Precise probing of the inert Higgs-doublet model at the LHC

Anupam Ghosh

Physical Research Laboratory, Ahmedabad

IISER Mohali

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In collaboration with: Partha Konar and Satyajit Seth

Outline

- Introduction
- Constraints
- Effects of NLO-QCD correction
- Collider search with MVA
- Conclusion

Introduction

Inert Higgs-doublet model ⇒ viable Higgs portal scalar dark matter candidate, together with other heavier scalars of mass 100 GeV or more.

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v+h+iG) \end{pmatrix}, \Phi_2 = \begin{pmatrix} H^+ \\ \frac{H+i\,A}{\sqrt{2}} \end{pmatrix}, \mathbb{Z}_2 \text{ Symmetry}$$

- No interaction with SM fermions. The lightest neutral scalar is DM

$$\begin{aligned} V_{IDM} =& \mu_1^2\Phi_1^\dagger\Phi_1 + \mu_2^2\Phi_2^\dagger\Phi_2 + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ &+ \lambda_4(\Phi_2^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \frac{\lambda_5}{2}\,[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2] \end{aligned}$$

$$M_{H^\pm}^2 = \mu_2^2 + \frac{1}{2}\lambda_3 v^2,\ M_A^2 = \mu_2^2 + \frac{1}{2}\lambda_c v^2,\ M_H^2 = \mu_2^2 + \frac{1}{2}\lambda_L v^2$$

$$\text{Where } \lambda_{L/c} = (\lambda_3 + \lambda_4 \pm \lambda_5)$$

- This model has five parameters
- H is DM in our study, but one can choose A by $\lambda_5 \rightarrow -\lambda_5$

Constraints

- bounded from below

$$\lambda_1 > 0,\ \lambda_2 > 0,\ \lambda_3 + 2\sqrt{\lambda_1\lambda_2} > 0,\ \lambda_3 + \lambda_4 + \lambda_5 + 2\sqrt{\lambda_1\lambda_2} > 0$$

- $h \to \gamma\gamma$ signal strength constraint

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)}{\sigma(pp \to h \to \gamma\gamma)_{SM}} = \frac{BR(h \to \gamma\gamma)_{IDM}}{BR(h \to \gamma\gamma)_{SM}} = 1.10^{+0.10}_{-0.09}$$

- Higgs invisible decay branching ratio

$$\Gamma_{h\to HH} = \frac{\lambda_L^2 v^2}{64\pi m_h}\sqrt{1 - \frac{4m_H^2}{m_h^2}}\,.$$

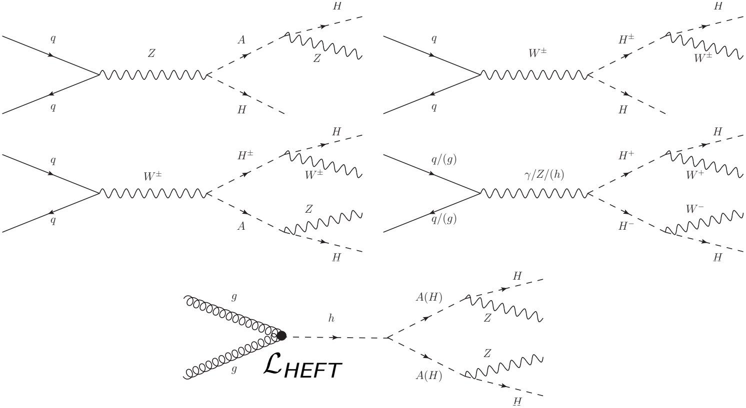
$$\Gamma_{h\to HH}/(\Gamma_{SM} + \Gamma_{h\to HH}) \leq 0.11$$

- Correct relic density ($\Omega_{DM}h^2 = 0.120 \pm 0.001$)

- Hierarchical mass region: $M_{DM} < 80$ GeV, $\Delta M \sim \mathcal{O}(100)$ GeV
- Degenerate region: $M_{DM} \sim 550$ GeV, $\Delta M \sim \mathcal{O}(1)$ GeV

Collider search

- $pp \to AH^{\pm} \to (ZH)(W^{\pm}H) \to 2J_V + \not{E}_T$
- $pp \to H^{+}H^{-} \to (W^{+}H)(W^{-}H) \to 2J_V + \not{E}_T$
- $pp \to AA \to (ZH)(ZH) \to 2J_V + \not{E}_T$
- $pp \to H^{\pm}H \to (W^{\pm}H)H \to 1J_V + \not{E}_T$
- $pp \to AH \to (ZH)H \to 1J_V + \not{E}_T$



- NLO-QCD correction of all these processes
- di-fatjet+$\not{E}_T$ → MVA (BDT-algorithm) with jet substructure variables

$$\mathcal{L}_{HEFT} = -\frac{1}{4} C_{eff} \; h \; G^{a}_{\mu\nu} G^{a\mu\nu}$$

$$\text{Where, } C_{eff} = \frac{\alpha_s}{3\pi v} \left(1 + \frac{11}{4} \frac{\alpha_s}{\pi}\right)$$

$$\mathcal{L} = \mathcal{L}_{SM} + (\mathcal{D}_\mu \Phi_2)^\dagger (\mathcal{D}^\mu \Phi_2) + V_{IDM} + \mathcal{L}_{HEFT}$$

- one order α_S correction of the full Lagrangian $\mathcal{L}$

Input Parameters	BP1	BP2	BP3	BP4	BP5	BP6	BP7
$M_{H^\pm}$(GeV)	255.3	304.8	350.3	395.8	446.9	503.3	551.8
M_A(GeV)	253.9	302.9	347.4	395.1	442.4	500.7	549.63

Table: $M_H = 53.71$ GeV, $\lambda_L = 5.4 \times 10^{-3}$.

Effects of NLO-QCD correction

- $\sigma(pp \to AH, H^{\pm}H)$: K factor $= 1.33 - 1.37$
- $\sigma(pp \to H^{\pm}A)$: K factor $= 1.35 - 1.39$
- $\sigma(pp \to H^{+}H^{-})$: K factor $= 1.38 - 1.56$
- $\sigma(pp \to AA)$: K factor $= 1.7 - 1.92$

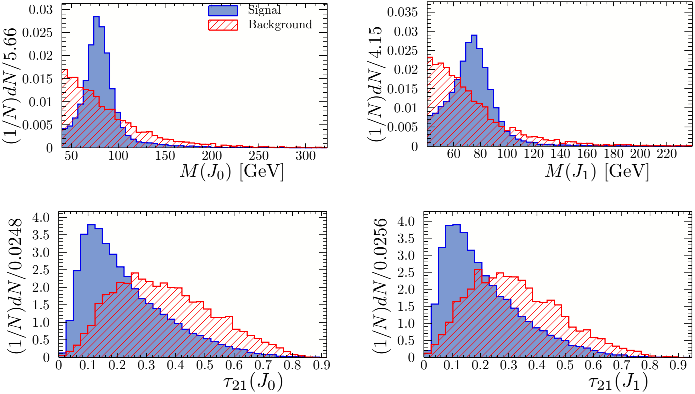
BP	Pre-selection cuts + $\not{E}_T > 200$ GeV, b-veto, 65 $GeV < M(J_0), M(J_1) < 105$ GeV, $\tau_{21}(J_0), \tau_{21}(J_1) < 0.35$					
	$H^{\pm}A$			$H^{+}H^{-}$		
	N_S^{NLO}	$N_S^{LO\times K}$	rel change%	N_S^{NLO}	$N_S^{LO\times K}$	rel change%
BP1	$168.2^{+2.8}_{-2.5}$	$119.5^{+3.3}_{-3.2}$	40.75%	$121.2^{+4.6}_{-4.6}$	$82.7^{+5.0}_{-4.1}$	46.55%
BP2	$190.7^{+3.1}_{-4.1}$	$155.6^{+5.7}_{-5.5}$	22.56%	$150.4^{+9.2}_{-8.0}$	$111.1^{+9.8}_{-7.7}$	35.37%
BP3	$202.8^{+4.2}_{-4.2}$	$162.8^{+7.0}_{-6.5}$	24.57%	$153.8^{+11.8}_{-9.8}$	$122.5^{+13.8}_{-10.9}$	25.55%

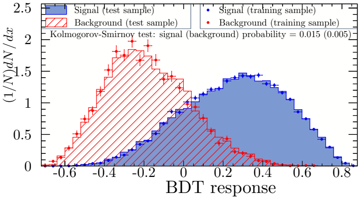
di-fatjet+ $\not{E}_T$ signal (MVA)

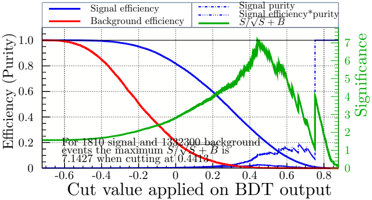
- Delphes tower objects are used to form the fat-jets
- Cambridge-Achen (CA) algorithm is applied to clustered fat-jets with radius parameter R $= 0.8$
- minimum P_T for each fat-jet 180 GeV, $\not{E}_T > 100\ GeV$
- veto the events: $P_T(l) > 10\ GeV$ and $|\eta(l)| < 2.4$
- To minimize the effect of jet mismeasurements: $\Delta\phi(J_i, \not{E}_T) > 0.2$
- $M_{J_0}, M_{J_1} > 40$ GeV
- b-veto

Backgrounds

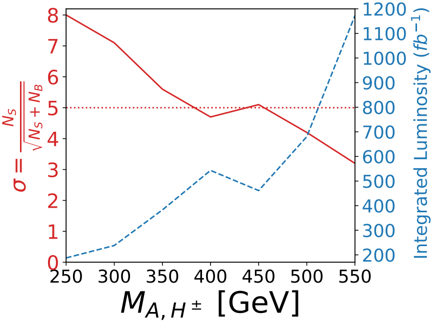
- Z+jets: $\Rightarrow \mathcal{O}(1000\text{ pb})$ while signal $\mathcal{O}(10\text{ fb})$
- W+jets:
- VV+jets: diboson processes: WZ, WW, ZZ
- Single t production
- tt+jets


Signal
Background
$(1/N)dN/5.66$
0 0.005 0.01 0.015 0.02 0.025 0.03
50 100 150 200 250 300
$M(J_0)$ [GeV]
$(1/N)dN/4.15$
0 0.005 0.01 0.015 0.02 0.025 0.03 0.035
60 80 100 120 140 160 180 200 220
$M(J_1)$ [GeV]
$(1/N)dN/0.0248$
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
$\tau_{21}(J_0)$
$(1/N)dN/0.0256$
0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
$\tau_{21}(J_1)$





For 1810 signal and 1332300 background events the maximum $S/\sqrt{S+B}$ is 7.1427 when cutting at 0.4413



Conclusions

- promising channel with NLO QCD precision
- QCD correction is significant for encrypting the correct search strategy at the LHC
- Notable improvement on scale uncertainties is achieved due to the inclusion of NLO corrections
- We take parton shower effect and its practicality at the low transverse momentum region
- Hadronically decayed heavy scalars are highly collimated in this signal region and therefore large-radius fatjets come naturally
- We find jet-substructure observables $M_{J_{0,1}}$ and $\tau_{21}(J_{0,1})$ are excellent discriminators
- 5σ for different benchmark points nearly up to 350 GeV of heavy scalar mass in the hierarchical mass region
- Heavy BSM scalar mass falling in the range of 250-550 GeV can be excluded with 1200 fb^{-1} integrated luminosity at the 14 TeV LHC

Thank You for your attention !

Backups

Model	N_S^{bc}	BDT_{opt}	N_S	N_B	σ
BP1	2129	0.6927	357	1650	8.0
BP2	1810	0.4413	474	3930	7.1
BP3	1511	0.6003	390	4516	5.6
BP4	1236	0.5270	207	1738	4.7
BP5	1003	0.6499	178	1041	5.1
BP6	800	0.6098	102	485	4.2
BP7	654	0.6462	97	820	3.2
N_{SM}	1332300				

Var	$\tau_{21}(J_0)$	$M(J_0)$	$\tau_{21}(J_1)$	$M(J_1)$	$\Delta R(J_0, J_1)$	$\sqrt{\hat{S}_{min}}$	$\Delta\phi(J_1, \not{E}_T)$	$\not{E}_T$	F
Sep	16.58	15.71	13.71	11.57	11.27	9.039	3.011	2.451	

Pruned jet mass

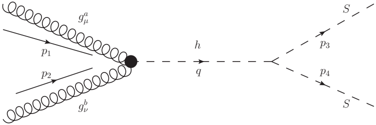
Pruned jet mass

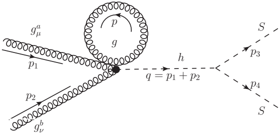
- two variables: z and ΔR_{ij}
- $$z = min(P_{T_i}, P_{T_j})/P_{T_{i+j}}$$
- ΔR_{ij}: angular separation between two proto-jets
- recombination between i-th and j-th proto-jets is not possible and softer one removed if
$$z < z_{cut} \text{ and, } \Delta R_{ij} > R_{fact}$$
- $z_{cut} = 0.1$ and $R_{fact} = 0.5$

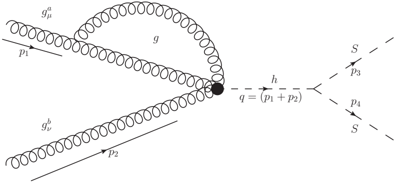
N-subjettiness ratio

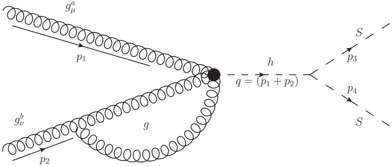
$$\tau_N = \frac{1}{\mathcal{N}_0} \sum_i p_{T,i} \, min\{\Delta R_{i,1}, \Delta R_{i,2}, ..., \Delta R_{i,N}\}$$

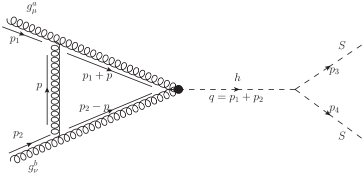
where $\mathcal{N}_0 = \sum_i \, p_{T,i} \, R$, R is the radius of the jet.

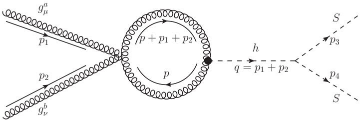

g^a_μ
p_1
p_2
g^b_ν
h
q
S
p_3
p_4
S


p
g
g^a_μ
p_1
p_2
g^b_ν
h
$q = p_1 + p_2$
S
p_3
p_4
S


g^a_μ
p_1
g
g^b_ν
p_2
h
$q = (p_1 + p_2)$
S
p_3
p_4
S


g^a_μ
p_1
g^b_ν
p_2
g
h
$q = (p_1 + p_2)$
S
p_3
p_4
S


g^a_μ
p_1
p
$p_1 + p$
$p_2 - p$
p_2
g^b_ν
h
$q = p_1 + p_2$
S
p_3
p_4
S


g^a_μ
p_1
p_2
g^b_ν
$p + p_1 + p_2$
p
h
$q = p_1 + p_2$
S
p_3
p_4
S

QCD loop correction

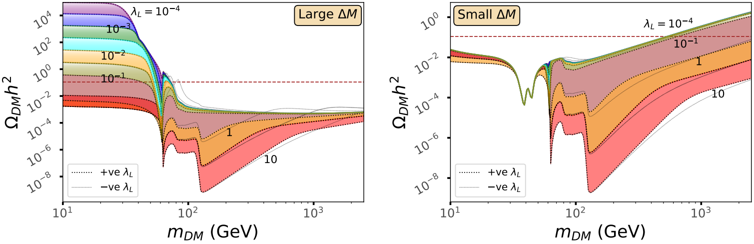
$$\begin{aligned}\alpha_s \rightarrow & \alpha_s^{\overline{MS}}(\mu_R) \\ & = \alpha_s\left[\ 1 - \frac{\alpha_s}{2\pi}(4\pi)^{\epsilon}\frac{\Gamma(1+\epsilon)\Gamma^2(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{\mu^2}{\mu_R^2}\right)^{\epsilon}\ \frac{b_0}{\epsilon}\ \right]\end{aligned}$$

Where, $b_0 = \frac{11}{6}C_A - \frac{2}{3}n_f T_r,\ C_A = 3,\ T_r = 0.5$ for SU(3) fundamental rep

$$Re[\overline{\mathcal{M}\mathcal{M}_0^*}] = \overline{|\mathcal{M}_{LO}|^2}\ prefactor\ \left[-\frac{6}{\epsilon^2} - \frac{2b_0}{\epsilon} + 3\pi^2 + 11\ \right]$$

We choose the central scale as $\mu^2 = \mu_R^2 = \hat{s}_{12}$

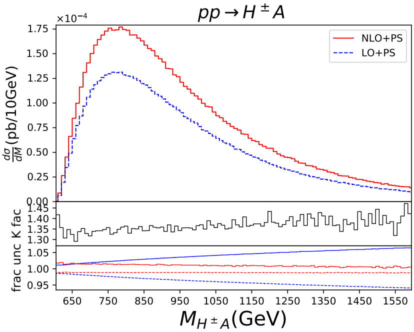
Where, $\overline{|\mathcal{M}_{LO}|^2} = \frac{1}{128}\frac{\Lambda^2 v^2 \hat{s}_{12}^2}{(\hat{s}_{12} - m_h^2)^2 + \Gamma_h^2}\left(\frac{\alpha_s}{3\pi v}\right)^2$

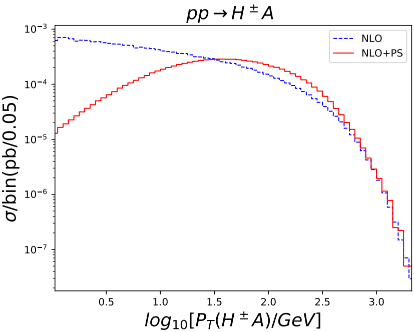


$$\text{annihilation}\begin{cases} h_2\ h_2 \rightarrow W^+\ W^- \\ h_2\ h_2 \rightarrow Z\ Z \end{cases}$$

$$\text{co-annihilation}\begin{cases} h^+\ h^- \rightarrow W^+\ W^- \quad (4\ m_{h_2}\ \Delta M/v^2 + \lambda_L) \\ a_0\ a_0 \rightarrow W^+\ W^- \\ a_0\ a_0 \rightarrow Z\ Z \end{cases}$$

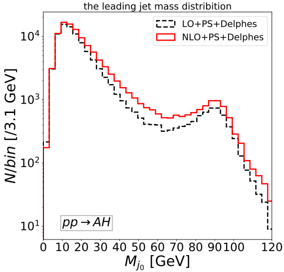
BP	$\sigma(pp \to f_1 f_2)$ (fb)								
	AH		$H^{\pm}H$		$H^{\pm}A$		$H^{+}H^{-}$		AA
	NLO(LO)	K-fac	NLO(LO)	K-fac	NLO(LO)	K-fac	NLO(LO)	K-fac	NLO(LO)
BP1	46.55(35.12)	1.33	82.42(61.67)	1.34	16.93(12.53)	1.35	11.01(7.98)	1.38	0.88(0.46)
BP2	25.34(19.01)	1.33	45.27(33.77)	1.34	8.41(6.21)	1.35	6.01(4.17)	1.44	0.72(0.38)
BP3	15.50(11.60)	1.34	27.78(20.69)	1.34	4.78(3.48)	1.37	3.76(2.57)	1.46	0.59(0.32)
BP4	9.68(7.19)	1.35	17.86(13.23)	1.35	2.81(2.04)	1.38	2.50(1.68)	1.49	0.48(0.27)
BP5	6.32(4.67)	1.35	11.34(8.39)	1.35	1.69(1.22)	1.38	1.68(1.10)	1.52	0.40(0.22)
BP6	3.90(2.87)	1.36	7.19(5.33)	1.35	0.97(0.70)	1.38	1.14(0.74)	1.54	0.31(0.18)
BP7	2.69(1.97)	1.37	5.01(3.68)	1.36	0.63(0.45)	1.39	0.85(0.55)	1.56	0.26(0.15)

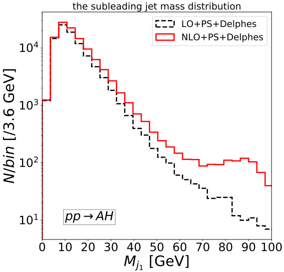


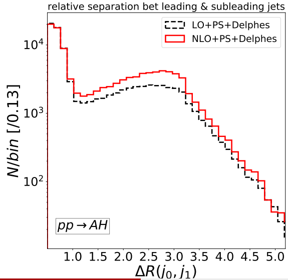


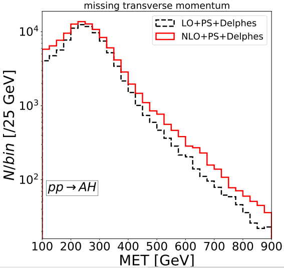
$\mu_R = \zeta_R\sqrt{s_{12}}$ and $\mu_F = \zeta_F\sqrt{s_{12}}$, $\zeta_R, \zeta_F = \{1/2, 1, 2\}$

- clustered jets using the anti-kt algorithm with radius parameter R=0.5
- $\not{E}_T$ (MET)$>$ 100 GeV, $P_T(J_0), P_T(J_1) > 100$ GeV


the leading jet mass distribition


the subleading jet mass distribution


relative separation bet leading & subleading jets


missing transverse momentum