Searching for resonances in the Higgs cascade decay

Dong Woo Kang
(SKKU & Yonsei U.)

Work in progress with

Seodong Shin (Yonsei U & Chicago U.)
Radovan Dermisek, Enrico Lunghi,
(Indiana U.)
Seongchan Park (Yonsei U.)

Plan

- Brief review of 2HDM status
- Higgs cascade decay
- Cut-based analysis
- MVA using BDT method
- Summary

Status of 2HDM

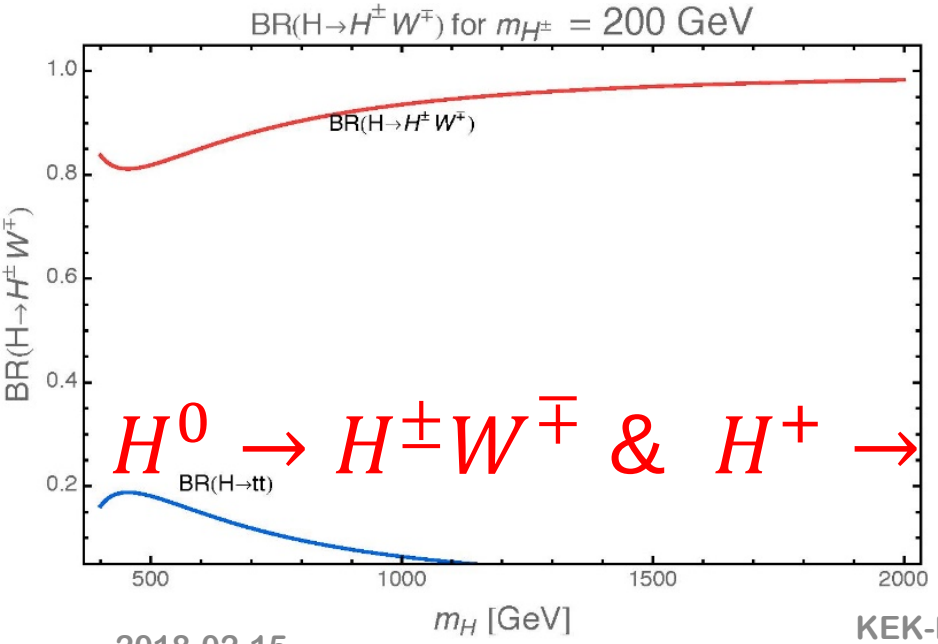
- LHC Higgs signal strength → Alignment limit
- No non-SM scalar is discovered → Heavy mass
- Electroweak precision test → $M_{H^0}, M_A, M_{H^\pm}$ Two are degenerated
- Flavor physics constraint → $M_{H^\pm} > 480$ GeV

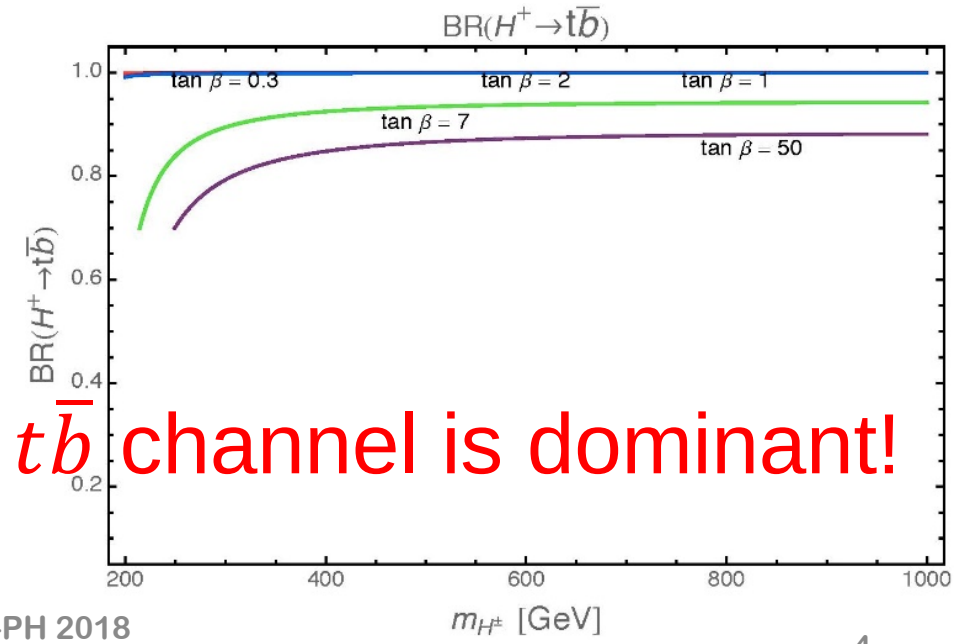
Heavy mass regime

- In alignment limit, $\cos(\beta-\alpha)\approx 0$
  (2HDM Type-II for example)

$$H^{\pm}W^{\mp}h \propto \frac{g}{2}\cos(\beta-\alpha) \quad H^{\pm}W^{\mp}H \propto \frac{g}{2}\sin(\beta-\alpha) \quad H^{\pm}W^{\mp}A \propto \frac{g}{2}$$

$$H^{-}t\bar{b} \propto \frac{g}{2\sqrt{2}m_W}V_{tb}[m_t \cot\beta P_L + m_b \tan\beta P_R]$$





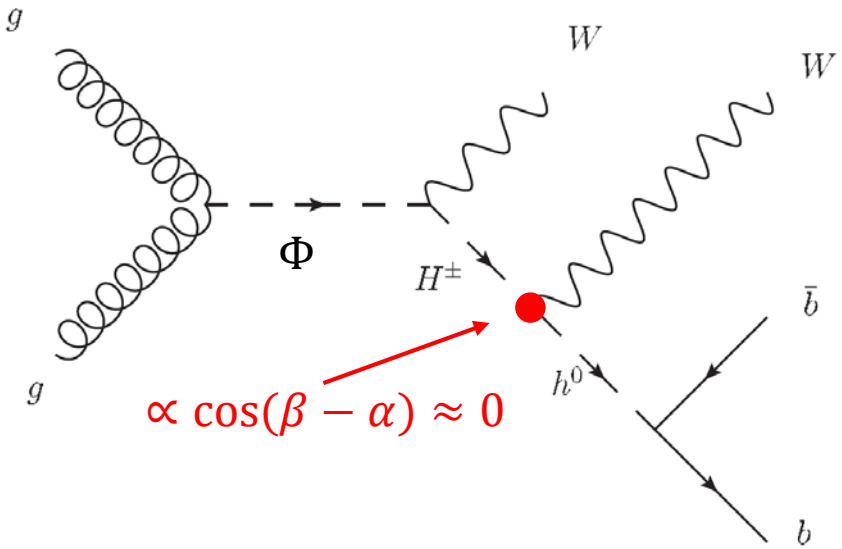
$H^0 \to H^{\pm}W^{\mp}$ & $H^+ \to t\bar{b}$ channel is dominant!

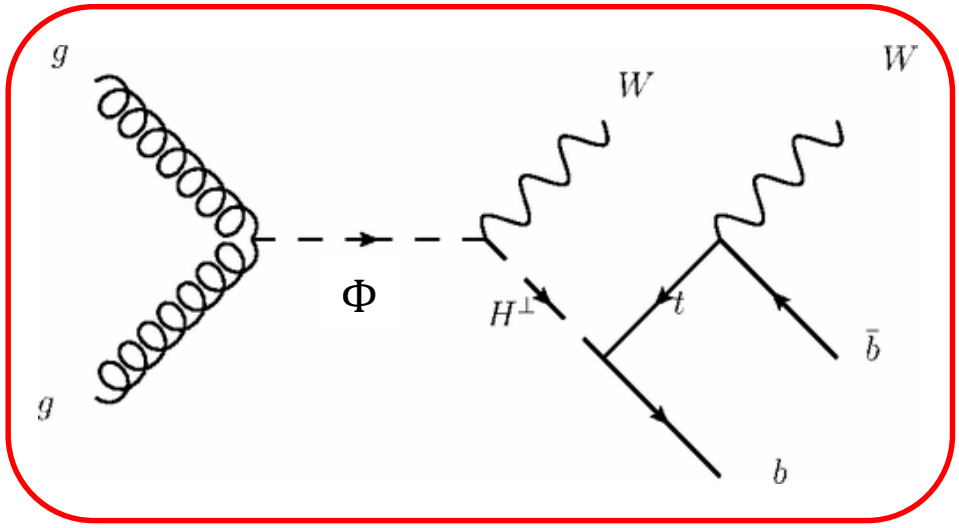
Higgs cascade decay

J. Evans, B. Kilminster, M. A. Luty, D. Whiteson, 1201.3691
R. Dermisek, J. P. Hall, E. Lunghi, S. Shin, 1311.7208

Φ : H^0 or A^0

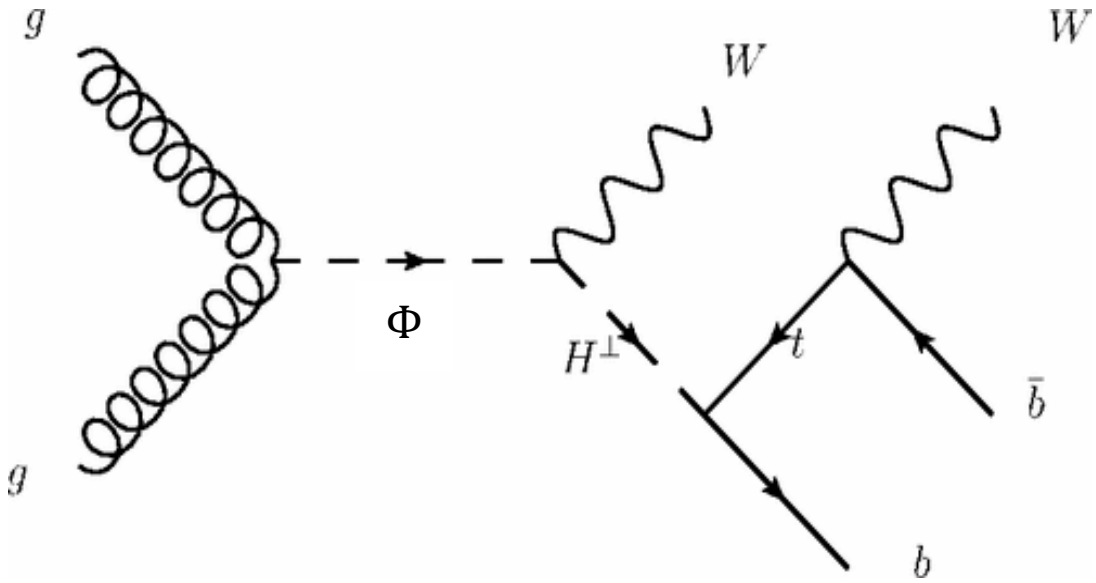
CMS: 1212.3837, ATLAS: 1312.1956





Our work

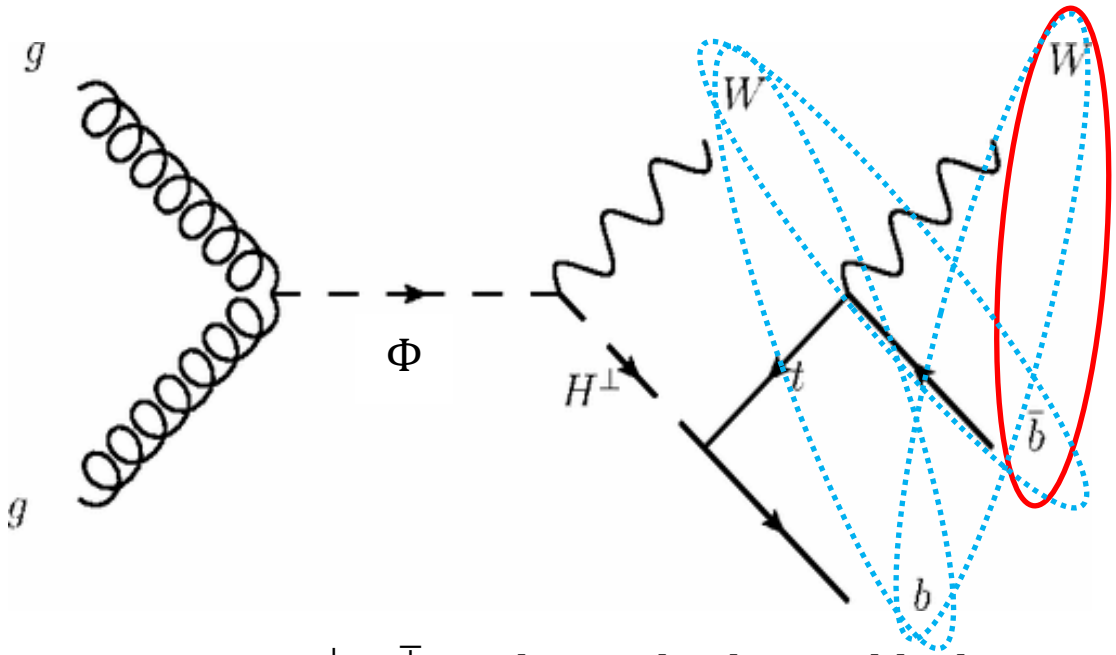
Higgs cascade decay



$$pp \to \Phi \to H^{\pm}W^{\mp} \to tbW \to bWbW \to bbjjl\nu$$

- Semileptonic channel
  - Can reconstruct neutrino momentum
  - Can reconstruct full event

Higgs cascade decay



$$pp \to \Phi \to H^{\pm}W^{\mp} \to tbW \to bWbW \to bbjjl\nu$$

- Combinatorial issue
  - Can solve by finding correct top (b W) candidate

$$\chi^2_{top} = \left(\frac{m_{jj}-m_W}{\sigma_W}\right)^2 + \min\left(\left(\frac{m_{bjj}-m_{t_h}}{\sigma_{t_h}}\right)^2, \left(\frac{m_{b\ell\nu}-m_{t_\ell}}{\sigma_{t_\ell}}\right)^2\right)$$

Useful kinematic variables

- $\chi^2_{t\bar{t}}$

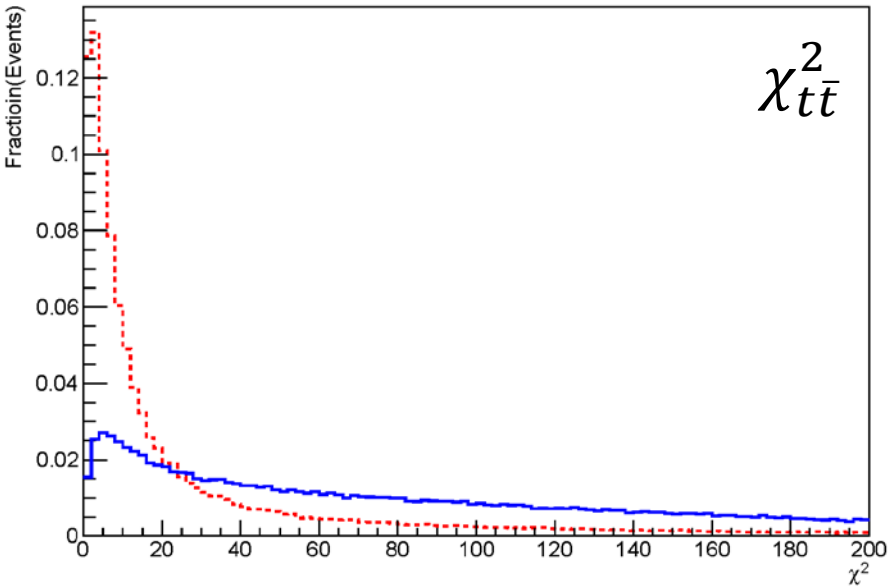
$$\chi^2_{t\bar{t}} = \left(\frac{m_{jj}-m_W}{\sigma_W}\right)^2 + \left(\frac{m_{jjb}-m_{jj}-m_{t_h-W}}{\sigma_{t_h-W}}\right)^2 + \left(\frac{m_{j\ell\nu}-m_{t_\ell}}{\sigma_{t_l}}\right)^2 + \left(\frac{(p_{T,jjb}-p_{T,j\ell\nu})-(p_{T,t_h}-p_{T,t_\ell})}{\sigma_{\mathrm{diff}p_T}}\right)^2$$

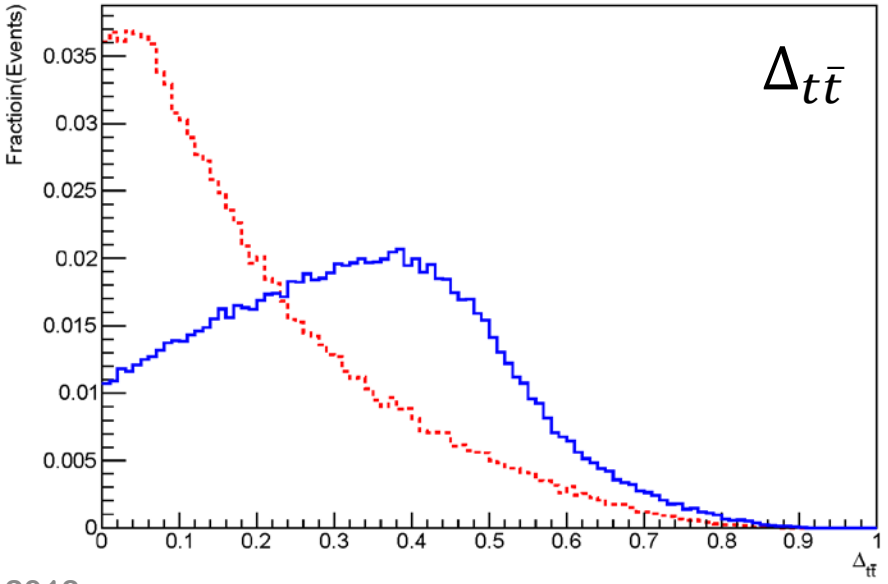
- Mass difference of top candidates

$$\Delta_{t\bar{t}} = \frac{|M_{bjj} - M_{b\ell\nu}|}{M_{bjj} + M_{b\ell\nu}}$$

$t\bar{t}$ background

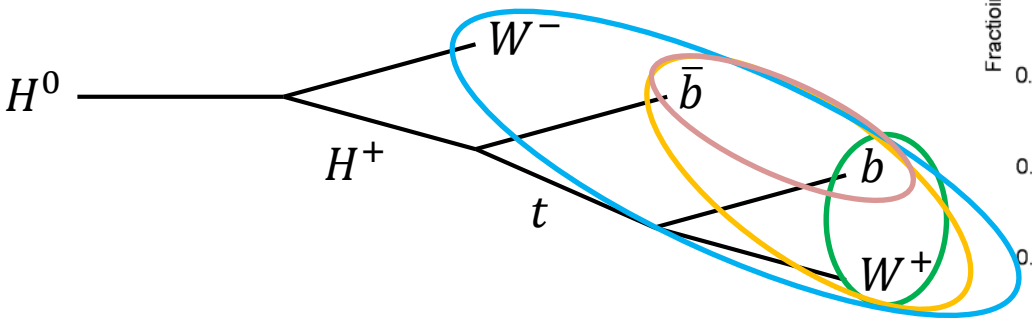
$M_{H^0} = 800$ GeV, $M_{H^\pm} = 600$ GeV





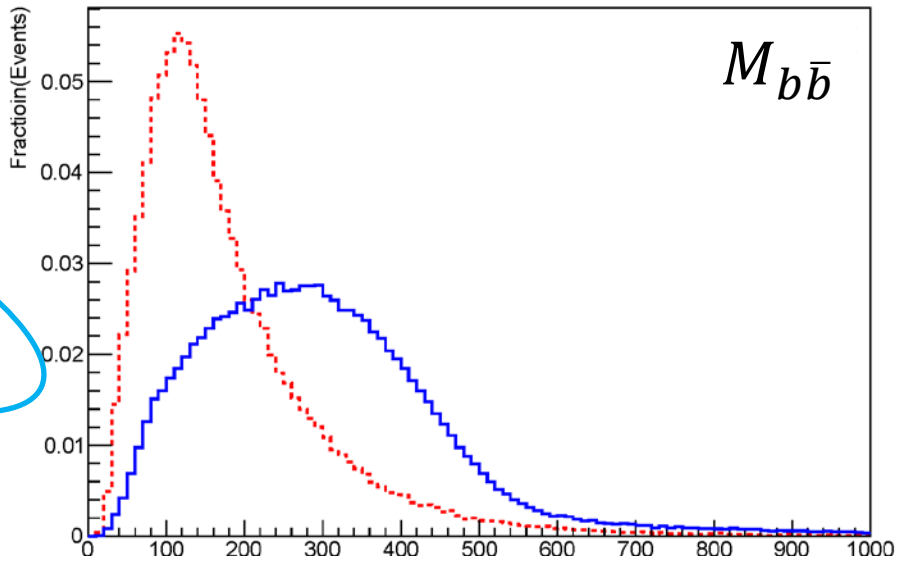
Useful kinematic variables

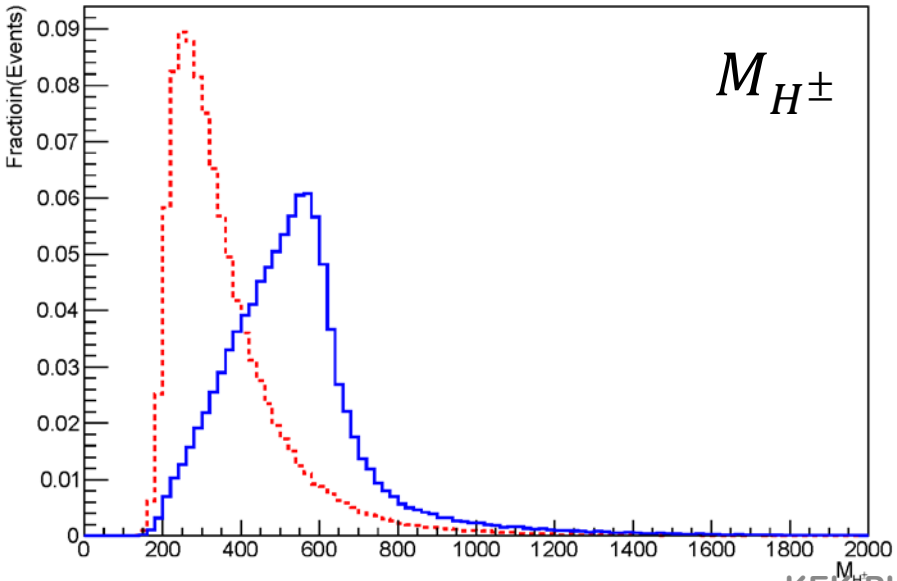
- Invariant masses

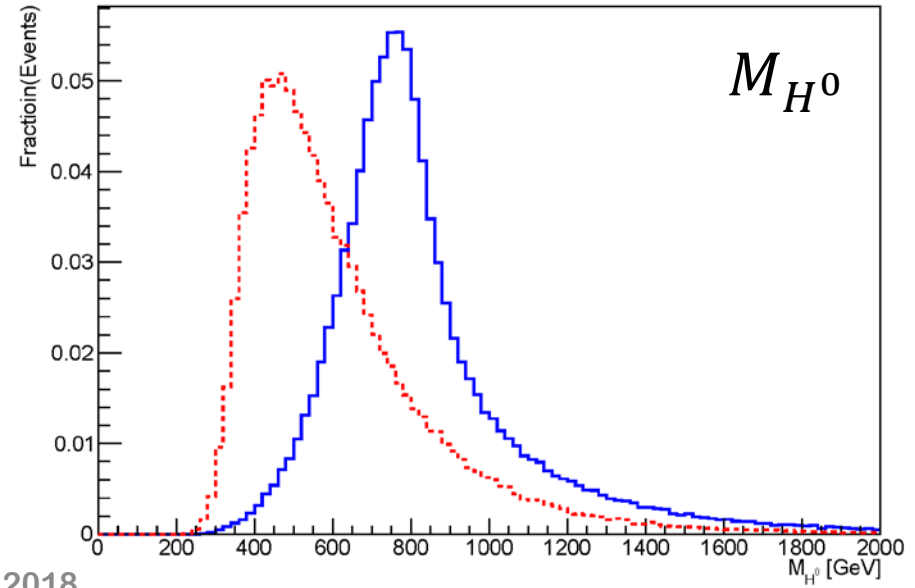


$t\bar{t}$ background

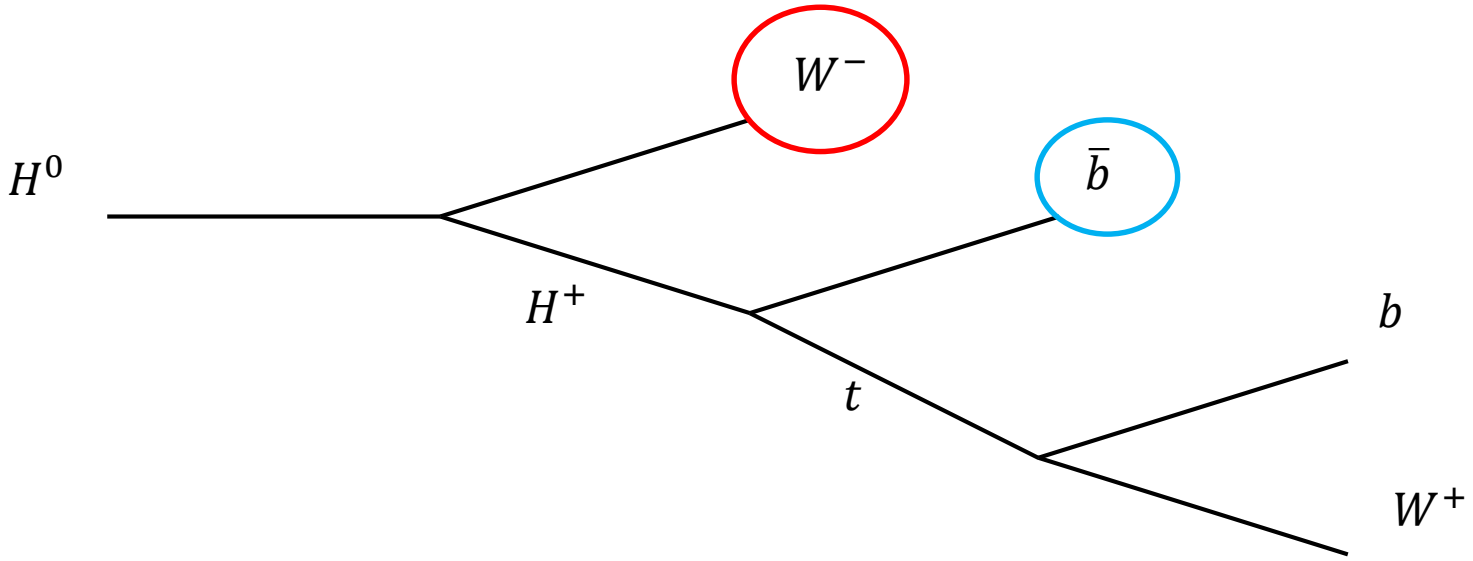
$M_{H^0} = 800$ GeV, $M_{H^\pm} = 600$ GeV





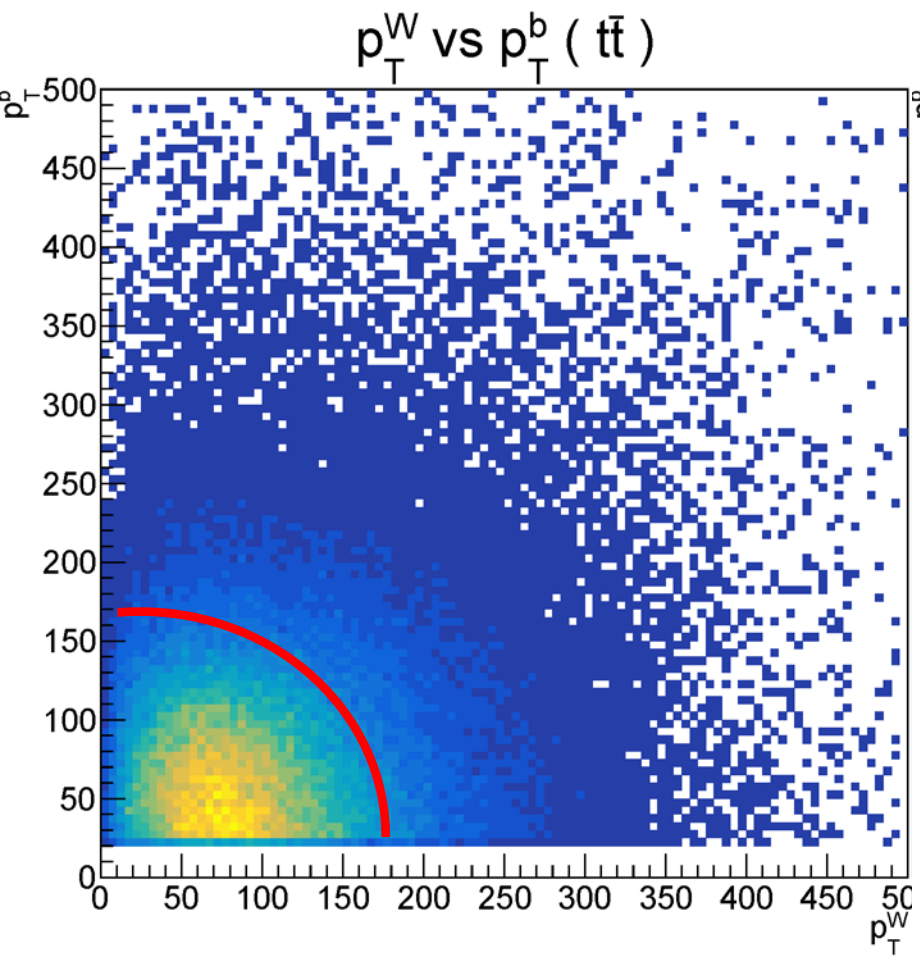


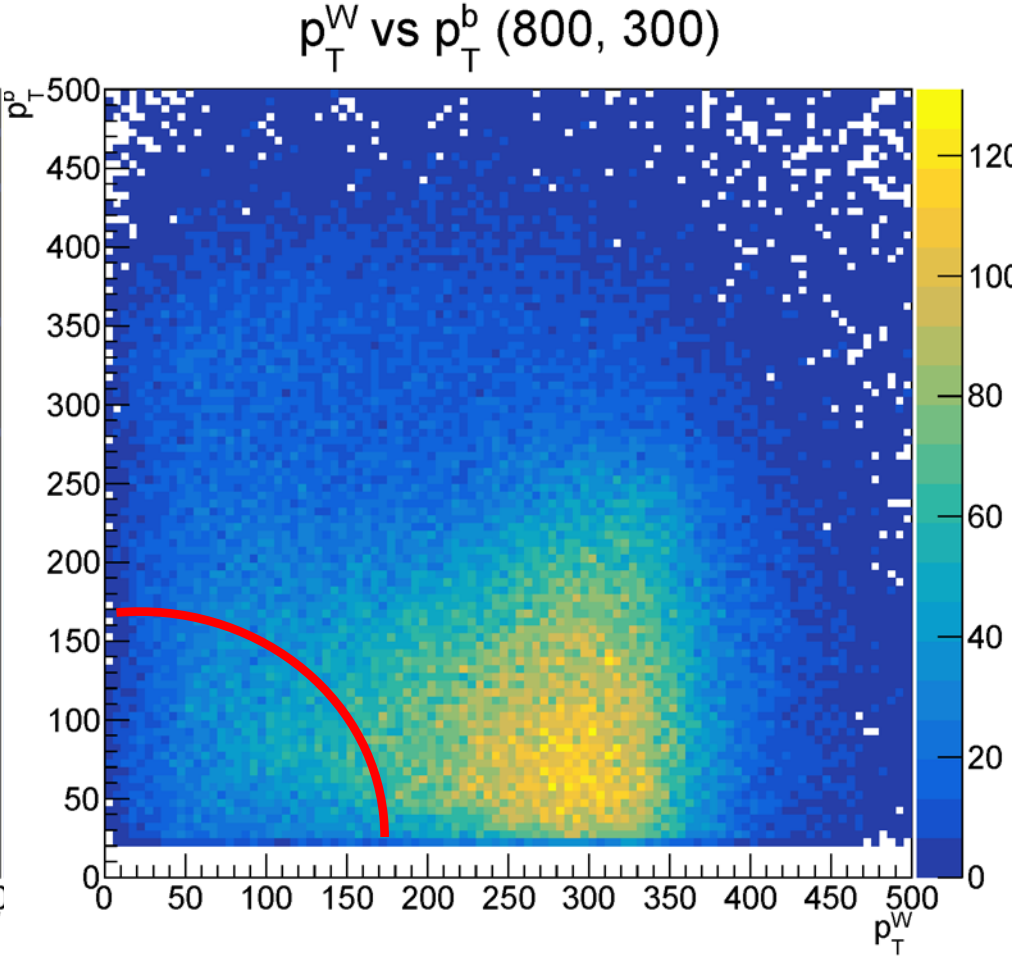
Prompt b & W pT



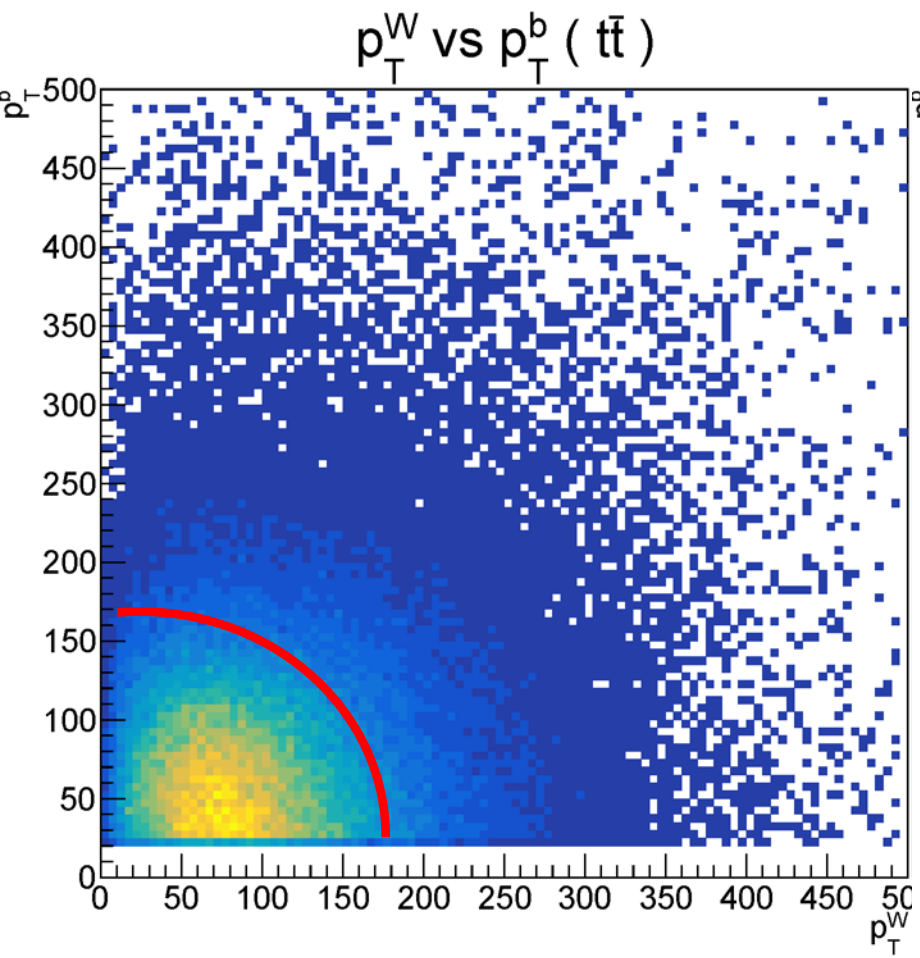
- $M_{H^0} - M_{H^\pm}$ is large, W have larger p_T
- $M_{H^0} - M_{H^\pm}$ is small, but $M_{H^\pm}$ is larger than M_{top}, b have larger p_T.

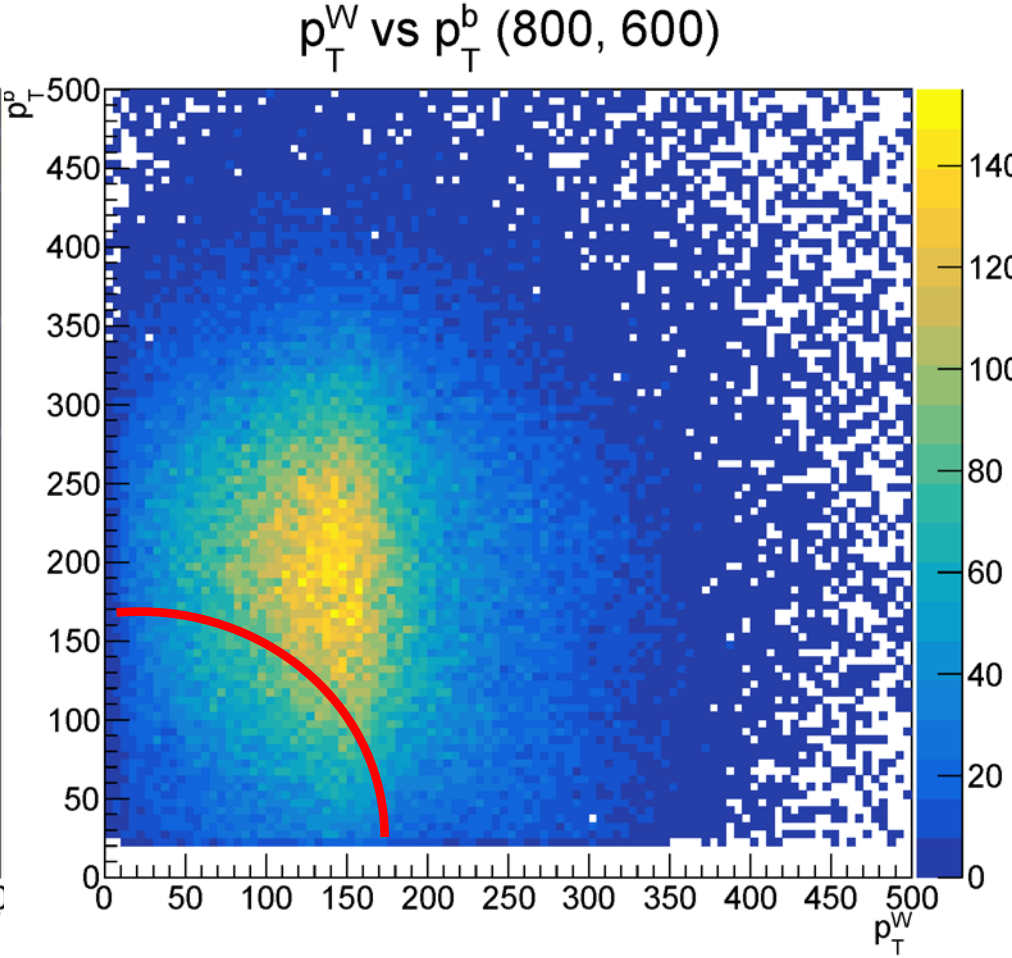
Prompt b & W pT


p_T^W vs p_T^b ($t\bar{t}$)
p_T^b
p_T^W
0
50
100
150
200
250
300
350
400
450
500

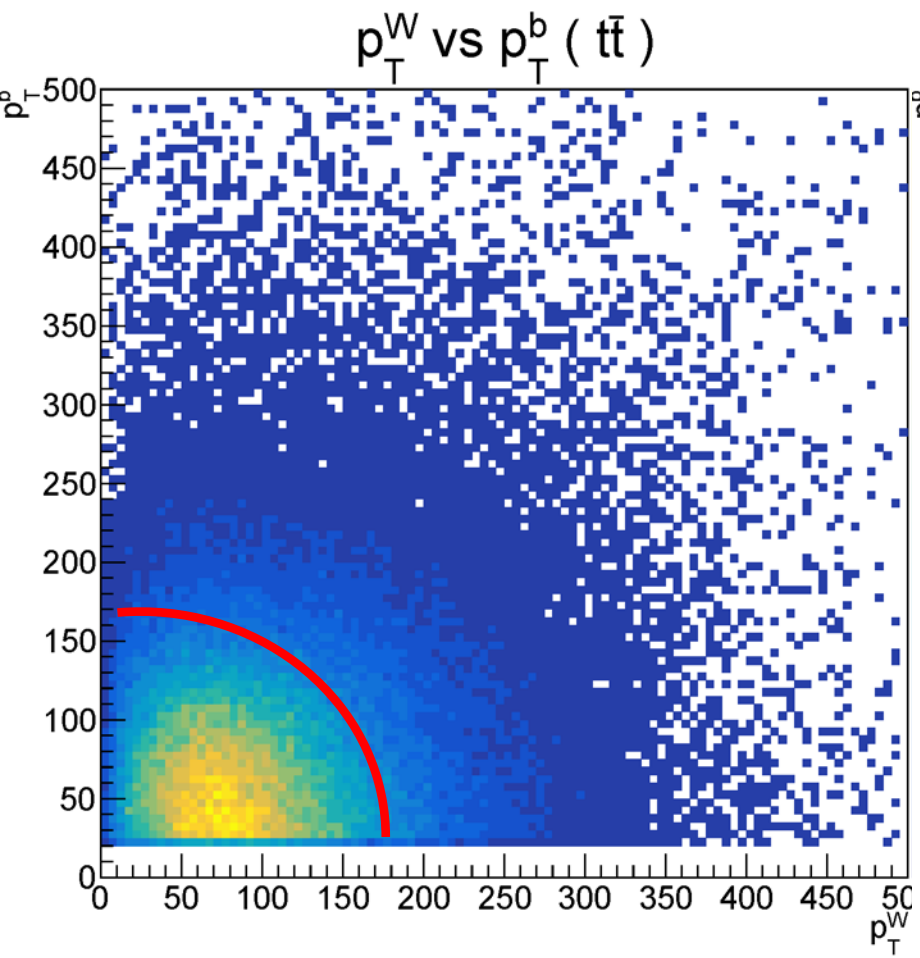

p_T^W vs p_T^b (800, 300)
p_T^b
p_T^W
0
50
100
150
200
250
300
350
400
450
500
120
100
80
60
40
20
0

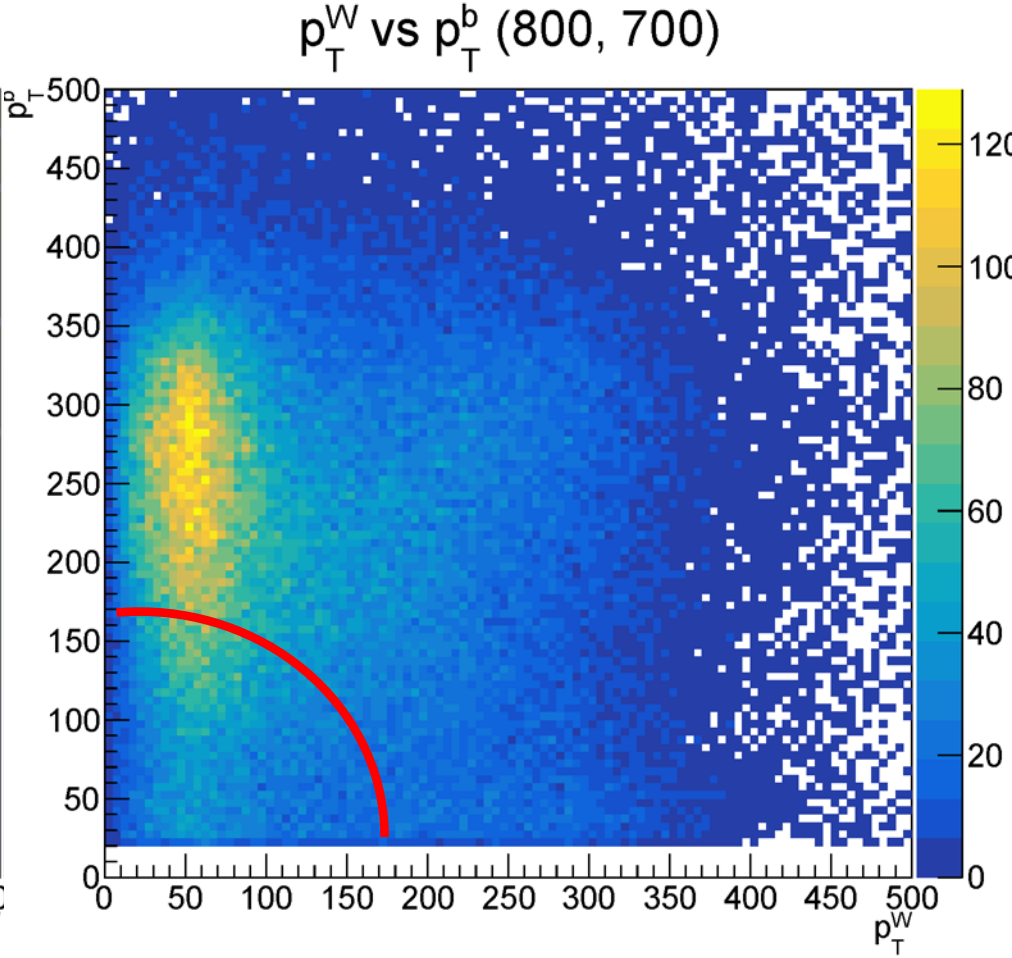
Prompt b & W pT


p_T^W vs p_T^b ($t\bar{t}$)
p_T^b
p_T^W
0
50
100
150
200
250
300
350
400
450
500


p_T^W vs p_T^b (800, 600)
p_T^b
p_T^W
0
50
100
150
200
250
300
350
400
450
500
0
20
40
60
80
100
120
140

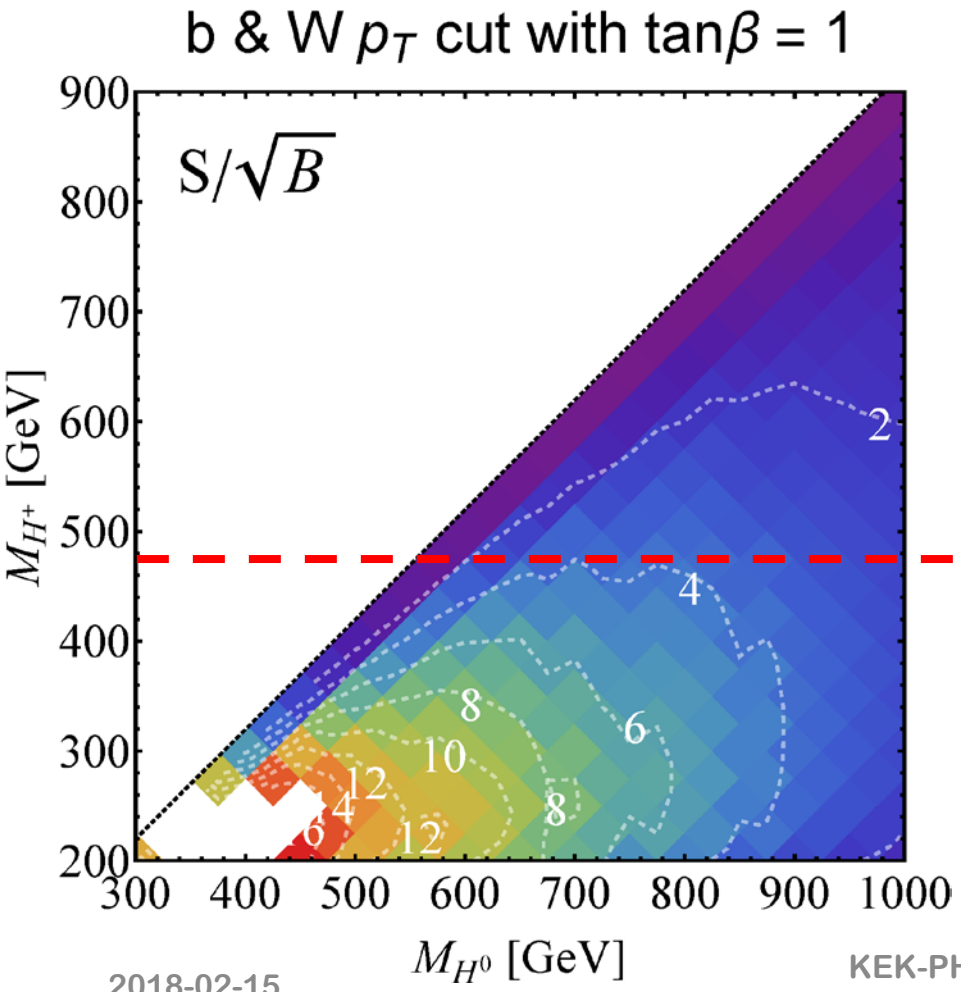
Prompt b & W pT

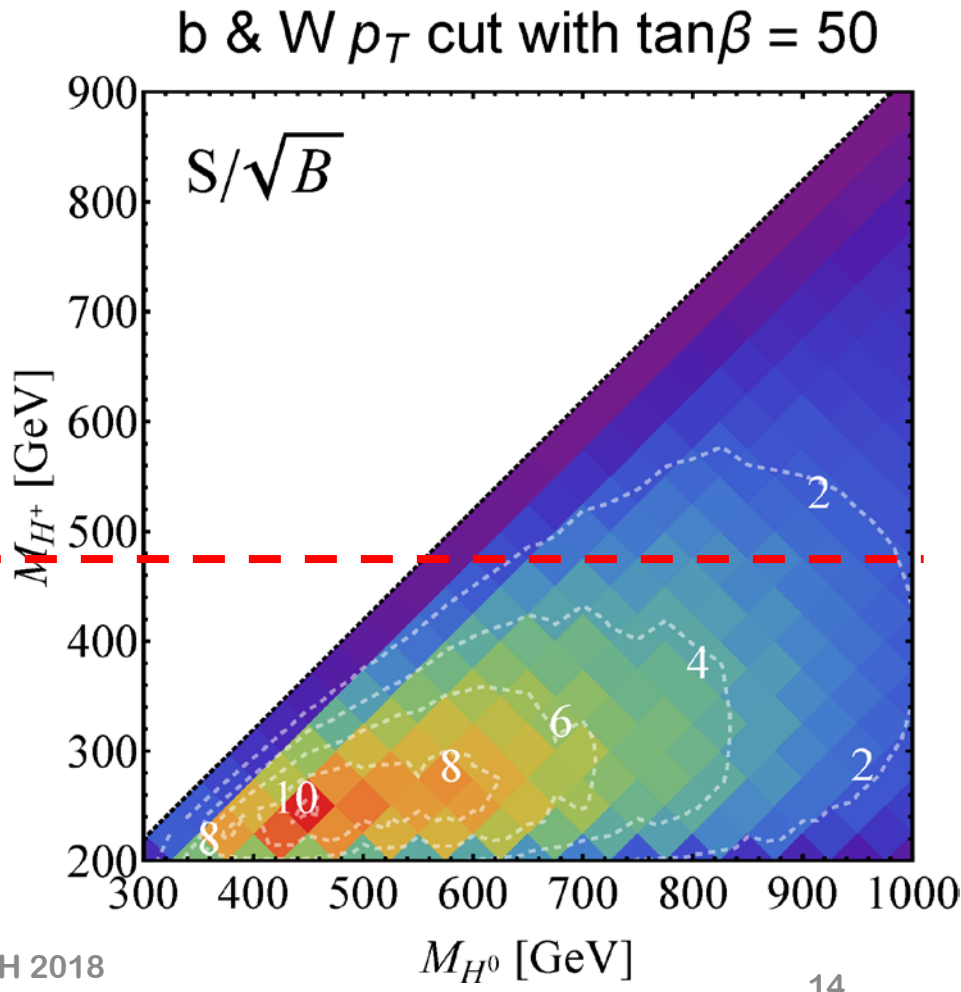

p_T^W vs p_T^b ($t\bar{t}$)
p_T^b
p_T^W
0
50
100
150
200
250
300
350
400
450
500


p_T^W vs p_T^b (800, 700)
p_T^b
p_T^W
0
50
100
150
200
250
300
350
400
450
500
120
100
80
60
40
20
0

Cut-based analysis results

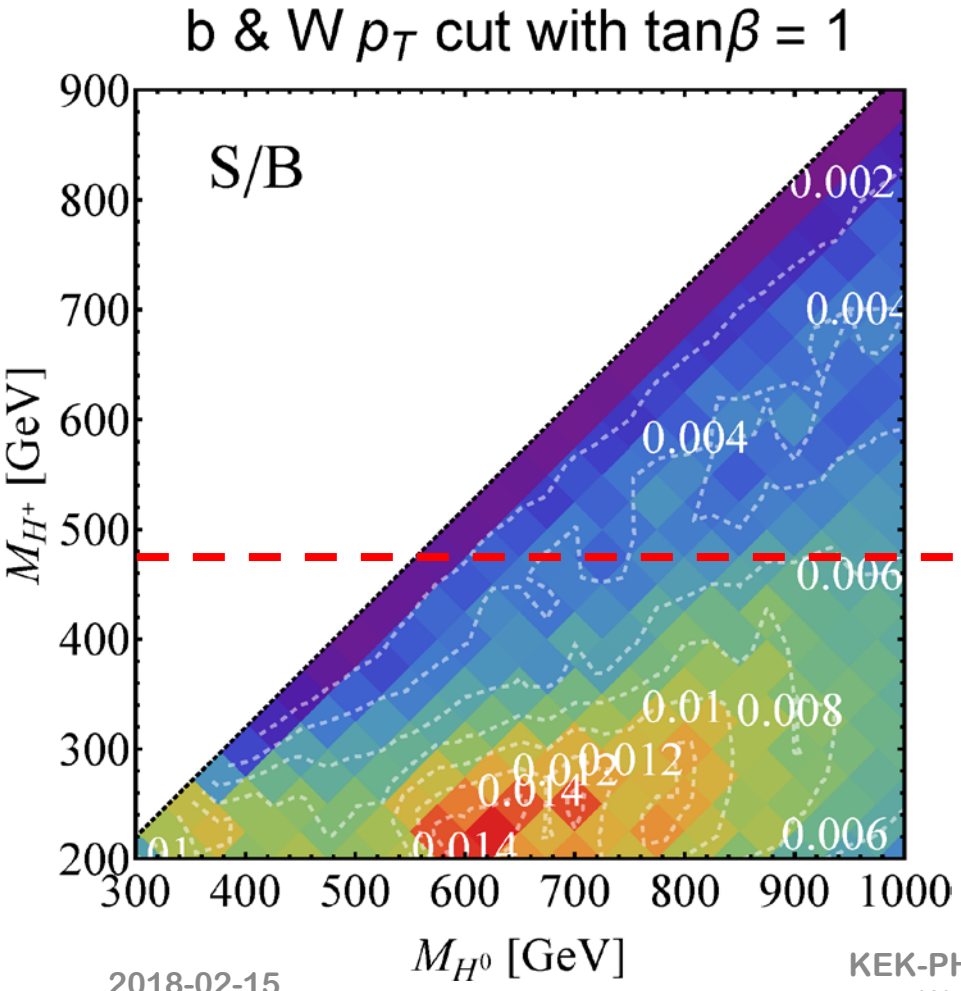
- LHC 13 TeV, $\mathcal{L} = 100\,\mathrm{fb}^{-1}$

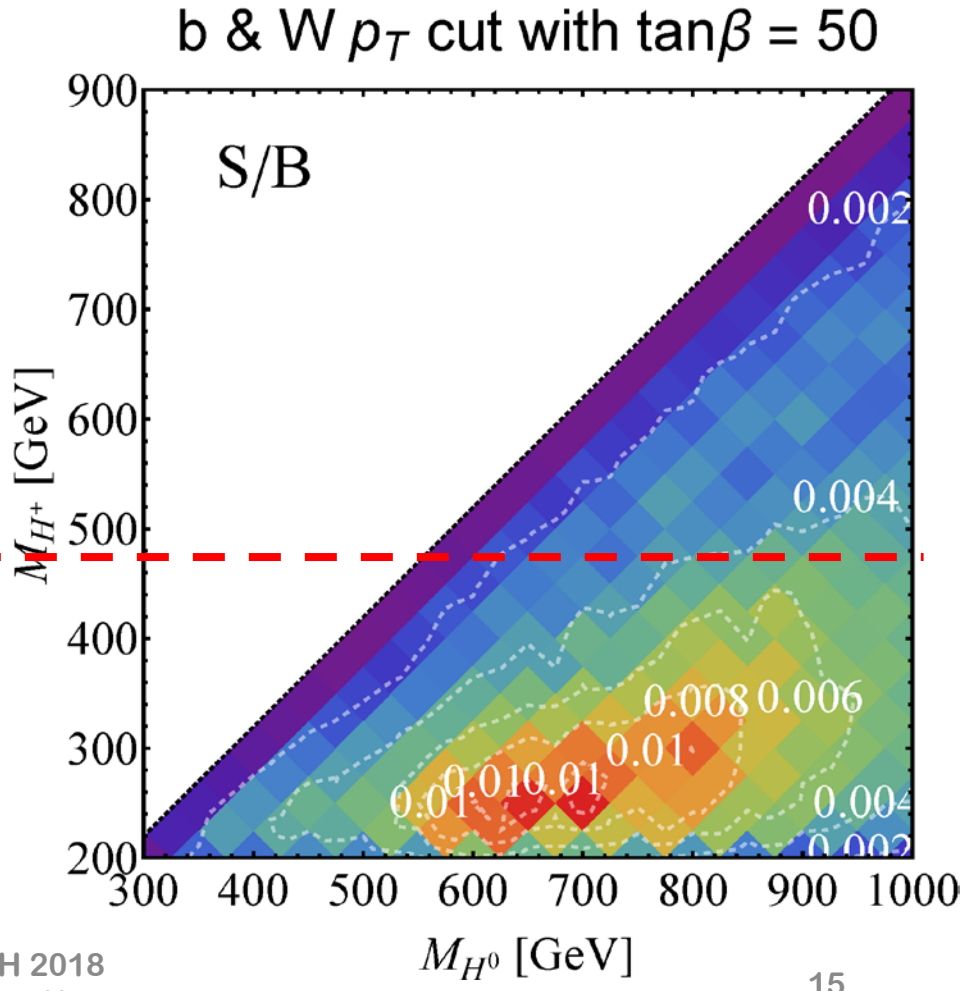




Cut-based analysis results

- LHC 13 TeV, $\mathcal{L} = 100\,\mathrm{fb}^{-1}$





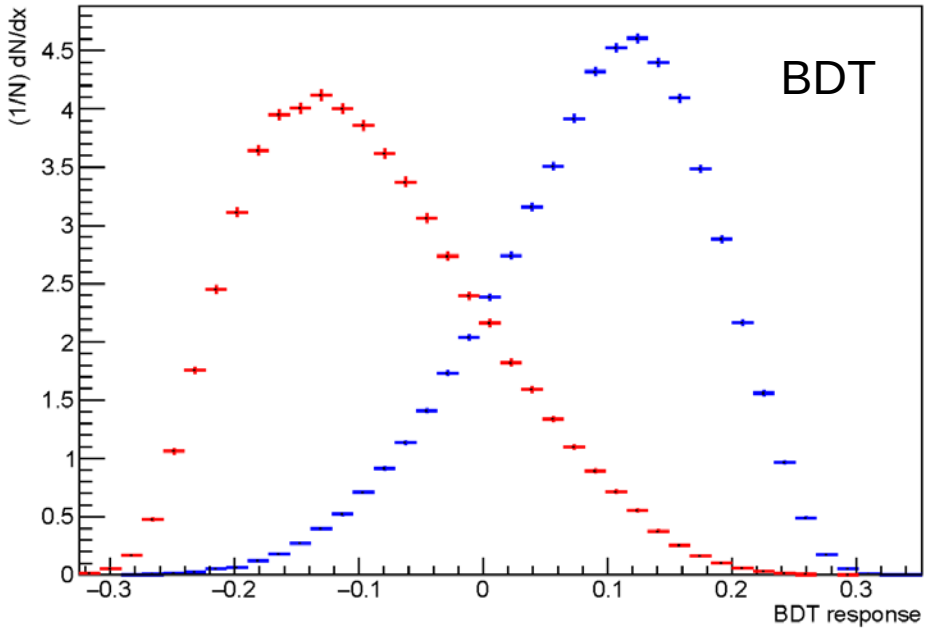
Multi-variable analysis with BDT

- MVA is performed by boosted decision tree method with TMVA toolkit

- Input variables
  - $\chi^2_{t\bar{t}}$, $\Delta_{t\bar{t}}$
  - Invariant masses
    - $M_{H^0}, M_{H^\pm}, M_{b\bar{b}}$, ….
  - Angular variables
    - $\Delta R_{ij}, \Delta\phi_{ij}$, ….
  - Transverse momentums
    - p_T^W, p_T^b, p_T^l, ….

$t\bar{t}$ background

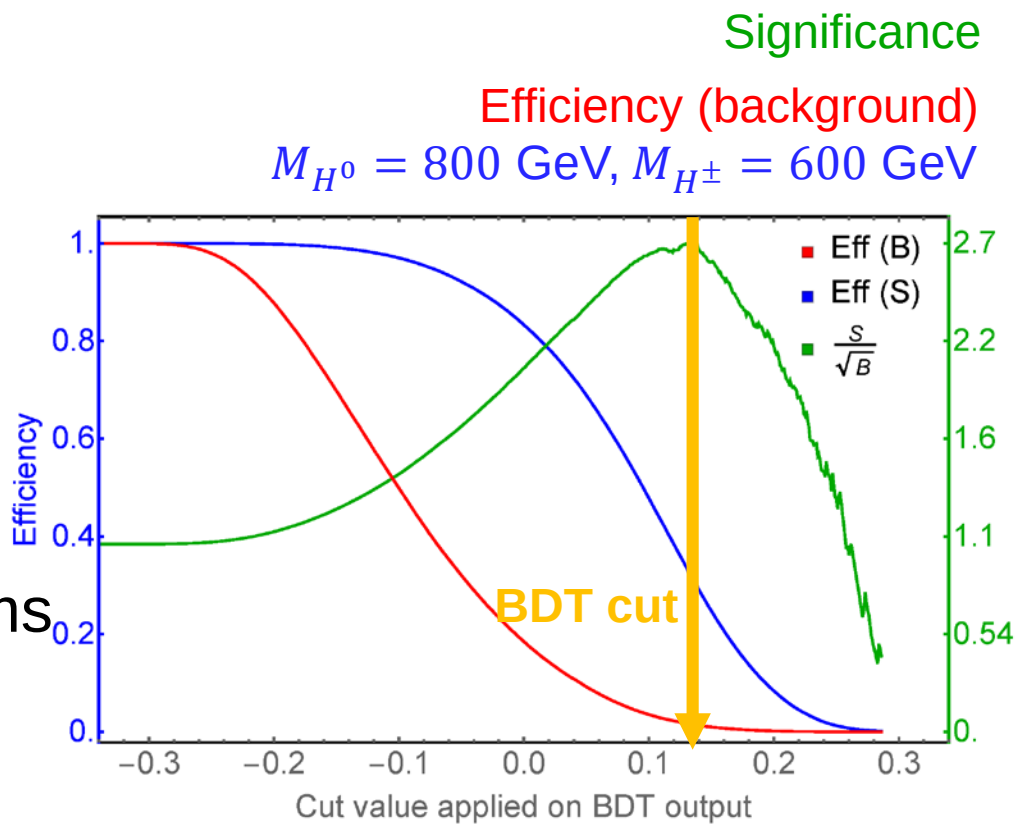
$M_{H^0} = 800$ GeV, $M_{H^\pm} = 600$ GeV



Multi-variable analysis with BDT

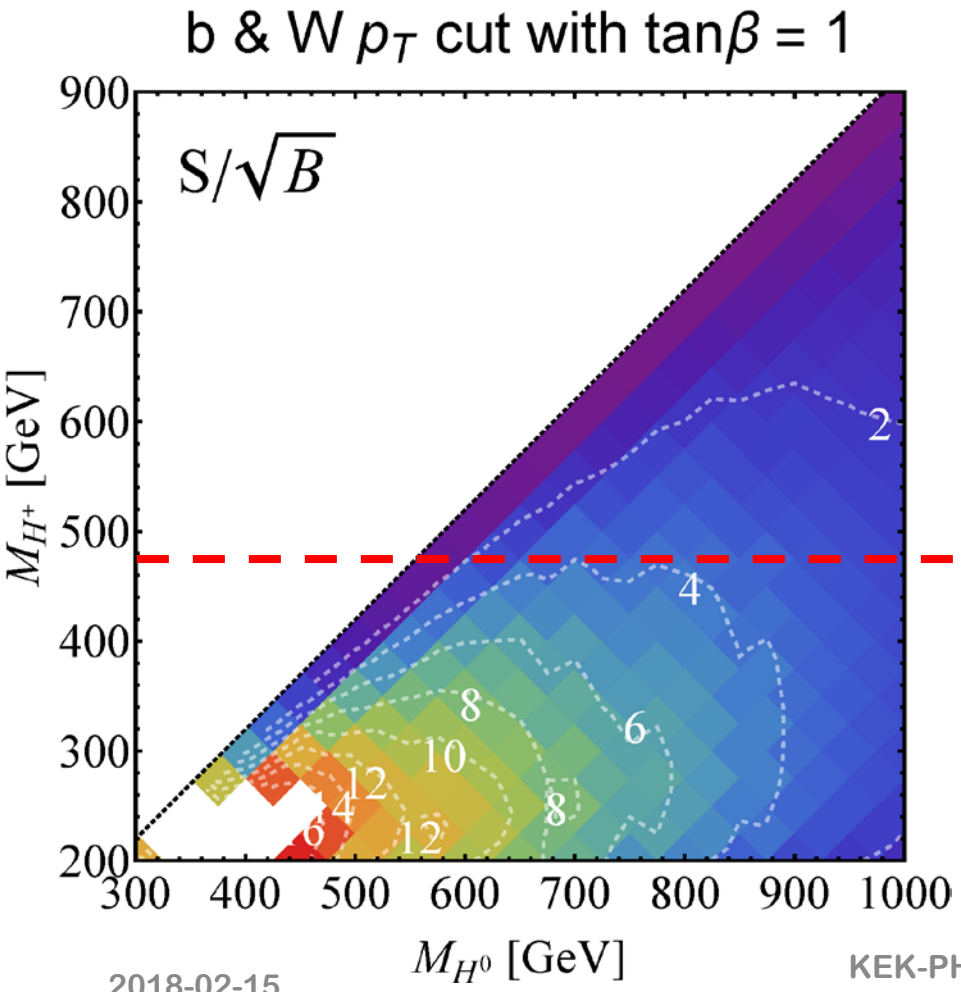
- MVA is performed by boosted decision tree method with TMVA toolkit

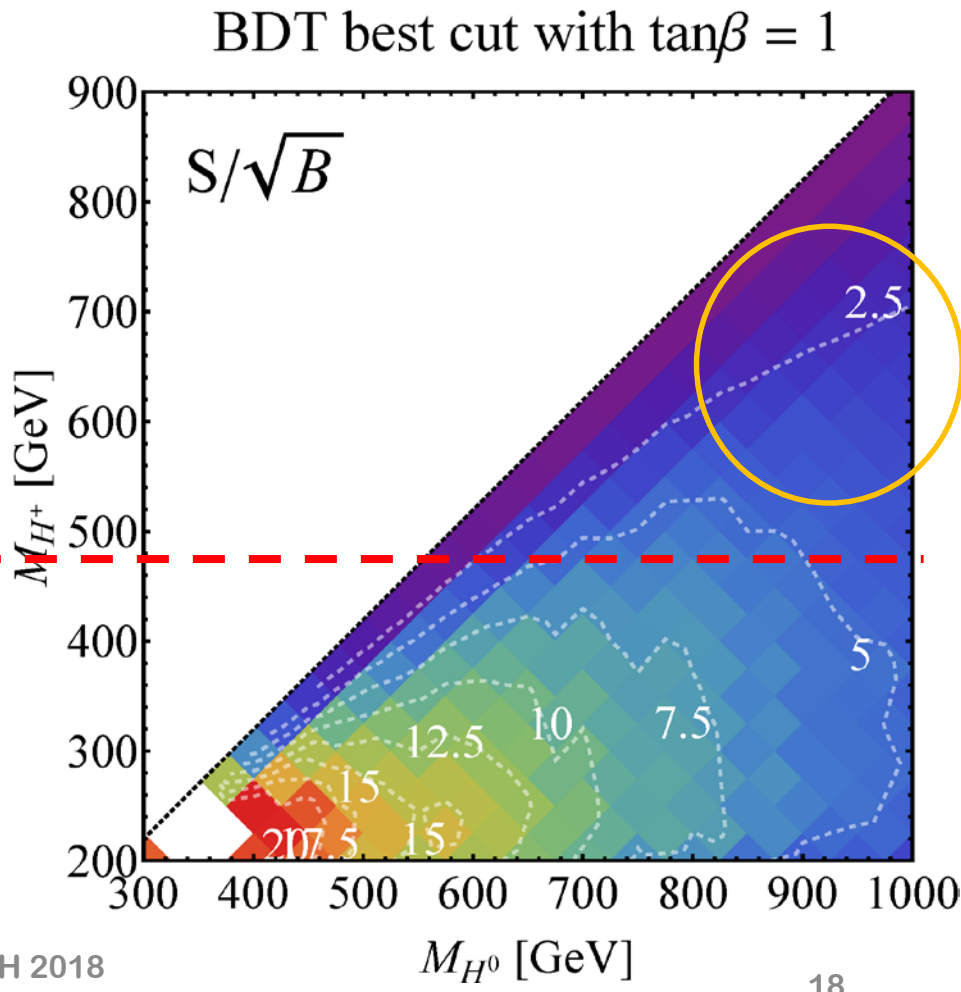
- Input variables
  - $\chi^2_{t\bar{t}}$, $\Delta_{t\bar{t}}$
  - Invariant masses
    - $M_{H^0}, M_{H^\pm}, M_{b\bar{b}}$, ….
  - Angular variables
    - $\Delta R_{ij}, \Delta\phi_{ij}$, ….
  - Transverse momentums
    - p_T^W, p_T^b, p_T^l, ….



BDT analysis results

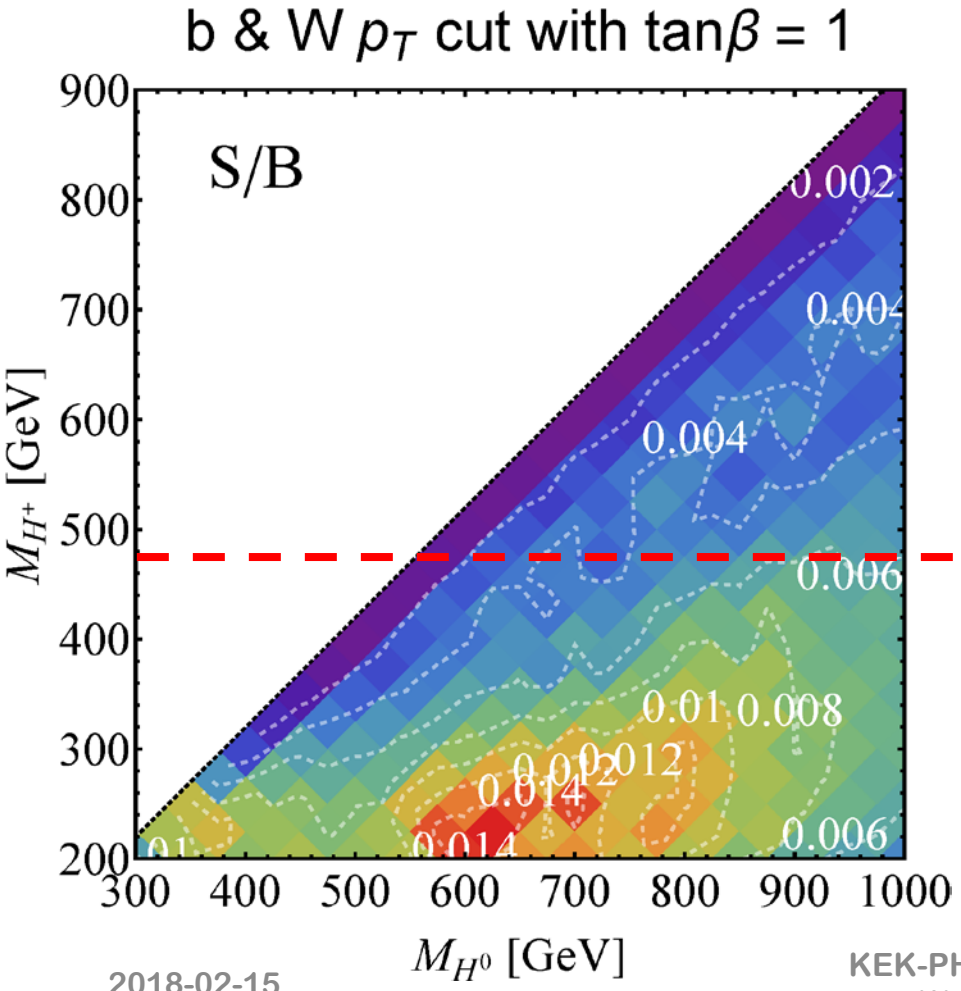
- LHC 13 TeV, $\mathcal{L} = 100\,\mathrm{fb}^{-1}$

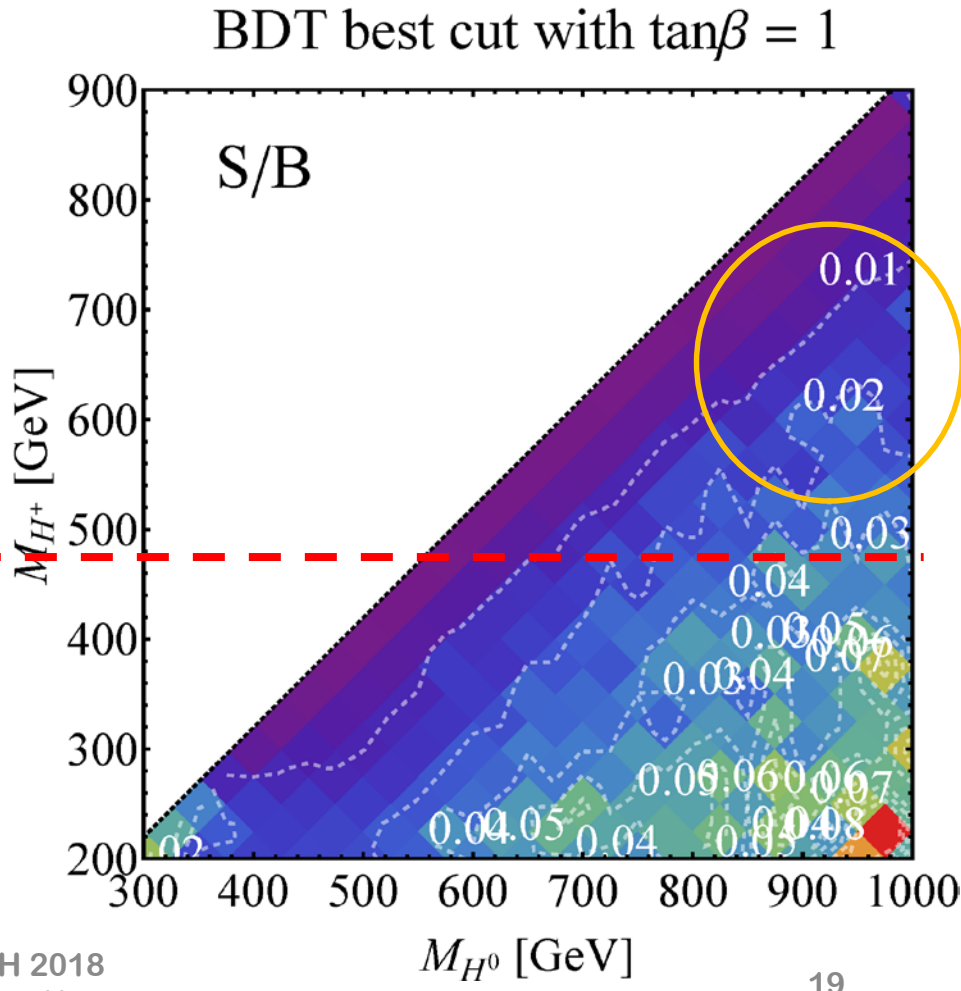




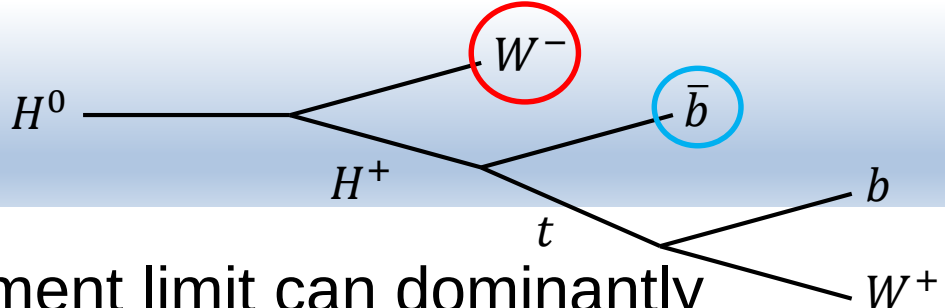
BDT analysis results

- LHC 13 TeV, $\mathcal{L} = 100\,\mathrm{fb}^{-1}$

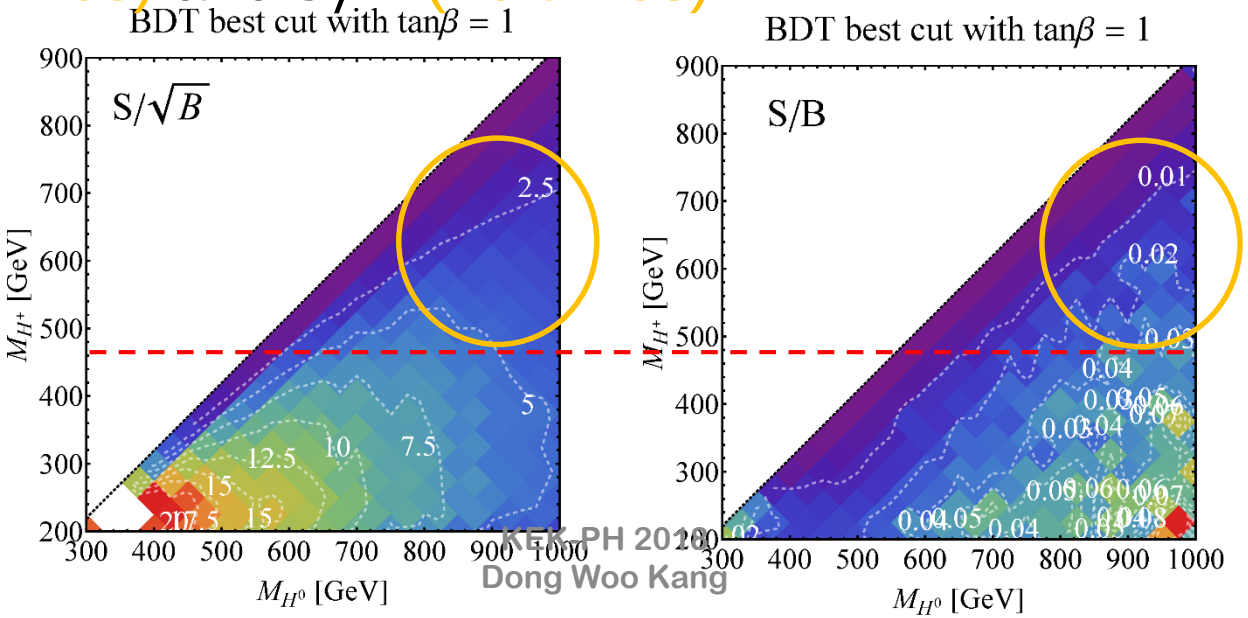




Summary



- Heavy neutral higgs in alignment limit can dominantly decay to $\underline{H^0 \to H^{\pm} W^{\mp} \to tbW}$
- We focus on the semileptonic decay channel and find p_T of prompt W & b is powerful cut to discriminate signal from the $t\bar{t}$ background.
- BDT multivariable analysis largely improve the $S/\sqrt{B}$ (~1.5 times) and S/B (~5 times).



Back up

Event generation & reconstruction

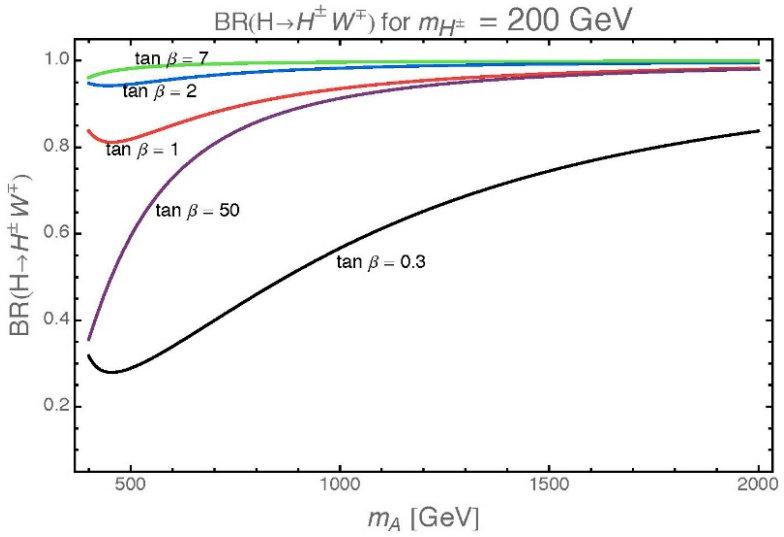
Event generation: MG5aMC@NLO + Pythia8 + Delphes.

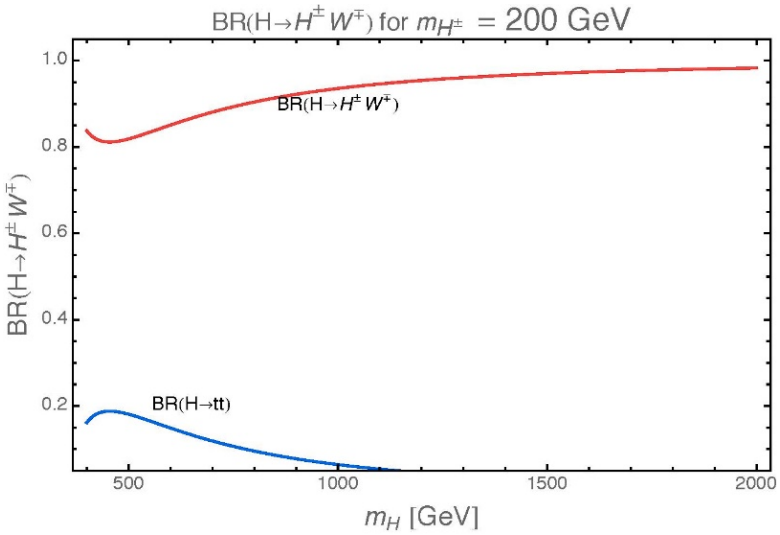
- **Background**: ttbar for simplicity

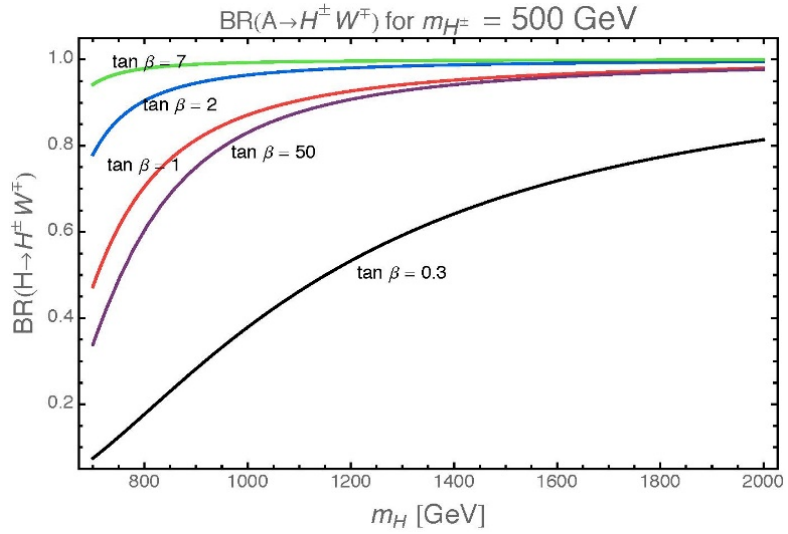
- Electron: p_T > 25 GeV and |η| < 2.5
- Muon: p_T > 25 GeV and |η| < 2.5
- Jet: p_T > 25 GeV and |η| < 2.5
- MET: E_T^{miss} > 35 GeV
- E_T^{miss}+ M_T > 60 GeV

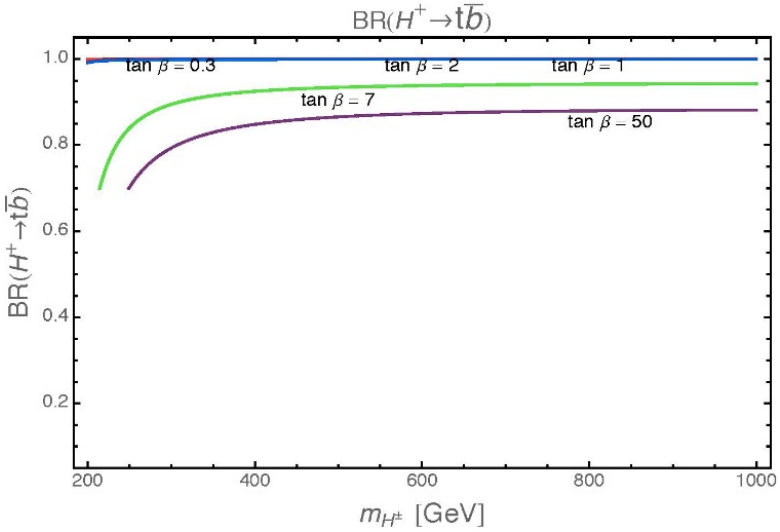
- Neutrino: reconstructed by $(p_l + p_\nu)^2 = m_W^2$.
- Hadronic W: reconstructed by 2 jet with $M_{jj} = M_W$.
- Top, Charged Higgs, Heavy Higgs : using χ^2_{top}criteria.

Branching fraction

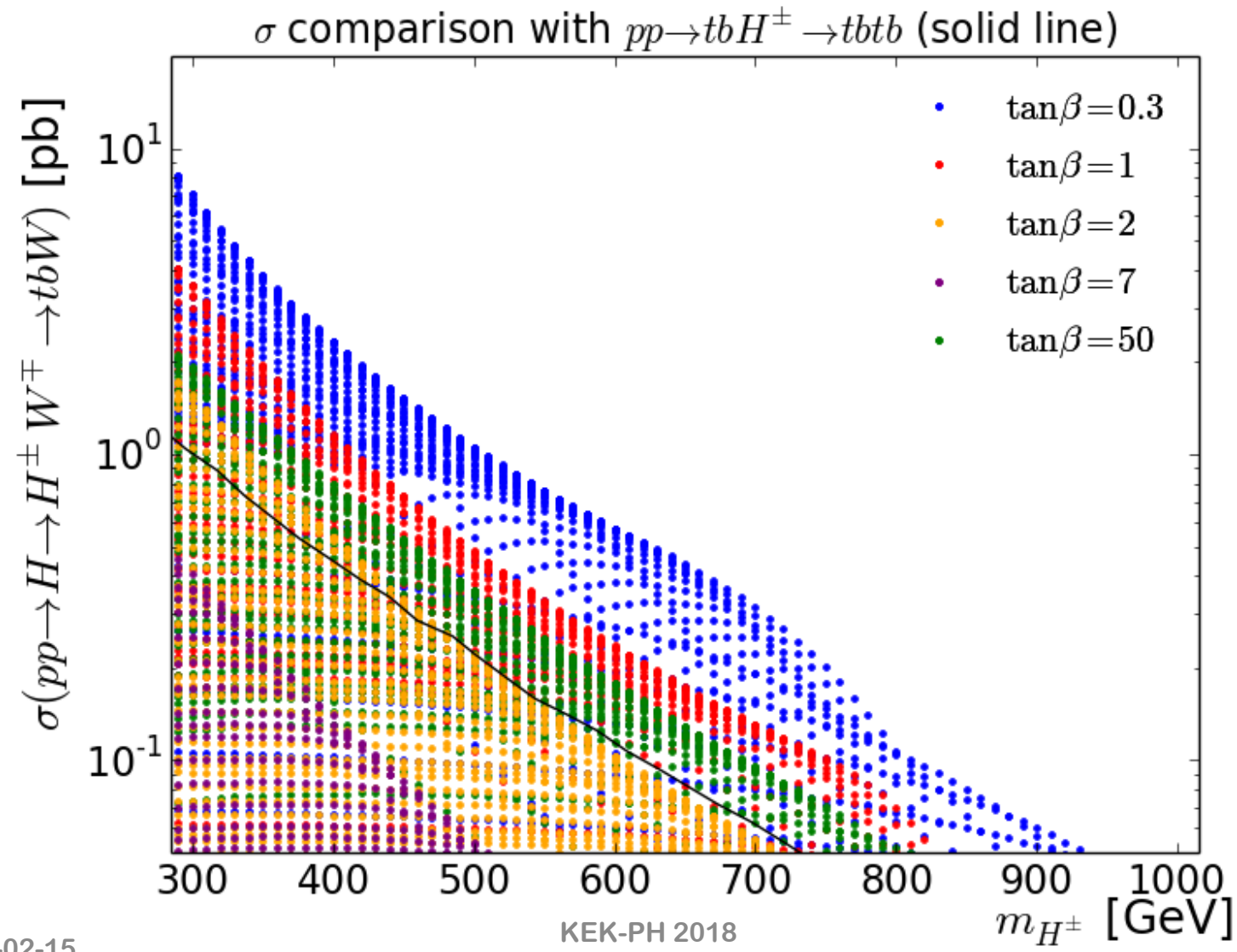






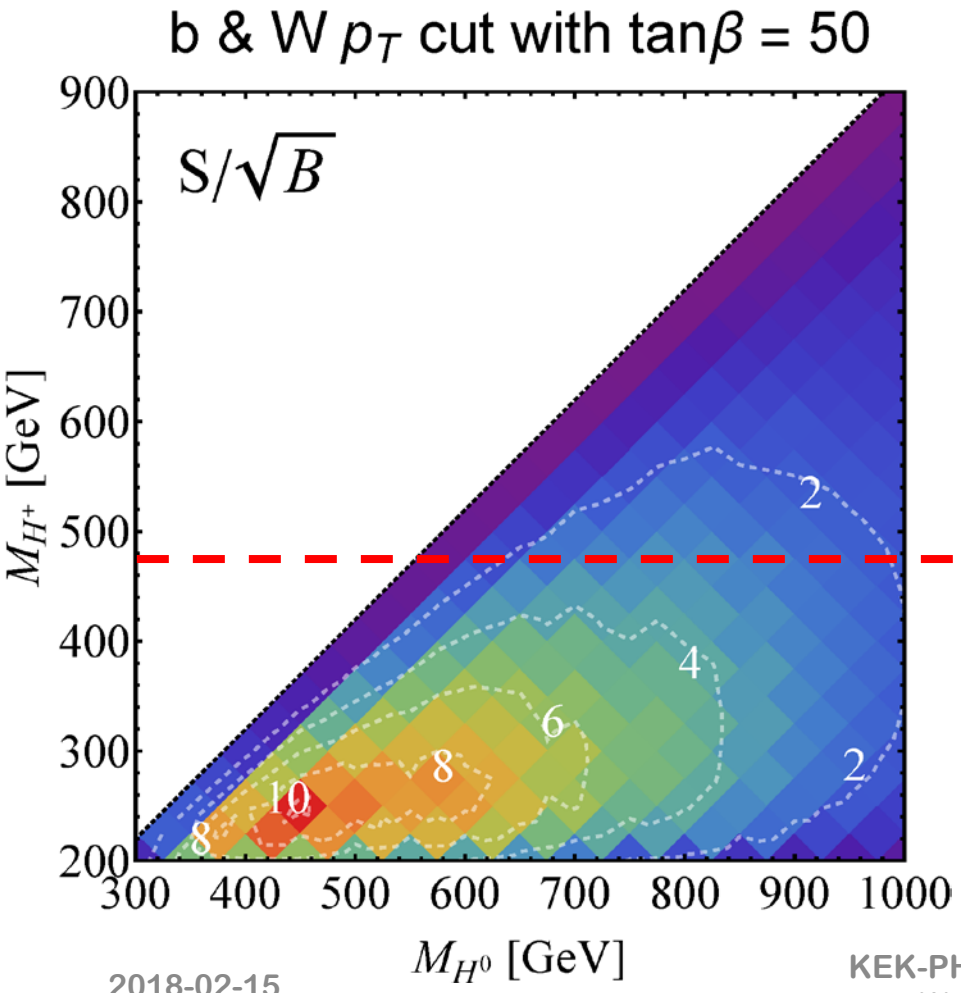


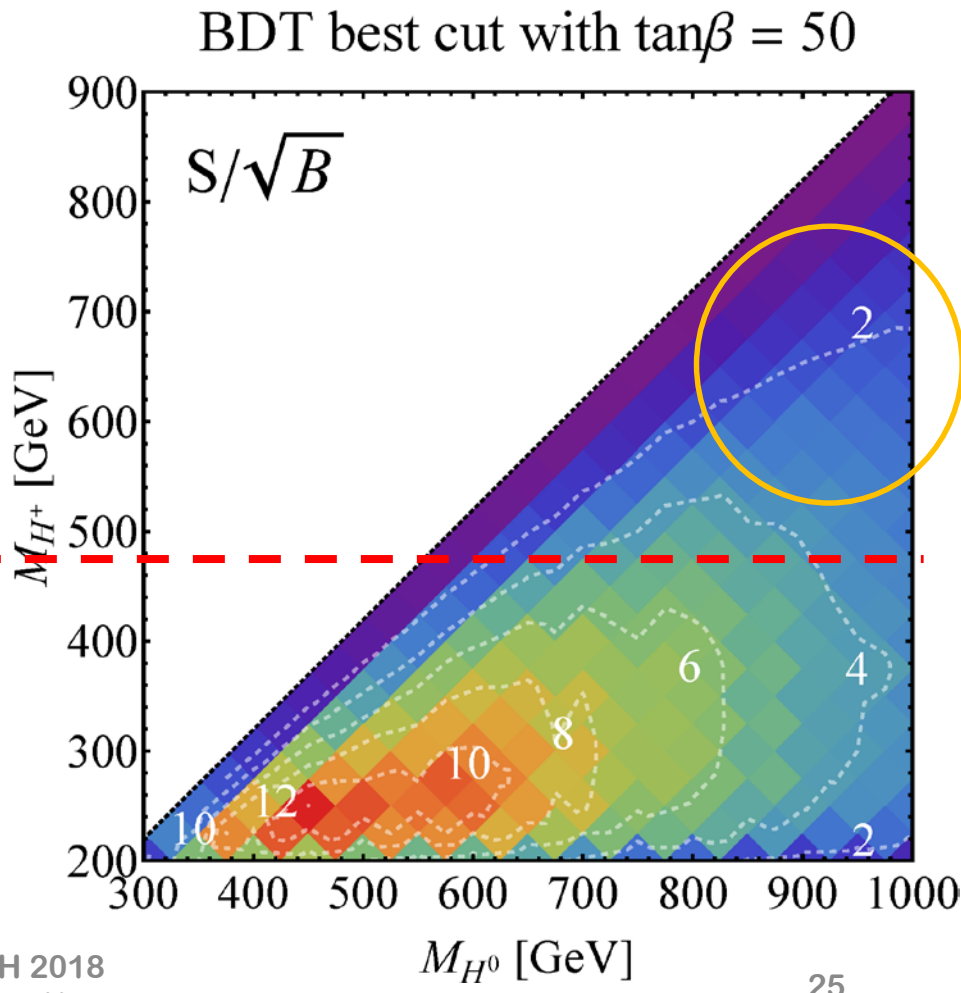
Cross sections



BDT analysis results

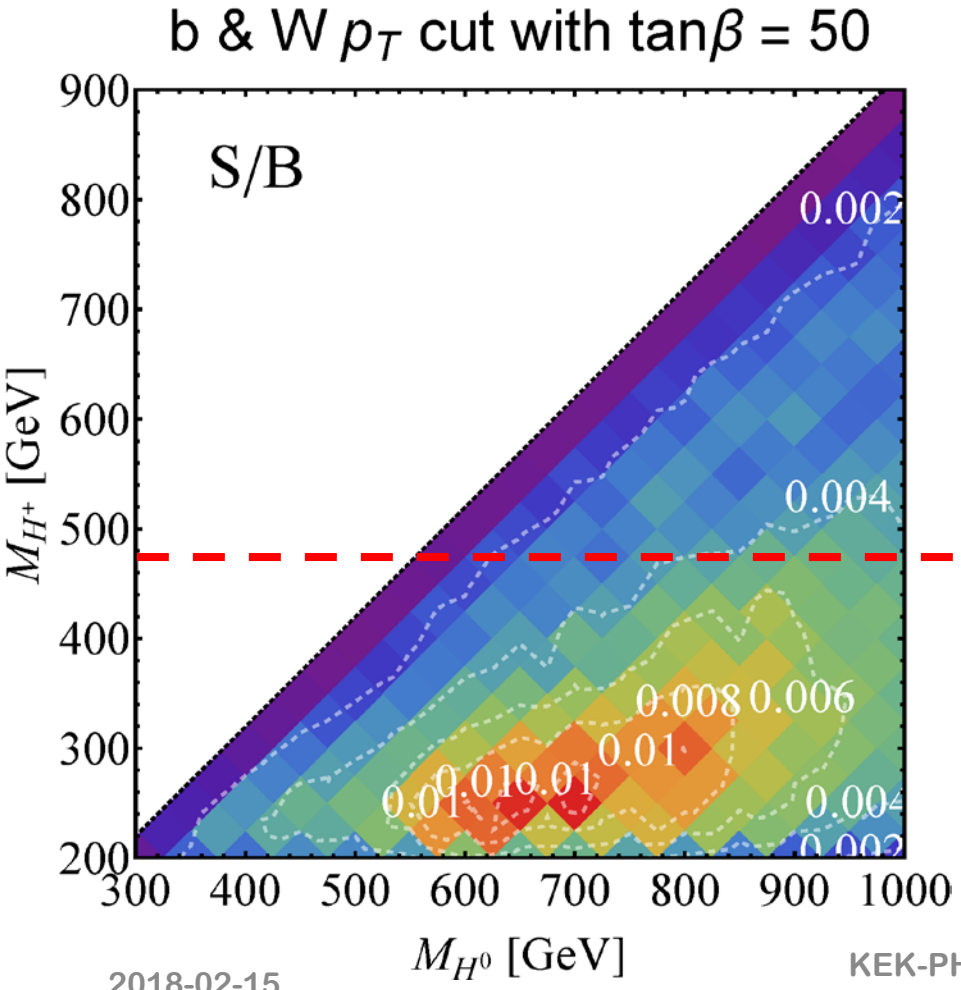
- LHC 13 TeV, $\mathcal{L} = 100\,\mathrm{fb}^{-1}$

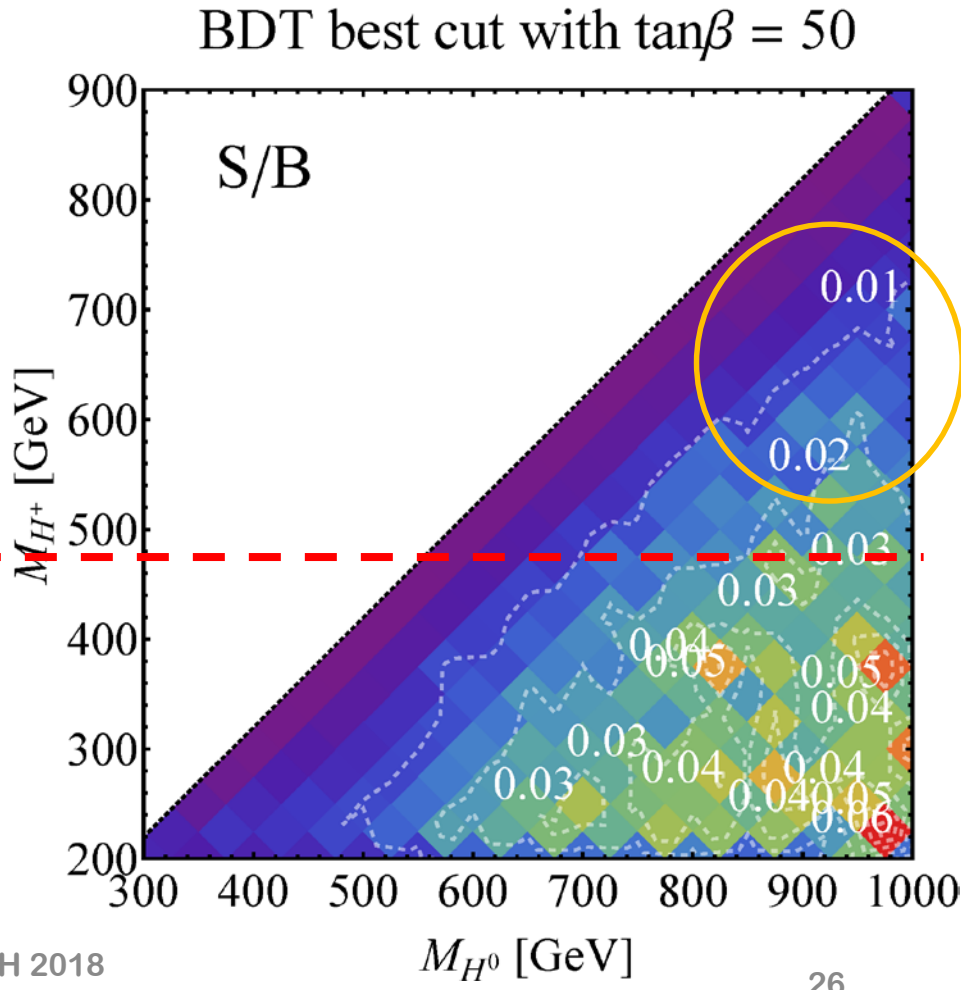




BDT analysis results

- LHC 13 TeV, $\mathcal{L} = 100\,\mathrm{fb}^{-1}$





Status of 2HDM

A. Arbey, F. Mahmoudi, O. Stal, T. Stefaniak 1706.07414