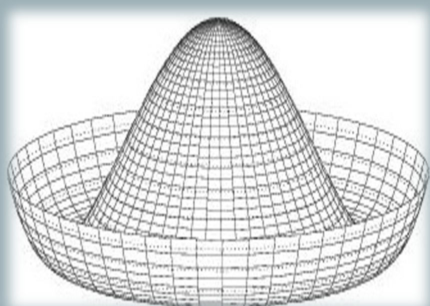
DOUBLE HIGGS AT FUTURE COLLIDERS



S. Dawson, BNL

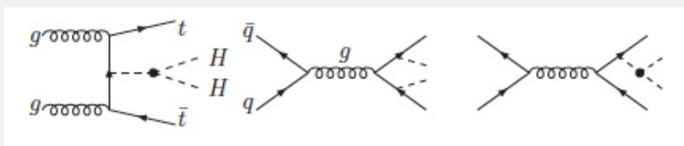
Sept 30, 2021

Future Colliders in a chart

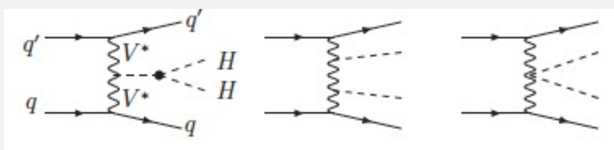
Collider	Type	$\sqrt{s}$	$\mathscr{P}$ [%] $[e^-/e^+]$	N(Det.)	$\mathscr{L}_{\text{inst}}$ $[10^{34}]$ cm^{-2}s^{-1}	$\mathscr{L}$ [ab^{-1}]	Time [years]	Refs.	Abbreviation
HL-LHC	pp	14 TeV	-	2	5	6.0	12	[10]	HL-LHC
HE-LHC	pp	27 TeV	-	2	16	15.0	20	[10]	HE-LHC
FCC-hh	pp	100 TeV	-	2	30	30.0	25	[1]	FCC-hh
FCC-ee	ee	M_Z	0/0	2	100/200	150	4	[1]	
		$2M_W$	0/0	2	25	10	1-2		
		240 GeV	0/0	2	7	5	3		FCC-ee$_{240}$
		$2m_{top}$	0/0	2	0.8/1.4	1.5	5		FCC-ee$_{365}$
							(+1)		(1y SD before $2m_{top}$ run)
ILC	ee	250 GeV	±80/±30	1	1.35/2.7	2.0	11.5	[3, 11]	ILC$_{250}$
		350 GeV	±80/±30	1	1.6	0.2	1		ILC$_{350}$
		500 GeV	±80/±30	1	1.8/3.6	4.0	8.5		ILC$_{500}$
							(+1)		(1y SD after 250 GeV run)
CEPC	ee	M_Z	0/0	2	17/32	16	2	[2]	CEPC
		$2M_W$	0/0	2	10	2.6	1		
		240 GeV	0/0	2	3	5.6	7		
CLIC	ee	380 GeV	±80/0	1	1.5	1.0	8	[12]	CLIC$_{380}$
		1.5 TeV	±80/0	1	3.7	2.5	7		CLIC$_{1500}$
		3.0 TeV	±80/0	1	6.0	5.0	8		CLIC$_{3000}$
							(+4)		(2y SDs between energy stages)
LHeC	ep	1.3 TeV	-	1	0.8	1.0	15	[9]	LHeC
HE-LHeC	ep	1.8 TeV	-	1	1.5	2.0	20	[1]	HE-LHeC
FCC-eh	ep	3.5 TeV	-	1	1.5	2.0	25	[1]	FCC-eh

PRODUCTION OF HH

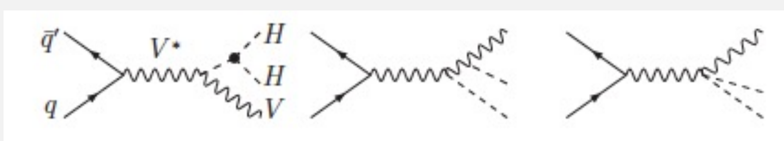
Sensitive to heavy colored particles (eg stops or top partners) and new resonances



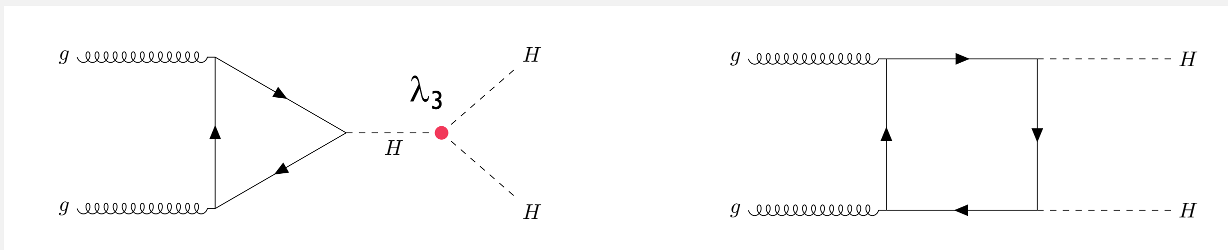
Sensitive to anomalous top-Higgs couplings



Sensitive to anomalous VVHH couplings



DOUBLE HIGGS IS GOAL OF HL-LHC AND FUTURE COLLIDERS



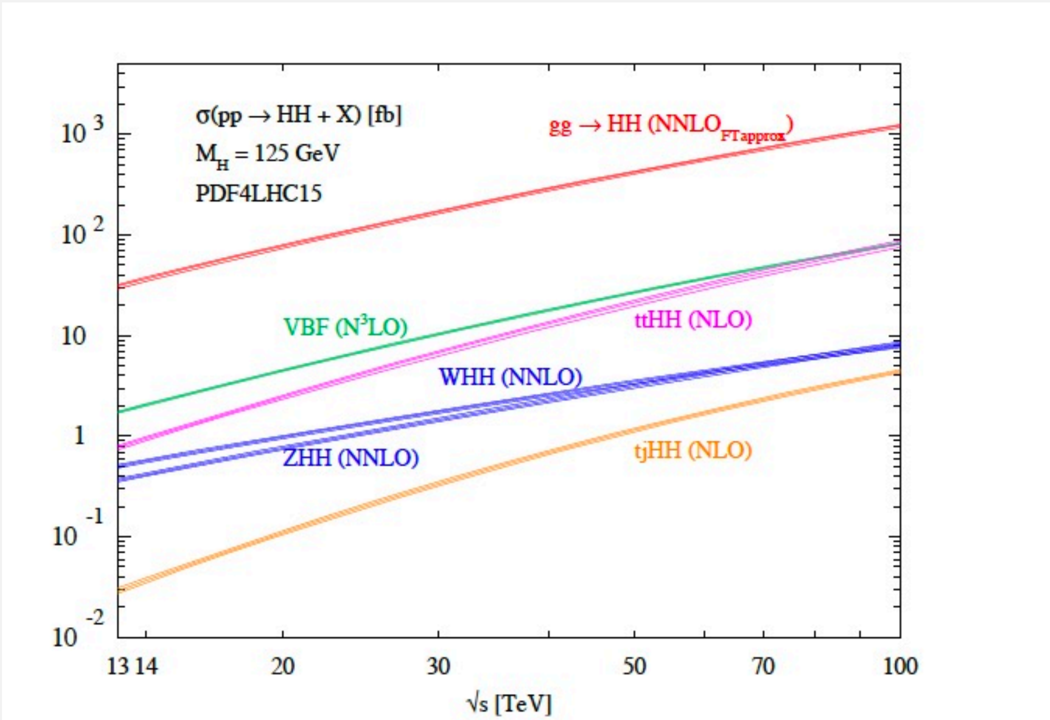
- $\lambda_3 = M_H^2/(2v)$ is SM HHH coupling
- In SM λ_3=1; any other value is a sign of new physics
- Contributions tend to cancel at threshold
- Theory includes NLO with all masses; NNLO with approximations

[See Spira talk]

SMALL RATES AT pp COLLIDERS

$$\frac{\sigma_{100}^{ggF}}{\sigma_{14}^{ggF}} \sim 33$$

$$\frac{\sigma_{100}^{VBF}}{\sigma_{14}^{VBF}} \sim 41$$



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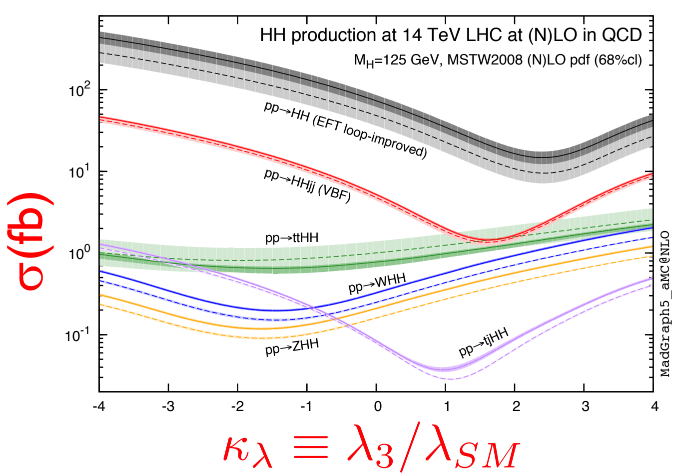
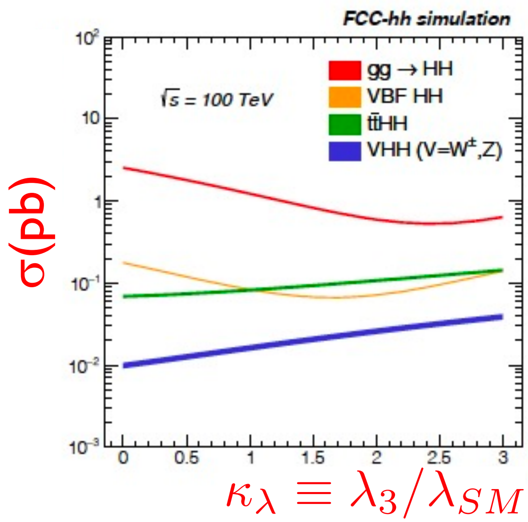
Most studies at HL-LHC consider gluon fusion or VBF only

ttHH+VBF ~15% of rate at 100 TeV

DEPENDENCE ON λ_3

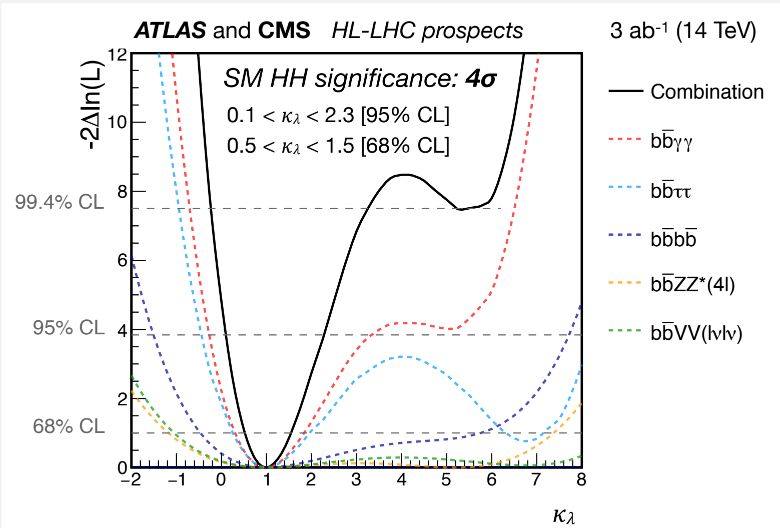




1903.08137

Everything SM except λ_3

HIGGS TRI-LINEAR COUPLING IN THE FUTURE



Difficult measurement

1902.00134 , 1905.03764

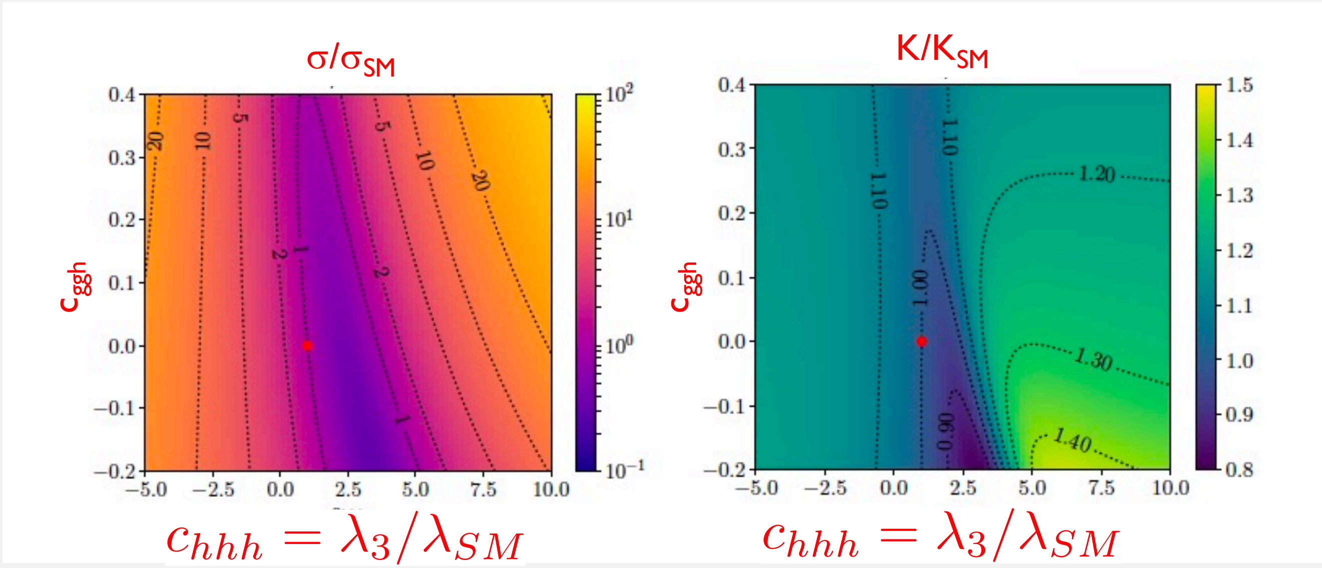
QCD EFFECTS

- NLO gg→ HH with anomalous couplings implemented in POWHEG

NNLO' sensitivity to anomalous couplings

$$L \sim \frac{C_g}{\Lambda^2} \mid H^\dagger H \mid G^A_{\mu\nu} G^{\mu\nu,A}$$

$$c_{ggh} = \frac{8\pi}{\alpha_s} \frac{v^2}{\Lambda^2} C_g$$



14 TeV

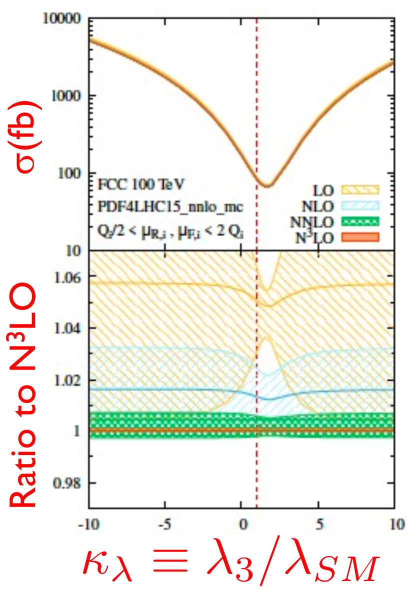
Red dot is SM

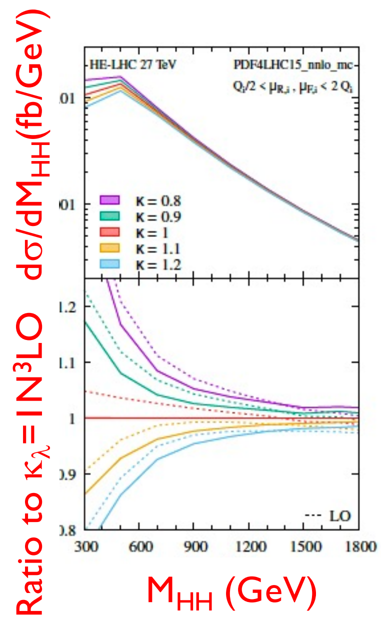
2006.16877.pdf

[See Heinrich talk]

QCD EFFECTS

K factors @ 100 TeV





VBF HH production

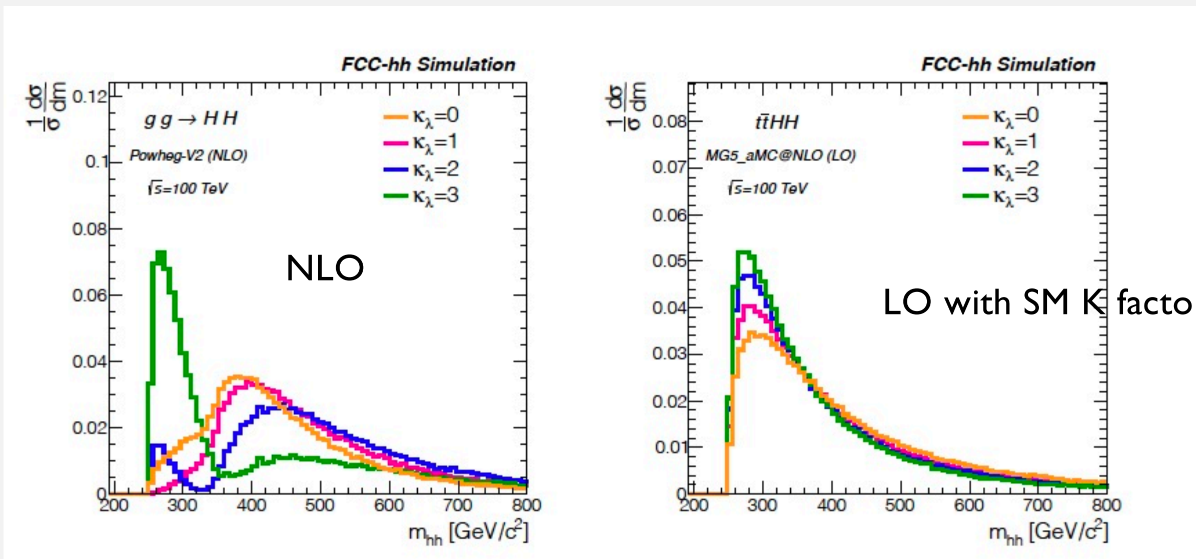
- Total cross section K factor relatively flat in VBF HH
- NLO gets most of the effect
- Distributions sensitive to λ_3/λ_{SM}

[1811.07906.pdf](1811.07906.pdf)

DISCOVERY OF HH AT FCC-hh

- Tools exist to include higher order QCD effects

100 TeV

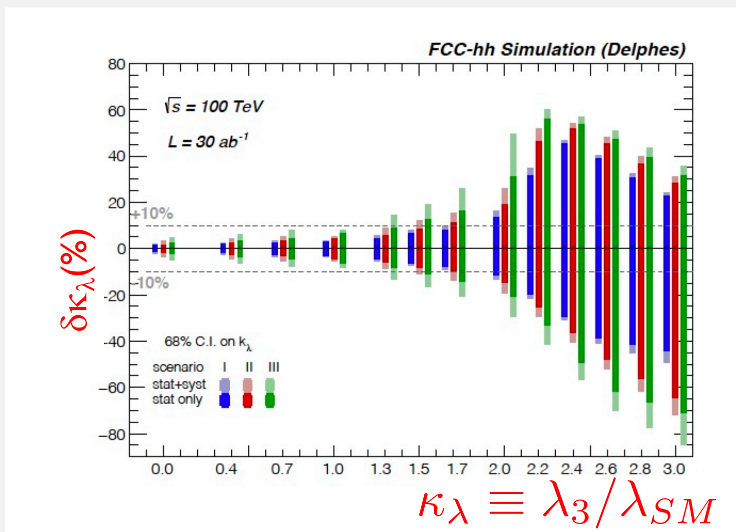


Include all production channels in study

2004.03505.pdf

FCC-hh PRECISION

- Combining bb$\gamma\gamma$, bb$\tau\tau$ and bbbb, precision on SM $\delta\kappa_\lambda$ ~ 3.4-7.8%
- Theory work needed: allow other couplings to vary



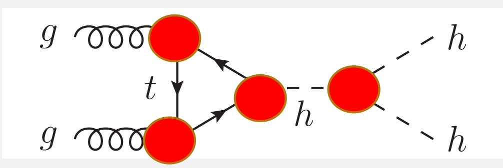
Precision depends on κ_λ and assumptions about systematics

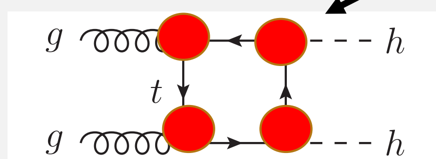
[2004.03505.pdf](2004.03505.pdf)

IT'S NOT JUST HHH……

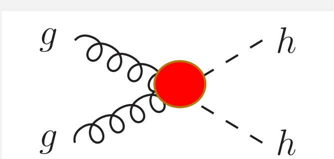
- In any realistic model, interactions other than HHH are also changed
- Limits are correlated

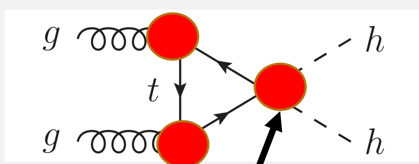
Non-SM top Yukawa

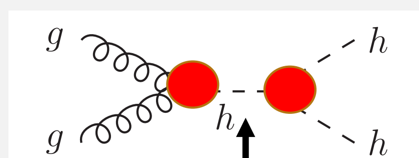




Different scaling with energy from different diagrams







ttHH coupling in composite higgs models

Large resonant enhancement with new scalars

POSSIBLE INTERACTIONS

- Quantify effects in terms of SMEFT
- Expect effects growing with energy to be significant at FCC-hh
- Effective field theory expansion in higher dimension operators

$$L \sim \frac{C_H}{\Lambda^2}(H^\dagger \partial_\mu H)^2 + \frac{C_6}{\Lambda^2} \mid H \mid^6 + \frac{C_g}{\Lambda^2} \mid H \mid^2 G_{\mu\nu}G^{\mu\nu}$$

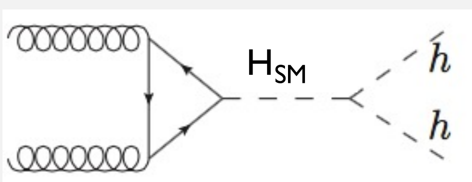
$$+ \left(\frac{y_t C_Y}{\Lambda^2} \overline{Q}_L \tilde{H} t_R \mid H \mid^2 + \frac{C_{tG}}{\Lambda^2} \overline{Q}_L \sigma_{\mu\nu} T^A \tilde{H} t_R G^A_{\mu\nu} + h.c. \right)$$

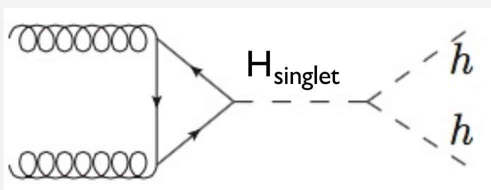
+ many more….

$$1 - \lambda_3/\lambda_{SM} \sim \frac{v^2}{\Lambda^2}\left(C_H + \frac{C_6}{\lambda_{SM}} \right)$$

THEORY MOTIVATION FOR ANOMALOUS COUPLINGS

- Singlet model: Large resonant enhancements; interesting interference pattern
- Singlet model: new decay channels with H_{SM} $H_{singlet}$ in final state



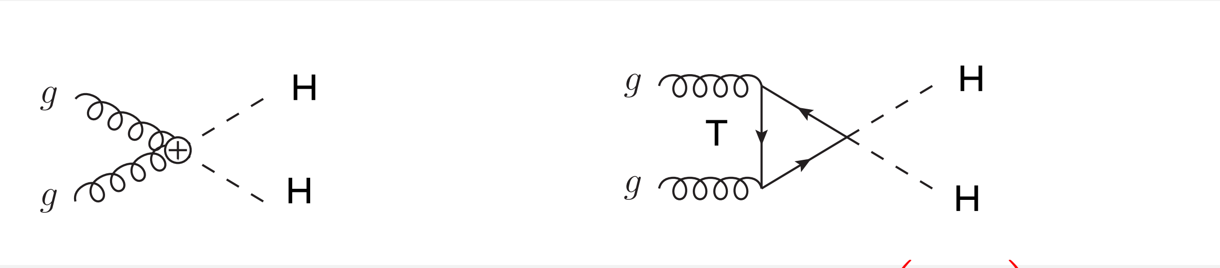


As the mass of $H_{singlet} \rightarrow \infty$, the model generates new effective interactions, C_6 and C_H

[See Englert, Roben talks]

THEORY MOTIVATION FOR ANOMALOUS COUPLINGS

- Composite Higgs models have heavy top-like particle T which generates new interactions: C_g, C_Y….

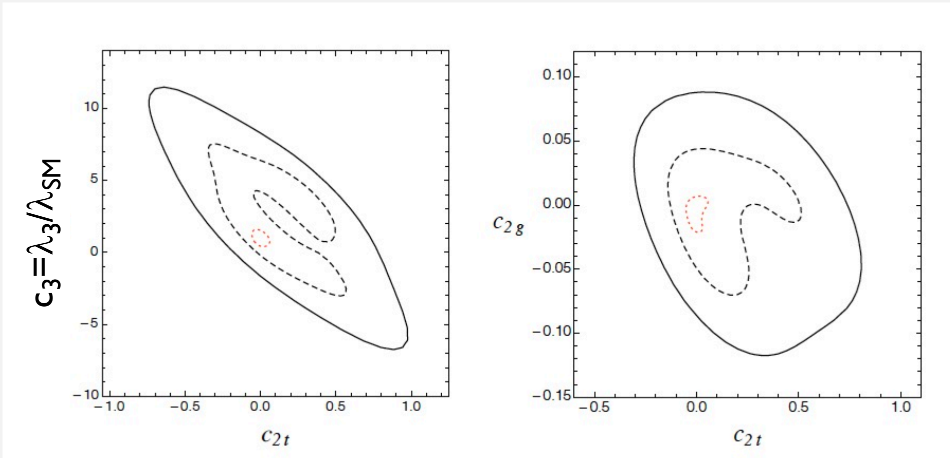


$$\sim C_g \frac{s}{\Lambda^2} \qquad \sim C_Y \log^2\left(\frac{s}{M_T^2}\right)$$

NOT JUST λ_3

HH→bbγγ

68% exclusion contours



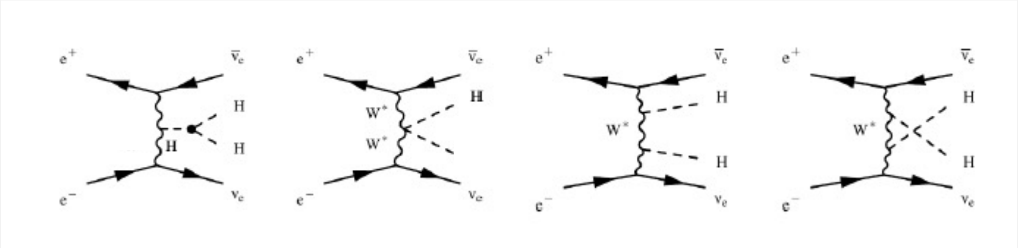
- ---- FCC-hh 3 ab^{-1}
- ---- HL-LHC, 3 ab^{-1}
- — LHC, 300 fb^{-1}

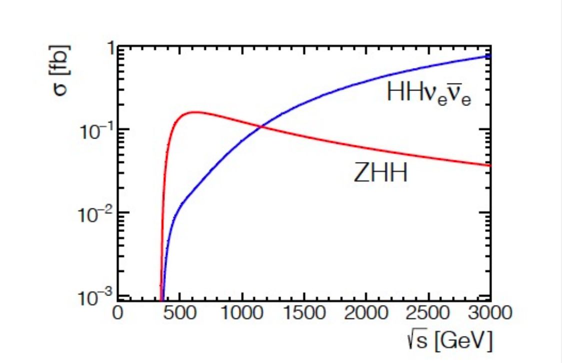
$$c_{2t} = -\frac{v^2}{\Lambda^2}\left(C_H + \frac{3}{2}C_Y\right)$$ (ttHH vertex)

[1502.00539](1502.00539)

DOUBLE HIGGS PRODUCTION AT e^+e^- COLLIDERS

- Very small cross sections
  - Not possible at 240 GeV e+ e^- colliders



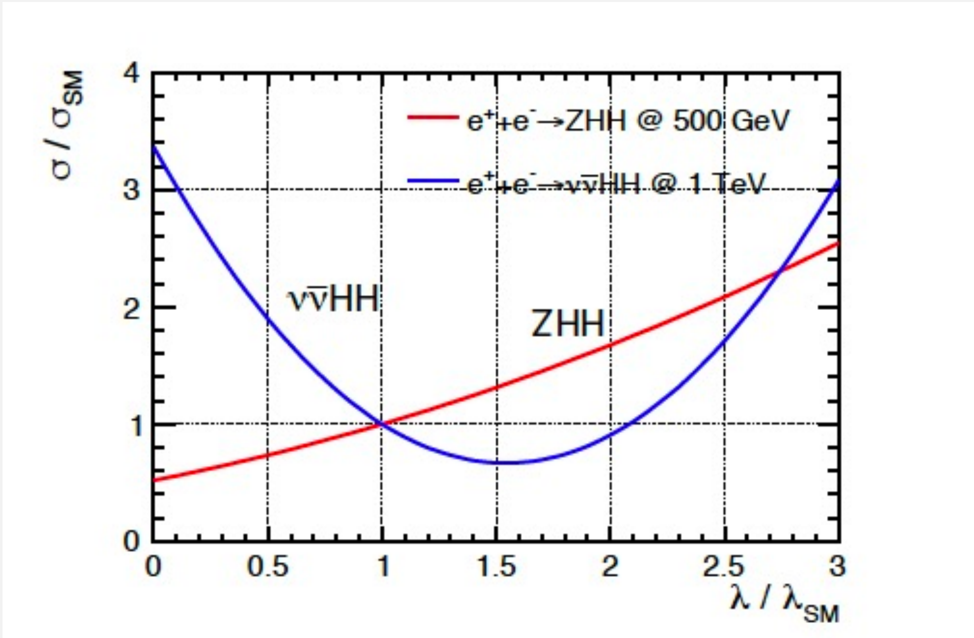


- Depends on HHH coupling and on WWH, WWHH couplings

LH polarization increases HHνν rate

HHH COUPLING IN e^+e^-

- Either ZHH or HHνν is greater than SM rate for anomalous HHH couplings



Only allow λ_3 to vary

[1908.11299.pdf](1908.11299.pdf)

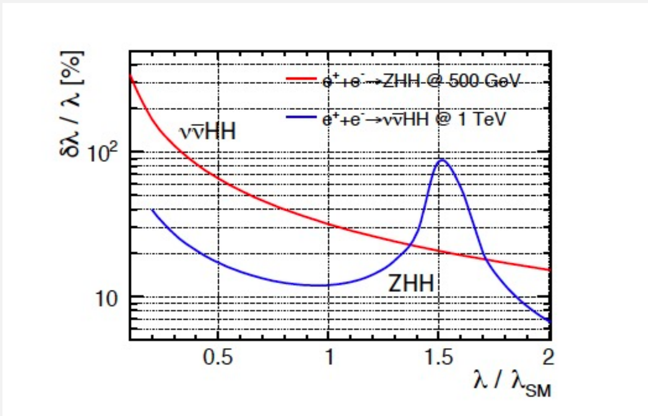
* Polarized beams as in ILC

~10% MEASUREMENTS

- CLIC at 1.4 TeV expects 5.9σ evidence for ZHH observation with 68%cl measurement

$$0.93 < \lambda/\lambda_{SM} < 1.11$$

- Many models have enhanced HHH couplings
- Shape of distributions change with λ_3

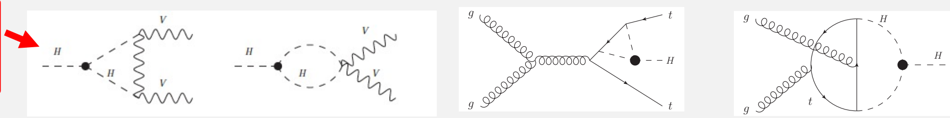


ILC with 4 ab^{-1} with 80% e^- and 30 % e+ polarizations in bbbb and bbWW channels

COMPLEMENTARITY WITH PRECISION MEASUREMENTS

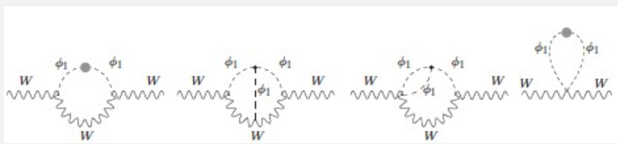
- Indirect constraints from Higgs measurements

Contributes to $e^+e^- \rightarrow ZH$



+ …

- Indirect constraints from precision observables



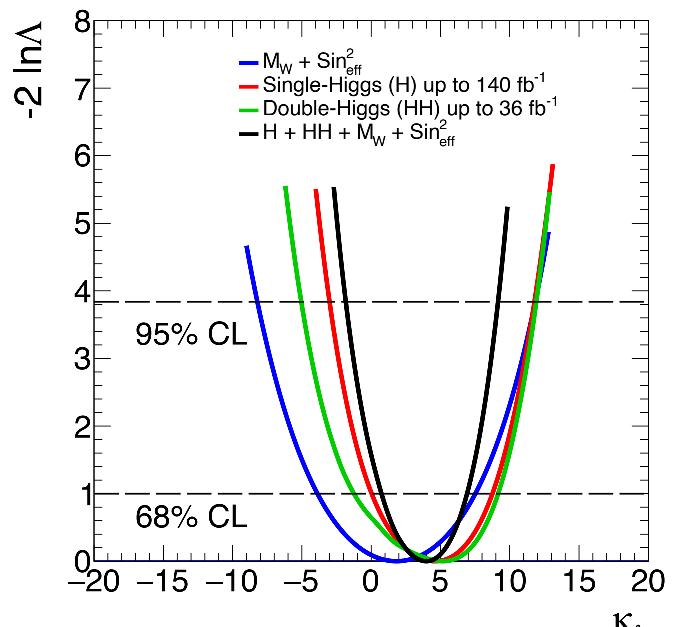
- Single H production sensitive to loops
- If you consider loops you get many more operators

Precision on κ_λ similar to that from direct measurements of HH

➡ Include in global fits

κ_λ IN SINGLE HIGGS PRODUCTION

- Include HH limits in global fits
- Theory is scenario where only new physics is scalar modification of HHH vertex
- EFT approach will have other contributions to HH production



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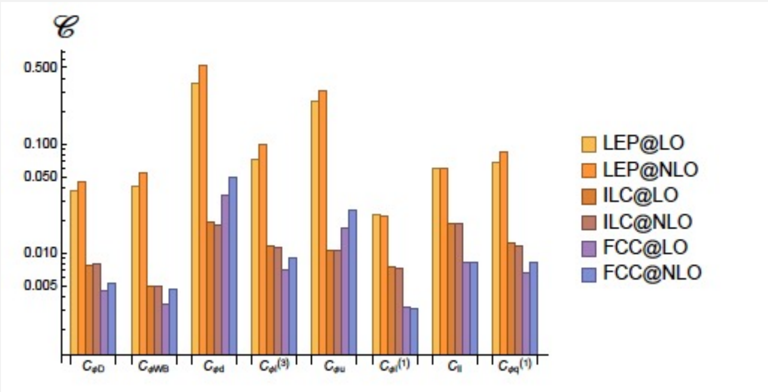
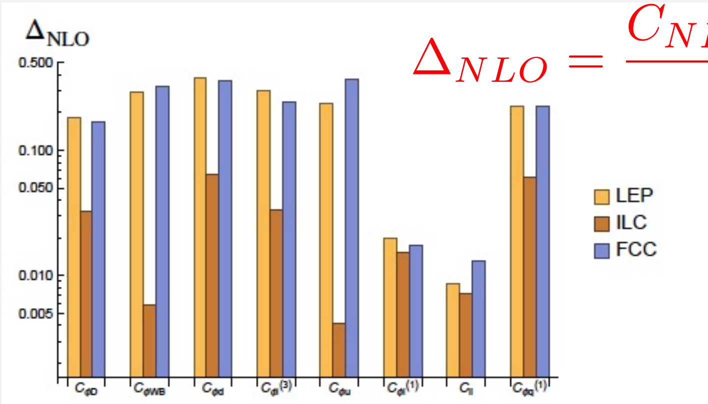
FIT TO PRECISION EW OBSERVABLES

- At NLO EW , dependence on many coefficients that don't arise at tree level when computing Z pole observables
- These effects can be numerically significant





$$\Delta_{NLO} = \frac{C_{NLO} - C_{LO}}{C_{LO}}$$

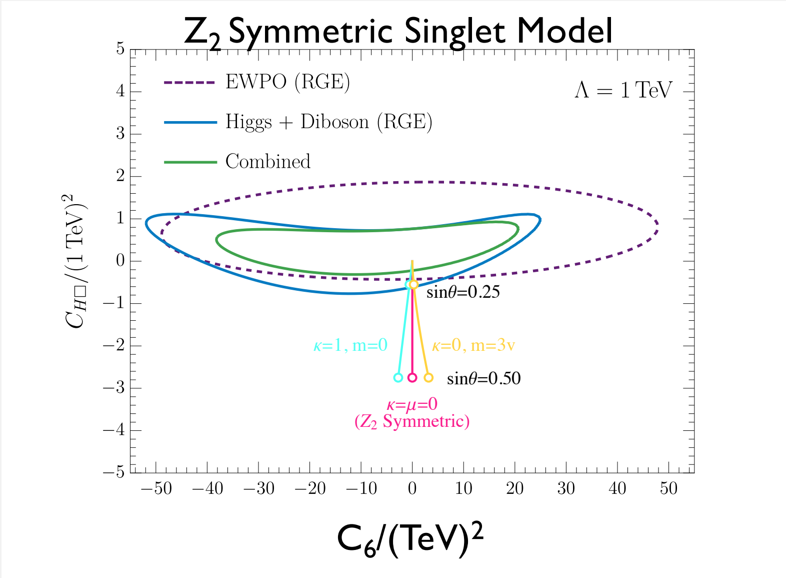
2007.01296.pdf

TARGET FOR PRECISION?

- Z_2 symmetric singlet model fit to single Higgs, VV data, electroweak precision observables
- Target measurement of λ_3/λ_{SM} to improve on current limit

$$-.27 < \frac{\lambda_3}{\lambda_{SM}} < .82$$

$C_{H\Box} = 0$ in Z_2 symmetric singlet model



$$\frac{\lambda_3}{\lambda_{SM}} = \frac{v^2}{\Lambda^2} C_6$$

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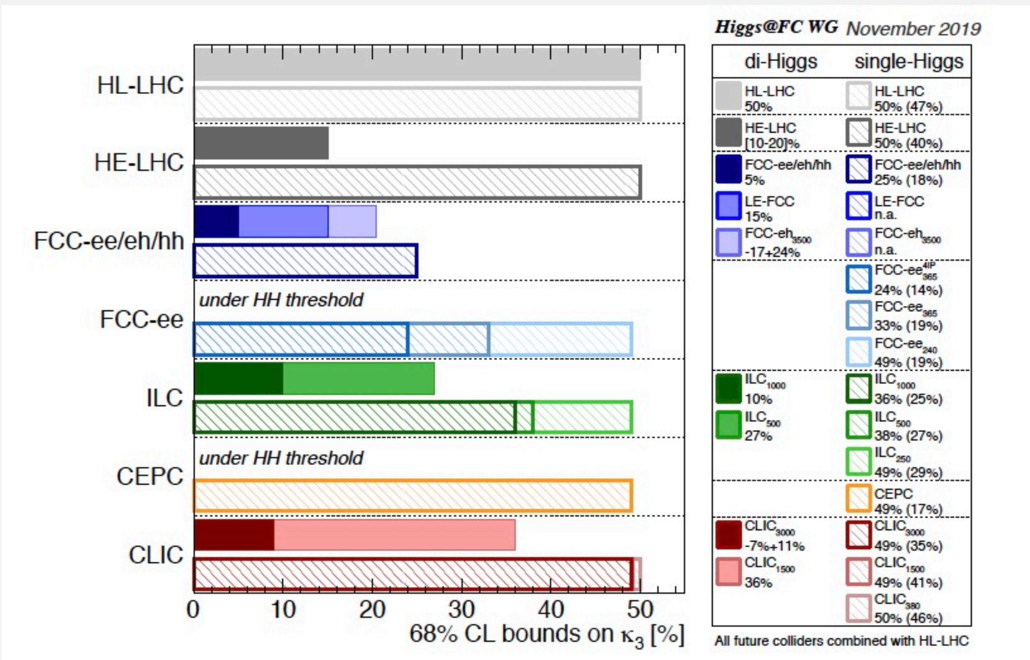
CONCLUSION



Single Higgs numbers have multi-parameter SMEFT fit with 1 parameter fit in ().

2 years later, we have better handles on SMEFT theory predictions (both QCD and EW)

Combine di-Higgs and single Higgs sensitivities

1905.03764.pdf

CONCLUSIONS

- Theory has advanced so that we have the tools to do NLO QCD studies for FCC-hh for HH production with anomalous couplings
  - SMEFT EW loop calculations not complete (and our understanding of when they are needed is also inadequate)
- Need to include more than just the HHH coupling in projections for HH sensitivities
  - This effort is taking hold
  - Models motivate choice of anomalous couplings
- Global fits (both e^+e^- and pp) sensitive to anomalous couplings in HH production