Measuring λ_{WZ} through tree-level interference

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SYSU-PKU Collider Physics Forum

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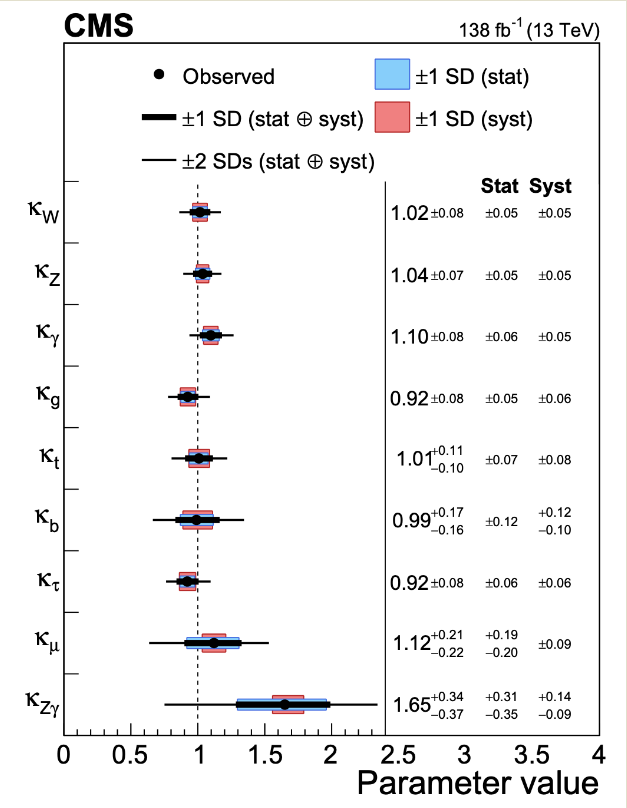
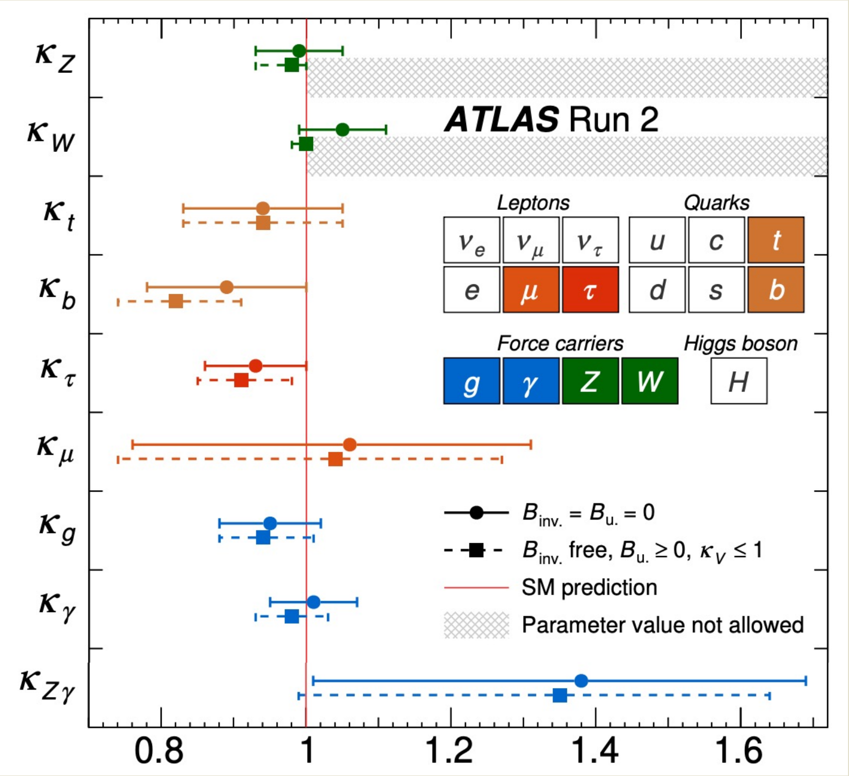
Daniel Stolarski, **YW**; Phys. Rev. D 102 (2020) 033006; 2006.09374
Chaitanya Paranjape, Daniel Stolarski, **YW**; 2203.05729

Higgs Coupling Measurements

- Electroweak Symmetry Breaking
  - $\kappa_V, \kappa_f, \kappa_3$ etc
- Current Measurement:



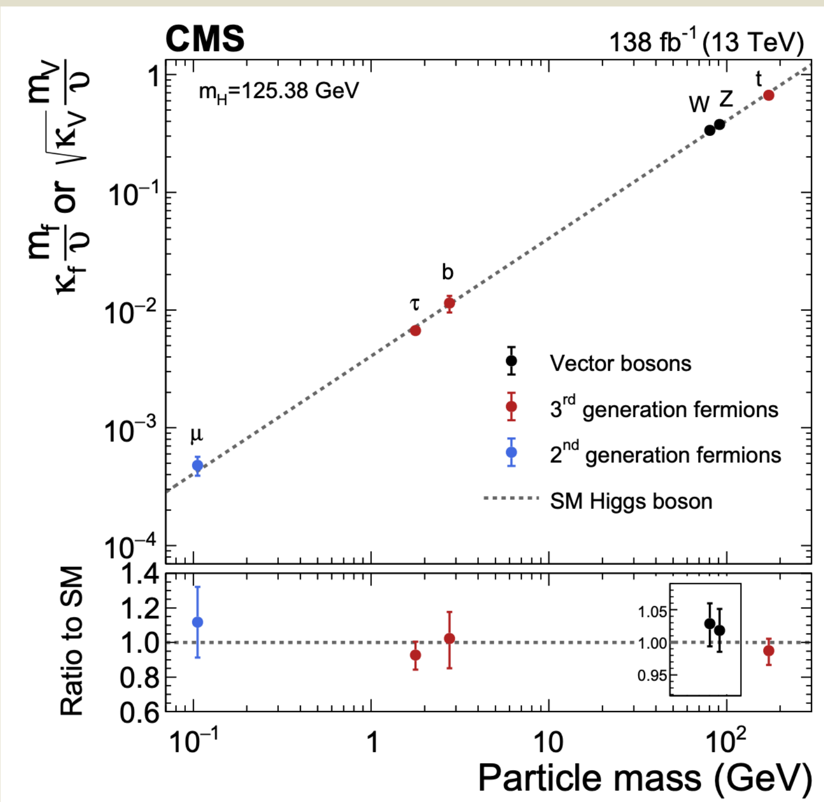


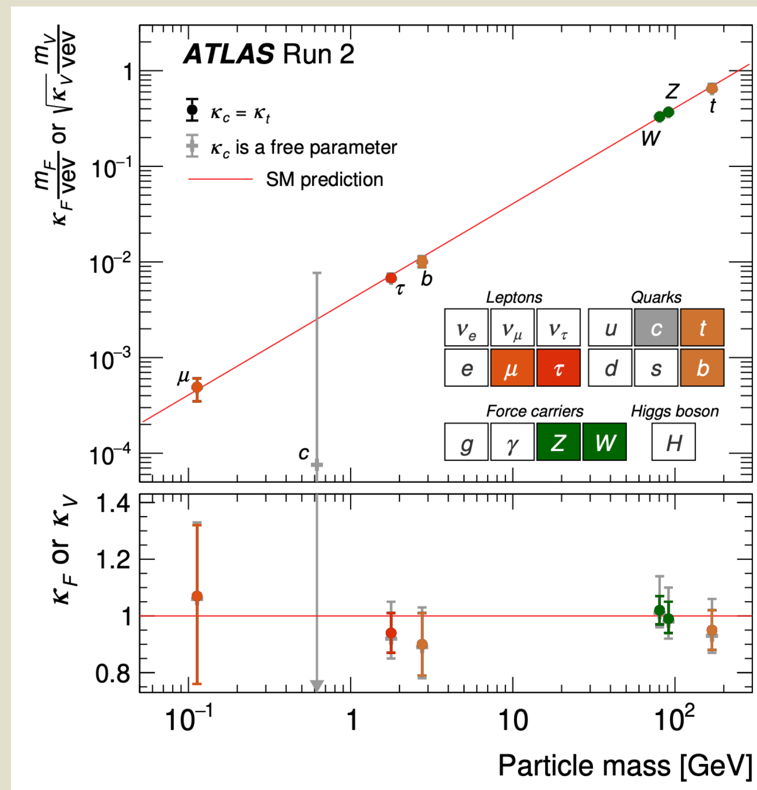
CMS: 2207.00043

ATLAS: 2207.00092

Higgs Coupling Measurements

- Electroweak Symmetry Breaking
  - κ_V, κ_f etc
- Current Measurement:



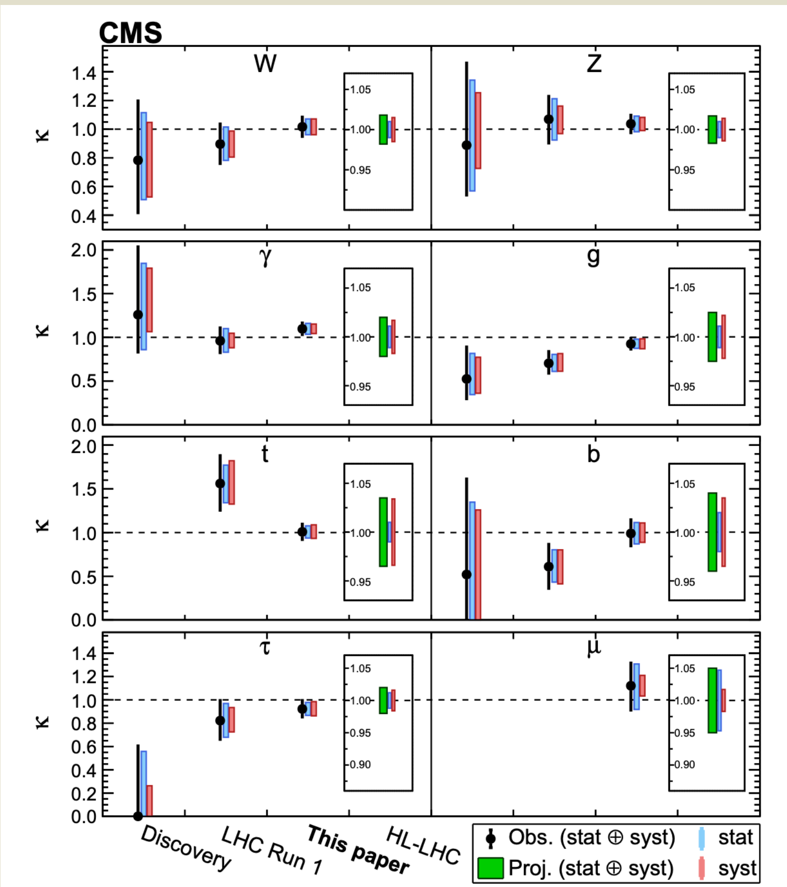


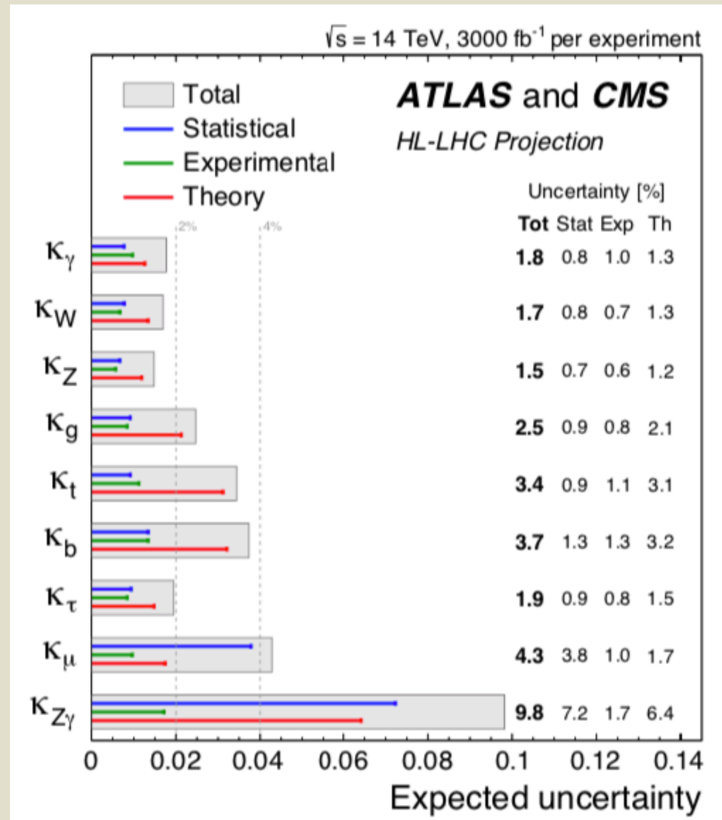
CMS: 2207.00043

ATLAS: 2207.00092

Higgs Coupling Measurements

- Electroweak Symmetry Breaking
- Prospects:





HL-LHC Prospects

- 1902.00134/1902.10229
- ATL-PHYS-PUB-2018-054
- CMS-PAS-FTR-18-011

CMS: 2207.00043

Higgs Coupling Measurements

- Electroweak Symmetry Breaking
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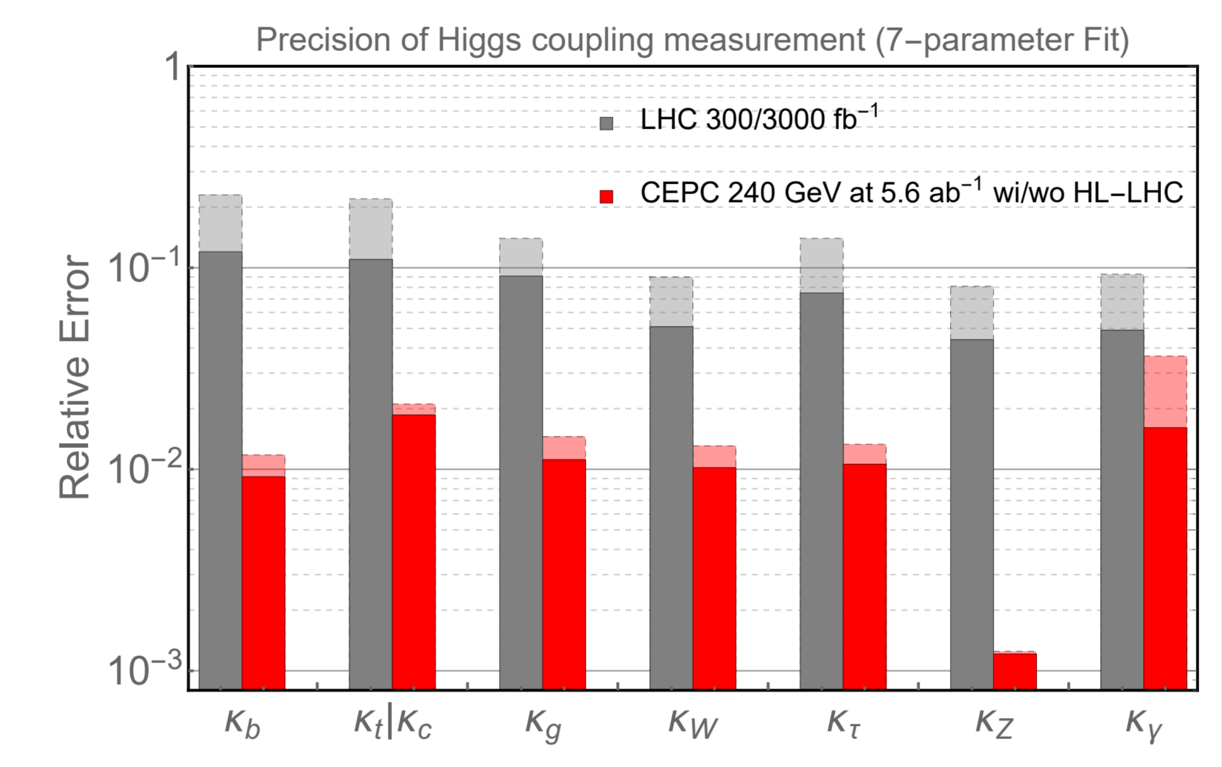
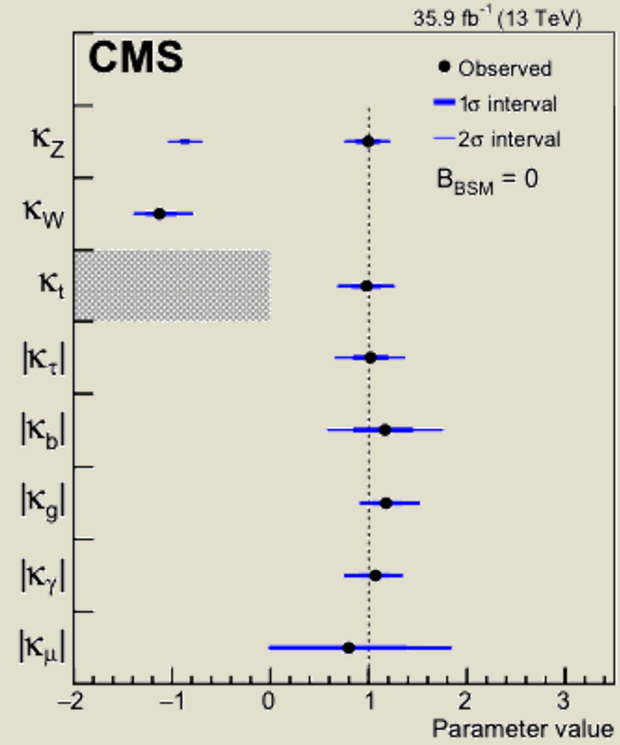


Higgs Coupling Measurements

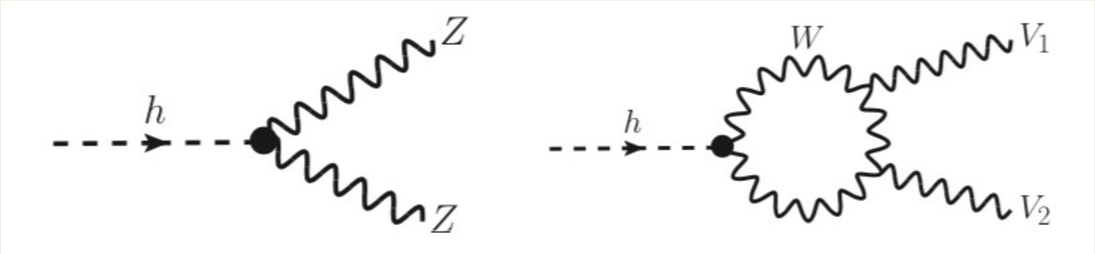
- Electroweak Symmetry Breaking
  - κ_W, κ_Z $\mathcal{L} = g m_W h\left(\kappa_W W^+ W^- + \frac{\kappa_Z}{2c_W^2} Z^2\right)$
  - $\lambda_{WZ} = \frac{\kappa_W}{\kappa_Z}$ **$\lambda_{WZ} = 1$ For SM**
- Georgi-Machacek Model:
  - $\lambda_{WZ} = -\frac{1}{2}$ for Fiveplet
- Current Measurement:
  - 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

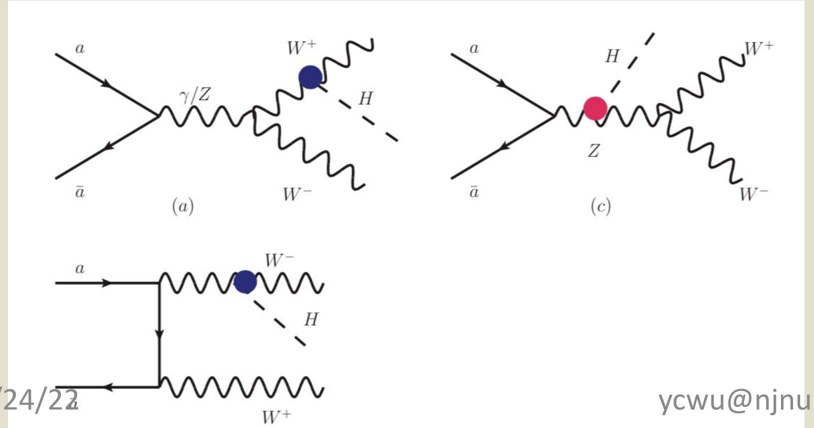


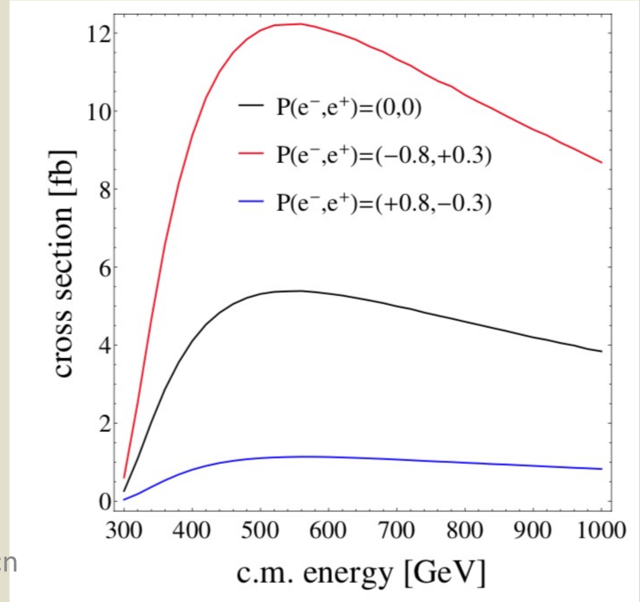
λ_{WZ} Measurements

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

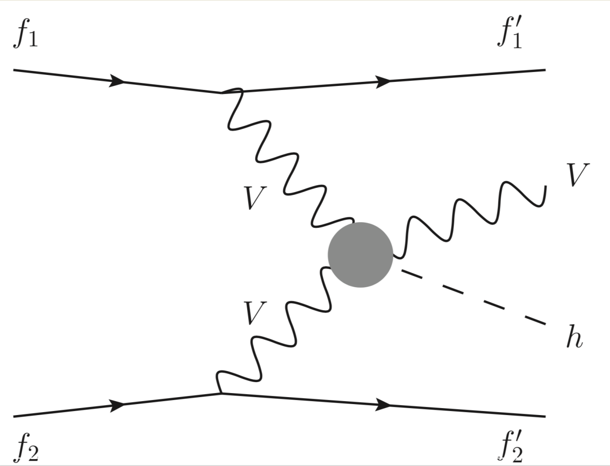


- Tree level interference:
  - $f\bar{f} \to W^+W^-h$ **1805.01689**

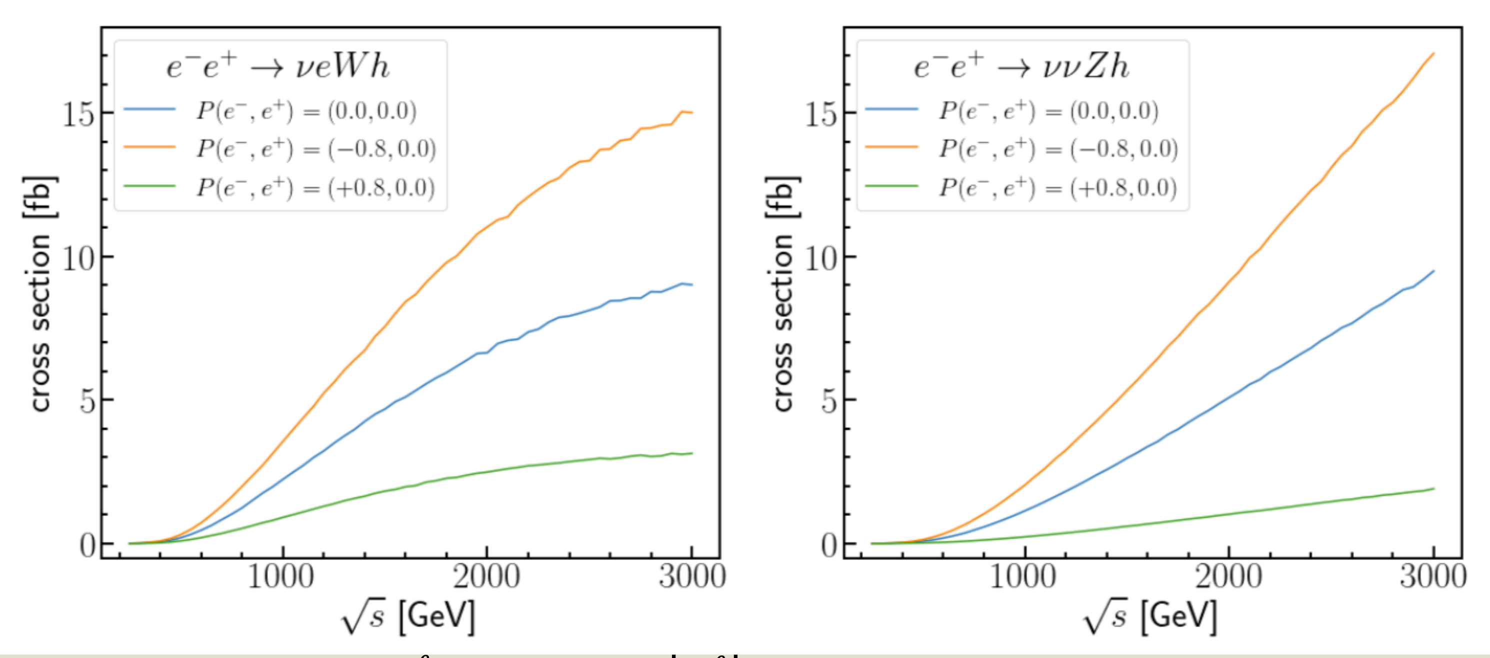




Proposed Process



- Processes:
  - Tree-level interferences
  - $W^{\pm}Z \to W^{\mp}h$
  - $W^{+}W^{-} \to \; Z\,h$
- VBF nature suitable for Higher energy collider

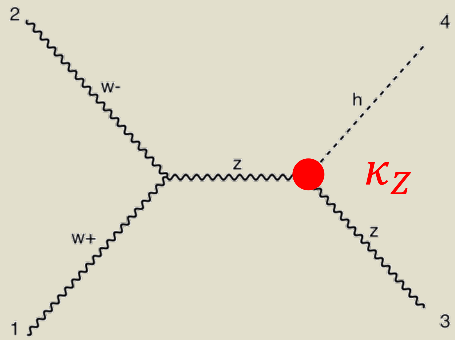


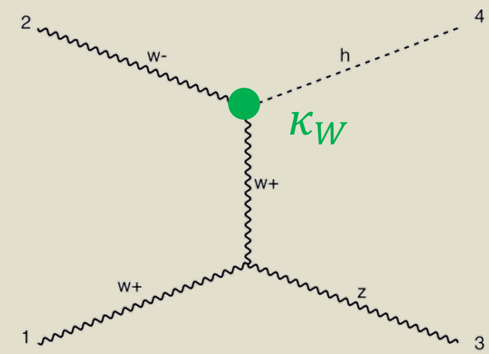
Fix-order MG5 w/ $p_T^{\ell} > 10\ GeV, \left|\eta^{\ell}\right| < 3.5$

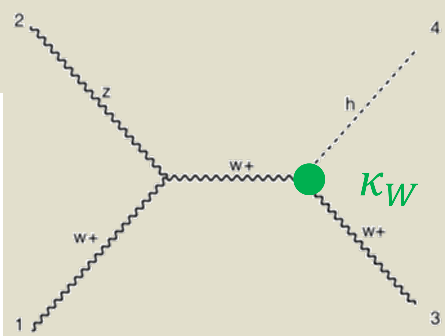
EW A/EW-PDF
2007.14300

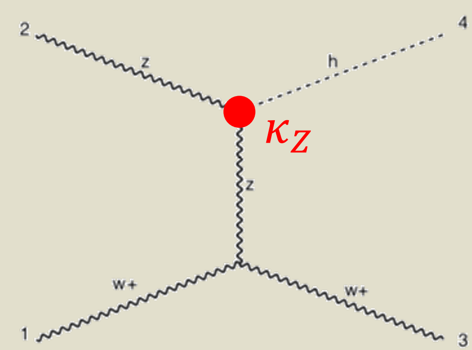
$2 \to 2$ Processes

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





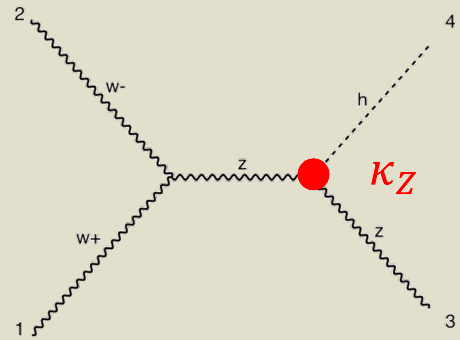


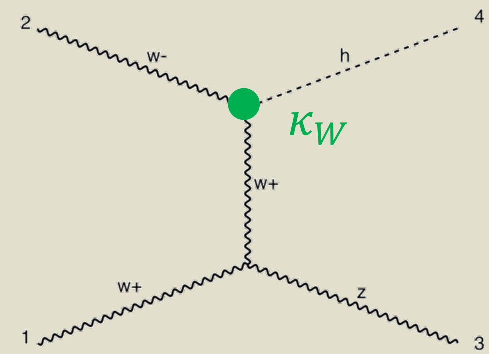


	$\mathcal{M}_{s/t}$	$\mathcal{M}_s + \mathcal{M}_t$	$d\sigma_{s/t}$	$d\sigma_{\text{tot}}$
TTT	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$	$\frac{1}{s^2}$	$\frac{1}{s^2}$
LTT	s^0	s^0	$\frac{1}{s}$	$\frac{1}{s}$
LLT	$\sqrt{s}$	$\frac{1}{\sqrt{s}}$	s^0	$\frac{1}{s^2}$
LLL	s	s^0	s	$\frac{1}{s}$

$2 \to 2$ Processes

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



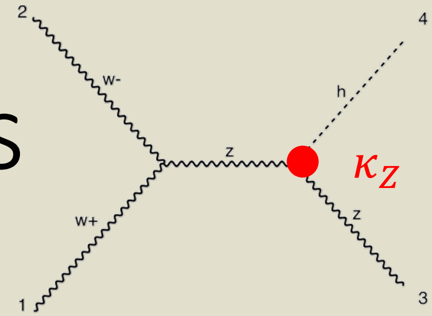


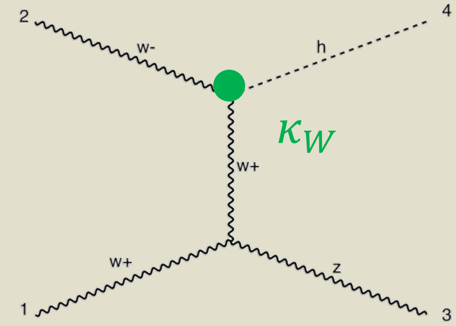
- For $W_L W_L \to Z_L h$:
  - $\mathcal{M}_s(W_L^+ W_L^- \to Z_L h) = \frac{\kappa_Z g^2 \cos\theta}{4\, m_W^2}\left(s - m_h^2 + 2m_Z^2\right) + \mathcal{O}\left(\frac{1}{s}\right)$
  - $\mathcal{M}_t(W_L^+ W_L^- \to Z_L h) = \frac{\kappa_W g^2}{4 m_W^2}\left(\cos\theta\left(-s + 2m_W^2 + m_Z^2 - m_h^2\right) + \frac{8 m_W^2 \cos\theta}{\sin^2\theta}\right) + \mathcal{O}\left(\frac{1}{s}\right)$
  - $\mathcal{M}(W_L^+ W_L^- \to Z_L h) = \kappa_Z \frac{g^2 c_\theta}{4 m_W^2}(1 - \lambda_{WZ})s + \mathcal{O}(s^0)$

Grow with Energy unless the parameter takes the exactly SM value

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

$2 \rightarrow 2$ Processes





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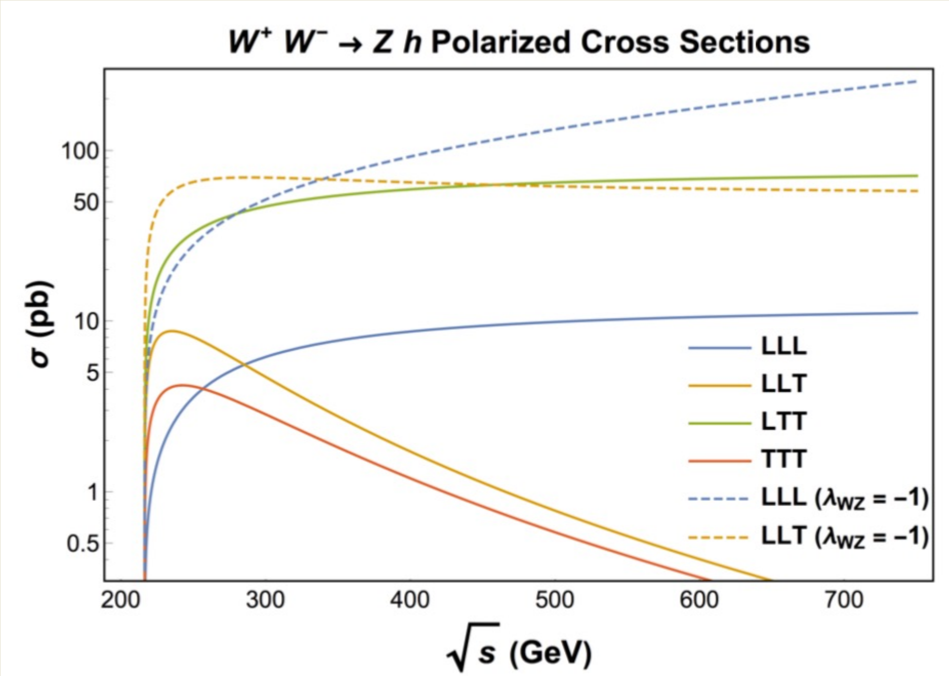
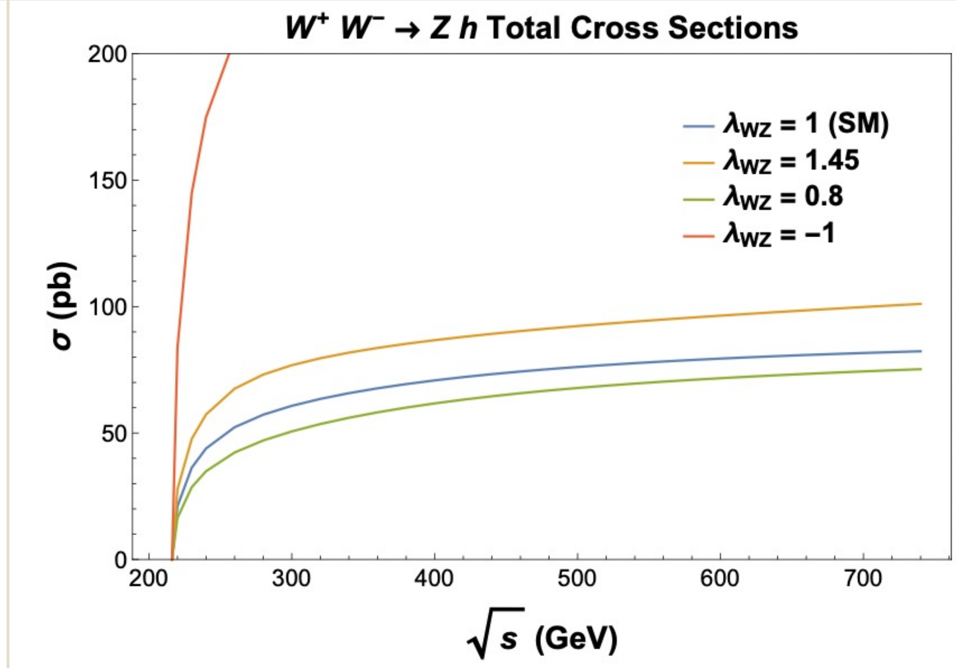
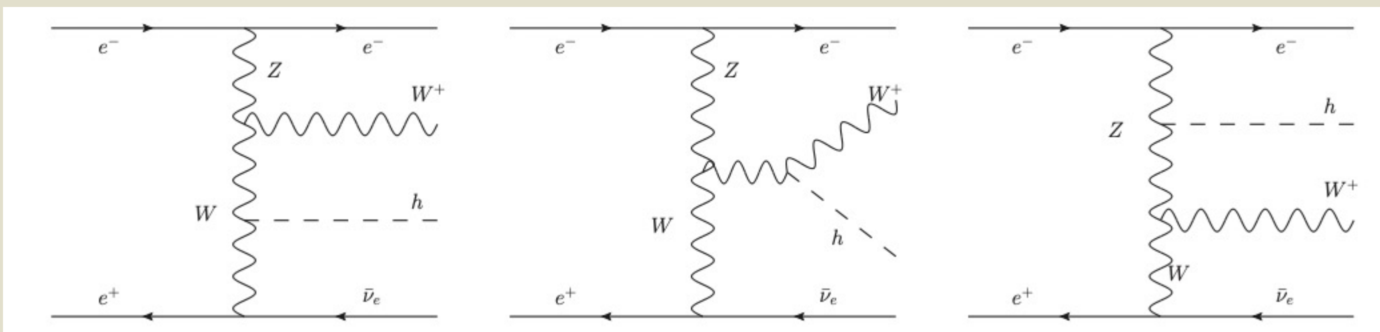
  - $\mathcal{M}(W_L^+ W_L^- \rightarrow Z_L h) = \kappa_Z \frac{g^2 c_\theta}{4m_W^2}(1-\lambda_{WZ})s + \mathcal{O}(s^0)$

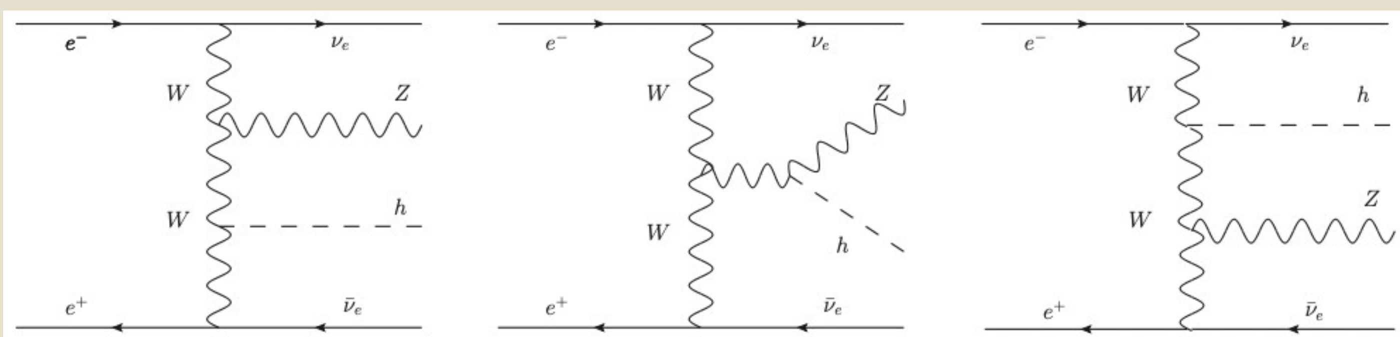




@ Lepton Collider

- CLIC (or future Muon Collider)
  - High C.M. Energy
- Processes:
  - $\ell^- \ell^+ \to \ell^\pm \nu \, W^\mp h$
  - $\ell^- \ell^+ \to \nu \, \nu \, Z \, h$





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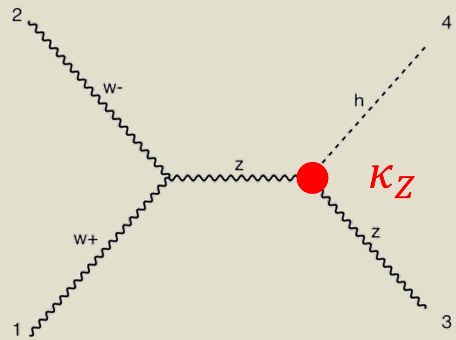
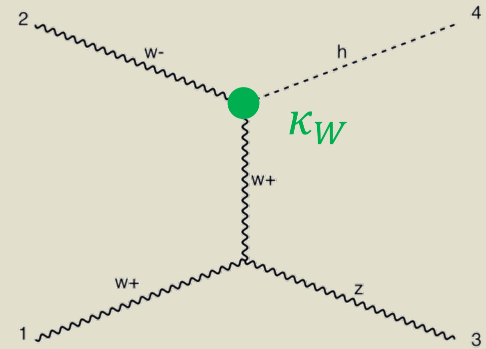




- Processes:
  - $\ell^-\ell^+ \to \ell^\pm \nu\, W^\mp h$
  - $\ell^-\ell^+ \to \nu\, \nu\, Z\, h$
- $\sigma = \kappa_W^2 \sigma_W + \kappa_W \kappa_Z \sigma_{WZ} + \kappa_Z^2 \sigma_Z^2$

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}

@ Lepton Collider

- CLIC (or future Muon Collider)
  - High C.M. Energy
- Processes:
  - $\ell^- \ell^+ \to \ell^\pm \nu\, W^\mp h$
  - $\ell^- \ell^+ \to \nu\, \nu\, Z\, h$
- Decays:
  - Leptonic Decay of W/Z
  - $h \to b\, \bar{b}$
- Final states:
  - Two b-jets
  - Two isolated leptons

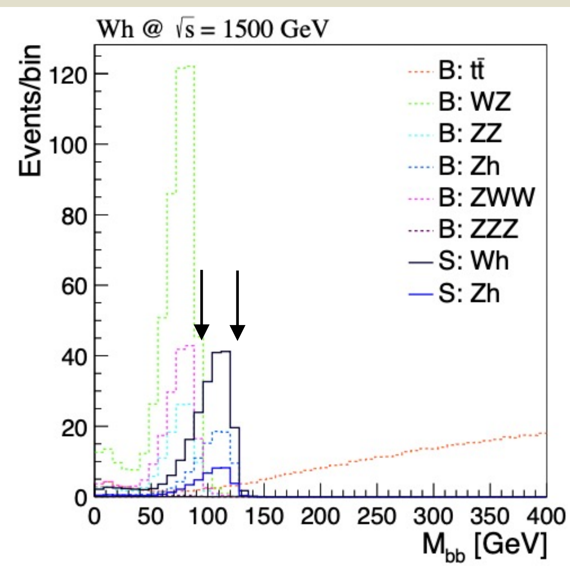
- **Backgrounds:**

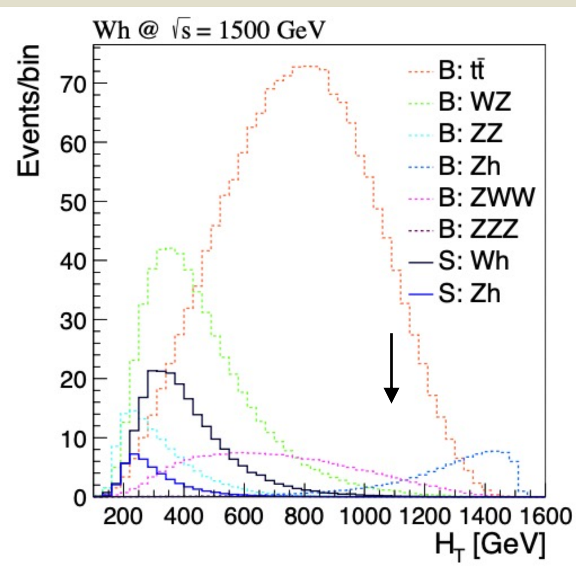
$$e^-e^+ \to t\bar{t} \to b\bar{b}\ell^-\ell^+\nu_\ell\bar{\nu}_\ell,$$
$$e^-e^+ \to e^\pm\nu_e W^\pm Z \to e^\pm\nu_e\ell^\mp\nu_\ell b\bar{b},$$
$$e^-e^+ \to \nu_e\bar{\nu}_e ZZ \to \nu_e\bar{\nu}_e\ell^-\ell^+ b\bar{b},$$
$$e^-e^+ \to Zh, Z \to \ell^-\ell^+, h \to b\bar{b},$$
$$e^-e^+ \to ZW^+W^-, Z \to b\bar{b}, W^+ \to \ell^+\nu_\ell, W^- \to \ell^-\bar{\nu}_\ell,$$
$$e^-e^+ \to ZZZ, Z \to b\bar{b}, Z \to \ell^-\ell^+, Z \to \nu_\ell\bar{\nu}_\ell.$$

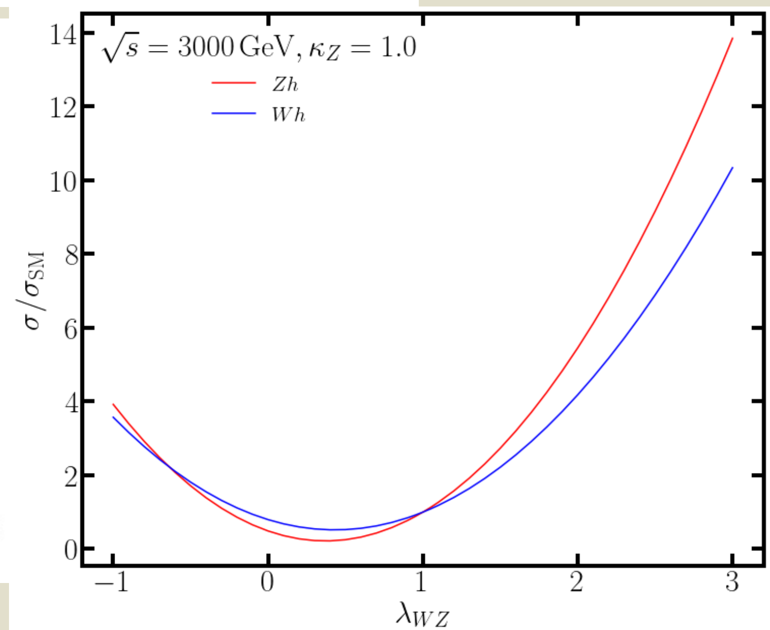
Total Rate @ Lepton Collider

- The cuts to extract the signal events

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}	$95 \text{ GeV} \leq m_{bb} \leq 130 \text{ GeV}$	
$m_{\ell\ell}$	$m_{\ell\ell} \leq 80$ GeV or $m_{\ell\ell} \geq 98$ GeV	$75 \text{ GeV} \leq m_{\ell\ell} \leq 100 \text{ GeV}$
H_T	$\begin{cases} H_T \leq 2500 \text{ GeV} & \sqrt{s} = 3000 \text{ GeV} \\ H_T \leq 1100 \text{ GeV} & \sqrt{s} = 1500 \text{ GeV} \end{cases}$	$\begin{cases} H_T \leq 1500 \text{ GeV} & \sqrt{s} = 3000 \text{ GeV} \\ H_T \leq 700 \text{ GeV} & \sqrt{s} = 1500 \text{ GeV} \end{cases}$







Total Rate @ Lepton Collider

- Cut Flow:

$\kappa_W = 1, \kappa_Z = 1$ $\boldsymbol{P(e^-) = -0.8}$

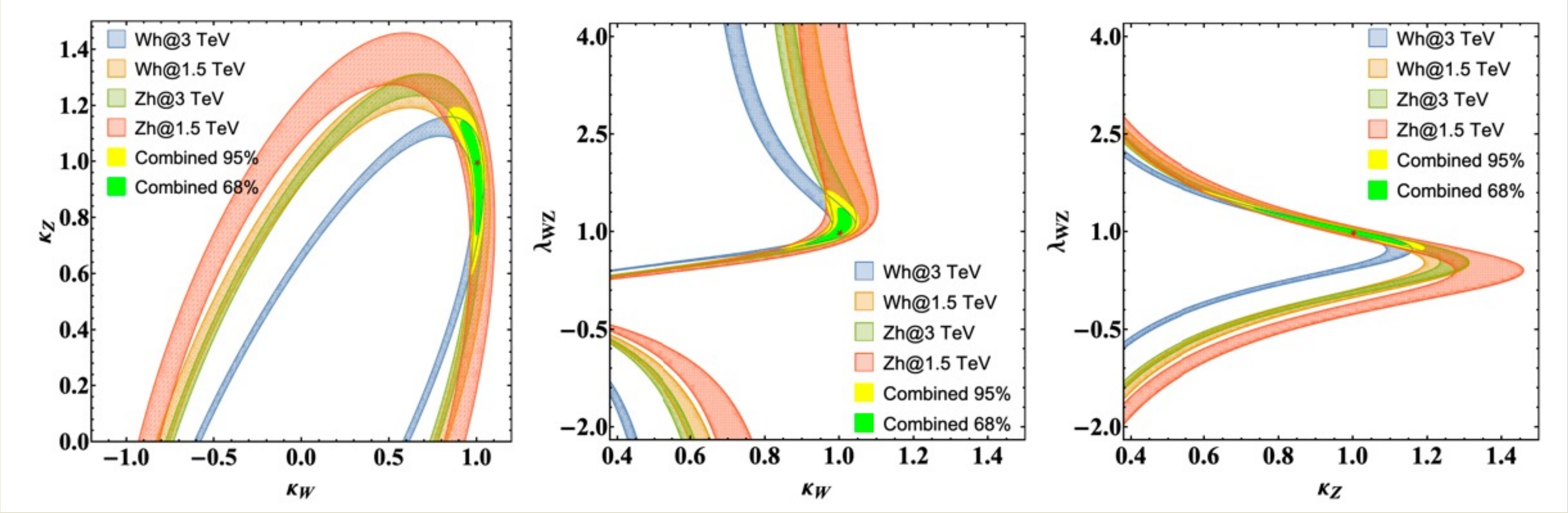
σ (fb)		$\sqrt{s} = 3.0$ TeV, $\mathcal{L} = 4$ ab^{-1} Before Cuts	Wh-Cuts	Zh-Cuts	$\sqrt{s} = 1.5$ TeV $\mathcal{L} = 2$ ab^{-1} Before Cuts	Wh-Cuts	Zh-Cuts
Signal	Wh(VBF)	1.97×10^0	7.26×10^{-2}	1.36×10^{-3}	9.62×10^{-1}	6.54×10^{-2}	2.37×10^{-3}
	Zh(VBF)	6.47×10^{-1}	3.49×10^{-3}	7.21×10^{-2}	2.03×10^{-1}	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

Total Rate @ Lepton Collider

- Benchmark point against SM at 95% C.L.

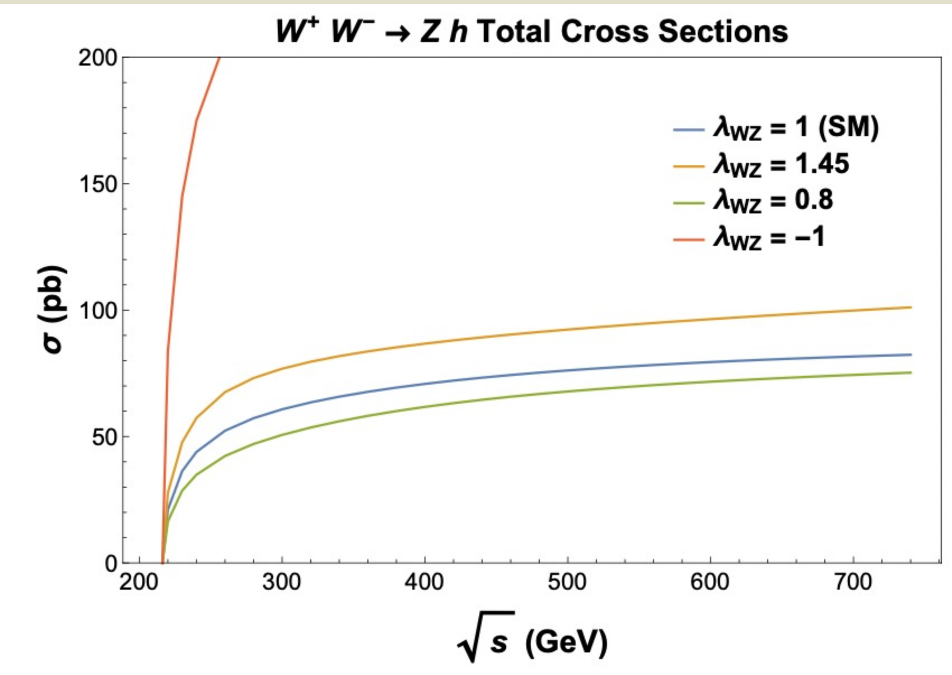
Benchmark	$\sqrt{s} = 3.0$ TeV	$\sqrt{s} = 1.5$ TeV
$\kappa_W = \pm 1,\ \kappa_Z = \mp 1$	3.4 fb^{-1}	14.1 fb^{-1}
$\kappa_W = 1,\ \kappa_Z = 0$	29.3 fb^{-1}	243.3 fb^{-1}
$\kappa_W = 0,\ \kappa_Z = 1$	62.1 fb^{-1}	1772.4 fb^{-1}

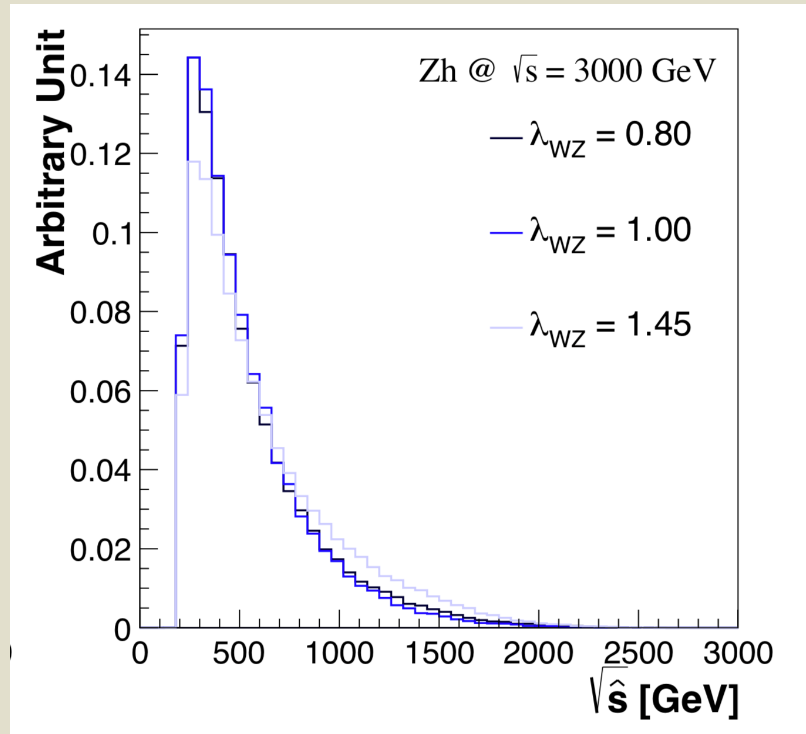
- For $\kappa_W, \kappa_Z, \lambda_{WZ}$



Distribution Measurement

- Differential Distribution

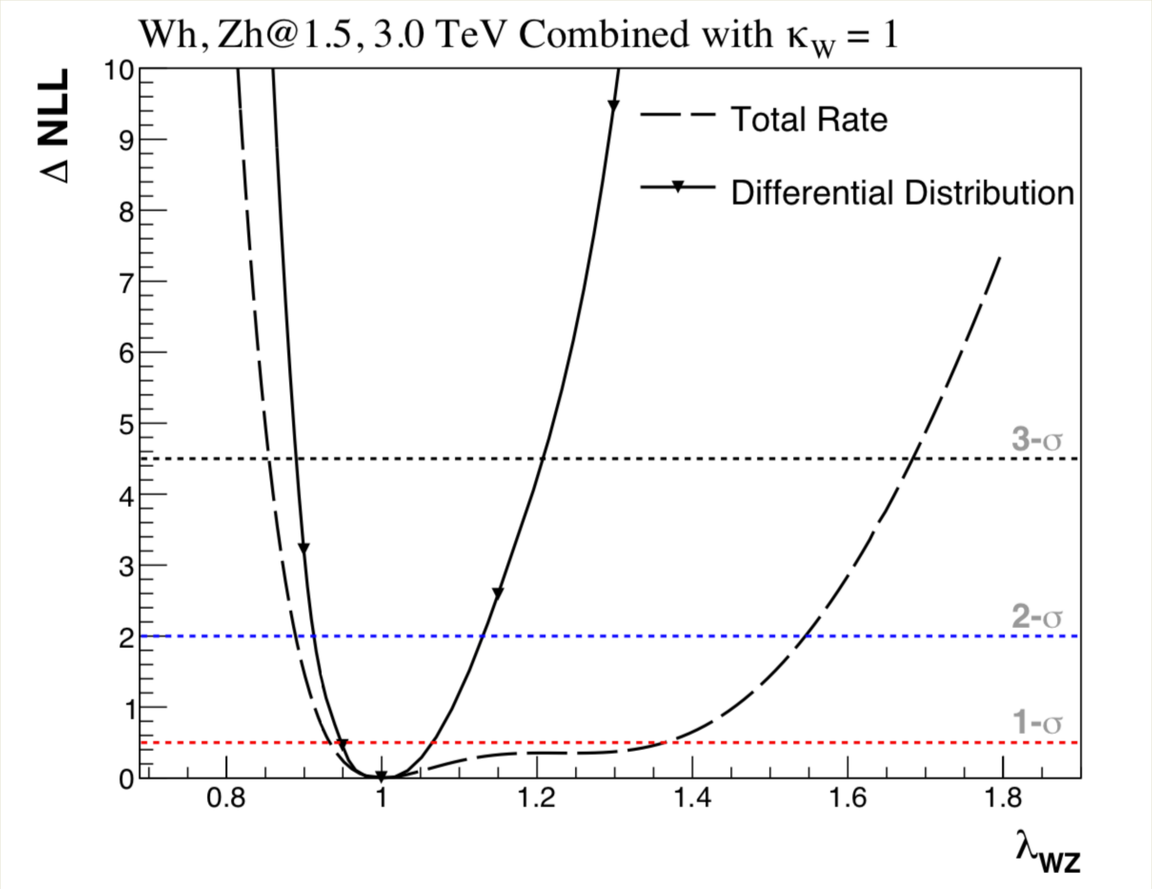




$\sqrt{\hat{s}}$: Invariant mass of all visible products of Zh or Wh

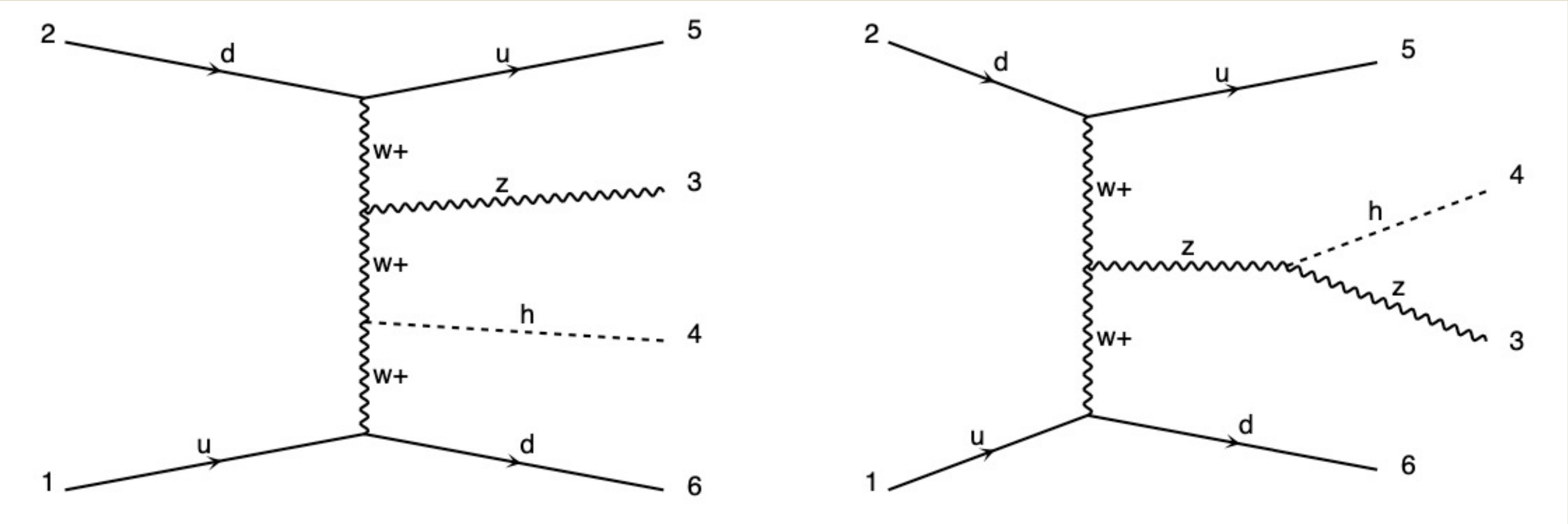
Distribution Measurement

- Differential Distribution



@ Hadron Collider

- Small Cross Section



Cross Section @ Hadron Collider

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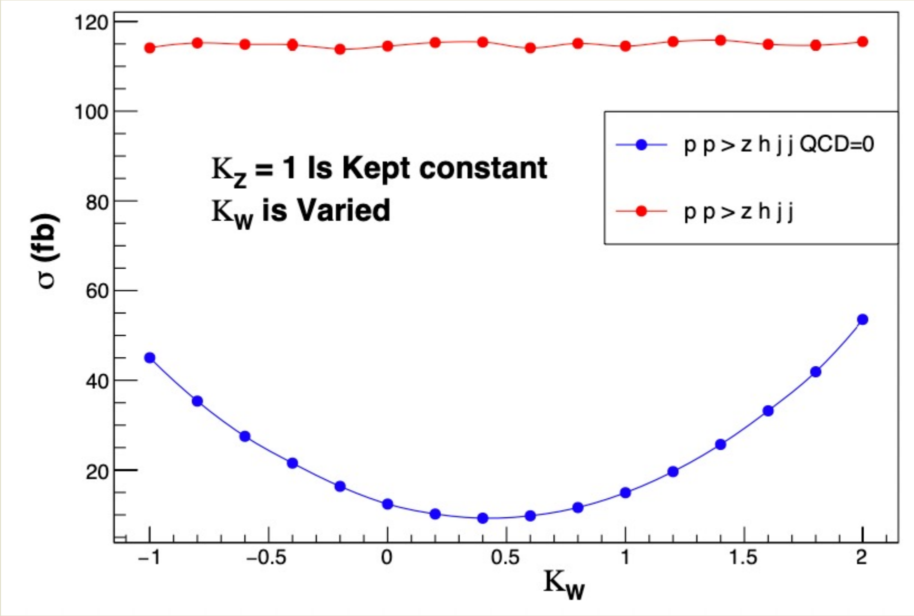
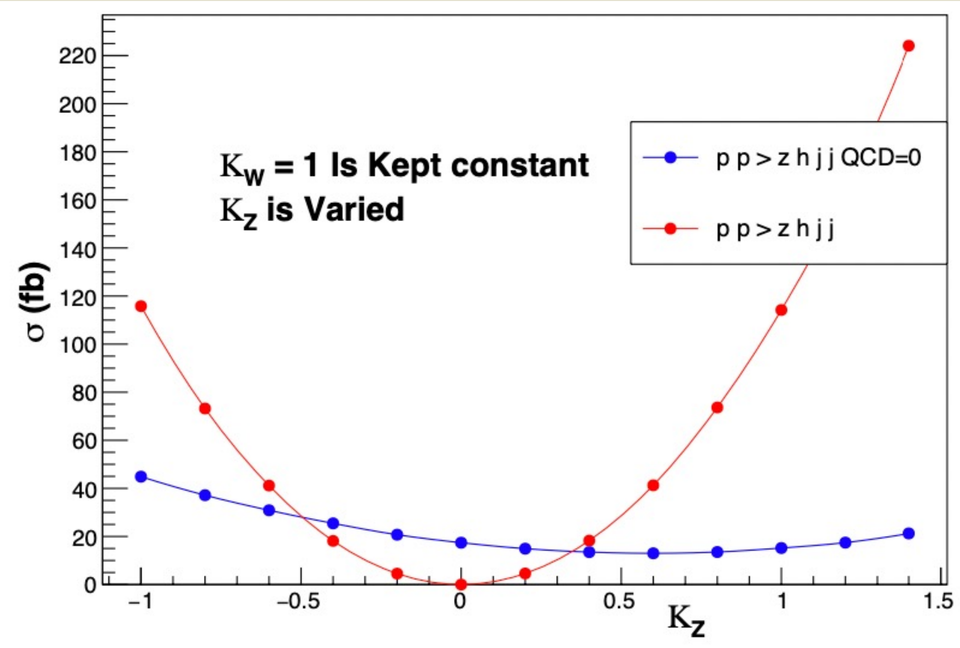




- $\sigma = \kappa_W^2 \sigma_W + \kappa_W \kappa_Z \sigma_{WZ} + \kappa_Z^2 \sigma_Z$

σ_W	17.41 fb
σ_{WZ}	-14.76 fb
σ_Z	12.41 fb

Cross Section @ Hadron Collider

- Worse Background
  - $h \to b\,\bar{b},\ z \to \ell\ell$

Processes	Cross Section [fb]
$\boldsymbol{p\,p\ \to z\,h\,j\,j}$ **Signal**	~0.4
$\boldsymbol{p\,p \to z\,h\,j\,j}$ **QCD**	~0.9
$\boldsymbol{p\,p \to t\,t}$	~5000
$\boldsymbol{p\,p \to z\,z\,j\,j}$	~10
$\boldsymbol{p\,p \to z\,b\,b\,j\,j}$	~1000

With Basic VBF cuts applied

Event Selection @ Hadron Collider

- $h \to b\,\bar{b},\ z \to \ell\ell$

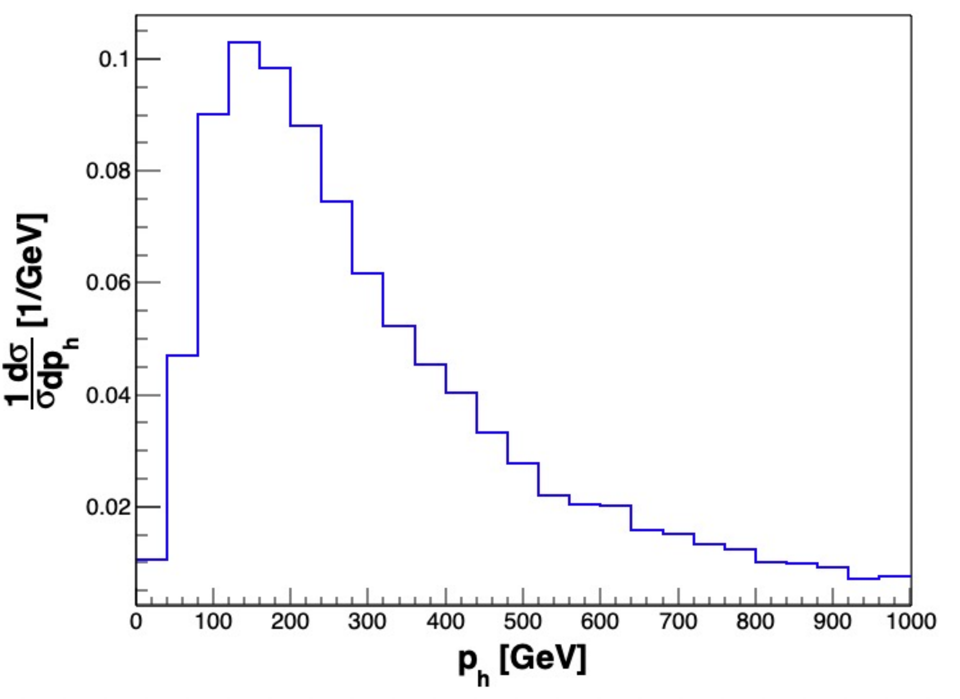
With Basic VBF cuts applied

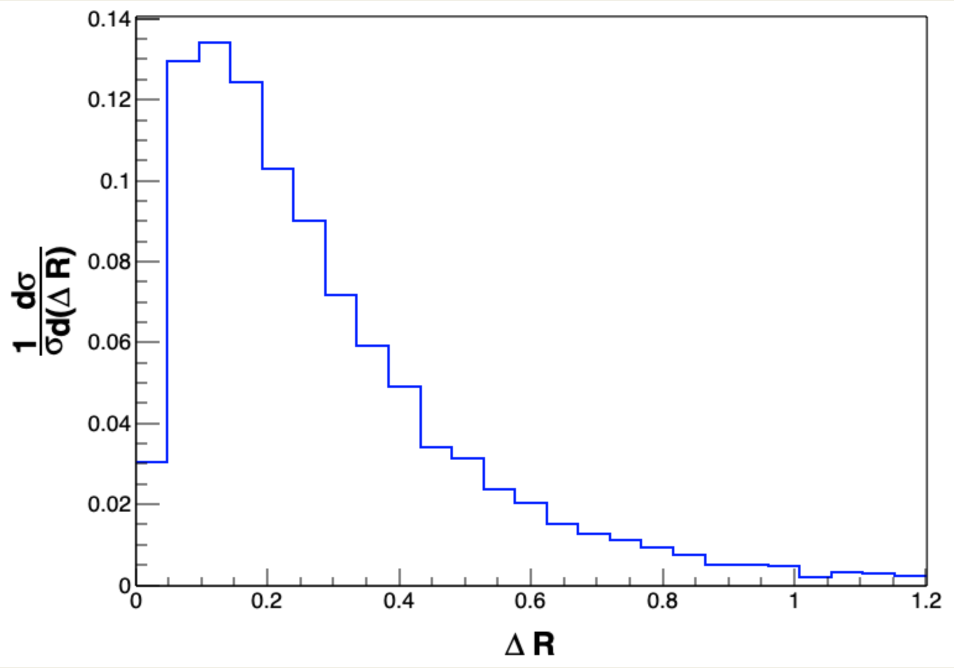
Processes	Cross Section [fb]	Cross Section With Cuts [fb]	Efficiency
$\boldsymbol{p\,p\ \to z\,h\,j\,j}$ Signal	~0.4	~0.002	5.0e-3
$\boldsymbol{p\,p \to z\,h\,j\,j}$ QCD	~0.9	~0.0001	1.1e-4
$\boldsymbol{p\,p \to t\,t}$	~5000	~0.003	6.0e-7
$\boldsymbol{p\,p \to z\,z\,j\,j}$	~10	~0.0004	4.0e-5
$\boldsymbol{p\,p \to z\,b\,b\,j\,j}$	~1000	~0.014	1.4e-5

- **VBF topology**
- **Higgs Invariant Mass**
- **Z peak**
- **Center Jet Veto**

Higgs @ Hadron Collider

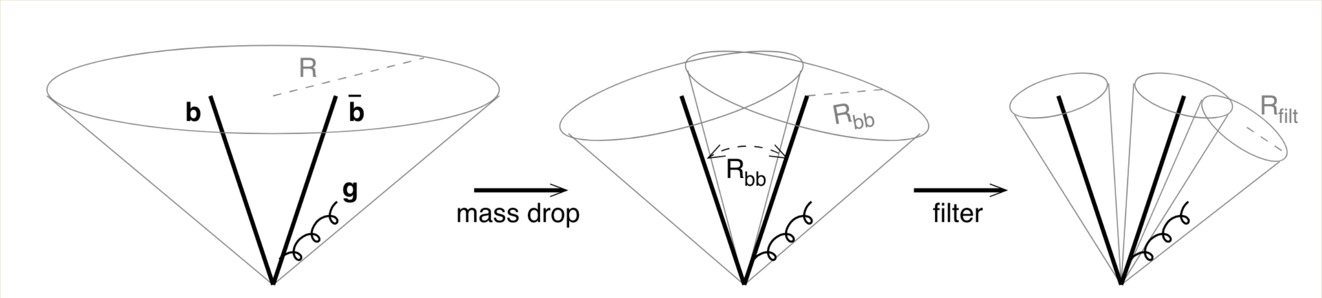
- $h \to b\,\bar{b}$
- Will be boosted at the LHC $\sqrt{s} = 13{\sim}14\ TeV$

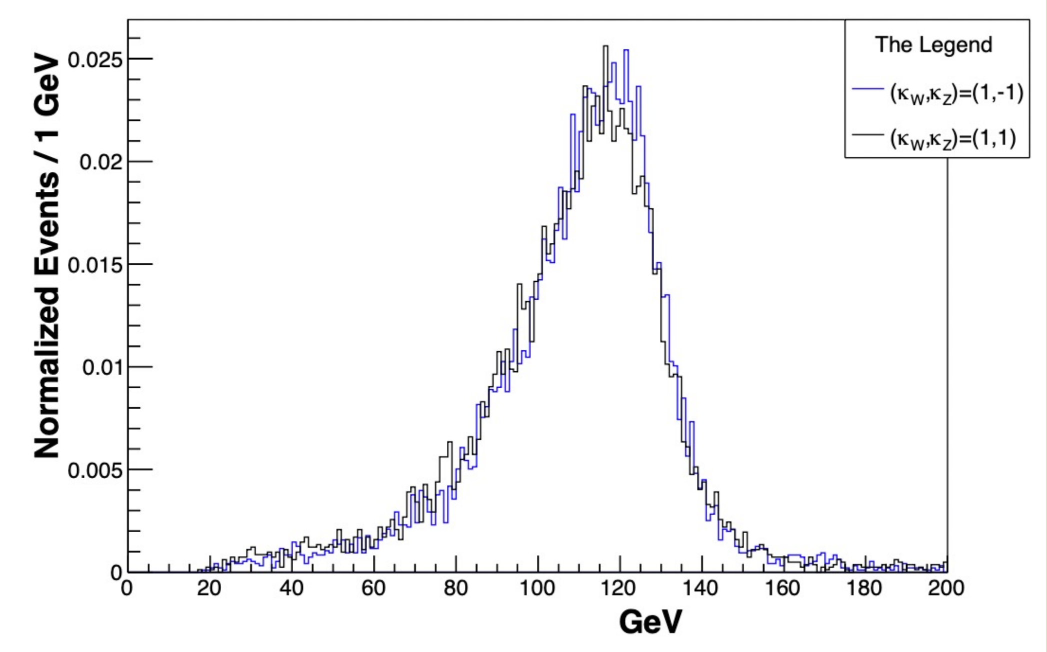




Higgs @ Hadron Collider

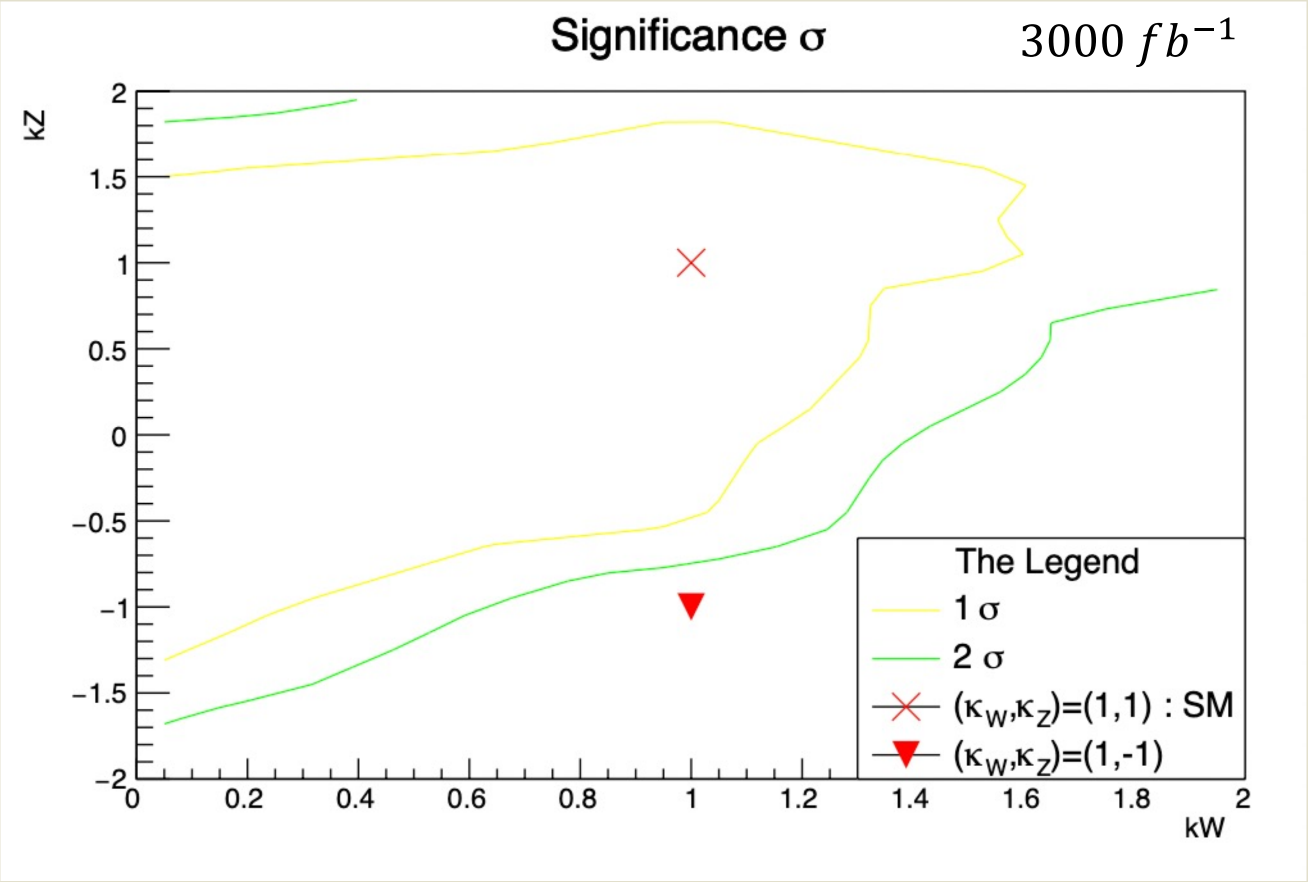
- Higgs Will be boosted at the LHC $\sqrt{s} = 13\sim14\ TeV$
- Boosted Higgs Tagging by BDRS algorithm





Result @ Hadron Collider

- In the $\kappa_W\ vs.\ \kappa_Z$ plane:



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
- Resolve the sign of λ_{WZ}
- Can be well probed at high energy colliders
  - Better at Lepton Collider
  - Possible to resolve the sign at the LHC

Thanks for your attention!

Backups

CMS: 1809.10733

$\mathcal{B}_{\mathrm{BSM}} = 0$	
Parameter	Best fit
κ_Z	$1.00\ ^{+0.11}_{-0.11}\ \left(^{+0.11}_{-0.11}\right)$
κ_W	$-1.13\ ^{+0.16}_{-0.13}\ \left(^{+0.12}_{-0.12}\right)$

HL-LHC: 1902.00134

		ATLAS				
		3000 fb^{-1} uncertainty [%]				
		Total	Stat	SigTh	BkgTh	Exp
λ_{WZ}	S1	2.7	0.9	1.5	1.3	1.5
	S2	2.2	0.9	1.0	1.0	1.4