Future collider discussion session

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(w input from Caterina Vernieri)

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Future collider discussion session
2.6.22

What I dont have to repeat here...

- **"everything measured now for the SM in the scalar sector ?"**

$$\Longrightarrow \textbf{NO !} \Longleftarrow$$

- complete understanding requires also determination of **triple and quartic coupling in potential**
- for this: **future colliders needed**

$\Rightarrow$ only these can confirm [or reject] SM scalar sector hypothesis

[slide from M. Selvaggi, talk at Higgs Pairs mini-workshop 09/21]

How?

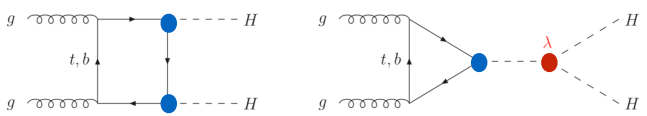
HH pair production

gluon fusion

top associated pair production

p-p

LHC
FCC-hh



y_t | y_t , λ_3 | y_t | y_t , λ_3

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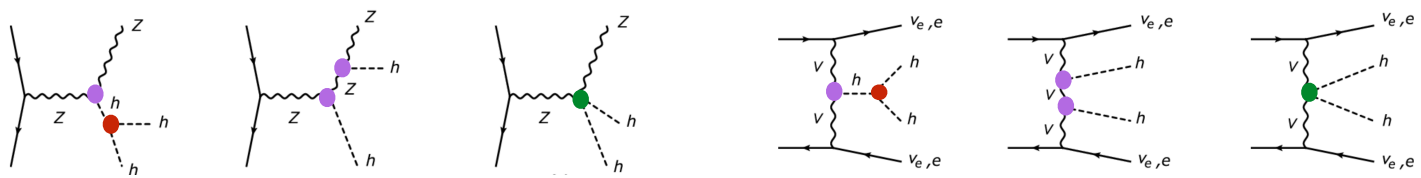
double Higgs-strahlung ($\sqrt{s}$ < 1 TeV)

weak boson fusion ($\sqrt{s}$ > 1 TeV)

e^+e^-
$\mu^+\mu^-$

ILC
CLIC
Muon Collider



g_Z , λ_3 | g_Z | λ_{VVHH} | g_Z , λ_3 | g_Z | λ_{VVHH}

[slide from M. Selvaggi, talk at Higgs Pairs mini-workshop 09/21]

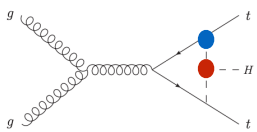
How?

single H production

p-p

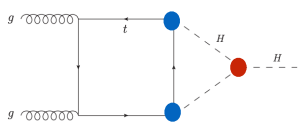
LHC
FCC-hh

ttH

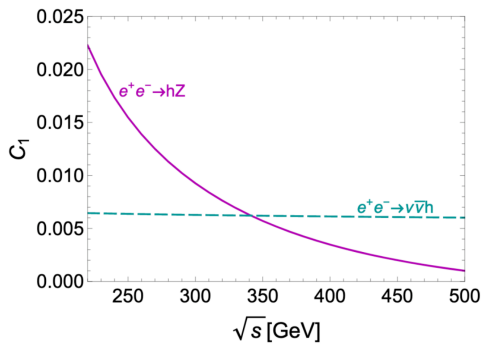


y_t

gluon fusion



y_t , λ_3



e^+e^-
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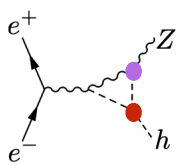
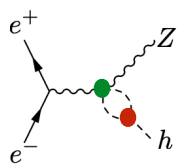
Higgs-strahlung

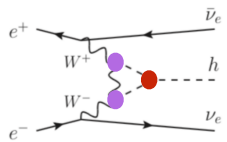


g_Z , λ_3

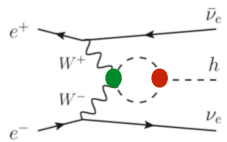


λ_3 , λ_{VVHH}

weak boson fusion



g_Z , λ_3



λ_3 , λ_{VVHH}

Current back of the envelope accuracy estimates

[for triple couplings, from M. Selvaggis talk at Higgs Pairs mini-workshop 09/21, and Snowmass WPs arXiv:2203.07622 (ILC)/ arXiv:2203.07646 (C^3)]

- HL-LHC/ ILC_{250}/ CLIC_{380}/ CEPC_{240}/$C^3_{250} \sim 50\%$
- $\text{FCC-ee}_{240/365}$, **ILC**$_{500}$, $C^3_{550} \sim 20-27\%$
- **ILC**$_{500-1000\text{GeV}}$, **CLIC**$_{3\text{TeV}} \sim 8-11\%$
- **FCC-hh** $\sim 3.5-8\%$
- $\mu\mu_{30\text{TeV}} \sim 2-3\%$

[*HH*/ single *H*; recent updates not included]

? What about quartic couplings ?

[slide from P. Meade, this morning]

Since this is Higgs Pairs...

collider	single-h	hh	combined
HL-LHC [56]	100-200%	50%	50%
$\text{ILC}_{250}/\text{C}^3$-250 [45, 57]	49%	–	49%
$\text{ILC}_{500}/\text{C}^3$-550 [45, 57]	38%	20%	20%
CLIC_{380} [58]	50%	–	50%
CLIC_{1500} [58]	49%	36%	29%
CLIC_{3000} [58]	49%	9%	9%
FCC-ee [49]	33%	–	33%
FCC-ee (4 IPs) [49]	24%	–	24%
FCC-hh [59]	-	2.9-5.5%	2.9-5.5%
μ(3 TeV) [50]	-	15-30%	15-30%
μ(10 TeV) [50]	-	4%	4%

Current/ open questions [personal brainstorm]

- What are the **largest impediments/ uncertainties** for each collider type ?

What about theoretical uncertainties ?

Do we need better PDFs/ higher order calculations/ ... ? [how feasible are these ? wishlists a la Les Houches?]

Current/ open questions [personal brainstorm]

What about experimental uncertainties ?

Are there "deadlocks" ? Are **new techniques/ ideas required ?** Which ones ?

- Can we make statements about **which collider would be able to best answer a specific question ?**
  E.g. wrt electroweak phase transitions/ connections to gravitational waves/ etc.
- Will this influence decisions regarding **science strategy** ?

E.g. the muon-electron connection...

- can the *ee* **techniques directly be transferred to $\mu\mu$?** If not, why ? [I remember people trying to redo the CLIC analysis at $\mu\mu$; is it feasible ?]
- Are **uncertainties for μ colliders understood enough ?** If not, what needs to be improved ?

! Your input needed !

Appendix

Incomplete list of papers looking at quartic coupling

- W. Bizon, U. Haisch and L. Rottoli, *Constraints on the quartic Higgs self-coupling from double-Higgs production at future hadron colliders*, JHEP 10 (2019) 267 [1810.04665].
- S. Borowka, C. Duhr, F. Maltoni, D. Pagani, A. Shivaji and X. Zhao, *Probing the scalar potential via double Higgs boson production at hadron colliders*, JHEP 04 (2019) 016 [1811.12366].
- T. Liu, K.-F. Lyu, J. Ren and H.X. Zhu, *Probing the quartic Higgs boson self-interaction*, Phys. Rev. D98 (2018) 093004 [1803.04359].
- J. Alison et al., *Higgs boson potential at colliders: Status and perspectives*, Rev. Phys. 5 (2020) 100045 [1910.00012].
- A. Papaefstathiou and K. Sakurai, *Triple Higgs boson production at a 100 TeV proton-proton collider*, JHEP 02 (2016) 006 [1508.06524].
- C.-Y. Chen, Q.-S. Yan, X. Zhao, Y.-M. Zhong and Z. Zhao, *Probing triple-Higgs productions via 4b2γ decay channel at a 100 TeV hadron collider*, Phys. Rev. D93 (2016) 013007 [1510.04013].
- D.A. Dicus, C. Kao and W.W. Repko, *Self Coupling of the Higgs boson in the processes p p $\to$ ZHHH + X and p p $\to$ WHHH + X*, Phys. Rev. D93 (2016) 113003 [1602.05849].
- R. Contino et al., *Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies*, CERN Yellow Rep. (2017) 255 [1606.09408].
- B. Fuks, J.H. Kim and S.J. Lee, *Scrutinizing the Higgs quartic coupling at a future 100 TeV proton-proton collider with taus and b-jets*, Phys. Lett. B771 (2017) 354 [1704.04298].
- A. Papaefstathiou, G. Tetlalmatzi-Xolocotzi and M. Zaro, *Triple Higgs boson production to six b-jets at a 100 TeV proton collider*, Eur. Phys. J. C 79 (2019) 947 [1909.09166]. $[-1.7; 13]$
- F. Maltoni, D. Pagani and X. Zhao, *Constraining the Higgs self-couplings at e+e- colliders*, JHEP 07 (2018) 087 [1802.07616]. $\text{CLIC}_{3\text{TeV}}$ $[-5; 7]$
- M. Chiesa, F. Maltoni, L. Mantani, B. Mele, F. Piccinini and X. Zhao, *Measuring the quartic Higgs self-coupling at a multi-TeV muon collider*, JHEP 09 (2020) 098 [2003.13628]. all $[0; 2]$ best (30TeV) $[0.7; 1.5]$

[slide from M. Selvaggi, talk at Higgs Pairs mini-workshop 09/21]

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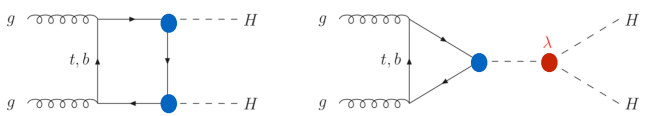

y_t | y_t , λ_3 | y_t | y_t , λ_3

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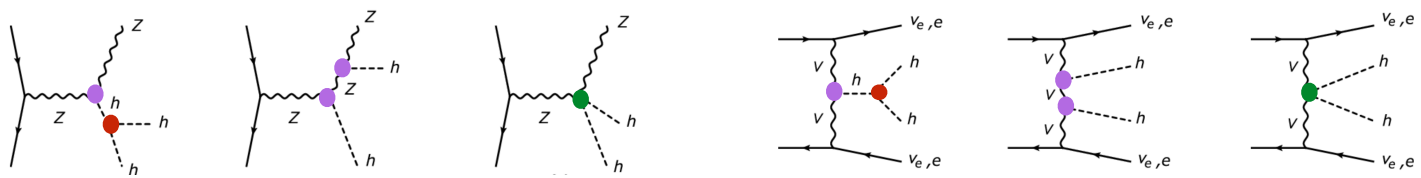

g_Z , λ_3 | g_Z | λ_{VVHH} | g_Z , λ_3 | g_Z | λ_{VVHH}

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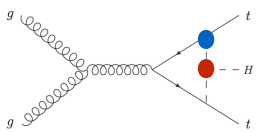
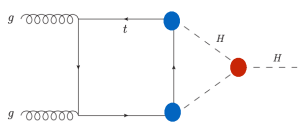
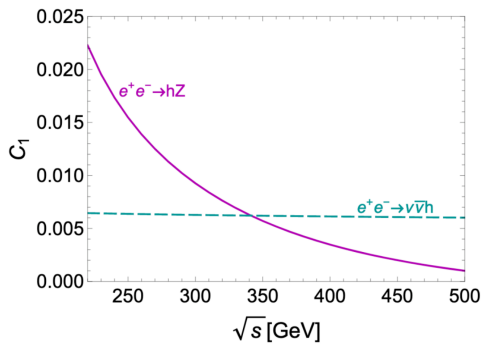


y_t

gluon fusion



y_t , λ_3



e^+e^-
$\mu^+\mu^-$

ILC
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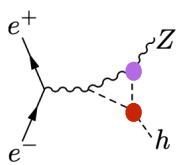
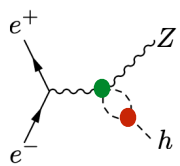
Higgs-strahlung

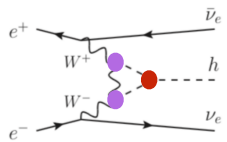


g_Z , λ_3



λ_3 , λ_{VVHH}

weak boson fusion



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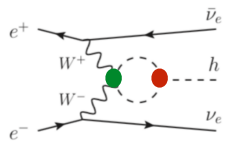
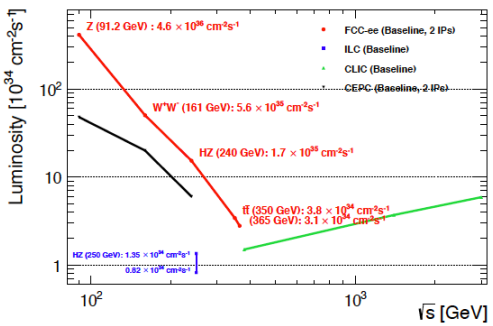
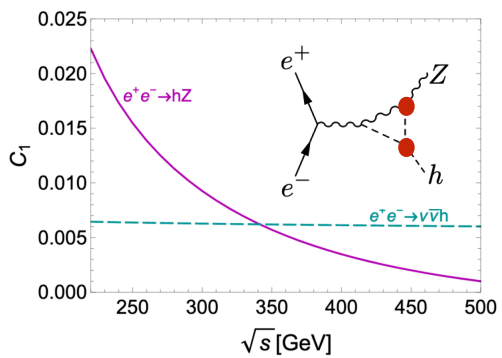


λ_3 , λ_{VVHH}

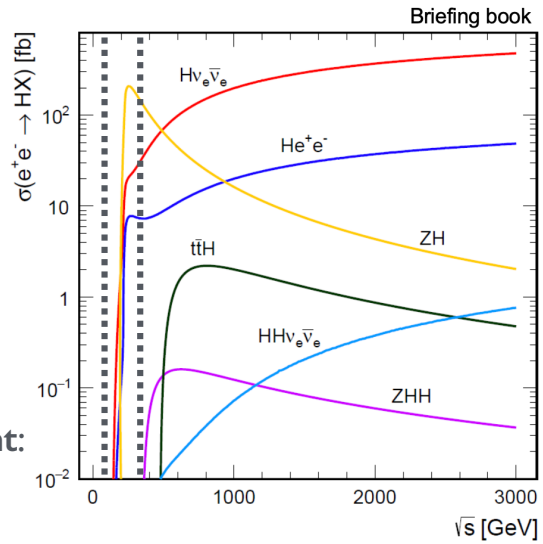
[slide from M. Selvaggi, talk at Higgs Pairs mini-workshop 09/21]

Self-coupling at circular e^+e^- colliders





- At **low energy √s < 500 GeV** the self-coupling is measured via **single Higgs production** (FCC-ee)
- Precise ZH, vvH cross-section measurement at various energies:
  - sqrt(s) = 240, 365 GeV
- can resolve λ_3, λ_{VVHH}
- **FCC-ee provides best measurement:**
  - $\delta\kappa_\lambda$ = 33% (2 IPs)
  - $\delta\kappa_\lambda$ = 24% (4 IPs)

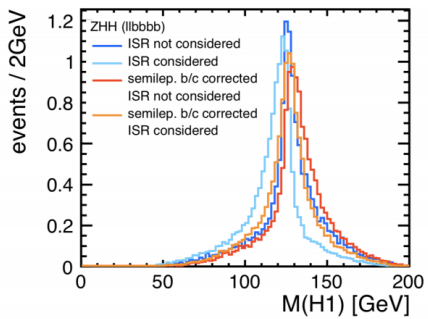


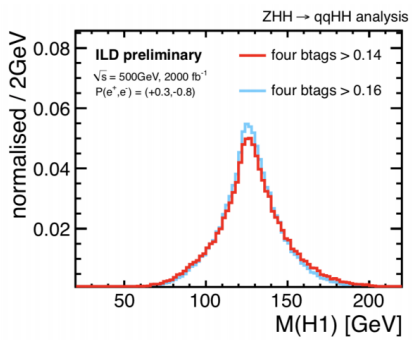
Collider	HL-LHC	ILC_{250}	$CLIC_{380}$	$CEPC_{240}$	$FCC\text{-}ee_{240\to365}$
Lumi (ab^{-1})	3	2	1	5.6	5 + 0.2 + 1.5
Years	10	11.5	8	7	3 + 1 + 4
g_{HHH} (%)	50.	– / 49.	– / 50.	– / 50.	44./33. 2IP 27./24. 4IP

global fit, with/without HL-LHC input

[slide from M. Selvaggi, talk at Higgs Pairs mini-workshop 09/21]

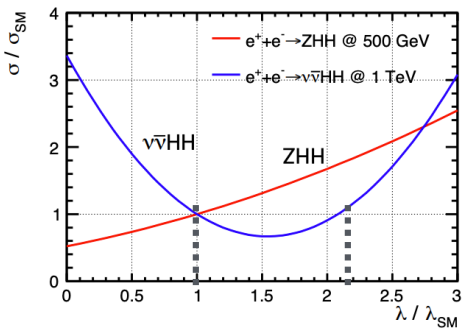
Self-coupling at ILC





- At high **energies √s > 500 GeV** self-coupling is measured via double Higgs production (ZHH and ννHH)
- ZHH/ννHH constructive/destructive interference
  - cross-section at various energies depends on λ_3 and $\lambda_{\nu\nu HH}$
- Polarisation **(80% LR/RL,20% LL/RR)** enhances ννHH production by x2

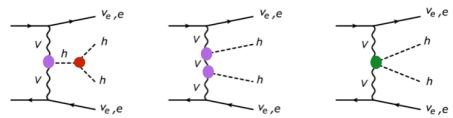
[1903.01629]

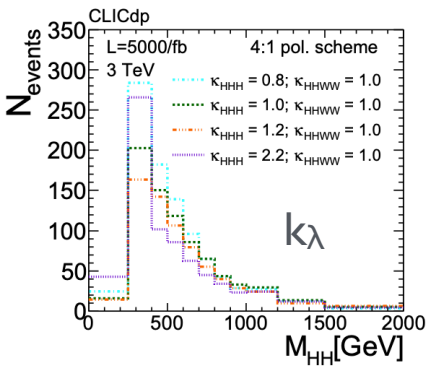


- √s = 500 GeV
  - Measured in ll(νν/jj) bbbb , bbWW (ZHH)
  - backgrounds: ZZZ, ZZH, bbqqqq
  - **δk_λ / k_λ = 27%**

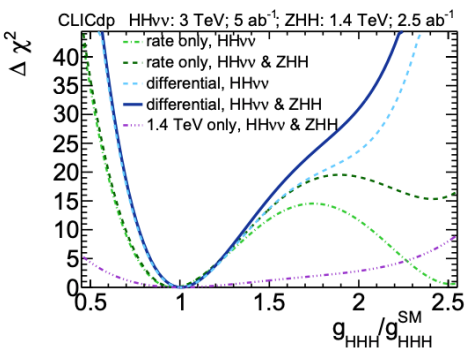
[slide from M. Selvaggi, talk at Higgs Pairs mini-workshop 09/21]

Self-coupling at CLIC

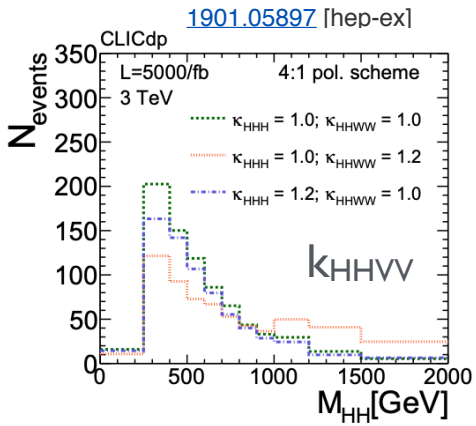


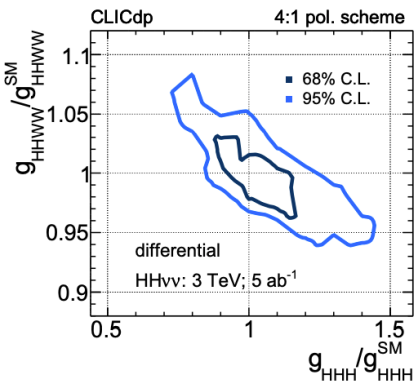


- 4:1 pol scheme 80% LR: 20% RL
- $\sqrt{s}$ = 1.4 TeV (early stage)
  - vvHH → 3.6σ evidence
  - ZHH → 2.1σ evidence
- $\sqrt{s}$ = 3 TeV (late stage)
  - Precision dominated by vvHH, but ZHH helps
  - Template fit on **differential** m_{HH} shape to resolve degeneracy at k_λ = 1 and 2.2
    - **$\delta k_\lambda / k_\lambda$ = 8-11% with 5 ab^{-1}**



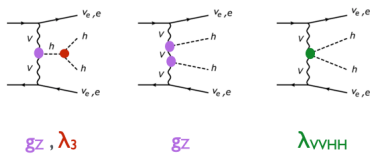
1901.05897 [hep-ex]



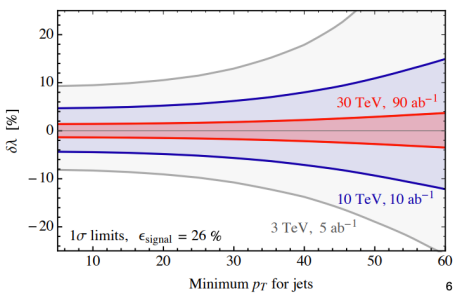


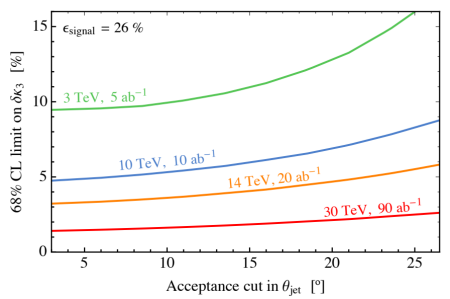
[slide from M. Selvaggi, talk at Higgs Pairs mini-workshop 09/21]

Self-coupling at the Muon Collider

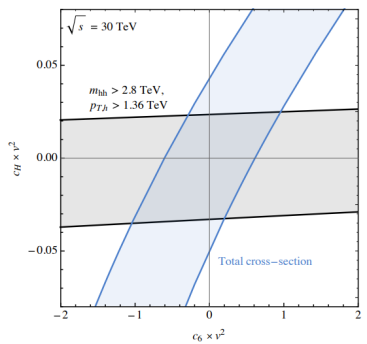


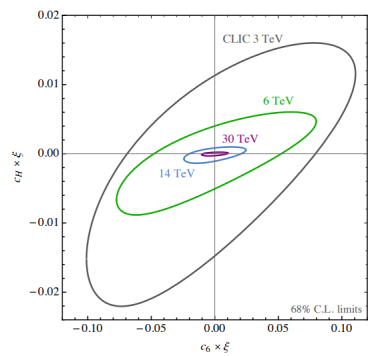
Buttazzo, Franceschini, Wulzer [2012.11555]





- Muon collider can potentially reach the highest energies (up to 30 TeV)
- At sqrt(s) >> 3 TeV muon collider, the VBF pair production dominates (~ CLIC)
- vvbbbb final state (4jets + ME)
- Muon collider could potentially provide the best precision at 30 TeV **~2-3% (stat only)** ?
- More studies needed, **parton level** only for now

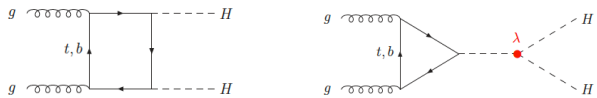




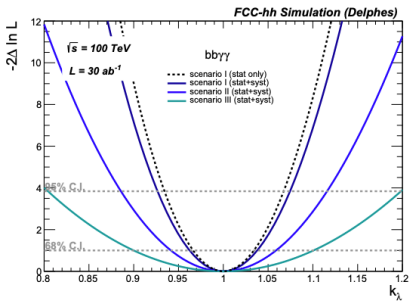
Apply gaussian smearing to jets, assuming 15% energy resolution

[slide from M. Selvaggi, talk at Higgs Pairs mini-workshop 09/21]

Self-coupling at the FCC-hh

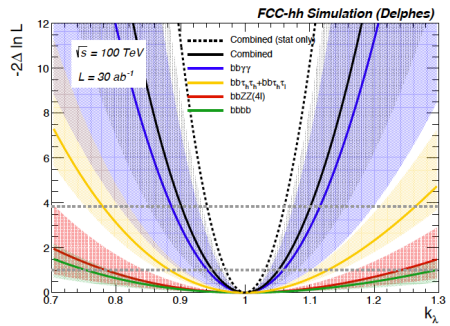


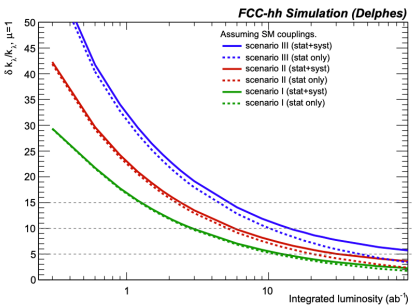
2004.03505 [hep-ph]



- Expected precision:

@68% CL	scenario I	scenario II	scenario III
bbγγ	3.8	5.9	10.0
bbττ	9.8	12.2	13.8
bbbb	22.3	27.1	32.0
comb.	3.4	5.1	7.8





- Combined precision:
  - **3.5-8%** for SM (3% stat. only)
  - **10-20%** for $\lambda_3 = 1.5 * \lambda_3^{SM}$