Higgs studies from Snowmass

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18th Workshop of the LHC Higgs Working Group

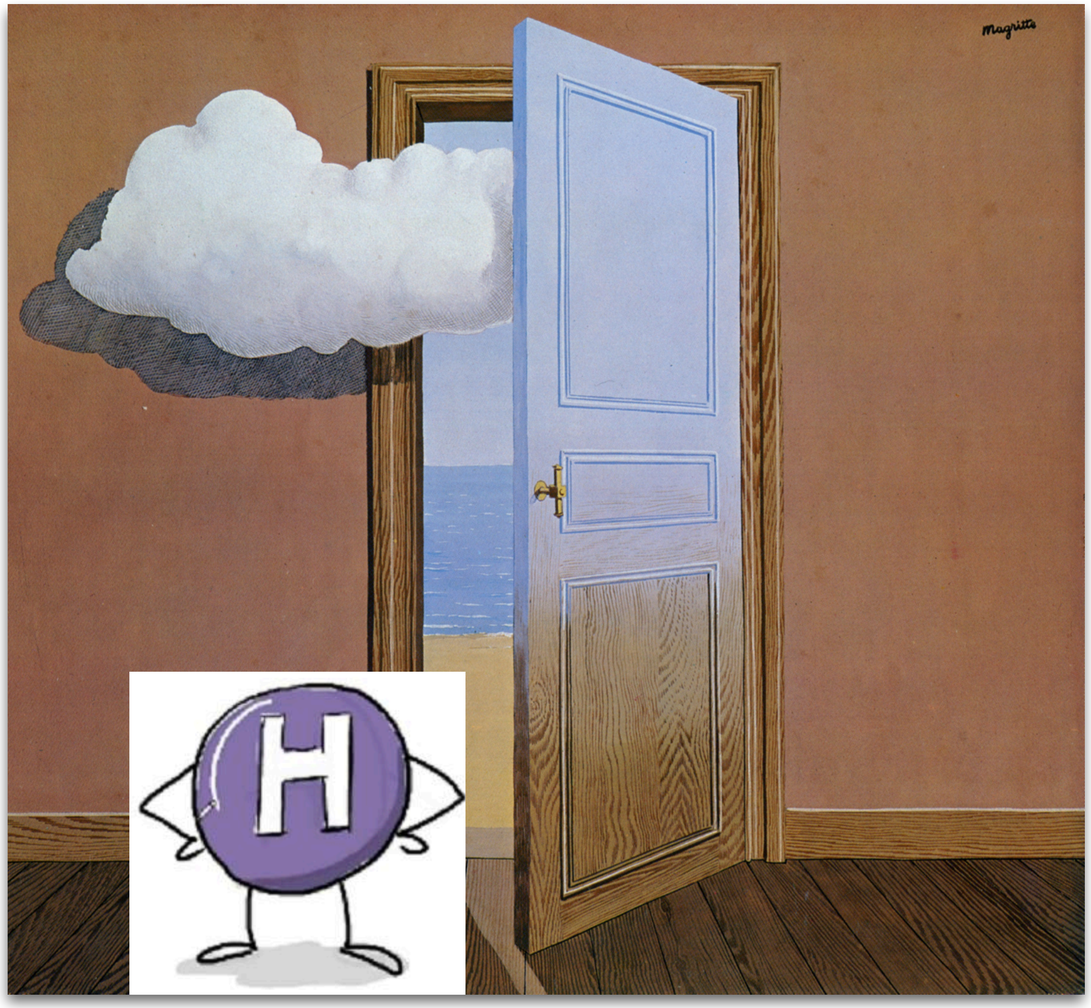
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Higgs and the exploration of the EF

Higgs plays a central element in the future of collider physics

- Searches for new Higgs bosons and interpretation with Higgs measurements
- Higgs Global fits



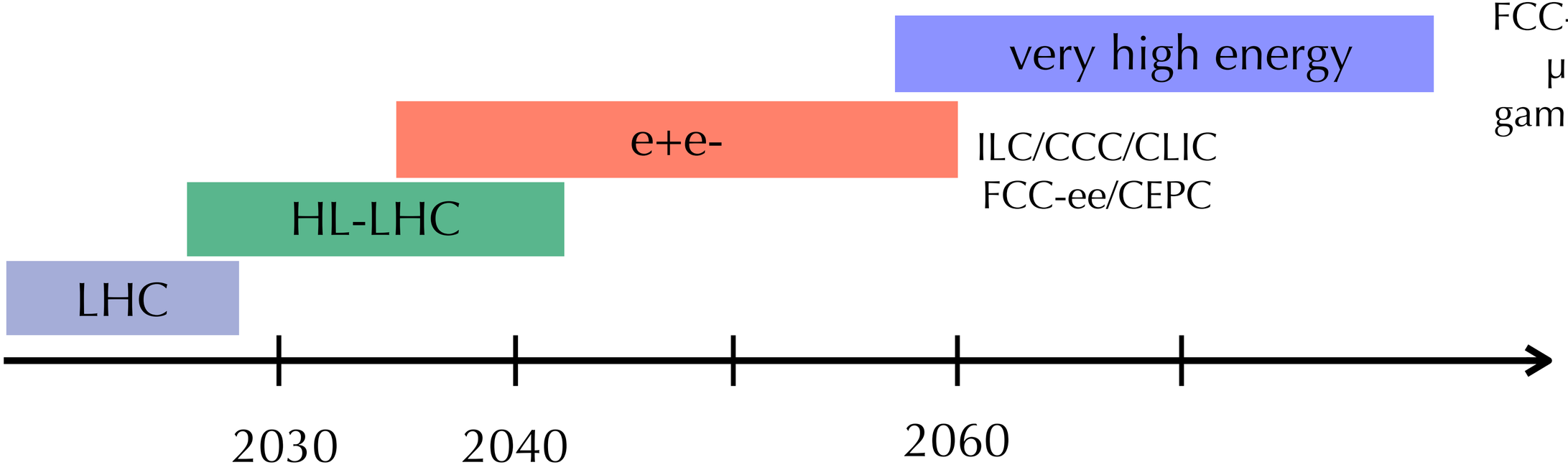
Snowmass timeline

- Snowmass is the on going community driven US HEP planning process
  - Energy Frontier (EF) explores the TeV energy scale and beyond at colliders
  - 10 topical groups (TG): **EF01** Higgs, **EF02** BSM Higgs, **EF04** Global Fits

8/30-9/3/21	3/15/22	3/28-4/1/22	4/9-12/22	5/31/22	6/30/22	7/17-26/22	9/30/22	10/31/22
EF Restart Workshop	Deadline **Contributed Papers**	**EF Spring Workshop**	**APS Meeting** (New York)	Preliminary **TG Reports**	Preliminary **Frontier Reports**	**Community Summer Study** (UW-Seattle)	**Final Reports**	Snowmass Book & online archive docs

- EF Workshop: March 28 - April 1, 2022 - Hosted by Brown University
  - Focus on contributed papers and TG reports.
  - Converge on summary plots

Higgs as a guide



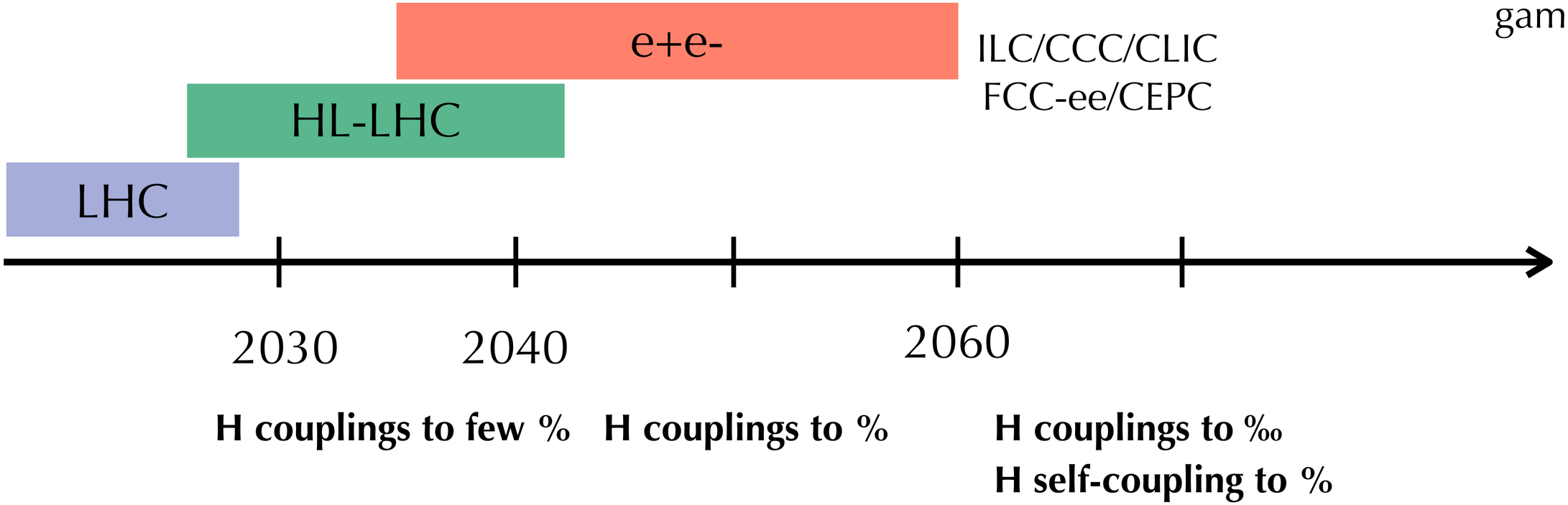
Higgs as a guide

Complementarity between e^+e^- and p-p machines will eventually lead to the most precise understanding of the Higgs couplings

- ***In particular, we need to prioritize what we want to learn on top of what HL-LHC will deliver?***
- ***Timelines matter.***

h

gamma



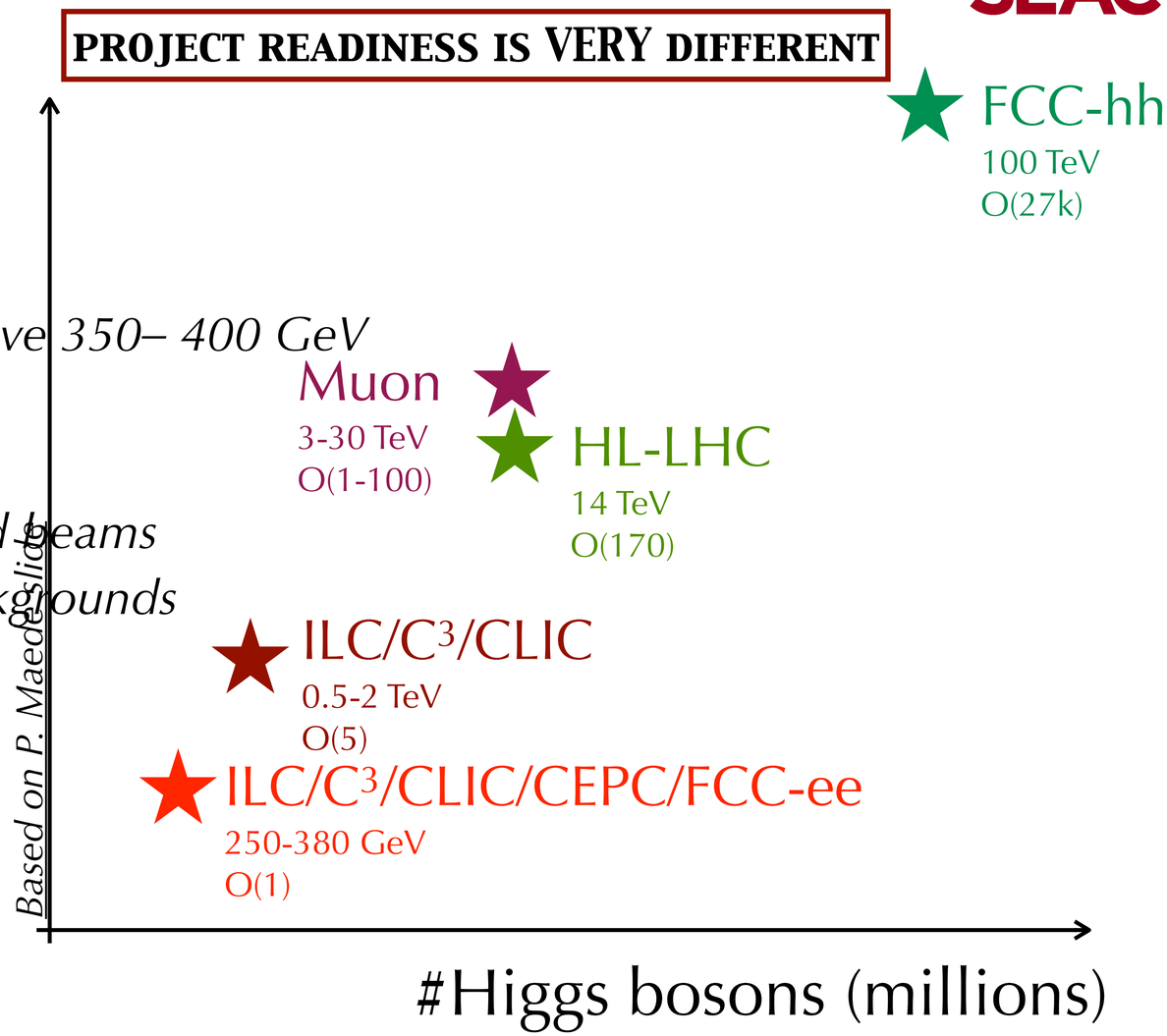
Which collider?

Lepton colliders

- **Circular e+e-** (CEPC, FCC-ee)
  - **90-350 GeV**
  - *strongly limited by synchrotron radiation above 350– 400 GeV*
- **Linear e+e-** (ILC, CLIC, C^3)
  - **250 GeV — 3TeV**
  - *Reach higher energies, and can use polarized beams*
  - *Relatively low radiation / beam induced backgrounds*
  - ***C^3** plans is to run at 250/550 GeV*
    C3 proposal - talk on Wed
- μ+μ-
  - **3-30 TeV**

Hadron colliders

- **75-200 TeV** (FCC-hh)



Which collider?

PROJECT READINESS IS VERY DIFFERENT

LEPTON COLLIDERS

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HADRON COLLIDERS

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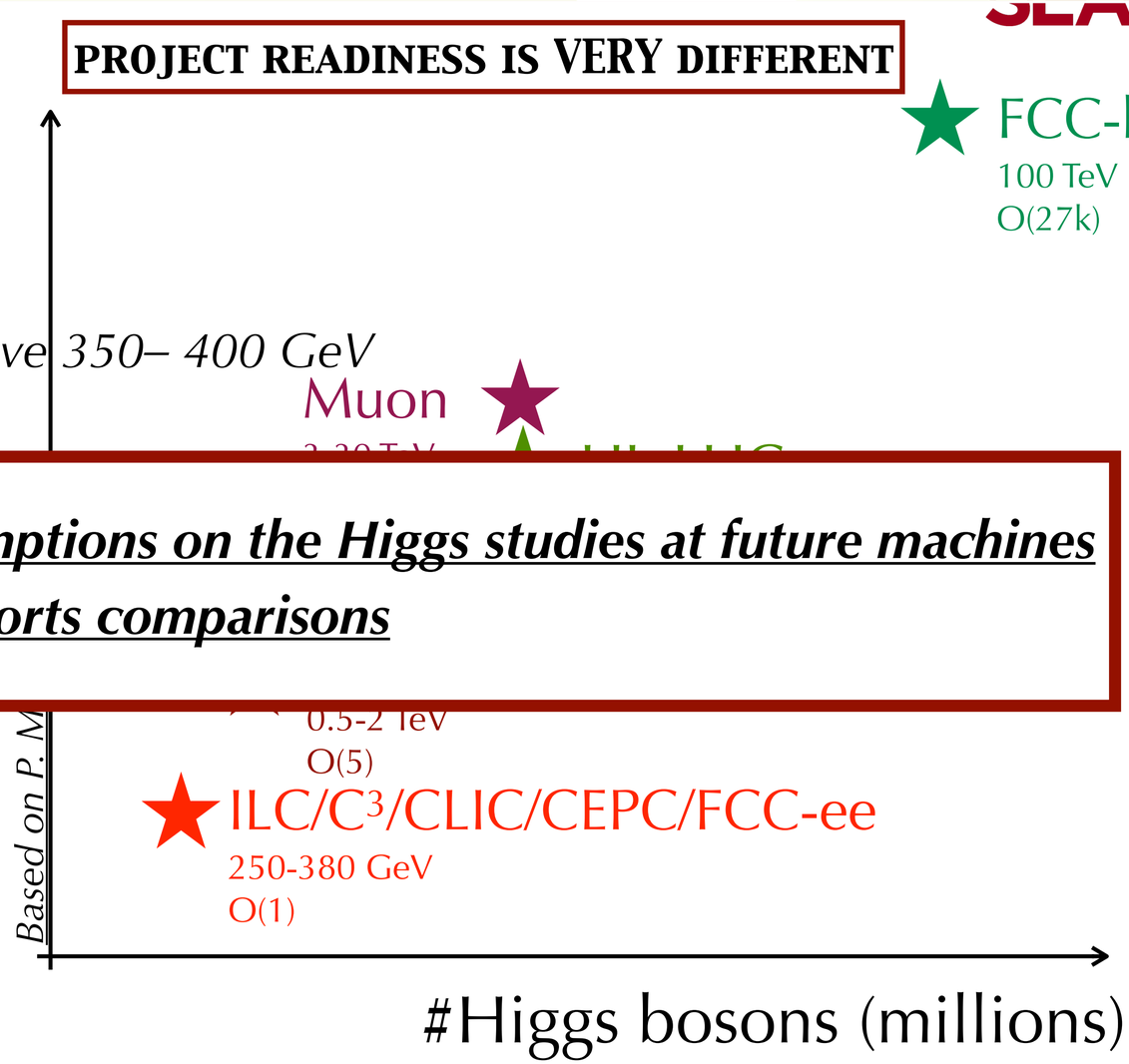
We will have to review & harmonize the assumptions on the Higgs studies at future machines for the final reports comparisons

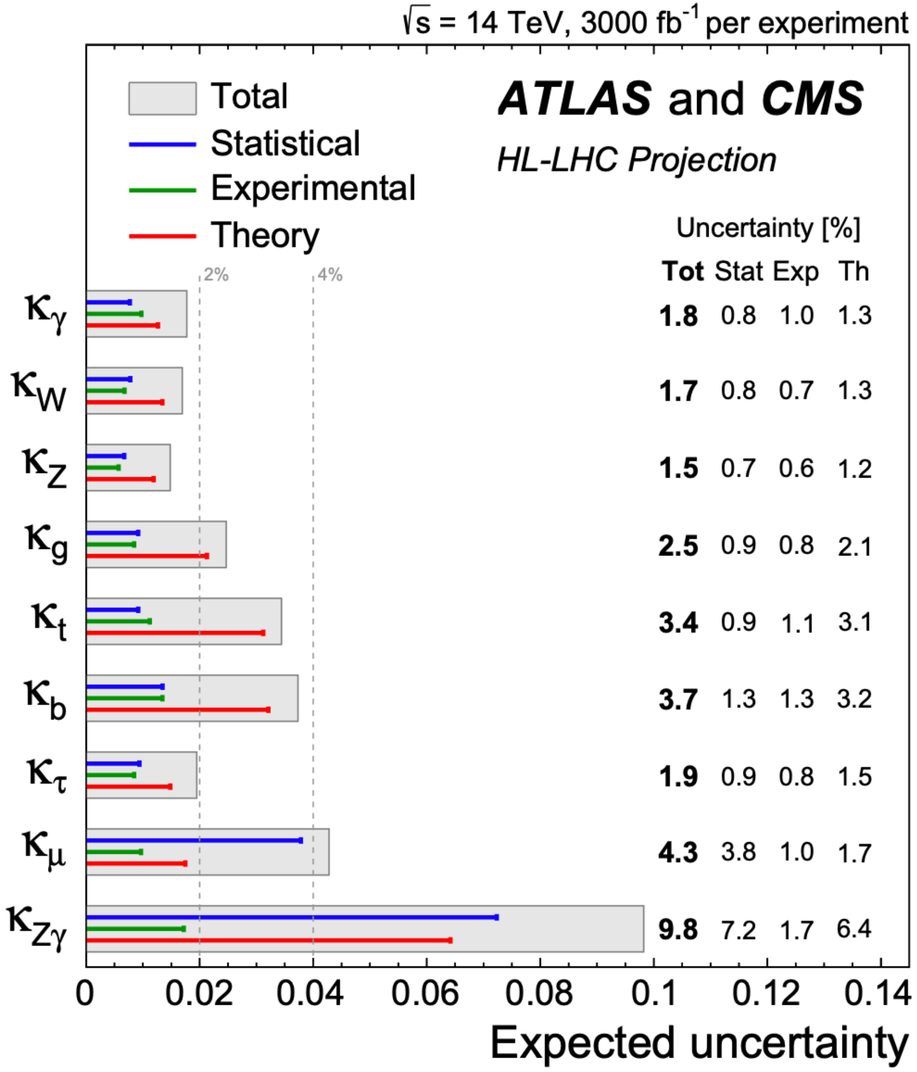


Higgs couplings at future colliders

arXiv:1910.11775, arXiv:1905.03764

CERN-LPCC-2018-04

- Future colliders under consideration will improve with respect to the HL-LHC the understanding of the Higgs boson couplings - 1-5%
  - **Coupling to charm** quark could be measured with an accuracy of ~1% in future e+e- machines
  - **Couplings to μ/γ/Zγ** benefit the most from the large dataset available at HL-LHC and not really improved at future colliders
  - At low energy top-Higgs coupling is not accessible at future lepton colliders
- **Complementarity between HL-LHC and future colliders** (depending on their timeline) **will be the key to explore the Higgs sector**
  - We expect new Hμμ from CMS & VH(bb/cc) from ATLAS



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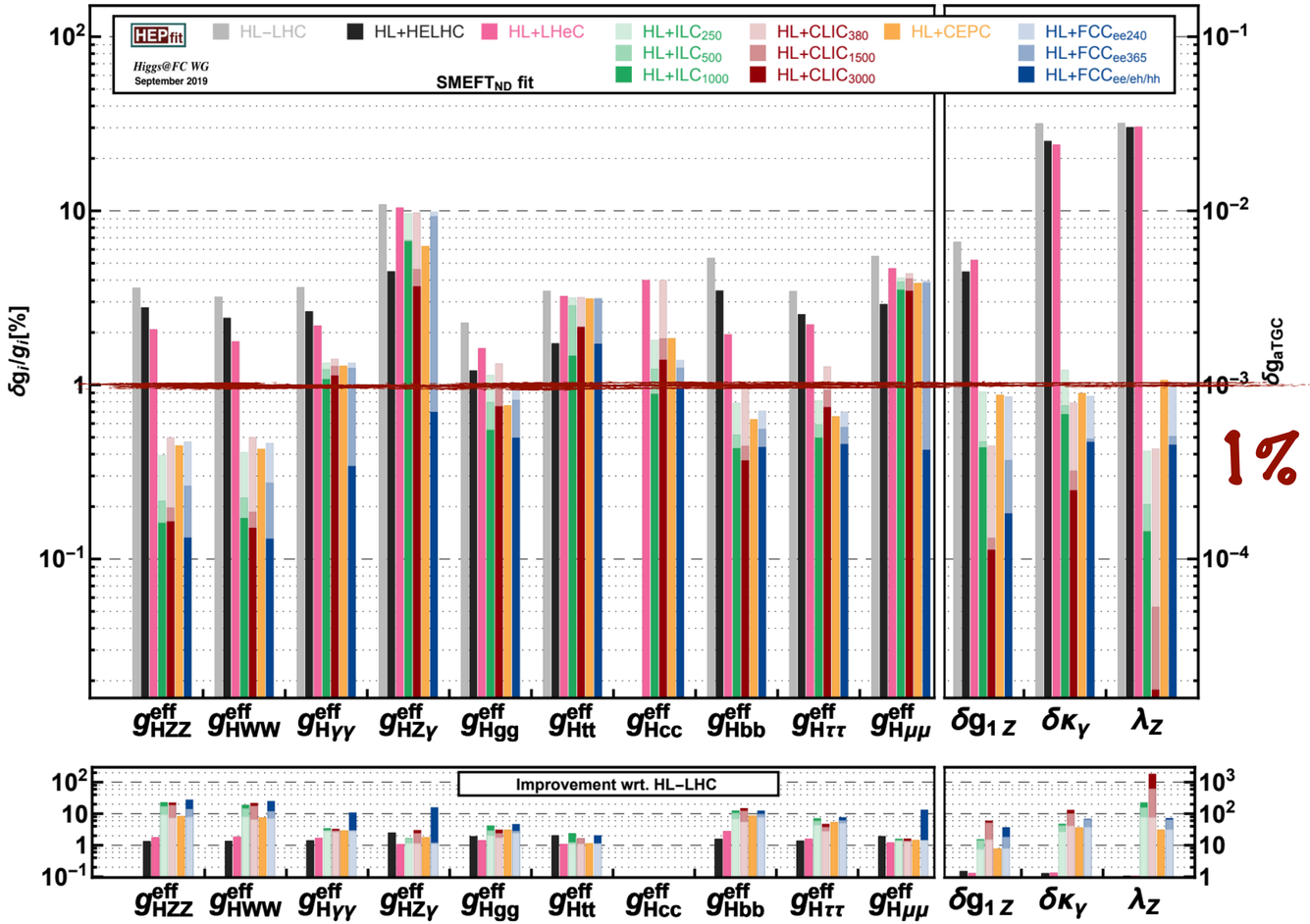
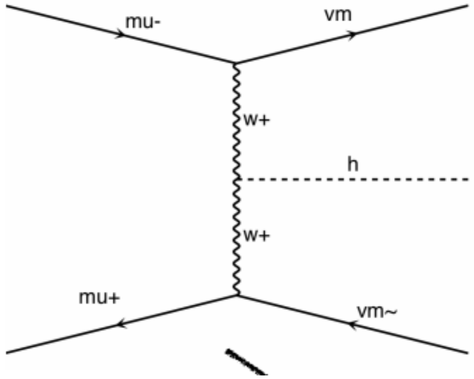


Higgs couplings at the muon collider

Fit Result [%]			
	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27

Higgs Updates at MuC EF Workshop EF01-02 Zhen Liu 09/01/2021

link to presentation



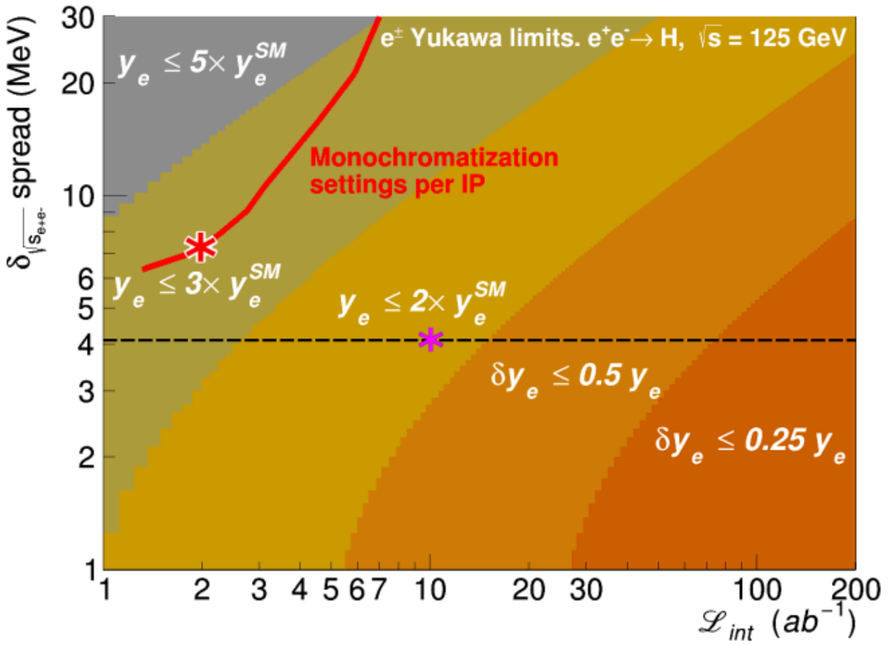
Ongoing work to improve muon collider Higgs coupling estimates

On going work

67 LOIs submitted to EF01 covering several topics:

- Progress on understanding light fermion Yukawa couplings
  - **Electron** Yukawa at FCC-ee with 4 years running, $Y_e < 1.6\ Y_e^{SM}$
  - **Strange** Yukawa
  - **Charm** Yukawa limit, $|\kappa_c| < 8.5$ (CMS) motivates new studies
    - Higgs production at high momentum and HH production could provide constraints at pp machines
  - Searches for flavor violating H couplings motivated by LHC limits on $H \to \mu e$, $H \to \mu\tau$ and by B flavor anomalies
- Progress on CP violation - expected an update of the 2013 study
  - Goal is to sharpen theoretical expectations / models
  - Connect to broader EFT and distinguish between linear and quadratic effects in the observables

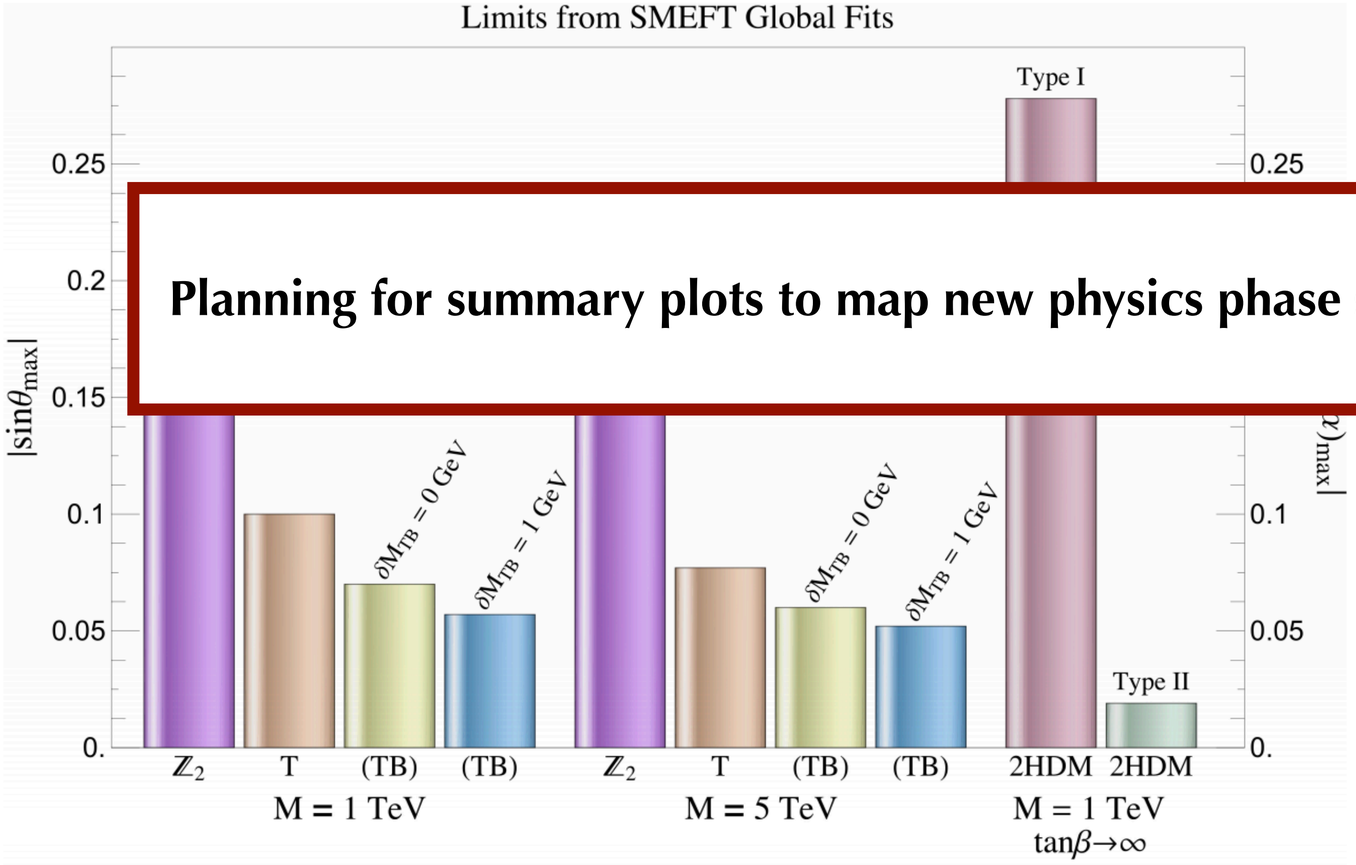
Arxiv:2107.02686



The inverse problem

arXiv:2007.01296

- Progress on how to map BSM models to SMEFT constraints
  - Include complete 1-loop matching for other models, more NLO effects in fits, and more distributions



Integrate out new particles at matching scale (M ~ few TeV)

Planning for summary plots to map new physics phase space with constraints on EFT operators

Evolve Coefficients down to EW scale

Fit to Higgs + Diboson + EWPO Data

→ Limits on physical parameters!

The Higgs self-coupling at future colliders

arXiv:1910.00012
arXiv:2004.03505

- We expect an update on the HL-LHC projections
  - Full Run 2 results are being published approaching the SM limits on the self-coupling
  - YR HL-LHC estimate was based on projections from early data analyses
  - CMS: HH and VBF HH for bbγγ, WWγγ, ttHH→bbbb
- **Muon collider** 25% (6%) at 3 (10) TeV

collider	single-H	HH	combined
HL-LHC	100-200%	50%	50%
$CEPC_{240}$	49%	–	49%
ILC_{250}	49%	–	49%
ILC_{500}	38%	27%	22%
ILC_{1000}	36%	10%	10%
$CLIC_{380}$	50%	–	50%
$CLIC_{1500}$	49%	36%	29%
$CLIC_{3000}$	49%	9%	9%
FCC-ee	33%	–	33%
FCC-ee (4 IPs)	24%	–	24%
HE-LHC	-	15%	15%
✱FCC-hh	-	5%	5%

These values are combined with an independent determination of the self-coupling with uncertainty 50% from the HL-LHC.

✱ arXiv:2004.03505 2.9-5.5% depending on the systematic assumptions

Towards the final reports:

- **Which physics beyond the Standard Model can be probed by precision measurements of Higgs couplings?**
  - How precise do these measurements need to be in order to probe BSM physics scenarios?
  - How are direct searches for new Higgs-like particles complementary to precision Higgs coupling measurements
    - This should be study by exploring the complementarity between HL-LHC and future colliders (accounting for their different timelines).
- Does the Higgs boson result from the scalar potential of the Standard Model?
  - How can measurements of double Higgs boson production be improved to better probe the potential ?
  - Which is the target precision for this? - taking into account the correlations with the other Higgs measurements
- How can measurements in the Higgs sector be combined with measurements in other sectors to improve our understanding of high scale physics?
- What theory calculations are needed to enable the theory precision to match the projected experimental precision of future measurements?

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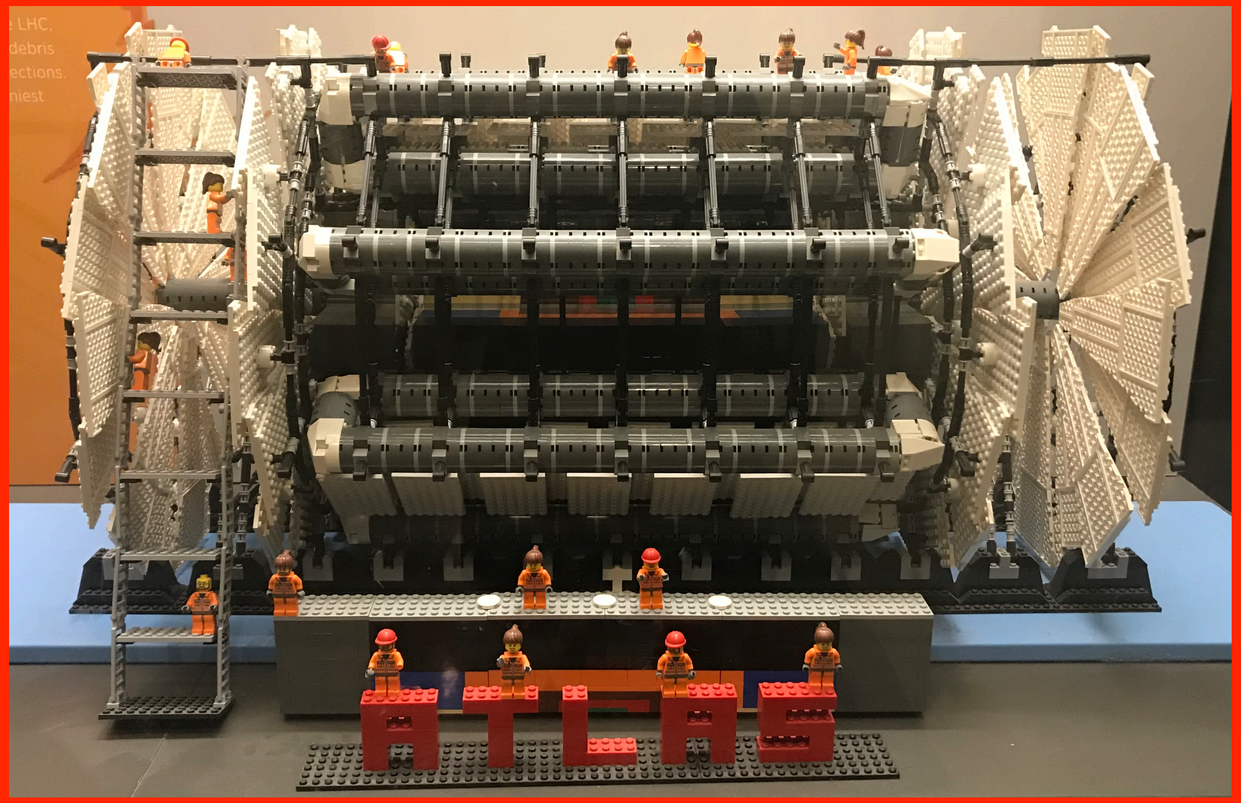
Please contribute to the white papers.

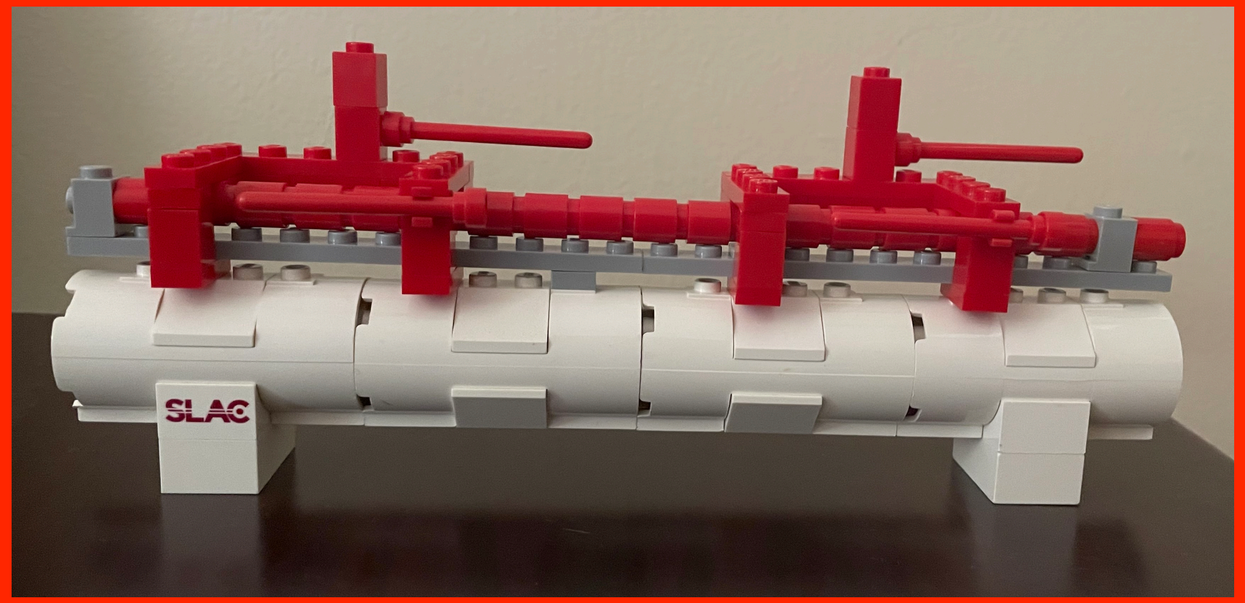
Get in touch with us, your input is welcome!

Summary plots/tables

- Higgs couplings:
  - Include updated list of machines (muon collider, C3 are recent developments) and their parameters
  - Re-visit some of the assumptions (i.e. flavor..) since the ESG
  - Summary of latest & greatest theory cross sections (distributions too if available)
  - New Global fits
- Some example maps of new physics phase space to constraints on EFT operators
  - Plots that demonstrate in creative ways the BSM sensitivities of various measurements
- New physics benchmarks for resonant and non-resonant HH that we could use for interpretations as the precision on the self-coupling improves

- Upcoming discussion:
  - January 12 meeting 12-2 EDT





Extra

Wish list for the global fit

Inputs: Higgs @ HL-LHC

in unit of %

EF04 link

HL-LHC	3 ab-1 @ 14 TeV ATLAS+CMS (S2)				
prod.	ggH	VBF	WH	ZH	ttH
σ	-	-	-	-	
$\sigma x BR_{bb}$	19.1	-	8.3	4.6	10.2
$\sigma x BR_{cc}$	-	-	-	-	-
$\sigma x BR_{gg}$	-	-	-	-	-
$\sigma x BR_{ZZ}$	2.5	9.5	32.1	58.3	15.2
$\sigma x BR_{WW}$	2.5	5.5	9.9	12.8	6.6
$\sigma x BR_{\tau\tau}$	4.5	3.9	-	-	10.2
$\sigma x BR_{\gamma\gamma}$	2.5	7.9	9.9	13.2	5.9
$\sigma x BR_{\gamma Z}$	24.4	51.2	-	-	-
$\sigma x BR_{\mu\mu}$	11.1	30.7	-	-	-
$\sigma x BR_{inv.}$	-	2.5	-	-	-
m_H	10-20MeV				

wishlist: correlation matrix; differential x-section is not included now, but can be considered if available