Probing anomalous Higgs couplings in $\mu^+ p$ collisions at the LHμC

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The Higgs boson

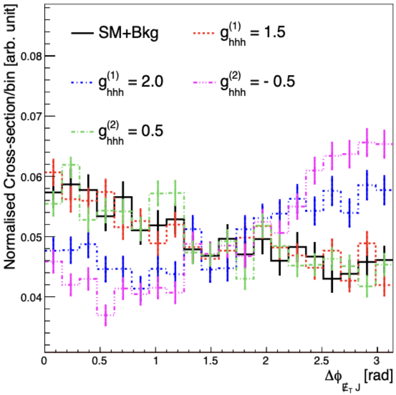
- The discovery of the Higgs boson in 2012 by the **ATLAS** and **CMS** experiments at the LHC is a landmark achievement in particle physics.
- Since then, its properties mass, spin, parity, and couplings to other particles have been studied extensively and found consistent with the SM predictions.
- Higgs pair production (*HH*) provides the **most direct probe** of the Higgs self-coupling $\kappa_\lambda \equiv \lambda_{HHH}/\lambda_{HHH}^{\mathrm{SM}}$; the quartic *HHVV* coupling is probed by $\kappa_{2V} \equiv g_{HHVV}/g_{HHVV}^{\mathrm{SM}}$ ($\kappa_\lambda = \kappa_{2V} = 1$ in the SM).
- The most stringent LHC constraints, from the ATLAS+CMS full-Run-2 combination:
  - $\mu_{HH} < 2.5$ (1.7) observed (expected) at 95% CL;
  - $\kappa_\lambda \in [-0.7, 6.1]$, $\quad \kappa_{2V} \in [0.7, 1.3]$.
- Still far from the SM point measuring deviations may reveal physics beyond the SM (BSM).

ATLAS+CMS *HH* combination, full Run 2, $\sqrt{s} = 13$ TeV. In the SM, $\sigma_{\mathrm{ggF}}^{\mathrm{SM}} \approx 31$ fb and $\sigma_{\mathrm{VBF}}^{\mathrm{SM}} \approx 1.9$ fb.

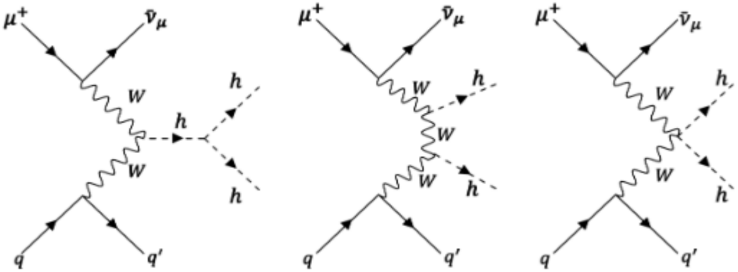
Motivation for di-Higgs production, and why lepton-proton collisions

- Di-Higgs production is the **only direct probe** of the trilinear vertex: the *hhh* coupling enters the amplitude at tree level.
- At the LHC the dominant $gg \to hh$ channel is doubly penalised a small cross section from destructive triangle/box interference, and a $4b$ final state buried in QCD multijet.
- In lepton-proton collisions the picture inverts: charged-current W-fusion $\ell p \to hh\, j\, \nu_\ell$ delivers a fully prescribed final state (two Higgs bosons, one forward jet, $E_{\mathrm{T}}^{\mathrm{miss}}$) free of pile-up.
- Kumar *et al.* demonstrated this at the FCC-he with electron beams; a **muon beam extends the reach** E_μ up to 1 TeV on the 7 TeV proton beam gives $\sqrt{s} = 5.29$ TeV.

Kumar *et al.*, PLB 764 (2017): $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j_{\mathrm{fwd}})$



Signal topology



- Three W-fusion topologies contribute; only the **first** carries the trilinear vertex $g_{hhh}^{(1)}$.
- Resonant and non-resonant amplitudes **interfere destructively** near the SM point, producing a minimum in the coupling scan.
- The topology **matches the $e^- p$ case**; the muon beam adds kinematic reach through higher $\sqrt{s}$.

Signal definition

Charged-current di-Higgs at the LHμC

$$\mu^+ p \to h\,h\,j\,\bar{\nu}_\mu, \qquad h \to b\bar{b}.$$

- CC W-boson-fusion production mode.
- $h \to b\bar{b}$ taken in the matrix element.
- Final state: $4b$ **+ forward jet +** E_T^{miss}.
- $g^{(1)}_{hhh}$ varied directly in the parameter card.

The neutrino gives genuine missing energy; the forward recoil jet tags the fusion topology; the two $h \to b\bar{b}$ give four b-quarks.

Di-Higgs proceeds through **both** charged-current and neutral-current modes the CC channel is analysed first for its larger signal strength.

Anomalous-coupling framework

- Deviations of the trilinear coupling are parametrised by a single rescaling of the SM vertex,
$$\lambda_{hhh} = g^{(1)}_{hhh}\,\lambda^{\mathrm{SM}}_{hhh}\ \ (\equiv \kappa_\lambda\,\lambda^{\mathrm{SM}}_{hhh}), \qquad g^{(1)}_{hhh} = 1 \text{ in the SM},$$
implemented in the HELv2 effective UFO model (`effdihiggs-v2`). (Our $g^{(1)}_{hhh}$ is the ATLAS κ_λ.)
- The cross section is a **quadratic form** in the coupling,
$$\sigma(g^{(1)}_{hhh}) = a + b\,g^{(1)}_{hhh} + c\,(g^{(1)}_{hhh})^2,$$
so a scan over $g^{(1)}_{hhh}$ resolves the interference term b and the pure trilinear term c separately.
- **Where the field sits today:** the most sensitive single channel, ATLAS $HH \to b\bar{b}\tau^+\tau^-$ (full Run 2), sets $\sigma(HH) < 5.9\ (3.3)\times$SM and $\kappa_\lambda \in [-3.1, 9.0]$, $\kappa_{2V} \in [-0.5, 2.7]$ still a very wide window.
- New-physics scenarios that modify the potential (extended scalar sectors, composite dynamics, first-order phase transitions) generically predict $g^{(1)}_{hhh} \neq 1$, often by tens of percent.

Collider configuration and event generation

Collider configuration

- $E_\mu = 500$ GeV and 1 TeV on $E_p = 7$ TeV
- $\sqrt{s} = 3.74$ and 5.29 TeV
- Integrated luminosity $L = 1\ \mathrm{ab}^{-1}$

Event generation

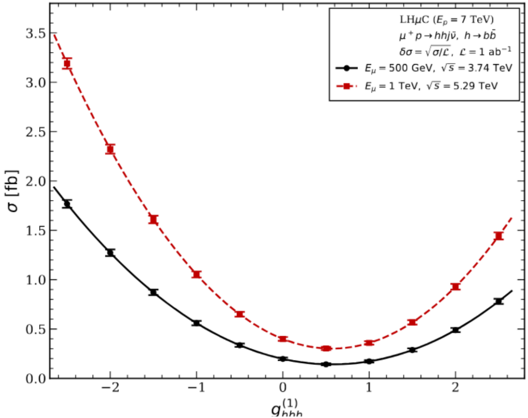
- MadGraph5_aMC v3.6.7, parton level
- HELv2 UFO model (`effdihiggs-v2`)
- CTEQ6L1 parton distribution functions

Monte Carlo production

- **2.9 million events**: signal plus seven CC backgrounds
- Generated and hosted on CERN LXPLUS/EOS
- $h \to b\bar{b}$ in the matrix element $\Rightarrow$ parton-level Higgs candidates reconstruct to 125 GeV exactly

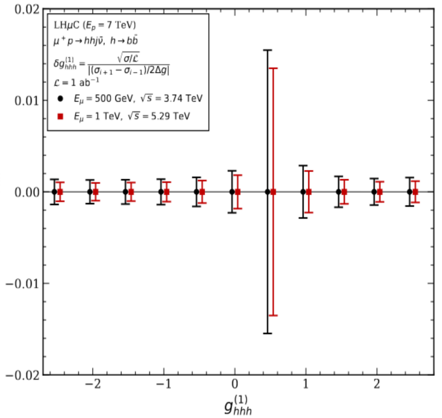
Signal topology and final-state definition established in the Motivation section.

Inclusive cross section across the coupling scan



- Thirteen-point scan of $g^{(1)}_{hhh}$ from -2.5 to $+2.5$ at both beam energies.
- SM point: $\sigma \approx 0.17$ fb at $\sqrt{s} = 3.74$ TeV and ≈ 0.33 fb at 5.29 TeV ($h \to b\bar{b}$ included).
- The minimum near $+0.5$ reflects **destructive interference** between resonant and non-resonant amplitudes.
- **Error bars are Poisson statistical**, $\delta\sigma = \sqrt{\sigma/L}$ at $L = 1\ \mathrm{ab}^{-1}$; MadGraph integration errors are *not* used as physics uncertainties.
- Doubling E_μ roughly doubles the rate across the scan.

Local sensitivity to the self-coupling



- Local sensitivity: the Poisson error propagated through the finite-difference slope,

$$\delta g^{(1)}_{hhh} = \frac{\sqrt{\sigma/L}}{|\mathrm{d}\sigma/\mathrm{d}g^{(1)}_{hhh}|}.$$

- At the SM point the precision reaches ≈ 0.003 at $\sqrt{s} = 3.74$ TeV and ≈ 0.002 at 5.29 TeV.
- The blow-up near $+0.5$ is **physical, not numerical**: where the slope vanishes at the interference minimum the rate carries no local information; differential observables such as $m(hh)$ lift the degeneracy.
- The higher-energy configuration is uniformly more sensitive.

Signal and background processes

Process	σ_{CC} [fb]	Events at 1 ab^{-1}	Generated MC
Signal $\mu^+ p \to hh\, j\, \bar{\nu}_\mu$ $(h \to b\bar{b})$	$\mathbf{3.30 \times 10^{-1}}$	**330**	300 k
$b\bar{b}b\bar{b}j$ (4b)	3.20×10^{1}	32 000	300 k
$b\bar{b}jjj$ (2b)	7.81×10^{3}	7 811 000	800 k
$t\bar{t}j$ (hadronic)	1.24×10^{0}	1 243	300 k
$t\bar{t}j$ (semi-leptonic)	4.15×10^{-1}	415	200 k
$hb\bar{b}j$ $(h \to b\bar{b})$	1.38×10^{0}	1 382	200 k
hZj $(Z, h \to b\bar{b})$	5.36×10^{-1}	536	300 k
ZZj $(Z \to b\bar{b})$	5.82×10^{-1}	582	500 k

The 2b continuum exceeds the signal by four orders of magnitude and dictates the selection design.

Normalisation of the 2b MC sample is under verification

Event selection at parton level

Object definitions

- b quarks, $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 5.0$
- Light jets, $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 3.5$
- $E_{\mathrm{T}}^{\mathrm{miss}}$ from the final-state $\bar{\nu}_{\mu}$
- Higgs candidates from the b pairing minimising the distance to $m_h = 125$ GeV

Parton level throughout; no b-tagging or detector smearing at this stage.

Sequential selection

C1 at least 4 b quarks and 1 light jet

C2 forward light jet, $\eta(j_1) < -1.0$

C3 $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV

C4 both Higgs candidates in $90 < m(b\bar{b}) < 135$ GeV

C5 di-Higgs system mass $m(4b) > 280$ GeV

Beyond this cut-based baseline, a ***DNN multivariate discriminant*** *is planned for signal/background separation.*

Discriminating observables why a cut-based analysis is not enough

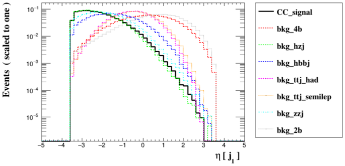


Figure 1.

$\eta(j_1)$ signal peaks near -2, the 2b continuum is central

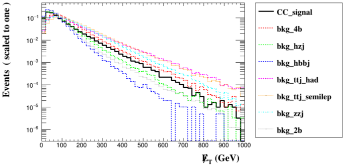


Figure 3.

$E_{\mathrm{T}}^{\mathrm{miss}}$ CC neutrino, harder than the QCD continuum

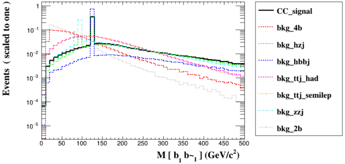


Figure 9.

$m(b\bar{b})$ parton-level Higgs peak at 125 GeV

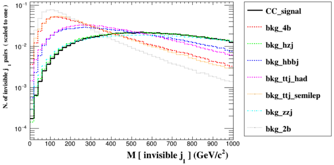


Figure 20.

$m(\bar{\nu} + j_1)$ signal pushed to high mass

With the forward jet less cleanly separated in μp than $e^- p$, a cut-based analysis will not give clean discrimination these observables become the input feature set of a neural-network classifier.

Cut-flow projection at 1 ab^{-1}

Selection	Signal	4b	$hb\bar{b}j$	hZj	ZZj	$t\bar{t}j$	2b	$S/\sqrt{S+B}$
Initial ($\sigma \times L$)	**330**	32 000	1 382	536	582	1 658	7 811 000	0.12
C1 $\geq 4b + \geq 1j$	**182**	11 200	484	214	233	0[1]	0[1]	1.6
C2 $\eta(j_1) < -1.0$	**155**	2 130	315	182	186	0	0	2.8
C3 $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV	**116**	1 700	189	127	158	0	0	2.4
C4 $90 < m(b\bar{b}) < 135$	**81**	85	23	13	13	0	0	5.5
C5 $m(4b) > 280$ GeV	**73**	**43**	**14**	**8**	**8**	**0**	**0**	**6.0**

[1] The 2b and $t\bar{t}j$ processes carry fewer than four b quarks at parton level and vanish under C1; detector-level mistags restore a residual contribution in the Delphes stage. Efficiencies estimated from the measured parton-level distributions.

$S \approx 73$, $B \approx 73$ after full selection $\Rightarrow \approx 6\sigma$ at 1 ab^{-1} in the CC channel alone

A DNN discriminant trained on the observables of the previous slide is expected to improve on this cut-based baseline.

Summary and outlook

Done

- Full coupling scan at both beam energies; cross section resolves the self-coupling to **0.002–0.003** at the SM point.
- Complete CC background suite: 2.9M events across seven processes, parton-level kinematics validated.
- Cut-based selection defined and motivated by four discriminating observables; projected $\approx 6\sigma$ at 1 ab^{-1}.

Next steps

Analysis pipeline

Definitive cut-flow yields from the LXPLUS analysis and working-point optimisation.

DNN-based signal/background separation, benchmarked against the cut-based baseline.

Delphes detector-level study, NC and photo-production modes, and the paper draft.

References

Predecessor & channel

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2. ATLAS Collaboration, "Search for non-resonant *HH* production in the $b\bar{b}\tau^+\tau^-$ final state," full Run 2, HIGP-2024-37 (2026).
3. ATLAS & CMS Collaborations, "Combination of *HH* searches," full Run 2, $\sqrt{s} = 13$ TeV.

Effective couplings

4. HELv2 effective Lagrangian / `effdihiggs-v2` UFO model.
5. Dimension-6 SMEFT parametrisation of the *HHH*, *HVV*, *HHVV* vertices.

Simulation tools

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Thank you

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