Higgs quartic coupling at a Muon Collider

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based on JHEP 09 (2020) 098 [arXiv:2003.13628]

in collaboration with Luca Mantani, Fabio Maltoni, Barbara Mele, Fulvio Piccinini and Xiaoran Zhao

H self-couplings measurement: future colliders (HHHH)

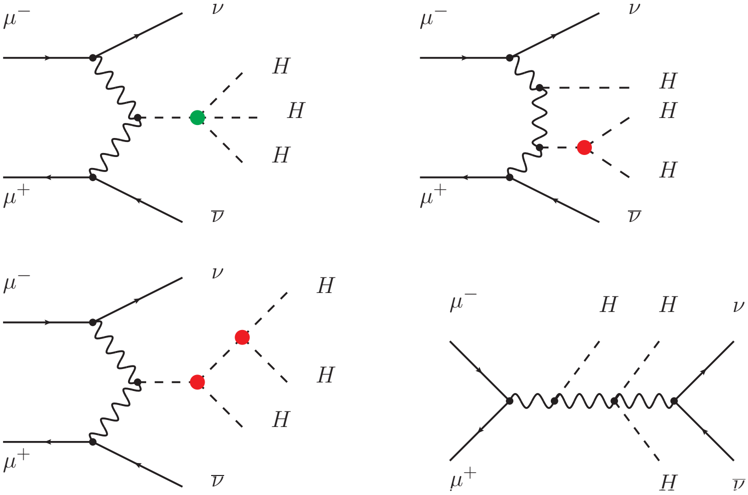
- the proposed future colliders can put strong constraints on the triple Higgs coupling δ_3: $\pm 10\%$ 1-σ bound at CLIC and ILC, $\pm 5\%$ at FCC
- the bounds on the quartic couplings δ_4 are very loose (68% CL)
  - ILC: $\sim [-10, +10]$ ($\pm 1000\%!$)
  - CLIC: $\sim [-5, +5]$
  - FCC: $\sim [-5, +15]$, from $pp \to HHH$
  - FCC: $\sim [-2, +4]$, from $pp \to HH$

I will focus on the sensitivity of the muon collider to the quartic coupling

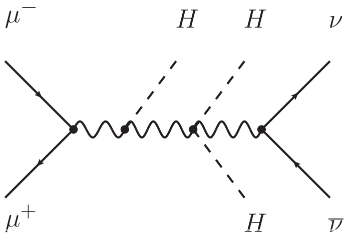
Spoiler:

under (reasonable) assumptions on the energy and the luminosity, the muon collider can do a pretty good job in constraining the quartic Higgs coupling

$\mu^+\mu^- \to HHH\nu\overline{\nu}$



Details of the calculations



- H produced on shell
- $H \to b\bar{b}$ (on-shell) decays added at the LHE level
- $\Gamma_W = \Gamma_Z = \Gamma_H = 0$ to avoid issues with gauge invariance
- technical cut $M(\nu\overline{\nu}) > 150$ GeV
- σ and $d\sigma$ computed with `WHIZARD` at LO
- all results cross-checked with `MadGraph` and an independent calculation by X. Zhao

$\mu^+\mu^- \to HHH\nu\bar{\nu}$: SM Higgs couplings (energy)

$\sqrt{s}$ (TeV) / L (ab^{-1})	1.5 / 1.2	3 / 4.4	6 / 12
σ_{SM} (ab) $[N_{\rm ev}]$			
$\sigma^{\rm tot}$	0.03 [0]	0.31 [1]	1.65 [20]
$\sigma(M_{HHH} < 3\text{TeV})$	0.03 [0]	0.31 [1]	1.47 [18]
$\sigma(M_{HHH} < 1\text{TeV})$	0.02 [0]	0.12 [1]	0.26 [3]

$\sqrt{s}$ (TeV) / L (ab^{-1})	10 / 20	14 / 33	30 / 100
σ_{SM} (ab) $[N_{\rm ev}]$			
$\sigma^{\rm tot}$	4.18 [84]	7.02 [232]	18.51 [1851]
$\sigma(M_{HHH} < 3\text{TeV})$	2.89 [58]	3.98 [131]	6.69 [669]
$\sigma(M_{HHH} < 1\text{TeV})$	0.37 [7]	0.45 [15]	0.64 [64]

σ increases with $\sqrt{s}$

$\mu^+\mu^- \to HHH\nu\bar{\nu}$: SM Higgs couplings (luminosity)

$\sqrt{s}$ (TeV) / L (ab^{-1})	1.5 / 1.2	3 / 4.4	6 / 12
σ_{SM} (ab) $[N_{\rm ev}]$			
$\sigma^{\rm tot}$	0.03 [0]	0.31 [1]	1.65 [20]
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The lower energy setups (1.5 and 3 TeV) do not have enough events to study the quartic Higgs self coupling

$\mu^+\mu^- \to HHH\nu\bar{\nu}$: SM Higgs couplings (luminosity)

- the luminosities assumed for $\sqrt{s} = 1.5, 3, 6, 14$ TeV are based on MAP studies

V. Shiltsev FERMILAB-FN_1083-AD-APC,

talks by D. Shulte and M. Palmer https://indico.cern.ch/event/847002/

- at $\sqrt{s} = 10, 30$ TeV, the luminosity is fixed by (see arXiv:1910.06150)

Luminosity:

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s_\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2}\text{s}^{-1}$$

Set by asking for 100K SM “hard” SM pair-production events.

- for the 10 and 30 TeV setups, it might be that higher luminosity could be achieved

Deviations from SM Higgs couplings

$$\mathcal{L} = -\frac{1}{2}M_H^2 H^2 - \left(1+\delta_3\right)\frac{M_H^2}{2v}H^3 - \left(1+\delta_4\right)\frac{M_H^2}{8v^2}H^4$$

We consider 3 different scenarios:

1. $\delta_3 = 0$, δ_4 arbitrary
2. δ_3 arbitrary, $\delta_4 = 6\delta_3$ (well behaved SMEFT)

S. Borowka et al. arXiv:1811.12366

3. δ_3 arbitrary and δ_4 arbitrary

Sensitivity to δ_3 and δ_4

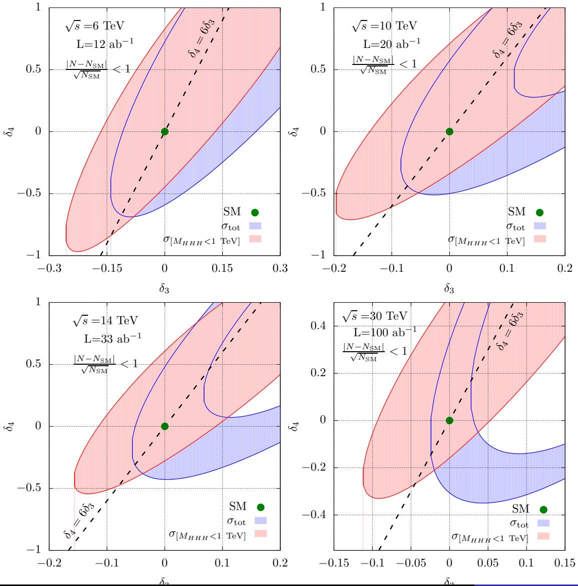
No background process considered:
we quantify the sensitivity in terms of standard deviations from the SM expectation

$$\frac{|N - N_{\mathrm{SM}}|}{\sqrt{N_{\mathrm{SM}}}}$$

Remarks

- no background is considered, but the environment should be rather clean
- no branching ratio is applied, but if the environment is clean enough all the main decay channels should be visible
- (almost) no optimization based on kinematics is performed, so there is room for improvement

Sensitivity to δ_3 and δ_4 (small δ_3)



- no cuts
- $M_{HHH} < 1$ TeV

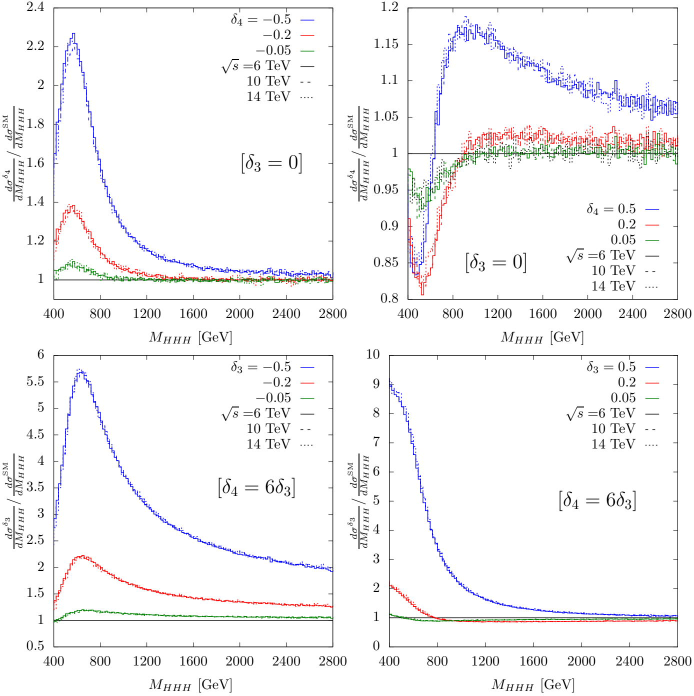
$$\delta_3 = 0$$

6 TeV $\delta_4 \sim [-0.45, 0.8]$

10 TeV $\delta_4 \sim [-0.4, 0.7]$

14 TeV $\delta_4 \sim [-0.35, 0.6]$

30 TeV $\delta_4 \sim [-0.2, 0.5]$


$\delta_4 = -0.5$
-0.2
-0.05
$\sqrt{s}$ =6 TeV
10 TeV
14 TeV
$[\delta_3 = 0]$
$\delta_4 = 0.5$
0.2
0.05
$\sqrt{s}$ =6 TeV
10 TeV
14 TeV
$[\delta_3 = 0]$
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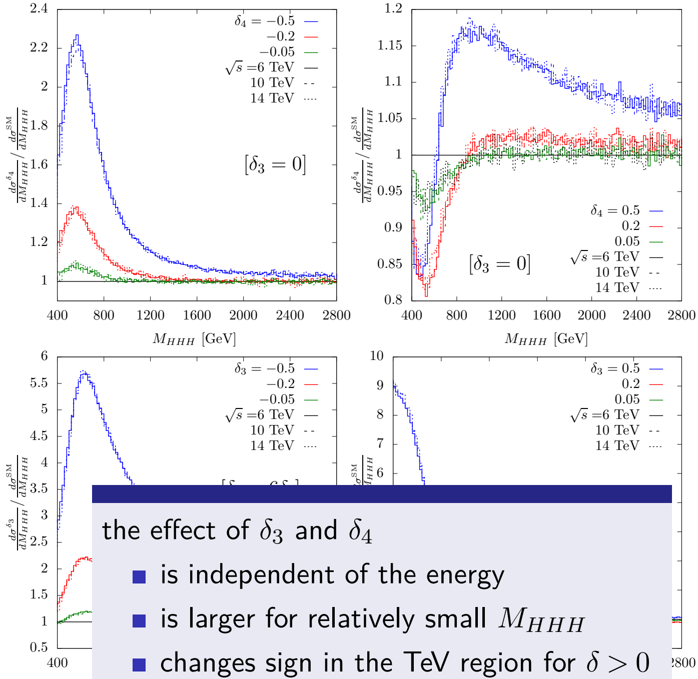
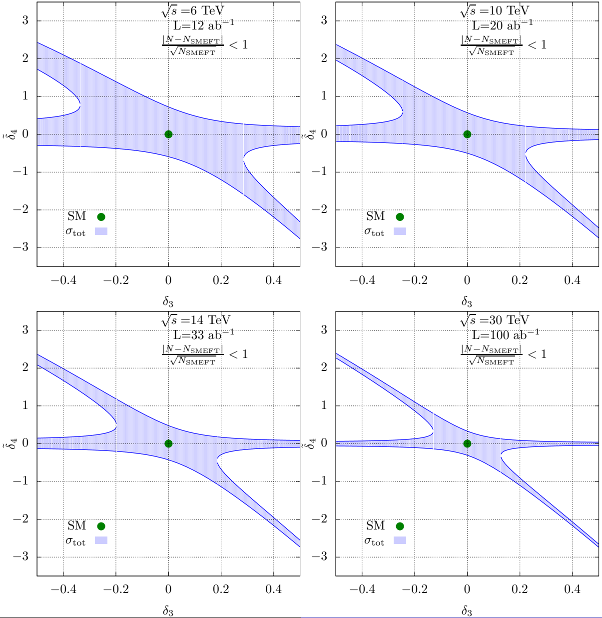
10 TeV
14 TeV
$[\delta_4 = 6\delta_3]$
$\delta_3 = 0.5$
0.2
0.05
$\sqrt{s}$ =6 TeV
10 TeV
14 TeV
$[\delta_4 = 6\delta_3]$
$\frac{d\sigma^{\delta_4}}{dM_{HHH}} / \frac{d\sigma^{SM}}{dM_{HHH}}$
$\frac{d\sigma^{\delta_3}}{dM_{HHH}} / \frac{d\sigma^{SM}}{dM_{HHH}}$
M_{HHH} [GeV]



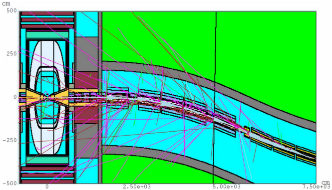
the effect of δ_3 and δ_4

- is independent of the energy
- is larger for relatively small M_{HHH}
- changes sign in the TeV region for $\delta > 0$

Sensitivity to $\tilde{\delta}_4$ (deviation from SMEFT)

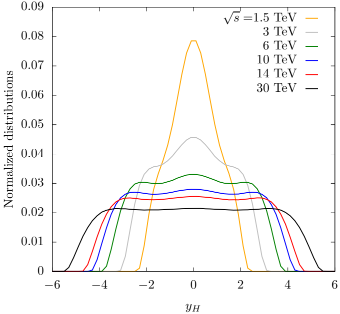


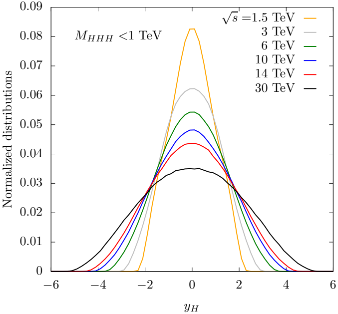
Remark on detector acceptance (1)



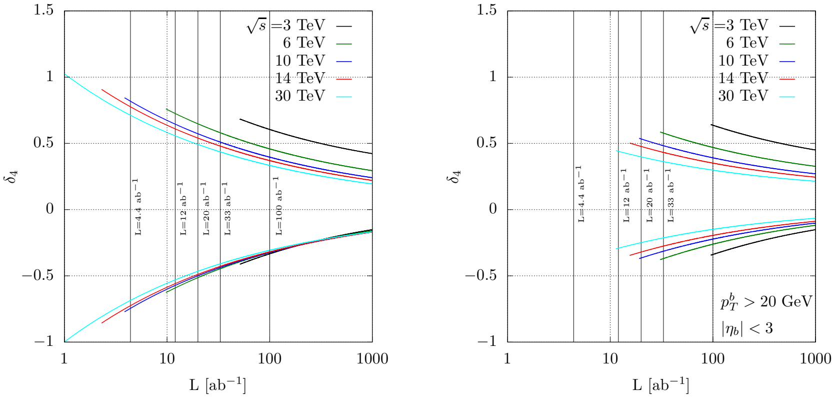
The detector must be shielded from the beam radiation

- 5-10 degrees blind spot in the forward region for $\sqrt{s} = 3$ TeV
- angle could be reduced at higher energies





Remark on detector acceptance (2)



- only geometric acceptance considered (no BR applied)
- sensitivity increases because the SM production is forward, the BSM central

Conclusions

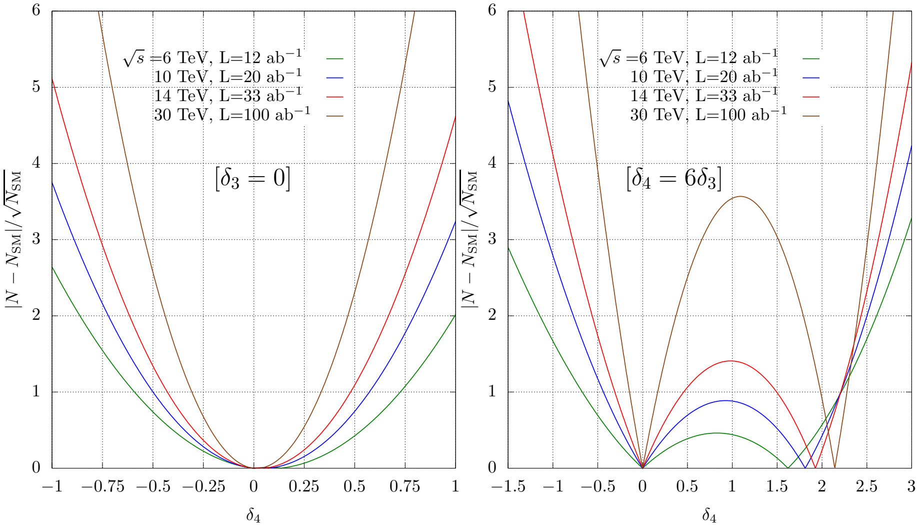
- we studied the sensitivity of the muon collider to the Higgs quartic coupling by considering the process $\mu^+\mu^- \to HHH\nu\overline{\nu}$
- no background was considered
- (almost) no optimization based on kinematics was performed
- the sensitivity increases with $\sqrt{s}$ and/or the luminosity

$\sqrt{s}$ [TeV]	L [ab^{-1}]	δ_4 (arbitrary δ_3)	δ_4 ($\delta_3 = 0$)
6	12	[-1,1.7]	[-0.45,0.8]
10	20	[-0.7,1.55]	[-0.4,0.7]
14	33	[-0.55,1.4]	[-0.35,0.6]
30	100	[-0.35,1.2]	[-0.2,0.5]

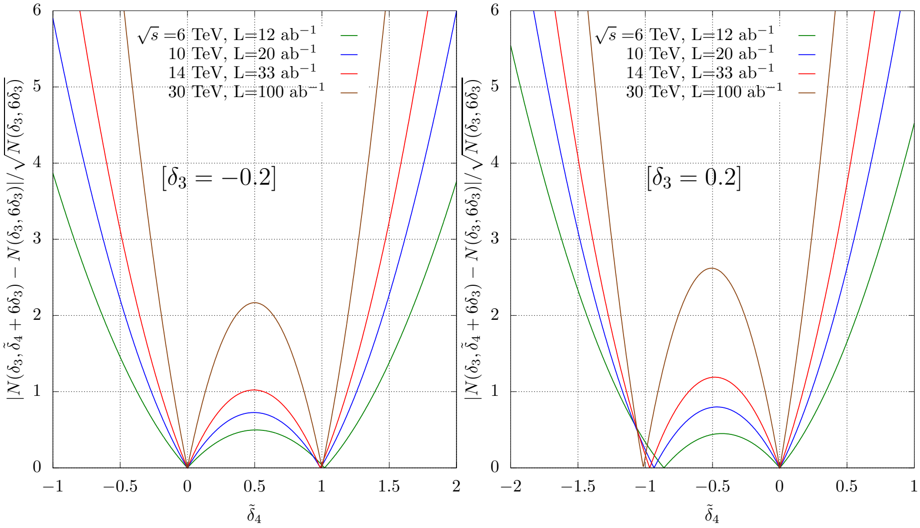
- under (reasonable) assumptions on the energy and the luminosity, the muon collider can do a pretty good job in constraining the quartic Higgs coupling

Backup slides

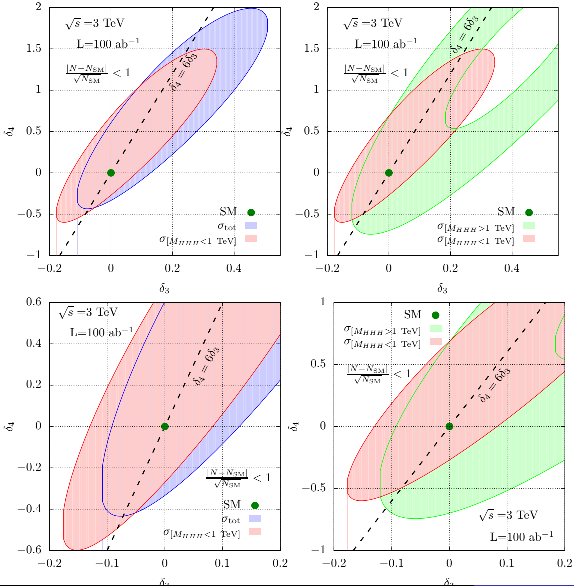
Sensitivity to δ_3 and δ_4



Sensitivity to $\tilde{\delta}_4$ (deviation from SMEFT)



Sensitivity to δ_3 and δ_4 ($\sqrt{s} = 3$ TeV, $L = 100$ ab^{-1})



- no cuts
- $M_{HHH} < 1$ TeV
- $M_{HHH} > 1$ TeV

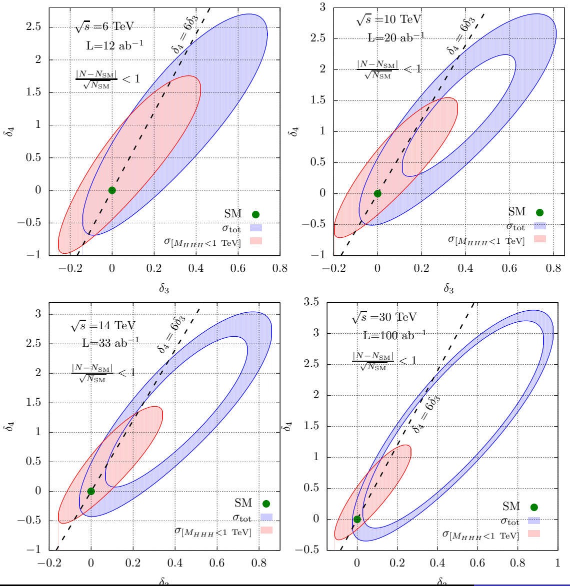
$\delta_4 \sim [-0.6, 1.5]$

if $\delta_3 = 0$

$\delta_4 \sim [-0.3, 0.65]$

Using 20 times the expected luminosity!

Sensitivity to δ_3 and δ_4 (arbitrary δ_3)



- no cuts
- $M_{HHH} < 1$ TeV

$\delta_3 = 0$

6 TeV $\delta_4 \sim [-0.1, 1.7]$

10 TeV $\delta_4 \sim [-0.7, 1.55]$

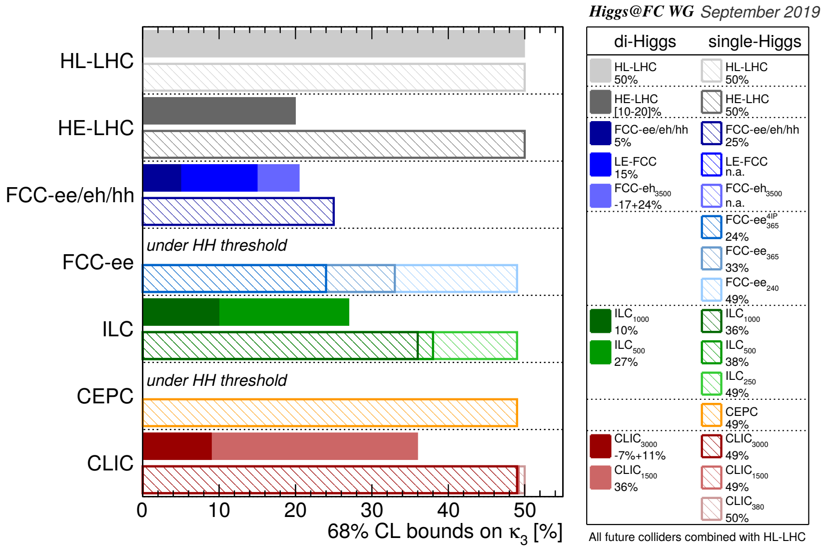
14 TeV $\delta_4 \sim [-0.55, 1.4]$

30 TeV $\delta_4 \sim [-0.35, 1.2]$

Sensitivity to δ_3 and δ_4: comments

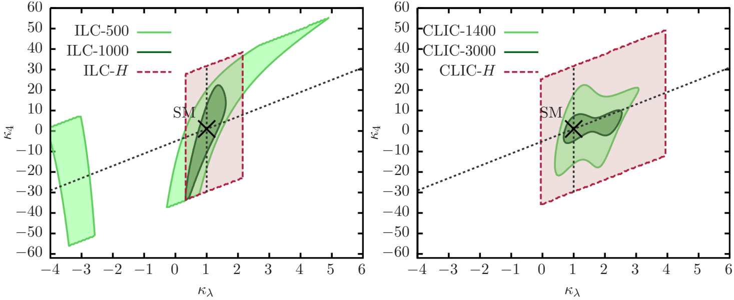
- stronger constraints on negative δs
- constraints on positive δs improve with the cut $M_{HHH} < 1$ TeV (provided that the cross section after the cut is large enough)
- the bounds improve at large $\sqrt{s}$ because the cross section increases
- the most interesting region is $\delta_3 \sim 0$, as bounds on δ_3 can be obtained form other processes (i.e. $\mu^+\mu^- \to HH\nu\overline{\nu}$). It is reasonable to assume that such bounds will be competitive or stronger than the ones form linear colliders
- if $\delta_3 \neq 0$, one can constrain possible deviations from the SMEFT expectation for δ_4: $\tilde{\delta}_4 = \delta_4 - 6\delta_3$

H self-couplings measurement: future colliders (HHH)



arXiv:1910.00012

H self-couplings measurement: future colliders (HHHH)

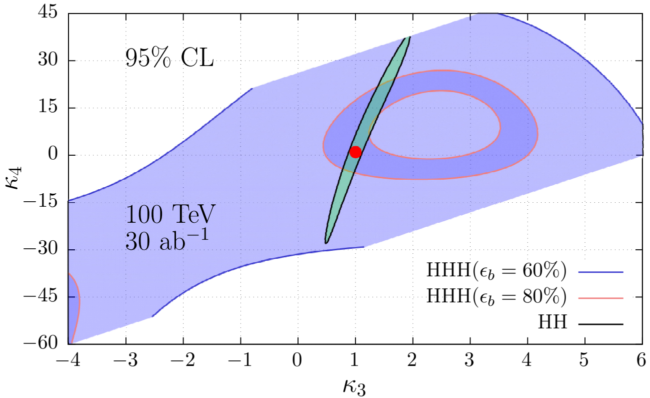


Process	λ_3	λ_4
$ZH\,,\ \nu_e\bar{\nu}_e H$	one-loop	two-loop
$ZHH\,,\ \nu_e\bar{\nu}_e HH$	tree	one-loop
$ZHHH\,,\ \nu_e\bar{\nu}_e HHH$	tree	tree

assuming $\lambda_3 = \lambda_3^{\rm SM}$
quartic coupling constrained
in $\pm \sim 10$ at ILC and $\pm \sim 5$ at CLIC

arXiv:1910.00012, F. Maltoni et al. arXiv:1802.07616, T. Liu et al. arXiv:1803.04359

H self-couplings measurement: future colliders (HHHH)



arXiv:1910.00012

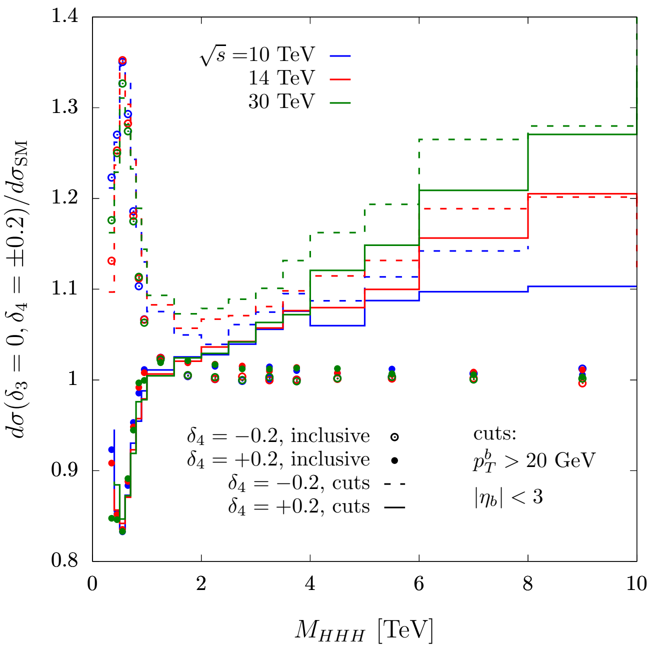
F. Maltoni et al. arXiv:1811.12366

W. Bizoń et al. arXiv:1810.04665

assuming $\lambda_3 = \lambda_3^{\text{SM}}$

λ_4 constrained in $\sim [-5, 15]$ at 68% CL from $pp \to HHH$

λ_4 constrained in $\sim [-2, 4]$ at 68% CL from $pp \to HH$


$\sqrt{s}$ =10 TeV
14 TeV
30 TeV
$\delta_4 = -0.2$, inclusive
$\delta_4 = +0.2$, inclusive
$\delta_4 = -0.2$, cuts
$\delta_4 = +0.2$, cuts
cuts:
$p_T^b > 20$ GeV
$|\eta_b| < 3$
$d\sigma(\delta_3 = 0, \delta_4 = \pm 0.2)/d\sigma_{\mathrm{SM}}$
M_{HHH} [TeV]
1.4
1.3
1.2
1.1
1
0.9
0.8
0
2
4
6
8
10