Search for BSM Higgses at the HL-LHC

Amit Adhikary
Indian Institute of Science, Bangalore, India

Based on

With Shankha Banerjee, Rahool K. Barman and Biplob Bhattacherjee (JHEP 1909 (2019) 068)

With Biplob Bhattacherjee, Rohini M. Godbole, Najimuddin Khan, Suchita Kulkarni
(JHEP 2104 (2021) 284)

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Introduction

- The last missing piece in SM, Higgs boson, has been discovered at the LHC in 2012 whose properties are more or less consistent with Standard Model.
- There are many reasons for exploring beyond the SM (BSM) physics: gauge hierarchy, dark matter, neutrino mass, baryon asymmetry etc.
- A very well motivated model to search for BSM particles is the Minimal Supersymmetric extension of the SM (MSSM).
  - lepton (e) or quark (u) $\rightarrow$ slepton ($\tilde{e}$) or squark ($\tilde{u}$)
  - gauge boson (g, $W^{\pm}$, W^0, B^0) $\rightarrow$ gaugino ($\tilde{g}$, $\tilde{W}^{\pm}$, $\tilde{W}^0$, $\tilde{B}^0$)
  - five Higgs bosons (h, H, A, $H^{\pm}$)
  - Higgs $(H_u^+, H_u^0, H_d^0, H_d^-)$ $\rightarrow$ Higgsino $(\tilde{H}_u^+, \tilde{H}_u^0, \tilde{H}_d^0, \tilde{H}_d^-)$
  - $\tilde{B}^0, \tilde{W}^0, \tilde{H}_u^0, \tilde{H}_d^0 \rightarrow \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ (neutralino)
  - $\tilde{W}^{\pm}, \tilde{H}_u^+, \tilde{H}_d^- \rightarrow \tilde{\chi}_1^{\pm}, \tilde{\chi}_2^{\pm}$ (chargino)

→ Electroweakinos

MSSM Higgs decaying to SM particles

- HL-LHC: $\sqrt{s}$ = 14 TeV @ 3 ab^{-1}
- Search channels :

A. $pp \to H \to hh$

- $b\bar{b}\gamma\gamma$ ($pp \to A \to Zh$)
- $b\bar{b}b\bar{b}$
- $b\bar{b}\tau_h\tau_h$
- $b\bar{b}WW^* \to (a)\ b\bar{b}\ell jj + \not{E}_T$ and $(b)\ b\bar{b}\ell\ell + \not{E}_T$
- $WW^*\gamma\gamma \to (a)\ \ell jj\gamma\gamma + \not{E}_T$ and $(b)\ \ell\ell\gamma\gamma + \not{E}_T$

B. $pp \to H \to t\bar{t}$

- fully leptonic
- semi-leptonic

C. $pp \to b\bar{b}H$

- $H \to \tau_h\tau_h$: b-tag category

- Cut-based and BDT analysis

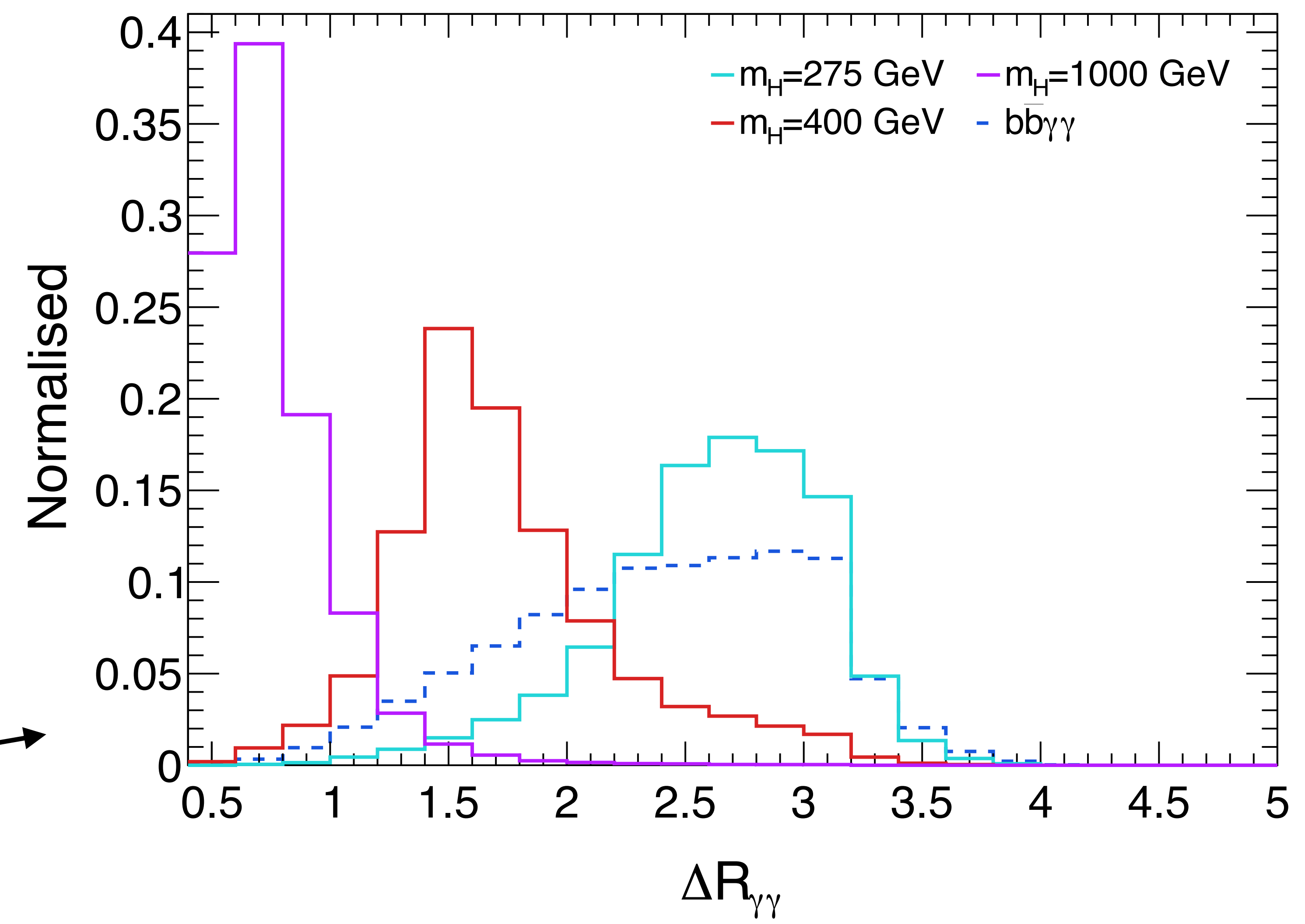
Signal significance, $Signi = \frac{S}{\sqrt{B}} = \frac{\epsilon_s\ \sigma_s\ L}{\sqrt{\sum_b \epsilon_b\ \sigma_b\ L}}$.

$\therefore$ Limit on cross section, $\sigma_s = \frac{Signi\sqrt{\sum_b \epsilon_b\ \sigma_b\ L}}{\epsilon_s\ L}$.

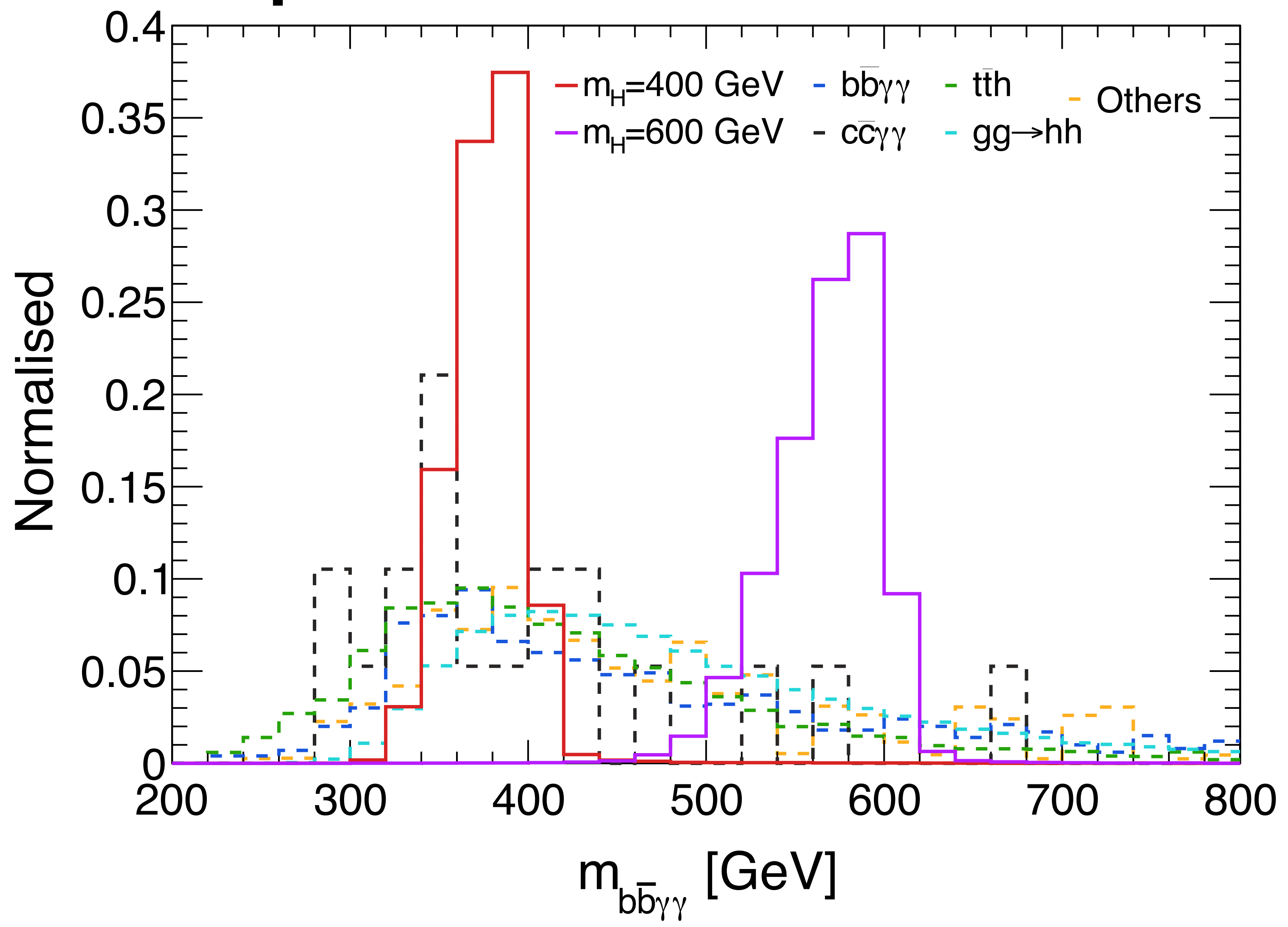
$pp \to H \to hh \to b\bar{b}\gamma\gamma$ channel

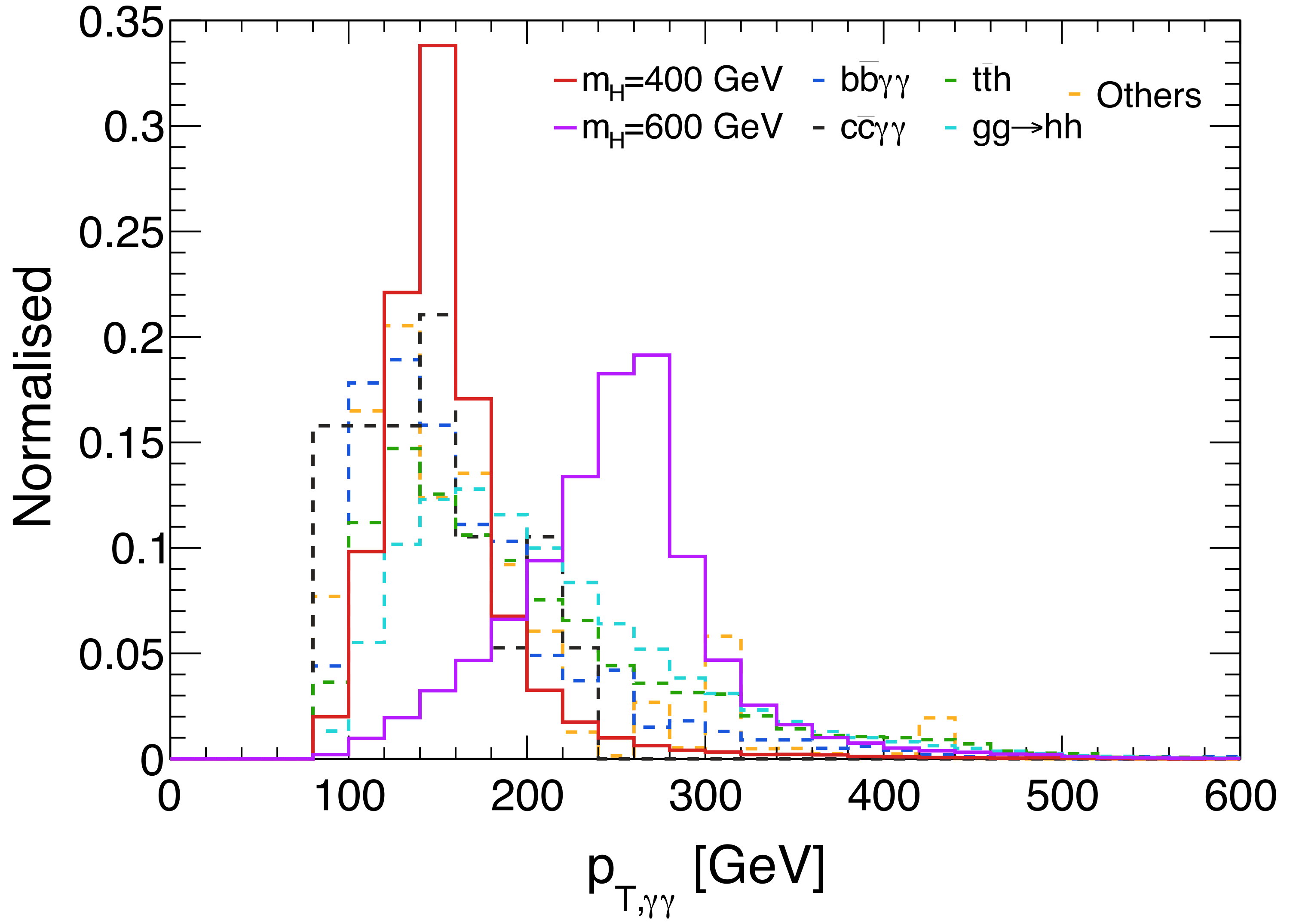
- Major backgrounds: $b\bar{b}\gamma\gamma$, $t\bar{t}h$, $b\bar{b}h$, Zh
- Fake backgrounds: $b\bar{b}jj$, $b\bar{b}j\gamma$, $jj\gamma\gamma$, $c\bar{c}jj$, $c\bar{c}j\gamma$

Fixed cuts
122 GeV $< m_{\gamma\gamma} <$ 128 GeV
$N_\ell = 0$
$p_{T,b} > 40$ (30) GeV, $p_{T,\gamma} > 30$ (30) GeV
$0.4 < \Delta R_{\gamma\gamma} < (3.0/2.0/1.5)$, $0.4 < \Delta R_{bb} < (3.0/2.0/1.5)$, $\Delta R_{\gamma b} > 0.4$
90 GeV $< m_{bb} <$ 130 GeV

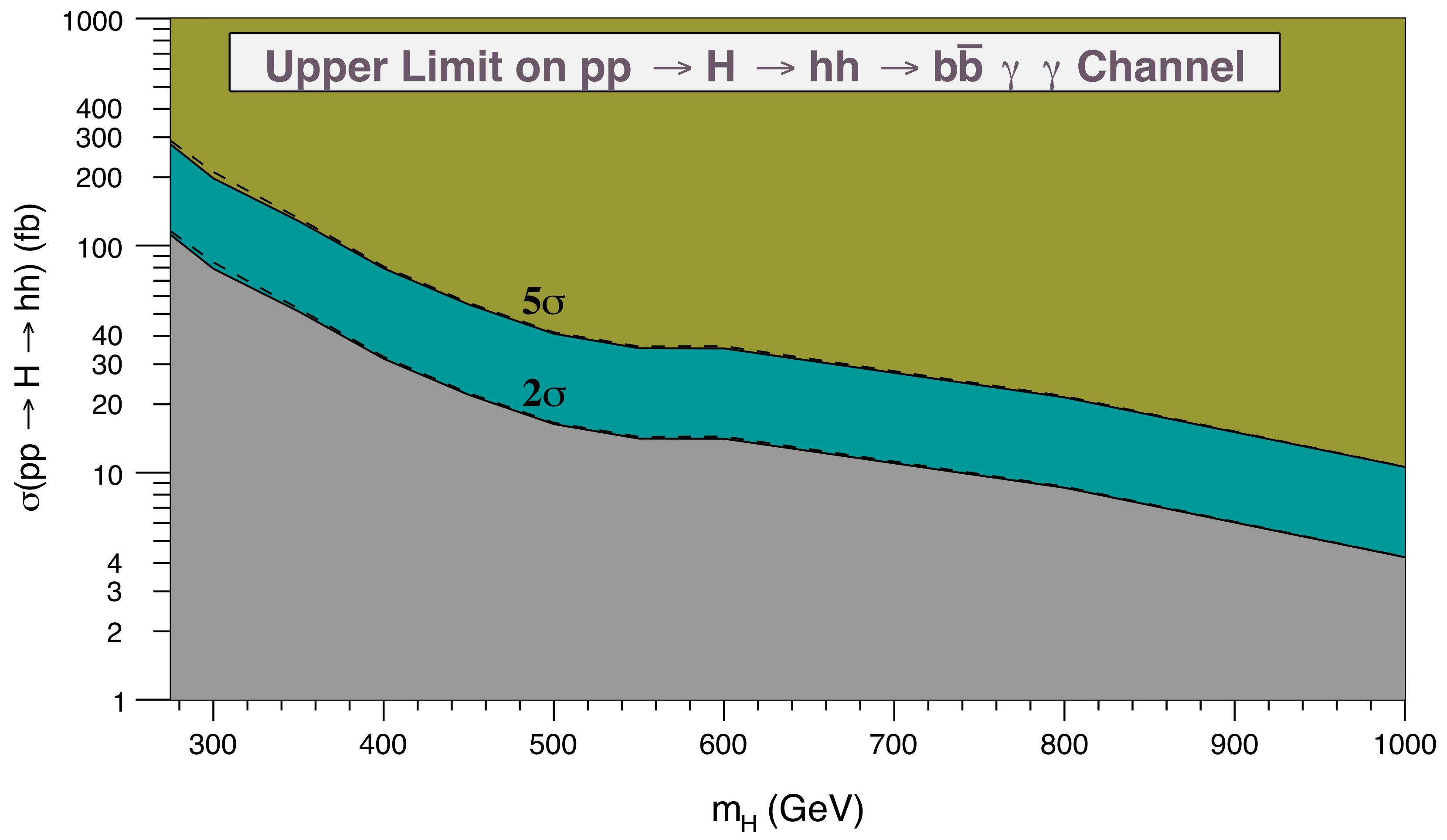


Optimisatiion over:





Cut-based Analysis and UL:



$pp \to H \to hh$: all channels

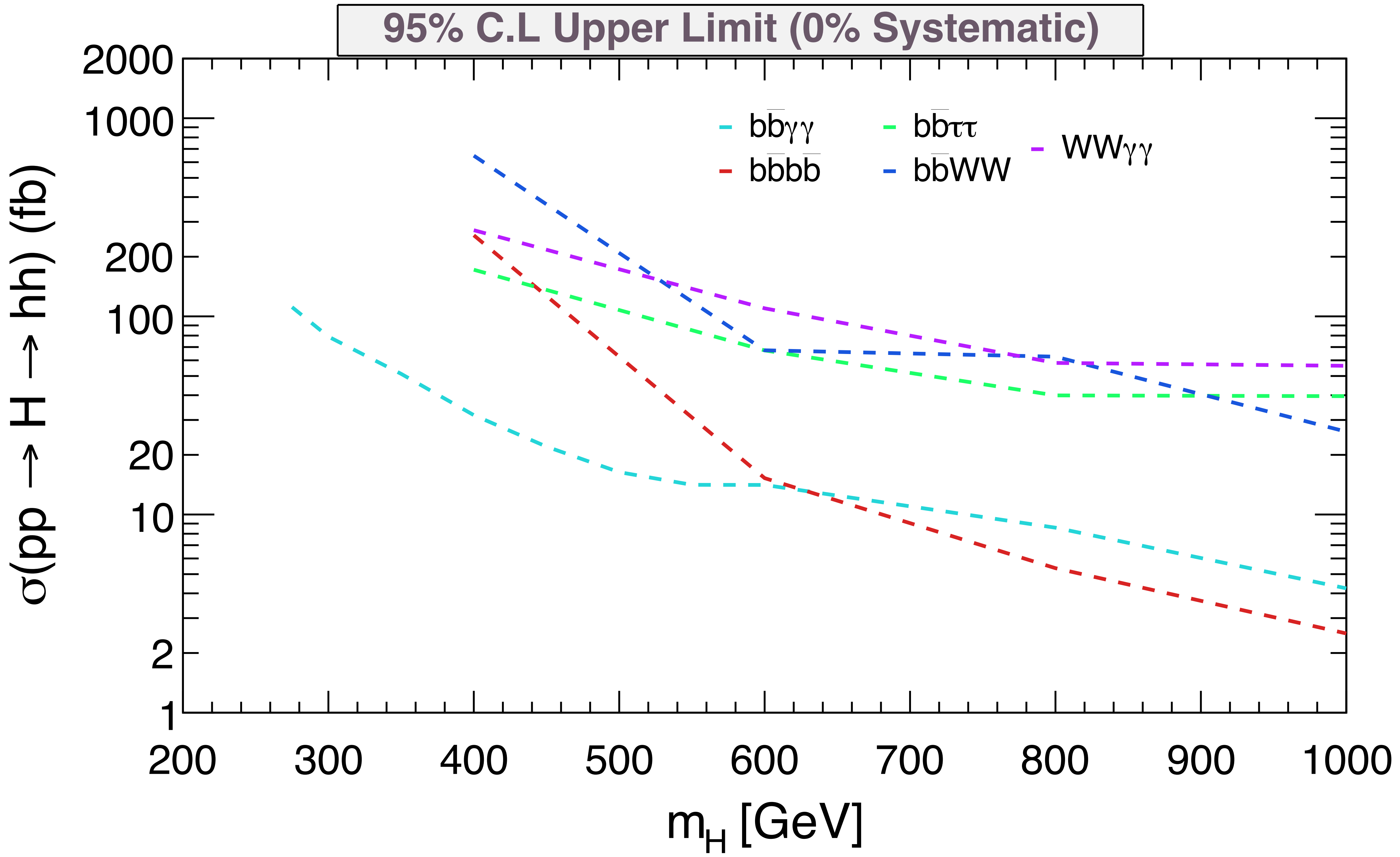


Fig. 95% CL upper limit from final states of $pp \to H \to hh$ channel

$pp \to H \to t\bar{t}$ channel

- Fully leptonic channel, backgrounds: $t\bar{t}$ leptonic, $t\bar{t}h$, $t\bar{t}Z$, $t\bar{t}W$, $pp \to hh$, $llb\bar{b}$.
- Semi-leptonic channel, additional backgrounds: $t\bar{t}$ semi-leptonic, $Wb\bar{b}$+jets.

BDT Analysis and upper limit on cross-section:

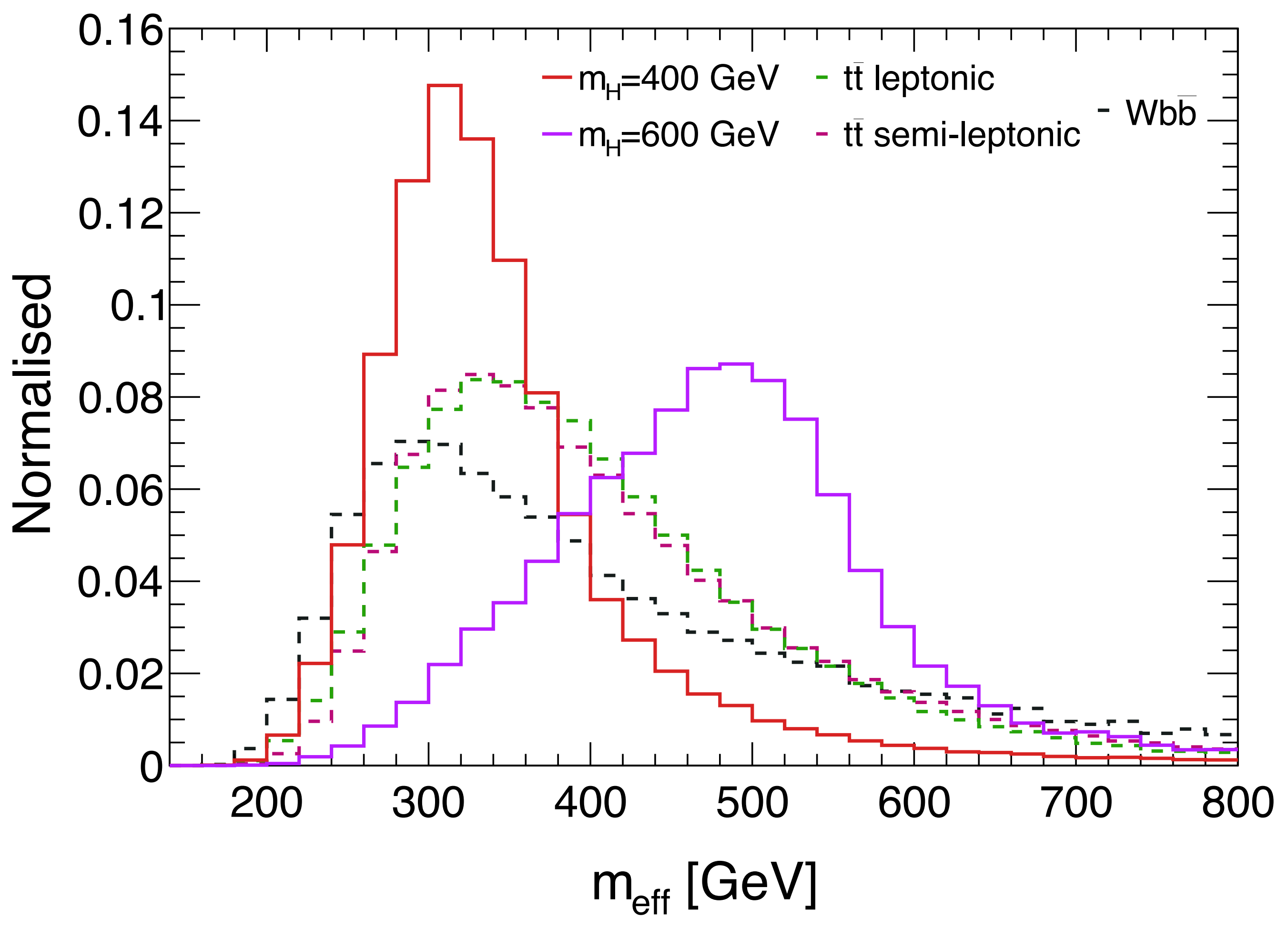


Fig. Normalised distribution of Effective mass

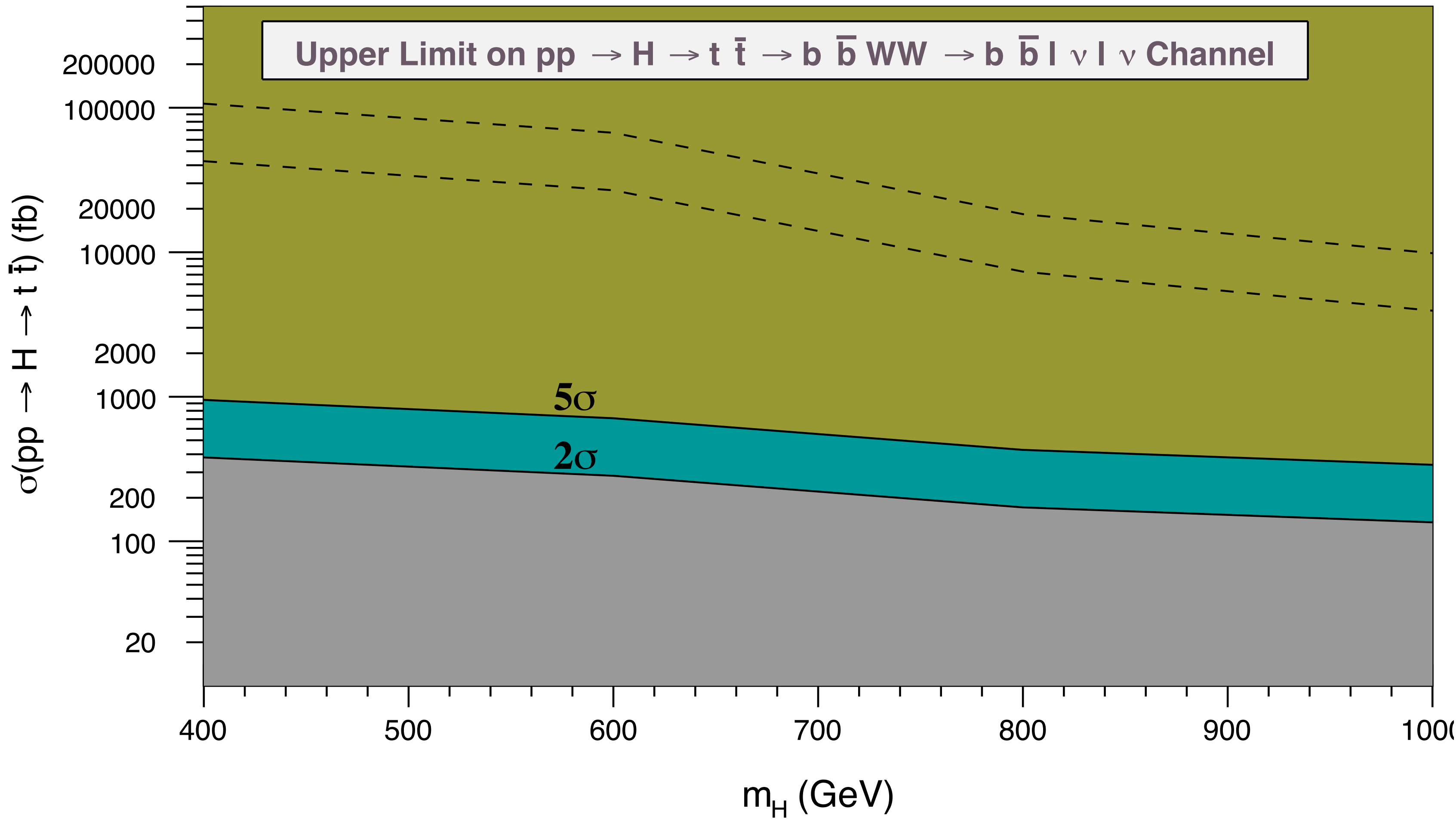


Fig. UL for fully leptonic channel

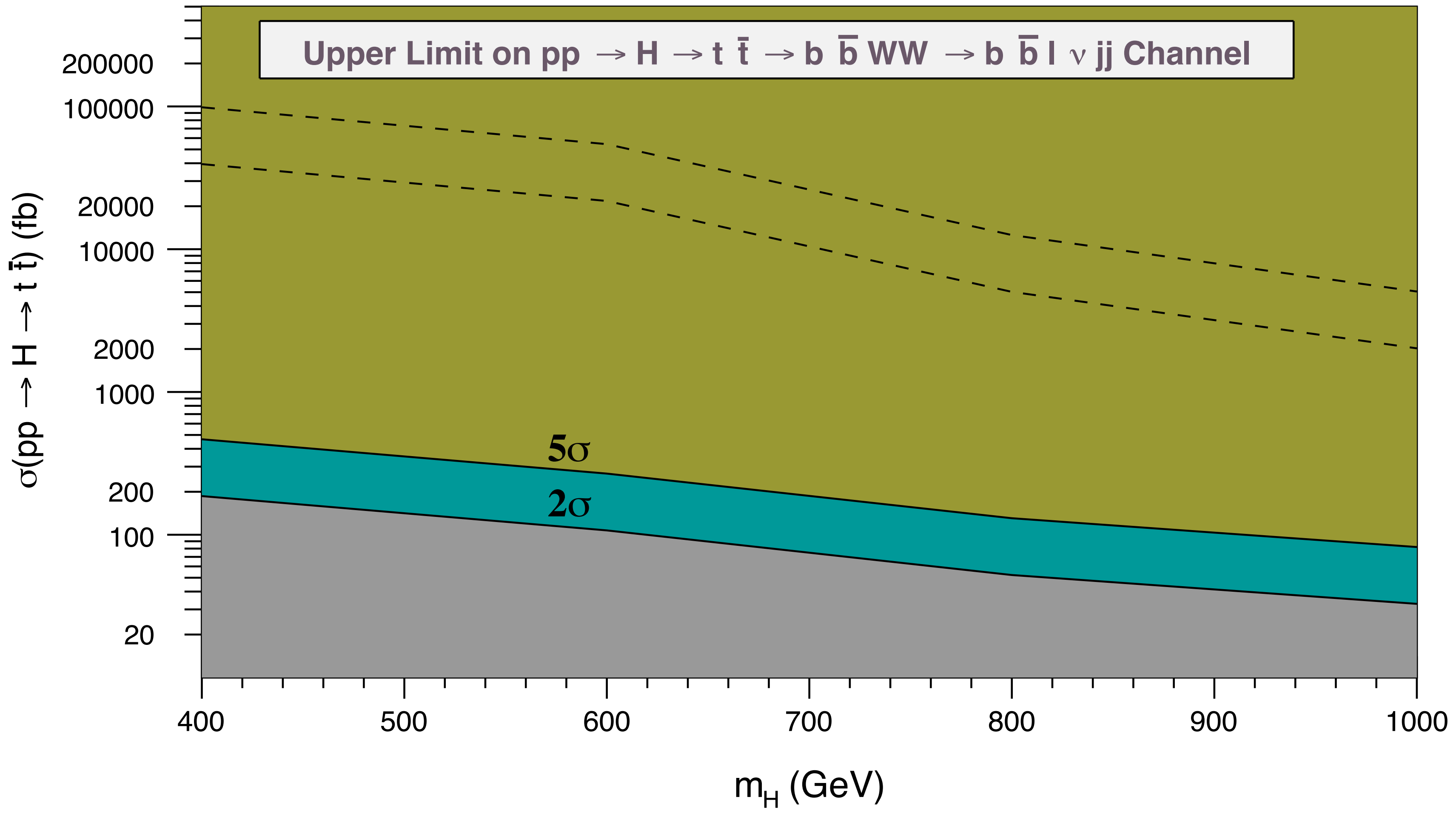


Fig. UL for semi-leptonic channel

$pp \to b\bar{b}H,\ H \to \tau\tau$ channel

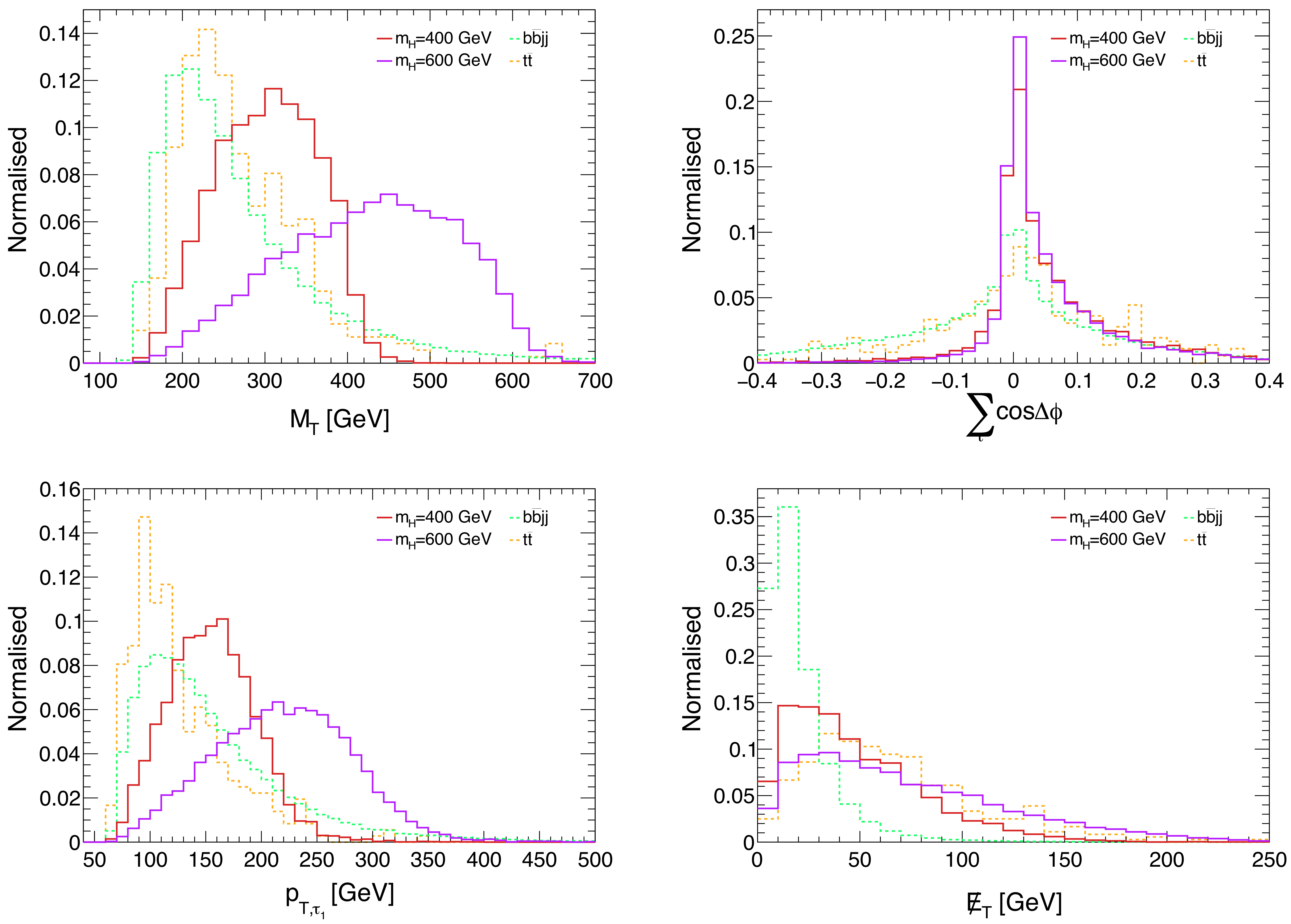


Fig. Normalised distribution of the optimised variables.

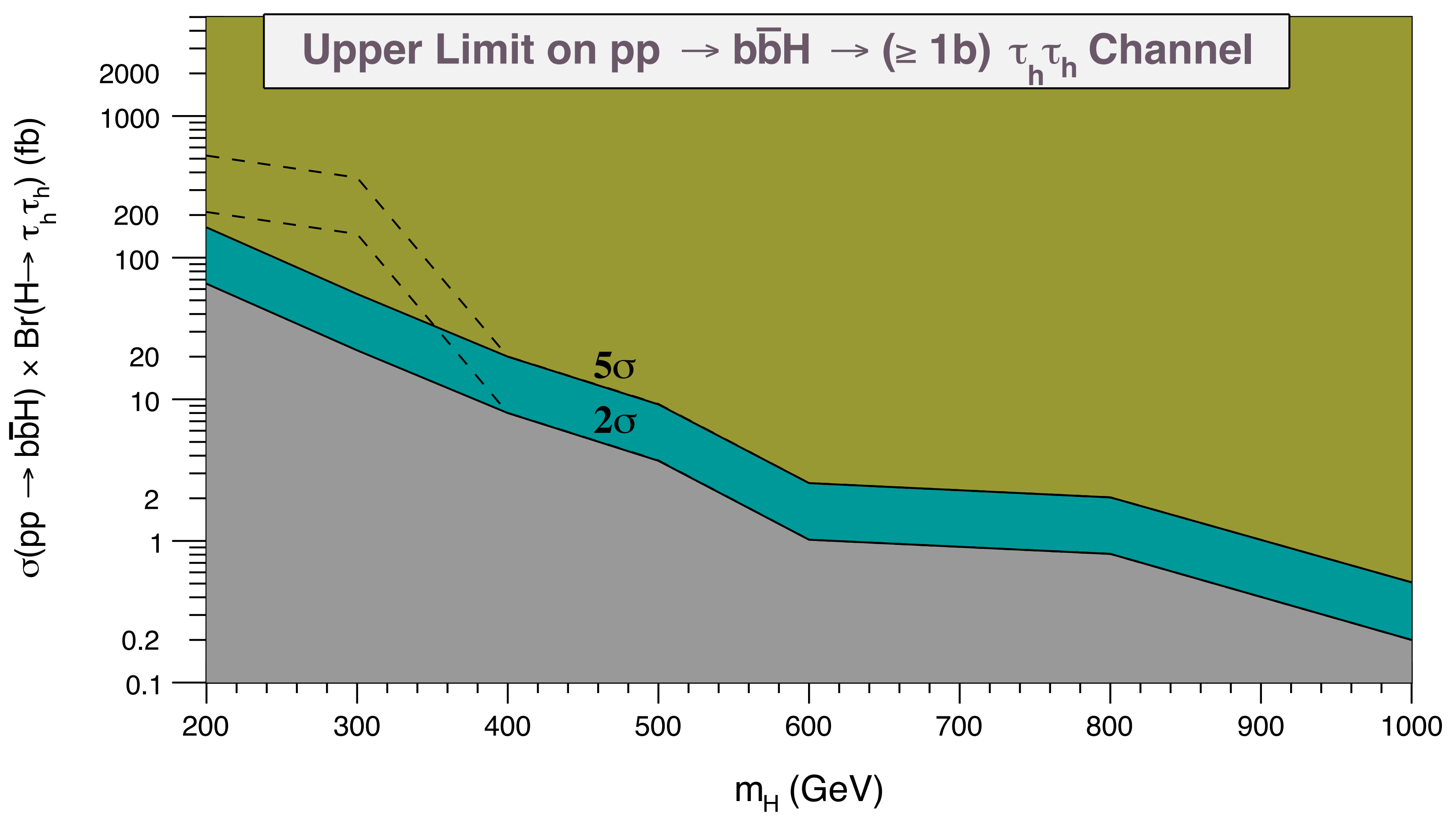


Fig. UL in the $b\bar{b}H$ channel

Status of pMSSM parameter space

All points satisfy:

- Higgs mass measurement
- Higgs signal strength

Gray → Excluded by Run-II ATLAS and CMS,

$$pp \to b\bar{b}H,\ H \to \tau\tau$$

Our HL-LHC projections:

Brown → Within projected reach of $pp \to H \to hh \to b\bar{b}\gamma\gamma$

Green → Within projected reach of $pp \to H \to t\bar{t}$

Orange → Within projected reach of $pp \to b\bar{b}H,\ H \to \tau\tau$

Blue → Remains allowed

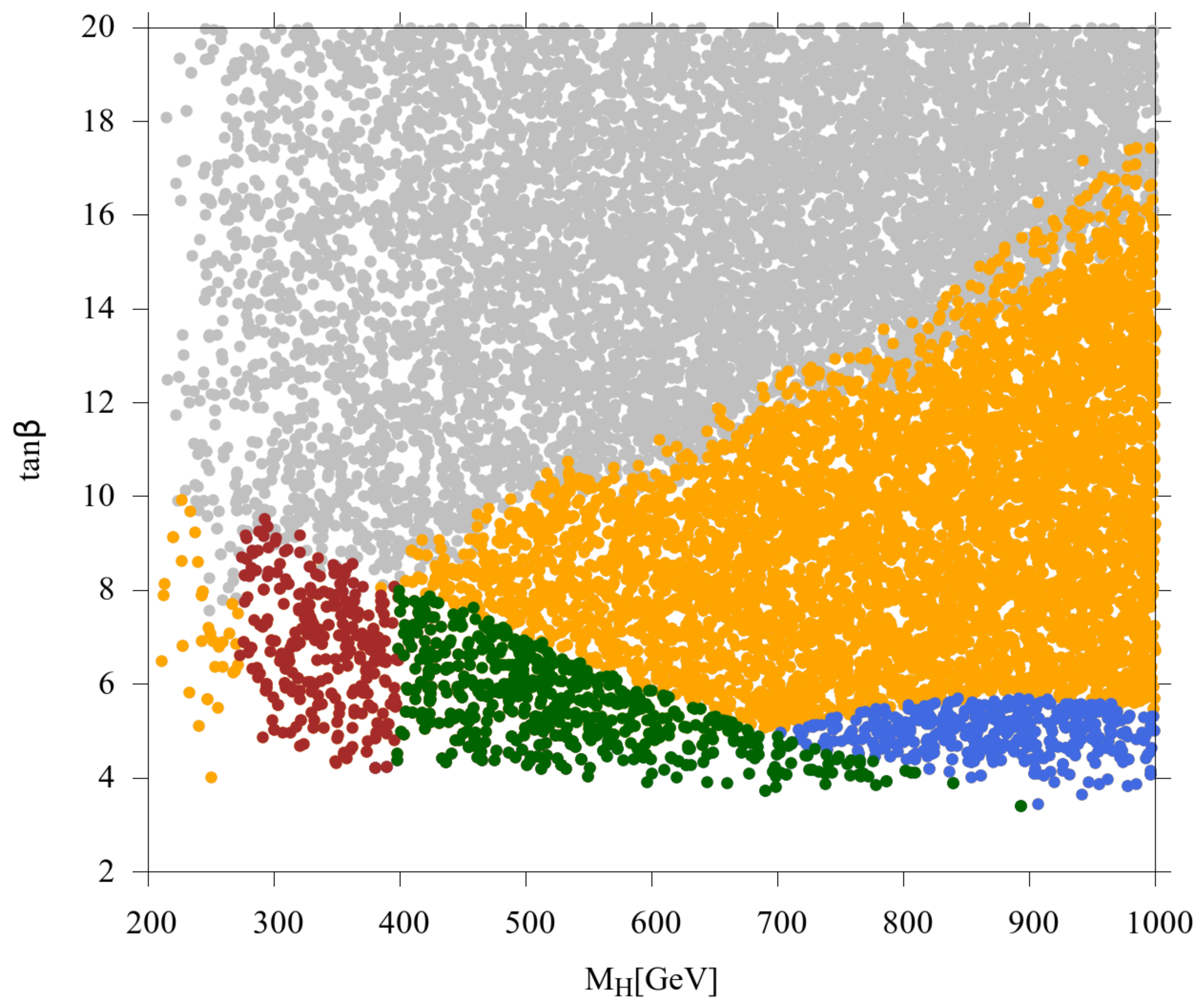


Fig. Projected limit in the $m_A - tan\beta$ parameter space.

Interesting heavy Higgs to susy decays

Adding heavy Higgs to susy decay:

- $H \to$ electroweakinos, $pp \to H \to \tilde{\chi}_1^0 \, \tilde{\chi}_2^0$

The $H \to$ SM branching ratios get modified.

The projected limit weakens.

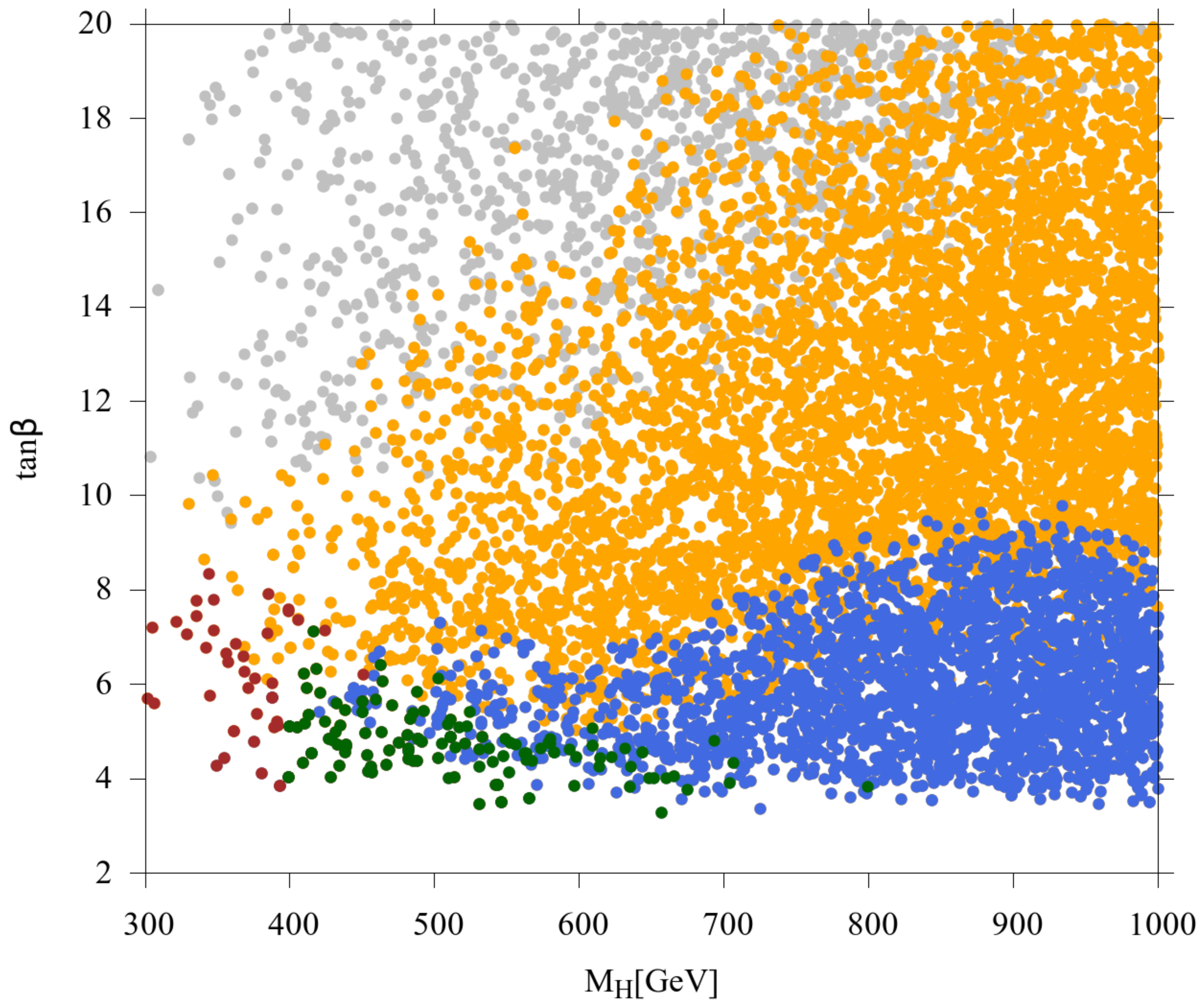


Fig. In presence of Higgs decaying to SUSY particles, projected limit in the $m_A - tan\beta$ parameter space.

MSSM Higgs decaying to SUSY particles

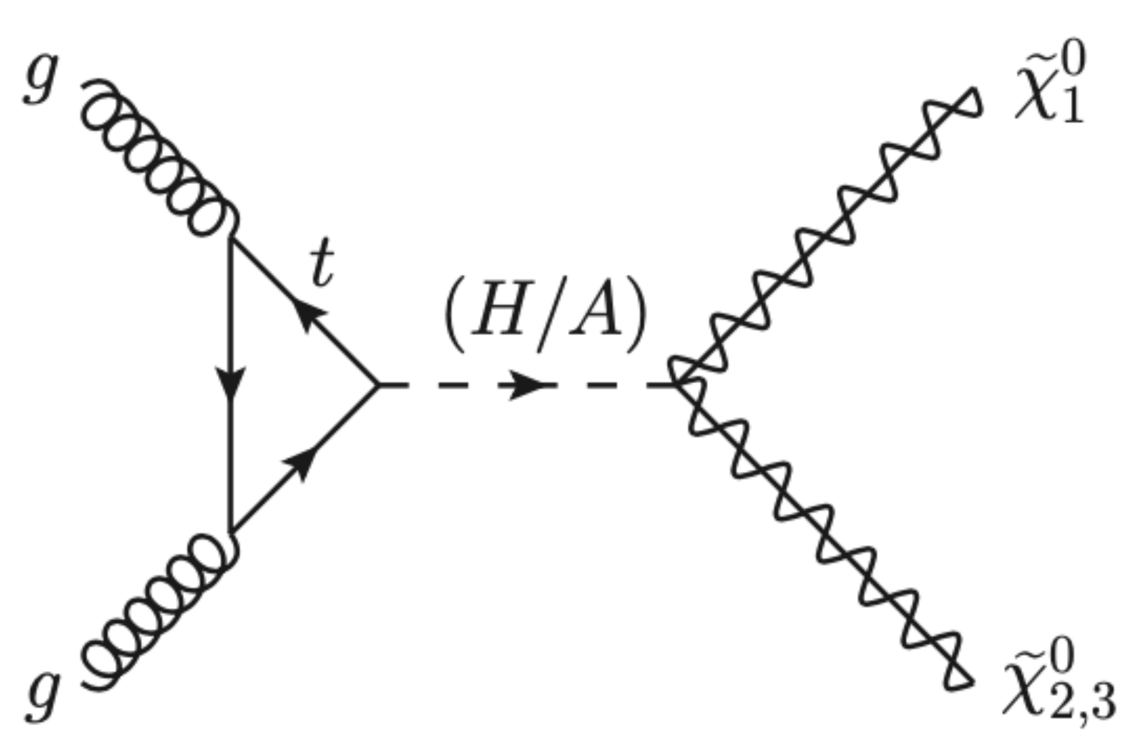


Fig. **Resonant** electroweakino production. Electroweakinos must have gaugino and higgsino component to couple to Higgs boson.

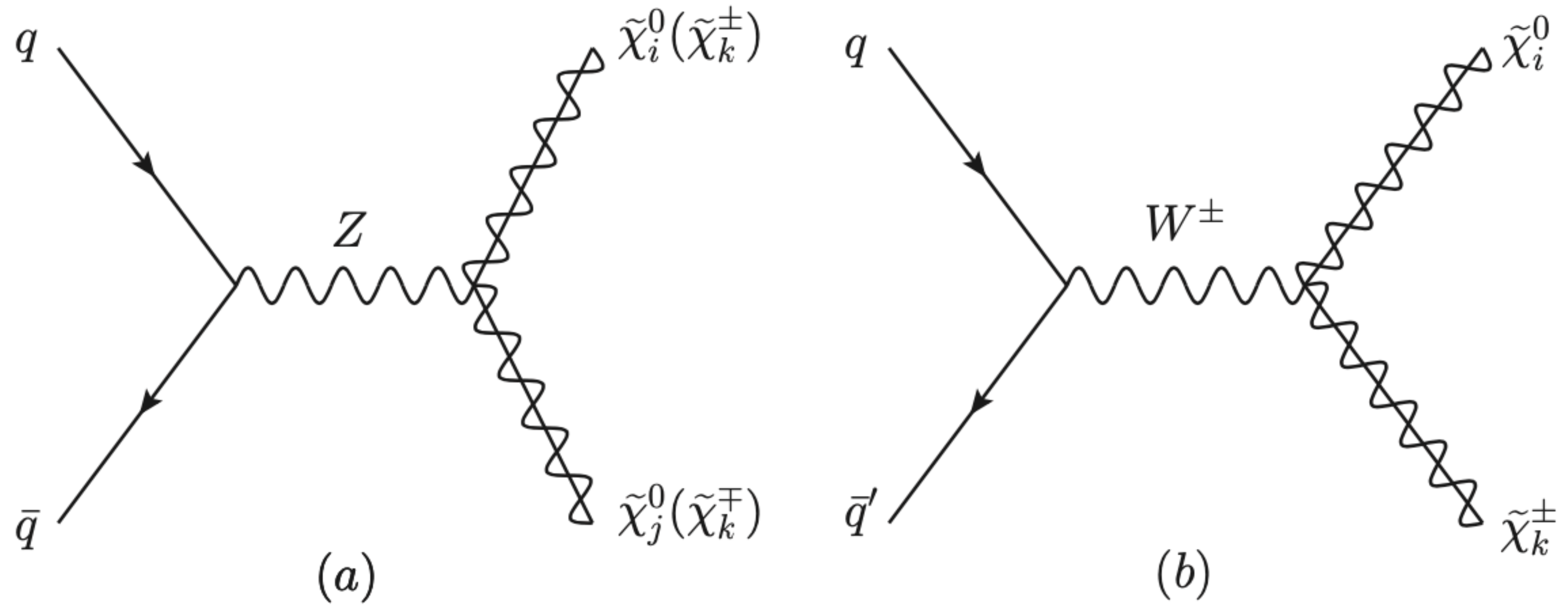


Fig. **Direct** electroweakino production.

- Allowed MSSM parameter space → Random scan + Experimental Constraints
- Experimental Constraint : Higgs signal strength, heavy Higgs searches, LEP constraints, dark matter direct detection, flavour physics.

Collider search

- Signal: **Mono-X (X=Z/h)** signatures arising from, pp $\rightarrow$ H/A $\rightarrow \widetilde{\chi}^0_1$ + ($\widetilde{\chi}^0_{2,3}$), ($\widetilde{\chi}^0_{2,3}$) $\rightarrow \widetilde{\chi}^0_1$ + (Z/h),
  - $Z \rightarrow ll \quad : ll \ + \ \not{E}_T$
  - $h \rightarrow b\bar{b} \ : b\bar{b} \ + \ \not{E}_T$
  - $h \rightarrow \gamma\gamma \ : \gamma\gamma \ + \ \not{E}_T$
- Two benchmark points are chosen for analysis :

  1. M_A = 650 GeV, tanβ = 10.80
  2. M_A = 750 GeV, tanβ = 12.10

  - with the common parameters,

$$M_1 = 5.04 \text{ GeV}, \, M_2 = 1.06 \text{ TeV}, \, \mu = 243.24 \text{ GeV}, \, M_3 = 2 \text{ TeV}, A_t = -\, 3.65 \text{ TeV}, \, A_\tau = -\, 1.44 \text{ TeV},$$

$$M_{\tilde{Q}_{1_L},\tilde{Q}_{2_L}} = M_{\tilde{u}_R,\tilde{d}_R,\tilde{c}_R,\tilde{s}_R} = M_{\tilde{e}_L,\tilde{\mu}_L,\tilde{e}_R,\tilde{\mu}_R} = 3 \text{ TeV}, \, M_{\tilde{Q}_{3_L},} = 4.91 \text{ TeV}, \, A_b = -\, 1.11 \text{ TeV}, \, A_{e,\mu,u,d,c,s} = 0,$$

$$M_{\tilde{\tau}_L} = 961.52 \text{ GeV}, \, M_{\tilde{\tau}_R} = 1.07 \text{ TeV}, \, M_{\tilde{t}_R} = 5.91 \text{ TeV}, \, M_{\tilde{b}_R,} = 2 \text{ TeV} \ .$$

$ll + \not{E}_T$ Channel

Signal : $pp \to H/A \to \widetilde{\chi}_1^0 + (\widetilde{\chi}_{2,3}^0)$, $(\widetilde{\chi}_{2,3}^0) \to \widetilde{\chi}_1^0 + Z$, $Z \to \ell\ell$, Two production modes: $gg \to H$, $pp \to b\bar{b}H$

Background :

- **SUSY** : $pp \to \widetilde{\chi}_1^0 \widetilde{\chi}_{2,3}^0$, $\widetilde{\chi}_1^\pm \widetilde{\chi}_{2,3}^0$, $\widetilde{\chi}_2^0 \widetilde{\chi}_3^0$
- SM : ZZ, WZ, VVV, $t\bar{t}Z$ and $t\bar{t}$

b-veto

	Selection cuts	
	BP 1	BP 2
fixed	2ℓ, $N_b = 0$ $76.0 < m_{\ell\ell} < 106.0$ $\lvert\eta_{\ell\ell}\rvert < 2.5$ $N_j \leq 1$	
Optimised	$\Delta R_{\ell\ell} < 1.3$ $\Delta\phi_{\ell\ell,\not{E}_T} > 2.1$ $\not{E}_T > 180$ GeV $\xi < 0.4$	$\Delta R_{\ell\ell} < 1.5$ $\Delta\phi_{\ell\ell,\not{E}_T} > 2.1$ $\not{E}_T > 210$ GeV $\xi < 0.3$

b-tag

	Selection cuts	
	BP 1	BP 2
fixed	2ℓ, $N_b \geq 1$ $76.0 < m_{\ell\ell} < 106.0$ $\lvert\eta_{\ell\ell}\rvert < 2.5$ $N_j \leq 1$	
Optimised	$\Delta R_{\ell\ell} < 1.3$ $\Delta\phi_{\ell\ell,\not{E}_T} > 2.1$ $\not{E}_T > 160$ GeV $\xi < 0.4$	$\Delta R_{\ell\ell} < 1.3$ $\Delta\phi_{\ell\ell,\not{E}_T} > 2.3$ $\not{E}_T > 170$ GeV $\xi < 0.8$

$\zeta = \lvert p_{T,\ell\ell} - \not{E}_T \rvert \,/\, p_{T,\ell\ell}$

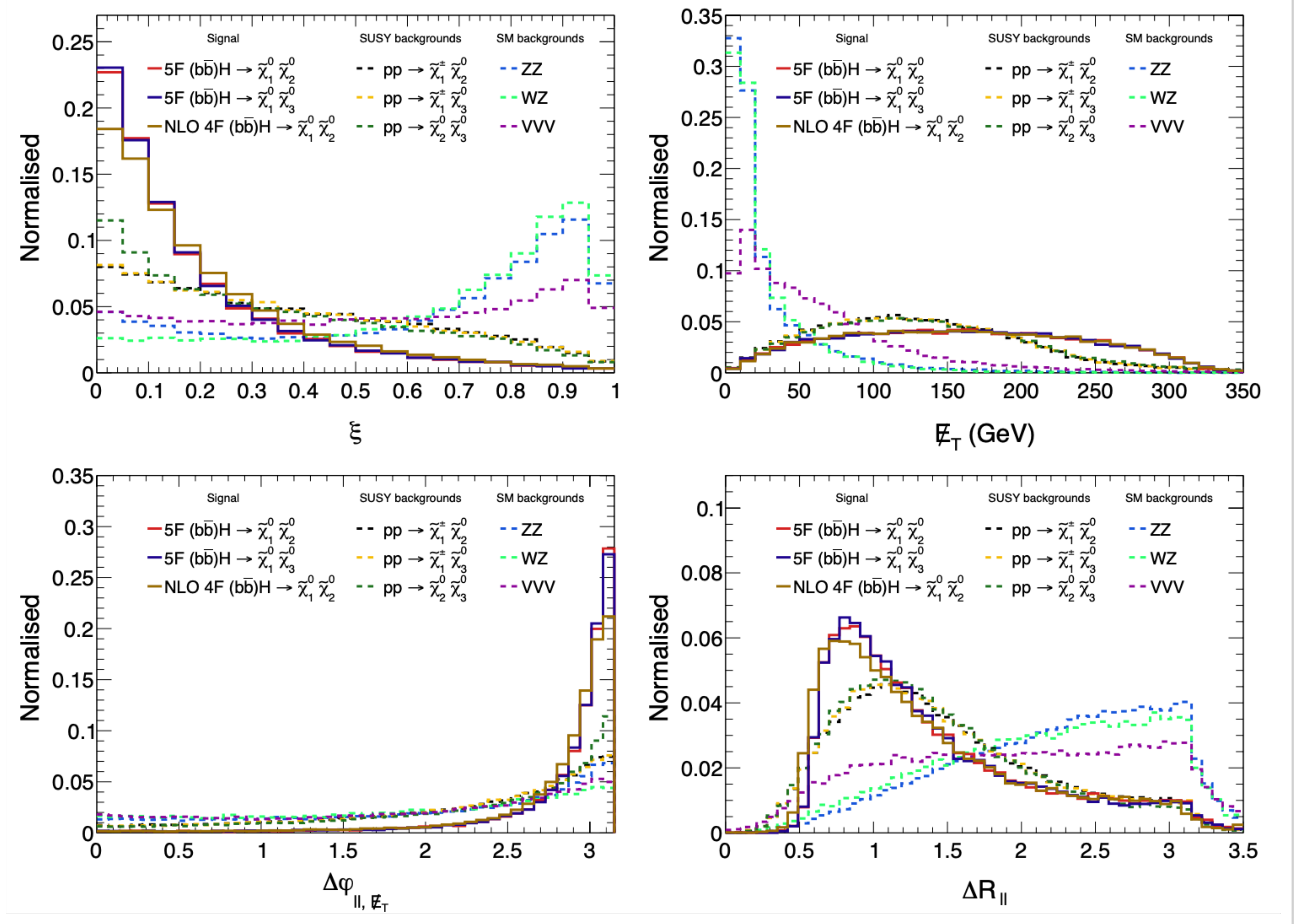


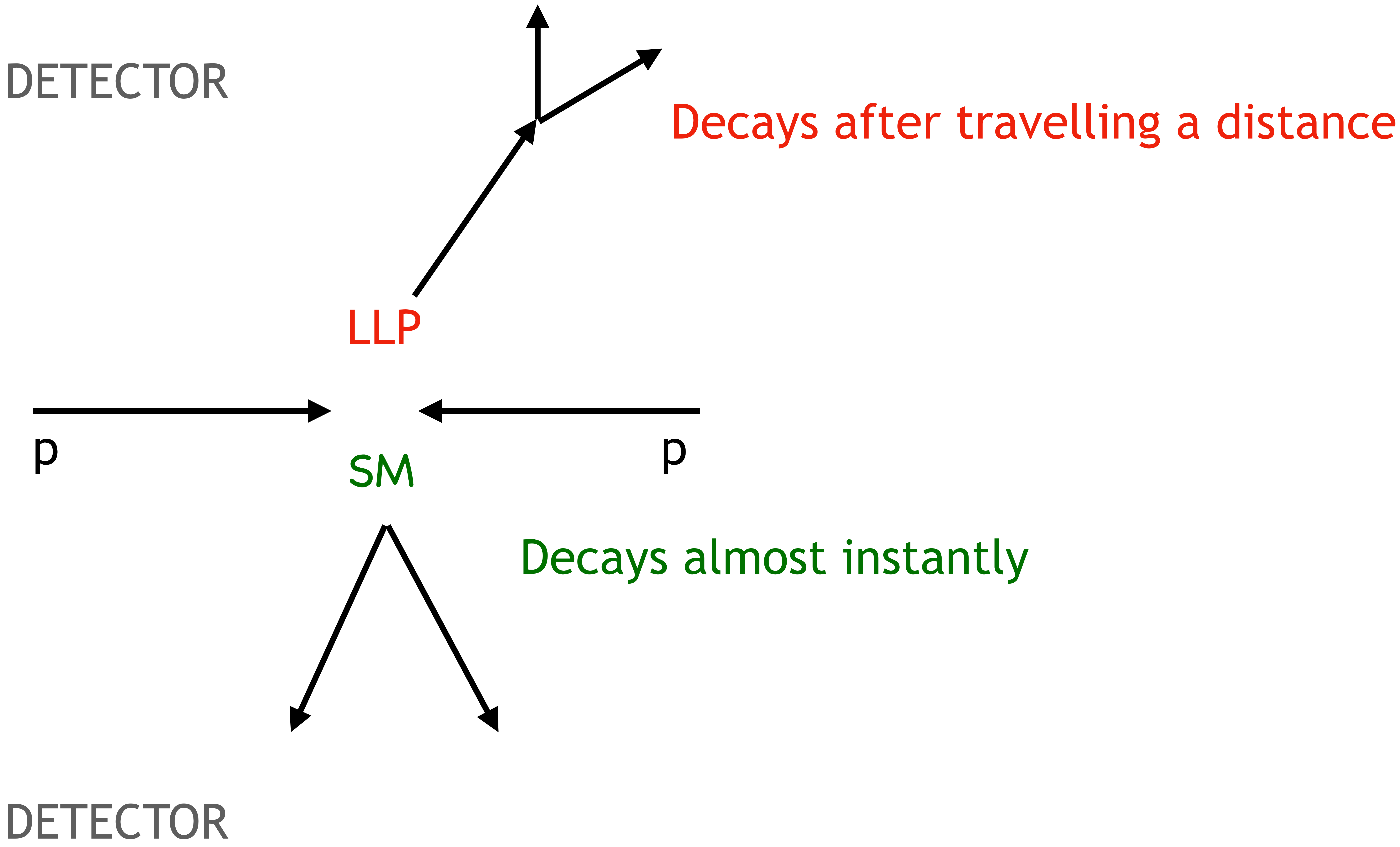
Fig. Normalised distributions of kinematic variables.

Results from all search Channel

1. $ll + \not{E}_T$ channel:
   - promising signature with high signal significance.
   - b-tag category improves the result up to $\sim 70\,\%$.
2. $b\bar{b} + \not{E}_T$ channel:
   - S/B is poor, large $Zb\bar{b}$, $t\bar{t}$ background.
3. $\gamma\gamma + \not{E}_T$ channel:
   - small event yield, but clean final state.

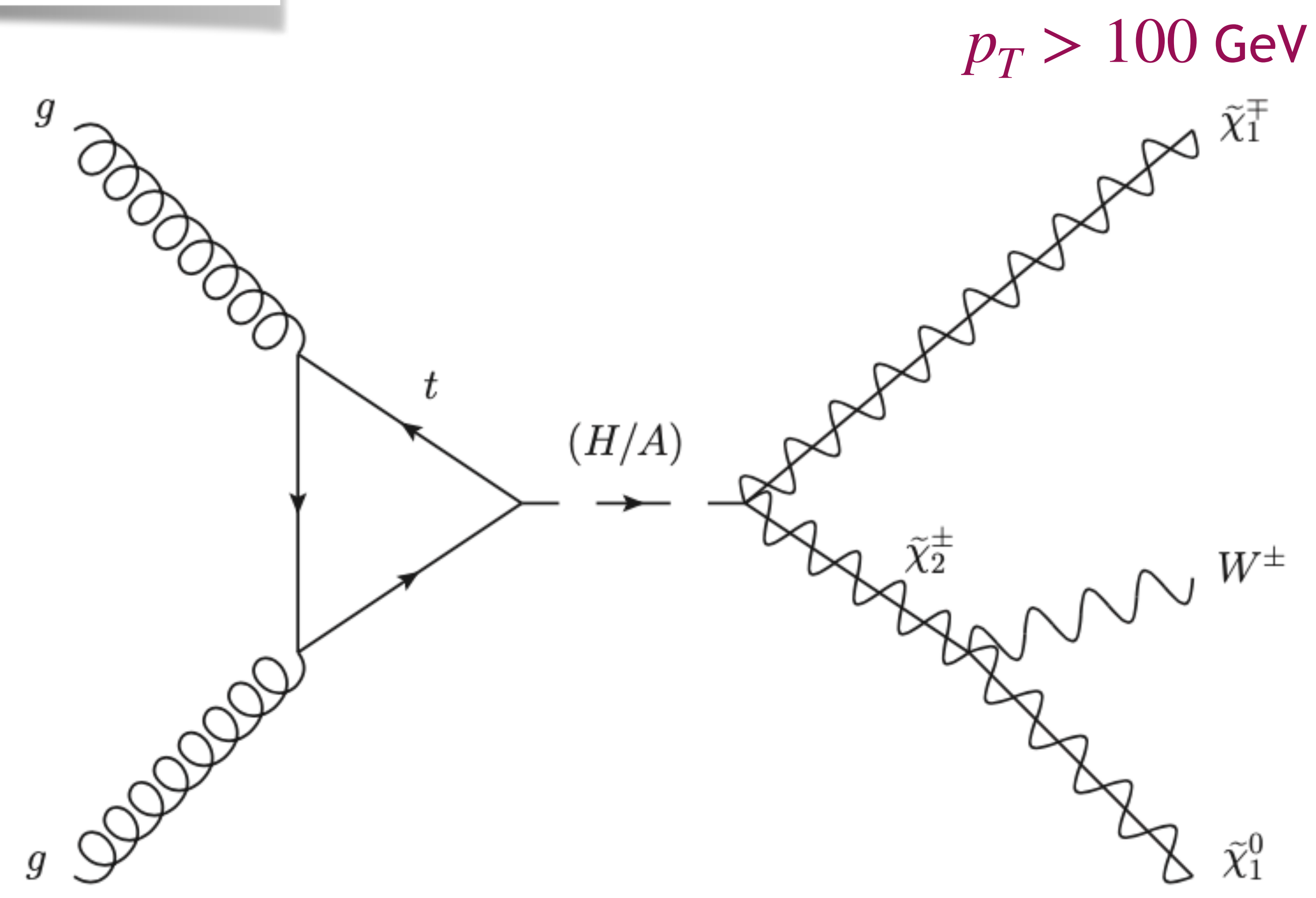
☑ Susy backgrounds can have significant contribution (in terms of cross-section) and overlap with the signal kinematic distribution.

Long-lived particle (LLP)



Probing neutral Higgs in LLCP decay

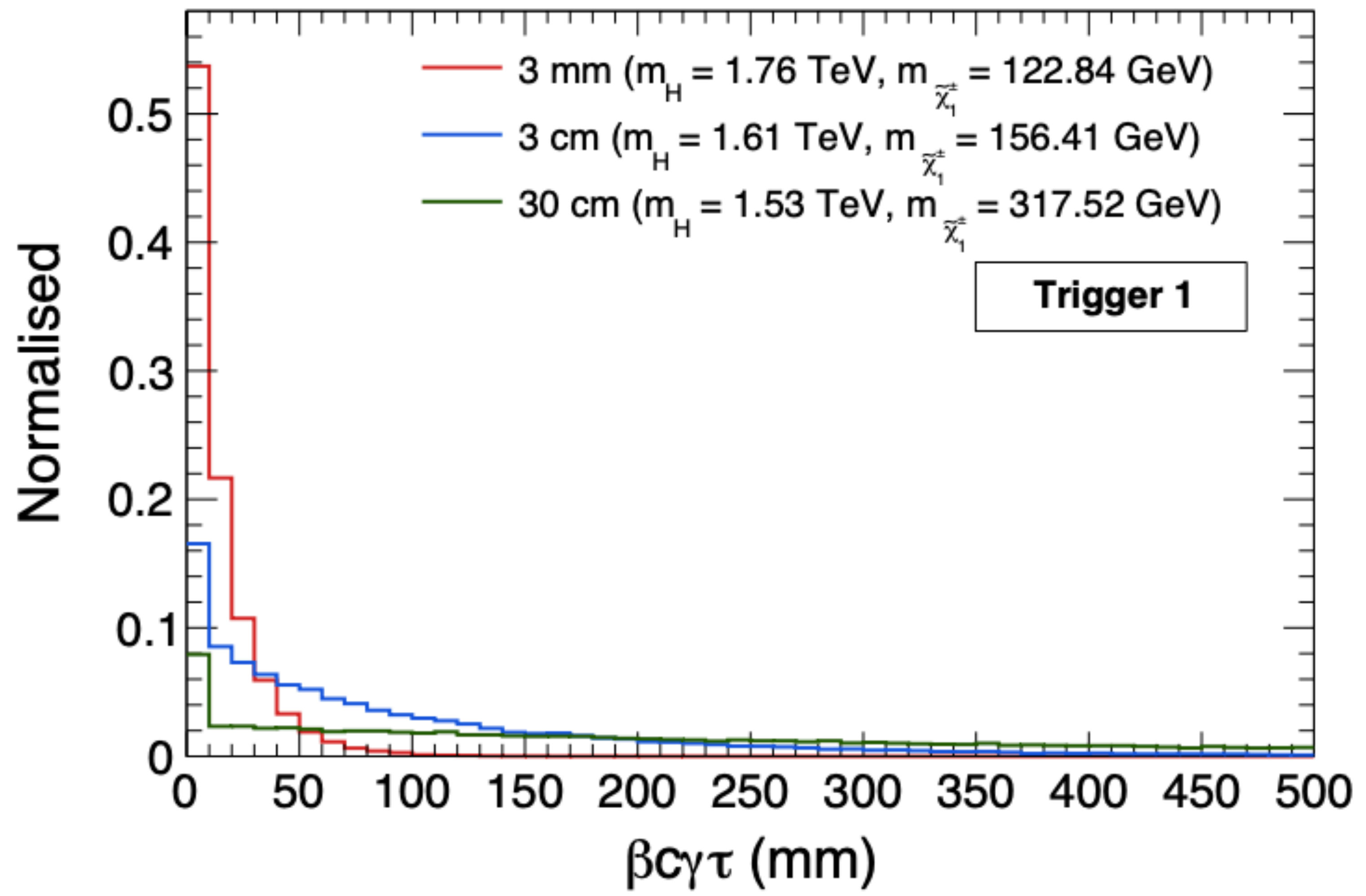
- $pp \to H \to \tilde{\chi}_1^{\pm}\, \tilde{\chi}_2^{\mp}, \quad \tilde{\chi}_2^{\pm} \to W^{\pm}\, \tilde{\chi}_1^{0}$ **[Long-lived charged particle]**
- **Good track reconstruction [12,30] cm [**JHEP 06 (2018) 022,ATL-PHYS-PUB-2019-011**]**
- 3 benchmark points with chargino decay length 3 mm, 3 cm and 30 cm.



Boosted $\tilde{\chi}_1^{\pm}$ → more distance

Trigger	Cuts
Trigger 1	$p_{T,\ell} > 30$ GeV, $\lvert\eta_\ell\rvert < 2.5$
Trigger 2	At least one jet with $p_T > 200$ GeV and $\lvert\eta\rvert < 2.5$
Trigger 3	At least two jets with $p_T > 150$ GeV and $\lvert\eta\rvert < 2.5$

Trigger cuts	$\beta c\gamma\tau$ of $\tilde{\chi}_1^{\pm}$	Fraction of events after trigger in % within					
		0 – 3 mm	3 – 30 mm	30 mm - 10 cm	10 – 30 cm	30 – 100 cm	> 100 cm
Trigger 1	3 mm	26.61	59.49	13.58	0.32	0.0	0.0
	3 cm	9.83	22.56	32.53	28.48	6.57	0.03
	30 cm	6.16	6.27	14.07	27.99	35.27	10.24
Trigger 2	3 mm	24.07	60.49	15.10	0.34	0.0	0.0
	3 cm	9.49	19.44	31.62	31.89	7.51	0.05
	30 cm	5.86	6.01	13.64	27.66	36.39	10.44
Trigger 3	3 mm	23.06	60.75	15.86	0.33	0.0	0.0
	3 cm	9.03	18.01	31.58	32.79	8.53	0.06
	30 cm	5.90	5.63	13.04	27.07	37.53	10.83



Probing charged Higgs in LLCP decay

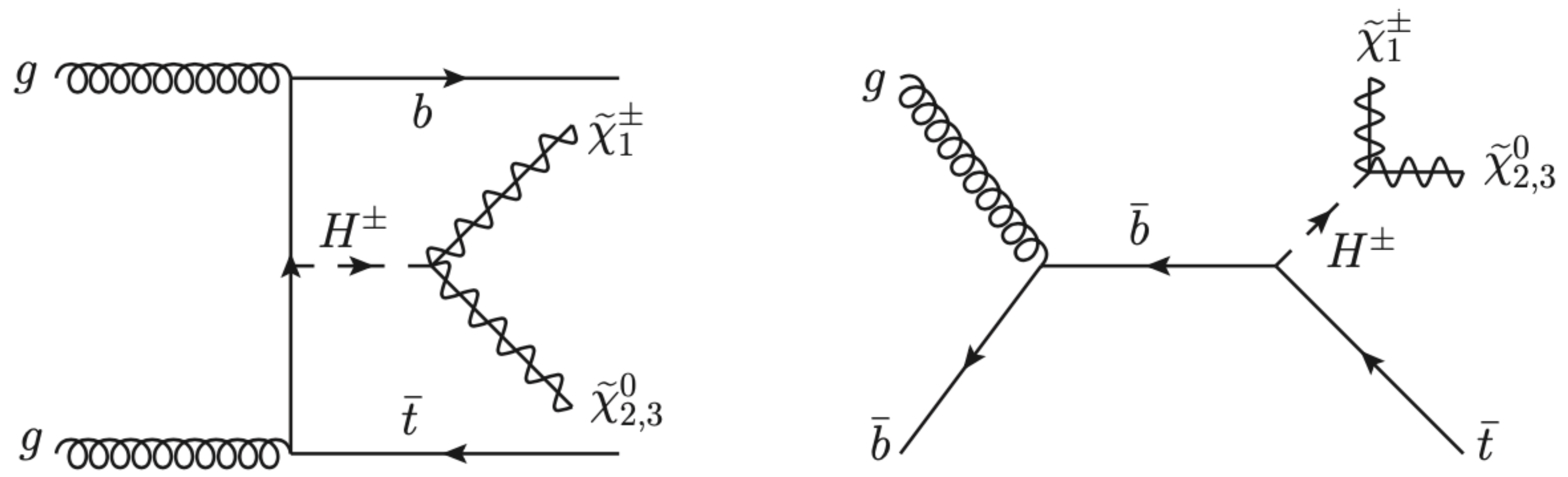


Fig. Feynman diagrams of charged Higgs production.

- $pp \to H^{\pm}\,(b\bar{t}/\bar{t})\;,\quad H^{\pm} \to \widetilde{\chi}_1^{\pm}\,\widetilde{\chi}_{2,3}^0\;,\quad \widetilde{\chi}_{2,3}^0 \to \widetilde{\chi}_1^0\,(Z/h)$
- 3 benchmark points chosen with, $m_{H^{\pm}} \sim$ 620, 820 and 1077 GeV
- 3 channels : (1) $Z \to ll$, (2) $h \to b\bar{b}$, (3) $h \to \gamma\gamma$

Summary

- We have explored various heavy Higgs final states, $H \to hh$, $H \to t\bar{t}$ and $b\bar{b}H$, $H \to \tau\tau$ and put upper limits on the production rates.

- The parameter space of Higgs sector in MSSM could be constrained more at the HL-LHC. Below $m_A \sim 2m_t$, the $pp \to hh \to b\bar{b}\gamma\gamma$ channel can probe upto $\tan\beta \sim 4$. The $pp \to H \to t\bar{t}$ can probe upto $\tan\beta \sim 4$ in $m_A \sim$ [400, 800] GeV. Finally, the $pp \to b\bar{b}H$, $H \to \tau\tau$ probes $\tan\beta \sim 5.5$ in $m_A \sim$ 1 TeV.

- Heavy Higgs can decay to susy particles with distinct kinematic features and susy backgrounds are important. Tagging additional b-jet will improve the final signal significance.

- A wino-like chargino is long-lived. If it comes from the decay of a heavy Higgs boson, it can be can travel more distance because of the boost received from heavy Higgs. This can improve the sensitivity of disappearing track searches at the LHC.

Thank you