Higgs Couplings at Muon Collider

Da Liu

UC, Davis

T. Han, DL, I. Low and X. Wang
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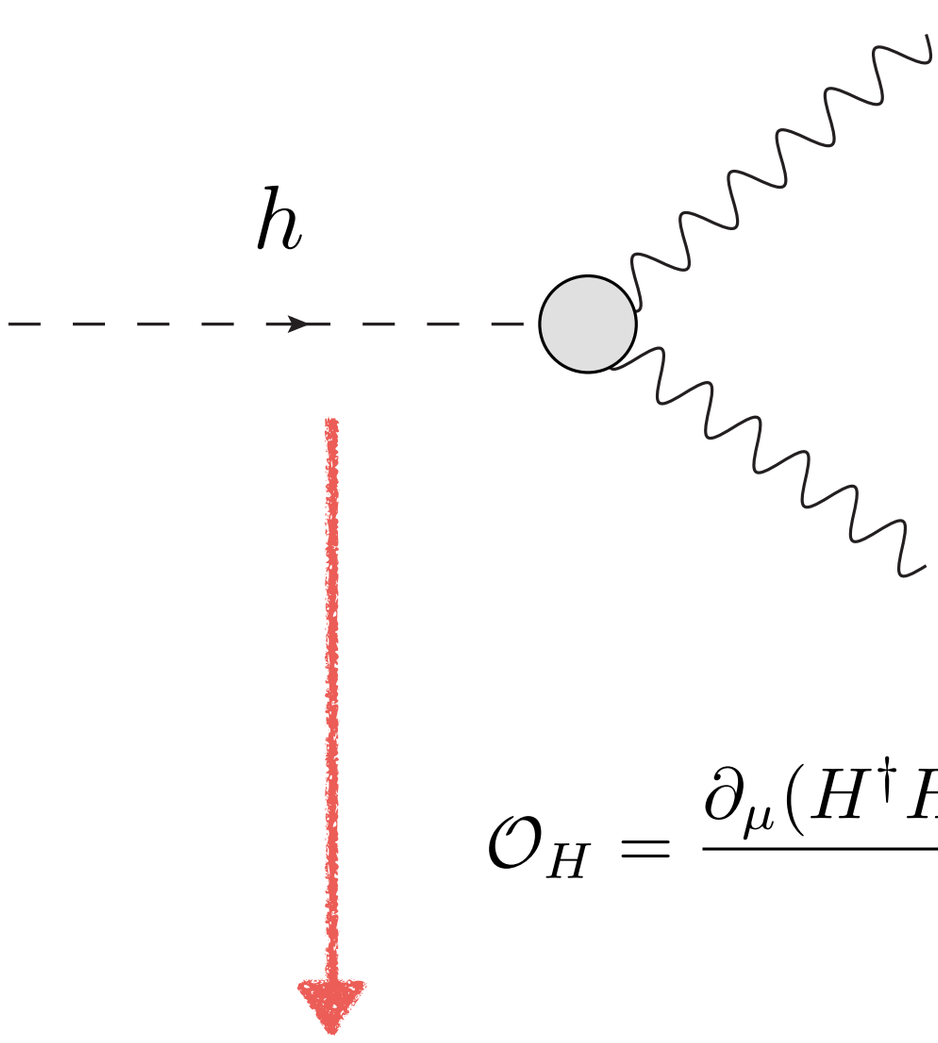
Outline

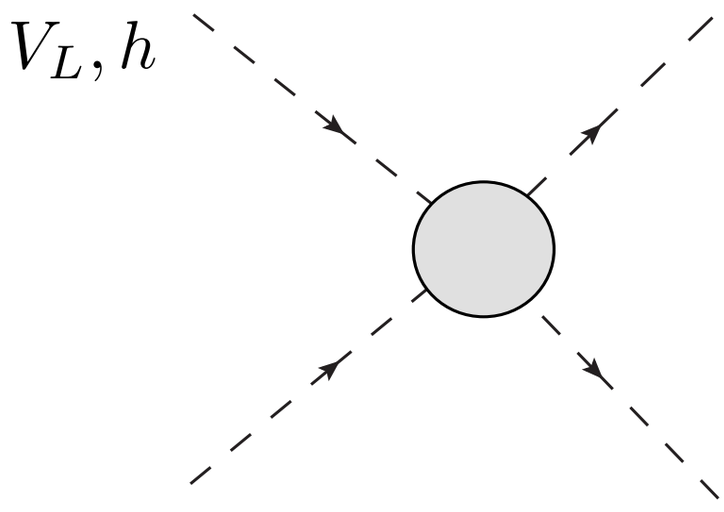
- Higgs coupling modification to energy growing behavior

- Higgs coupling measurements at Muon Collider

Higgs-Gauge Boson couplings

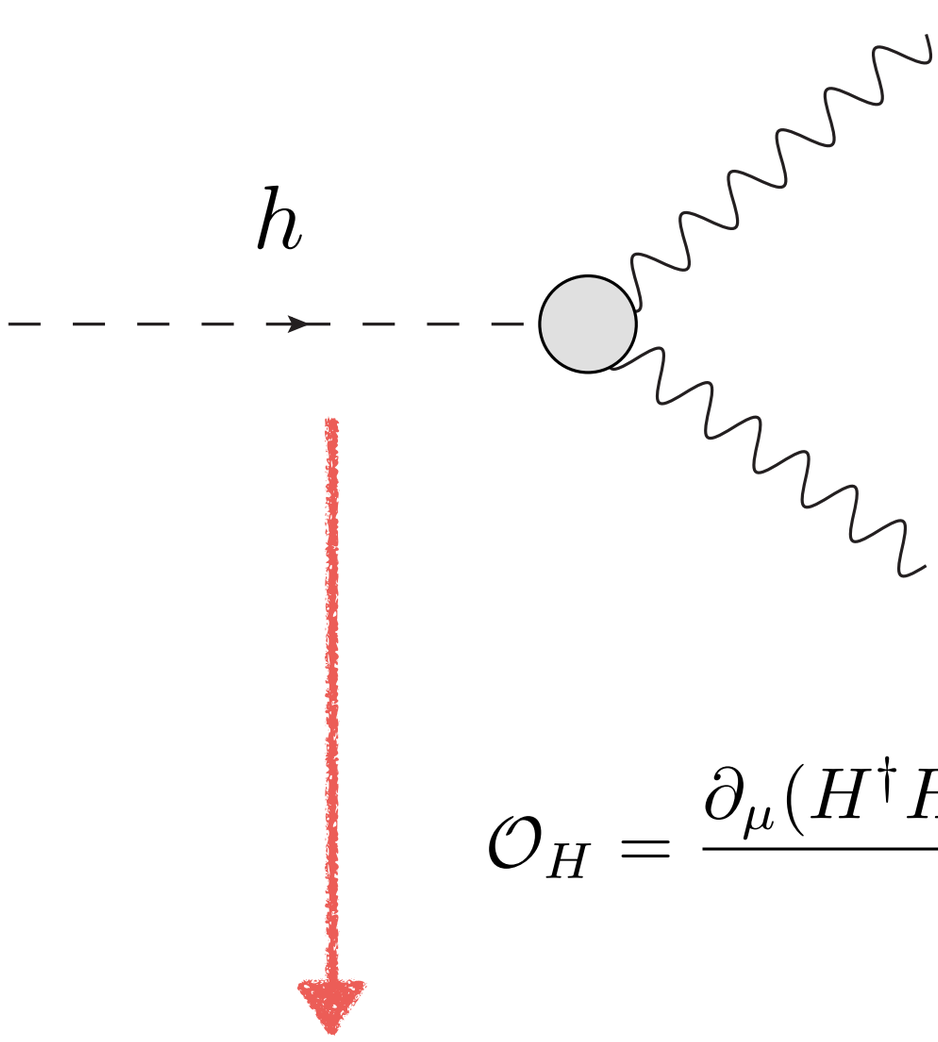


$$\mathcal{O}_H = \frac{\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)}{2\Lambda^2}$$

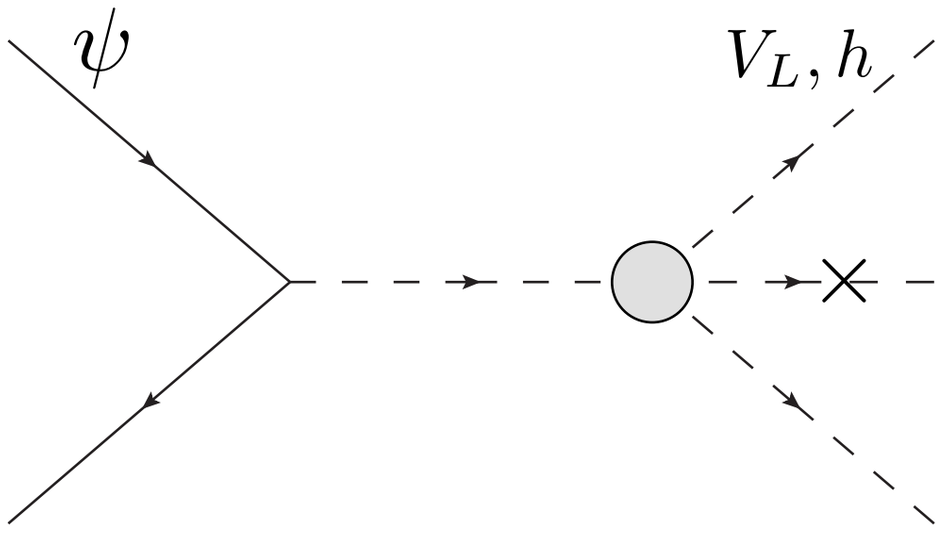


$$\sim c_H \frac{E^2}{\Lambda^2}$$

Higgs-Gauge Boson couplings

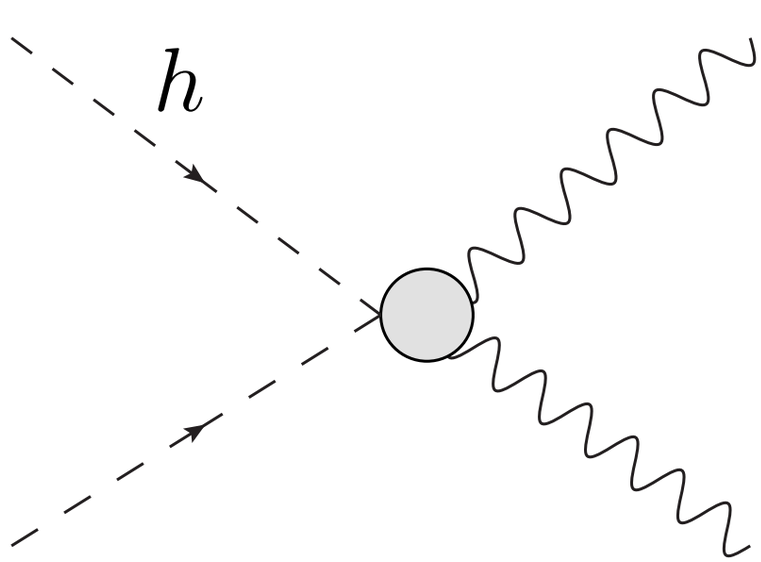


$$\mathcal{O}_H = \frac{\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)}{2\Lambda^2}$$



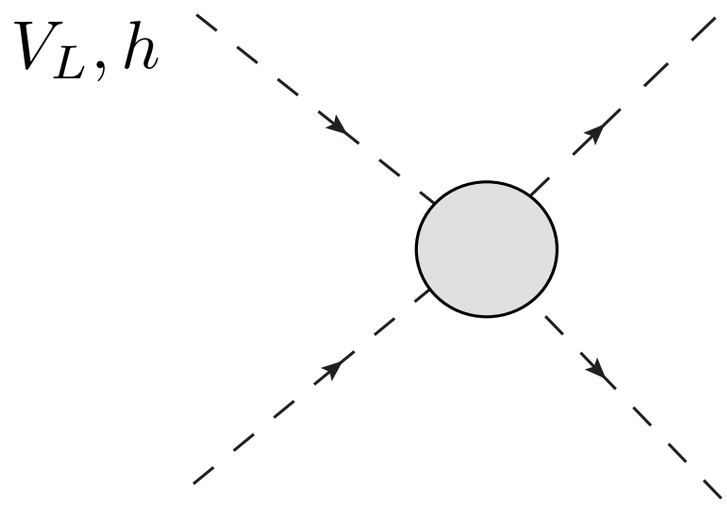
$$\sim c_H \frac{vE}{\Lambda^2}$$

Higgs-Higgs-Gauge Boson couplings



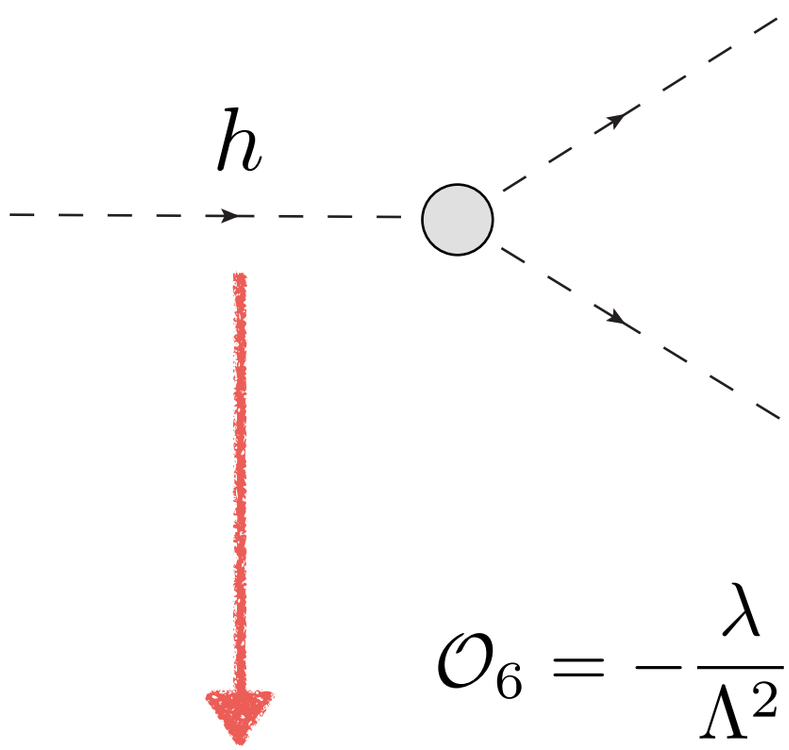
$$V = W^{\pm}, Z$$

$$\mathcal{O}_H = \frac{\partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H)}{2\Lambda^2}$$

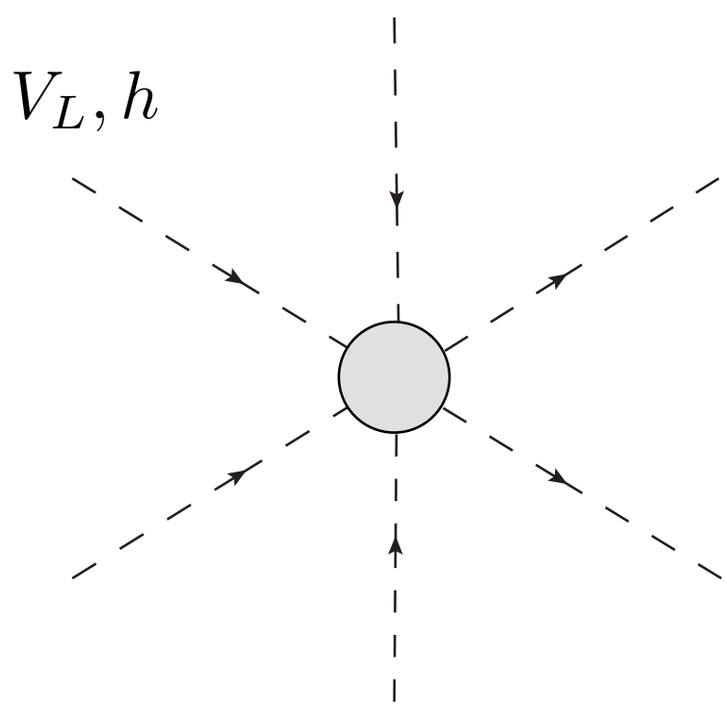


$$\sim c_H \frac{E^2}{\Lambda^2}$$

Higgs self couplings



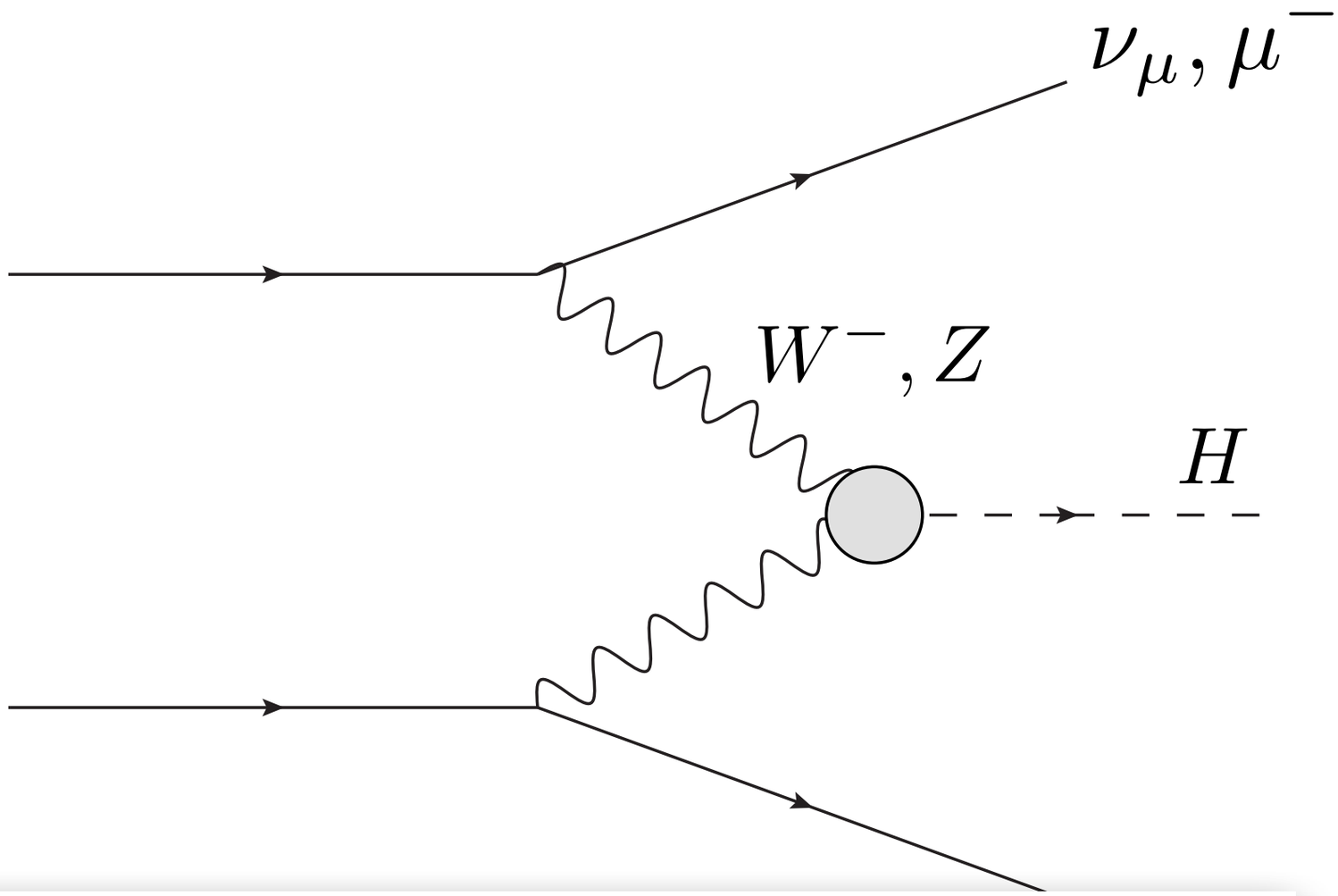
$$\mathcal{O}_6 = -\frac{\lambda}{\Lambda^2}(H^\dagger H)^3$$



$$\sim c_6 \frac{E^2}{\Lambda^2}$$

S. Chang, M. Luty 19'
A. Falkowski, R. Rattazzi 19'

VBF Single Higgs



$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120

$WW \to Z$	2200	3100	3600	4200	5200
$WW \to ZZ$	57	130	200	260	420

$\mathcal{O}(10^7)\, H$

$\frac{S}{B} \sim \frac{1}{4}$

Basic Cuts: H->bb

- Basic Acceptance cuts

$$p_{T,b} > 30\,\mathrm{GeV} \qquad 10^\circ < \theta_b < 170^\circ \;\; (|\eta_b| < 2.44)$$

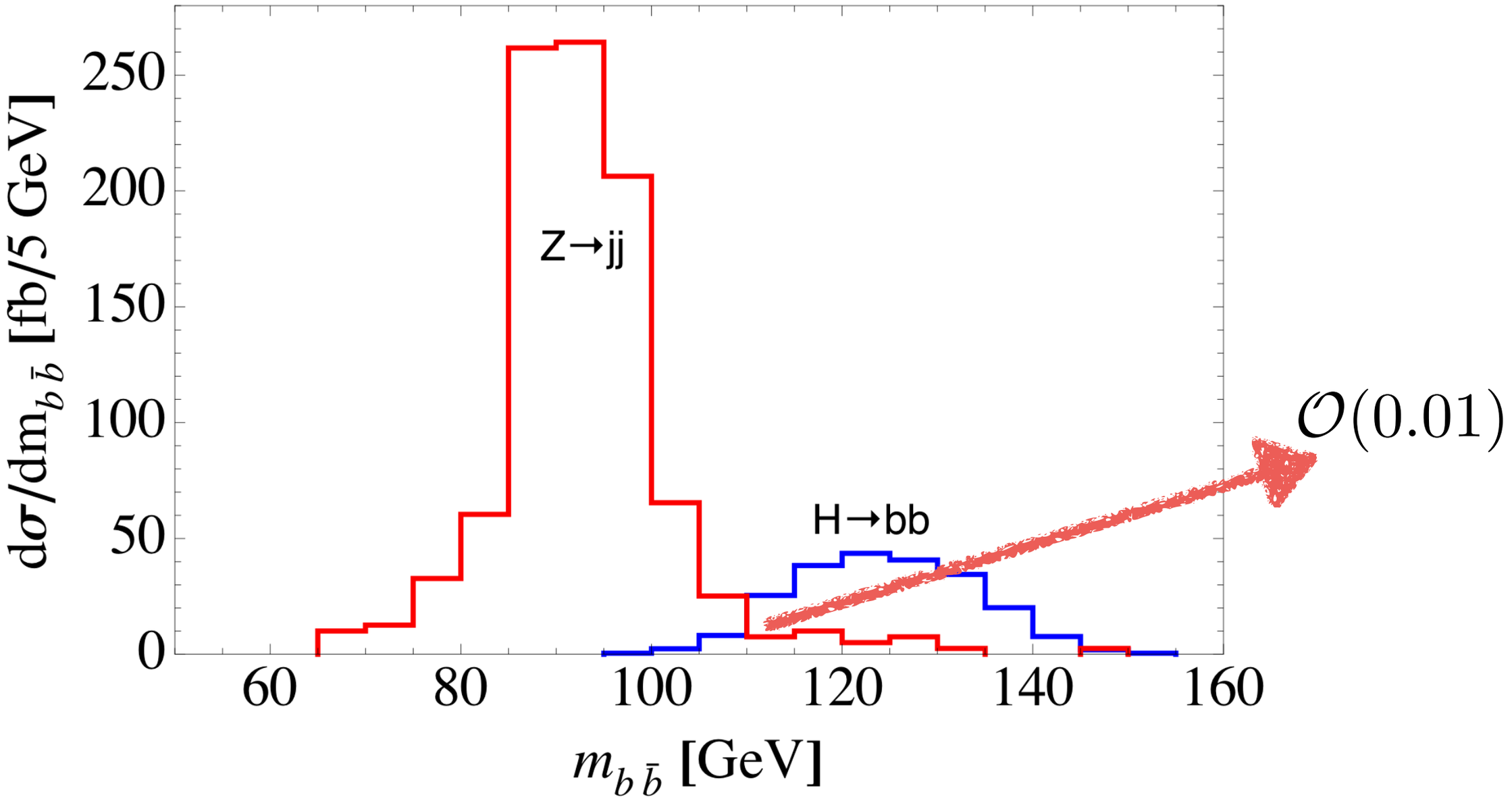
- Smearing Effects

$$\frac{\Delta E}{E} = 10\%$$

- Recoil mass cut to suppress ZZ(vv) background

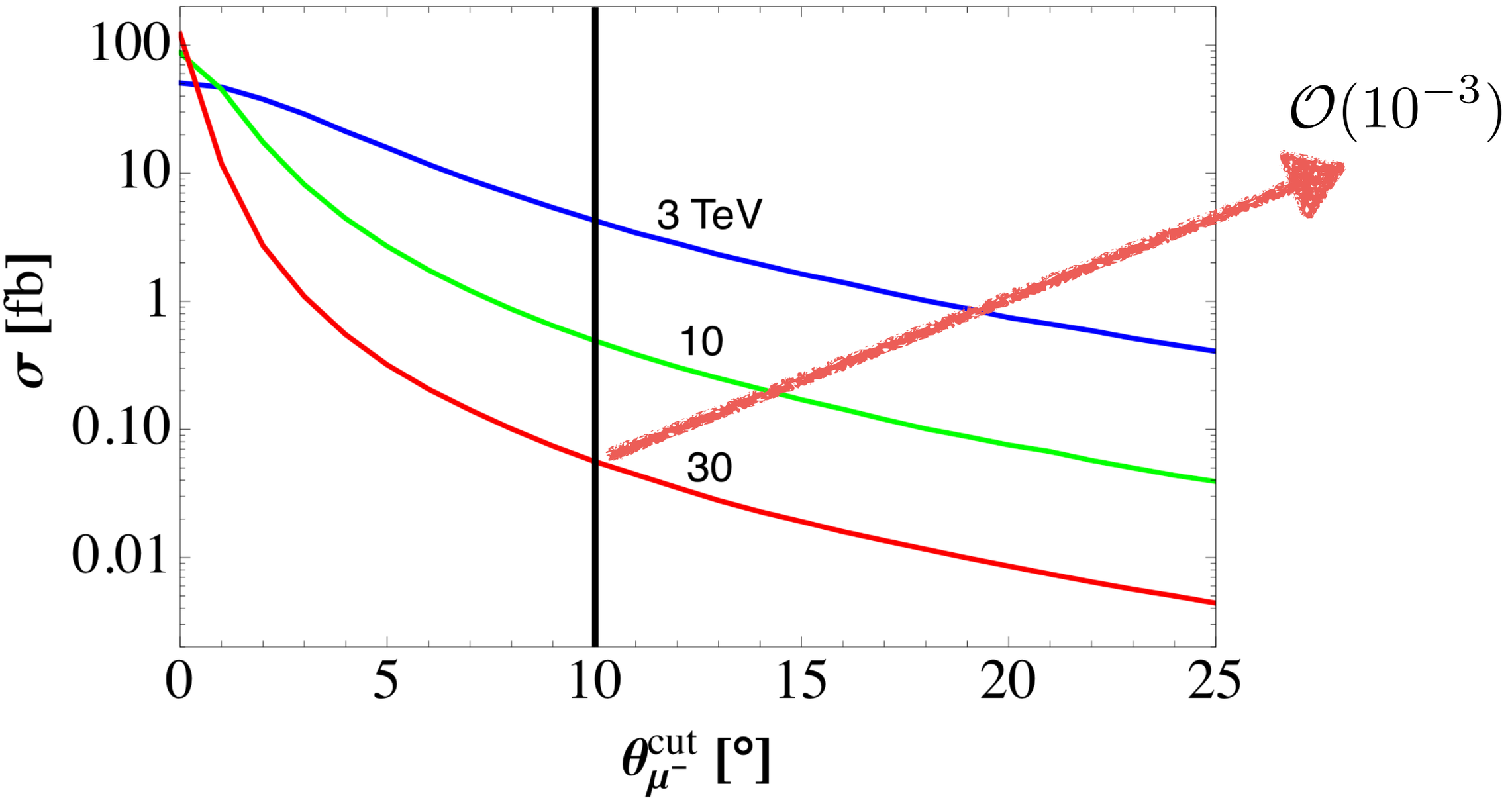
$$M_{\mathrm{recoil}} = \sqrt{(p_{\mu^+} + p_{\mu^-} - p_{H,HH})^2} > 200\mathrm{GeV}$$

Invariant Mass Distribution

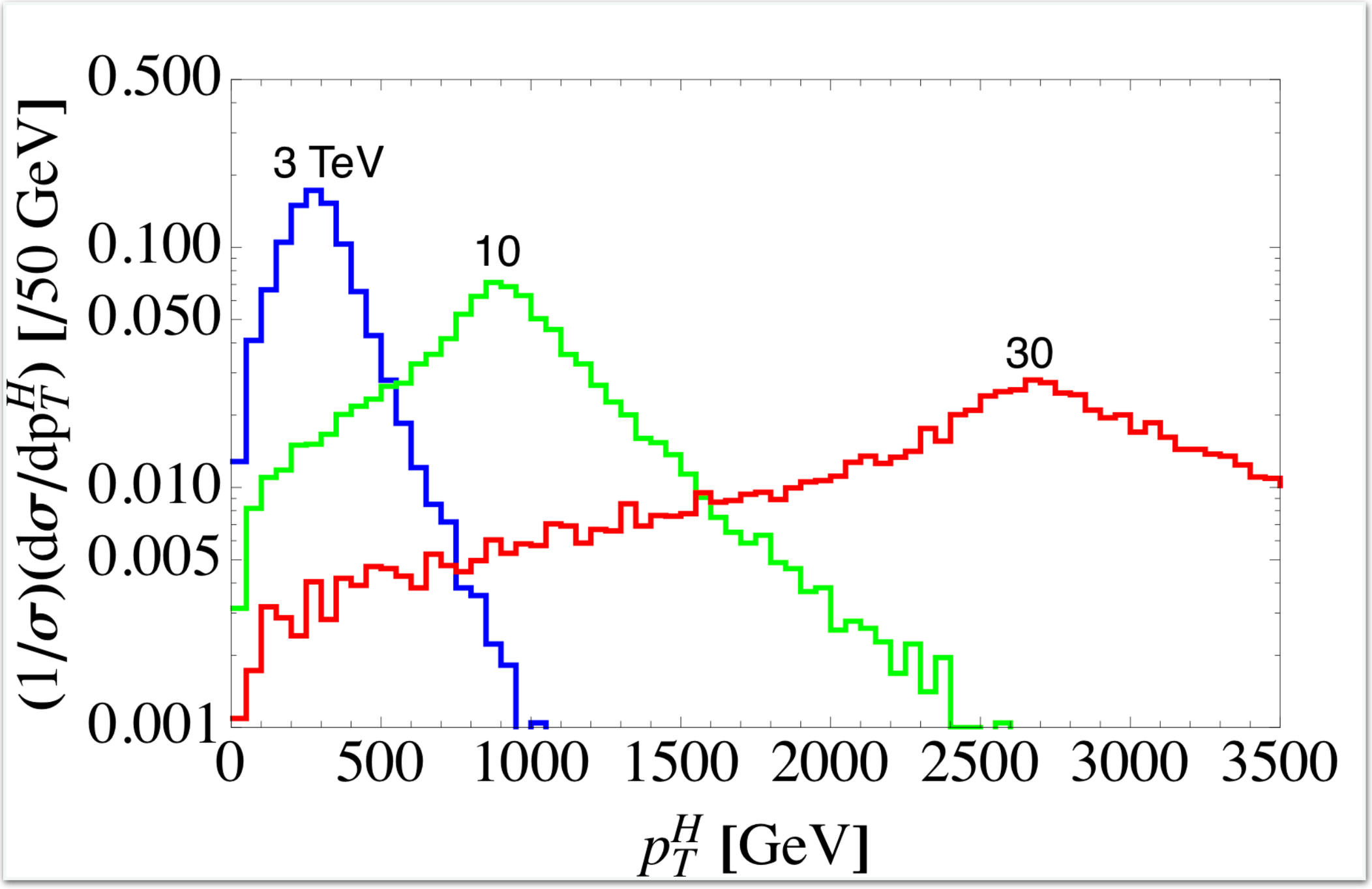


$$|m_{b\bar{b}} - m_H| < 15\,\mathrm{GeV}$$

HZZ: Forward muons



One muon tagged



$10^\circ < \theta_\mu < 170^\circ$

$p_T^\mu > 0.17 E_\mu$

Results: Efficiency

$\sqrt{s}$ (TeV)	3	6	10	14	30
$WW \to H$: ϵ_{in} (%)	54	46	42	39	32
$ZZ \to H$: ϵ_{in} (%)	57	49	44	41	35
Cross section σ_{in} (fb)	170	200	220	240	240
$ZZ \to H$: $\epsilon_{1\mu}$ (%)	11	2.7	0.84	0.37	0.071
Cross section $\sigma_{1\mu}$ (fb)	3.1	1.1	0.43	0.20	0.050
$VV \to HH$: ϵ_{hh} (%)	27	18	13	11	7.2
Cross section σ_{hh} (ab)	81	140	150	170	200

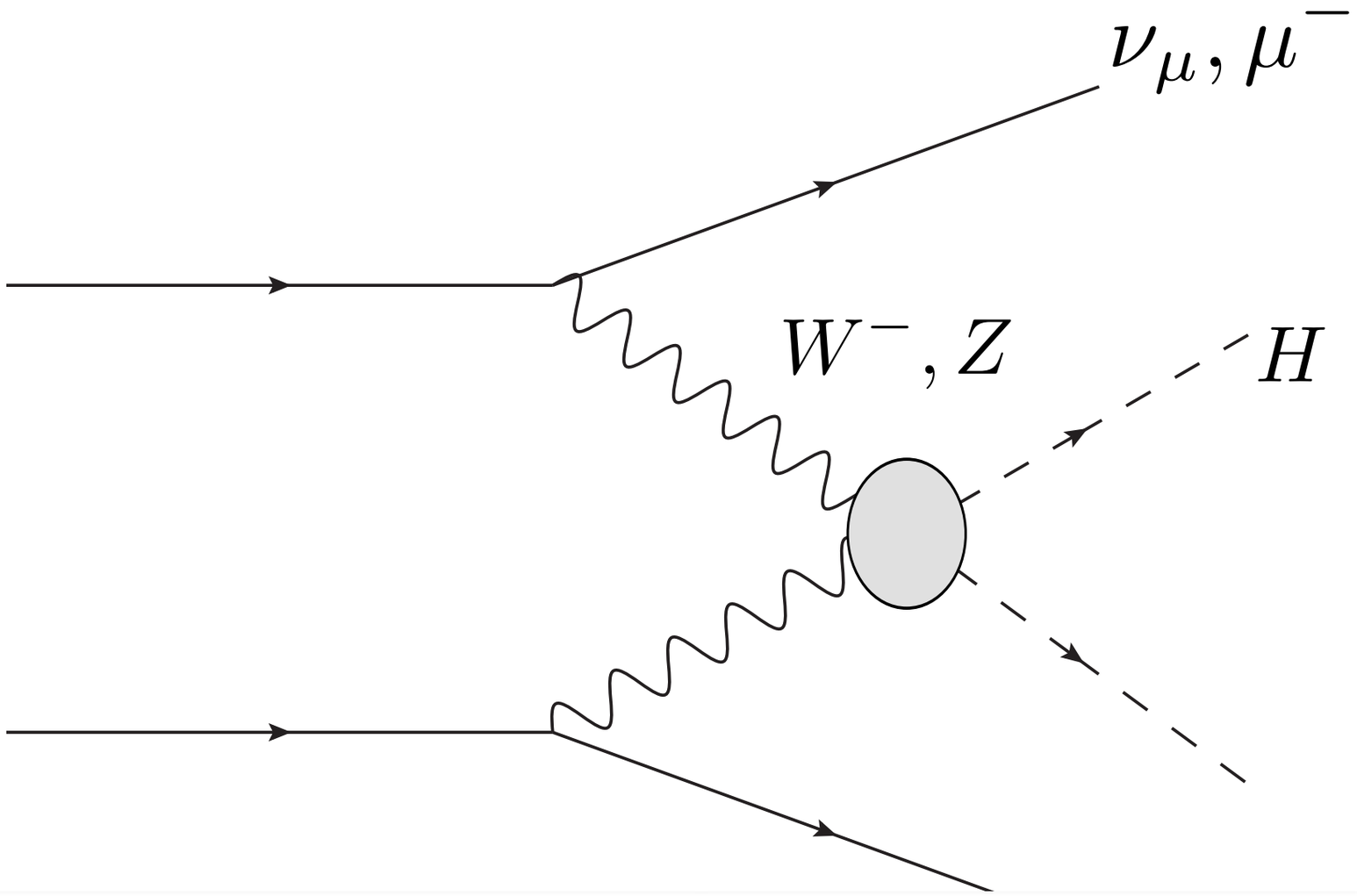
Forward muon effect

Results: Sensitivity

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
$(\Delta\kappa_W)_{\rm in}$	0.26%	0.12%	0.073%	0.050%	0.023%
$(\Delta\kappa_Z)_{\rm in}$	2.4%	1.1%	0.65%	0.46%	0.20%
$(\Delta\kappa_Z)_{1\mu}$	1.7%	1.5%	1.5%	1.5%	1.5%

- 3 to 30 TeV, a factor of 10 improvement
- Mainly due to luminosity increase

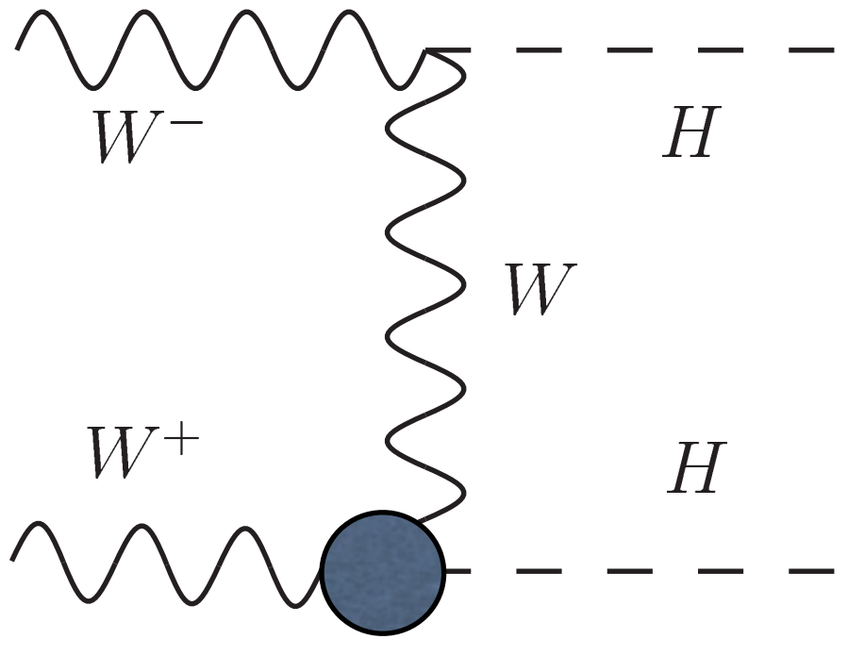
VBF Double Higgs

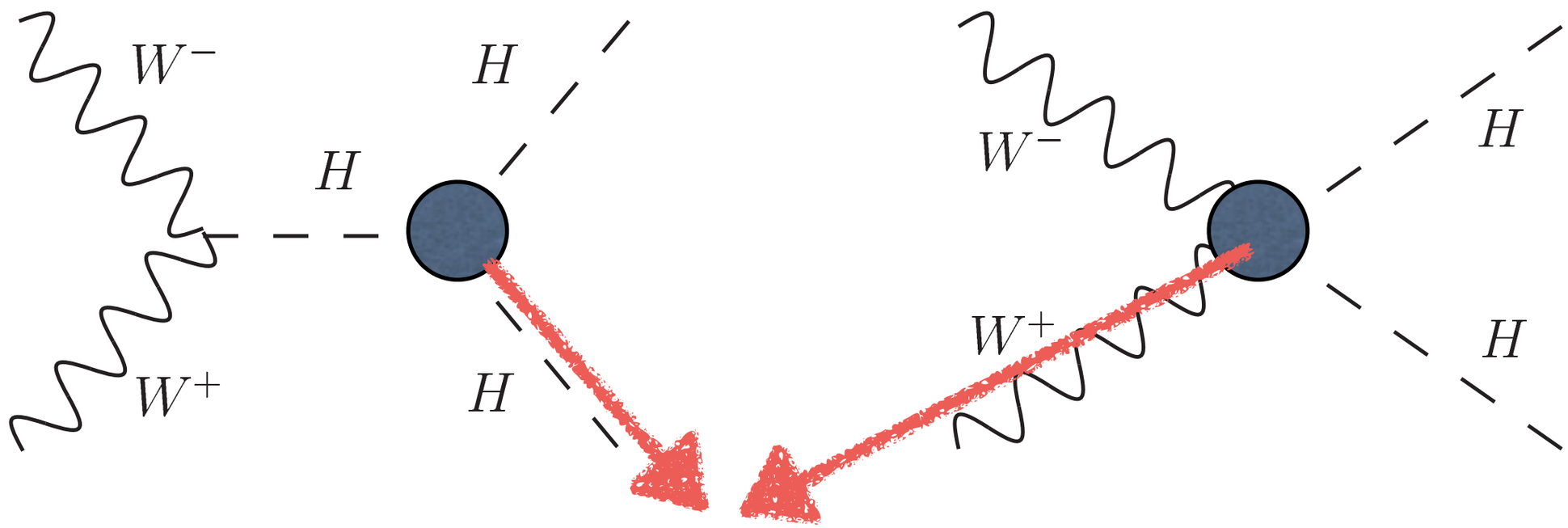


$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91
$WW \to ZZ$	57	130	200	260	420

fb $\mathcal{O}(10^4)\, HH$ $\frac{S}{B} \sim 0.02$

VBF Double Higgs





HHH vs HHVV

$$\sigma = \sigma_{\rm SM}\left[1 + r_1\Delta\kappa_{W_2} + r_2\Delta\kappa_3 + r_3\Delta\kappa_{W_2}\Delta\kappa_3 + r_4\left(\Delta\kappa_{W_2}\right)^2 + r_5\left(\Delta\kappa_3\right)^2\right]$$

m_{HH} [GeV]	$\sigma_{\rm SM}$ [ab]	r_1	r_2	r_3	r_4	r_5
$[0, 350)$	15	-2.7	-1.7	7.6	6.7	2.6
$[350, 450)$	24	-3.4	-1.2	5.2	7.8	0.95
$[450, 550)$	24	-4.0	-0.91	4.6	12	0.52
$[550, 650)$	21	-4.6	-0.70	4.7	17	0.36
$[650, 750)$	17	-5.3	-0.60	5.1	26	0.28
$[750, 950)$	24	-6.9	-0.52	6.3	46	0.23
$[950, 1350)$	23	-11	-0.47	8.7	120	0.19
$[1350, 5000)$	15	-18	-0.30	7.2	240	0.075

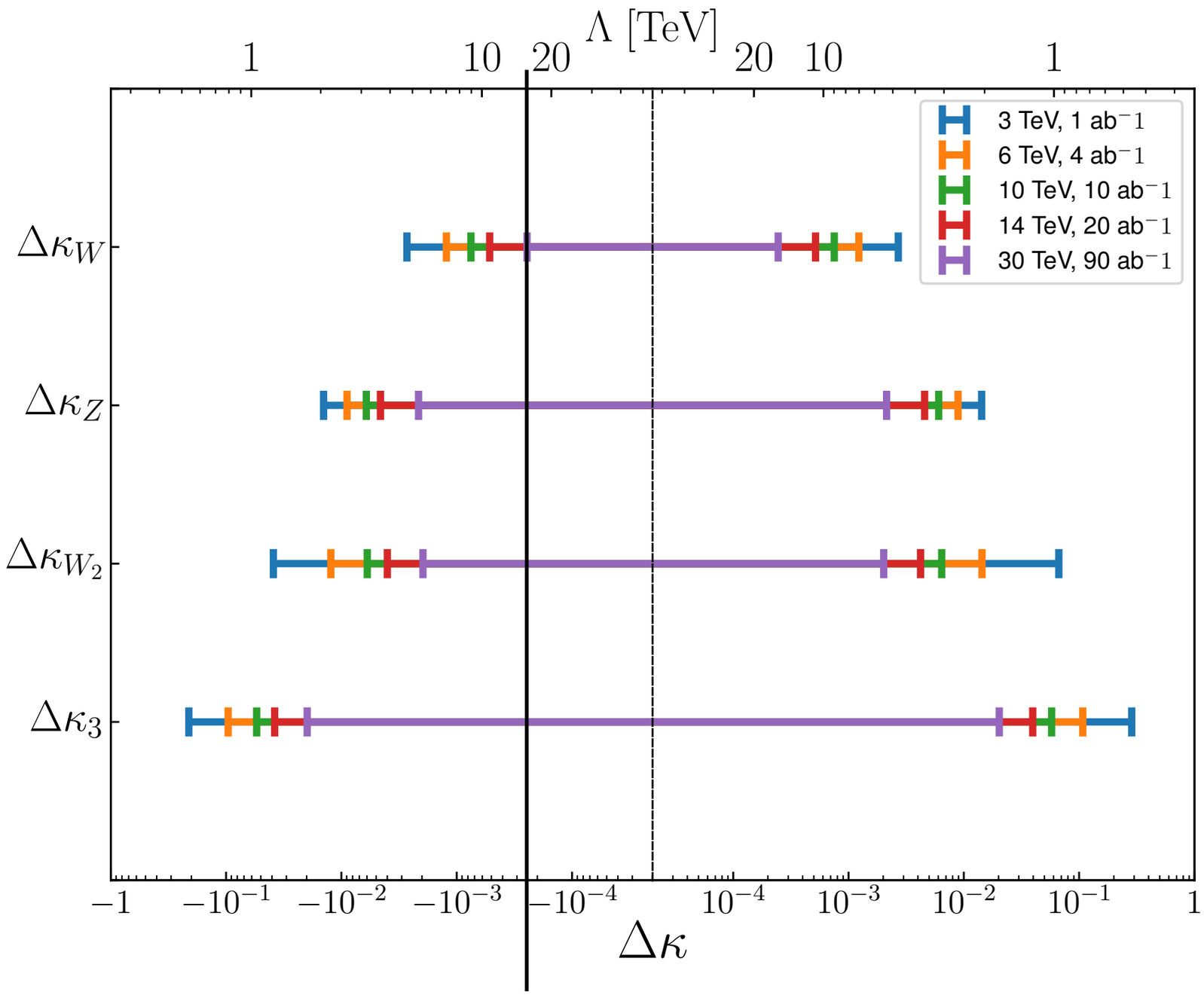
Sign of energy growing behavior

HHH vs HHVV: Sensitivity

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
$(\Delta\kappa_{W_2})_{\mathrm{in}}$	5.3%	1.3%	0.62%	0.41%	0.20%
$(\Delta\kappa_3)_{\mathrm{in}}$	25%	10%	5.6%	3.9%	2.0%

- 3 to 30 TeV, a factor of 25 improvement
- luminosity plus energy growing behavior

Result Summary



10 - 20 TeV

Implication: Composite Higgs Models

$$\Delta\kappa_W = -\frac{1}{2}\xi$$

$$\xi < 0.15\%$$

$$f > 6.4\text{TeV}$$

$$\Delta\kappa_{W_2} = -2\xi$$

$$\xi < 0.31\%$$

$$f > 4.4\text{TeV}$$

$$\xi = \frac{v^2}{f^2}$$

$10\,\text{TeV} @ 10\,\text{ab}^{-1}$

$95\,\%\text{CL}$

Implication: Nonlinearity Test

$$\mathcal{O}_H = \frac{c_H}{2f^2}\partial_\mu|H|^2\partial^\mu|H|^2 \qquad \mathcal{O}'_H = \frac{c'_H}{2f^4}|H|^2\partial_\mu|H|^2\partial^\mu|H|^2$$

$$\Delta\kappa_W = -\frac{1}{2}\xi + \left(\frac{3}{8}c_H^2 - \frac{c'_H}{4}\right)\xi^2$$

$$\Delta\kappa_{W_2} = -2\xi + \left(3c_H^2 - \frac{3c'_H}{2}\right)\xi^2$$

PNGB

$$c'_H = 2c_H^2$$

Promising for $\xi \gtrsim 0.1$

R.C., C. G., D. P. , R. R., A.T.13'
DL, I. Low, Z. Yin18'

Conclusion

✓ Sub-permille level on HVV

✓ Sub-percent level on HHVV

✓ Percent level on HHH

Back-up Slides

Cross Section

$\sqrt{s}$ (TeV)	3	6	10	14	30
benchmark lumi (ab^{-1})	1	4	10	20	90
σ (fb): $WW \to H$	490	700	830	950	1200
$ZZ \to H$	51	72	89	96	120
$WW \to HH$	0.80	1.8	3.2	4.3	6.7
$ZZ \to HH$	0.11	0.24	0.43	0.57	0.91
$WW \to ZH$	9.5	22	33	42	67
$WW \to t\bar{t}H$	0.012	0.046	0.090	0.14	0.28
$WW \to Z$	2200	3100	3600	4200	5200
$WW \to ZZ$	57	130	200	260	420

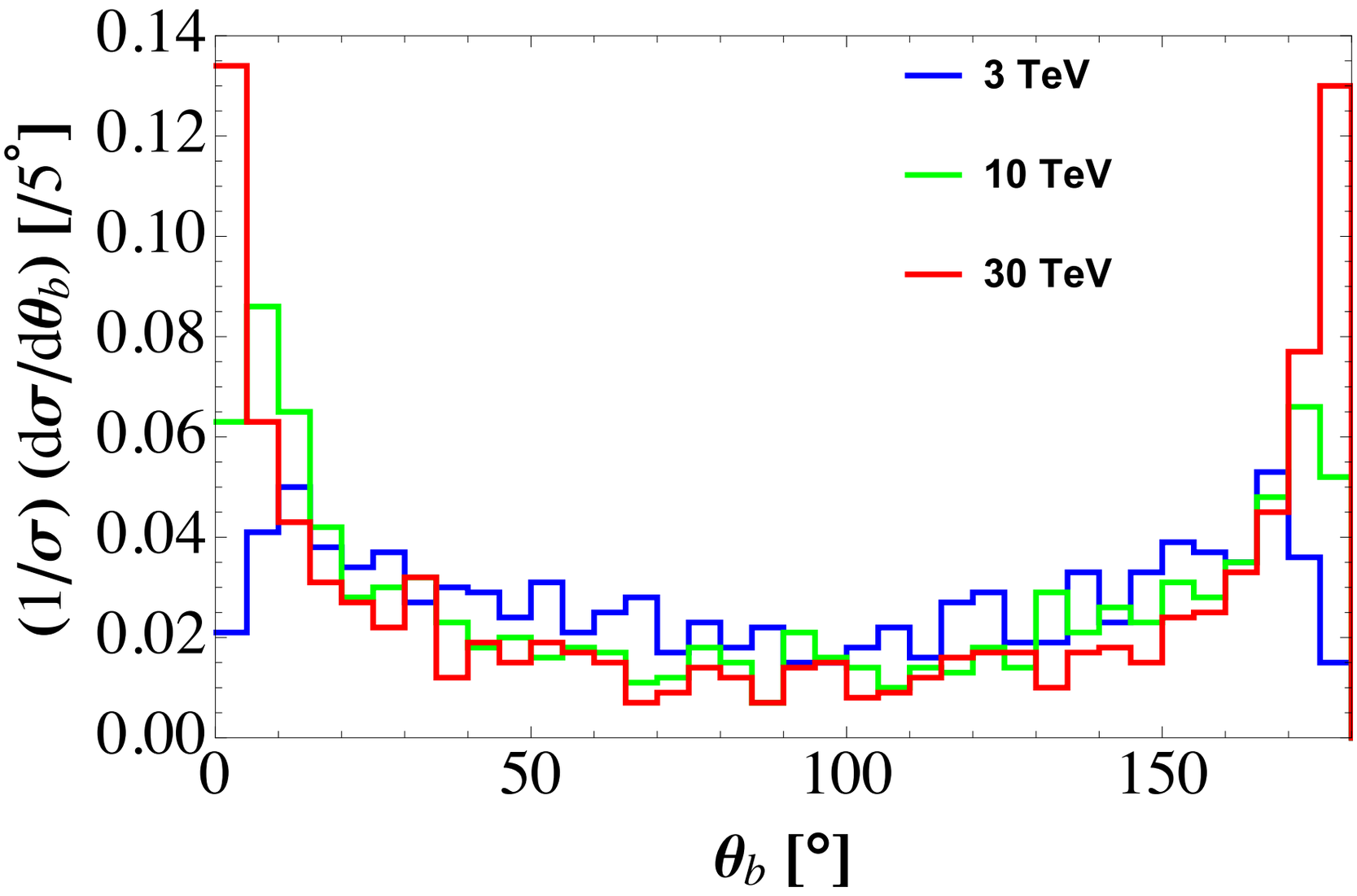
Cross Section

$\sqrt{s}$ [TeV]	$\sigma_{\rm SM}$ [fb]	R_1	R_2	R_3	R_4	R_5
3 TeV	0.91	-3.5	-0.65	3.1	14	0.49
6 TeV	2.0	-3.9	-0.50	2.8	29	0.35
10 TeV	3.6	-4.3	-0.43	2.7	54	0.29
14 TeV	4.9	-4.4	-0.38	2.6	80	0.25
30 TeV	7.6	-4.4	-0.28	2.3	210	0.19

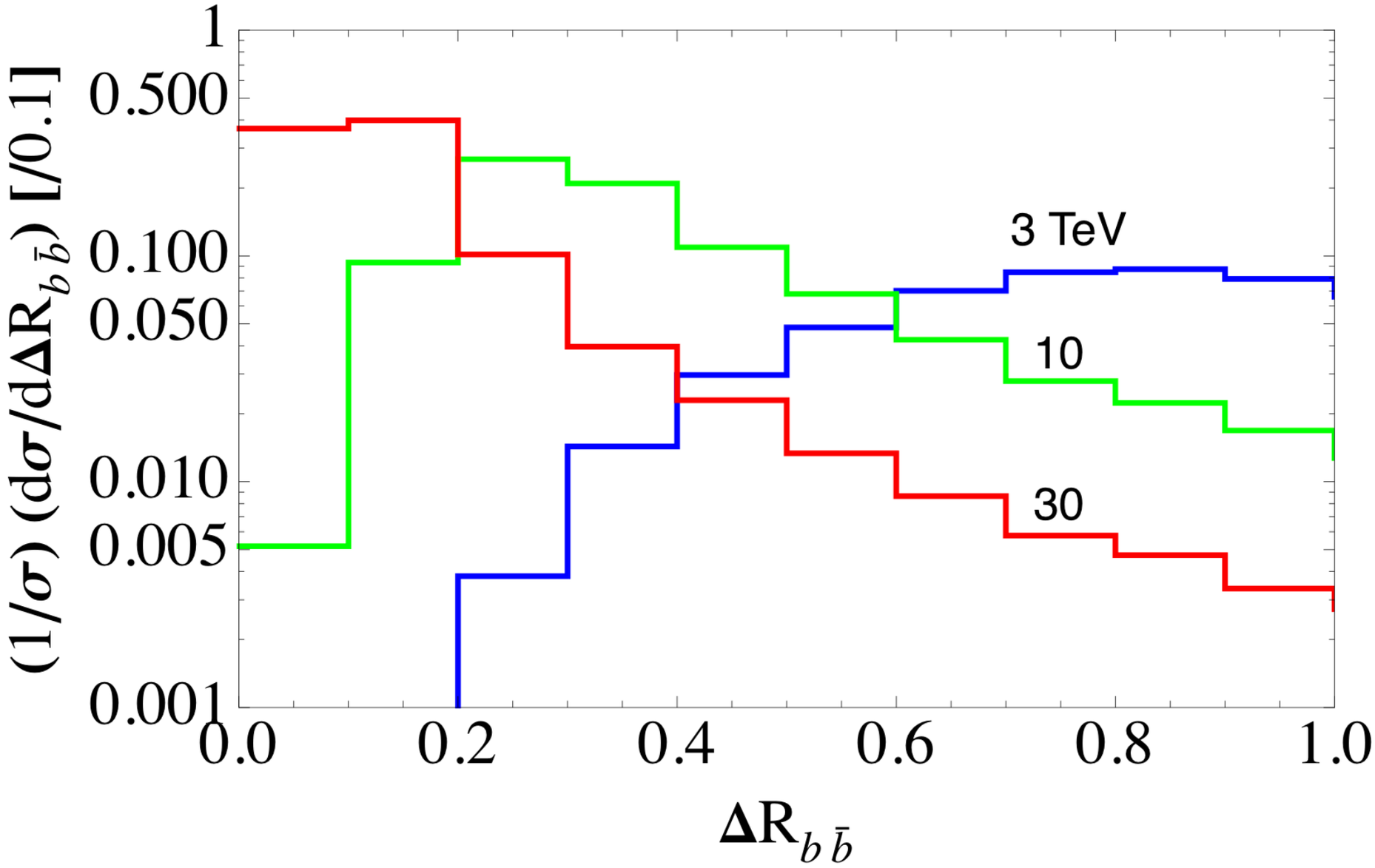
Sensitivity Comparison

$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [43]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [38], 1% [24]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

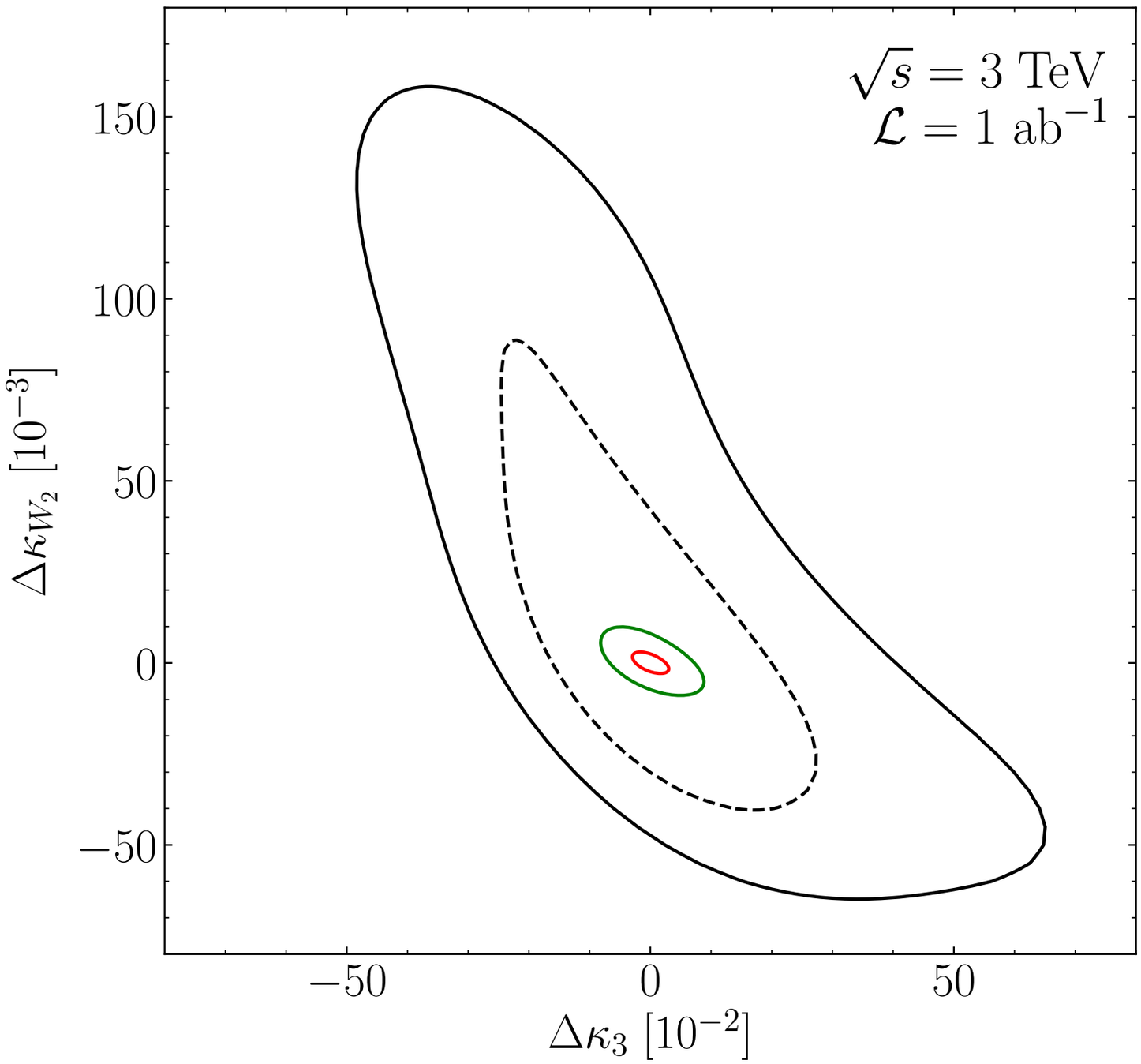
Kinematical Variable Distribution



Kinematical Variable Distribution



HHH vs HHVV


$\sqrt{s} = 3$ TeV
$\mathcal{L} = 1$ ab^{-1}
150
100
50
0
−50
−50
0
50
$\Delta\kappa_{W_2}$ [10^{-3}]
$\Delta\kappa_3$ [10^{-2}]