Probing Triple Higgs Coupling at the future lepton collider

Presented by

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High energy probes of Higgs self-coupling via W boson fusion at future lepton colliders

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We investigate the sensitivity to the Higgs self-coupling through W boson fusion di-Higgs production at CLIC with a center-of-mass energy of $\sqrt{s} = 3$ TeV. We study the interplay between the Higgs self-coupling modifier (κ_λ) and Higgs-gauge boson coupling modifiers (κ_V and κ_{2V}) within the κ framework. To enhance the separation between signal and background, we develop a graph neural network (GNN) based classifier that achieves a signal significance of $\mathscr{Z} \approx 20\ \sigma$ at 5 ab^{-1}, substantially exceeding projected HL-LHC sensitivity. Our results demonstrate that high-energy lepton colliders, combined with graph-based machine learning, provide excellent sensitivity to the Higgs self-coupling and offer a powerful probe of new physics in the electroweak sector, potentially disentangling underlying SMEFT-like and HEFT-like structures.

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(Accepted in PRD)

Higgs self-coupling:

- SM predicts that Higgs field interacts with itself, and the strength of this effect.
- Lack of this self-interaction, or any deviation from SM would indicate presence of new physics.

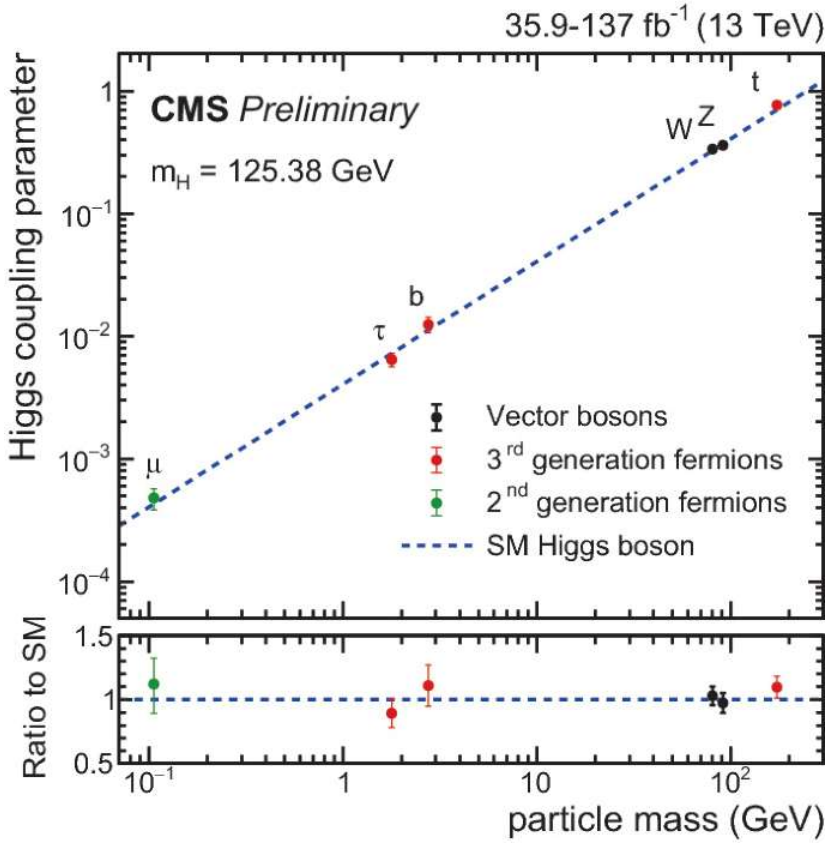

Fig: Higgs to other SM articles interaction strength

Higgs self-coupling:

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The SM lagrangian determines how Higgs couples to other particles/fields:

$$\pounds = \frac{m_t}{v}\bar{t}tH + \frac{m_H^2}{2v}H^3 + \frac{m_H^2}{8v^2}H^4 + \delta_V\frac{2m_V^2}{v}V_\mu V^\mu H + \frac{\delta_V m_V^2}{v^2}V_\mu V^\mu H^2 + \cdots.$$

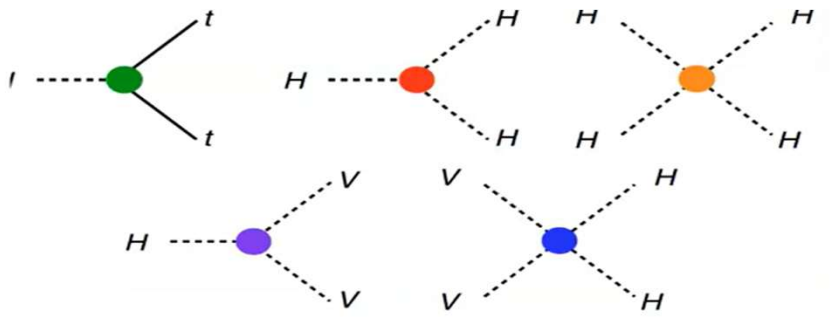


Fig: Higgs-other SM couplings

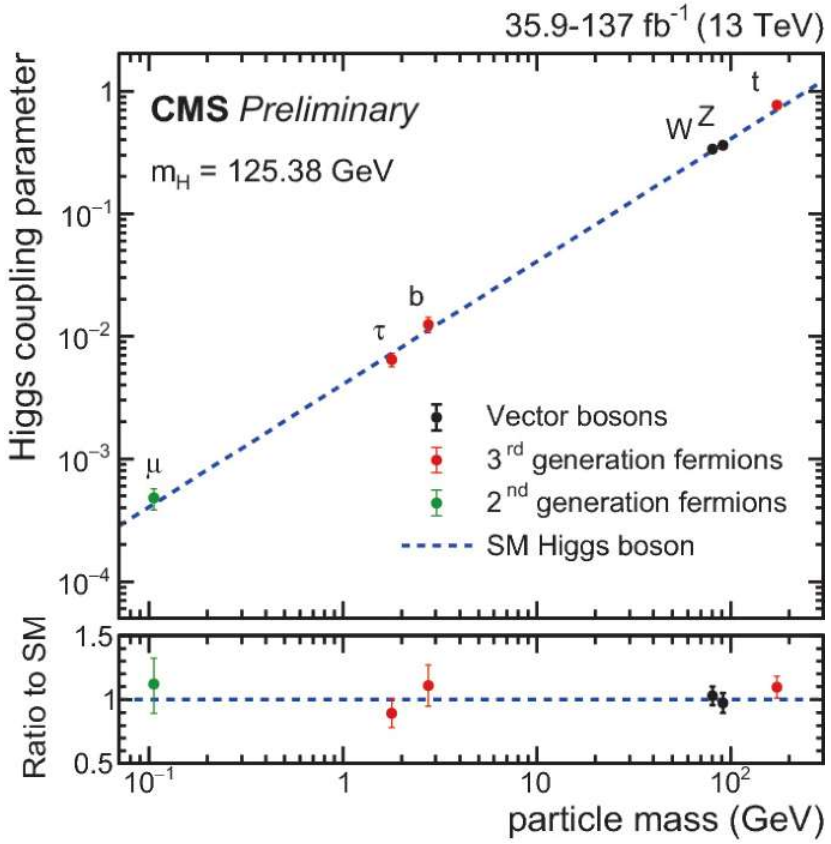
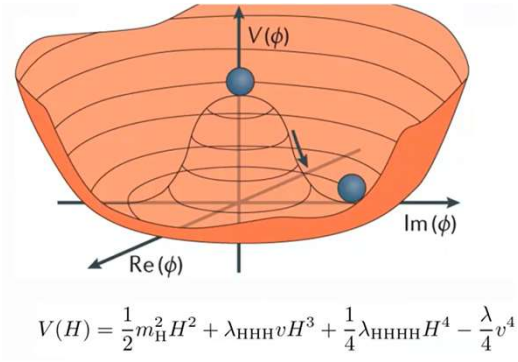


Fig: Higgs to other SM articles interaction strength

In SM, $\lambda_{HHH} = \lambda_{HHHH} = \lambda = \frac{m_H^2}{2v^2} \approx 0.13$

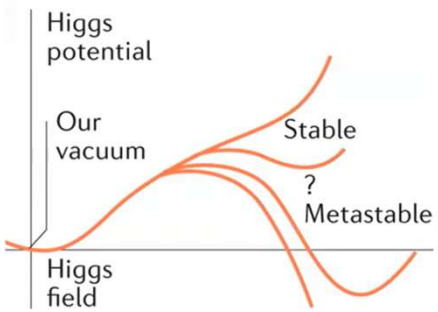
Higgs self-coupling:

In SM:



$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_{HHH} v H^3 + \frac{1}{4}\lambda_{HHHH} H^4 - \frac{\lambda}{4}v^4$$

BSM:



- Measuring λ is a **direct test of EWSB** mechanism of the SM.
- The shape of the Higgs potential has direct consequences for the (meta)stability of the EW vacuum.
- And the shape depends on the value of the self coupling λ

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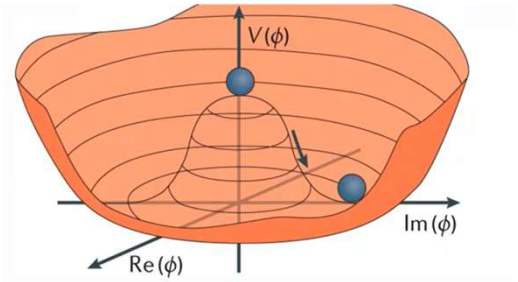

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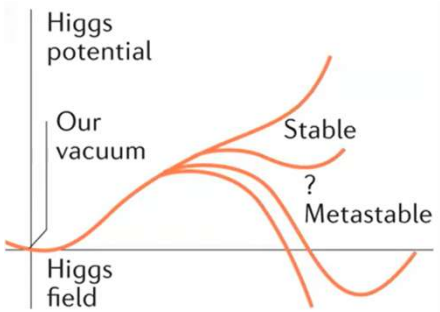

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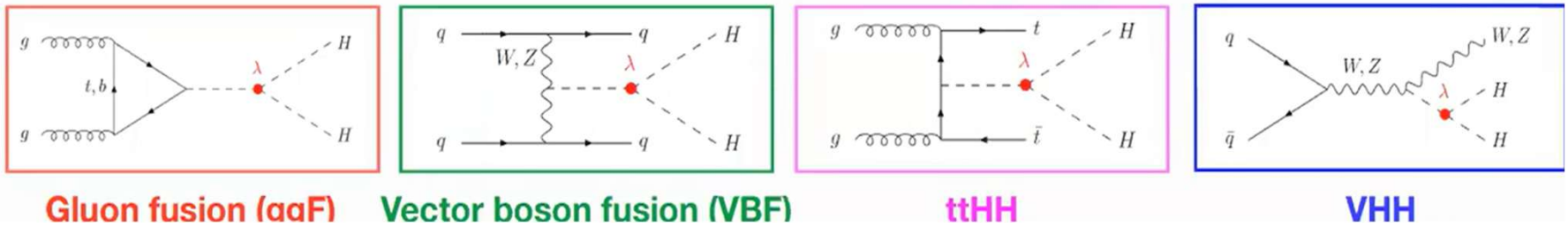
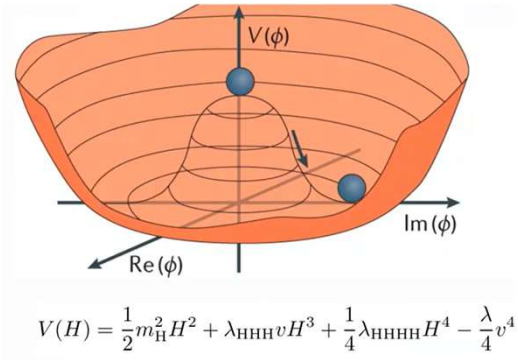
Di-Higgs production modes at LHC:



Gluon fusion (ggF) | Vector boson fusion (VBF) | ttHH | VHH

Higgs self-coupling:

In SM:



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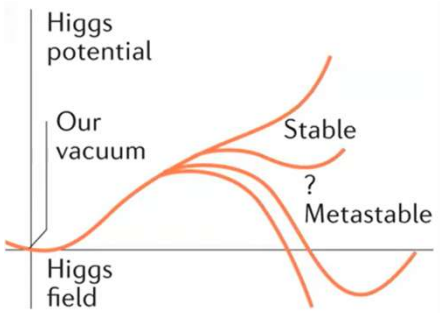


We define:

$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}},$$

In SM, $\kappa_\lambda = 1$

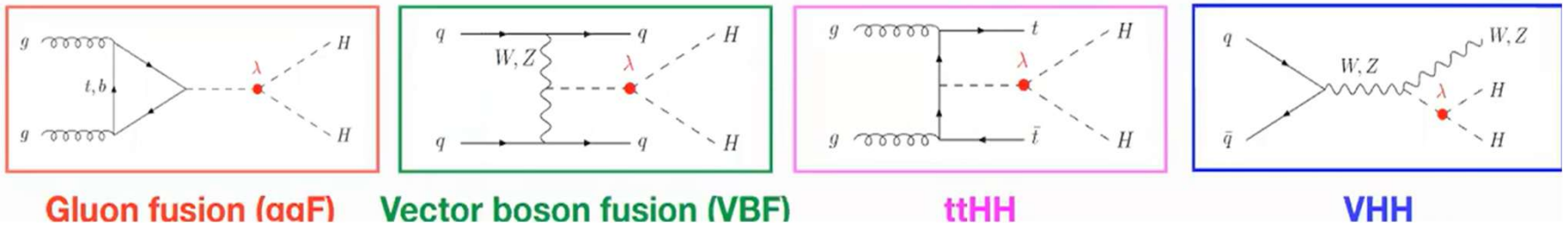
- ❑Measuring λ is a **direct test of EWSB** mechanism of the SM.
- ❑The shape of the Higgs potential has direct consequences for the (meta)stability of the EW vacuum.
- ❑And the shape depends on the value of the self coupling λ

Current limit on κ_λ: (Experiment)

LHC13 : [-1.35, 6.37] at 95% CL
(A. Hayrapetyan et al. (CMS),

HL-LHC : [0.3, 1.9]
(ATL-PHYS-PUB-2022-053)

Di-Higgs production modes at LHC:



Gluon fusion (ggF) | Vector boson fusion (VBF) | ttHH | VHH

Probing Higgs self-coupling:

We choose $e^+ e^-$ collider at $\sqrt{s} = 3$ TeV:

- ❖ Clean background
- ❖ Large VBF cross section

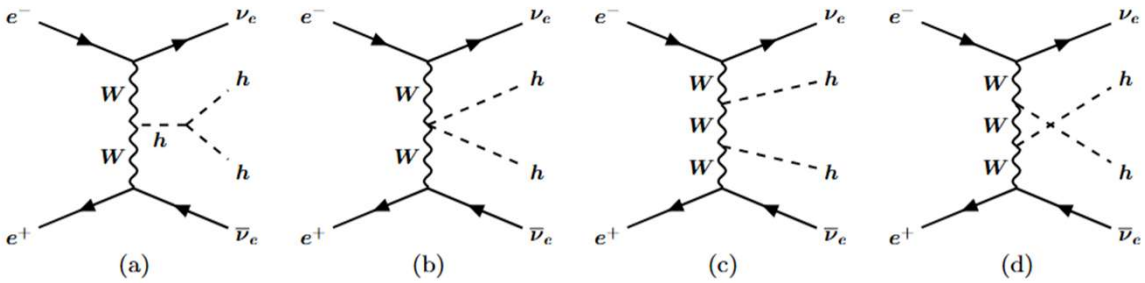


FIG. 2. Feynman diagrams contributing to di-Higgs production via WBF.

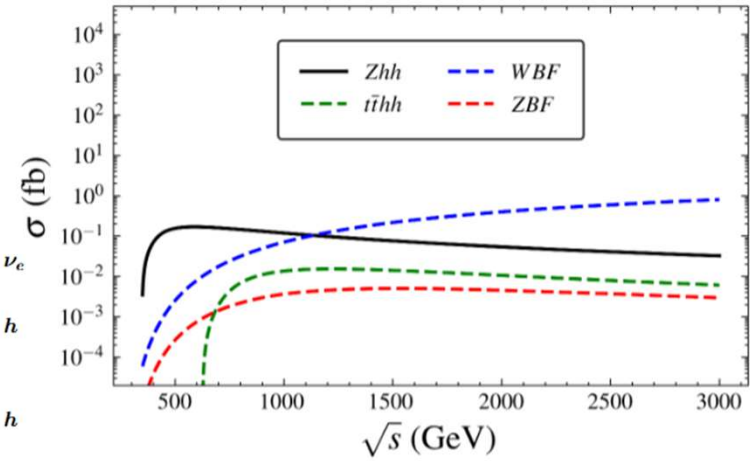


FIG1 : Di-Higgs production cross-section for different channels.

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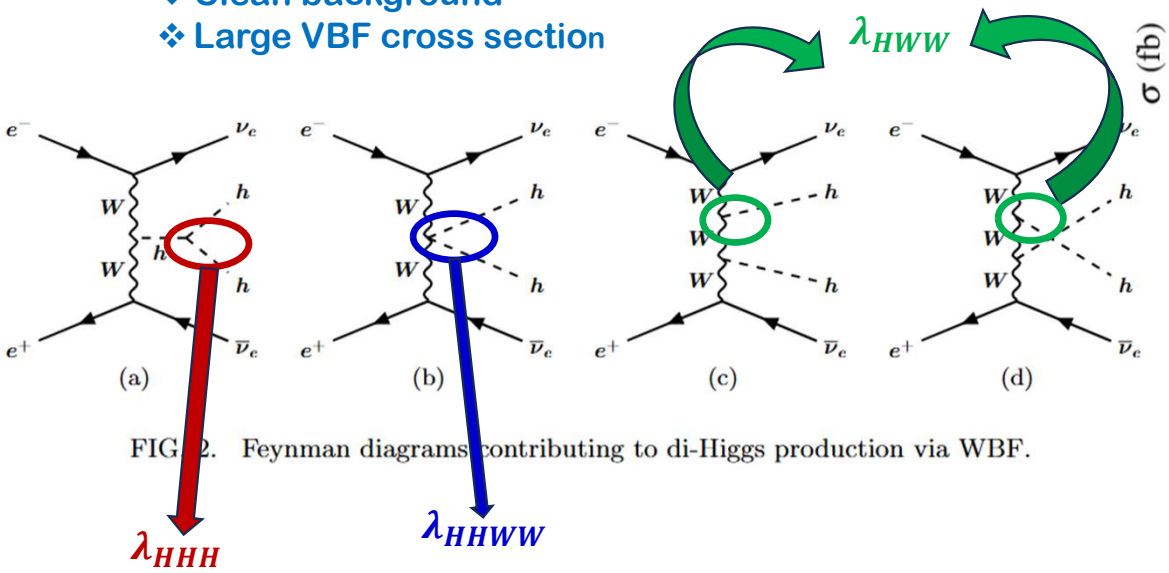

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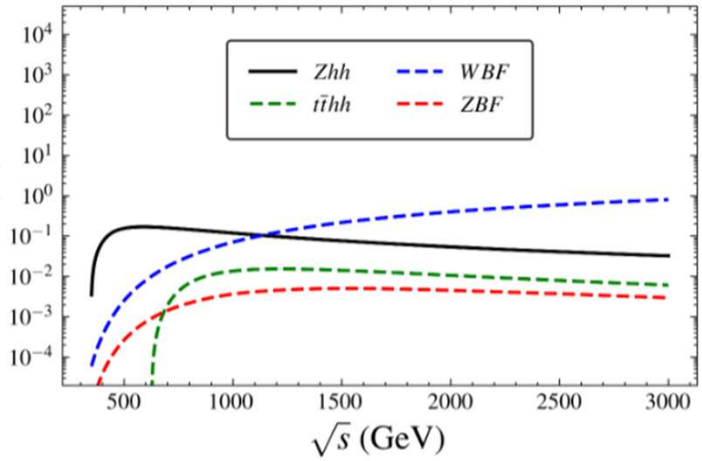

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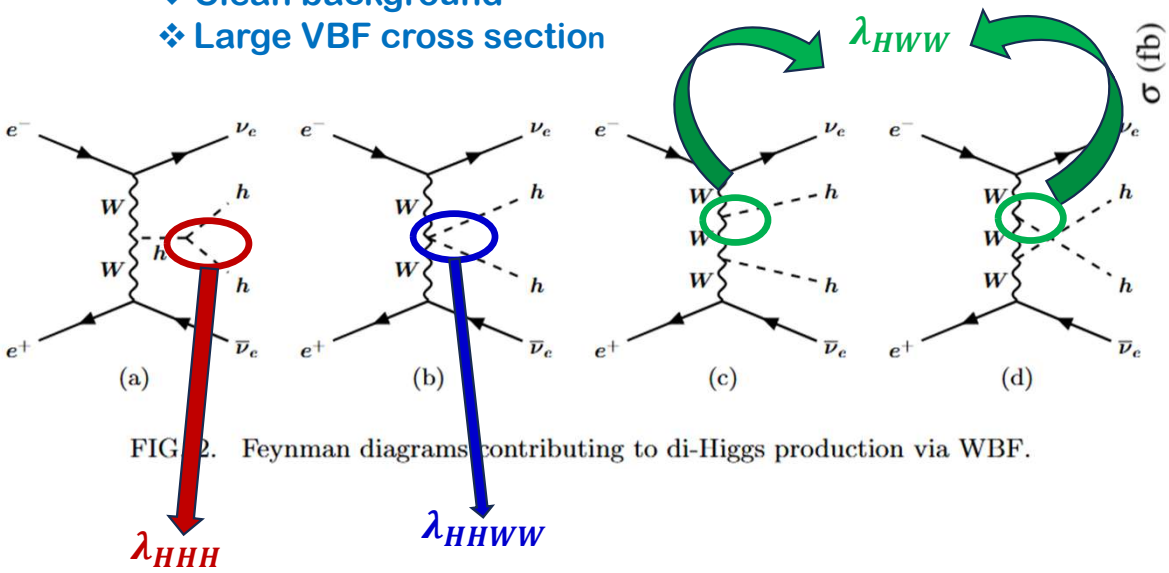

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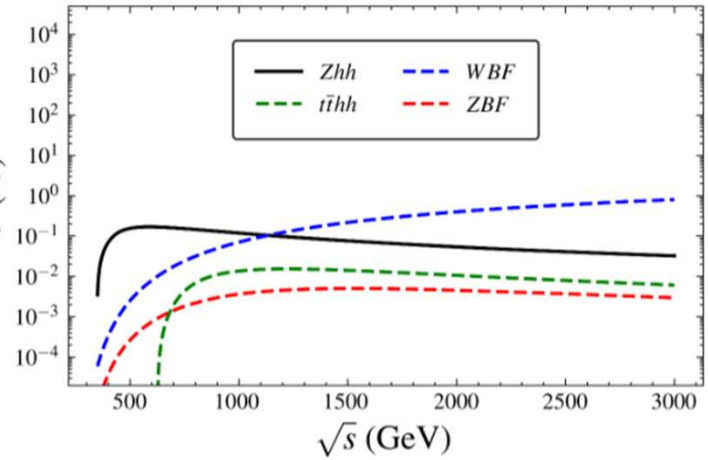

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Pre-selection cuts

Jet multiplicity:	$N_j \geq 4$,
b-tag multiplicity:	$N_b \geq 2$,
Missing energy:	$E_T \geq 20$ GeV,
Lepton veto:	$N_\ell = 0 \quad (p_T^\ell > 10$ GeV),
Higgs mass window:	$\lvert m_{jj} - m_h \rvert \leq 25$ GeV, $\quad m_h = 125$ GeV.

Signal: $4b + \not{E}$, **Channel**: $e^- e^+ \to hh\nu\bar{\nu}$

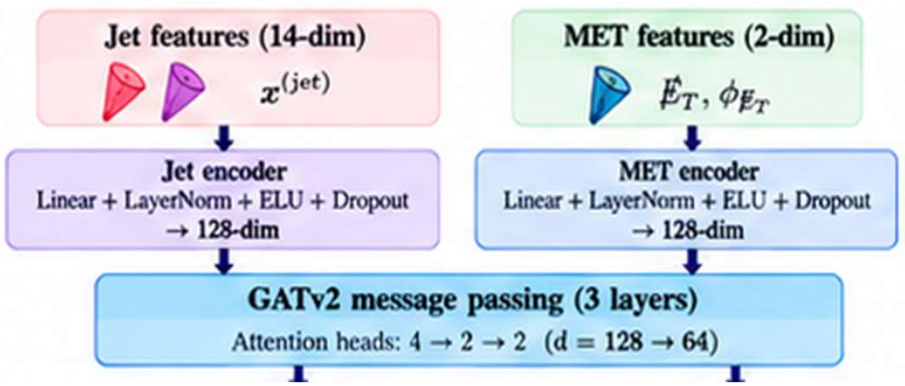
Main backgrounds:

- ➢ Single Higgs associated production $(hb\bar{b}\not{E})$
- ➢ multi-b production $(4b\not{E})$
- ➢ top-quark processes $(t\bar{t}X)$

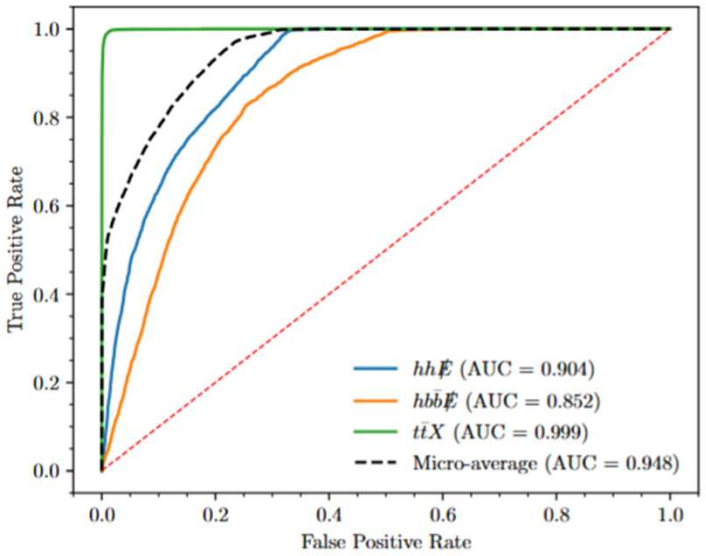
Makes $(4b\not{E})$ background contribution negligible.
Still $t\bar{t}X$ processes are there.

We use GNN based multivariate to discriminate signal-background.

GNN Architecture:



GNN performance:



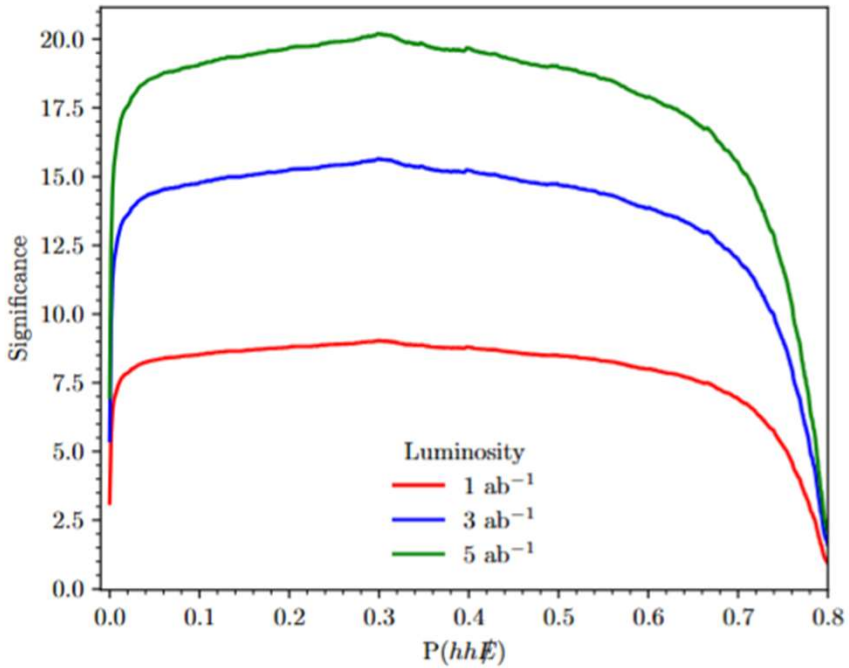


Fig: Significance at different luminosities

Key observations:

- ❖ **Near perfect separation of $t\bar{t}X$**
- ❖ **Overall micro-avg AUC of 0.95 indicates excellent discriminating power.**

$$\mathscr{Z} = \sqrt{2\left[(S+B)\ln\left(1+\frac{S}{B}\right) - S\right]},$$

Probing Higgs self-coupling:

SENSITIVITY OF COUPLINGS:

- Di-Higgs production may affect Higgs-Gauge coupling , We define:

$$\kappa_V = \frac{\lambda_{HVV}}{\lambda_{HVV}^{SM}}; \quad \kappa_{2V} = \frac{\lambda_{HHVV}}{\lambda_{HHVV}^{SM}}$$

- We focus on dependence of di-Higgs production on κ_λ and κ_{2V} , with κ_V treated under two representative scenarios:
  - **Case 1 : $\kappa_V = 1$, with κ_λ and κ_{2V} vary independently. (HEFT like)**
  - **Case 2 : $\kappa_V = \kappa_{2V}$, with κ_λ and κ_{2V} are free parameters. (SMEFT like)**

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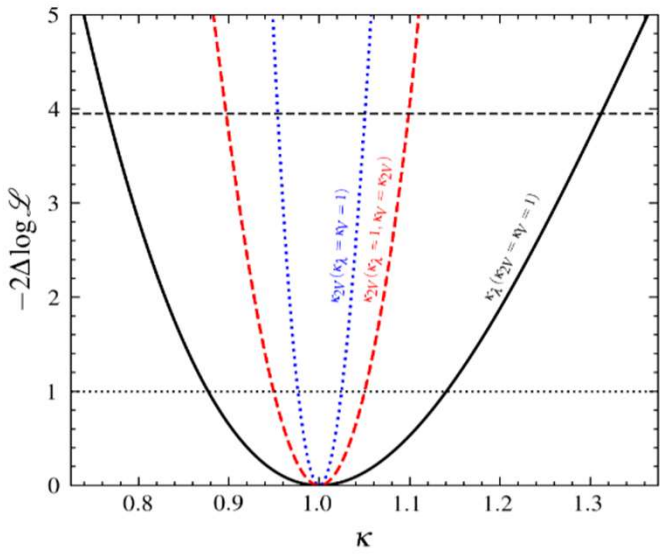


Fig: 1D likelihood scans and 95% CL.

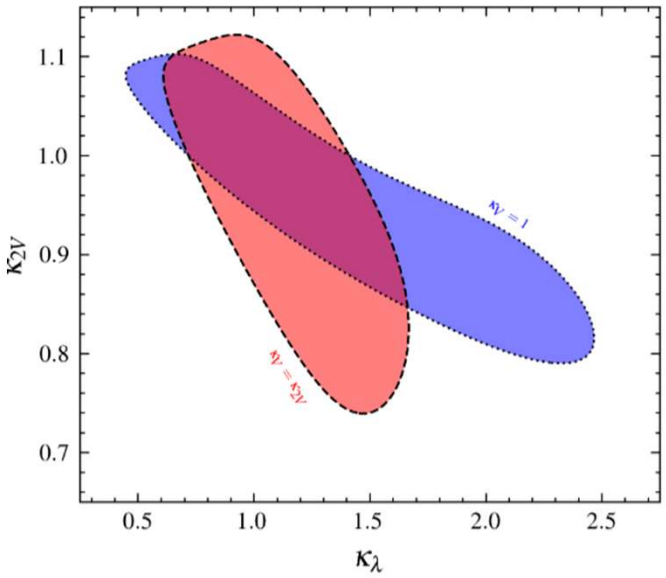


Fig: 2D sensitivity contours (95% CL)

Results:

$$\kappa_\lambda = \begin{cases} [0.88,\ 1.14] & (68\%\ \text{C.L.}) \\ [0.76,\ 1.31] & (95\%\ \text{C.L.}) \end{cases}.$$

$$\kappa_{2V} = \begin{cases} [0.98,\ 1.02] & (68\%\ \text{C.L.}) \\ [0.95,\ 1.05] & (95\%\ \text{C.L.}) \end{cases},$$

Case1

$$\kappa_{2V} = \begin{cases} [0.95,\ 1.05] & (68\%\ \text{C.L.}) \\ [0.90,\ 1.10] & (95\%\ \text{C.L.}) \end{cases}.$$

Case2

Better than predictions of HL-LHC!!!

THANK YOU

BACK-UP

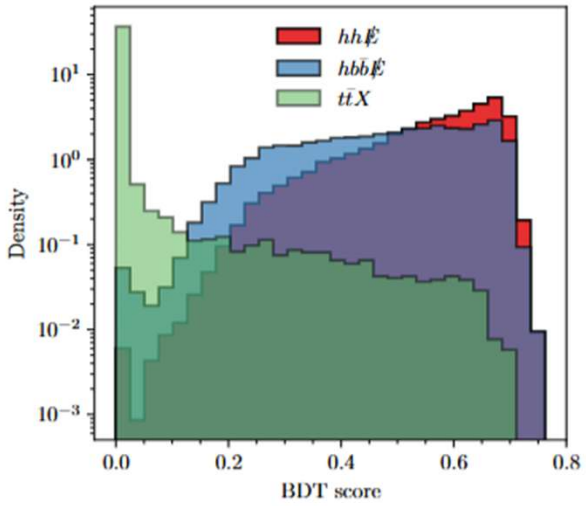
LHC Limits on κ_V, κ_{2V}:

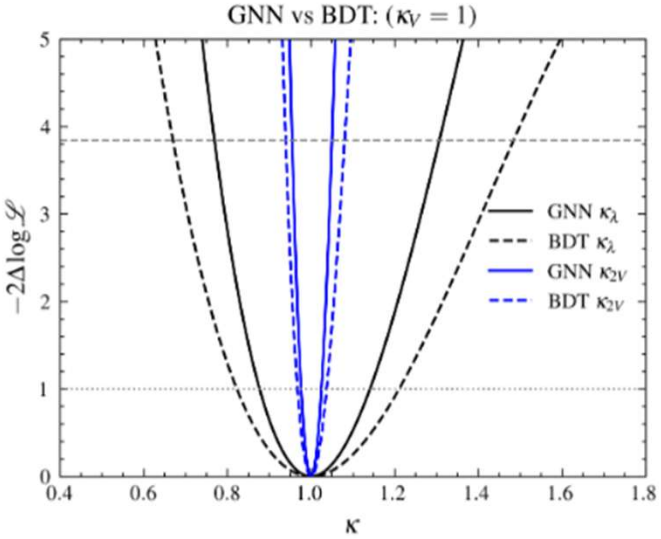
$\kappa_{2V} = [0.6, 1.5]$, LHC13 (Phys. Rev. Lett.133, 101801 (2024))
$= [0.8, 1.2]$, HL-LHC (ATL-PHYS-PUB-2022-053)

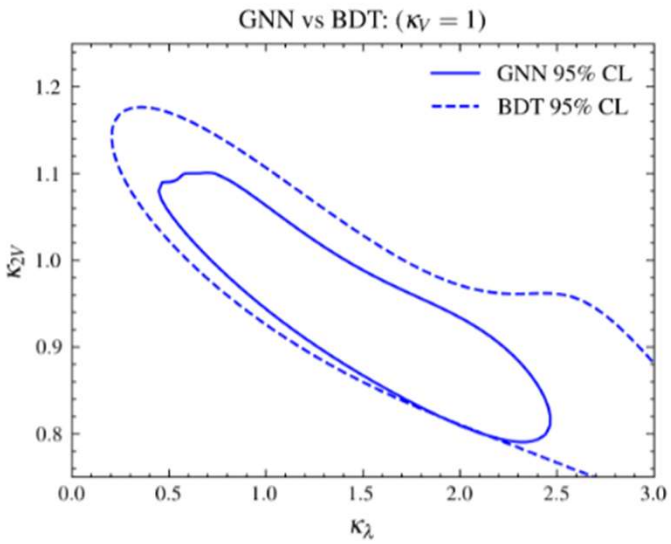
$\kappa_V = 1.023 \pm 0.026$, LHC13 (IJMP A 2026 41:22)

BACK-UP

BDT vs GNN:







$$\kappa_\lambda = \begin{cases} \text{GNN} & \begin{cases} [0.88,\ 1.14] & (68\%\ \text{C.L.}) \\ [0.76,\ 1.31] & (95\%\ \text{C.L.}) \end{cases} \\ \text{BDT} & \begin{cases} [0.82,\ 1.21] & (68\%\ \text{C.L.}) \\ [0.67,\ 1.48] & (95\%\ \text{C.L.}) \end{cases} \end{cases}.$$

SMEFT vs HEFT: Two EFT descriptions of electroweak symmetry breaking

The key distinction is how the Higgs boson and electroweak Goldstone modes are organised.

SMEFT | Linear realisation

Higgs belongs to an $SU(2)_L$ doublet:

$$H(x) = \begin{pmatrix} \phi^+(x) \\ \frac{v + h(x) + i\phi^0(x)}{\sqrt{2}} \end{pmatrix}$$

Expand around the SM with operators of increasing dimension:

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d>4} \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Example dimension-6 operators

$\mathcal{O}H = (H\dagger H)^3$
$\mathcal{O}H\Box = (H\dagger H)\Box(H\dagger H)$
$\mathcal{O}HWB = (H\dagger\tau^I H)\, W^I\mu\nu\, B\mu\nu$

Best suited when the observed Higgs is part of a linear doublet and the new-physics scale Λ is above the electroweak scale.

HEFT | Nonlinear realisation

Goldstones and the physical Higgs are separate:

$$U(x) = \exp\left(\frac{i\tau^a \pi^a(x)}{v}\right), \qquad \text{h is singlet}$$

A generic leading-order bosonic structure:

$$\mathcal{L}_{\text{HEFT}} \supset \frac{v^2}{4} F_C(h)\, \text{Tr}\left[(D_\mu U)^\dagger D^\mu U\right] + \frac{1}{2}(\partial_\mu h)^2 - V(h) + \cdots$$

Example HEFT interactions

$\mathcal{O}WW = (h/v)\, W^a\mu\nu W^a\mu\nu$
$\mathcal{O}BB = (h/v)\, B\mu\nu B\mu\nu$

More general: Higgs couplings need not follow the correlations imposed by embedding h in a doublet.

SMEFT = linear Higgs-doublet expansion • HEFT = nonlinear Goldstone matrix + independent singlet h

SMEFT vs HEFT: Two EFT descriptions of electroweak symmetry breaking

SMEFT: $C_{HW}(H^+H)W^I_{\mu\nu}W^{\mu\nu\, I}$

1. $\mathcal{L} \supset \frac{2C_{HW}}{v} h W^+_{\mu\nu} W^{\mu\nu -} + \frac{C_{HW}}{v^2} h^2 W^+_{\mu\nu} W^{\mu\nu -}$

$\delta_V = 2v\delta_{2V}$

HEFT: $W^I_{\mu\nu} W^{\mu\nu I} \{ a_w \frac{h}{v} + b_w \frac{h^2}{v^2} + \ldots . \}$

$\delta_V \neq 2v\delta_{2V}$

2. $\mathcal{L} \supset \frac{2a_w}{v} h W^+_{\mu\nu} W^{\mu\nu -} + \frac{2b_w}{v^2} h^2 W^+_{\mu\nu} W^{\mu\nu -}$

How it enters in κ_V and κ_{2V}:

3. $\mathcal{L}_{hWW} = \kappa_V \frac{2m_W^2}{v} h W^+_\mu W^{\mu -} + \kappa_{2V} \frac{m_W^2}{v^2} h^2 W^+_\mu W^{\mu -}.$

(1) , (3) motivates $\kappa_V = \kappa_{2V}$

(1) , (2) motivates $\kappa_V \neq \kappa_{2V}$