Multijet (4j/6j) background to HH and HHH production at the muon collider

Mauro Chiesa

University of Pavia and INFN

Muon Collider Physics and Detector Workshop, June 4th, 2021

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

DISCLAIMER 1

I will only talk about 4j/6j background to HH/HHH production at the muon collider

DISCLAIMER 2

all the results in this talk are preliminary

Higgs self couplings at the muon collider

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

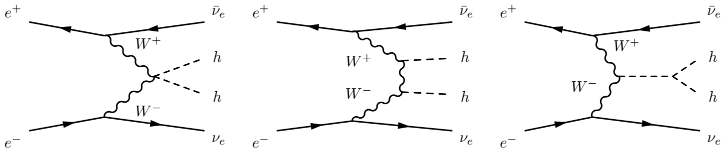
δ_3 related to the HHH vertex, can be measured from $HH\nu\bar{\nu}$ production

δ_4 related to the $HHHH$ vertex, can be measured from $HHH\nu\bar{\nu}$ production

Considering $H \to b\bar{b}$, the signature is

- $4b$ or $4j$ for HH production
- $6b$ or $6j$ for HHH production

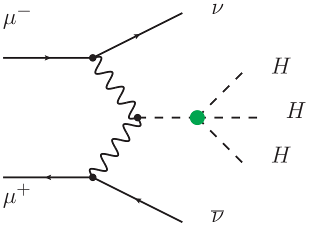
δ_3 from $\mu^+\mu^- \to HH\nu\bar{\nu}$

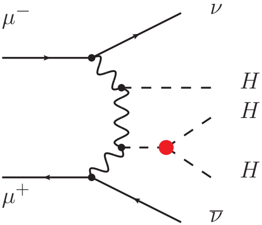


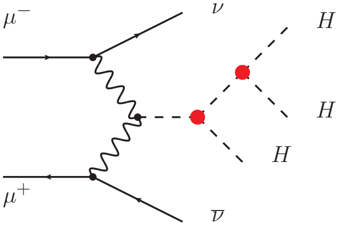
- Sensitivity to δ_3 at the μ-coll. studied in:
    - A. Constantini et al. 2005.10289
    - T. Han et al. 2008.12204
    - D. Buttazzo et al. 2012.11555

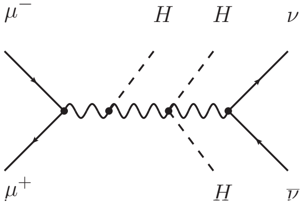
- roughly speaking (under reasonable assumptions on the luminosity):
    - $\delta_3 \in \pm 6\%$ for $\sqrt{s} = 10$ TeV at 2σ
    - $\delta_3 \in \pm 2\%$ for $\sqrt{s} = 30$ TeV at 2σ

δ_4 from $\mu^+\mu^- \to HHH\nu\bar{\nu}$ (1)







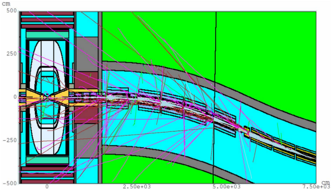


δ_4 from $\mu^+\mu^- \to HHH\nu\bar{\nu}$, 2003.13628

$\sqrt{s}$ [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]

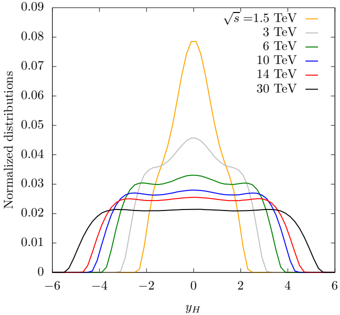
- under (reasonable) assumptions on the energy and the luminosity, the muon collider can do a pretty good job in constraining the quartic Higgs coupling
- no background considered!
    - is the background really negligible?
    - should we adopt any background suppression strategy?

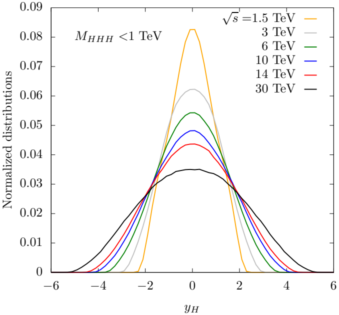
Remark on detector acceptance



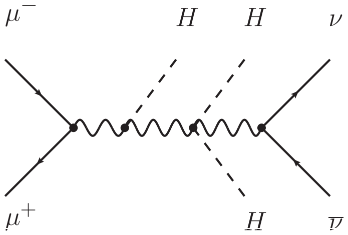
The detector must be shielded from the beam radiation

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





Event selections



- Inclusive:

$$M(\nu\overline{\nu}) > 150 \text{ GeV} \qquad M(jj) > 30 \text{ GeV}$$

- Acceptance cuts:

$$M(\nu\overline{\nu}) > 150 \text{ GeV} \qquad M(jj) > 30 \text{ GeV}$$

$$p_T^j > 20 \text{ GeV} \qquad -3 < y^j < 3$$

$\mu^+\mu^- \to HHH\nu\bar{\nu}$, background estimate with b-tagging

signature: $6b$+missing energy

- signal: $\mu^+\mu^- \to HHH\nu\bar{\nu}$, $H \to b\bar{b}$
- background processes:
  - $\mu^+\mu^- \to HHb\bar{b}\nu\bar{\nu}$, if $b(\bar{b})$ not from H and $H \to b\bar{b}$
  - $\mu^+\mu^- \to Hb\bar{b}b\bar{b}\nu\bar{\nu}$, if $b(\bar{b})$ not from H and $H \to b\bar{b}$
  - $\mu^+\mu^- \to b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$, if $b(\bar{b})$ not from H
- $\mu^+\mu^- \to HHb\bar{b}\nu\bar{\nu}$ ($\mu^+\mu^- \to Hb\bar{b}b\bar{b}\nu\bar{\nu}$?) can be generated with `Madgraph` or `Whizard`
  - setting the b Yukawa to zero in the production matrix element
  - considering the on-shell decay $H \to b\bar{b}$ for FS Higgses
- $\mu^+\mu^- \to b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$ it's a different story...

$\mu^+\mu^- \to b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$ background

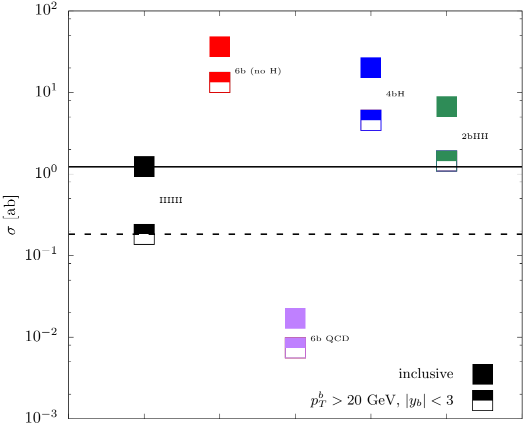
- $\mu^+\mu^- \to b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$:
    - too many final state particles
    - too many possible resonance histories

  `Madgraph` and `Whizard` fail to converge in reasonable runtimes

- in the following $\mu^+\mu^- \to b\bar{b}b\bar{b}b\bar{b}\nu\bar{\nu}$ simulated with a private version of `Alpgen`
    - matrix elements computed with the same strategy used in `Whizard`
    - phase-space integration tailored on the process under consideration

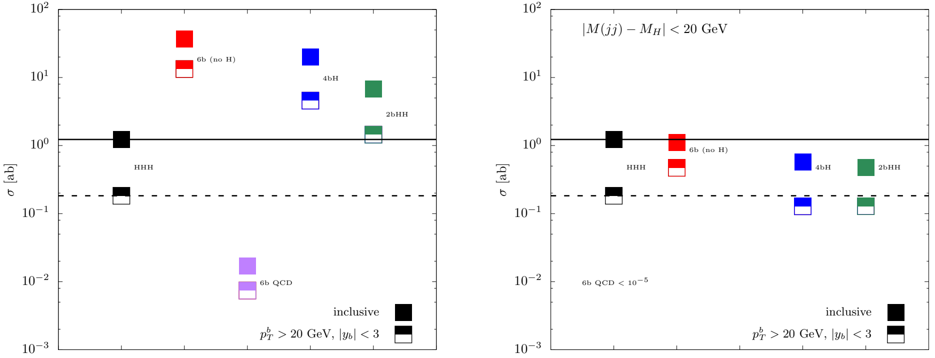
- this version of `Alpgen` used for these studies might become public at some point: stay tuned!

$\mu^+\mu^- \to HHH\nu\bar{\nu}$, with b-tagging, no H reconstruction



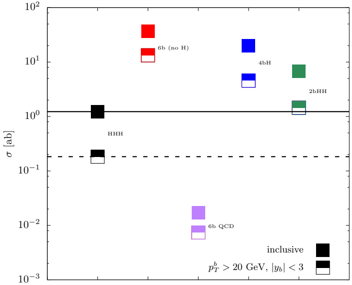
- only 1/5 of the signal survives after selecting $H \to bb$
- background not negligible
- pure QCD $6b$ production suppressed

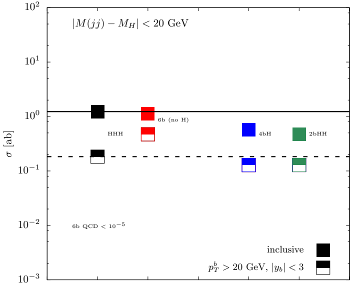
$\mu^+\mu^- \to HHH\nu\bar{\nu}$, with b-tagging, H reconstruction (1)

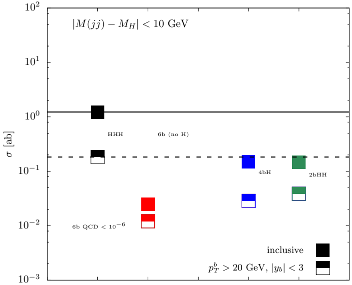


at least 3 jet pairs with $|M(jj) - M_H| < 20$ GeV

$\mu^+\mu^- \to HHH\nu\bar{\nu}$, with b-tagging, H reconstruction (2)







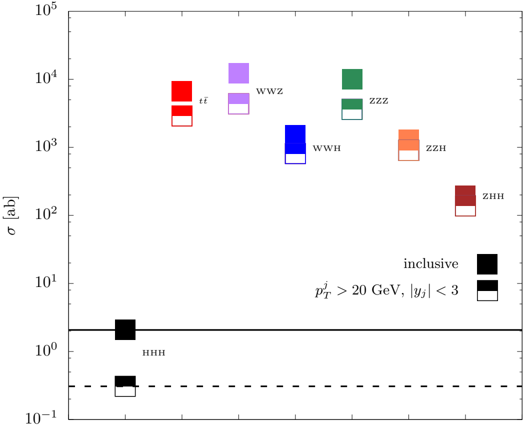
- only 1/5 of the signal survives after selecting $H \to bb$
- Higgs reconstruction needed (at least with 20 GeV resolution, better with 10 GeV res)
- full simulation for 6b quarks (no Higgses) computed with a modified version of `ALPGEN`

$\mu^+\mu^- \to HHH\nu\bar{\nu}$, background estimate without b-tagging

signature: $6j$+missing energy

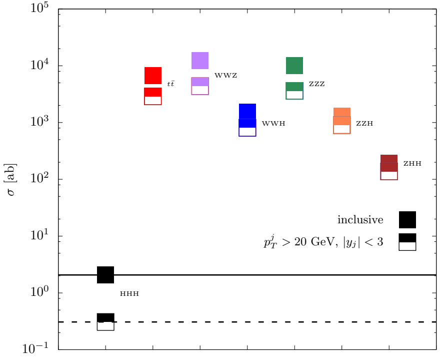
- signal: $\mu^+\mu^- \to HHH\nu\bar{\nu}$, $H \to jj$
- background processes:
  - $\mu^+\mu^- \to t\bar{t}\nu\bar{\nu}$, with $t \to bW$ and $W \to jj$
  - $\mu^+\mu^- \to WWZ\nu\bar{\nu}$, if $W \to jj$ and $Z \to jj$
  - $\mu^+\mu^- \to WWH\nu\bar{\nu}$, if $W \to jj$ and $H \to jj$
  - $\mu^+\mu^- \to ZZZ\nu\bar{\nu}$, if $Z \to jj$
  - $\mu^+\mu^- \to ZZH\nu\bar{\nu}$, if $Z \to jj$ and $H \to jj$
  - $\mu^+\mu^- \to ZHH\nu\bar{\nu}$, if $Z \to jj$ and $H \to jj$
- Background estimate in narrow width approx. can be generated with `Madgraph` or `Whizard`

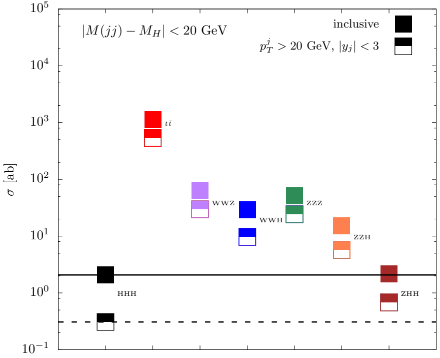
$\mu^+\mu^- \to HHH\nu\bar{\nu}$, NO b-tagging, NO H reconstruction



- only 1/3 of the signal survives after selecting $H \to jj$
- very large background
- full simulation for 6j still missing, however the largest contribution should be from 6q (gluons have larger combinatorics, but pure QCD is suppressed)

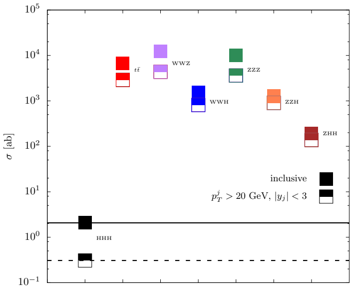
$\mu^+\mu^- \to HHH\nu\bar{\nu}$, NO b-tagging, H reconstruction (1)

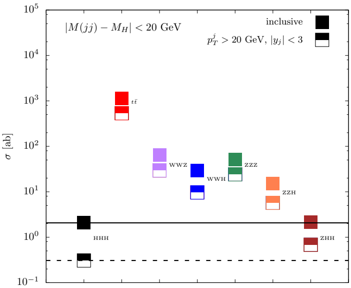


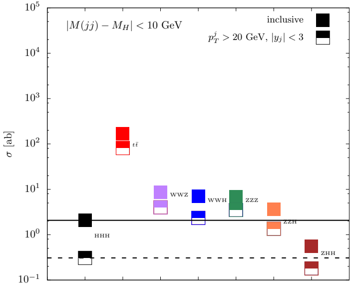


at least 3 jet pairs with $|M(jj) - M_H| < 20$ GeV

$\mu^+\mu^- \to HHH\nu\bar{\nu}$, NO b-tagging, H reconstruction (2)

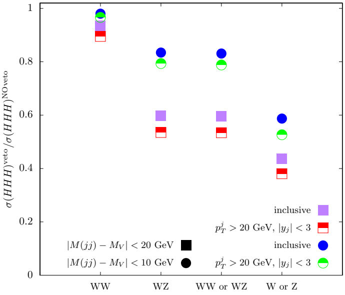


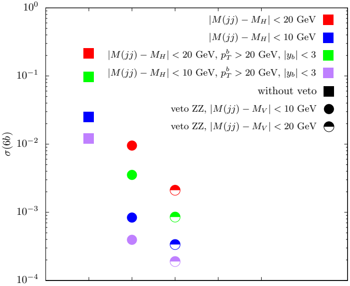




- only 1/3 of the signal survives after selecting $H \to jj$
- Higgs reconstruction needed (at least with 20 GeV resolution, better with 10 GeV res)
- full simulation for 6j still missing, however the largest contribution should be from 6q (gluons have larger combinatorics, but pure QCD is suppressed)

No b-tagging, background suppression: veto W and/or Z bosons





- vetoing Ws and/or Zs does not kill too much signal (10 GeV resolution)
- vetoing Ws and/or Zs kills the corresponding background
- best background suppression strategy should involve vetoes on Ws and/or Zs

δ_3 from $\mu^+\mu^- \to HH\nu\bar{\nu}$, $H \to b\bar{b}$: background

Similar calculation is ongoing for $\mu^+\mu^- \to HH\nu\bar{\nu}$

$\sqrt{s}$	$HH\nu\bar{\nu}$	$ZH\nu\bar{\nu}$	$ZZ\nu\bar{\nu}$	sum $\nu\bar{\nu}$	4b($Y_b = 0$)	4b(EW)
1.5	0.06992(9)	0.2355(3)	0.3299(4)	0.6353	0.3077(9)	0.650(2)
3	0.2666(3)	0.784(1)	1.130(1)	2.180	1.069(2)	2.210(5)
6	0.6612(8)	1.807(2)	2.629(2)	5.098	2.55(8)	5.16(1)
10	1.100(1)	2.922(3)	4.248(4)	8.270	4.11(3)	8.35(2)
14	1.461(2)	3.825(5)	5.557(7)	10.843	5.46(1)	10.84(3)
30	2.501(2)	6.396(5)	9.233(8)	18.13	9.1(3)	18.00(5)

In this case, $\mu^+\mu^- \to b\bar{b}b\bar{b}\nu\bar{\nu}$ ($b(\bar{b})$ not from H) can be simulated using `Madgraph` or `Whizard`, though event generation might take a while

Conclusions

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

- are definitively there
- might be large
- they can be largely suppressed with some combination of:
  - b-tagging (soft?)
  - Higgs reconstruction
  - Z/W vetoes
- optimal suppression strategy seems to require good resolution in dijet invariant mass reconstruction

Backup slides

H self-couplings measurement: future colliders (HHHH)

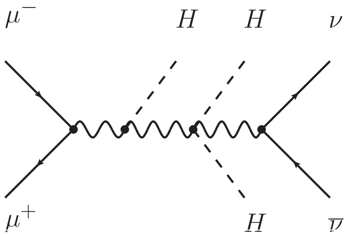
- the proposed future colliders can put strong constraints on the triple Higgs coupling δ_3: $\pm 10\%$ 1-σ bound at CLIC and ILC, $\pm 5\%$ at FCC
- the bounds on the quartic couplings δ_4 are very loose (68% CL)
  - ILC: $\sim [-10, +10]$ ($\pm 1000\%!$)
  - CLIC: $\sim [-5, +5]$
  - FCC: $\sim [-5,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

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) $[N_{ev}]$			
σ^{tot}	0.03 [0]	0.31 [1]	1.65 [20]
$\sigma(M_{HHH} < 3$TeV)	0.03 [0]	0.31 [1]	1.47 [18]
$\sigma(M_{HHH} < 1$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) $[N_{ev}]$			
σ^{tot}	4.18 [84]	7.02 [232]	18.51 [1851]
$\sigma(M_{HHH} < 3$TeV)	2.89 [58]	3.98 [131]	6.69 [669]
$\sigma(M_{HHH} < 1$TeV)	0.37 [7]	0.45 [15]	0.64 [64]

σ increases with $\sqrt{s}$

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

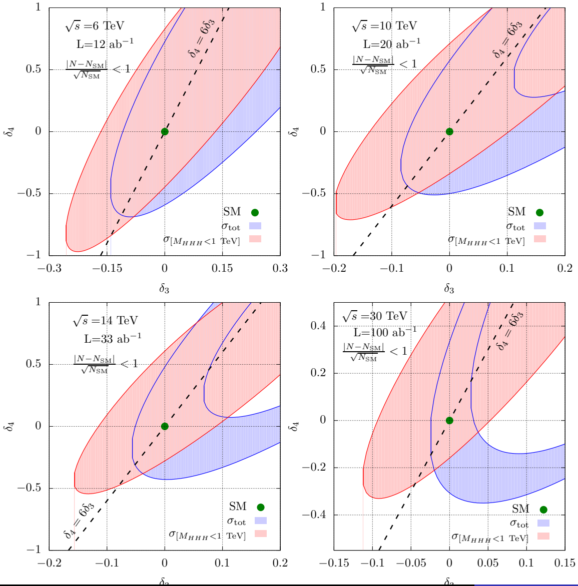
- at $\sqrt{s} = 10, 30$ TeV, the luminosity is fixed by (see arXiv:1910.06150)

Luminosity:

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

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

Sensitivity to δ_3 and δ_4 (small δ_3)



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

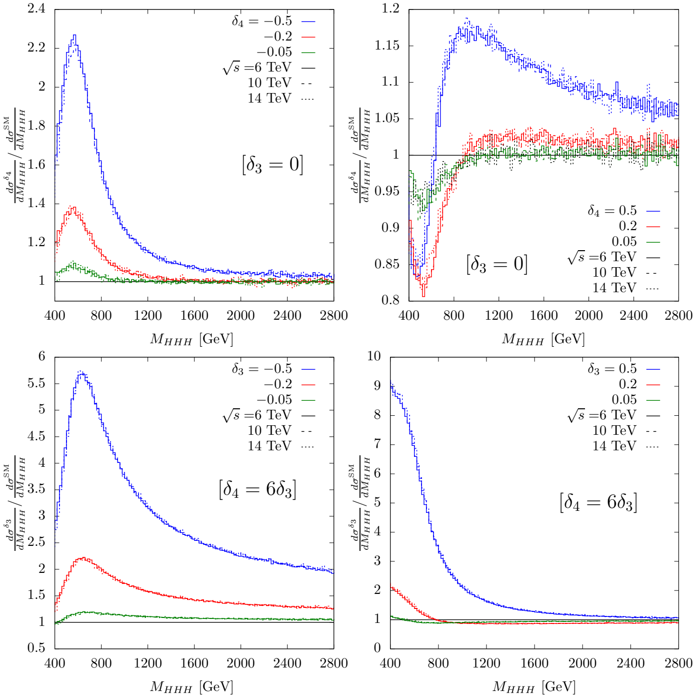
$$\delta_3 = 0$$

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

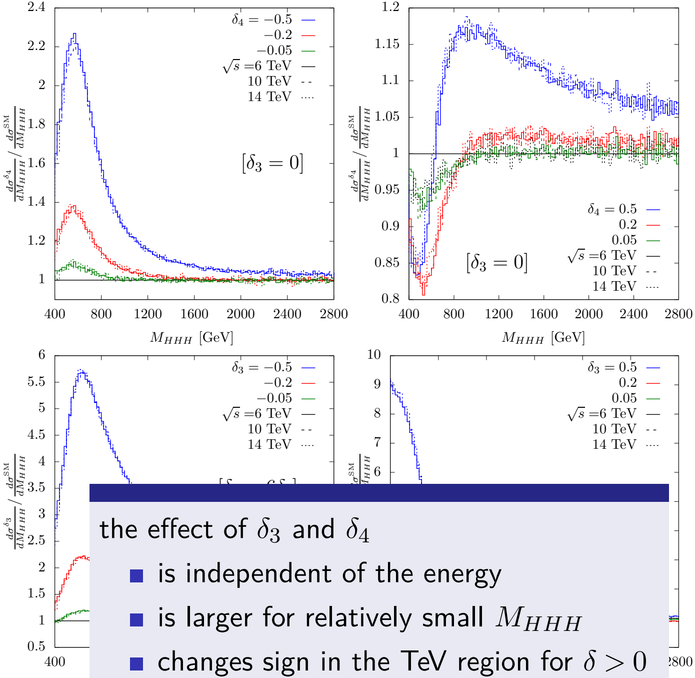
10 TeV $\delta_4 \sim [-0.4, 0.7]$

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

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



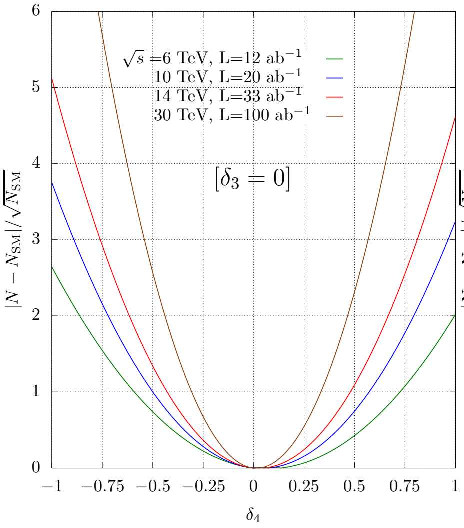
$\delta_4 = -0.5$
-0.2
-0.05
$\sqrt{s}$ =6 TeV
10 TeV
14 TeV
$[\delta_3 = 0]$
$\frac{d\sigma^{\delta_4}}{dM_{HHH}} / \frac{d\sigma^{\rm SM}}{dM_{HHH}}$
M_{HHH} [GeV]
$\delta_4 = 0.5$
0.2
0.05
$\sqrt{s}$ =6 TeV
10 TeV
14 TeV
$[\delta_3 = 0]$
$\frac{d\sigma^{\delta_4}}{dM_{HHH}} / \frac{d\sigma^{\rm SM}}{dM_{HHH}}$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

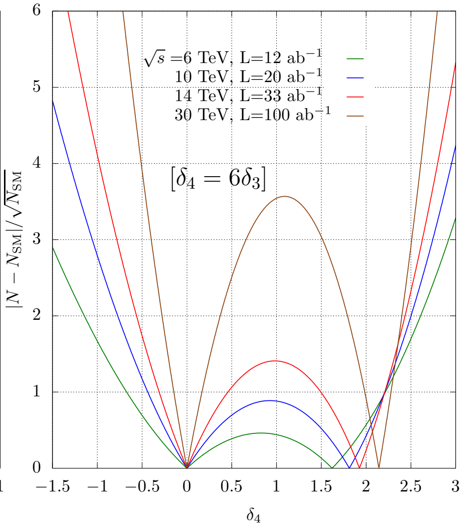


the effect of δ_3 and δ_4

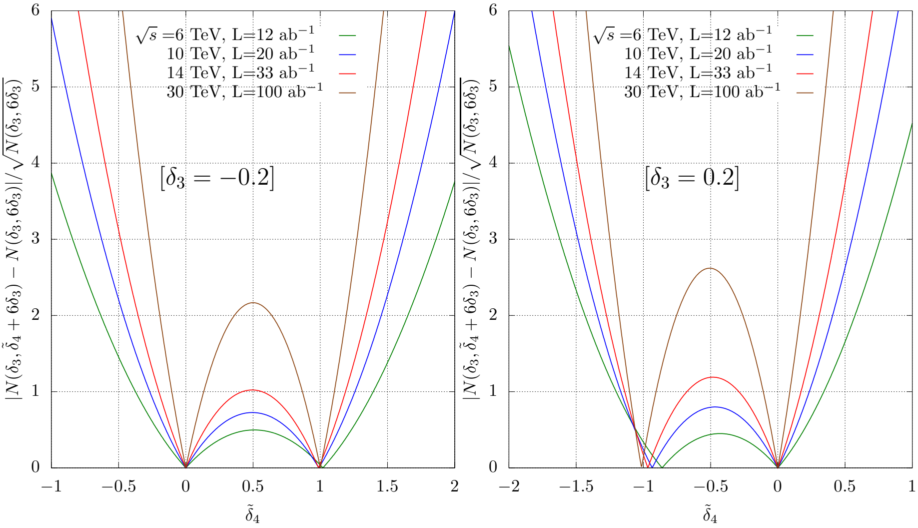
- is independent of the energy
- is larger for relatively small M_{HHH}
- changes sign in the TeV region for $\delta > 0$

Sensitivity to δ_3 and δ_4

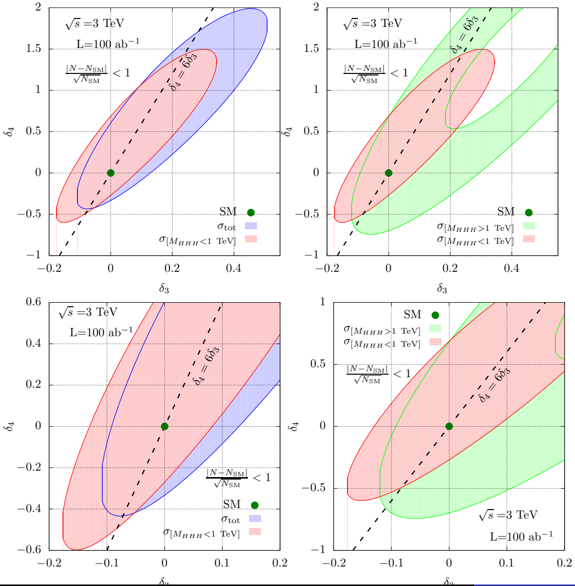




Sensitivity to $\tilde{\delta}_4$ (deviation from SMEFT)



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

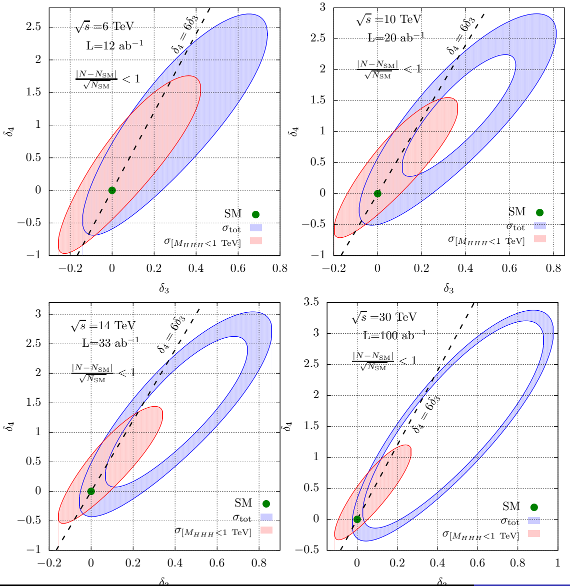
$\delta_4 \sim [-0.6, 1.5]$

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: $\tilde{\delta}_4 = \delta_4 - 6\delta_3$

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