https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF1_EF4-057.pdf

Measuring λ_{WZ} through tree-level interference

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SNOWMASS21-EF01, 2020.11.05

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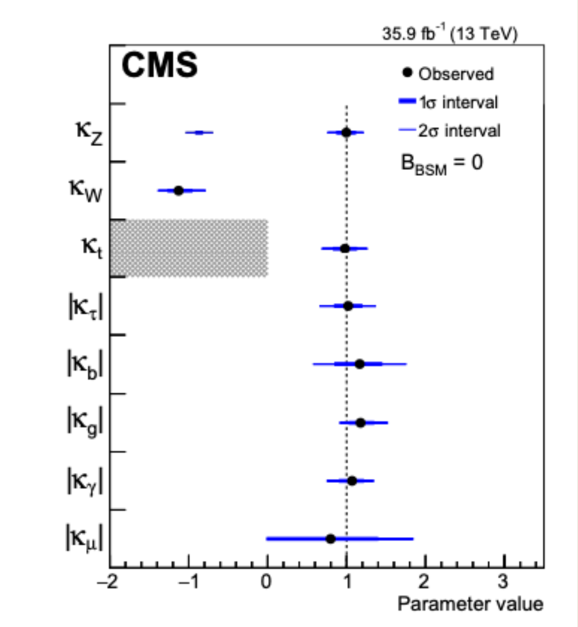
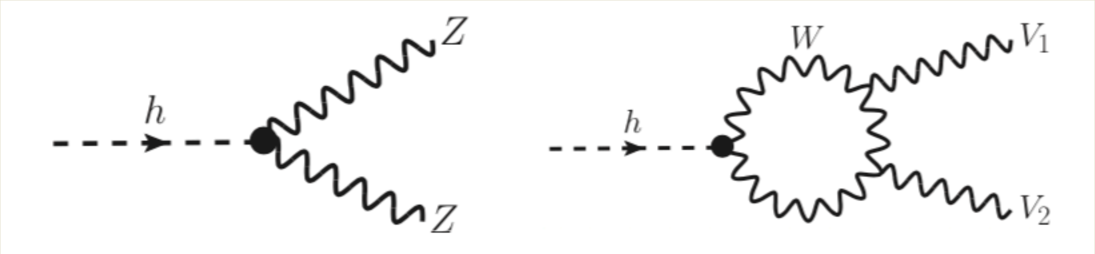
Higgs Coupling Measurements

- Electroweak Symmetry Breaking
  - κ_W, κ_Z
  - $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$ $\qquad \mathcal{L} = g m_W h \left(\kappa_W W^+ W^- + \frac{\kappa_Z}{2c_W^2} Z^2 \right)$
- Current Measurement:
  - LHC Run I: **ATLAS+CMS, 1606.02266**
    - $\lambda_{WZ} \in [-1.10, -0.73] \cup [0.72, 1.10]$
  - CMS Run II 35.9 fb^{-1}:
    CMS: 1809.10733

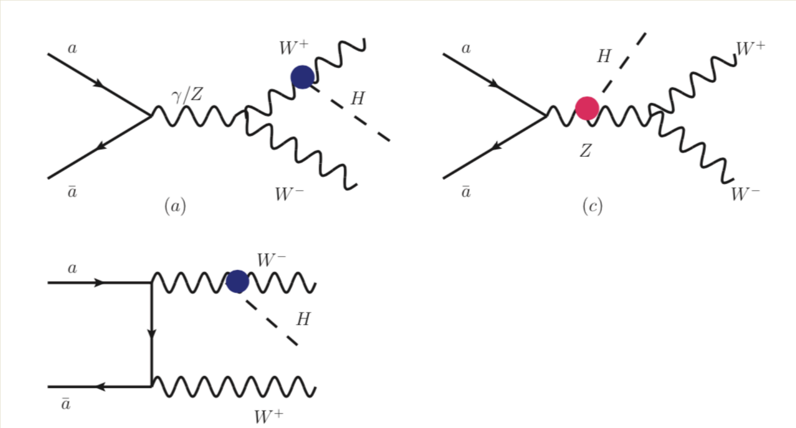


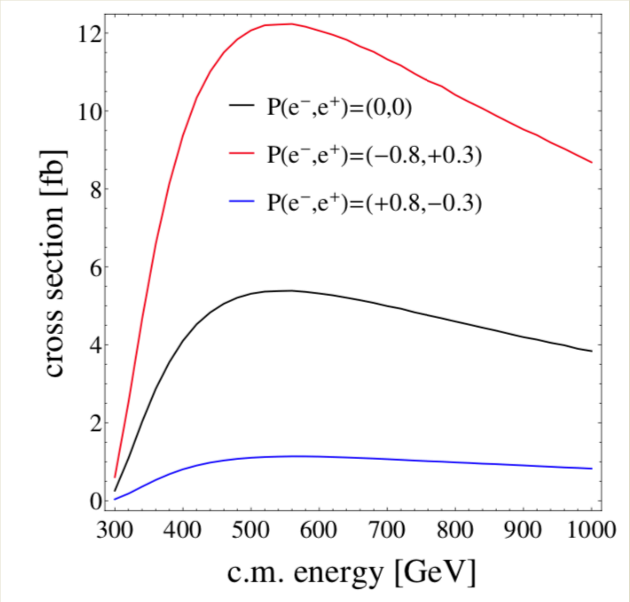
λ_{WZ} Measurements

- Interference Effects are needed to resolve the sign
- Tree/loop interference: **1608.02159**



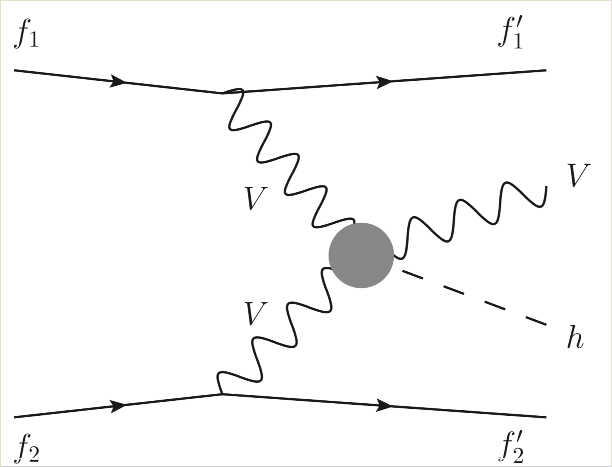
- Tree level interference:
  - $f\bar{f} \to W^+W^-h$ **1805.01689**

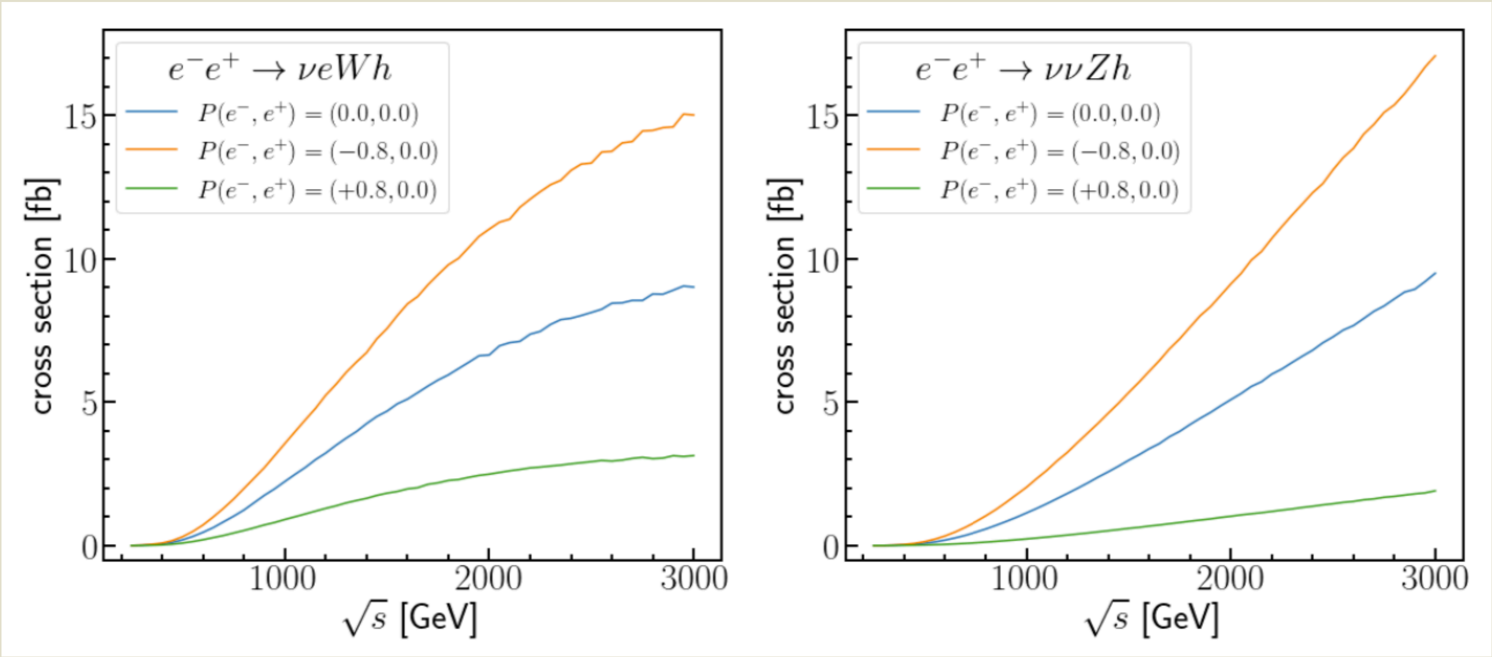




Proposed Process

- Processes @ Lepton Collider:
  - $\ell^+\ell^- \to \ell^\pm \nu_\ell W^\mp h$ $(W^\pm Z \to W^\pm h)$
  - $\ell^+\ell^- \to \nu_\ell \nu_\ell Z h$ $(W^+W^- \to Z h)$
- VBF nature suitable for Higher energy lepton collider



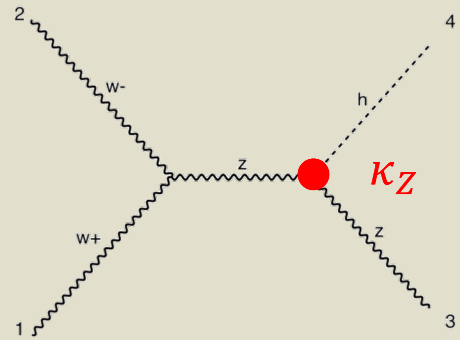


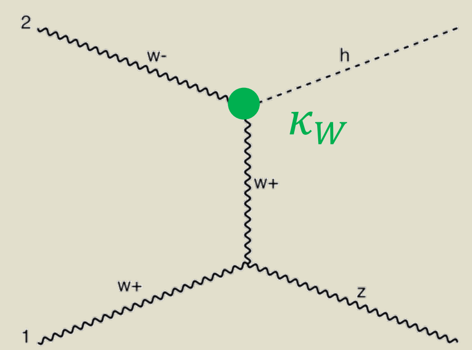
Fix-order MG5 w/ $p_T^\ell > 10\ GeV, |\eta^\ell| < 3.5$

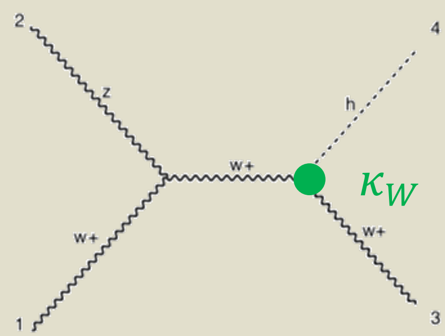
EWA/EW-PDF
2007.14300

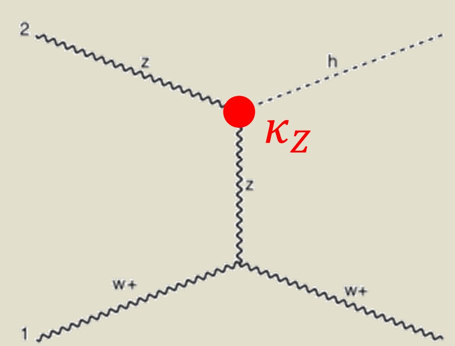
$2 \to 2$ Processes

- $VV \to Vh$ Processes:
  - $W^+W^- \to Zh$
  - $W^\pm Z \to W^\pm h$
- Parameterization:
  - $\mathcal{L} = g m_W h \left(\kappa_W W^+ W^- + \frac{\kappa_Z}{2c_W^2} Z^2 \right)$
  - $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$





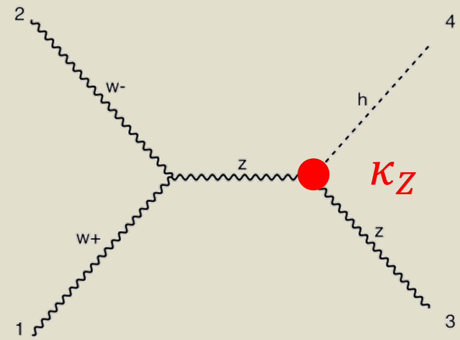


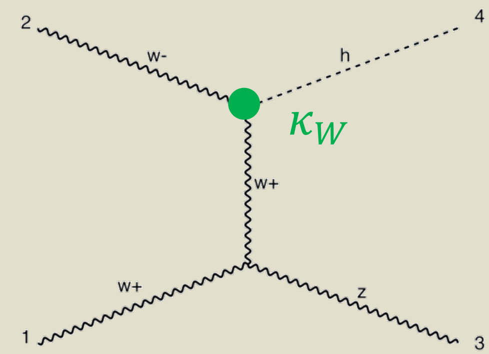


	$\mathcal{M}_{s/t}$	$\mathcal{M}_s + \mathcal{M}_t$	$d\sigma_{s/t}$	$d\sigma_{\text{tot}}$
TTT	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$	$\frac{1}{s^2}$	$\frac{1}{s^2}$
LTT	s^0	s^0	$\frac{1}{s}$	$\frac{1}{s}$
LLT	$\sqrt{s}$	$\frac{1}{\sqrt{s}}$	s^0	$\frac{1}{s^2}$
LLL	s	s^0	s	$\frac{1}{s}$

$2 \to 2$ Processes

- $VV \to Vh$ Processes:
  - $W^+W^- \to Zh$
  - $W^\pm Z \to W^\pm h$





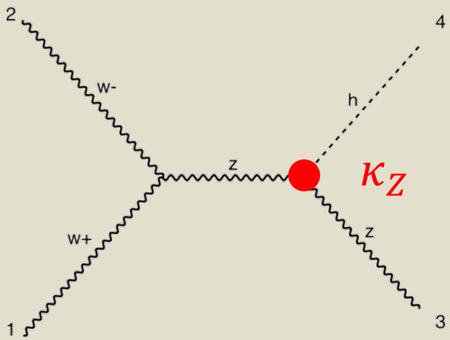
- Parameterization:
  - $\mathcal{L} = g m_W h \left(\kappa_W W^+ W^- + \frac{\kappa_Z}{2c_W^2} Z^2 \right)$
  - $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$
- For $W_L W_L \to Z_L h$:
  - $\mathcal{M}(W_L^+ W_L^- \to Z_L h) = \kappa_Z \frac{g^2 c_\theta}{4 m_W^2} (1 - \lambda_{WZ}) s + \mathcal{O}(s^0)$

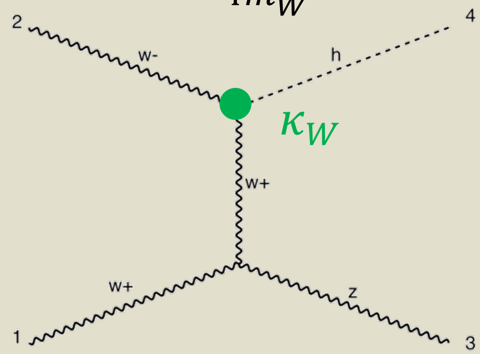
Grow with Energy unless the parameter takes the exactly SM value

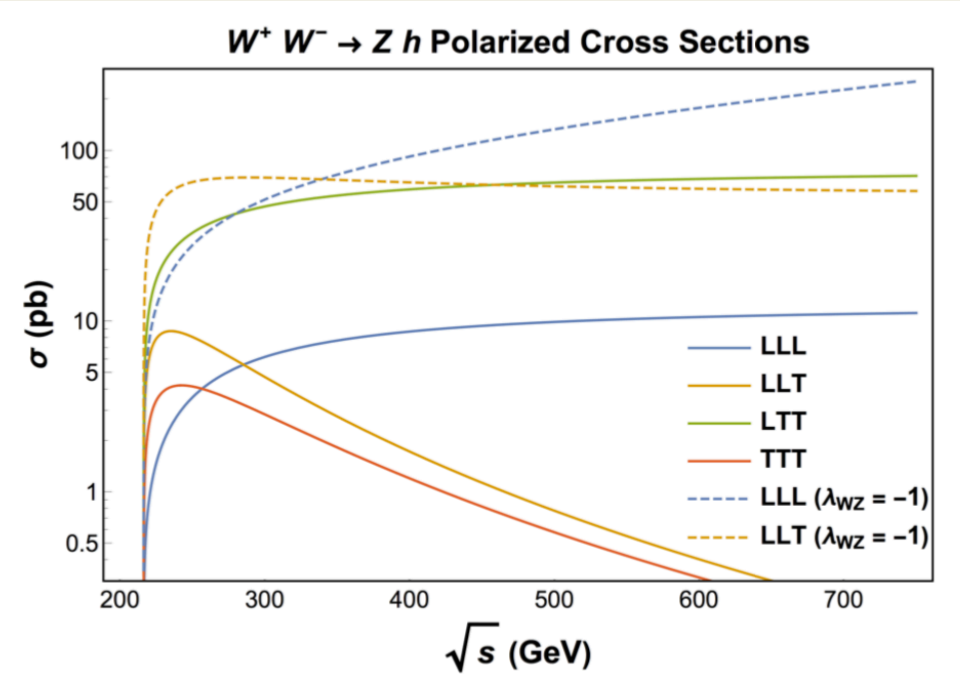
The energy dependence will be cut-off at new physics scale Λ

2 → 2 Processes

- For $W_L W_L \to Z_L h$:
  - $\mathcal{M}(W_L^+ W_L^- \to Z_L h) = \kappa_Z \frac{g^2 c_\theta}{4 m_W^2} (1 - \lambda_{WZ}) s + \mathcal{O}(s^0)$



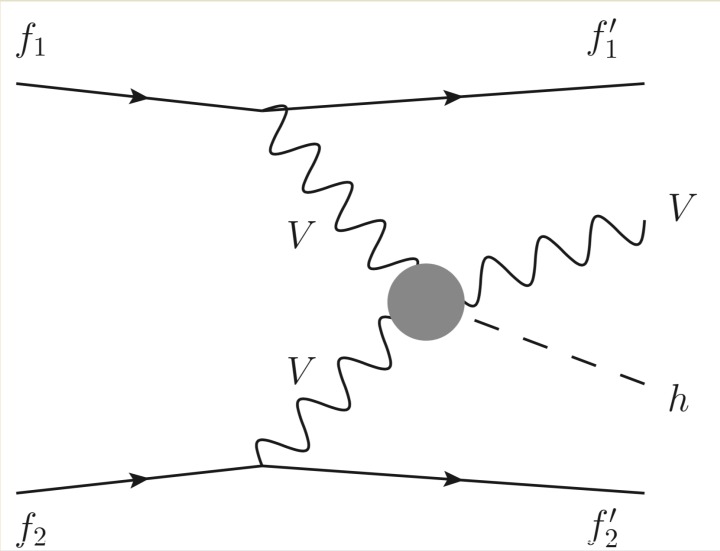




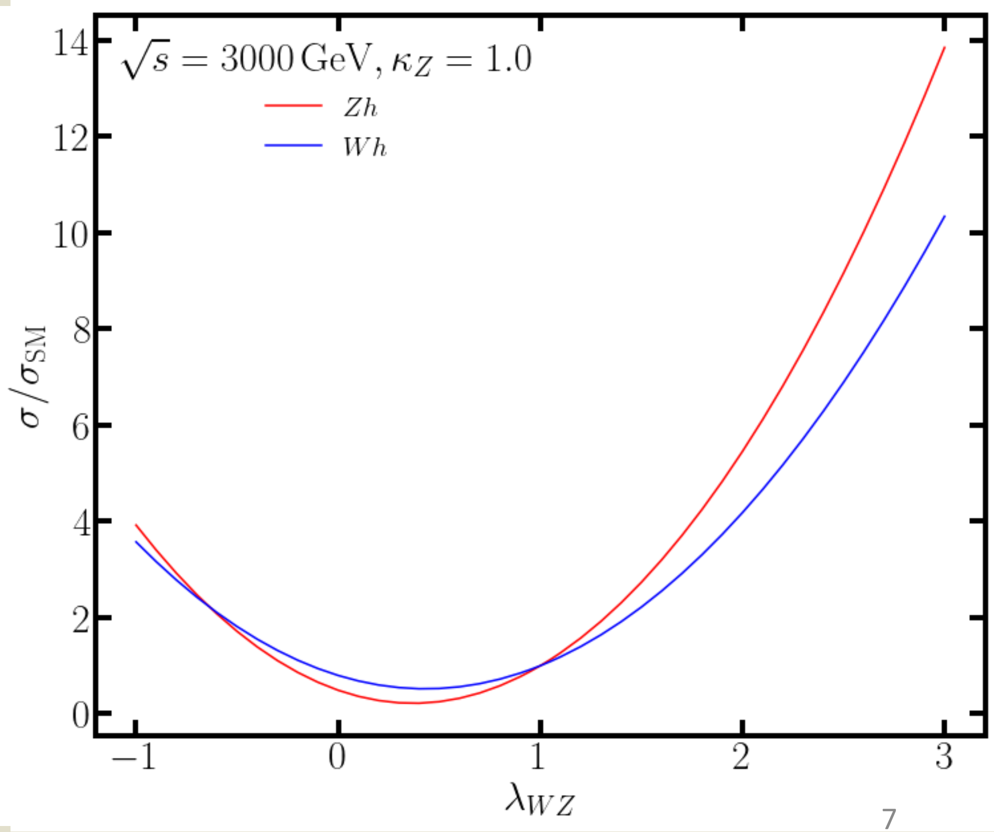
@ Lepton Collider

- At Lepton Collider
  - CLIC, Muon Collider

$$\sigma = \kappa_W^2 \sigma_W + \kappa_W \kappa_Z \sigma_{WZ} + \kappa_Z^2 \sigma_Z$$



$\sqrt{s}$ [GeV]		σ [fb] for Wh
3000	σ_Z	3.51×10^1
	σ_W	4.31×10^1
	σ_{WZ}	-6.32×10^1

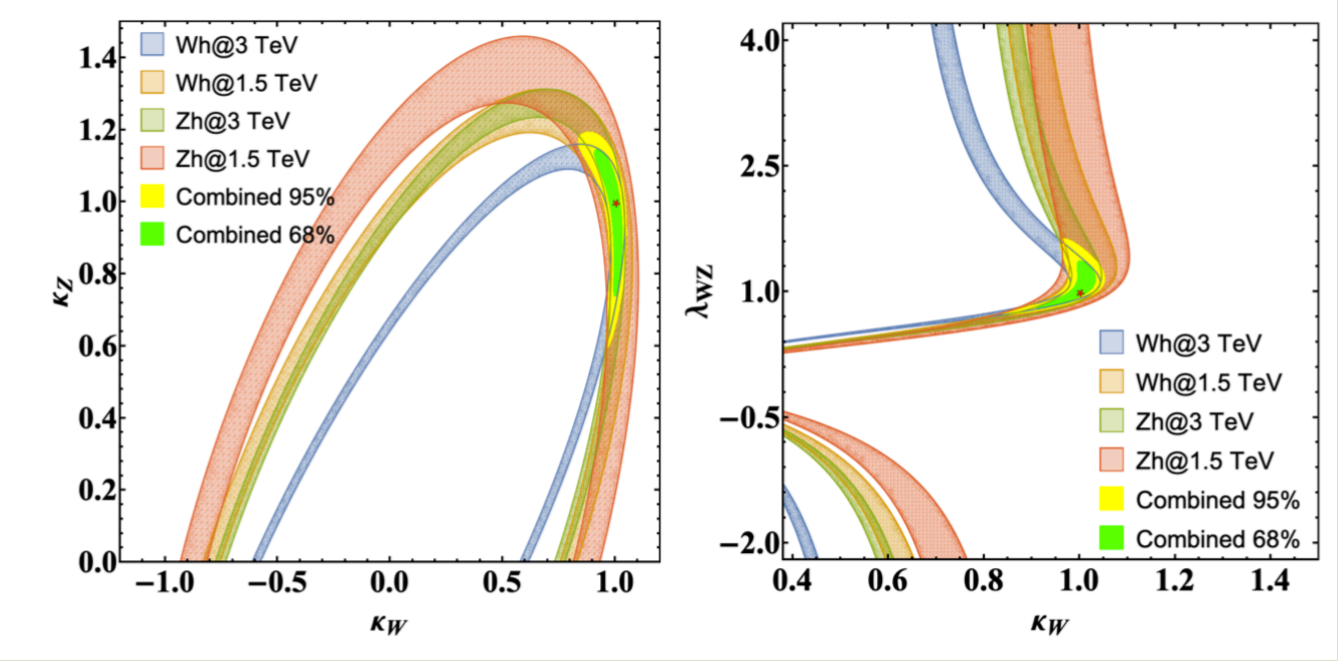


Prospects from Rate Measurements

- Luminosity needed to exclude several benchmark

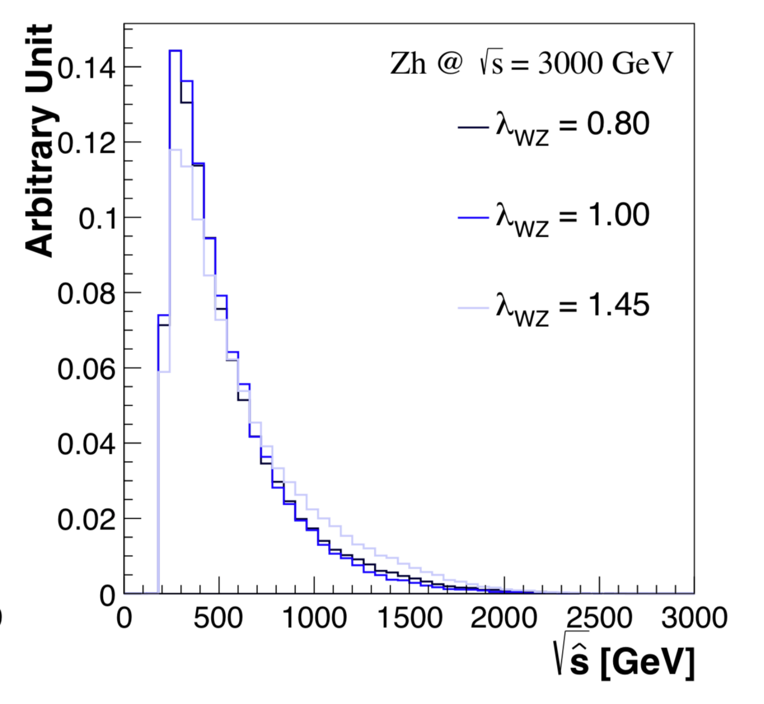
Benchmark	$\sqrt{s} = 3.0$ TeV	$\sqrt{s} = 1.5$ TeV
$\kappa_W = \pm 1,\ \kappa_Z = \mp 1$	3.4 fb^{-1}	14.1 fb^{-1}
$\kappa_W = 1,\ \kappa_Z = 0$	29.3 fb^{-1}	243.3 fb^{-1}
$\kappa_W = 0,\ \kappa_Z = 1$	62.1 fb^{-1}	1772.4 fb^{-1}

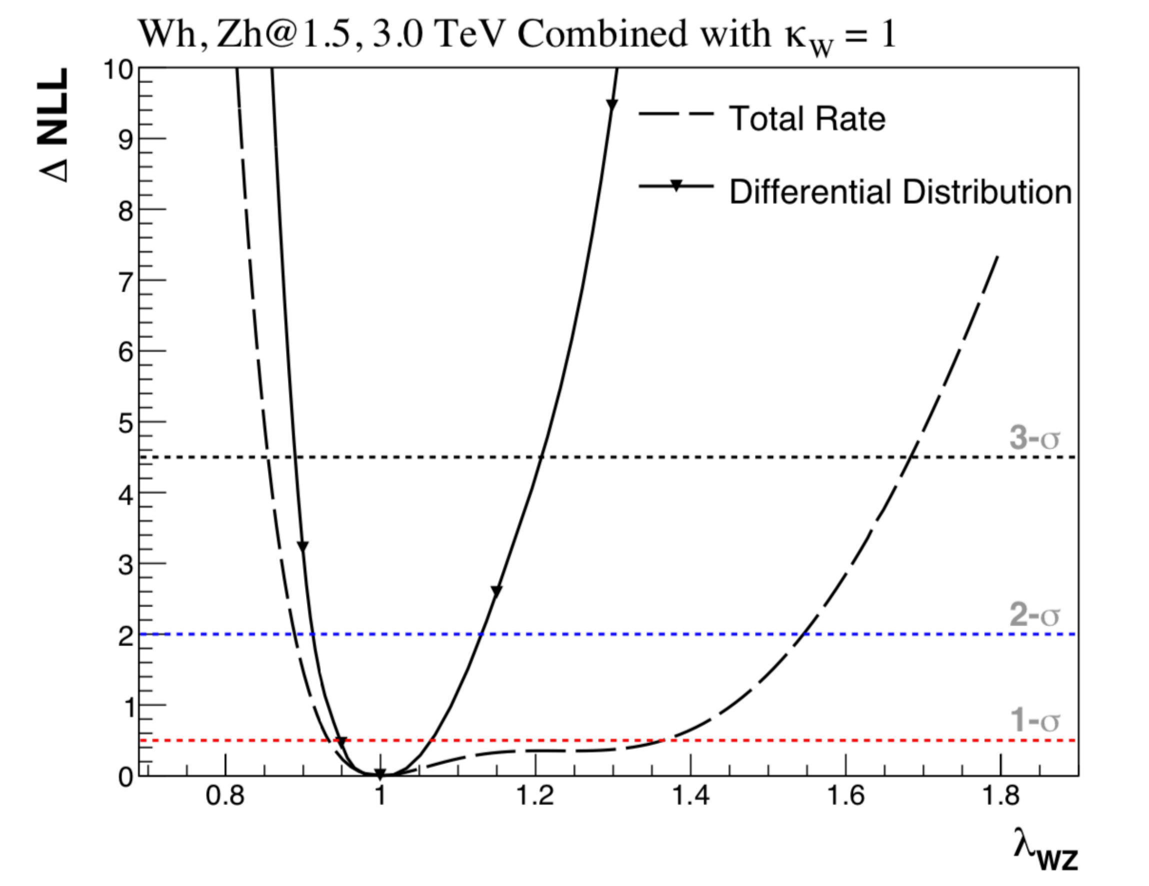
CLIC 1.5TeV/3TeV Scenario are considered



Prospects from Distribution

- Differential Distribution Improves the rate measurement





$\sqrt{\hat{s}}$: Invariant mass of all visible products of Zh or Wh

Summary

- VBF process:
  - $W^+W^- \to Zh$
  - $W^\pm Z \to W^\pm h$
- Tree level interferences, sensitive to the relation between κ_W and κ_Z
- Can be well probed at high energy lepton collider
- Plan:
  - Operators in SMEFT
  - Muon Collider/LHC

Thanks for your attention!

Backups

σ [fb]		Wh		Zh	
$\sqrt{s}$ [GeV]		$P(e^-) = -80\%$	$P(e^-) = 80\%$	$P(e^-) = -80\%$	$P(e^-) = 80\%$
350	σ_Z	6.81×10^{-3}	2.46×10^{-3}	1.08×10^{-2}	2.91×10^{-3}
	σ_W	3.85×10^{-2}	8.27×10^{-2}	1.49×10^{-2}	1.65×10^{-3}
	σ_{WZ}	-3.94×10^{-3}	-2.22×10^{-3}	-1.03×10^{-2}	-1.16×10^{-3}
1500	σ_Z	8.25×10^{0}	3.18×10^{0}	3.85×10^{0}	4.25×10^{-1}
	σ_W	1.22×10^{1}	4.11×10^{0}	6.85×10^{0}	7.66×10^{-1}
	σ_{WZ}	-1.28×10^{1}	-5.46×10^{0}	-5.38×10^{0}	5.93×10^{-1}
3000	σ_Z	3.51×10^{1}	1.34×10^{1}	1.87×10^{1}	2.09×10^{0}
	σ_W	4.31×10^{1}	1.50×10^{1}	2.97×10^{1}	3.27×10^{0}
	σ_{WZ}	-6.32×10^{1}	-2.52×10^{1}	-3.13×10^{1}	-3.45×10^{0}

Monte Carlo Analysis

- Cuts

Cuts	Wh-Cuts	Zh-Cuts
Basic Cuts	$p_T^\ell > 20$ GeV, $N_\ell = 2$ $p_T^j > 20$ GeV, $N_b = 2$	
	$N_e \geq 1$	1 OSSF Pair
m_{bb}	95 GeV $\leq m_{bb} \leq$ 130 GeV	
$m_{\ell\ell}$	$m_{\ell\ell} \leq 80$ GeV or $m_{\ell\ell} \geq 98$ GeV	75 GeV $\leq m_{\ell\ell} \leq$ 100 GeV
H_T	$\begin{cases} H_T \leq 2500 \text{ GeV} & \sqrt{s} = 3000 \text{ GeV} \\ H_T \leq 1100 \text{ GeV} & \sqrt{s} = 1500 \text{ GeV} \end{cases}$	$\begin{cases} H_T \leq 1500 \text{ GeV} & \sqrt{s} = 3000 \text{ GeV} \\ H_T \leq 700 \text{ GeV} & \sqrt{s} = 1500 \text{ GeV} \end{cases}$

Monte Carlo Analysis

- Signal vs. Background

	σ (fb)	$\sqrt{s}=3.0$ TeV, $\mathcal{L}=4$ ab^{-1}			$\sqrt{s}=1.5$ TeV $\mathcal{L}=2$ ab^{-1}		
		Before Cuts	Wh-Cuts	Zh-Cuts	Before Cuts	Wh-Cuts	Zh-Cuts
Signal	Wh(VBF)	1.97×10^{0}	7.26×10^{-2}	1.36×10^{-3}	9.62×10^{-1}	6.54×10^{-2}	2.37×10^{-3}
	Zh(VBF)	6.47×10^{-1}	3.49×10^{-3}	7.21×10^{-2}	2.03×10^{-1}	1.30×10^{-3}	2.87×10^{-2}
BG	tt	1.17×10^{0}	5.83×10^{-4}	6.10×10^{-6}	4.65×10^{0}	5.64×10^{-3}	8.05×10^{-5}
	WZ(VBF)	4.47×10^{0}	9.97×10^{-3}	2.16×10^{-4}	1.84×10^{0}	5.86×10^{-3}	1.96×10^{-4}
	ZZ(VBF)	1.92×10^{0}	4.21×10^{-4}	8.07×10^{-3}	5.92×10^{-1}	1.48×10^{-4}	2.88×10^{-3}
	Zh	5.88×10^{-2}	1.83×10^{-4}	4.15×10^{-4}	2.39×10^{-1}	4.10×10^{-4}	1.12×10^{-3}
	ZWW	4.01×10^{-1}	1.14×10^{-3}	4.97×10^{-6}	6.36×10^{-1}	2.02×10^{-3}	1.72×10^{-5}
	ZZZ	5.06×10^{-3}	6.04×10^{-7}	1.12×10^{-5}	9.79×10^{-3}	1.74×10^{-6}	2.34×10^{-5}
	Sum	8.02×10^{0}	1.23×10^{-2}	8.72×10^{-3}	7.97×10^{0}	1.41×10^{-2}	4.32×10^{-3}
		Precision (%)	6.18	6.17	Precision (%)	9.53	13.5