1. At least one Z boson from a $\mu^+\mu^-$ pair.
- 2. $m_{\mu^+\mu^-} \in [86, 96] \text{ GeV}$

3.
$$p_T^{\mu^+\mu^-} \in [20, 70] \text{ GeV}$$

4. $\left|\cos\theta_{missing}\right| < 0.98$

5. $M_{\text{recoil}} \in [120, 140] \text{ GeV}$

Compared to Pre-Selection, APC-2-Selection keeps ~75% signals but rejects

- > Main background:
 - ~87% WW
 - ~96% ZZ
 - ~99.88% $Z \rightarrow l\bar{l}$
- Additional background
 - ~99.99% γγμμ,
 - ~00.07% *eeZ*

• Fitting functions

- Signal: 2CBG or Two-Sided Crystal Ball
- Background: Second Order Polynomial
- S + B = nsig*signal + nbkg*background

Initial signal modelling using Two-Sided Crystal-Ball (DSCB), further optimized to 2CBG by Jan: <u>Jan's presentation</u>

- Two CB functions (left and right), sharing mean and width
- Added Gaussian to cope with the high tails
- In total three terms, which can float, but Gaussian suppressed in norm (sigfrac1 + sigfrac2 > 0.8)
- In total 10 "free" parameters (+1 normalization)

 $pdf(M_{recoil})$

 $= sigfrac1 \cdot CB(M_{recoil}; \mu, \sigma, \alpha_L, n_L) + sigfrac2 \cdot CB(M_{recoil}; \mu, \sigma, \alpha_R, n_R) + (1 - sigfrac1 - sigfrac2) \cdot Gauss(M_{recoil}; \mu_{2}, \sigma_{2})$

Signal Only fit with different p.d.f. in the Higgs region (120-140 GeV)



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Background Only fit in the Higgs region (120-140 GeV)



7.75

1.47

0.14

Entries/# of Events

9.91

29.47

Signal + Background fit with different p.d.f. in the Higgs region (120-140 GeV)



Parameters fixing for Signal + Background fit in the Higgs region (120-140 GeV)



Signal Only fit with different p.d.f. in the Higgs region (120-140 GeV)



2CBG

25/06/2024130

125.0870

1.49

Compared to Pythia, Whizard sample has larger CB width and lower CB mean

Signal + Background fit with different p.d.f. in the Higgs region (120-140 GeV)



ZH Pythia	σ_{CB} (GeV)	M _{CB} (GeV)	$\Delta_{N_{sig}}/N_{sig}$	$N_{sig}^{fit}/N_{sig}^{integral}$	χ^2/NDF
DSCB	0.4685	125.1328	2.50	107.9%	1.31
2CBG 25,	^{/06/2024} 190	125.0880	3.11	108.5%	1.29

- M_{recoil} [GeV]
- Nothing is improved using 2CBG
- Need further investigate on Whizard samples

Parameters fixing for Signal + Background fit in the Higgs region (120-140 GeV)



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Conclusions and Outlook

Conclusion:

Compared to Pre-Selection, APC-2-Selection keeps ~75% signals but rejects

- ~87% WW
- ~96% ZZ
- ~99.88% ZII
- 2CBG function has better description of signal than Two-sided Crystal-Ball function for both Pythia and Whizard sample
- For signal + background fit, compared to Two-sided Crystal-Ball function, 2CBG improves the $N_{sig}^{fit}/N_{sig}^{integral}$ but neither $\Delta_{N_{sig}}/N_{sig}$ nor χ^2/NDF is improved for Pythia signal samples
- > After fixing the tails of Crystal-Ball functions, the $\Delta_{N_{sig}}/N_{sig}$ decreases to ~ 1.4%

> After fixing the backgrounds, the $\Delta_{N_{sig}}/N_{sig}$ decreases to ~ 2.2%

*****Outlook:

Derive uncertainty on cross section and mass determination

Study the impact of improving the magnet from 2T to 3T 25/06/2021

Backup

Background Only fit in the Higgs region (120-140 GeV)



APC-FCC-2-selection vs. "ILC" Selection on APC-FCC-Windows



APC-FCC-2-selection vs. "ILC" Selection on ILC-Windows

"ILC"-selection to compare to:

- 1. At least one Z boson from a $\mu^+\mu^-$ pair
- 2. $m_{\mu^+\mu^-} \in [73, 120] \text{ GeV}$
- 3. $p_T^{\mu^+\mu^-} \in [10, 70] \text{ GeV}$
- 4. $\left|\cos\theta_{missing}\right| < 0.98$
- 5. $M_{\text{recoil}} \in [110, 155] \text{ GeV}$

APC-FCC-2 -Selection:

- 1. At least one Z boson from a $\mu^+\mu^-$ pair.
- 2. $m_{\mu^+\mu^-} \in [86, 96]$ GeV
- 3. $p_T^{\mu^+\mu^-} \in [20, 70] \text{ GeV}$
- 4. $\left|\cos\theta_{missing}\right| < 0.98$
- 5. $M_{\text{recoil}} \in [120, 140] \text{ GeV}$



25/06/2021

#Events, error and #Entries

	APC-FCC-2-Selection		"ILC" Selection			
Sample	#Events	Error	#Entries	#Events	Error	#Entries
ZH inclusive P8	18150.6	42.8	179826	24276.9	49.5	240523
$Z(\mu^+\mu^-)H$	18181.1	24.8	537560	23021.3	27.9	680672
$Z(\tau^+\tau^-)H$	12.4	0.7	330	42.1	1.3	1123
$Z(q\bar{q})H$	171.5	3.4	2491	424.1	5.4	6159
Total Signal	18365.0	28.9	540381	23487.6	34.6	687954
$W^+(\nu\mu^+)W^-(\bar{\nu}\mu^-)$	16927.3	46.7	131260	128997.4	129.0	1000290
ZZ(inclusive)	11219.8	87.3	16512	37207.1	159.0	54757
$Z \rightarrow l\bar{l}$	9471.1	256.7	1361	56833.7	628.9	8167
Total Main Bkgs.	37618.2	390.8	149133	223038.2	916.9	1063214
γγμμ	4.7	1.1	18	73.0	4.3	282
γγττ	6.3	1.1	30	124.6	5.1	596
еү	24.0	1.6	231	76.8	2.8	741
$Z \rightarrow q \bar{q}$	0.0	0.0	0	0.0	0.0	0
$Z(\nu\bar{\nu})H$	69.3	2.3	900	180.2	3.7	2341
$Z(e^+e^-)H$	9.3	0.6	234	21.8	0.9	549
Additional Bkgs.	113.5	6.7	1413	476.4	16.9	4509

> APC-FCC-2-Selection

- 1. At least one Z boson from a $\mu^+\mu^-$ pair.
- 2. $m_{\mu^+\mu^-} \in [86, 96] \text{ GeV}$

3.
$$p_T^{\mu^+\mu^-} \in [20, 70] \text{ GeV}$$

- 4. $\left|\cos\theta_{missing}\right| < 0.98$
- 5. $M_{\text{recoil}} \in [120, 140] \text{ GeV}$

"ILC"-selection

- 1. At least one Z boson from a $\mu^+\mu^-$ pair
- 2. $m_{\mu^+\mu^-} \in [73, 120] \text{ GeV}$
- 3. $p_T^{\mu^+\mu^-} \in [10, 70] \text{ GeV}$
- 4. $\left|\cos\theta_{missing}\right| < 0.98$
- 5. $M_{\text{recoil}} \in [110, 155] \text{ GeV}$

Compared to "ILC"-selection, APC-FCC-2-Selection has ~80% total signals but only ~17% backgrounds

#Events, error and #Entries

	Pre-Selection			APC-FCC-1-Selection		
Sample	#Events	Error	#Entries	#Events	Error	#Entries
ZH inclusive P8	22845.7	48.0	226343	19403.9	44.3	192243
$Z(\mu^+\mu^-)H$	24190.7	28.6	715246	19199.7	25.5	567676
$Z(\tau^+\tau^-)H$	34.5	1.1	919	12.5	0.7	334
$Z(q\bar{q})H$	425.6	5.4	6180	184.8	3.6	2684
Total Signal	24650.7	35.2	722345	19397.0	29.7	570694
$W^+(\nu\mu^+)W^-(\bar\nu\mu^-)$	133536.7	131.2	1035489	16951.8	46.8	131450
ZZ(inclusive)	316393.9	463.7	465631	20204.8	117.2	29735
$Z \rightarrow l\bar{l}$	7846489.5	7389.4	1127541	45254.0	561.2	6503
Total Background	8296420.1	7984.3	2628661	82410.6	725.1	167688
γγμμ	384090.8	315.2	1484600	90.8	4.8	351
γγττ	304.3	8.0	1456	6.3	1.1	30
еγ	793603.7	286.8	7654357	6449.4	25.9	62205
$Z \rightarrow q \overline{q}$	0.0	0.0	0	0.0	0.0	0
$Z(\nu\bar{\nu})H$	173.9	3.7	2259	69.6	2.3	904
$Z(e^+e^-)H$	23.4	1.0	587	10.3	0.6	259
Add. Background	1178196.1	614.7	9143259	6626.4	34.8	63749

Pre-Selection

1. At least one Z boson from a $\mu^+\mu^-$ pair

2. $m_{\mu^+\mu^-} \in [80, 100] \text{ GeV}$

> APC-FCC-1-Selection

1. At least one Z boson from a $\mu^+\mu^-$ pair

- 2. $m_{\mu^+\mu^-} \in [86, 96] \text{ GeV}$
- 3. $p_T^{\mu^+\mu^-} \in [20, +\infty] \text{ GeV}$
- 4. $M_{\text{recoil}} \in [120, 140] \text{ GeV}$

Signal Only fit with different selections in the Higgs region (120-140 GeV)



Signal Only fit with Local and Spring 2021 in the Higgs region (120-140 GeV)



Signal Only fit with different selections in the Higgs region (120-140 GeV)

