
Brookhaven
National Laboratory
U.S. DEPARTMENT OF
ENERGY
HH projections at future colliders
Elizabeth Brost
December 17th, 2021
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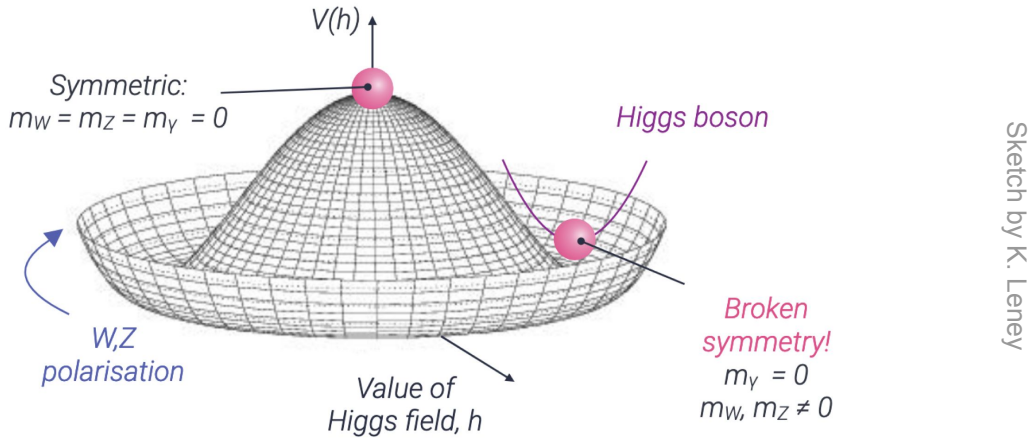
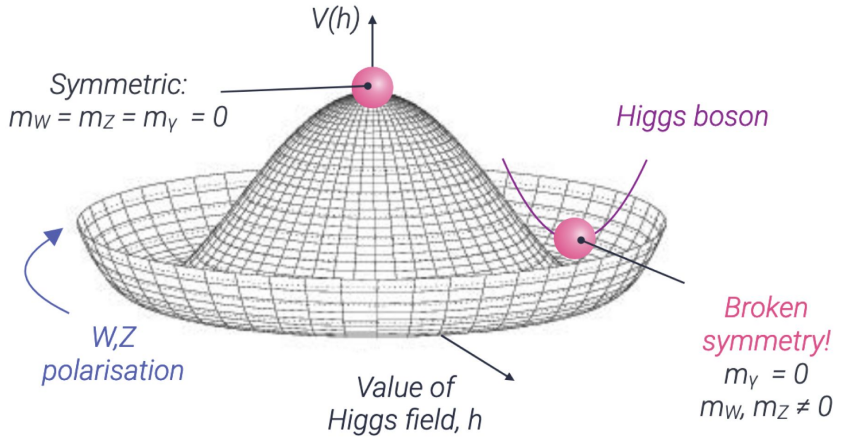
Electroweak symmetry breaking



Sketch by K. Leney

Is the current minimum the TRUE minimum - and thus the universe is stable - or is there another, deeper minimum elsewhere, allowing for decay?

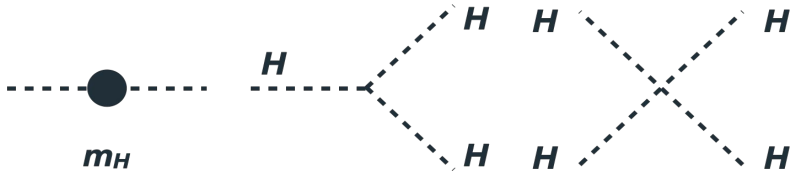
Electroweak symmetry breaking



Sketch by K. Leney

We want to measure the shape of the Higgs potential:

$$V(h) \sim (1/2)m_H^2h^2 + \lambda v h^3 + (\lambda/4)h^4 \ldots$$



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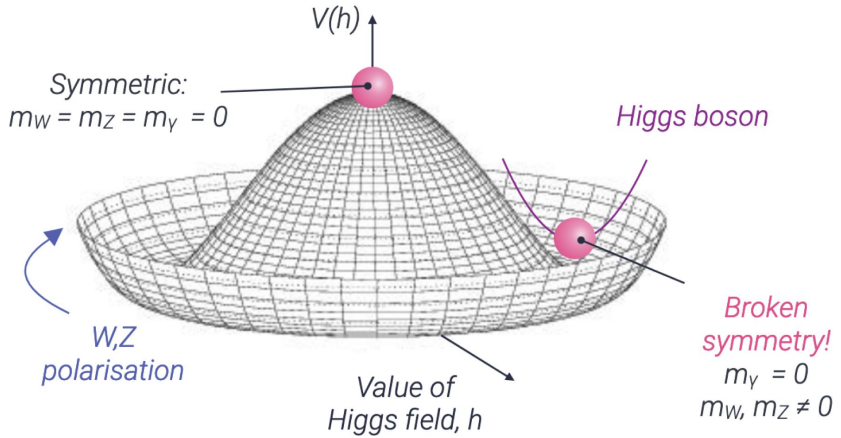

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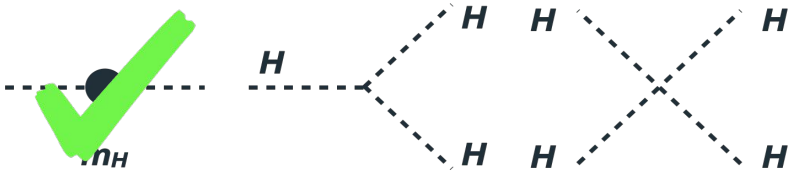

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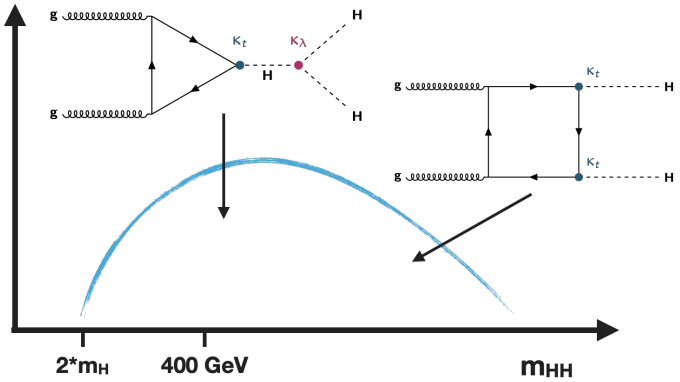
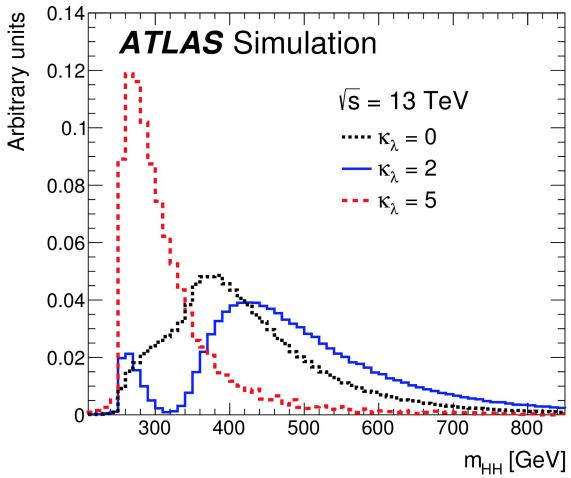
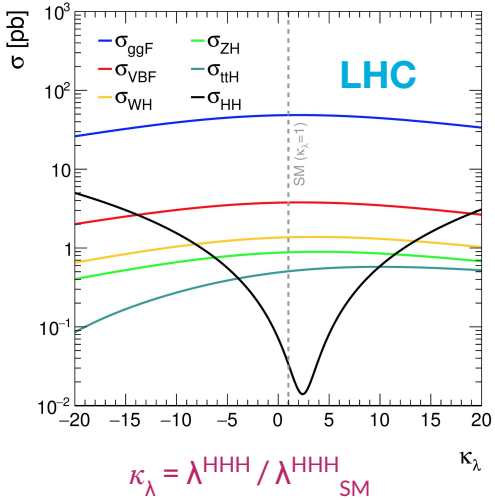
Searching for Higgs pair production

- **The HH cross section is very small in the Standard Model**
  - Two processes interfere destructively in HH production via gluon fusion: one involving a loop of top quarks, one involving the trilinear Higgs self-coupling, λ_{HHH}
- **The cross section and kinematics of Higgs pair production vary widely with the value of the Higgs self-coupling:**







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HH projections for the HL-LHC

- **Studying HH production is a major goal of the HL-LHC - it offers a direct probe of electroweak symmetry breaking**
  - We would also like to constrain the value of the Higgs self-coupling
- **We will need the full HL-LHC dataset (20x more data than we have now!) to measure the HH cross section**
  - The Yellow Report projects that we'll get to **~4.0σ** on the HH cross section with the HL-LHC dataset
  - Projections based on partial Run-2 analyses (some with dedicated studies)

Uncertainty on the value of the self-coupling: **50%**

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	

CERN Yellow Report: Higgs physics at the HL-LHC and HE-LHC

What precision do we need on the Higgs self-coupling?

- **Is 50% enough?**
  - Depends which models you would like to study
- **Motivates future colliders**
  - "**The goal for future machines beyond the HL-LHC should be to probe the Higgs potential quantitatively. This requires at least gold quality precision for the self-coupling parameter.** … achievable … at the highest energy lepton machines (ILC_{1000} or $CLIC_{3000}$) and hadron machines (FCC-hh)"

- **Bronze (100%):** sensitive to models with the largest new physics effects
- **Silver (25-50%):** can exclude a physical hypothesis with realistic deviations in the Higgs self-coupling
- **Gold (5-10%):** sensitive to a broad class of loop diagram effects… could complement measurements on new particles that could be discovered at the HL-LHC.
- **Platinum (1%):** sensitive to typical quantum corrections to the Higgs self-coupling generated by loop diagrams.

HH White Paper 2018 arXiv:1910.00012

New HL-LHC ATLAS HH projections

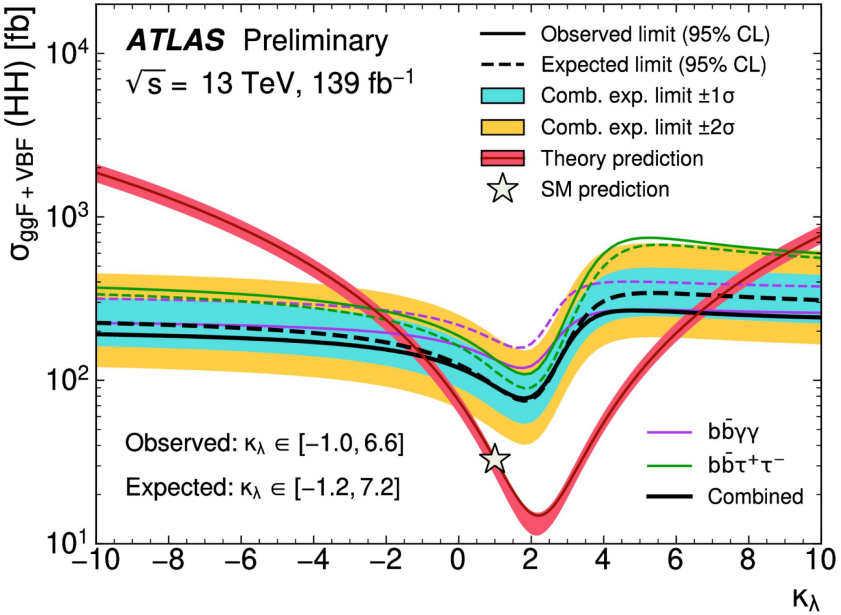
ATLAS submitted one LOI to Snowmass, summarizing the HL-LHC projections that we intend to update on the Snowmass timescale, including:

Higgs boson properties and couplings (EF01)

- Production modes: ggF, VBF, WH, ZH, $t\bar{t}H$ [13]
- Branching ratios and coupling parameters: $\gamma\gamma$, ZZ, W^+W^-, $\tau^+\tau^-$, $b\bar{b}$, $\mu^+\mu^-$, $Z\gamma$ [13, 14]
- Mass: $H \to ZZ^* \to 4\ell$ [13]
- Differential cross sections in $\gamma\gamma$ and 4ℓ final states: Higgs boson p_{T}, η, jet multiplicity, p_{T} of leading jet [15]
- Probing the CP nature of the coupling to τ leptons [16]
- **Sensitivity to differential measurements of $VH(b\bar{b})$ production**
- **$H \to c\bar{c}$ using charm tagging** [17]
- **Pair-production and self-coupling measurements: $HH \to b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, and $b\bar{b}\gamma\gamma$** [18]

New HH projections based on full Run-2 results planned for Snowmass!

New full Run-2 (139 fb^{-1}) ATLAS HH results



Compare to previous ATLAS-only HL-LHC projections (3000 fb^{-1}):

Scenario	2σ CI
Statistical uncertainties only	$-0.10 \leq \kappa_\lambda \leq 2.7 \cup 5.5 \leq \kappa_\lambda \leq 6.9$
Systematic uncertainties	$-0.4 \leq \kappa_\lambda \leq 7.3$

ATL-PHYS-PUB-2018-053

ATLAS-CONF-2021-052

What happens after HL-LHC?

- 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

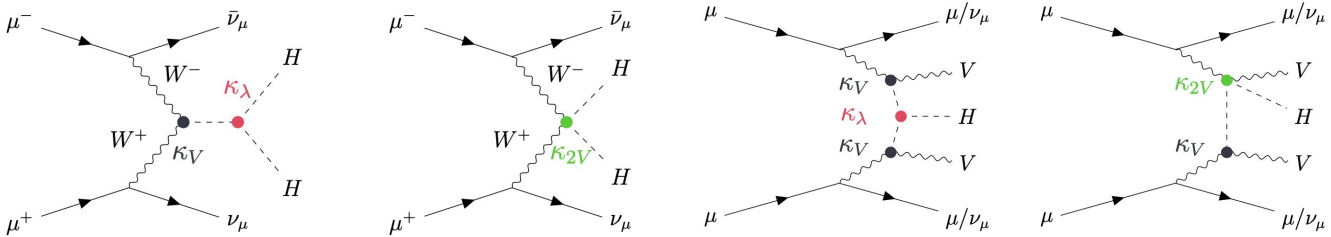
✱ arXiv:2004.03505 2.9-5.5% depending on the systematic assumptions

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.

Muon collider @ Snowmass

- **Snowmass muon collider forum recently formed (this year)**
  - Muon collider simulation efforts ongoing since original Snowmass start, mostly focused on understanding the unique backgrounds (BIB) and developing reconstruction techniques
  - Planning at least one white paper with the muon collider simulation crowd, to summarize DELPHES physics studies
- **Recently kicked off dedicated HH analysis effort, with colleagues from UCI, Princeton, Wisconsin, TRIUMF**



HH @ muon collider

- **Goal: Constraints on Higgs self-coupling at 3 benchmark energies (3,10,30 TeV)**
  - HH→bbbb, HH→bb+XX (hadronic)
  - Simulation chain Whizard→Pythia→DELPHES up and running, producing signals and backgrounds, will smear objects using knowledge from BIB studies
- **Questions we would like to answer**
  - How much do we gain by adding extra channels to the dominant bbbb?
  - How do background modeling and jet reconstruction techniques impact the results?
- **Leverage expertise from LHC HH searches**
- **Compare to previous study (25%, 6%, 2% @ 3,10,30 TeV)**

	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

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Backup