Prospects for double Higgs production

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'LFC15'

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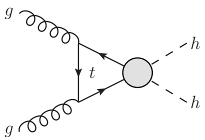
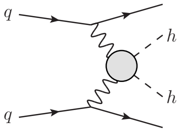
Processes for double Higgs production

pp colliders (HL-LHC, FCC-hh)

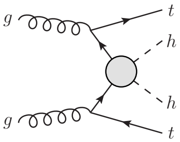
Gluon Fusion (GF)



Vector Boson Fusion (VBF)

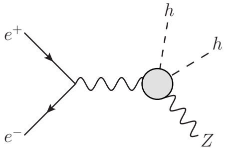


$tthh$ associated production



e^+e^- colliders (ILC, FCC-ee, CLIC)

Double HiggsStrahlung (DHS)



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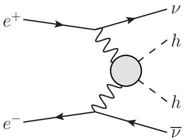

The Effective Field Theory approach

❖ EFT is a perfect framework for **low-energy machines with high precision** (e^+e^-, HL-LHC)

Can not access directly the new states ➠ Probe their **tail effects** with precision measurements

❖ Primary goal of **high-energy machines** (FCC-hh) is to directly produce new states

EFT can only be used near threshold, well below the new resonances

- useful to obtain a model-independent parametrization of the contributions of the new states in terms of few local operators

The Effective Field Theory approach

❖ New-physics effects in Higgs production typically grow with energy

on-shell single production $\dfrac{\delta c}{c} \sim \dfrac{g_*^2}{g_{\rm SM}^2} \dfrac{m_h^2}{m_*^2}$

$2 \to 2$ processes $\dfrac{\delta \mathcal{A}}{\mathcal{A}} \sim \dfrac{g_*^2}{g_{\rm SM}^2} \dfrac{E^2}{m_*^2}$

m_* scale of NP

g_* coupling of new states

➢ useful to extend the analysis to higher energies and to use differential distributions to increase the sensitivity

range of validity: $m_h \ll E \ll m_*$

The effective Lagrangian for a Higgs doublet

Assumptions:

- Higgs is an $\mathrm{SU}(2)_L$ doublet
- derivative expansion
- expansion in Higgs powers

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}_6 + \Delta\mathcal{L}_8 + \cdots$$

[Buchmuller and Wyler; ... Giudice at al.; Grzadkowski et al.]

$$\Delta\mathcal{L}_6 \supset \frac{\overline{c}_H}{2v^2}[\partial_\mu(H^\dagger H)]^2 + \frac{\overline{c}_u}{v^2} y_u H^\dagger H \overline{q}_L H^c u_R - \frac{\overline{c}_6}{v^2}\frac{m_h^2}{2v^2}(H^\dagger H)^3 + \frac{\overline{c}_g}{m_w^2} g_s^2 H^\dagger H G_{\mu\nu} G^{\mu\nu}$$

$c_V \simeq 1 - \frac{\overline{c}_H}{2}$ $\quad c_{2V} \simeq 1 - 2\overline{c}_H$ $\quad c_t \simeq 1 - \frac{\overline{c}_H}{2} - \overline{c}_u$ $\quad c_{2t} \simeq -\frac{1}{2}(\overline{c}_H + 3\overline{c}_u)$

$c_g = c_{2g} = \overline{c}_g \left(\frac{4\pi}{\alpha_2}\right)$ $\quad c_3 \simeq 1 - \frac{3}{2}\overline{c}_H + \overline{c}_6$

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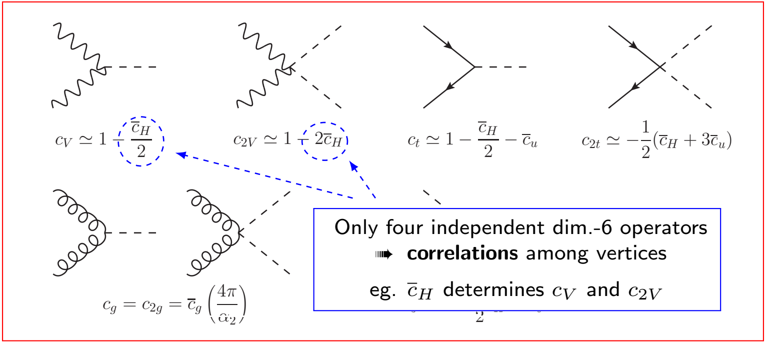


The effective Lagrangian for a Higgs doublet

The effective vertices correspond to the interactions in the unitary gauge

$$\mathcal{L} \supset \left(m_W^2 W_\mu^2 + \frac{m_Z^2}{2} Z_\mu^2\right)\left(1 + 2c_V \frac{h}{v} + c_{2V}\frac{h^2}{v^2}\right) - m_t \bar{t}t\left(1 + c_t \frac{h}{v} + c_{2t}\frac{h^2}{2v^2}\right)$$

$$- c_3 \frac{m_h^2}{2v} h^3 + \frac{g_s^2}{4\pi^2}\left(c_g \frac{h}{v} + c_{2g}\frac{h^2}{2v^2}\right) G^a_{\mu\nu} G^{a\,\mu\nu}$$

This parametrization is more general than the previous one

- valid for a generic Higgs (even not part of a doublet)
- resums the expansion in Higgs powers (if Higgs is a doublet)

Double Higgs at Hadron Colliders

Literature (for $\mathbf{FCC_{100}}$):

Baglio, Djouadi, Groeber, Muellheitner, Quevillon, Spira, JHEP 1304 (2013) 151
Yao, arXiv:1308.6302 (Snowmass Summer Study 2013)
Barr, Dolan, Englert, De Lima, Spannowsky, JHEP 1502 (2015) 016
Azatov, Contino, G.P, Son, Phys.Rev. D92 (2015) 3

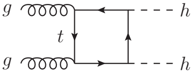
Benchmark Scenarios:

	$\mathbf{LHC_{14}}$	$\sqrt{s} = 14$ TeV, $L = 300$ fb^{-1}
	HL-LHC	$\sqrt{s} = 14$ TeV, $L = 3$ ab^{-1}
	$\mathbf{FCC_{100}}$	$\sqrt{s} = 100$ TeV, $L = 3$ ab^{-1}

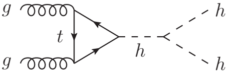
Double Higgs production via Gluon Fusion

results from Azatov, Contino, G.P., Son, Phys.Rev. D92 (2015) 3

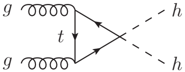
Double Higgs production via gluon fusion



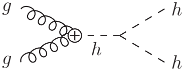
$\sim c_t^2 \times const.$



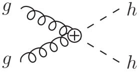
$\sim c_t c_3 \times \frac{m_h^2}{\hat{s}} \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



$\sim c_{2t} \times \log^2\left(\frac{m_t^2}{\hat{s}}\right)$



$\sim c_g c_3 \frac{\alpha_s}{4\pi} \times const.$



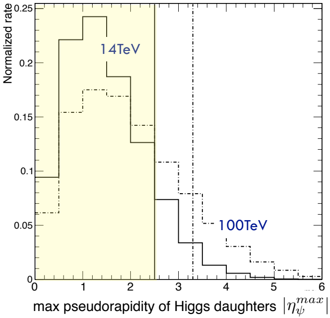
$\sim c_{2g} \frac{\alpha_s}{4\pi} \frac{\hat{s}}{v^2}$

- Different behaviour at high energy $\sqrt{\hat{s}} = m_{hh} \gg 2m_h$
- Dependence on Higgs trilinear suppressed at high energy
  - events at threshold more sensitive to Higgs trilinear, events at large m_{hh} more important to determine the other operators

Kinematics of the signal

Two **main differences** between 14 TeV and 100 TeV:

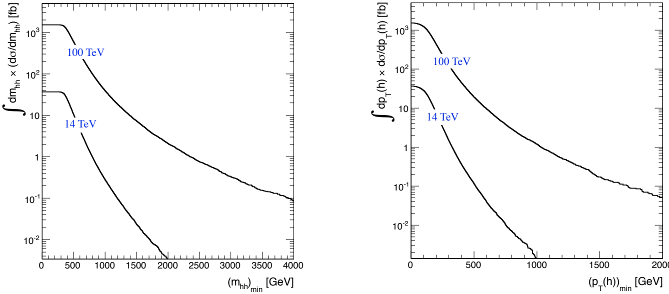
1. Larger boost of the hh system ➠ higher fraction of decay products outside the detector region



- Fraction of events with $|\eta| > 2.5$: 13% at LHC ➠ 30% at 100 TeV
- Need to extend to $|\eta| \leq 3.3$ to keep same fraction of events

Kinematics of the signal

2. **Larger invariant mass** of the hh system



Highest accessible m_{hh} and p_T estimated by requiring at least 5 events beyond the threshold

channel	$b\bar{b}b\bar{b}$ (33.3%)	$b\bar{b}WW^*$ (24.9%)	$b\bar{b}\tau^+\tau^-$ (7.35%)	$b\bar{b}\gamma\gamma$ (0.264%)
Cross section	> 0.05 fb	> 0.067 fb	> 0.227 fb	> 6.31 fb
m_{hh} [GeV]	$< 1340(4290)$	$< 1280\ (4170)$	$< 1039\ (3235)$	$< 558\ (1552)$
p_T [GeV]	$< 575(2000)$	$< 575\ (2000)$	$< 550\ (1890)$	$< 210\ (664)$

[We use $L = 3/\mathrm{ab}$ and assume 10% efficiency. Numbers in parenthesis for a 100 TeV collider]

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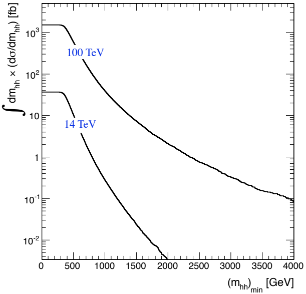
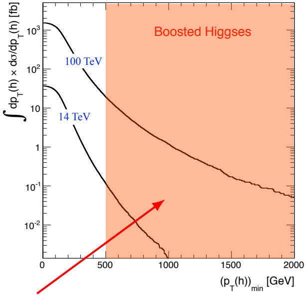




H ... least 5 events

be

Jet substructure techniques crucial at 100 TeV

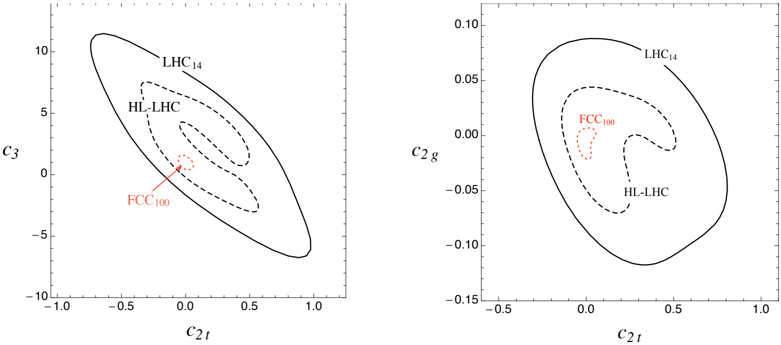
$$\Delta R \sim \frac{2m_h}{p_T(h)} \lesssim 0.5 \quad \text{for} \quad p_T(h) \gtrsim 500 \text{ GeV}$$

				$b\bar{b}\gamma\gamma$ (0.264%)
Cross section	> 0.05 fb	> 0.067 fb	> 0.227 fb	> 6.31 fb
m_{hh} [GeV]	$< 1340(4290)$	< 1280 (4170)	< 1039 (3235)	< 558 (1552)
p_T [GeV]	$< 575(2000)$	< 575 (2000)	< 550 (1890)	< 210 (664)

[We use $L = 3/\text{ab}$ and assume 10% efficiency. Numbers in parenthesis for a 100 TeV collider]

Higgs couplings from the $b\bar{b}\gamma\gamma$ channel

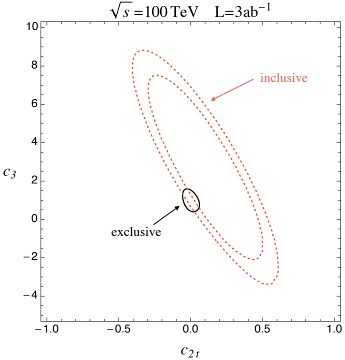
The non-linear Higgs couplings c_3, c_{2t}, c_{2g} can only be directly accessed in double-Higgs production

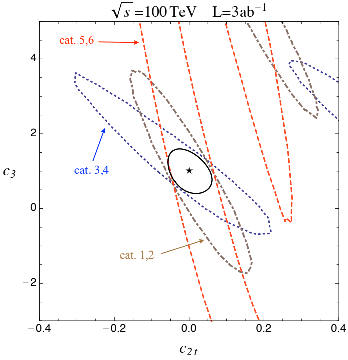


- Higgs trilinear can only be extracted at FCC (at LHC only $\mathcal{O}(1)$ determination possible)
- good precision on c_{2t} and c_{2g}

Exclusive vs inclusive analysis

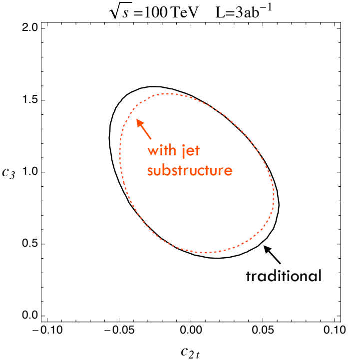
- **Exclusive analysis** is crucial at FCC_{100}!

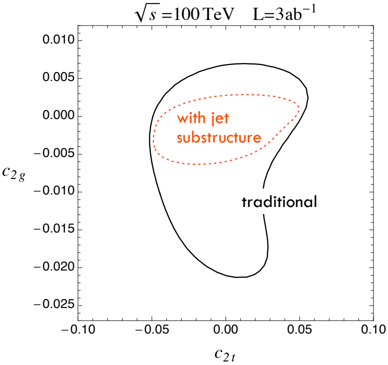




category	1	2	3	4	5	6
m_{hh} [GeV]	$250-400$	$400-550$	$550-700$	$700-850$	$850-1000$	$1000-$

Improvement from jet substructure

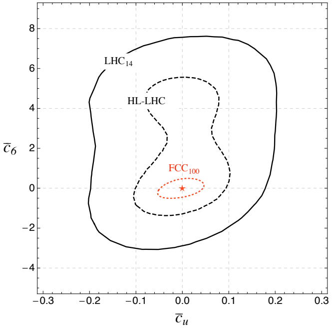


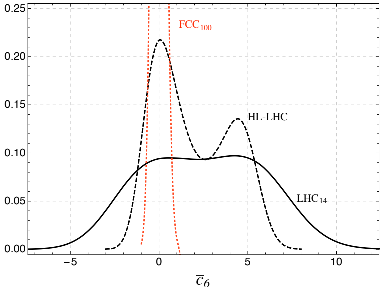


Jet substructure efficiently improves the sensitivity to boosted events

- important to extract c_{2g} (effects in the tail of the distribution)
- not crucial to determine c_3 and c_{2t} (effects close to threshold)

Constraining the dim.-6 operators: $\overline{c}_u$ and $\overline{c}_6$

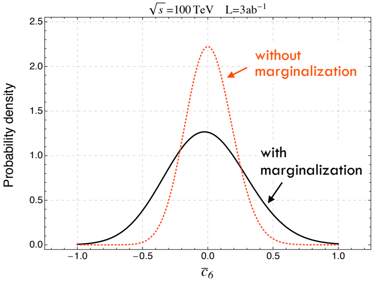




68% probability intervals on $\overline{c}_6$

LHC$_{14}$	HL-LHC	FCC$_{100}$
$[-1.2, 6.1]$	$[-1.0, 1.8] \cup [3.5, 5.1]$	$[-0.33, 0.29]$

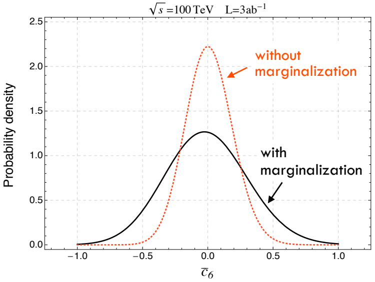
The statistical treatment



Marginalization has a significant impact on the precision on $\bar{c}_6$

	with marginalization	without marginalization
precision at FCC_{100}	$[-0.33, 0.29]$	$[-0.18, 0.18]$

The statistical treatment



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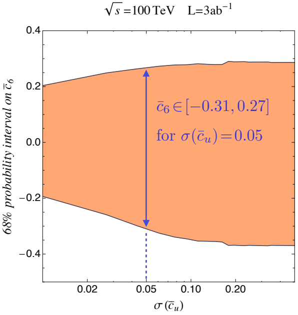
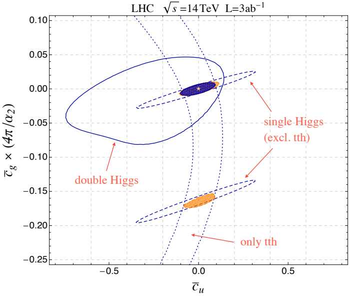
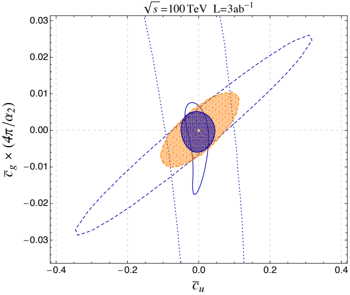
	with marginalization	without marginalization
precision at FCC_{100}	$[-0.33, 0.29]$	$[-0.18, 0.18]$

e.g. uncertainty on $\bar{c}_u$ increases uncertainty on $\bar{c}_6$



Constraining the dim.-6 operators: $\bar{c}_u$ and $\bar{c}_g$





- ➢ double Higgs can resolve the degeneracy in c_g
- ➢ at FCC_{100} it can be competitive with $t\bar{t}h$ for the determination of the top Yukawa $\bar{c}_u$ (if precision from single Higgs similar to the LHC one)

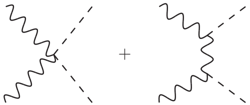
Orange region: single Higgs incl. $t\bar{t}h$

Blue region: single + double Higgs

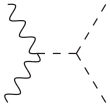
Double Higgs production via Vector Boson Fusion

results from Contino, Rojo, work in progress (courtesy of R. Contino)

Double Higgs production via vector boson fusion



$\sim \frac{\hat{s}}{v^2}(c_V^2 - c_{2V})$

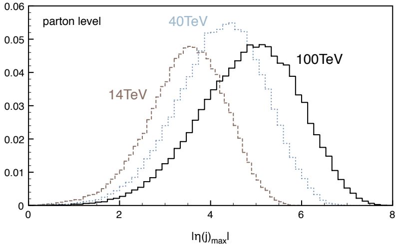


$\sim \frac{m_h^2}{v^2} c_3 c_V$

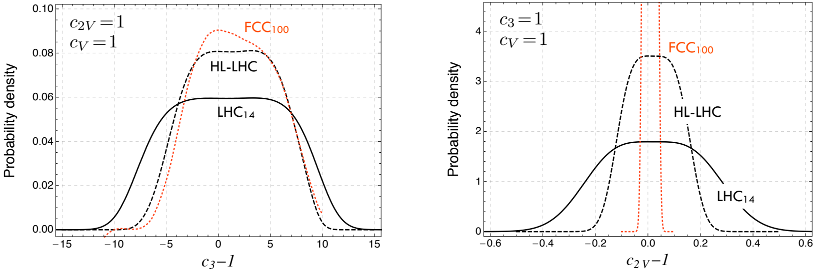
- Sensitivity on c_3 mainly from events at threshold
- Events with large m_{hh} more important to extract c_{2V}

Study of double Higgs in VBF at 100 TeV requires a detector in the very forward region

$\sim 67\%$ of signal events has $|\eta(j)_{max}| > 4.5$



Higgs couplings from the $hh \to 4b$ channel



Huge background, sensitive only if deviations much larger than the SM

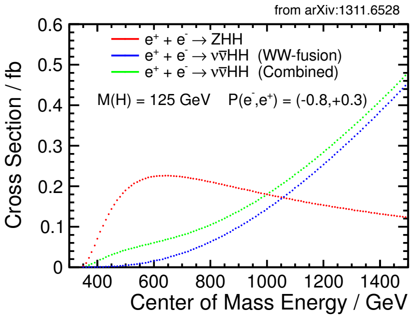
- Poor precision on Higgs trilinear (not competitive with gluon fusion)
- FCC_{100} can provide good bounds on $\Delta c_{2V} \equiv c_{2V} - 1$

68% probability intervals on Δc_{2V}	LHC_{14}	HL-LHC	FCC_{100}
	$[-0.18, 0.22]$	$[-0.08, 0.12]$	$[-0.01, 0.03]$

Double Higgs at e^+e^- Colliders

taken from R. Contino, talk at HPPC2015 (Mainz)

Main production channels



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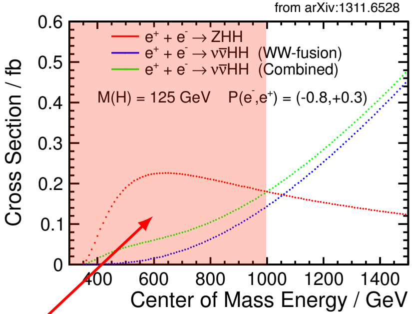
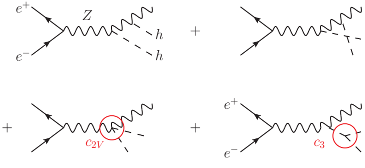


Double Higgs-strahlung (DHS)

dominant below 1 TeV



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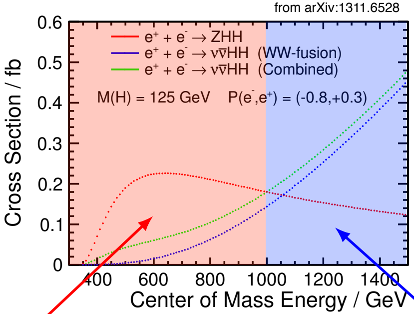

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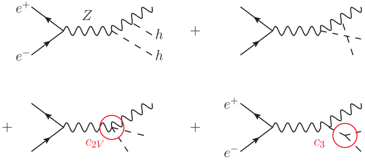
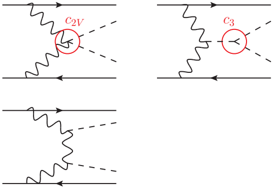


Vector Boson Fusion (VBF)

dominant above 1 TeV



Expected precision on c_3 and c_{2V}

	COM Energy	Precision	Process	Reference
ILC	500 GeV $[L = 500 \text{ fb}^{-1}]$	$\Delta c_3 \sim 104\%$	DHS	ILC TDR, Volume 2, arXiv:1306.6352
	1 TeV $[L = 1 \text{ ab}^{-1}]$	$\Delta c_3 \sim 28\%$	VBF	ILC TDR, Volume 2, arXiv:1306.6352
		$\Delta c_{2V} \sim 20\%$	DHS	Contino et al., JHEP 1402 (2014) 006
CLIC	1.4 TeV $[L = 1.5 \text{ ab}^{-1}]$	$\Delta c_3 \sim 24\%$	VBF	Roloff (CLICdp Coll.), talk at LCWS14
		$\Delta c_{2V} \sim 7\%$		
	3 TeV $[L = 2 \text{ ab}^{-1}]$	$\Delta c_3 \sim 12\%$		
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Precision on Higgs trilinear slightly better than FCC_{100} (effects at threshold)

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Precision on c_{2V} worse than FCC_{100}

(effects grow with energy)

Conclusions

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❖ Double Higgs production is an essential channel to extract information on the non-linear Higgs couplings

- Measure the Higgs trilinear coupling c_3
- Access new couplings to top and gluon: c_{2t}, c_{2g}, c_{2V}

❖ Leptonic vs Hadronic colliders

- e^+e^- machines
  - can extract c_3 and c_{2V}, but $\sqrt{s} \gtrsim 1$ TeV is needed
- pp machines
  - better precision with energy-growing interactions c_{2t}, c_{2g}, c_{2V}
  - good precision on Higgs trilinear thanks to high statistics

Backup material

Sensitivity on the EFT coefficients

Precision on single-Higgs observables from ATLAS projection

[ATL-PHYS-PUB-2013-014]

	300 fb^{-1}	3 ab^{-1}
$\sigma(\bar{c}_H)$	7.9%	5.4%
$\sigma(\bar{c}_u)$	5.9% $(w/t\bar{t}h)$	5.4% $(w/t\bar{t}h)$
	20% $(t\bar{t}h)$	7.7% $(t\bar{t}h)$
$\sigma(\bar{c}_d)$	6.3%	4.4%