EBERHARD KARLS UNIVERSITÄT TÜBINGEN

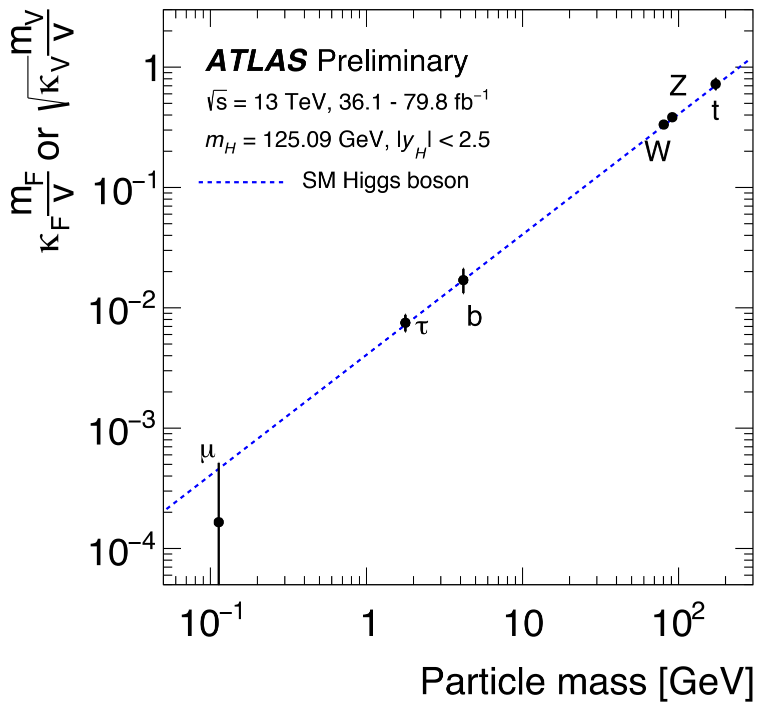
Institut für Theoretische Physik

Future collider projects in the light of the triple Higgs coupling

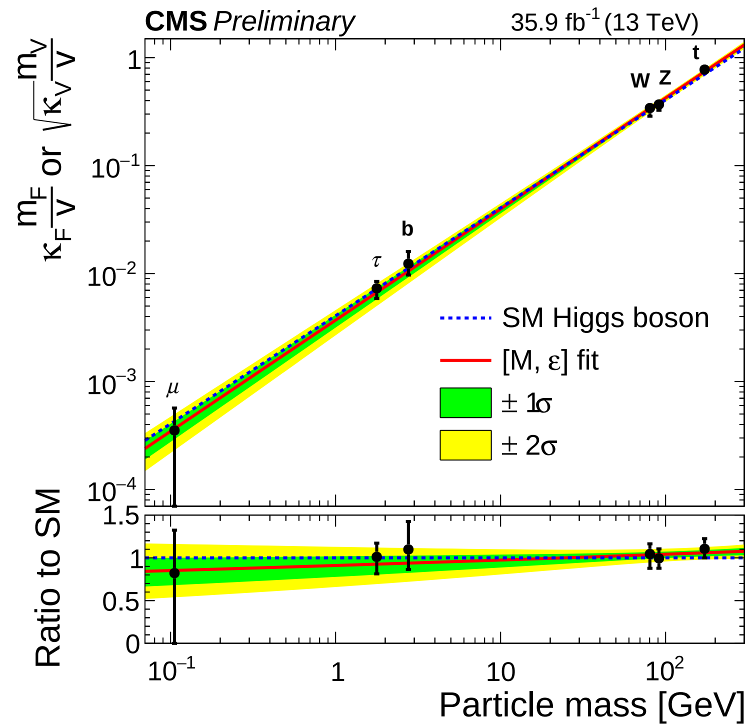
The Future of Particle Physics: A Quest for Guiding Principles

02.10.2018, Julien Baglio

Higgs physics: where are we in 2018?



[ATLAS Collaboration, ATLAS-CONF-2018-031]



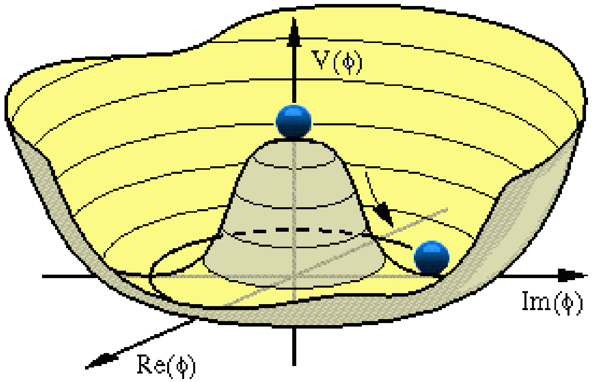
[CMS Collaboration, CMS-PAS-HIG-17-031]

- Higgs boson discovered in 2012 very much like **Standard Model Higgs boson!**
- Nothing else seen at the LHC yet! **What are the prospects at future colliders?**

Measuring the triple Higgs coupling: A major target

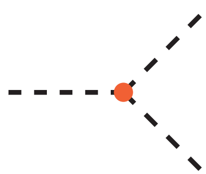
From the scalar potential before EWSB (ϕ as the Higgs field):

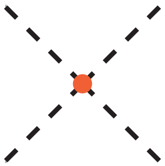
$$V(\phi) = -m^2|\phi|^2 + \lambda|\phi|^4$$



To $V(\phi)$ after EWSB, with $M_H^2 = 2m^2$, $v^2 = m^2/\lambda$:

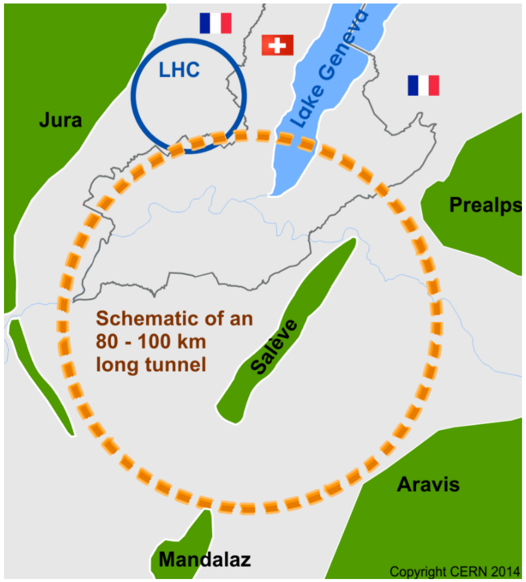
$$\phi = \begin{pmatrix} 0 \\ \frac{v + H(x)}{\sqrt{2}} \end{pmatrix} \Rightarrow V(H) = \frac{1}{2}M_H^2 H^2 + \frac{1}{2}\frac{M_H^2}{v}H^3 + \frac{1}{8}\frac{M_H^2}{v^2}H^4 + \text{constant}$$





EBERHARD KARLS UNIVERSITÄT TÜBINGEN

A recap on future collider projects



Future Circular Collider @ CERN

HE-LHC: pp with $\sqrt{s} = 27$ TeV in LHC tunnel

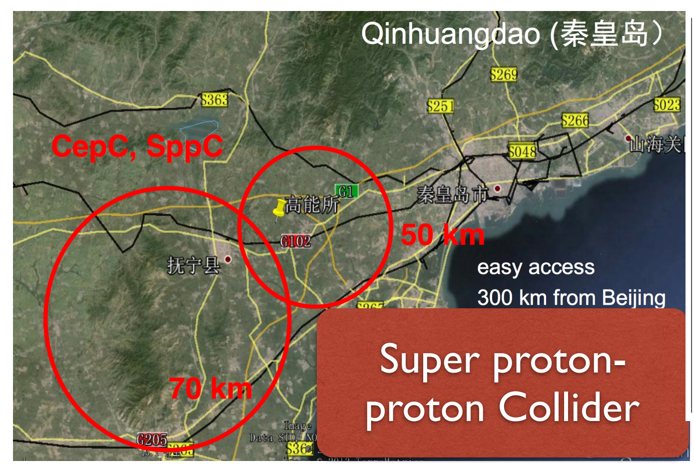
FCC-ee: e^+e^- with $\sqrt{s} = 90 - 350$ GeV

FCC-hh: pp with $\sqrt{s} = 100$ GeV

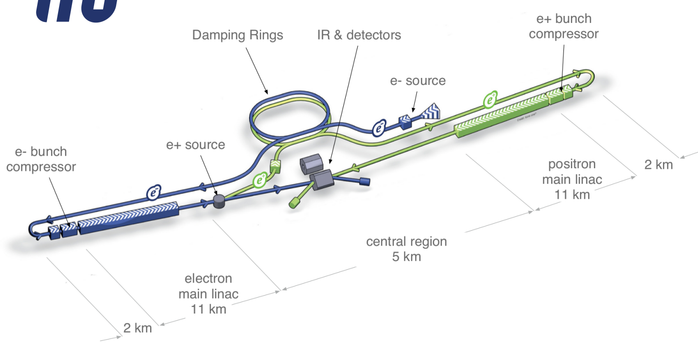
Circular Electron Positron Collider / Super Proton Proton Collider, in China

CEPC: e^+e^- with $\sqrt{s} = 240 - 250$ GeV

SPPC: pp with $\sqrt{s} = 70 - 100$ GeV



A recap on future collider projects



e^+e^- International Linear Collider, in Japan

ILC 1: $\sqrt{s} = 250$ GeV, $\mathcal{L} = 2$ ab^{-1}

ILC 2: $\sqrt{s} = 350$ GeV, $\mathcal{L} = 0.2$ ab^{-1}

ILC 3: $\sqrt{s} = 500$ GeV, $\mathcal{L} = 4$ ab^{-1}

[see arXiv:1710.0762, arXiv:1711.00568]

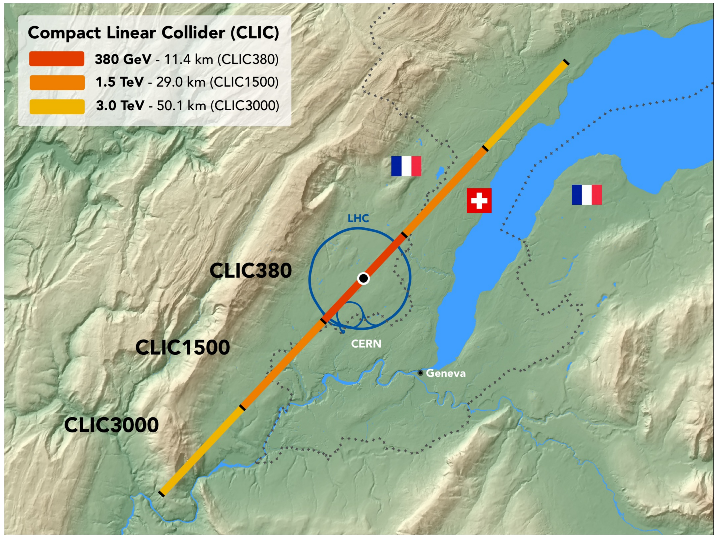
e^+e^- Compact Linear Collider @ CERN

CLIC 1: $\sqrt{s} = 0.38$ TeV, $\mathcal{L} = 1$ ab^{-1}

CLIC 2: $\sqrt{s} = 1.5$ TeV, $\mathcal{L} = 2.5$ ab^{-1}

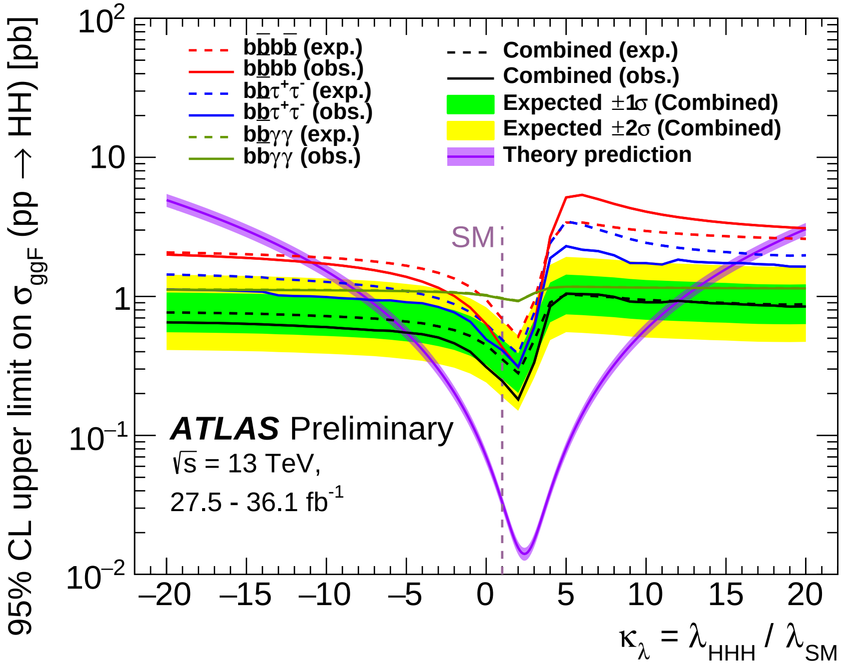
CLIC 3: $\sqrt{s} = 3$ TeV, $\mathcal{L} = 5$ ab^{-1}

[see CERN-2016-004]



The starting point

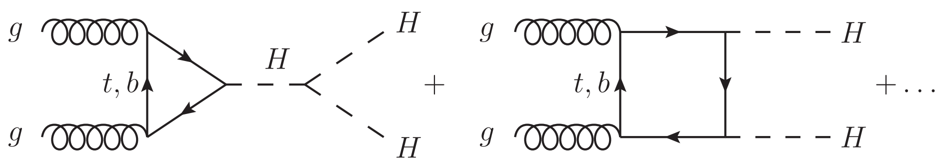
- **Higgs couplings measurements: see Felix Yu's talk!**
- **Latest results from ATLAS at the LHC for λ_{hhh}:**



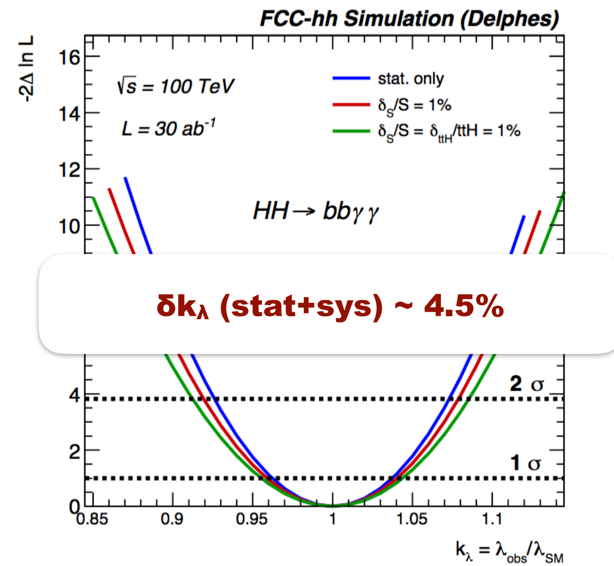
[ATLAS Collaboration, ATLAS-CONF-2018-043]

What about the future? Can we reach the 5σ discovery of *HH* production? Can we pin down λ_{hhh}?

Higgs pair production at future hadron colliders



- **Projected sensitivities at FCC-hh:** [see A. Canepa, HH Workshop@Fermilab, 9/2018]



$HH \to b\bar{b}\gamma\gamma$: $\delta\kappa_\lambda \sim$ 4.5%!

$HH \to 4b$: $\delta\kappa_\lambda \sim 30\%$

$b\bar{b}\tau\tau$: $\delta\kappa_\lambda \sim 8\%$ (no sys included)

$HH \to b\bar{b}4\ell$: $\delta\kappa_\lambda \sim 24\%$ (3% sys included)

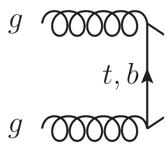
(similar studies exist also for SPPC)

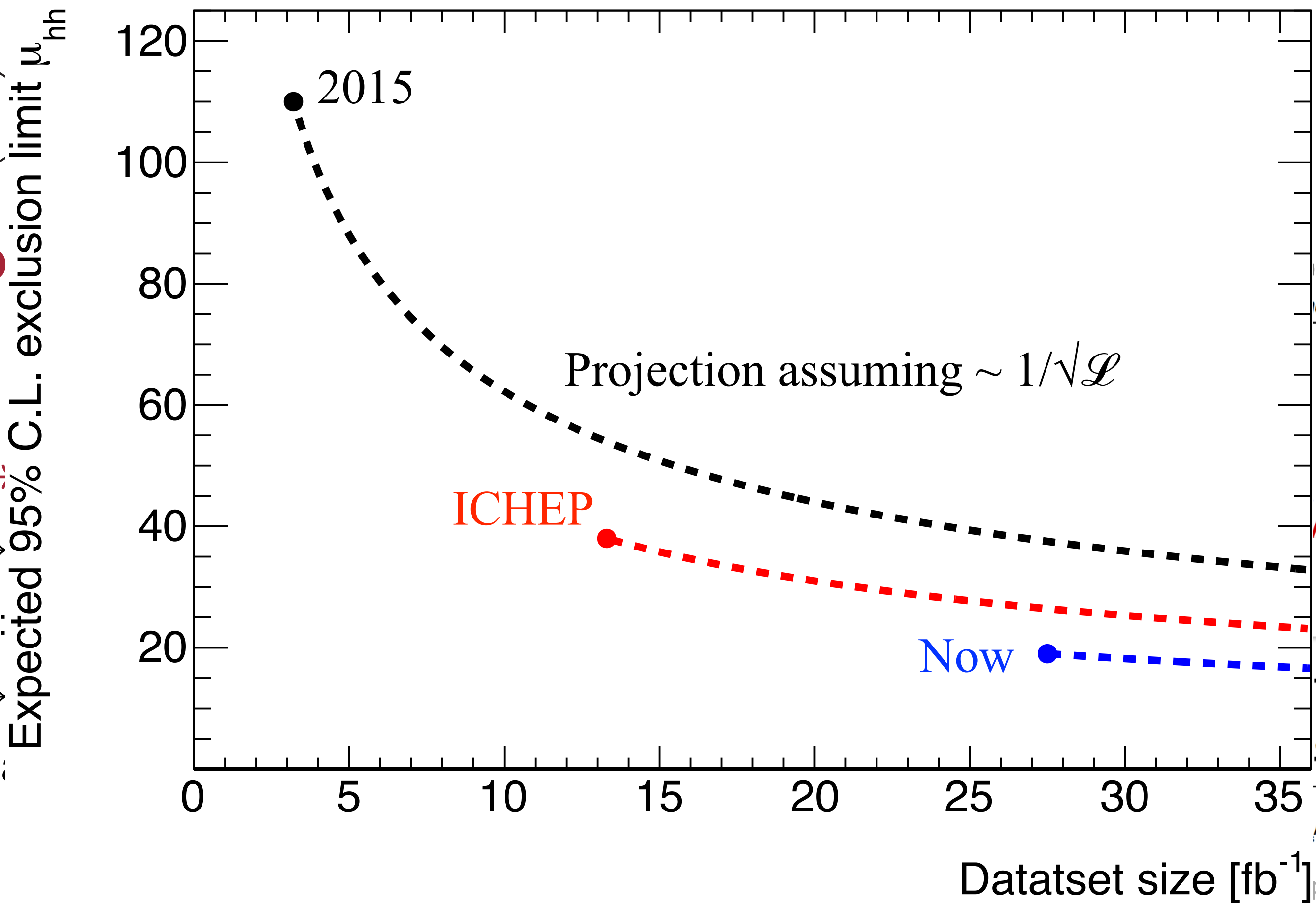
M. Selvaggi, FCC Workshop June 2018

- We should remember to remain optimistic in projections!

[see C. Vernieri, J. Alison, HH Workshop@Fermilab, 9/2018]

Higgs pair production at future hadron colliders





- **Pro**

HH →

HH →

$b\bar{b}\tau\tau$:

HH →

(simil

18]

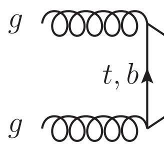
es)

p June 2018

- We should remember to remain optimistic in projections!

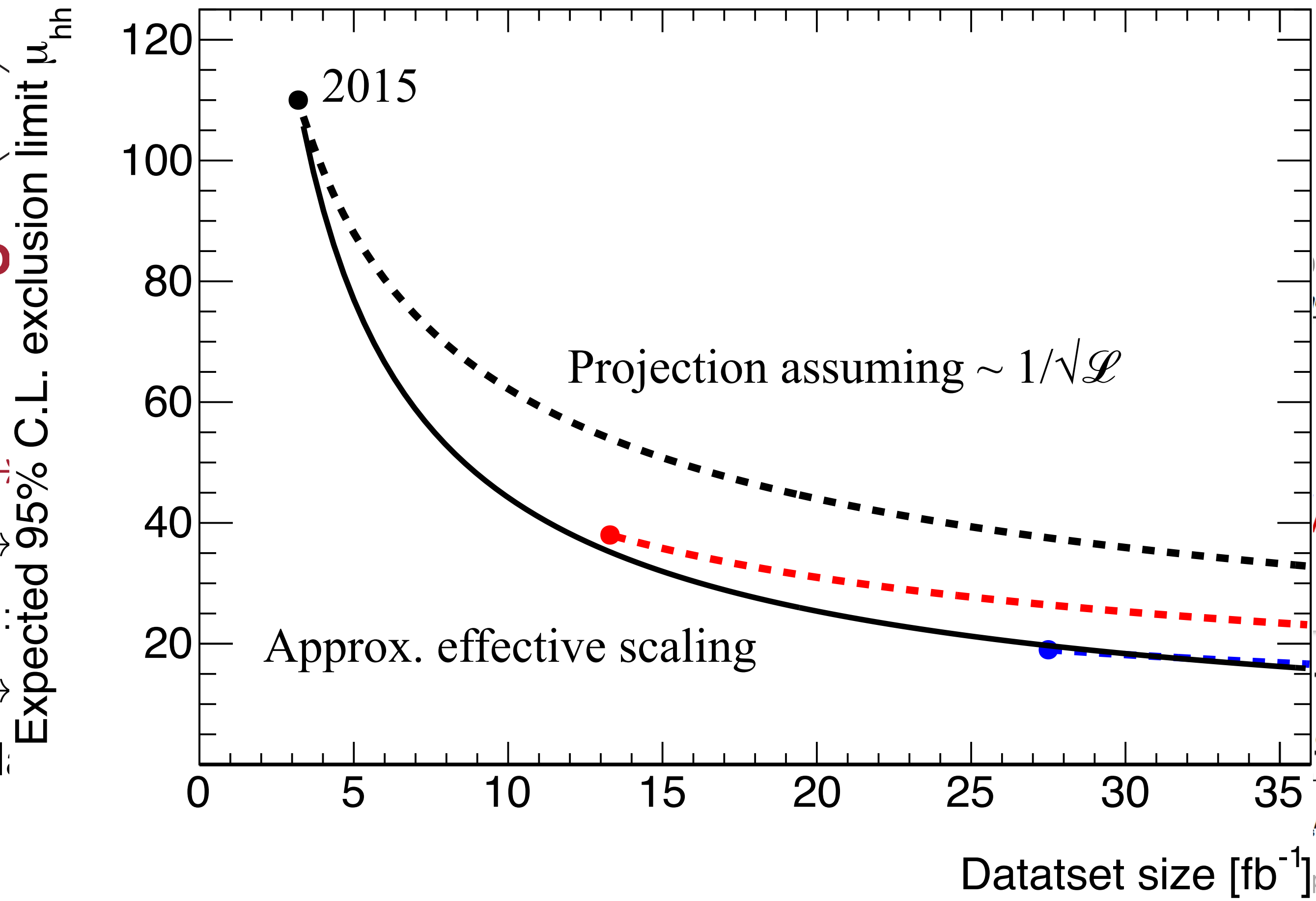
[see C. Vernieri, J. Alison, HH Workshop@Fermilab, 9/2018]

Higgs pair production at future hadron colliders



- **Pro**

HH →
HH →
$b\bar{b}\tau\tau$:
HH →
(simil

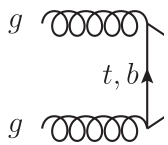


p June 2018

- We should remember to remain optimistic in projections!

[see C. Vernieri, J. Alison, HH Workshop@Fermilab, 9/2018]

Higgs pair production at future hadron colliders



- **Pro**

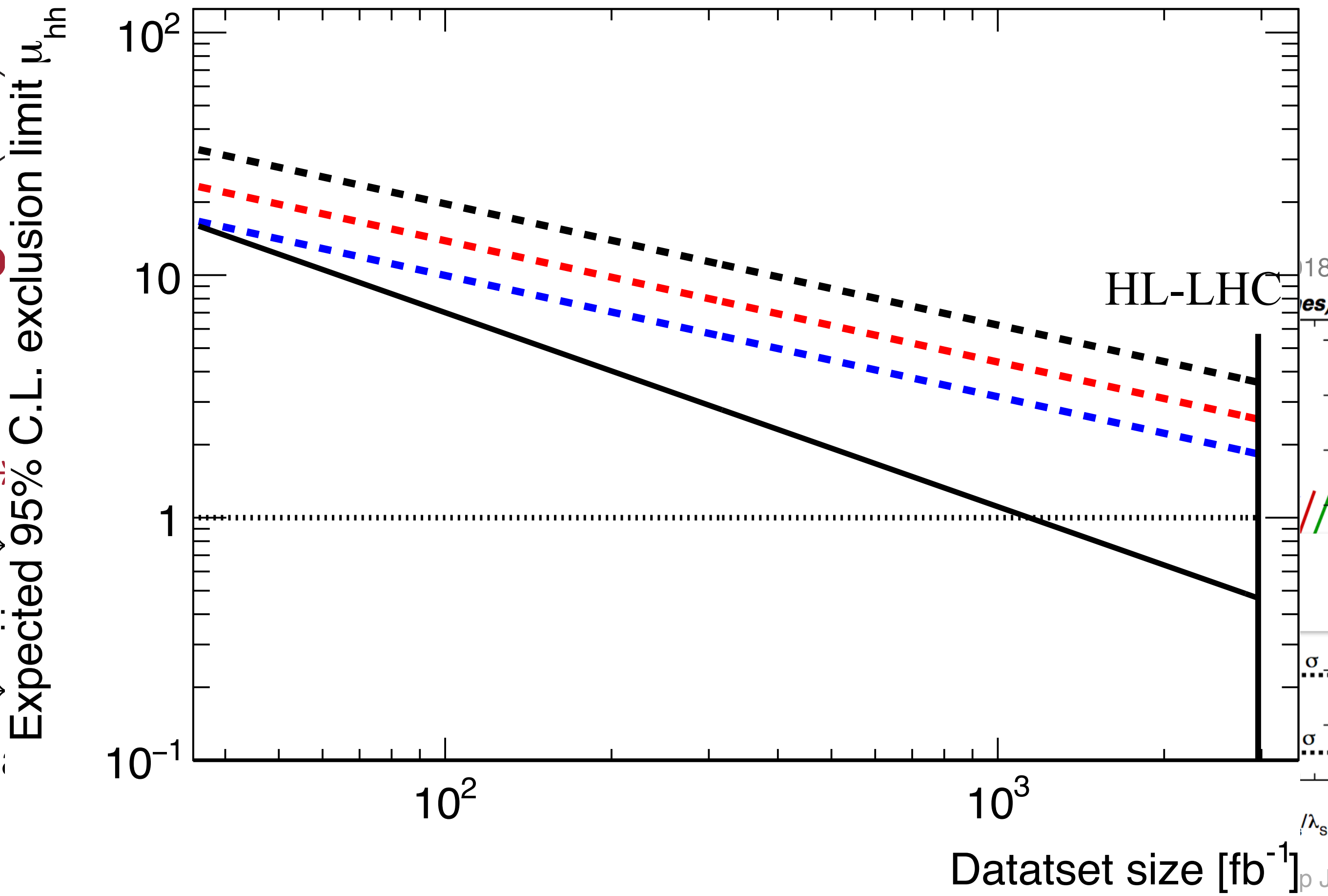
HH →

HH →

$b\bar{b}\tau\tau$:

HH →

(simil

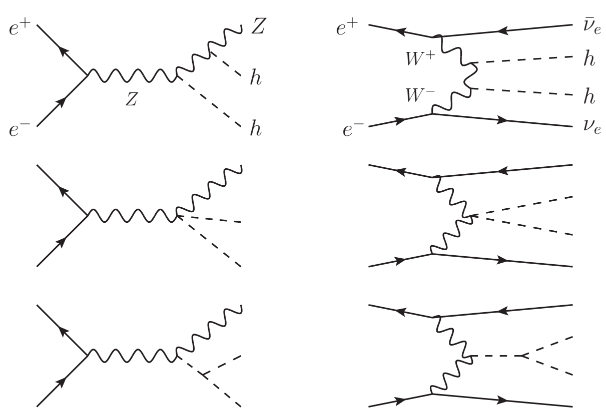


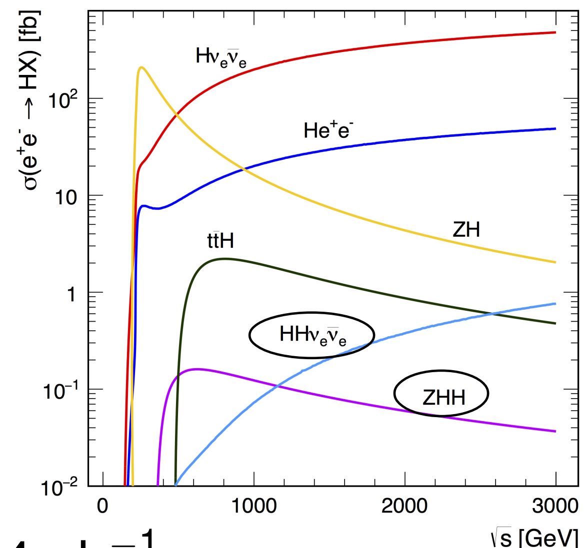
- We should remember to remain optimistic in projections!

[see C. Vernieri, J. Alison, HH Workshop@Fermilab, 9/2018]

Higgs pair production at future lepton colliders

Direct search only possible at the 500 TeV ILC and at CLIC;
FCC-ee, CEPC, 250/350 ILC only probe via precision measurement in single H production





$\delta\kappa_\lambda \sim$ 28% at the 500 GeV ILC, $\mathcal{L} = 4$ ab^{-1}

[see C. Düring, DESY-THESIS-2016-027; T. Barklow, K. Fujii, S. Jung, M. Peskin, J. Tian, Phys.Rev. D97 (2018) 053004]

$\delta\kappa_\lambda \sim$ 13% at the CLIC, 2.5 ab^{-1}@1.4 TeV + 5 ab^{-1}@3 TeV

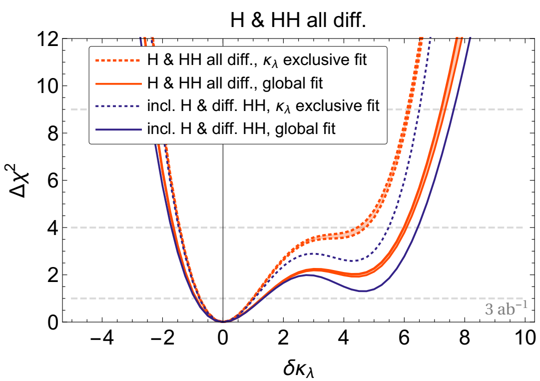
[H. Abramowicz *et al*, Eur.Phys.J C77 (2017) 475]

An EFT analysis of *H* and *HH* productions

Combine direct detection (*HH* production) and indirect probe (*H* production) [see Maltoni *et al*, Degrassi *et al*, Grojean *et al*, etc.]

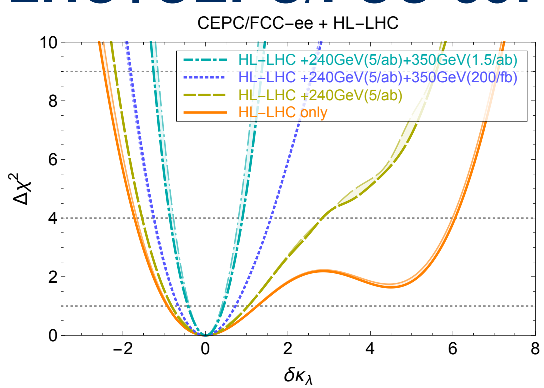
According to results in [Di Vita, Grojean, Panico, Riembau, Vantalon, JHEP 09 (2017) 069; Di Vita, Durieux, Grojean, Gu, Liu, Panico, Riembau, Vantalon, JHEP 02 (2018) 178] we get the following picture:

LHC only:



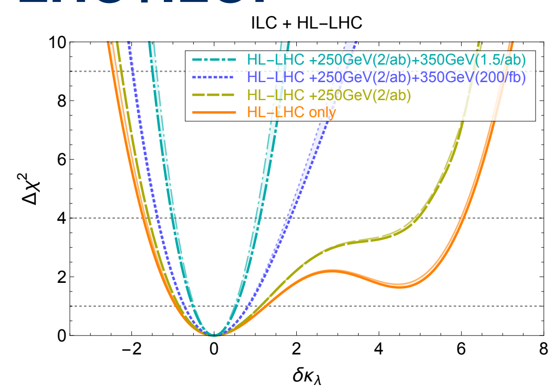
$pp \to WH, ZH, t\bar{t}H, HH$

LHC+CEPC/FCC-ee:



LHC + $e^+e^- \to ZH, \nu\bar{\nu}H, WW$

LHC+ILC:



LHC + $e^+e^- \to ZH, \nu\bar{\nu}H, WW, ZHH, \nu\bar{\nu}HH$

- LHC alone does not remove the second minimum at $\delta\kappa_\lambda \simeq 5$
- **240/250 GeV lepton colliders are not enough to lift this degeneracy! Why not starting directly at 350 GeV?**

Using the Higgs window to study neutrino mass models

- **Standard Model:** $L = \binom{\nu_L}{\ell_L}, \tilde{\phi} = \binom{H^{0*}}{H^-}$

  No right-handed neutrino $\nu_R \Rightarrow$ No Dirac mass term

$$\mathcal{L}_{\rm mass} = -Y_\nu \bar{L}\tilde{\phi}\nu_R + \text{h.c.}$$

  No Higgs triplet $T \Rightarrow$ No Majorana mass term

$$\mathcal{L}_{\rm mass} = -\frac{1}{2} m \bar{L} T L^c + \text{h.c.}$$

- **Necessary to go beyond the Standard Model for ν mass**

  Seesaw mechanisms are very appealing!

  $\rightarrow \nu$ mass at tree-level

  $\rightarrow$ **heavy sterile fermions**

  $\Rightarrow$ **neutrino portal for Dark Matter?**

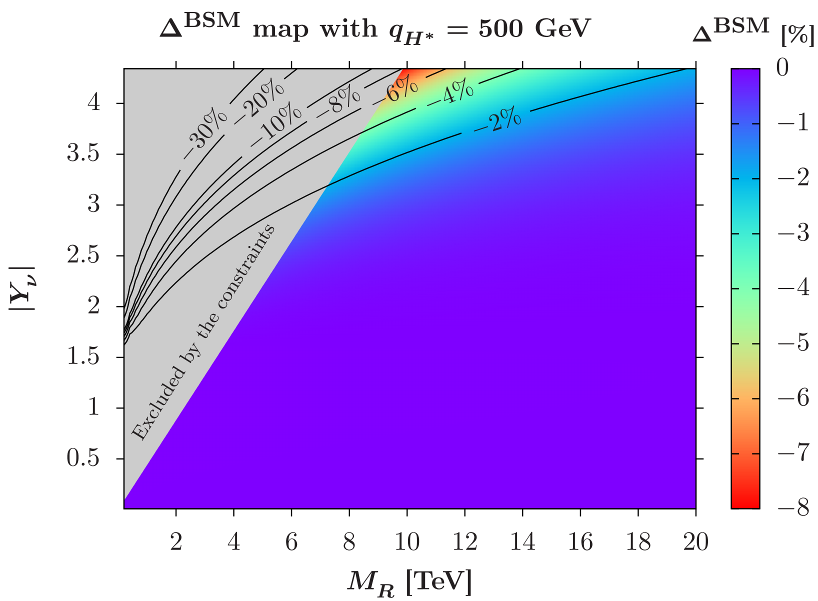
Using the Higgs window to study neutrino mass models

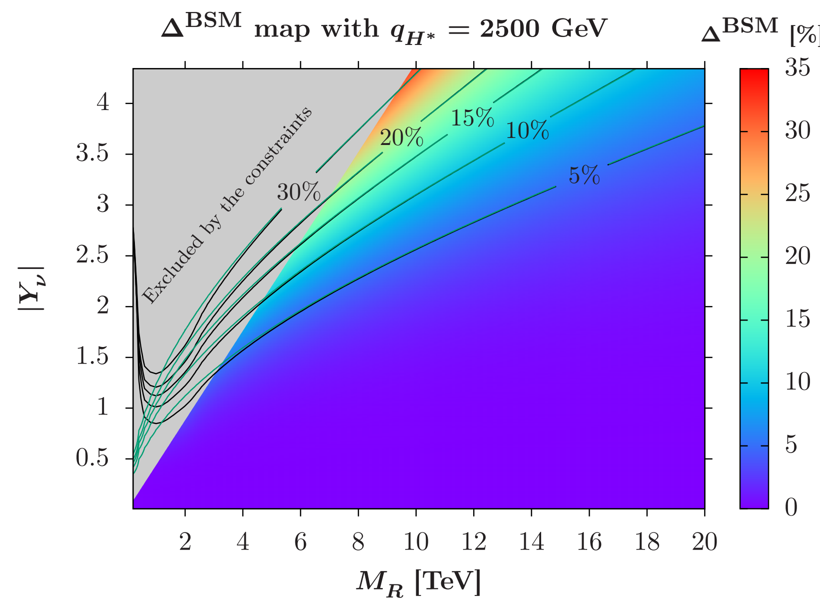
How to search for heavy neutrino with $m_\nu > \mathcal{O}(1\,\text{TeV})$?

Use the Higgs sector to probe neutrino mass models

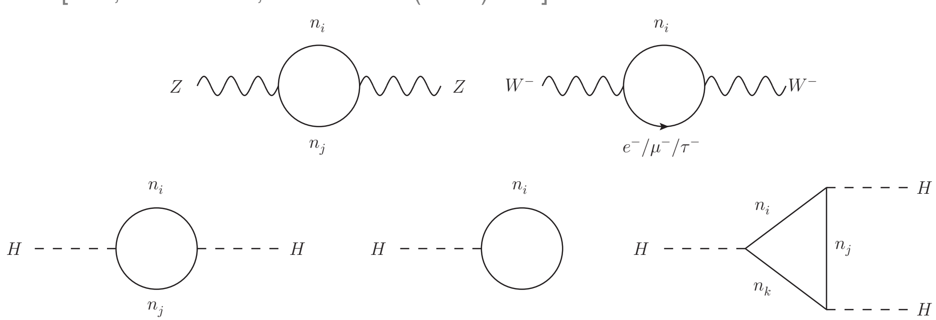
- TeV-scale neutrinos + Large Yukawa couplings
  $\Rightarrow$ Possibly large deviations from SM properties in the Higgs sector
- ***HH* production:** one of the main motivation for high-luminosity LHC and future colliders $\Rightarrow$ need to study the impact of BSM on λ_{HHH} $\Rightarrow$ impact of heavy neutrino(s) on λ_{HHH}?
  - Sensitive to diagonal Yukawa couplings Y_ν

The triple Higgs coupling: A new observable for neutrino physics at future colliders





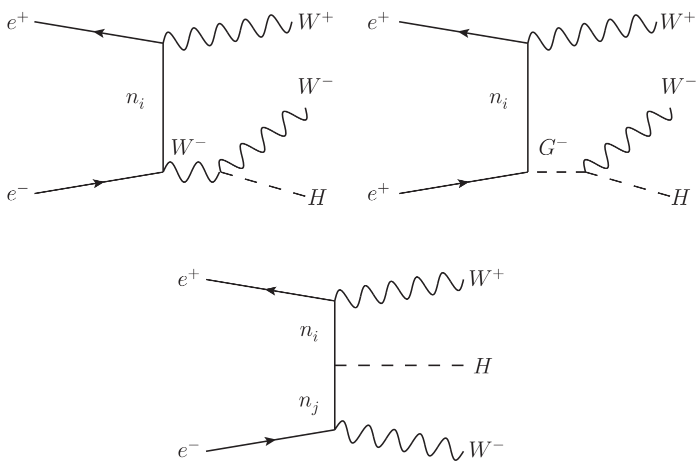
[J.B., C. Weiland, JHEP 1704 (2017) 038]

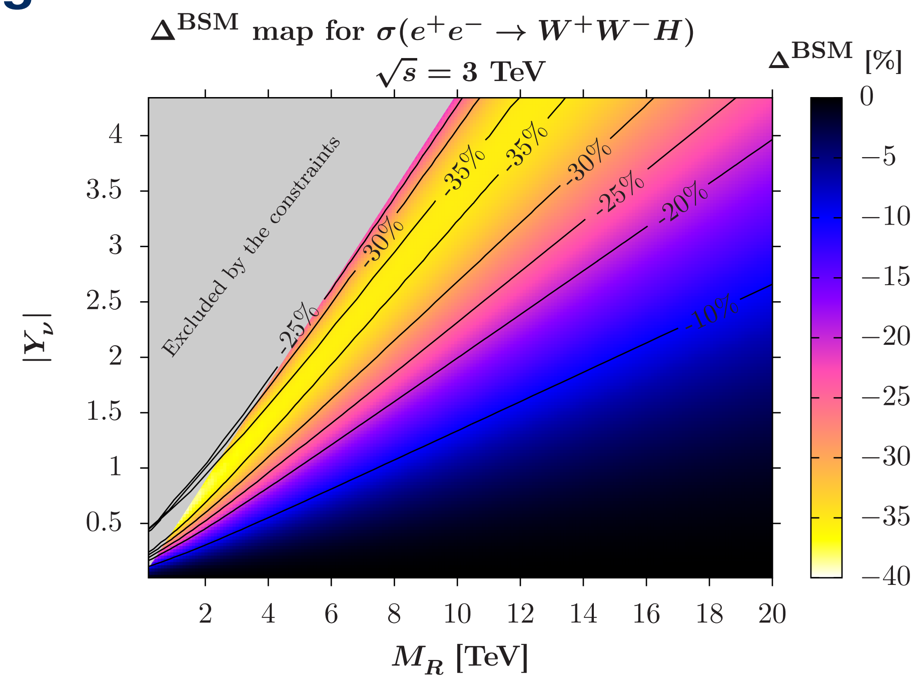


This can be probed at the CLIC and at the FCC-hh!

Looking further: Direct probe in *WWH* production at CLIC

Can 3 TeV CLIC enlarge the coverage of the inverse seesaw model in the intermediate regime?



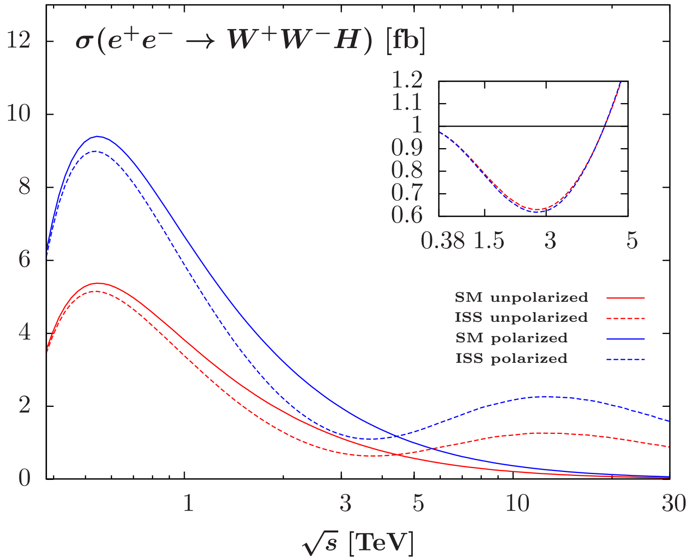


[J.B., S. Pascoli, C. Weiland, arXiv:1712.07621, to appear in EPJC (2018)]

The potential is there! Needs to be confirmed with a dedicated analysis!

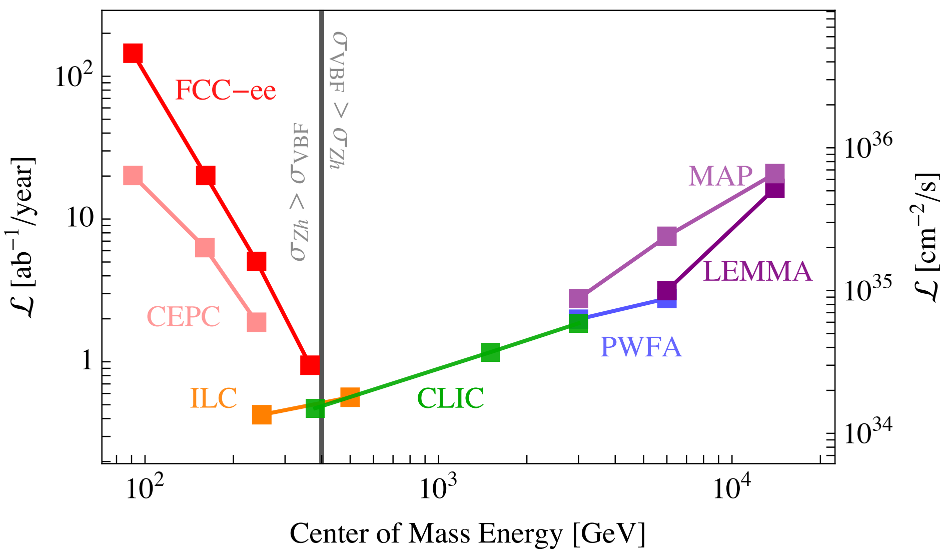
The great dream of a muon collider?

Circular muon colliders of 14 to 30 TeV center-of-mass energies? LEMMA, MAP, ALEGRO projects



(scenario where $M_R = 2.4$ TeV, $|Y_\nu| = 1$)

[J.B., C. Weiland, in CLIC Yellow Report (to appear)]



[D. Buttazzo, D. Redigolo, F. Sala, A. Tesi, arXiv:1807.04743]

The ideal place to look further beyond! Still a long way to go...

Some personal statements on future collider projects

- 250 GeV ILC will be of no use to probe the triple Higgs coupling in precision measurements
- Starting at 350 GeV removes the flat direction in the analyses on λ_{hhh}
  $\Rightarrow$ **DO IT at the ILC[1]! FCC-ee and CLIC 380 GeV are even better**
- **FCC-hh and high-energy muons colliders: My ultimate dreams**, but I'm not sure to live long enough to see them...

[1] And we can also start the top-quark program, by the way...

Outlook

Measuring the triple Higgs coupling: A major goal of collider physics!

- **The future of triple Higgs coupling measurement is bright!** Lots of progress in the past few years, towards higher precision and better tools for next experimental analyses
- We are too pessimistic when projecting to the future!
  $\Rightarrow$ **Let's be more optimistic**
- **Assessing the energy for a lepton collider:**
  350 GeV would be a better start for the ILC!
- **Higgs physics as a window on neutrino mass models:**
  High-energy colliders can probe deeply the intermediate regime of low-scale seesaw models!