Quartic Higgs couplings

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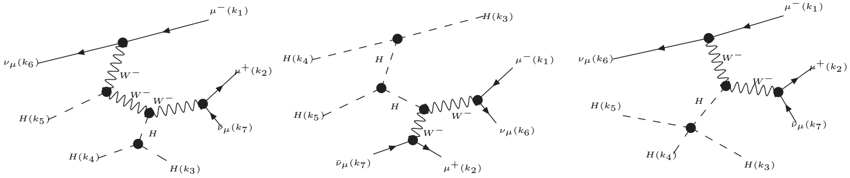
$\mu^+\mu^- \to HHH\nu\bar{\nu}$

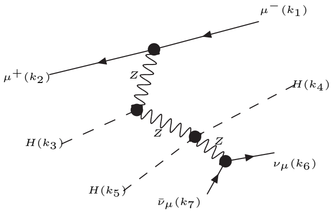


$\sqrt{s}$ [TeV]	3	14	30
σ^{SM} [ab]	0.31	7.02	18.51
L [ab^{-1}]	20×L_{CLIC}	20	100
N^{SM}	31	140	1851

with $\text{L}_{\text{CLIC}} = 5$ ab^{-1}

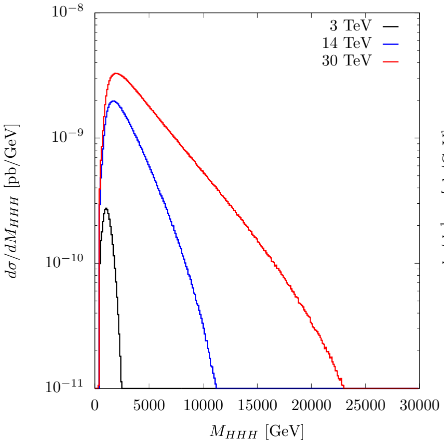
Details of the calculations

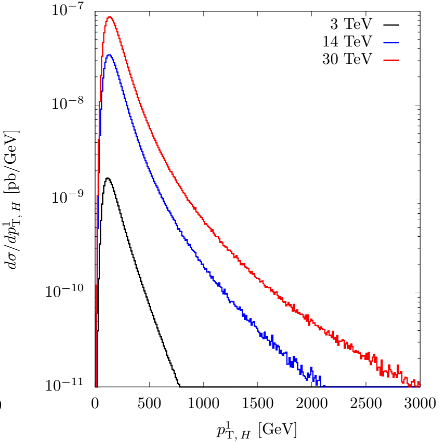
- σ and $d\sigma$ computed at LO with `WHIZARD`
- H produced on shell
- $H \to b\bar{b}$ decays added at the LHE level
- $\Gamma_W = \Gamma_Z = \Gamma_H = 0$ to avoid issues with gauge invariance
- technical cut $M(\nu\bar{\nu}) > 150$ GeV



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

$\sqrt{s}$ [TeV]	3	14	30
σ^{SM} [ab]	0.31	7.02	18.51





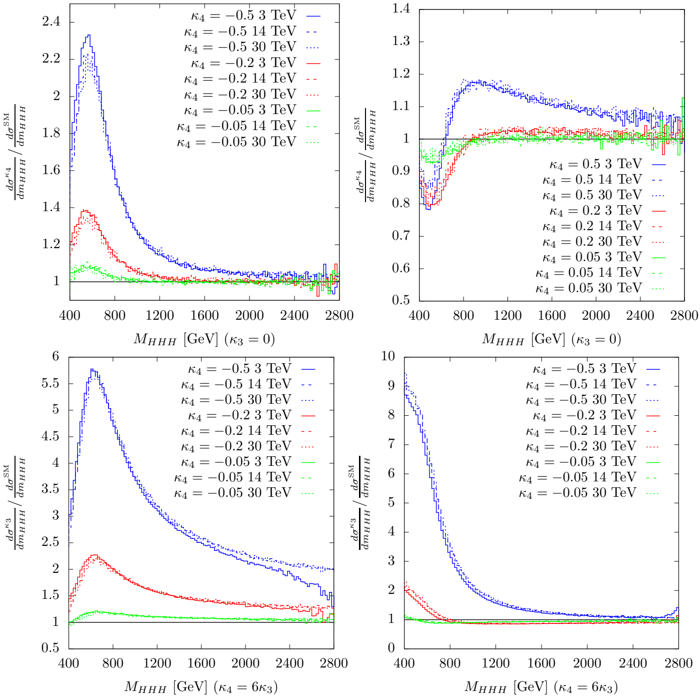
Deviations from SM Higgs couplings

$$g_{3H} = \left(1 + \kappa_3\right) g_{3H}^{SM} \qquad\qquad g_{4H} = \left(1 + \kappa_4\right) g_{4H}^{SM}$$

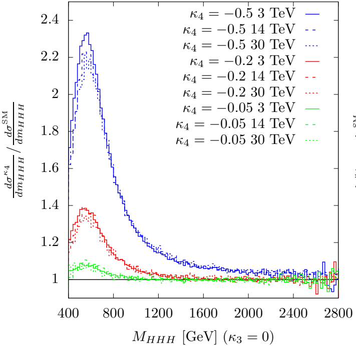
We consider 3 different scenarios:

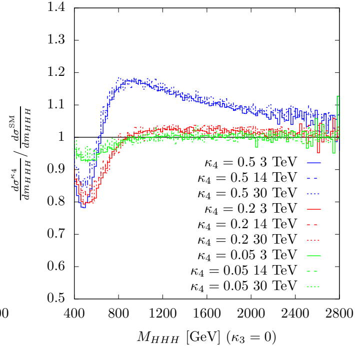
1. $\kappa_3 = 0$, κ_4 arbitrary
2. κ_3 arbitrary, $\kappa_4 = 6\kappa_3$ (SMEFT[1])
3. κ_3 arbitrary and κ_4 arbitrary

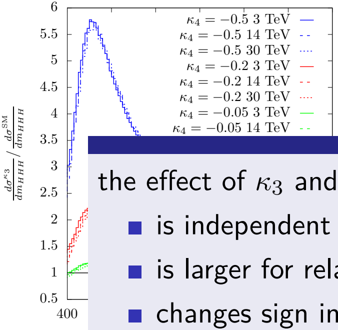
[1] S. Borowka *et al.* arXiv:1811.12366

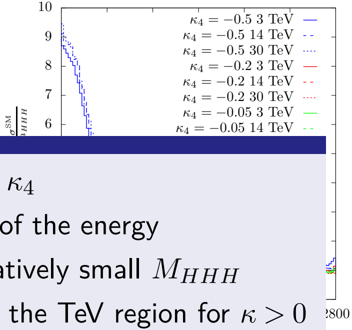


$\kappa_4 = -0.5$ 3 TeV
$\kappa_4 = -0.5$ 14 TeV
$\kappa_4 = -0.5$ 30 TeV
$\kappa_4 = -0.2$ 3 TeV
$\kappa_4 = -0.2$ 14 TeV
$\kappa_4 = -0.2$ 30 TeV
$\kappa_4 = -0.05$ 3 TeV
$\kappa_4 = -0.05$ 14 TeV
$\kappa_4 = -0.05$ 30 TeV
$\frac{d\sigma^{\kappa_4}}{dm_{HHH}} / \frac{d\sigma^{SM}}{dm_{HHH}}$
M_{HHH} [GeV] ($\kappa_3 = 0$)
$\kappa_4 = 0.5$ 3 TeV
$\kappa_4 = 0.5$ 14 TeV
$\kappa_4 = 0.5$ 30 TeV
$\kappa_4 = 0.2$ 3 TeV
$\kappa_4 = 0.2$ 14 TeV
$\kappa_4 = 0.2$ 30 TeV
$\kappa_4 = 0.05$ 3 TeV
$\kappa_4 = 0.05$ 14 TeV
$\kappa_4 = 0.05$ 30 TeV
$\frac{d\sigma^{\kappa_4}}{dm_{HHH}} / \frac{d\sigma^{SM}}{dm_{HHH}}$
M_{HHH} [GeV] ($\kappa_3 = 0$)
$\kappa_4 = -0.5$ 3 TeV
$\kappa_4 = -0.5$ 14 TeV
$\kappa_4 = -0.5$ 30 TeV
$\kappa_4 = -0.2$ 3 TeV
$\kappa_4 = -0.2$ 14 TeV
$\kappa_4 = -0.2$ 30 TeV
$\kappa_4 = -0.05$ 3 TeV
$\kappa_4 = -0.05$ 14 TeV
$\kappa_4 = -0.05$ 30 TeV
$\frac{d\sigma^{\kappa_3}}{dm_{HHH}} / \frac{d\sigma^{SM}}{dm_{HHH}}$
M_{HHH} [GeV] ($\kappa_4 = 6\kappa_3$)
$\kappa_4 = -0.5$ 3 TeV
$\kappa_4 = -0.5$ 14 TeV
$\kappa_4 = -0.5$ 30 TeV
$\kappa_4 = -0.2$ 3 TeV
$\kappa_4 = -0.2$ 14 TeV
$\kappa_4 = -0.2$ 30 TeV
$\kappa_4 = -0.05$ 3 TeV
$\kappa_4 = -0.05$ 14 TeV
$\kappa_4 = -0.05$ 30 TeV
$\frac{d\sigma^{\kappa_3}}{dm_{HHH}} / \frac{d\sigma^{SM}}{dm_{HHH}}$
M_{HHH} [GeV] ($\kappa_4 = 6\kappa_3$)





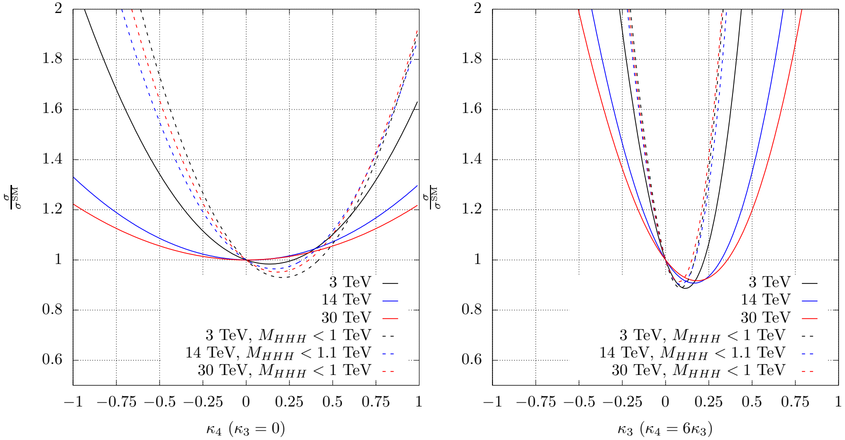




the effect of κ_3 and κ_4

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

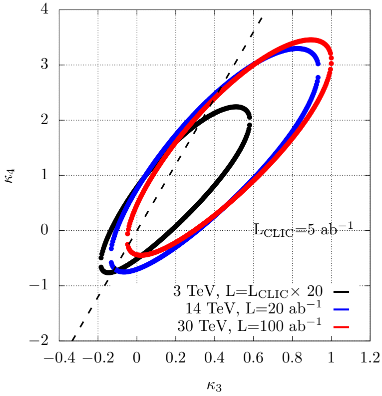
$\mu^+\mu^- \to HHH\nu\bar{\nu}$: deviations from SM Higgs couplings



Sensitivity to κ_3 and κ_4

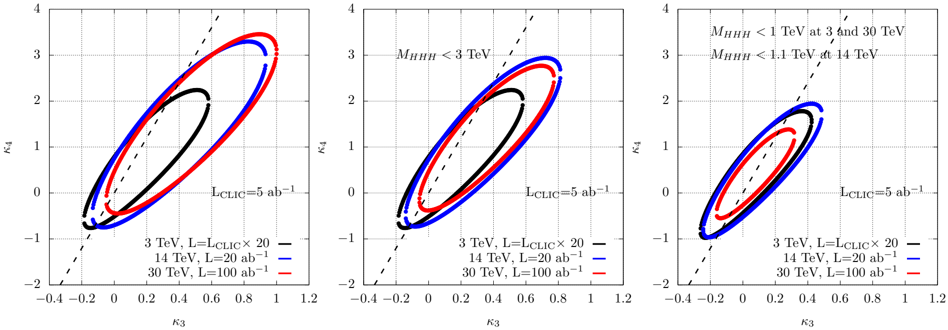
- no background process considered
- we quantify the sensitivity in terms of standard deviations from the SM expectation:

$$\frac{N - N_{\rm SM}}{\sqrt{N_{\rm SM}}}$$



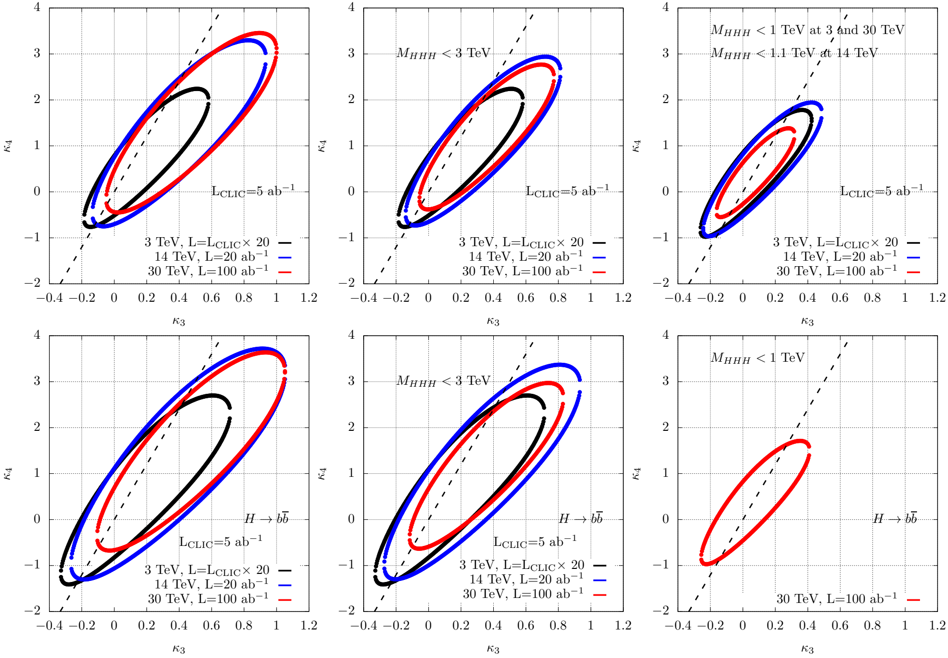
2σ constraint without cuts

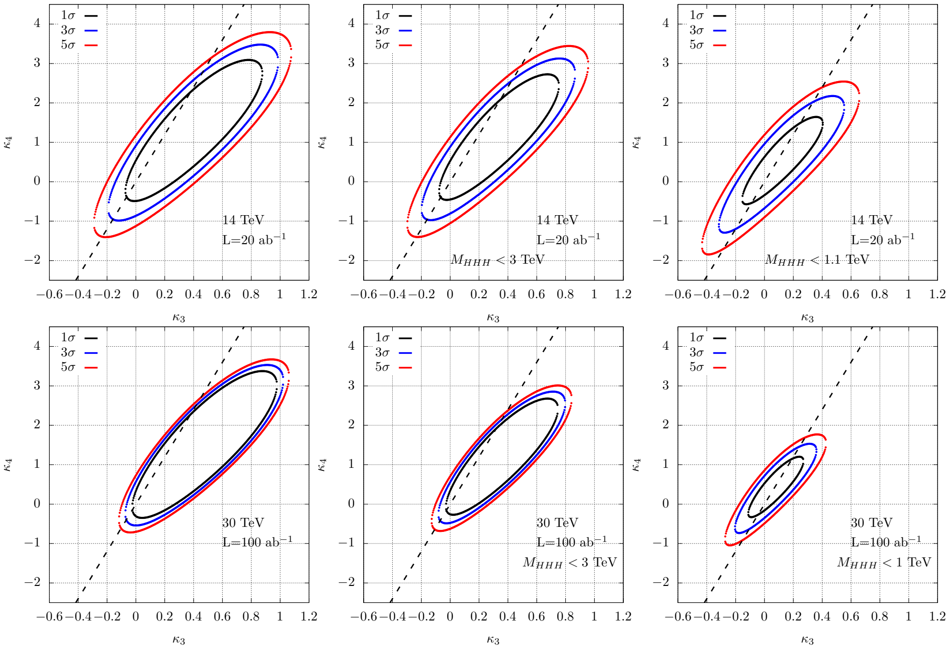
Sensitivity to κ_3 and κ_4



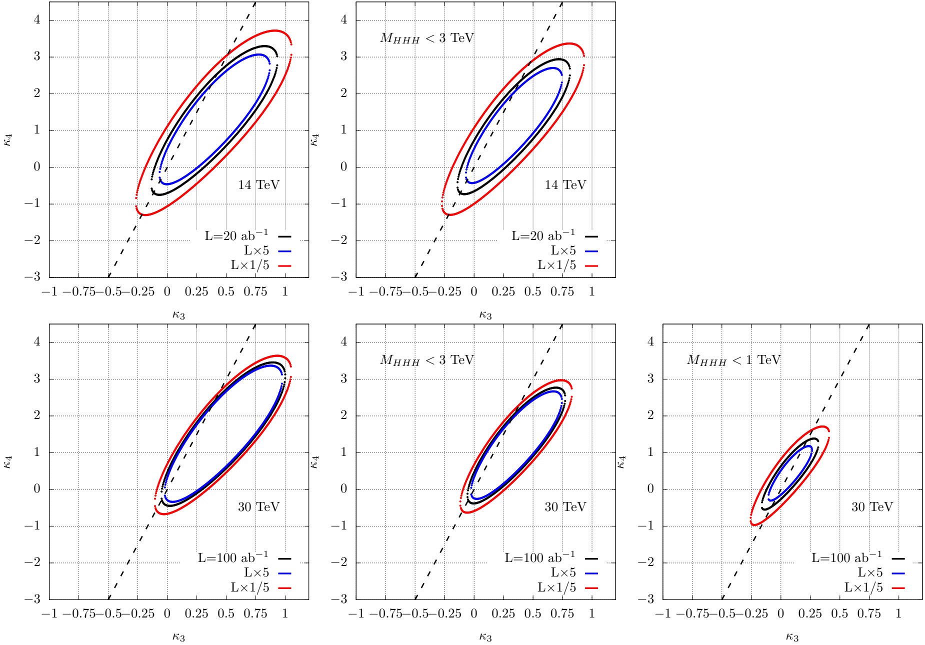
imposing an upper cut on M_{HHH}:

- the sensitivity to positive κ improves
- sensitivity improves at 30 TeV because of the larger cross section


$M_{HHH} < 3$ TeV
$M_{HHH} < 1$ TeV at 3 and 30 TeV
$M_{HHH} < 1.1$ TeV at 14 TeV
$M_{HHH} < 1$ TeV
$\mathrm{L_{CLIC}}$=5 ab^{-1}
$H \to b\bar{b}$
3 TeV, L=$\mathrm{L_{CLIC}}\times$ 20
14 TeV, L=20 ab^{-1}
30 TeV, L=100 ab^{-1}
κ_3
κ_4



1σ
3σ
5σ
κ4
κ3
14 TeV
L=20 ab−1
14 TeV
L=20 ab−1
MHHH < 3 TeV
14 TeV
L=20 ab−1
MHHH < 1.1 TeV
30 TeV
L=100 ab−1
30 TeV
L=100 ab−1
MHHH < 3 TeV
30 TeV
L=100 ab−1
MHHH < 1 TeV



$M_{HHH} < 3$ TeV
$M_{HHH} < 3$ TeV
$M_{HHH} < 1$ TeV
14 TeV
30 TeV
L=20 ab^{-1}
L=100 ab^{-1}
L×5
L×1/5
κ_3
κ_4

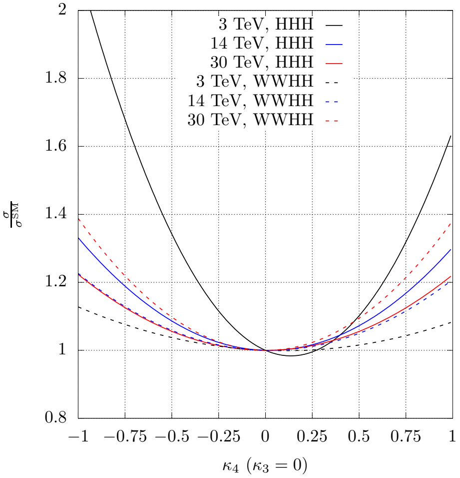
$\mu^+\mu^- \to HHW^+W^-\nu\bar{\nu}$: preliminary results

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

Xsect [ab] \ $\sqrt{s}$ [TeV]	3	14	30
SM	0.31	7.02	18.51

$\mu^+\mu^- \to HHW^+W^-\nu\bar{\nu}$

Xsect [ab] \ $\sqrt{s}$ [TeV]	3	14	30
SM	0.24	9.88	31.80
$\kappa_3 = 0,\ \kappa_4 = -0.5$	0.25	10.46	34.91
$\kappa_3 = 0,\ \kappa_4 = 0.5$	0.24	10.37	34.81
$\kappa_4 = 6\kappa_3,\ \kappa_3 = -0.5$	0.32	12.12	39.36
$\kappa_4 = 6\kappa_3,\ \kappa_3 = 0.5$	0.36	12.01	38.49



Conclusions

- in the worst case (inclusive setup, $H \to b\bar{b}$) κ_3 and κ_4 can be constrained at 2σ in the intervals:

$$\Big[-0.2, +1\Big] \quad \text{for} \quad \kappa_3, \qquad \Big[-1, +3.5\Big] \quad \text{for} \quad \kappa_4$$

- the constraints can be improved to $[-0.2, +0.3]$ for κ_3 and $[-0.5, +1.5]$ for κ_4 by imposing the cut $M_{HHH} < 1$ TeV.
  However this requires large luminosity and/or large cross section (30 TeV setup)

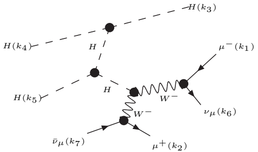
- a more realistic study of the sensitivity to κ should include also background processes (work in progress)

Backup slides

$\mu^+\mu^- \to HHH\nu\bar{\nu}$: deviations from SM Higgs couplings

Xsect [ab] \ $\sqrt{s}$ [TeV]	3	14	30	14	30	14	30	14	30	3	14
$M_{HHH} < X$, X [TeV]				10	10	5	5	3	3	1	1.1
SM	0.31	7.02	18.51	6.99	16.48	5.91	11.30	3.98	6.69	0.12	0.6
$\kappa_3 = 0,\ \kappa_4 = -0.5$	0.42	7.63	19.55	7.60	17.49	6.50	12.21	4.52	7.49	0.20	0.9
$\kappa_3 = 0,\ \kappa_4 = -0.2$	0.34	7.13	18.68	7.10	16.65	6.02	11.45	4.09	6.83	0.14	0.6
$\kappa_3 = 0,\ \kappa_4 = -0.05$	0.32	7.03	18.52	7.00	16.49	5.92	11.31	3.99	6.69	0.12	0.6
$\kappa_3 = 0,\ \kappa_4 = 0.05$	0.31	7.02	18.52	6.99	16.49	5.91	11.30	3.98	6.68	0.11	0.5
$\kappa_3 = 0,\ \kappa_4 = 0.2$	0.31	7.09	18.68	7.06	16.64	5.97	11.42	4.02	6.76	0.11	0.5
$\kappa_3 = 0,\ \kappa_4 = 0.5$	0.34	7.53	19.54	7.50	17.48	6.39	12.15	4.37	7.33	0.12	0.6
$\kappa_4 = 6\kappa_3,\ \kappa_3 = -0.5$	1.09	15.92	36.79	15.88	33.91	14.17	25.76	10.71	17.50	0.55	2.6
$\kappa_4 = 6\kappa_3,\ \kappa_3 = -0.2$	0.52	9.43	23.51	9.40	21.24	8.14	15.22	5.78	9.59	0.23	1.1
$\kappa_4 = 6\kappa_3,\ \kappa_3 = -0.05$	0.35	7.46	19.45	7.43	17.37	6.32	12.02	4.30	7.21	0.14	0.6
$\kappa_4 = 6\kappa_3,\ \kappa_3 = 0.05$	0.29	6.69	17.79	6.66	15.80	5.61	10.75	3.75	6.29	0.11	0.5
$\kappa_4 = 6\kappa_3,\ \kappa_3 = 0.2$	0.30	6.40	16.99	6.38	15.07	5.37	10.25	3.62	6.06	0.13	0.6
$\kappa_4 = 6\kappa_3,\ \kappa_3 = 0.5$	0.79	9.48	22.18	9.45	20.18	8.37	15.01	6.40	10.29	0.51	2.2

$$d\sigma = A_0 + A_1\kappa_3 + A_2\kappa_4 + A_3\kappa_3\kappa_4 + A_4\kappa_3^2$$
$$+ A_5\kappa_4^2 + A_6\kappa_3^3 + A_7\kappa_3^2\kappa_4 + A_8\kappa_3^4$$



generate 9 samples with different $\kappa_{3(4)}$ with `WHIZARD`

invert $d\sigma = A_i\kappa_i$ to get A_i

use A_i to compute $d\sigma$ for arbitrary $\kappa_{3(4)}$