

Charged Higgs Searches in the Georgi-Machacek Model @ ep Colliders

Ke Chen Wang (DESY)

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Outline

Georgi-Machacek Model

Current limits on charged Higgs

Singly charged Higgs H_5^\pm

[study by K. Wang, G. Azuelos, H. Sun]

Doubly charged Higgs $H_5^{\pm\pm}$

[study by H. Sun, X. Luo, W. Wei and T. Liu]

[slides based on talks of X. Luo and H. Sun]

Georgi – Machacek (GM) Model

Scalar sector of the GM model:

complex isospin doublet (ϕ^+, ϕ^0) with hypercharge $Y=1$;

real triplet (ξ^+, ξ^0, ξ^-) with $Y=0$;

complex triplet $(\chi^{++}, \chi^+, \chi^0)$ with $Y = 2$;

→ Scalar potential is chosen to preserve a **global**
 $SU(2)_L \times SU(2)_R$ symmetry

Using $SU(2)_L \times SU(2)_R$ covariant forms of the fields:

$$\Phi = \begin{pmatrix} \phi^{0*} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix} \quad \Delta = \begin{pmatrix} \chi^{0*} & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^0 \end{pmatrix}$$

$$v^2 = v_\Phi^2 + 8v_\Delta^2$$

$$\sin \theta_H = \frac{2\sqrt{2} v_\Delta}{v}$$

$$\cos \theta_H = \frac{v_\Phi}{v}$$

mixing : θ_H



Physical fields under the custodial $SU(2)$ symmetry

5 - plet $H_5^{++}, H_5^+, H_5^0, H_5^-, H_5^{--}$

3 - plet H_3^+, H_3^0, H_3^-

singlet H_1^0

singlet H_1^0

mixing : α

H

h

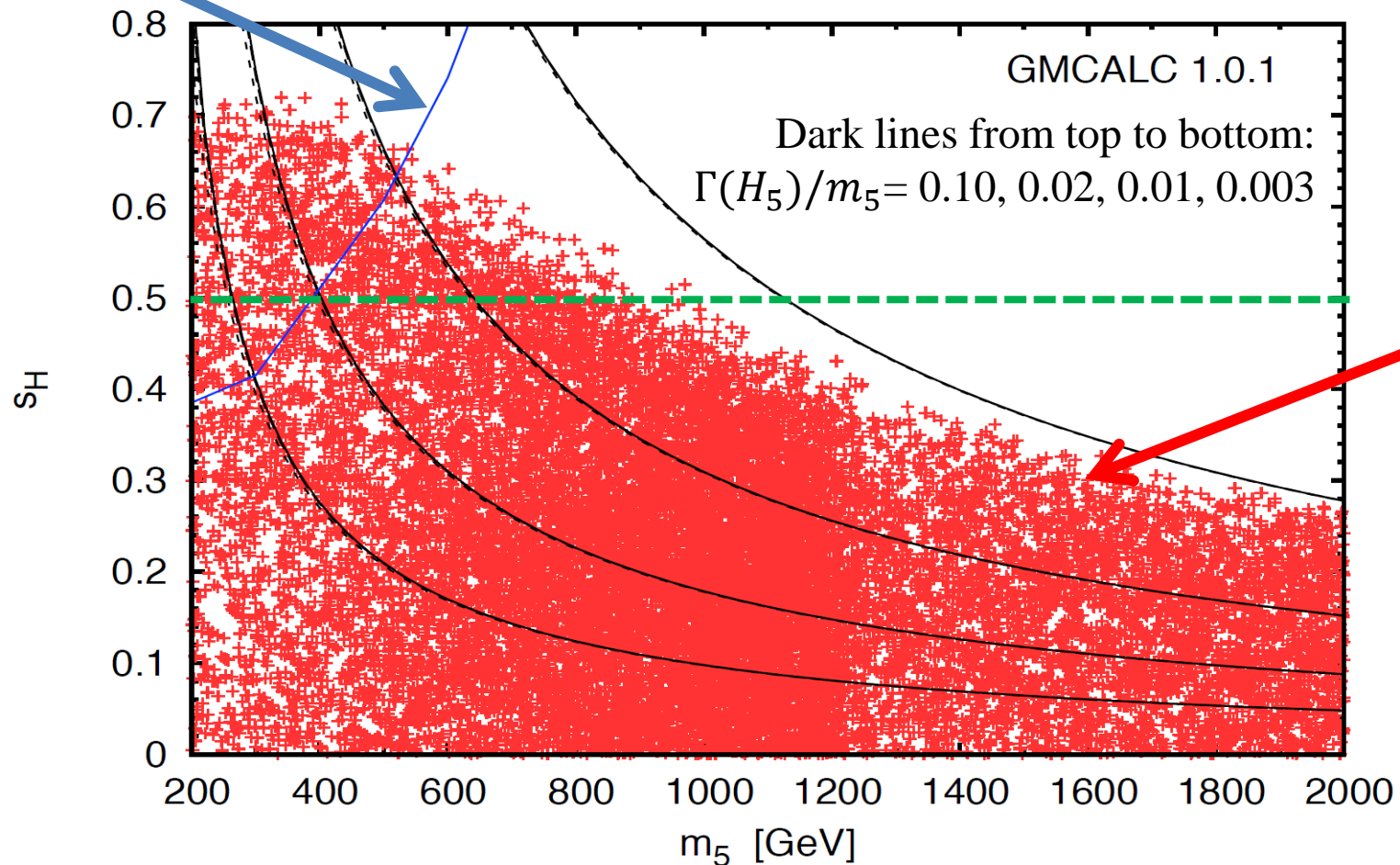
125GeV Higgs

- ◆ Have a common mass $M(H_5)$;
- ◆ Do not couple to fermions;
- ◆ Tree-level $H_5 VV$ interaction;
- ◆ Production via **VBF**;
- ◆ $g(H_5 VV) \propto \sin \theta_H$
 $\Rightarrow \sigma(VBF \rightarrow H_5) \propto \sin^2 \theta_H$;
- ◆ $BR(H_5^\pm \rightarrow W^\pm Z) \approx 100\%$;
 $BR(H_5^{\pm\pm} \rightarrow W^\pm W^\pm) \approx 100\%$;
- ◆ 2 free pars. $M(H_5), \sin \theta_H$.

GM Model Constraints & Parameter Scan

From [H. Logan and M. Zaro, LHCHSWG-2015-001]

LHC data Exc.



Constraints:

Perturbative Unitarity

EW vacuum stability

S parameter

Z-pole observable R_b

$B_s^0 - \bar{B}_s^0$ mixing

$B_s^0 \rightarrow \mu\bar{\mu}$

$b \rightarrow s\gamma$

$$s_H = \sin\theta_H$$

$$m_5 = M_{H_5}$$

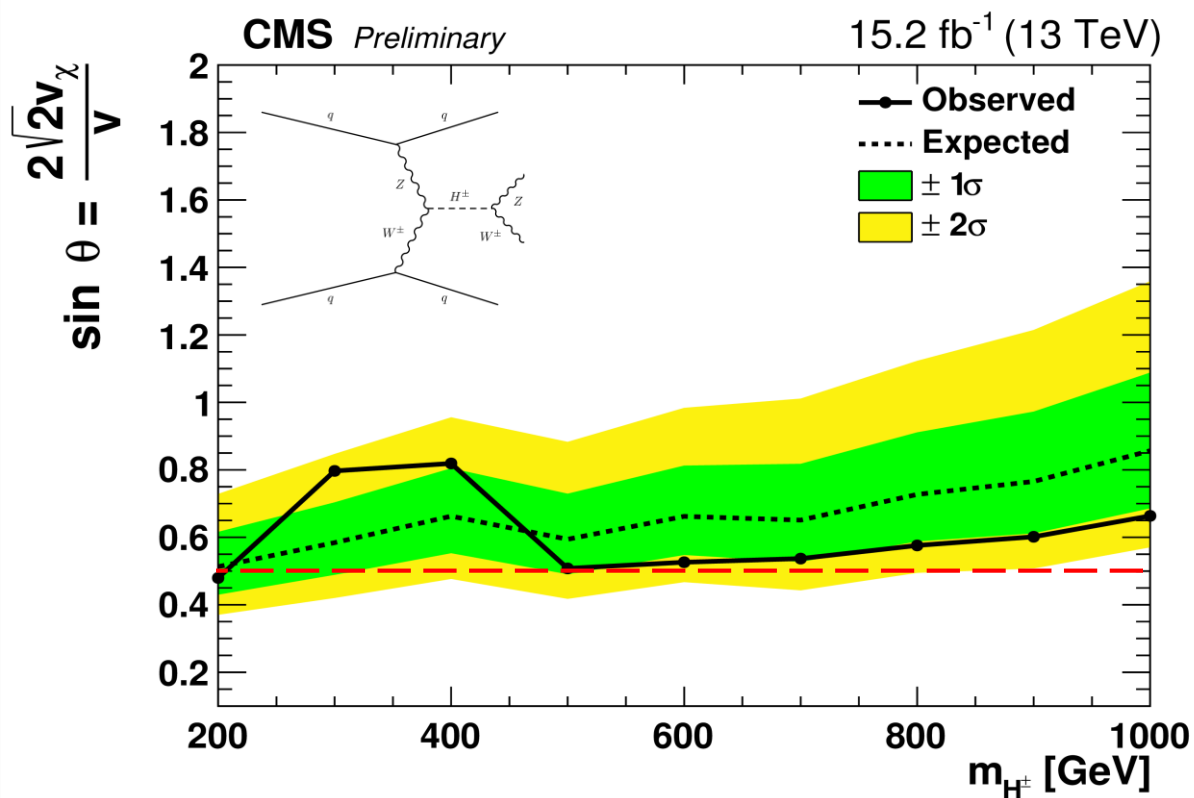
Current LHC limits on H_5^\pm & $H_5^{\pm\pm}$

95% CL limits @ CMS

from [CMS-PAS-HIG-16-027]

2 VBF j + 3 l + MET

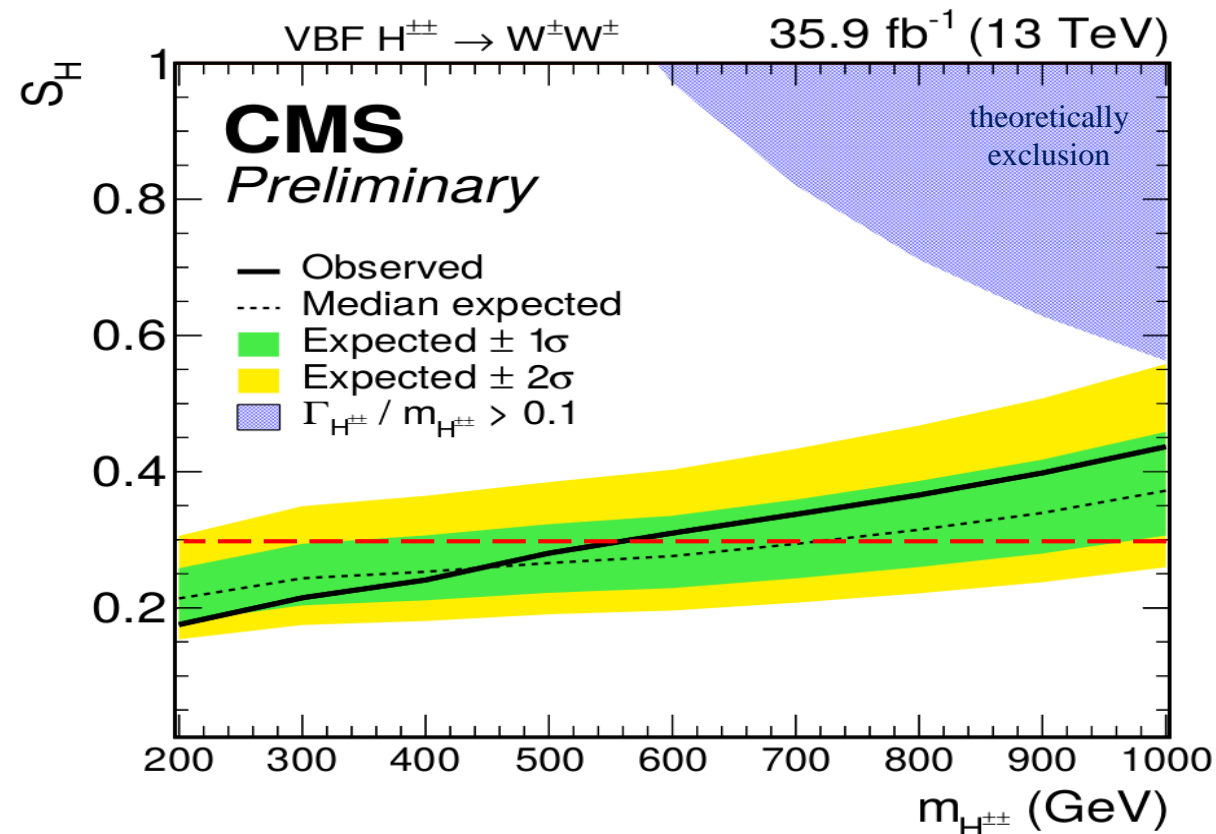
three leptons, electrons and muons, two jets with large rapidity separation and high dijet mass, and moderate missing transverse energy



from [CMS-PAS-SMP-17-004]

2 VBF j + 2 SSSF ($\# \#$) + MET

requiring exactly two leptons of the same charge, moderate missing momentum, and two jets with large rapidity separation and large dijet mass



Signal Scenarios for H_5^\pm Search

Collider:

FCC-eh ($E(p) = 50$ TeV, $E(e) = 60$ GeV).

Final state:

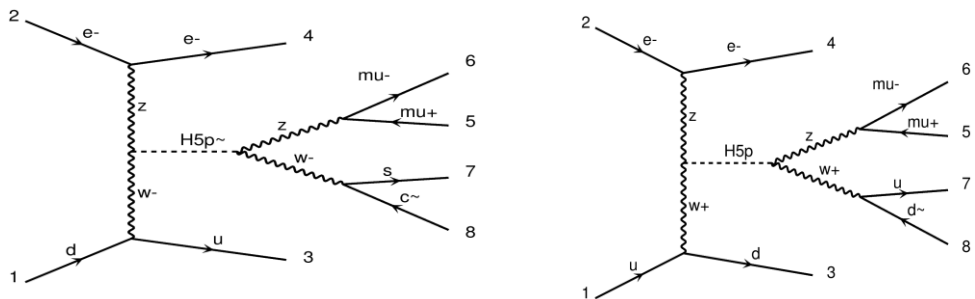
$1 e^- + 1 j + 1 Z(-> l^+ l^-) + 1 W(-> jj)$

$l = e, \mu$

Signal: Production of H_5^+ & H_5^- , inclusively

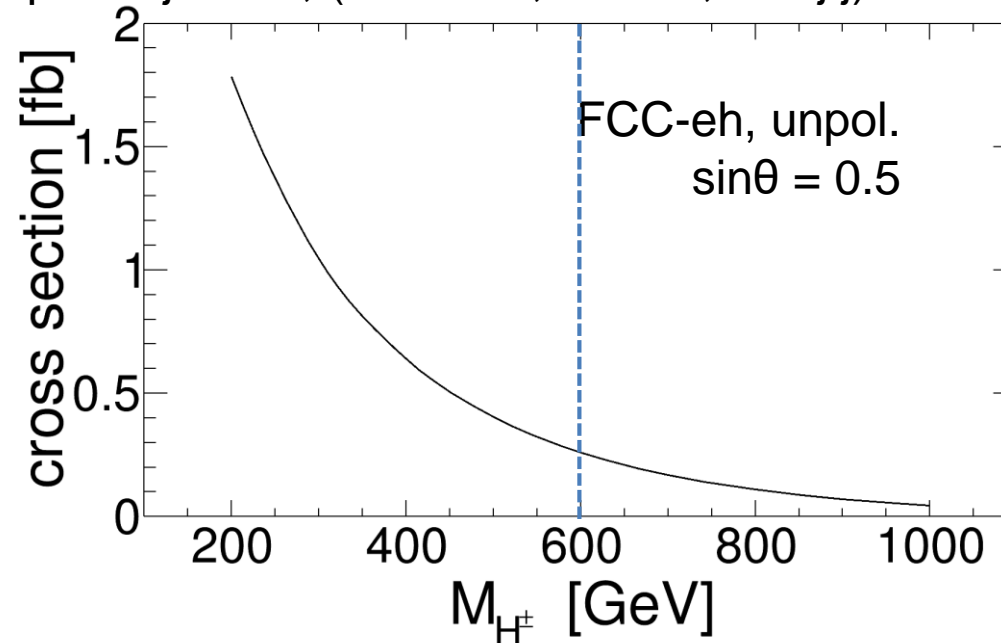
$p e^- \rightarrow j e^- H_5^+$, ($H_5^+ \rightarrow z w^+$, $z \rightarrow l^+ l^-$, $w^+ \rightarrow jj$)

$p e^- \rightarrow j e^- H_5^-$, ($H_5^- \rightarrow z w^-$, $z \rightarrow l^+ l^-$, $w^- \rightarrow jj$)



Signal production cross section

$p e^- \rightarrow j e^- H^\pm$, ($H^\pm \rightarrow z w$, $z \rightarrow l^+ l^-$, $w \rightarrow jj$)



Background: $p e^- \rightarrow j e^- z \nu$

generate $p e^- \rightarrow j e^- z w^+$, $z \rightarrow l^+ l^-$, $w^+ \rightarrow jj$

add process $p e^- \rightarrow j e^- z w^-$, $z \rightarrow l^+ l^-$, $w^- \rightarrow jj$

add process $p e^- \rightarrow j e^- z z$, $z \rightarrow l^+ l^-$, $z \rightarrow jj$

Search Strategy for H_5^\pm Search

Final state:

1 $e^- + 1 j + 1 Z(-\rightarrow l^+ l^-) + 1 W(-\rightarrow jj)$

$l = e, \mu$

Simulation by "MadGraph + PYTHIA + Delphes".

Pre-selection cuts:

- (1) selecting **at least 3 jets** with $p_T > 20$ GeV;
 - (2) selecting **at least 3 leptons** with $p_T > 10$ GeV,
and requiring charges (e^-, e^-, e^+) or (e^-, μ^+, μ^-);
 - (3) **veto b-jets** with $p_T > 20$ GeV;
 - (4) **veto taus** with $p_T > 10$ GeV.
- **2 jets with invariant mass closest to the W mass** are considered as the jets from W decay.
- **(μ^+, μ^-) , or (e^-, e^+) with invariant mass closet to the Z mass** are considered as the leptons from Z decay

Analysis **at detector-level** using the **BDT method**.

Input observables for BDT Training & Test:

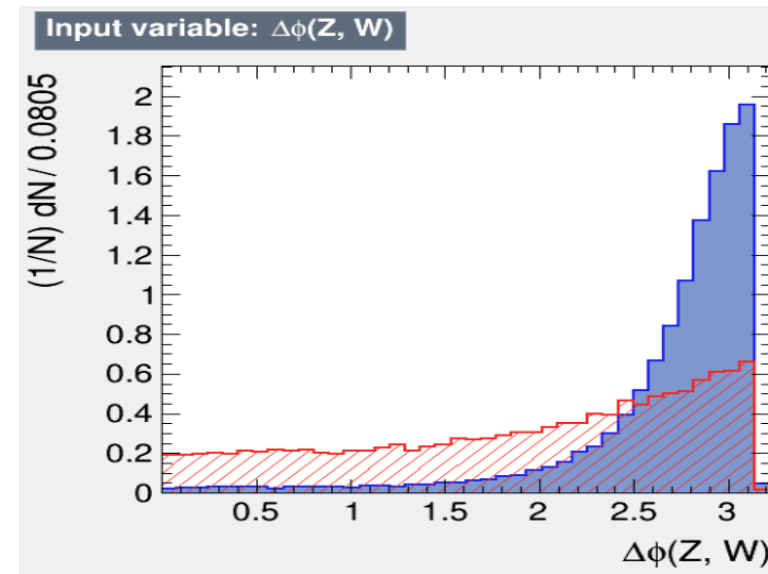
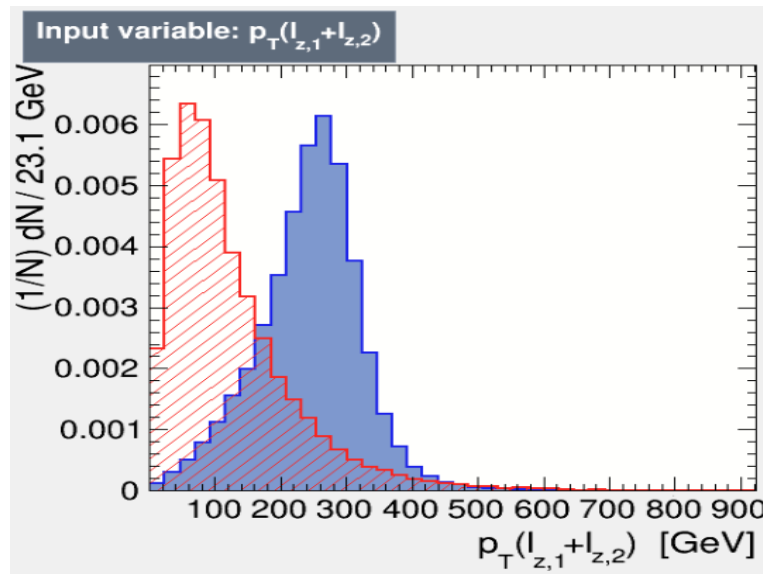
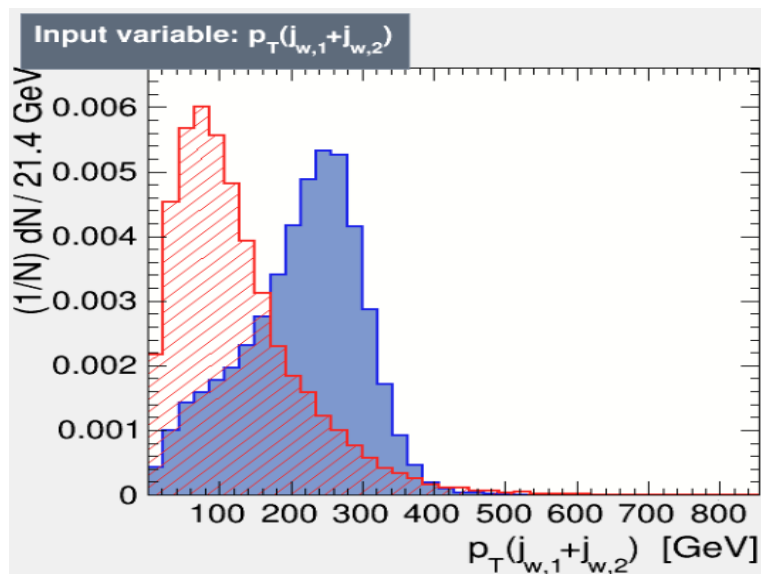
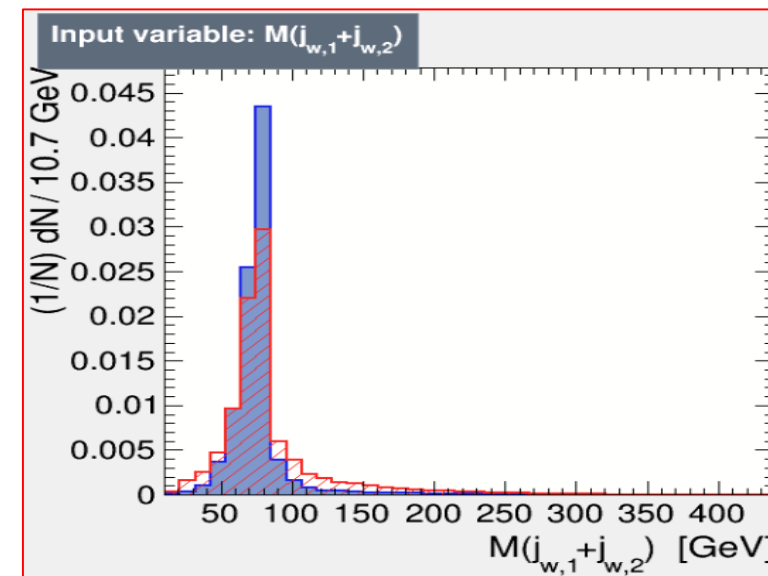
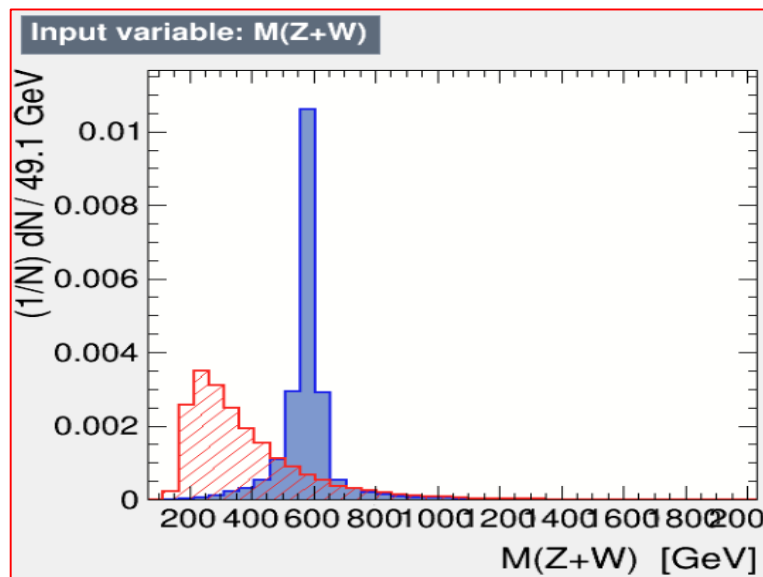
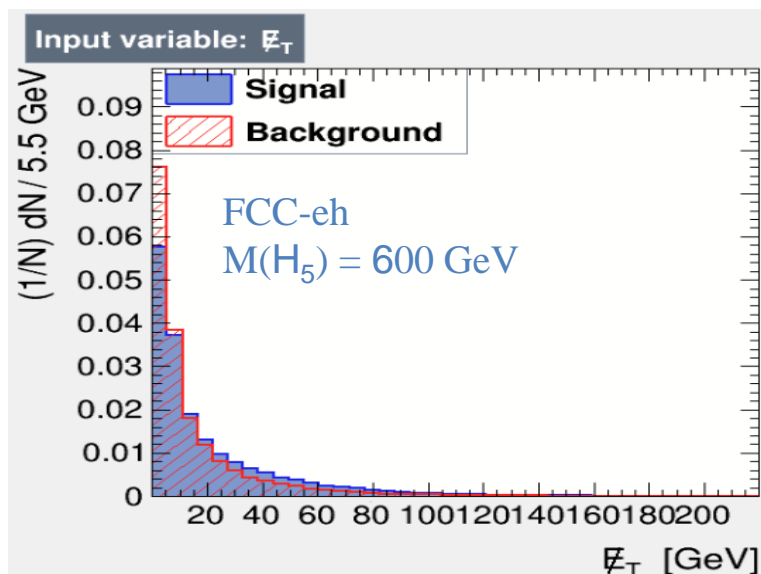
MET, H_T ;

$p_T(e_{fwd}), \eta(e_{fwd}), p_T(j_{fwd}), \eta(j_{fwd}),$
 $p_T(e_{fwd}+j_{fwd}), \eta(e_{fwd}+j_{fwd}), M(e_{fwd}+j_{fwd}),$
 $\Delta\eta(e_{fwd}, j_{fwd}), \Delta\phi(e_{fwd}, j_{fwd});$

$p_T(j_{w,1}), \eta(j_{w,1}), p_T(j_{w,2}), \eta(j_{w,2}),$
 $p_T(j_{w,1}+j_{w,2}), \eta(j_{w,1}+j_{w,2}), M(j_{w,1}+j_{w,2}),$
 $\Delta\eta(j_{w,1}, j_{w,2}), \Delta\phi(j_{w,1}, j_{w,2});$

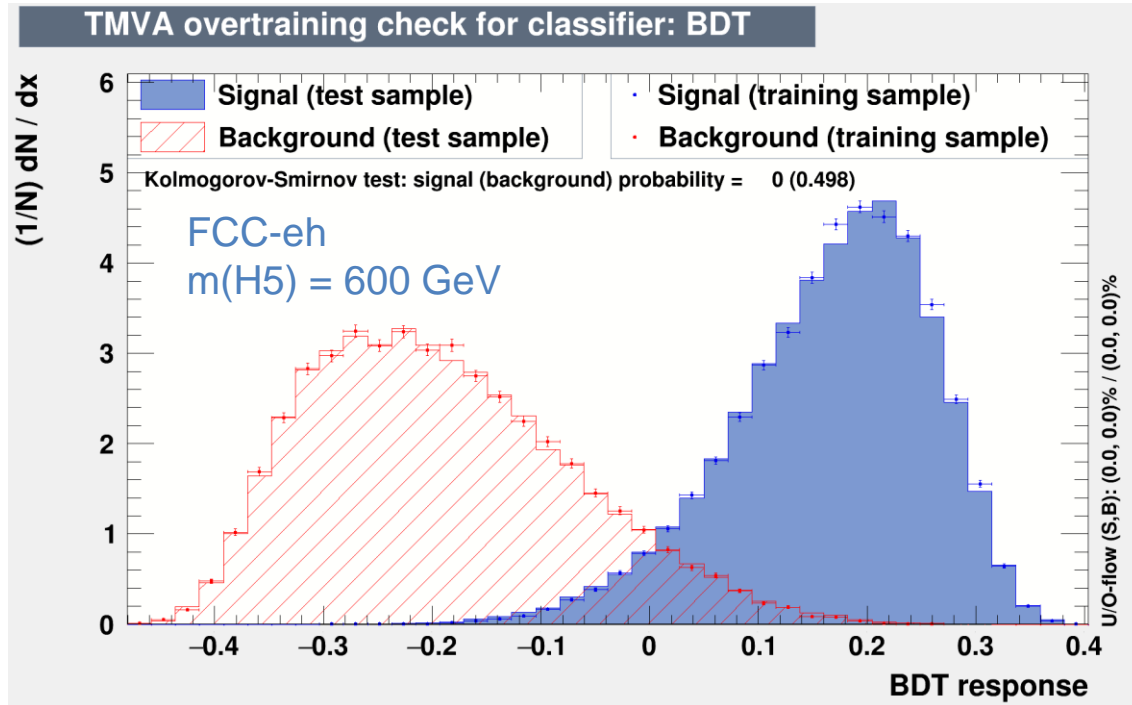
$p_T(l_{z,1}), \eta(l_{z,1}), p_T(l_{z,2}), \eta(l_{z,2}),$
 $p_T(l_{z,1}+l_{z,2}), \eta(l_{z,1}+l_{z,2}), M(l_{z,1}+l_{z,2}),$
 $\Delta\eta(l_{z,1}, l_{z,2}), \Delta\phi(l_{z,1}, l_{z,2});$

$p_T(Z+W), \eta(Z+W), M(Z+W),$
 $\Delta\eta(Z, W), \Delta\phi(Z, W) .$

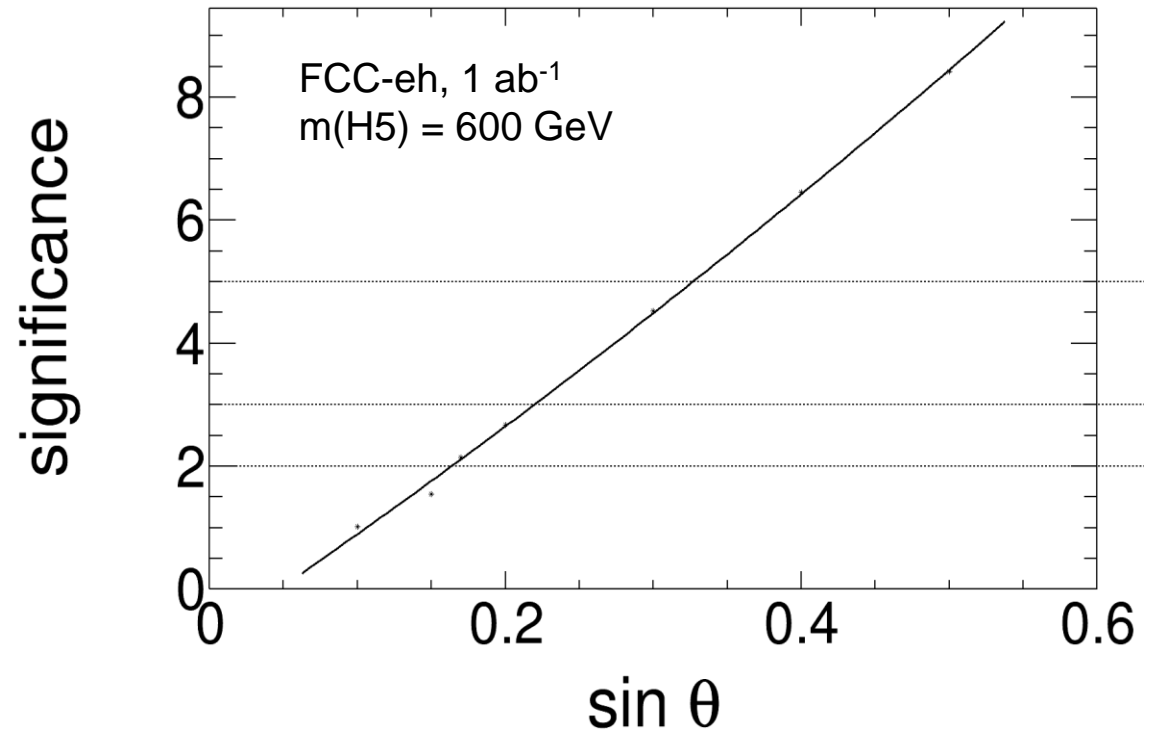
Input Observables for H_5^\pm Search

Limits for H_5^\pm Search

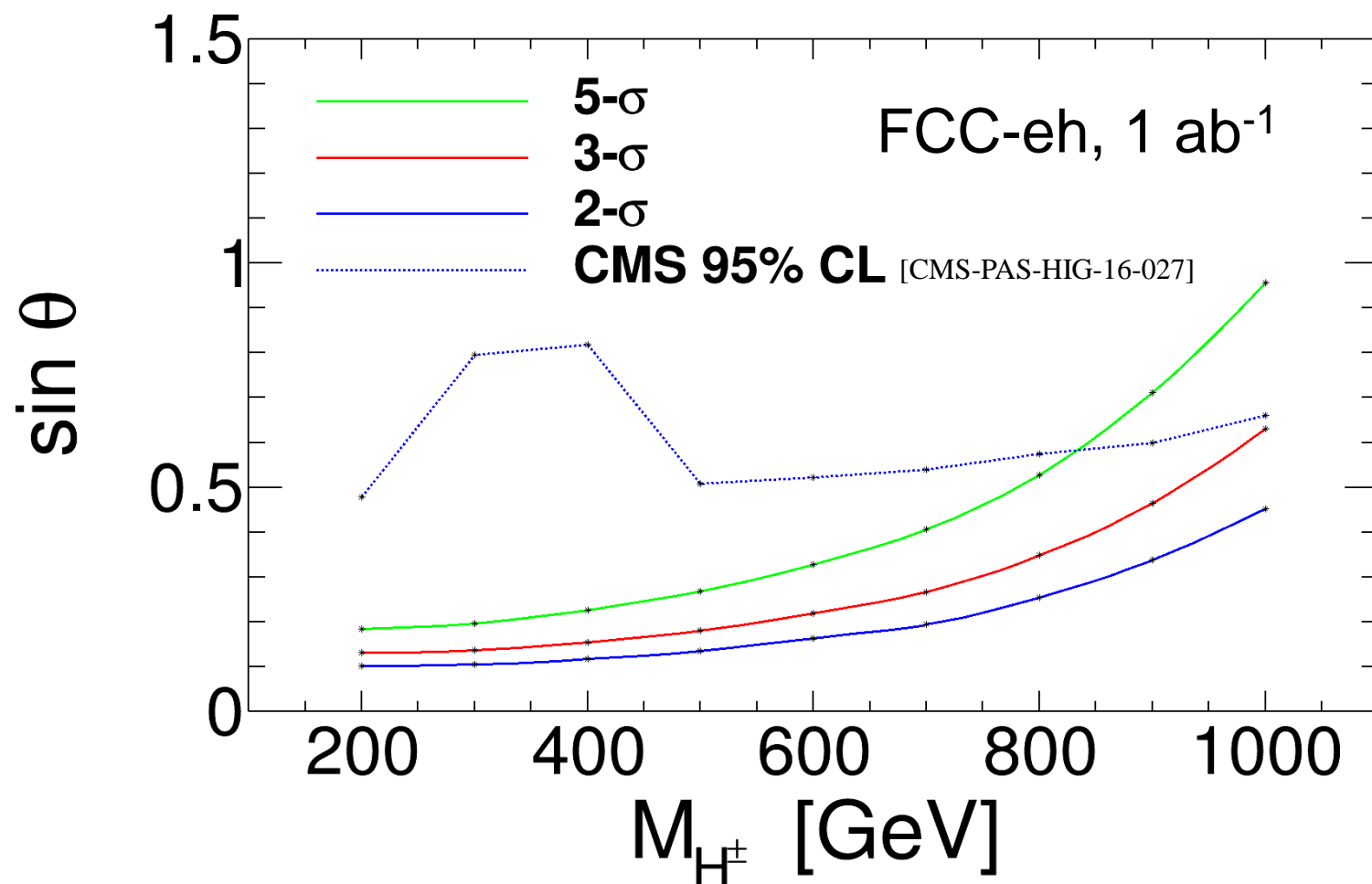
BDT Distribution

@FCC-eh, 1 ab^{-1} Cut-flow table for $m(H_5) = 600 \text{ GeV}$ & $\sin\theta = 0.5$

# of events	Signal	Background
initial production	259.9	10930
pre-selection	102.3	760.8
BDT > 0.0733	86.5	19.1
Significance	8.4	

@FCC-eh, 1 ab^{-1} limits on $\sin\theta$ for $m(H_5) = 600 \text{ GeV}$

$\sin\theta$	Significance
0.33	5.0
0.22	3.0
0.16	2.0

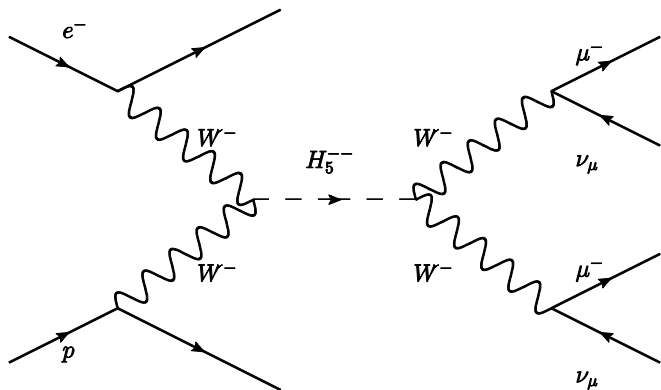
Limits for H_5^\pm Search"sin θ vs. Mass" contour curve@FCC-eh, 1 ab⁻¹
2- σ limits on sin θ

Mass [GeV]	sin θ
200	0.10
300	0.11
400	0.12
500	0.14
600	0.16
700	0.19
800	0.25
900	0.34
1000	0.45

Search Strategy for H^- Search

Signal in the Georgi-Machacek model:
via **WW-fusion**

$$p e^- \rightarrow j \nu_e (H_5^- \rightarrow W^- W^-) \rightarrow j \nu_e (\mu^- \nu_\mu)(\mu^- \nu_\mu)$$



Simulation by "MadGraph + PYTHIA + Delphes".

Event selection:

Basic cut

$$\begin{aligned} E_T &\geq 10\text{GeV} \\ p_T^{j,\ell} &\geq 10\text{GeV} \\ |\eta^j| &\leq 5, |\eta^\ell| \leq 2.5, \\ \Delta R_{jj} &\geq 0.4, \Delta R_{j\ell} \geq 0.4, \Delta R_{\ell\ell} \geq 0.4 \end{aligned}$$

Basic selection

$$E_T + 2\mu^- + \geq 1\text{jet}(s)$$

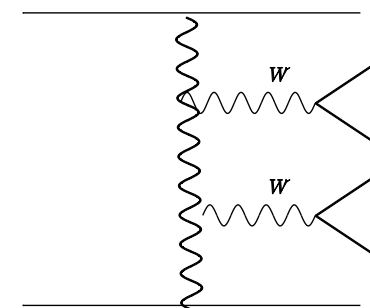
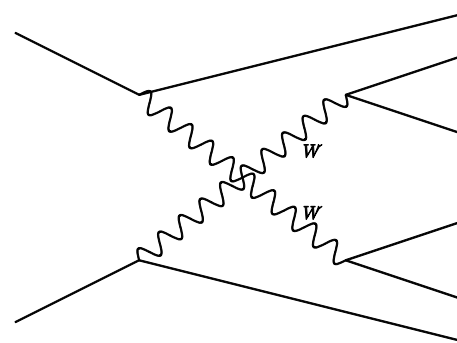
Optimized

$$\begin{aligned} \Delta\Phi^{\mu\mu} &\in (-\pi, -1.28) \text{ or } (1.36, \pi) \\ \Delta R^{\mu\mu} \quad M_{\text{inv}}^{\mu\mu} &> 75\text{GeV} \\ M_T^{\mu\mu} &> 40\text{GeV} \end{aligned}$$

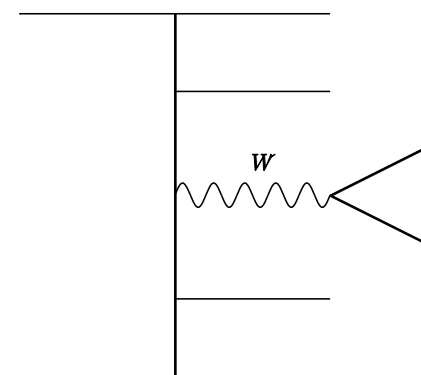
Final state: $\geq 1 j + 2 \mu^- + \text{MET}$

SM Background:

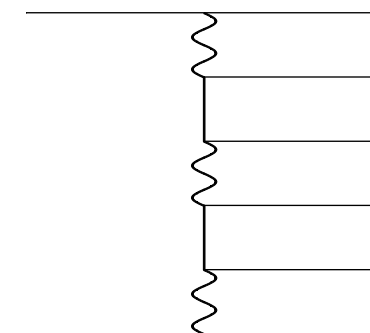
2-W process: dominated



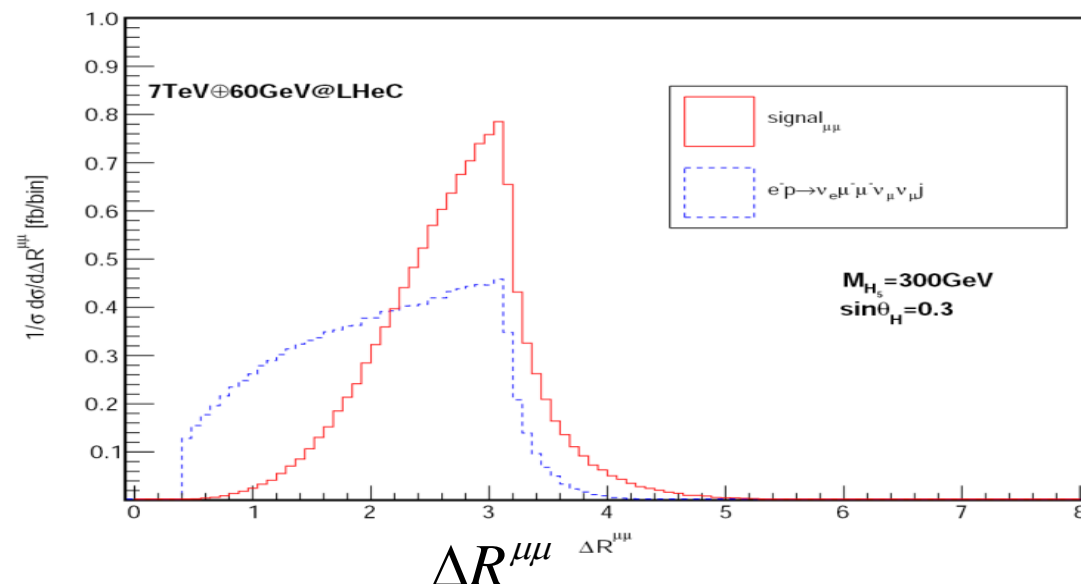
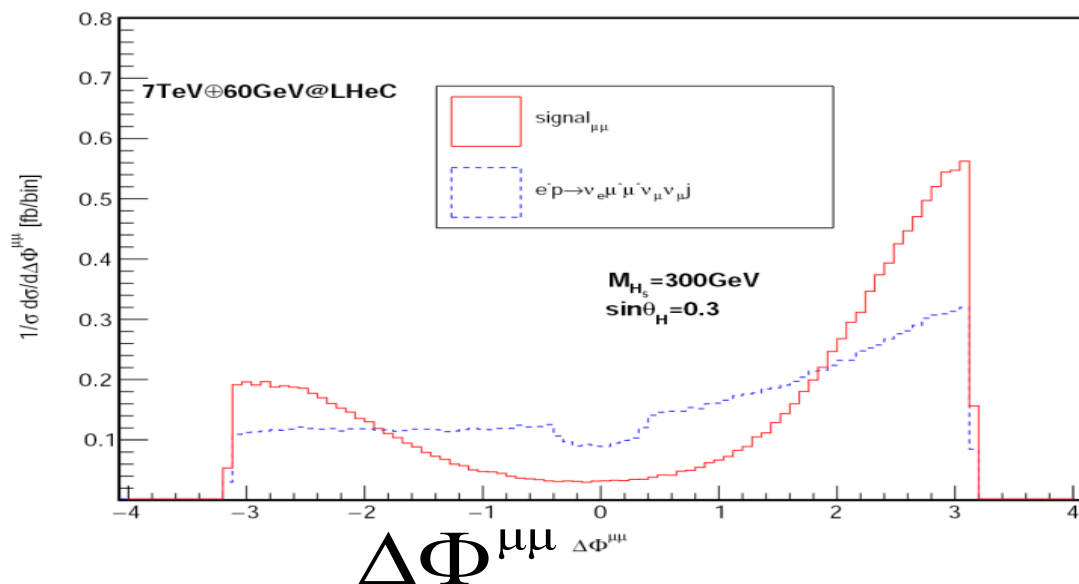
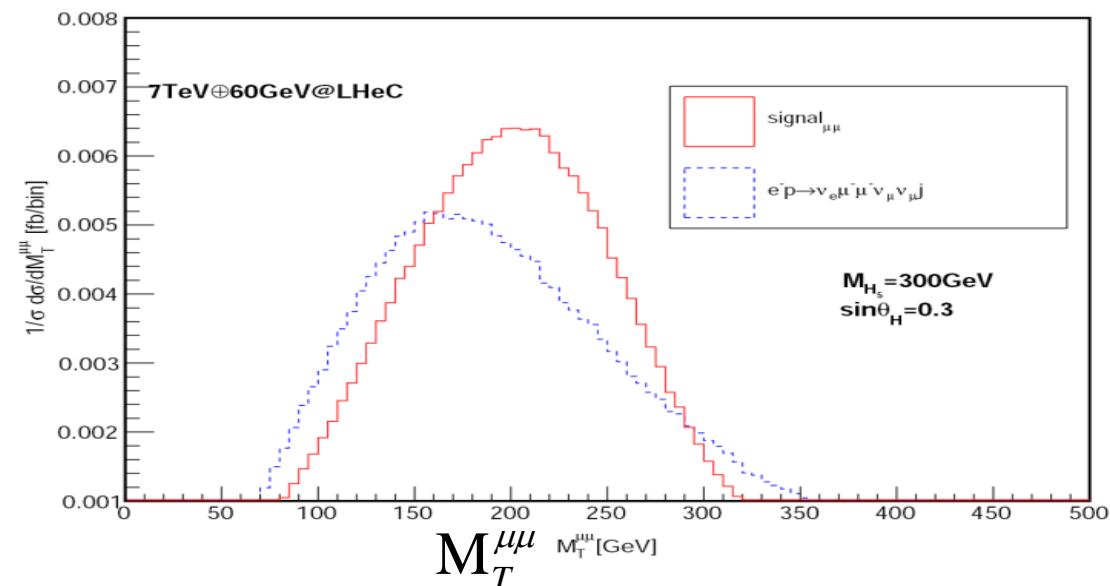
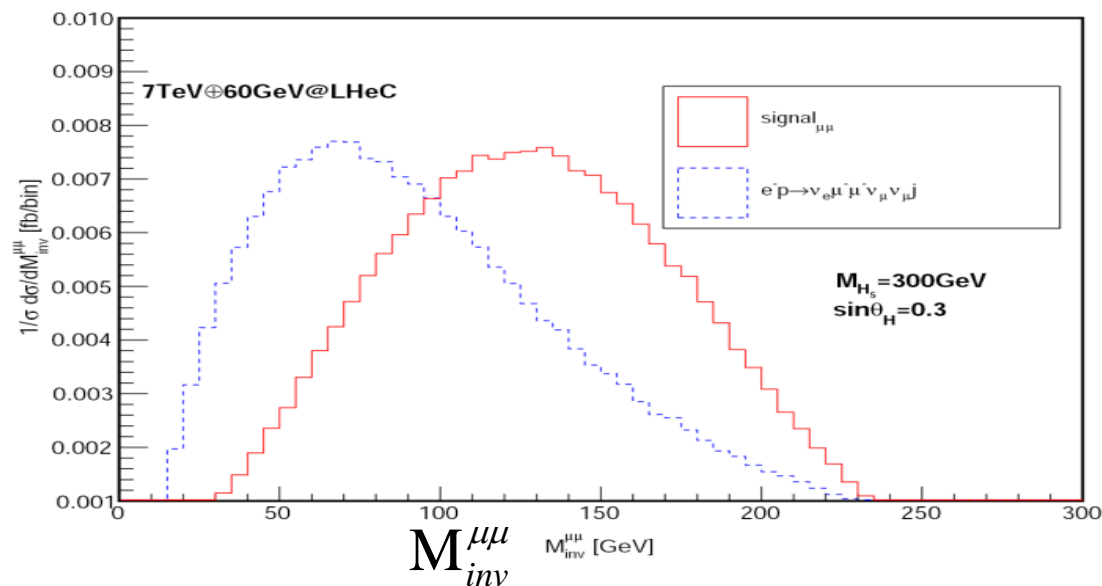
1-W process:

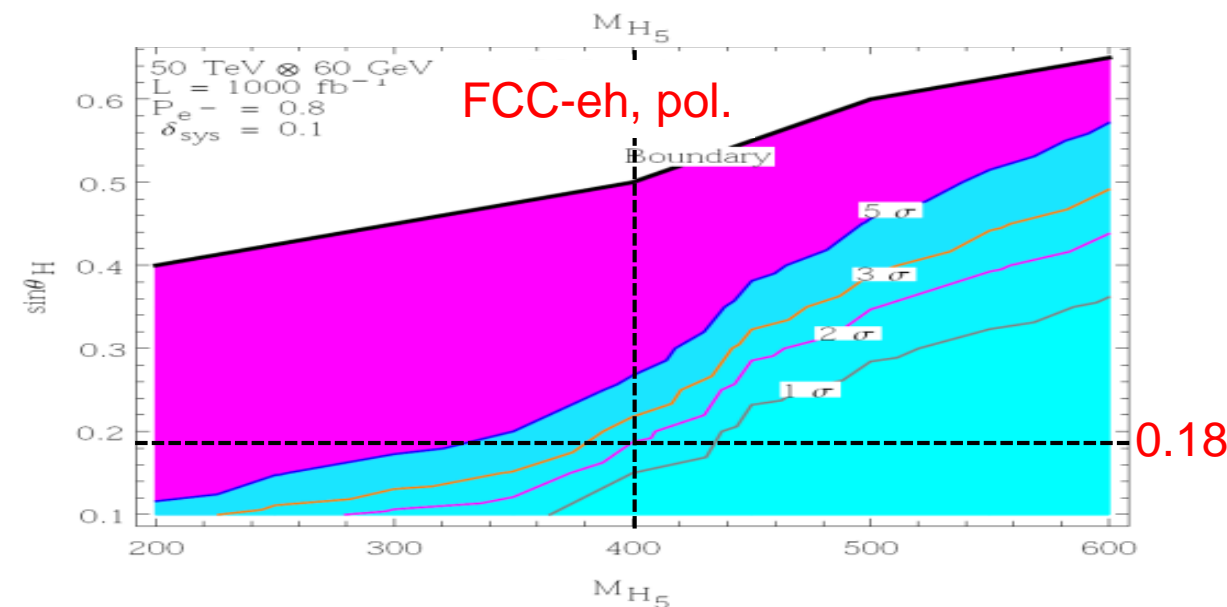
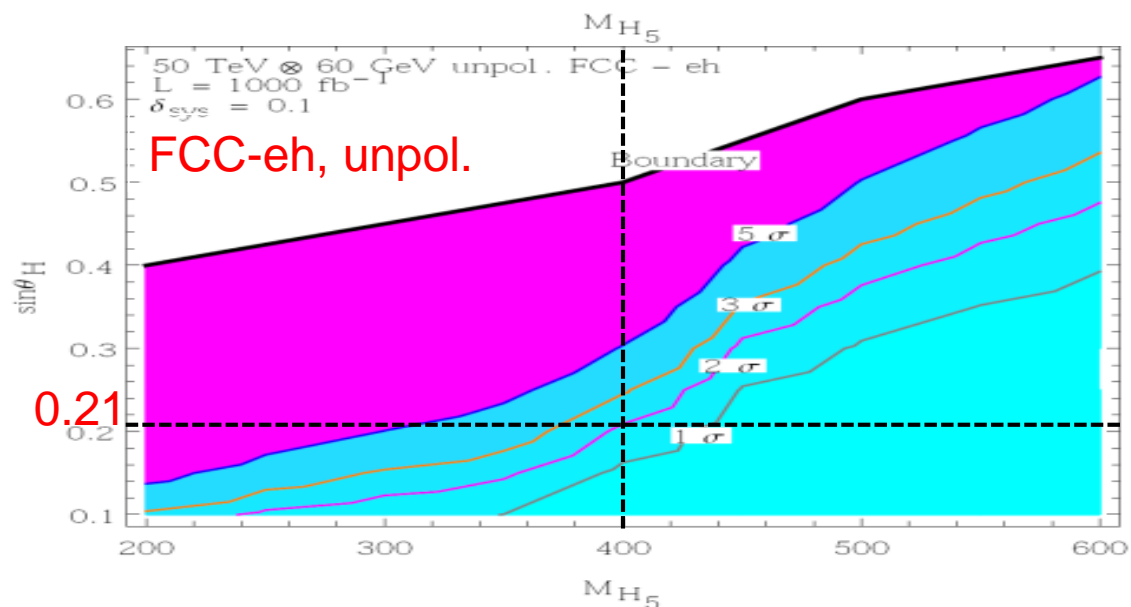
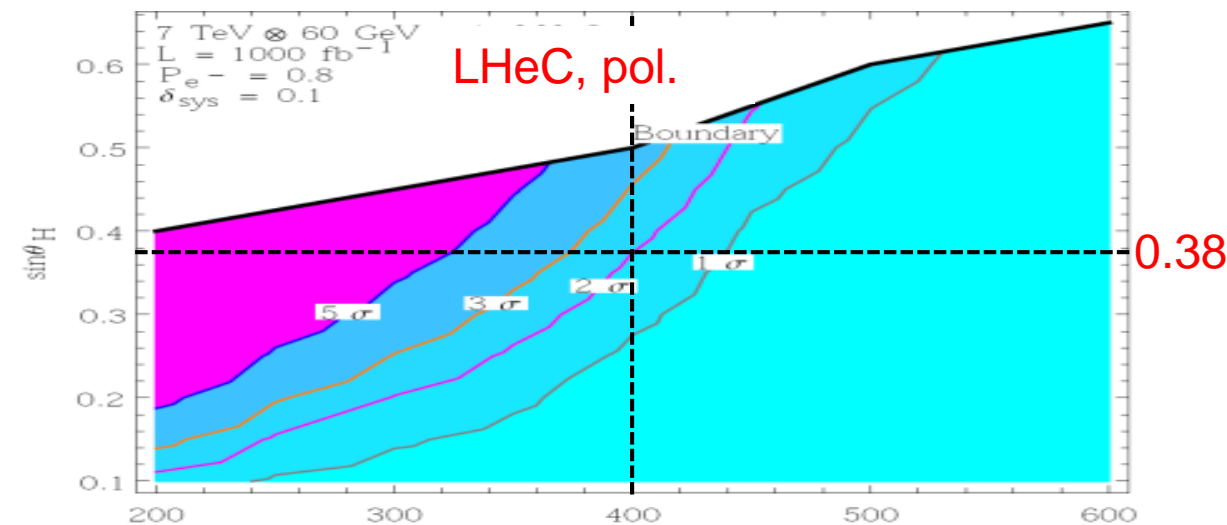
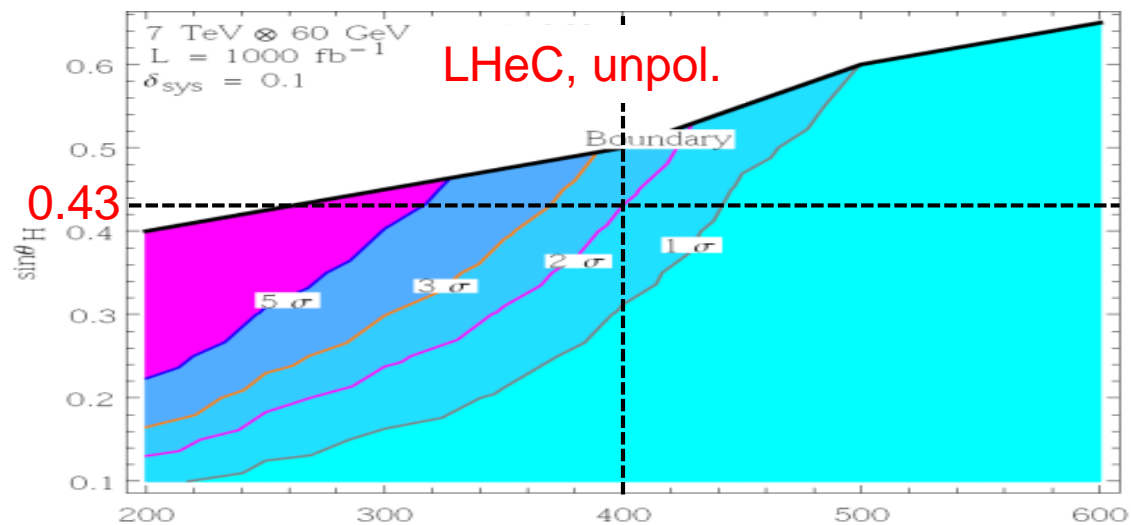


0-W process:



Kinematical Distributions @ LHeC



Significances in $\sin\theta_H$ vs. M_{H_5} PlainLuminosity = 1000 fb^{-1} , systematical uncertainty $\sigma_{\text{sys}} = 10\%$ 

Conclusion

Search for H_5^\pm and $H_5^{\pm\pm}$ in the GM model at the LHeC & FCC-eh

- ◆ 2 free model parameters $M(H_5)$, $\sin \theta_H$;
- ◆ Production via **VBF** ;
- ◆ $g(H_5 VV) \propto \sin \theta_H \Rightarrow \sigma(\text{VBF} \rightarrow H_5) \propto \sin^2 \theta_H$;
- ◆ $\text{BR}(H_5^\pm \rightarrow W^\pm Z) \approx 100\%$; $\text{BR}(H_5^{\pm\pm} \rightarrow W^\pm W^\pm) \approx 100\%$.

Singly charged Higgs H_5^\pm [study by K. Wang, G. Azuelos, H. Sun]

- ◆ Final state: $1 e^- + 1 j + 1 Z(-\rightarrow \ell^+ \ell^-) + 1 W(-\rightarrow jj)$;
- ◆ **Detector-level** analysis using the **BDT method** ;
- ◆ 2- σ limits on $\sin \theta_H$ @FCC-eh, 1 ab^{-1} , unpol. e^- beam
 $\rightarrow 0.12, 0.16, 0.45$ for 400, 600, 1000 GeV .

Doubly charged Higgs $H_5^{\pm\pm}$ [study by H. Sun, X. Luo, W. Wei and T. Liu]

- ◆ $p e^- \rightarrow j \nu_e (H_5^{--} \rightarrow W^- W^-) \rightarrow j \nu_e (\mu^- \nu_\mu)(\mu^- \nu_\mu)$;
- ◆ Final state: $\geq 1 j + 2 \mu^- + \text{MET}$;
- ◆ **Detector-level** analysis using the **cut-and-count method** ;
- ◆ 2- σ limits on $\sin \theta_H$ for 400 GeV with 1 ab^{-1}
 $\rightarrow 0.21, 0.18$ @ FCC-eh with unpol., pol. e^- beam ;
 $\rightarrow 0.43, 0.38$ @ LHeC with unpol., pol. e^- beam .