

Probing doubly charged scalar bosons from the doublet at hadron colliders

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Collaborators

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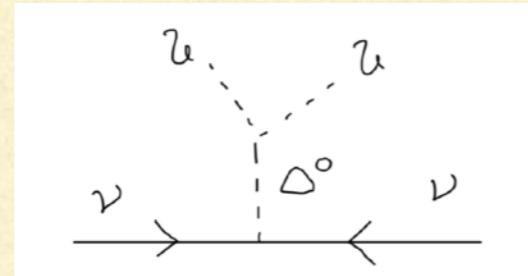
Phys. Rev. D104 (2021) 3, 035040 [arXiv:2102.12950 [hep-ph]]

Doubly charged scalar bosons

- The standard model (SM) cannot explain some phenomena.
(ν masses, DM, etc.)
- We need physics beyond the SM. **Extensions of the SM**
- One of the interesting extensions is to introduce **doubly charged scalars**.
- They are sometimes introduced in models for tiny ν masses.

Triplet ($Y = 1$)

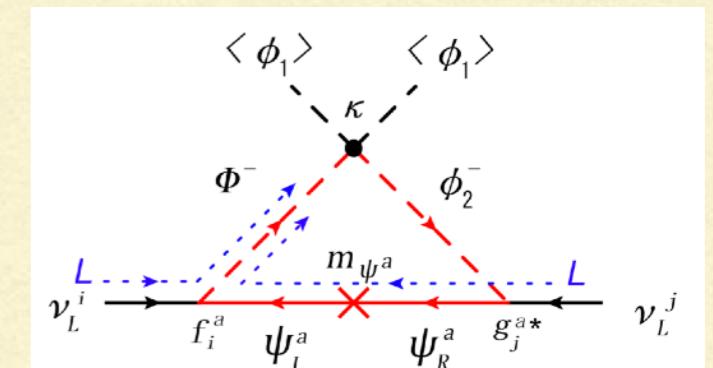
$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$



J. Schechter, J. W. F. Valle, PRD (1980); W. Konetschny, W. Kummer, PLB (1977);
R. N. Mohapatra, G. Senjanovic, M. Magg, C. Wetterich, PLB (1980);
G. Lazarides, Q. Shafi, C. Wetterich, NPB (1981).

Doublet ($Y = 3/2$)

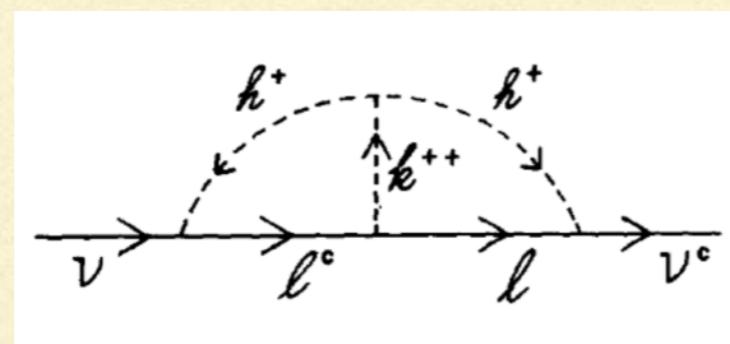
$$\Phi = \begin{pmatrix} \Phi^{++} \\ \Phi^+ \end{pmatrix}$$



M. Aoki, S. Kanemura, K. Yagyu, PLB (2011)

Singlet ($Y = 2$)

$$k^{++}$$



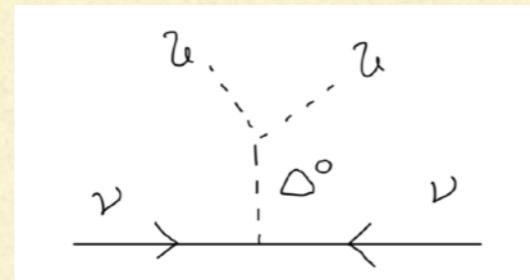
A. Zee, PLB (1986); K. S. Babu, PLB (1988).

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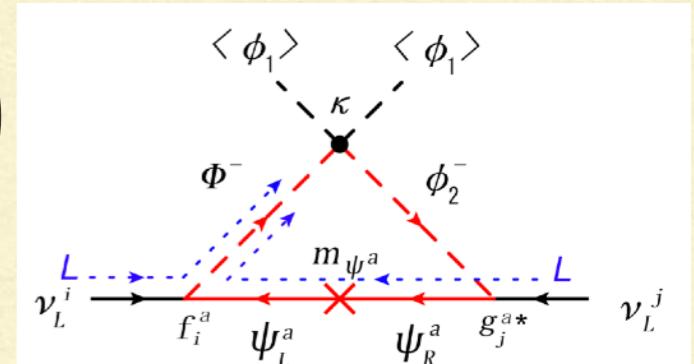
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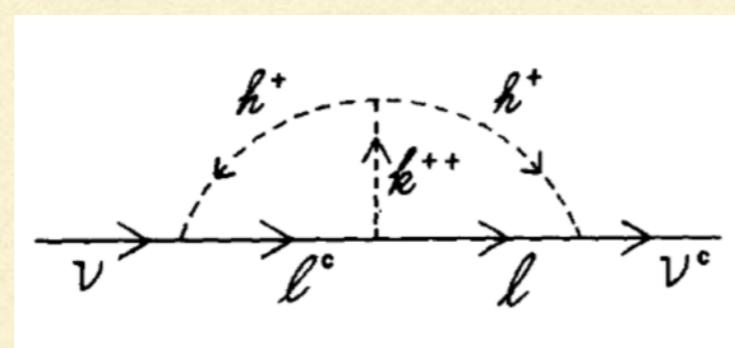
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Today's talk!

$Y = 3/2$ doublet scalar boson

$Y = 3/2$ doublet cannot interact with the SM fermions at the renormalizable level.

$$\mathcal{L}_\Phi = |D_\mu \Phi|^2 + (\text{scalar interactions})$$

$Y = 3/2$ doublet scalar boson

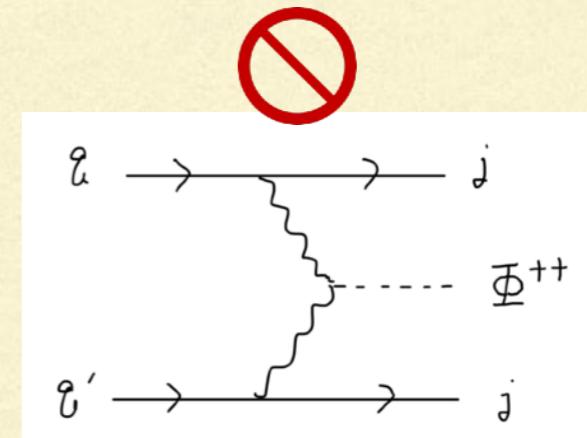
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- Production of $\Phi^{\pm\pm}$ @ pp collider

Pair production $pp \rightarrow Z^* \rightarrow \Phi^{++}\Phi^{--}$

Associated prod. $pp \rightarrow W^* \rightarrow \Phi^{++}\Phi^-$



$$\langle \Phi \rangle = 0$$

$Y = 3/2$ doublet scalar boson

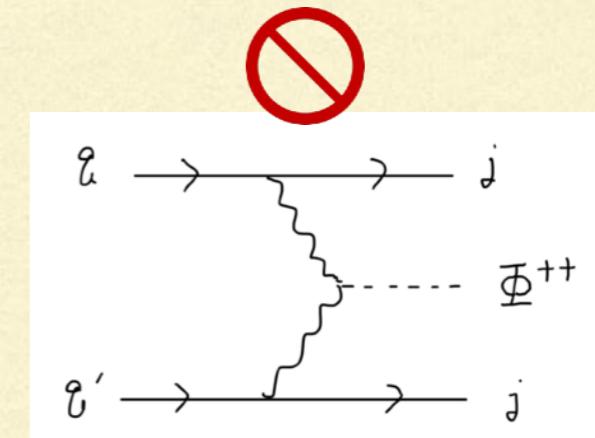
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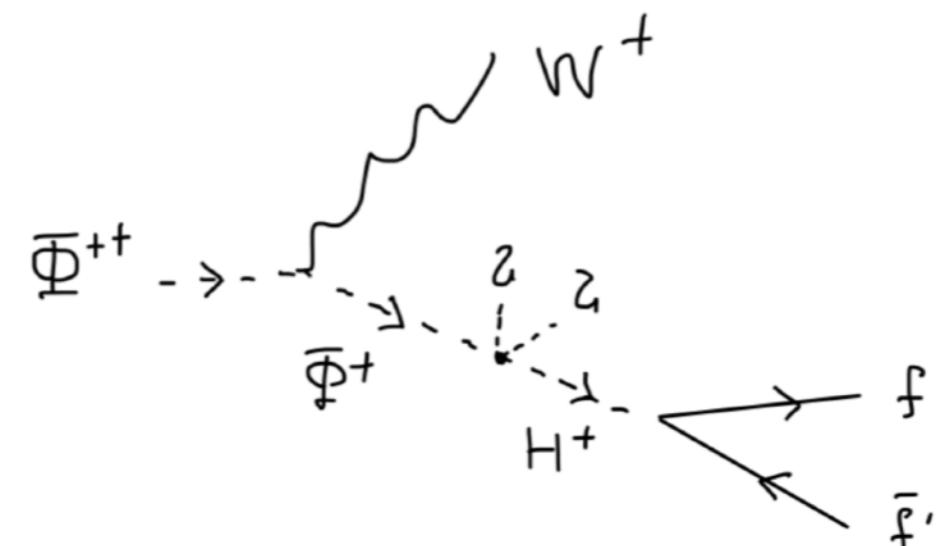


$$\langle \Phi \rangle = 0$$

- Decay of $\Phi^{\pm\pm}$: $\Phi^{++} \rightarrow W^+\Phi^{+(*)}$

Φ^+ decays into the SM fermions via mixings with other scalar bosons

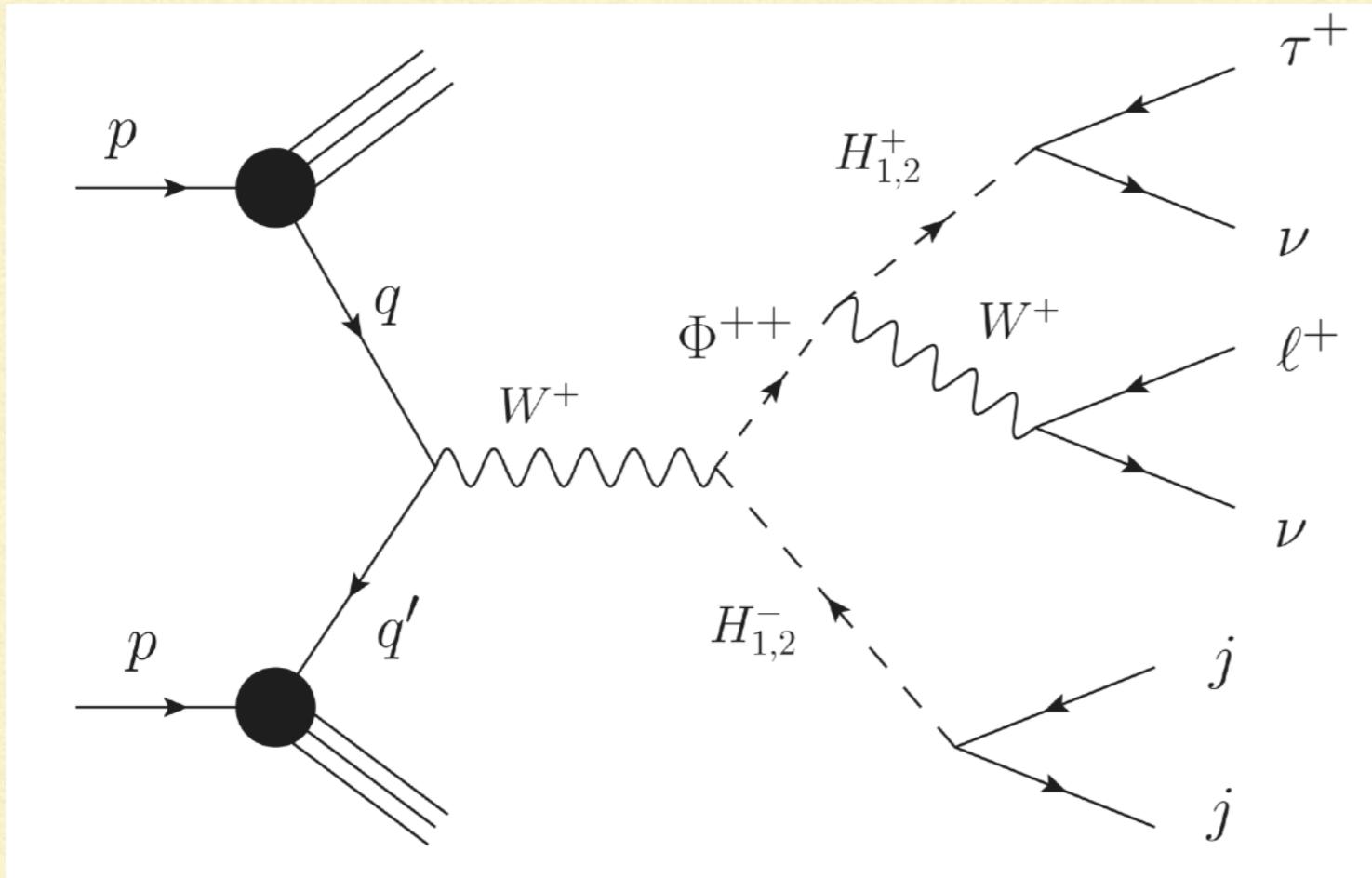
Example) 2HDM + Φ



H^+ is from the $Y = 1/2$ doublet.

$Y = 3/2$ doublet @ pp colliders

2HDM + Φ model M. Aoki, S. Kanemura, K. Yagyu, PLB (2011)



The masses of all charged states may be measurable from this single process by looking at the Jacobian peaks of transverse masses.

Transverse mass

$$M_T^2 = (E_{T1} + E_{T2} + \dots + E_{Tn})^2 + |\vec{p}_{T1} + \vec{p}_{T2} + \dots + \vec{p}_{Tn}|^2$$

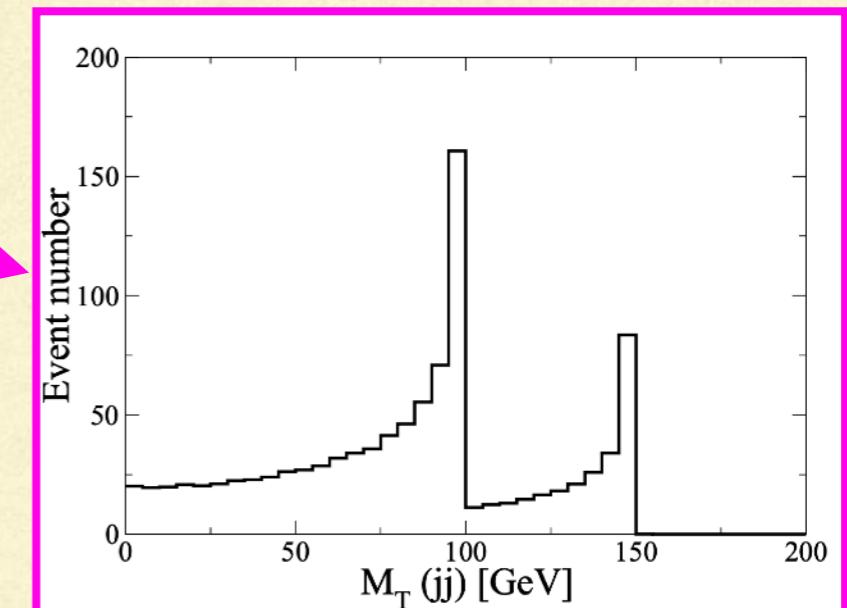
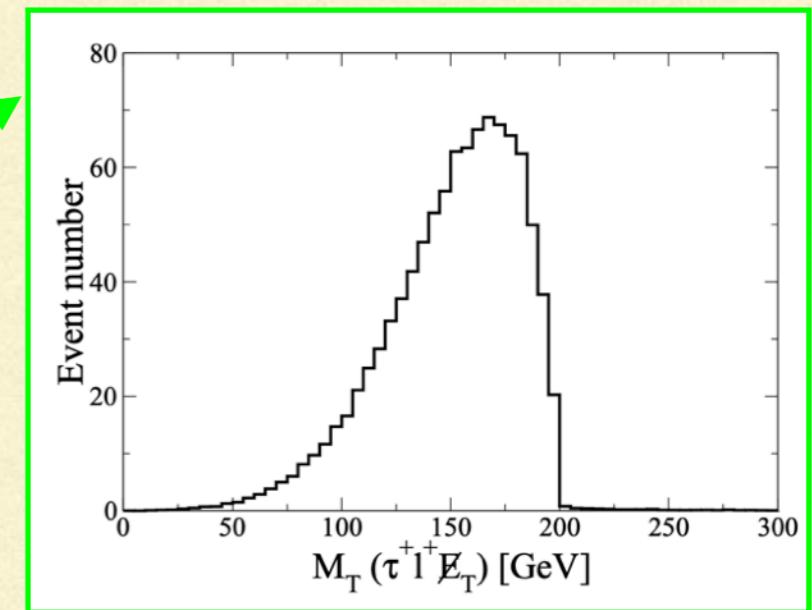
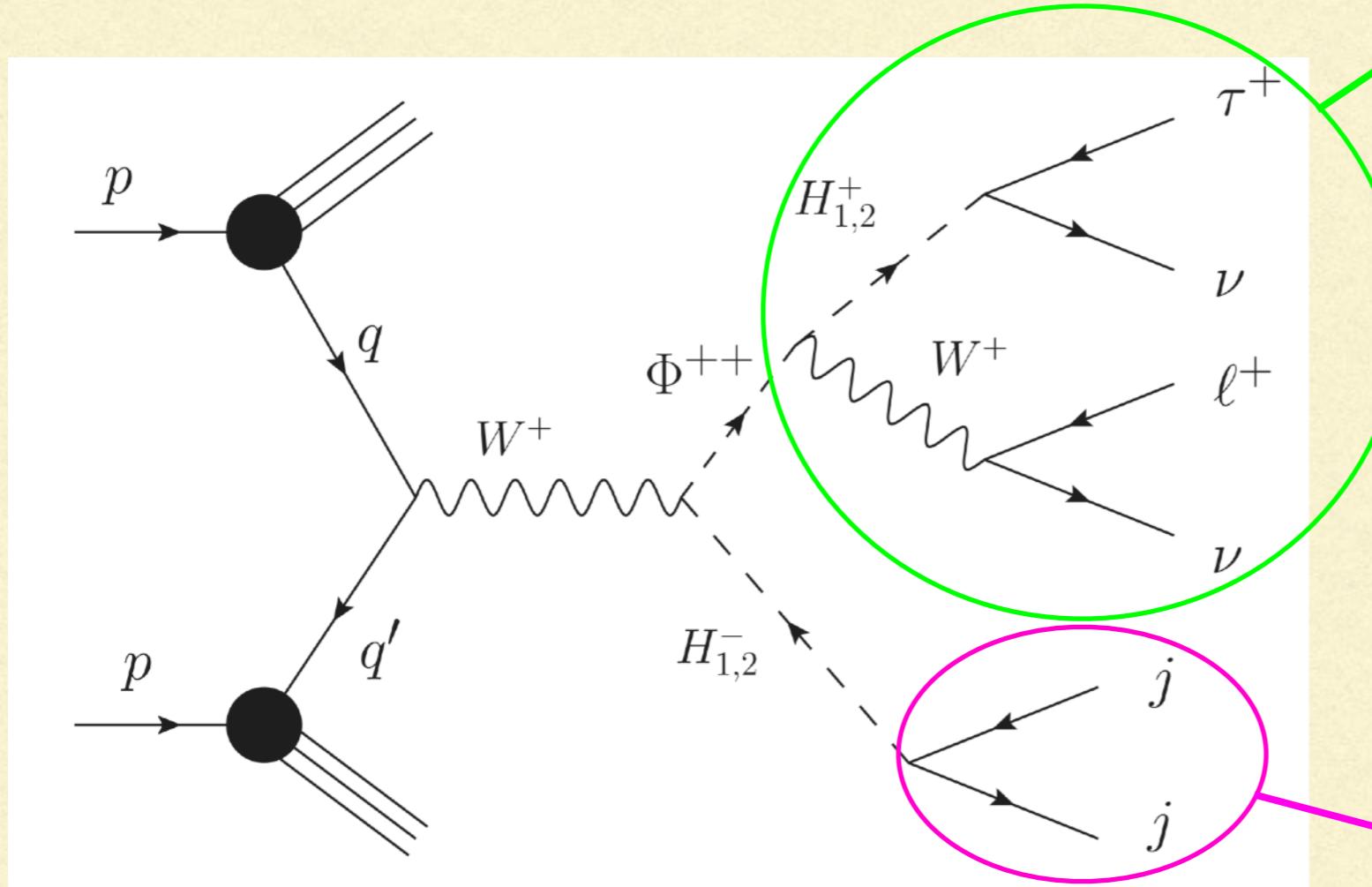
$$E_{Ti}^2 = |\vec{p}_{Ti}|^2 + m_i^2 \quad (i = 1, 2, \dots, n)$$

\vec{p}_{Ti} : transverse momentum
of i -th particle

m_i : mass of i -th particle

$Y = 3/2$ doublet @ pp colliders

2HDM + Φ model M. Aoki, S. Kanemura, K. Yagyu, PLB (2011)



The masses of all charged states may be measurable at this single process by looking at the Jacobian peaks of transverse masses.

It is interesting! but detailed analyses of this signal had not been done yet.

Our work!

Definition of the Model

Extended scalar sector

	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	Z_2
ϕ_1	1	2	1/2	+
ϕ_2	1	2	1/2	-
Φ	1	2	3/2	-

Z_2 : softly broken Z_2 symmetry.

(To prohibit FCNC
at tree level)

$$\Phi = \begin{pmatrix} \Phi^{++} \\ \Phi^+ \end{pmatrix} \quad \phi_a = \begin{pmatrix} \omega_a^+ \\ \frac{1}{\sqrt{2}}(v_a + h_a + iG_a^0) \end{pmatrix} \quad a = 1, 2$$

$$\begin{aligned}
 V = & \mu_1^2 |\phi_1|^2 + \mu_2^2 |\phi_2|^2 + (\mu_{12}^2 \phi_1^\dagger \phi_2 + \text{h.c.}) + \frac{1}{2} \lambda_1 |\phi_1|^4 + \frac{1}{2} \lambda_2 |\phi_2|^4 \\
 & + \lambda_3 |\phi_1|^2 |\phi_2|^2 + \lambda_4 |\phi_1^\dagger \phi_2|^2 + \frac{1}{2} (\lambda_5 (\phi_1^\dagger \phi_2)^2 + \text{h.c.}) \\
 & + \mu_\Phi^2 |\Phi|^2 + \frac{1}{2} \lambda_\Phi |\Phi|^4 + \sum_{a=1}^2 (\rho_a |\phi_a|^2 |\Phi|^2 + \sigma_a |\phi_a^\dagger \Phi|^2) \\
 & + \boxed{\kappa (\Phi^\dagger \phi_1)(\tilde{\phi}_1^\dagger \phi_2) + \text{h.c.}}
 \end{aligned}$$

Mixing between Φ^+ and ω_a^+

Definition of the Model

Mass eigenstates

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} \quad \begin{pmatrix} z \\ A \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} z_1 \\ z_2 \end{pmatrix}$$

$$\begin{pmatrix} \omega^\pm \\ H_1^\pm \\ H_2^\pm \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \chi & \sin \chi \\ 0 & -\sin \chi & \cos \chi \end{pmatrix} \begin{pmatrix} \cos \beta & \sin \beta & 0 \\ -\sin \beta & \cos \beta & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \omega_1^\pm \\ \omega_2^\pm \\ \Phi^\pm \end{pmatrix} \quad \tan \beta = v_2/v_1$$

Physical scalar: $\Phi^{\pm\pm}, H_1^\pm, H_2^\pm, h, H, A$ NG boson: ω^\pm, z

We assume that $\sin(\alpha - \beta) = 1$ so that h is SM-like Higgs boson.

Yukawa interaction

(Alignment limit)

We consider the Type-I Yukawa interaction where all fermions couple to ϕ_2

$$-\frac{\sqrt{2}}{v} \left\{ V_{ij} \bar{u}_i (m_{u_i} P_L + m_{d_j} P_R) d_j + m_{\ell_i} \bar{\nu}_i P_R \ell_i \right\} (\cos \chi H_1^+ - \sin \chi H_2^+) + \text{h.c.}$$

$H_1^\pm \bar{f} f' \propto \cot \beta \cos \chi, \quad H_2^\pm \bar{f} f' \propto \cot \beta \sin \chi$

Mass spectrum (two scenarios)

For simplicity, we assume that new neutral scalars H, A are enough heavy, and charged states $\Phi^{\pm\pm}$ and $H_{1,2}^\pm$ cannot decay into them.

We consider the following **two scenarios**.

$$\textcircled{1} \quad m_\Phi = 200 \text{ GeV}, \quad m_{H_1} = 100 \text{ GeV}, \quad m_{H_2} = 120 \text{ GeV}, \quad \tan\beta = 10, \quad \chi = \frac{\pi}{4}$$

$$\begin{array}{lll} \text{Br}(\Phi^{\pm\pm} \rightarrow H_1^\pm W^\pm) \simeq 100 \% & \text{Br}(H_2^\pm \rightarrow H_1^\pm Z^*) \simeq 40 \% & \text{Br}(H_1^\pm \rightarrow cs) \simeq 60 \% \\ \\ \text{Br}(H_2^\pm \rightarrow cs) \simeq 30 \% & & \text{Br}(H_1^\pm \rightarrow \tau\nu) \simeq 40 \% \\ \\ \text{Br}(H_2^\pm \rightarrow \tau\nu) \simeq 20 \% & & \end{array}$$

$$\textcircled{2} \quad m_\Phi = 300 \text{ GeV}, \quad m_{H_1} = 200 \text{ GeV}, \quad m_{H_2} = 250 \text{ GeV}, \quad \tan\beta = 3, \quad \chi = \frac{\pi}{4}$$

$$\text{Br}(\Phi^{\pm\pm} \rightarrow H_1^\pm W^\pm) \simeq 100 \% \quad \text{Br}(H_2^\pm \rightarrow tb) \simeq 100 \% \quad \text{Br}(H_1^\pm \rightarrow tb) \simeq 100 \%$$

Scenario-I: Signal

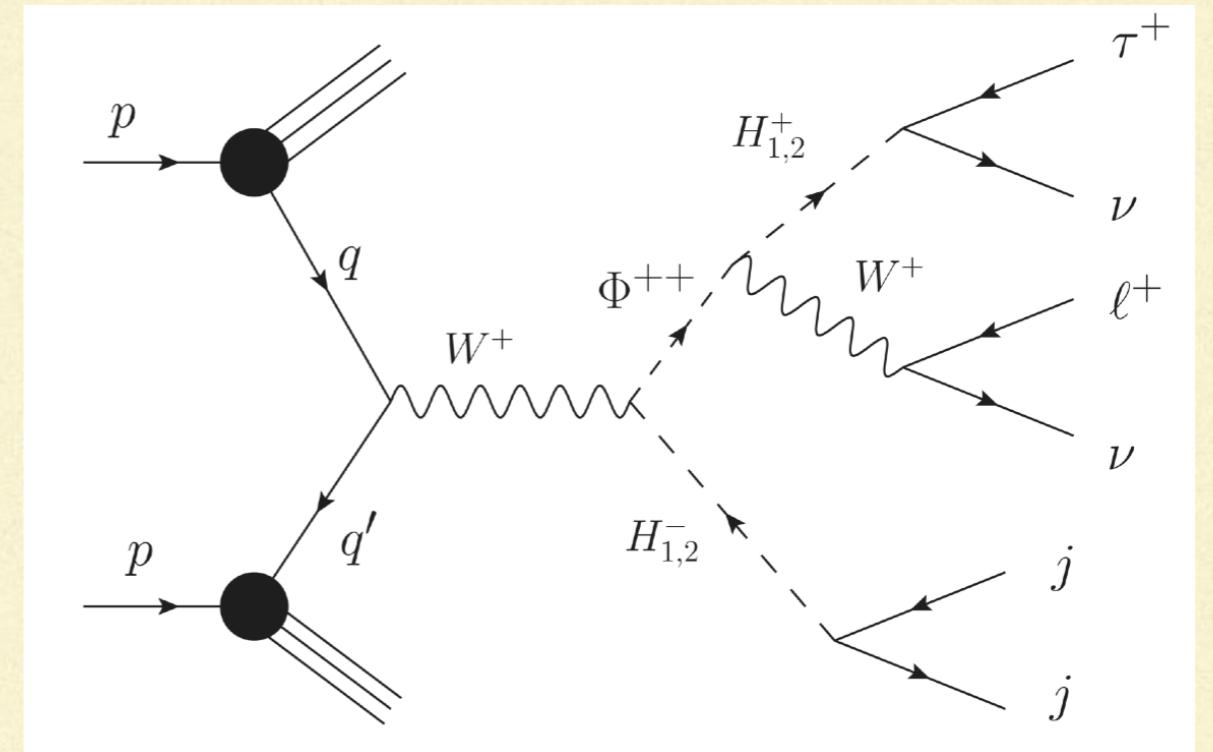
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Signal

$$pp \rightarrow \Phi^{++} H_{1,2}^- \rightarrow \tau^+ \ell^+ 2\nu 2j \quad (\ell = e, \mu)$$

We consider the decay $\tau^+ \rightarrow \pi^+ \nu$

$$\text{Br}(\tau \rightarrow \pi\nu) \simeq 11 \text{ \%}$$



We assume that $\tau \rightarrow$ hadron identification efficiency is 60 %

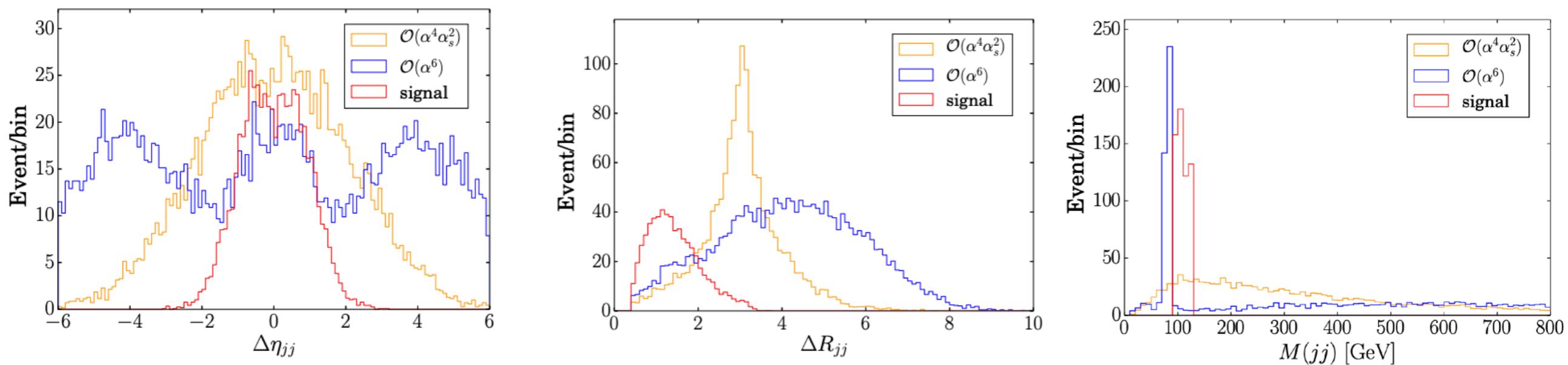
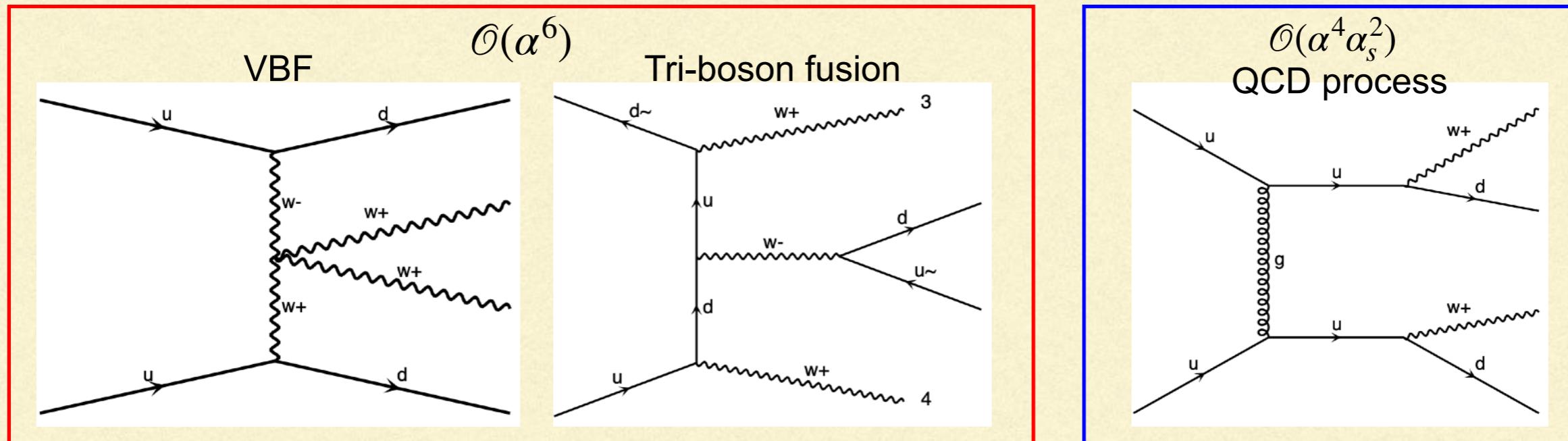
Then, misidentification probability of τ is about 1 %

A. M. Sirunyan, et al, [CMS], JINST 13, no.10, P10005 (2018).

Background (BG) processes including τ mis-id would be negligible small.

Scenario-I: Background

Main Background $pp \rightarrow W^+W^+jj$



Kinematical cuts to reduce BG

$|\Delta\eta_{jj}| < 2.5, \quad \Delta R_{jj} < 2, \quad 90 \text{ GeV} < M_{jj} < 180 \text{ GeV}$

BG reduction: 98 %

Scenario-I: Results

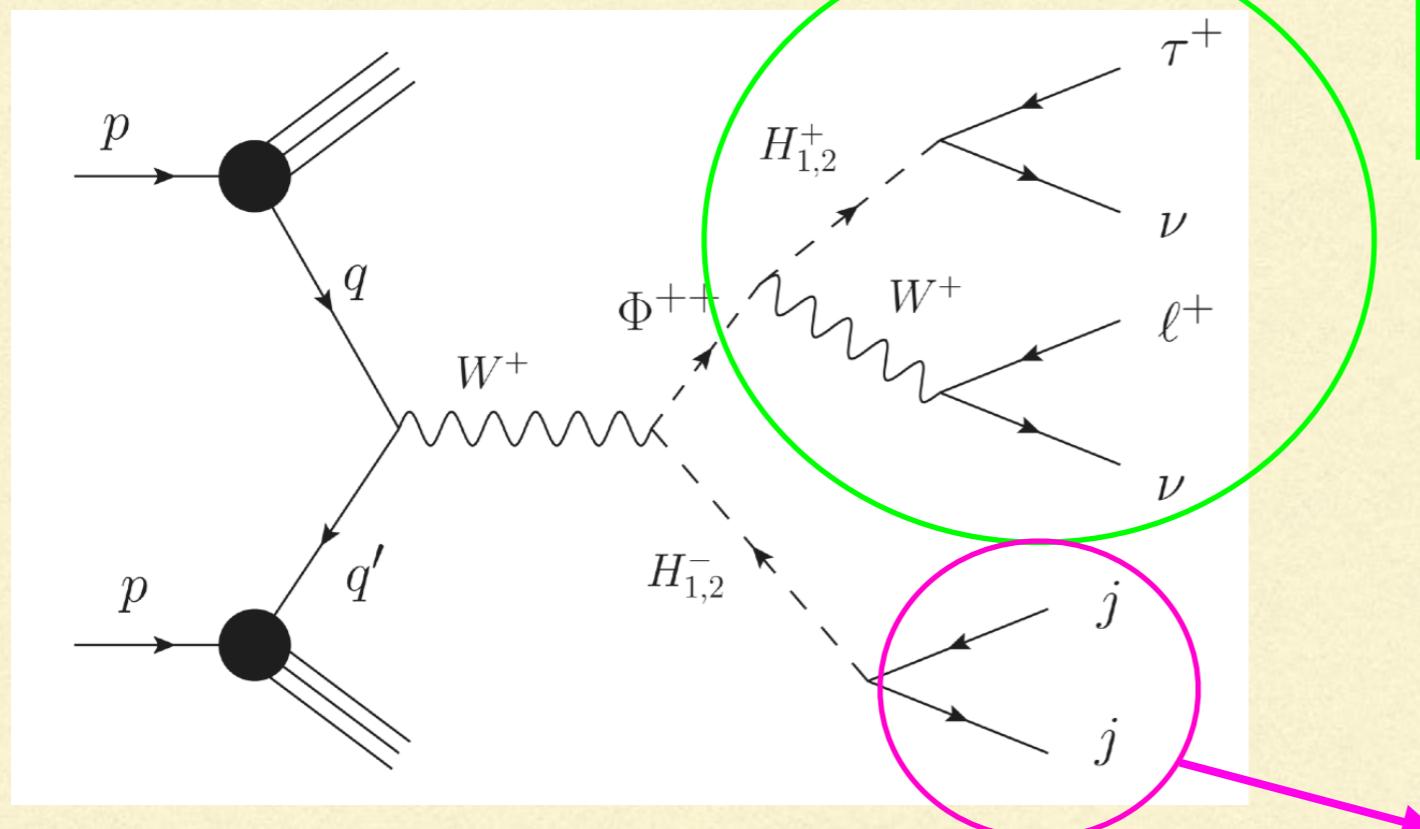
The detector performance.

$$p_T^j > 20 \text{ GeV}, \quad p_T^\ell > 10 \text{ GeV},$$

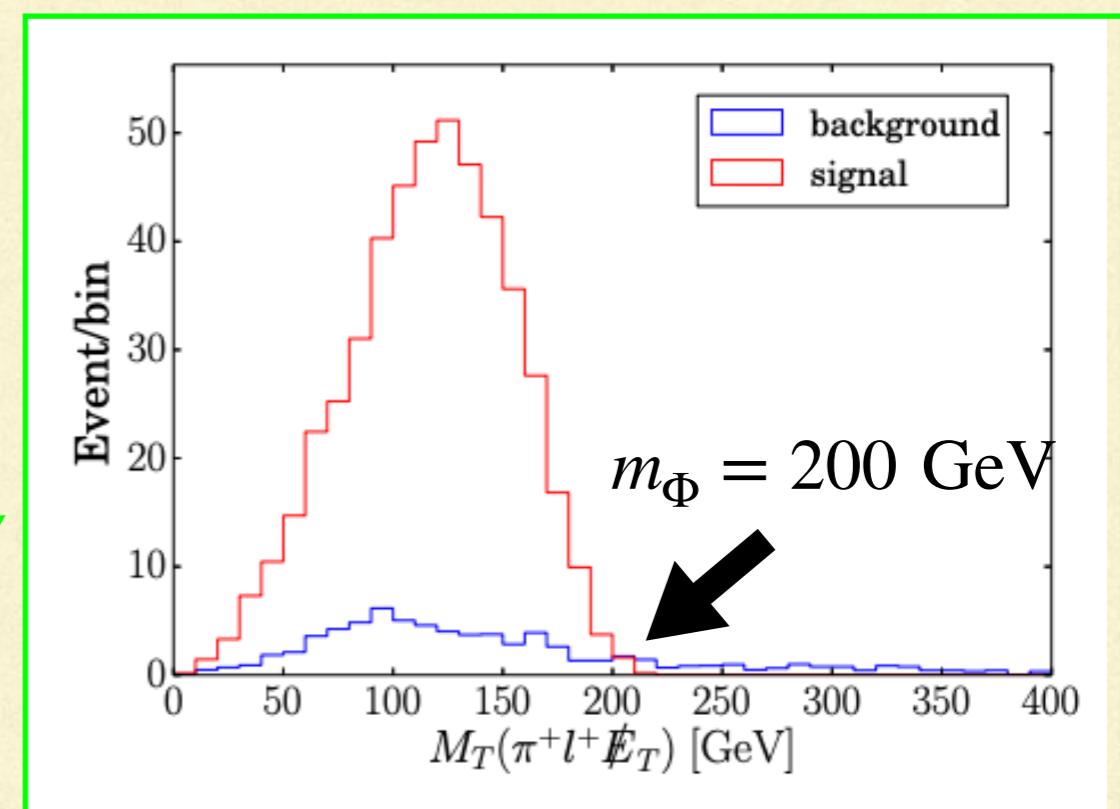
$$|\eta^j| < 5, \quad |\eta^\ell| < 2.5,$$

$$\Delta R_{jj} > 0.4, \quad \Delta R_{\ell j} > 0.4, \quad \Delta R_{\ell\ell} > 0.4$$

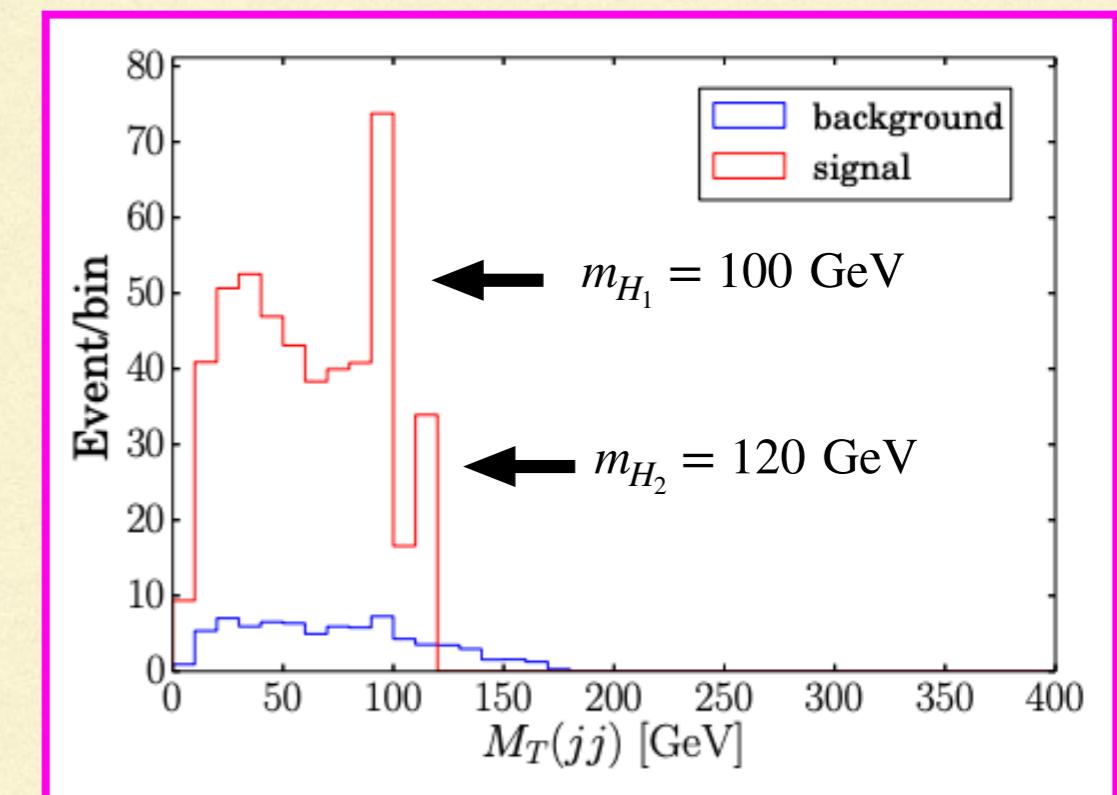
Madgraph5_aMC@NLO



It would be possible to obtain information of
 m_Φ , m_{H_1} , and m_{H_2} @ HL-LHC !



$\sqrt{s} = 14 \text{ TeV}, L = 3000 \text{ fb}^{-1}$



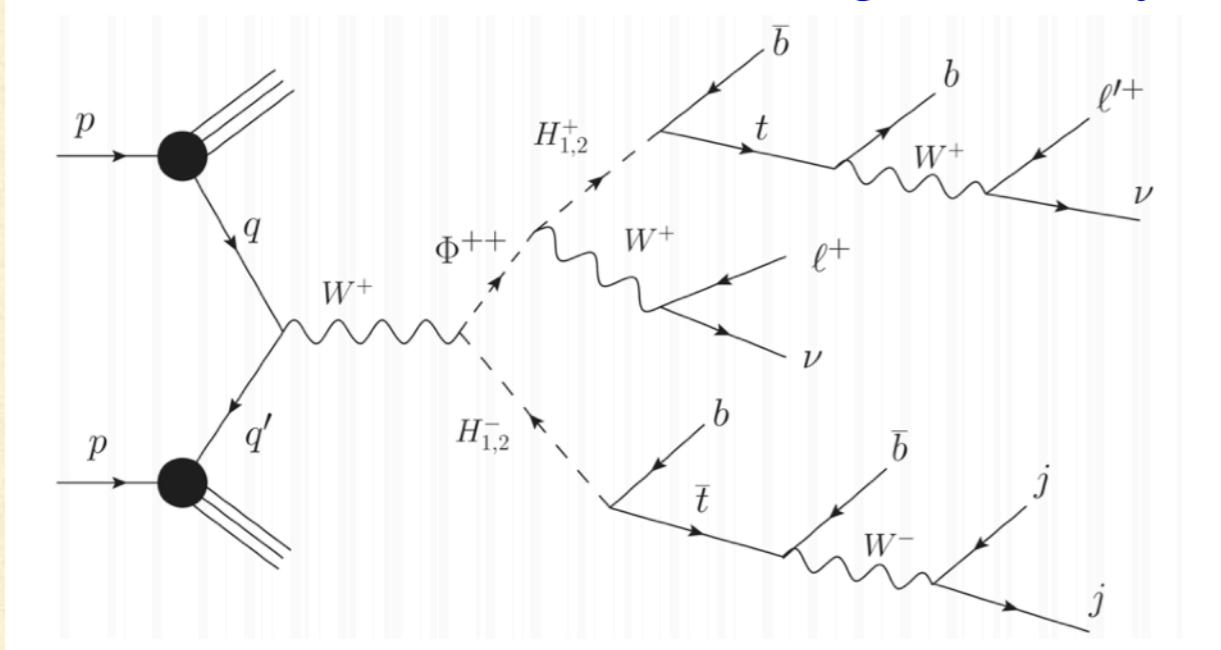
Scenario-II

$$m_\Phi = 300 \text{ GeV}, \quad m_{H_1} = 200 \text{ GeV}, \quad m_{H_2} = 250 \text{ GeV}, \quad \tan\beta = 3, \quad \chi = \frac{\pi}{4}$$

$$\begin{aligned} \text{Br}(H_{1,2}^\pm \rightarrow tb) &\simeq 100 \% \\ \text{Br}(\Phi^{++} \rightarrow H_1^+ W^+) &\simeq 100 \% \end{aligned}$$

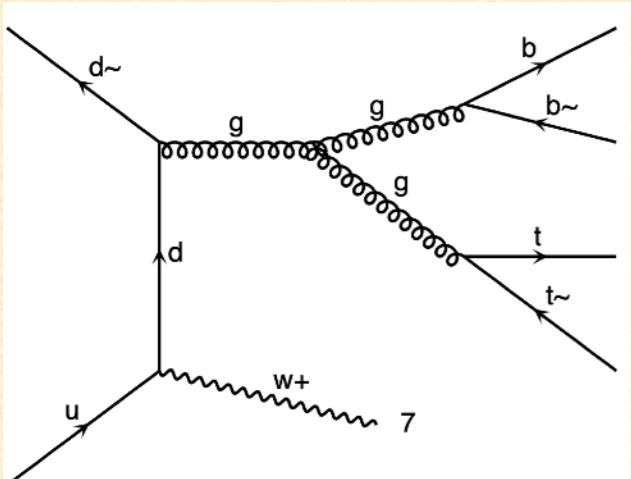
Signal: $pp \rightarrow H_{1,2}^- \Phi^{++} \rightarrow t\bar{t}b\bar{b}\ell^+\nu \rightarrow 2b2\bar{b}2\nu2j\ell^+\ell'^+$

b-tag efficiency = 70 %



Main backgrounds

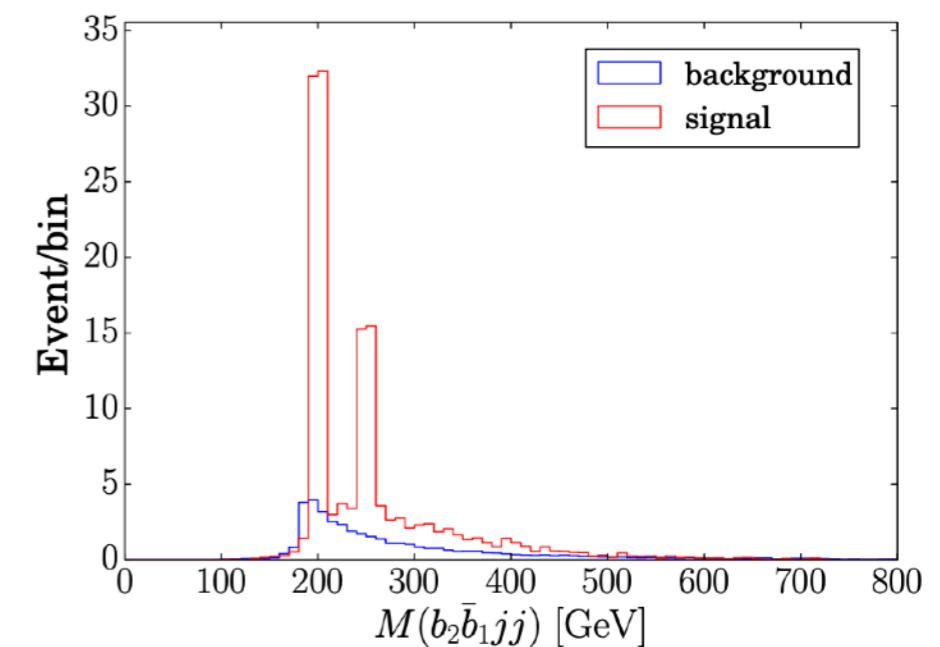
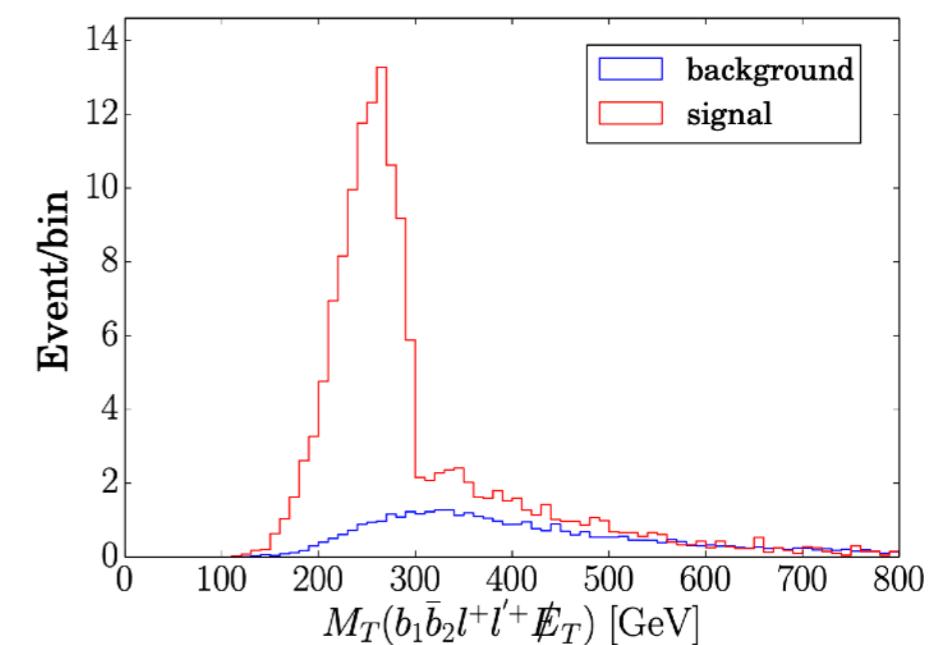
$pp \rightarrow t\bar{t}b\bar{b}W^+$



detector performance

$$\begin{aligned} p_T^j &> 20 \text{ GeV}, \quad p_T^\ell > 10 \text{ GeV}, \\ |\eta^j| &< 5, \quad |\eta^\ell| < 2.5, \\ \Delta R_{jj} &> 0.4, \quad \Delta R_{\ell j} > 0.4, \\ \Delta R_{\ell\ell} &> 0.4 \end{aligned}$$

$$\sqrt{s} = 14 \text{ TeV}, \quad L = 3000 \text{ fb}^{-1}$$



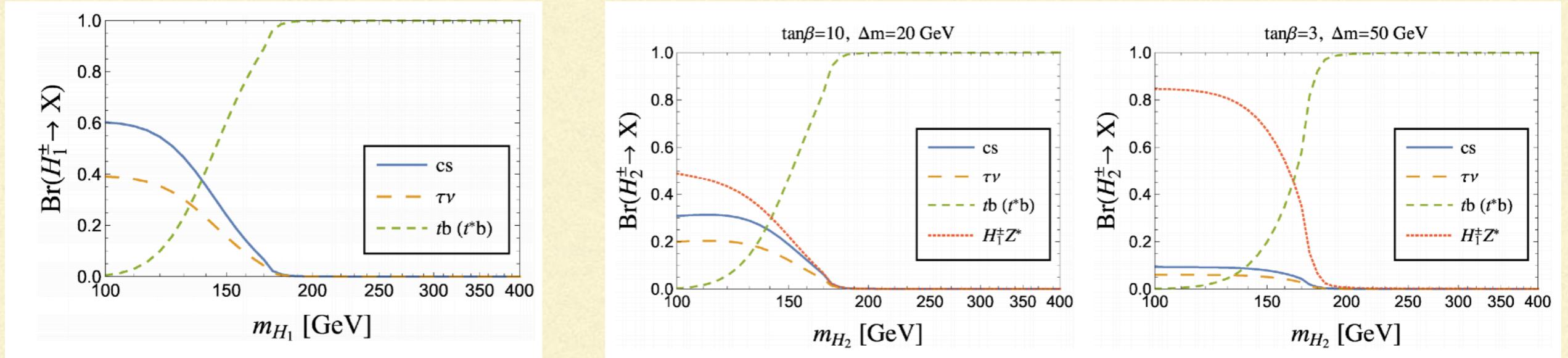
Summary

- Doubly charged scalars are sometimes introduced to models for tiny ν masses
- In the previous work, it is suggested that in the model (THDM + Φ), the masses of all charged states are measurable from the single process by looking at the Jacobian peaks of transverse masses of several combinations of final states.
- In our work, we did background analysis of the signal @ HL-LHC, and investigated whether the signal can be observed or not.
- We considered two scenarios. In one of them, $H_{1,2}^\pm$ decays into $\tau\nu$ or cs . In the other case, $H_{1,2}^\pm$ decays into tb at almost 100 %
- We found that it would be possible to obtain the information on the masses of all charged states from the signal @ future HL-LHC in both cases by using appropriate kinematical cuts.

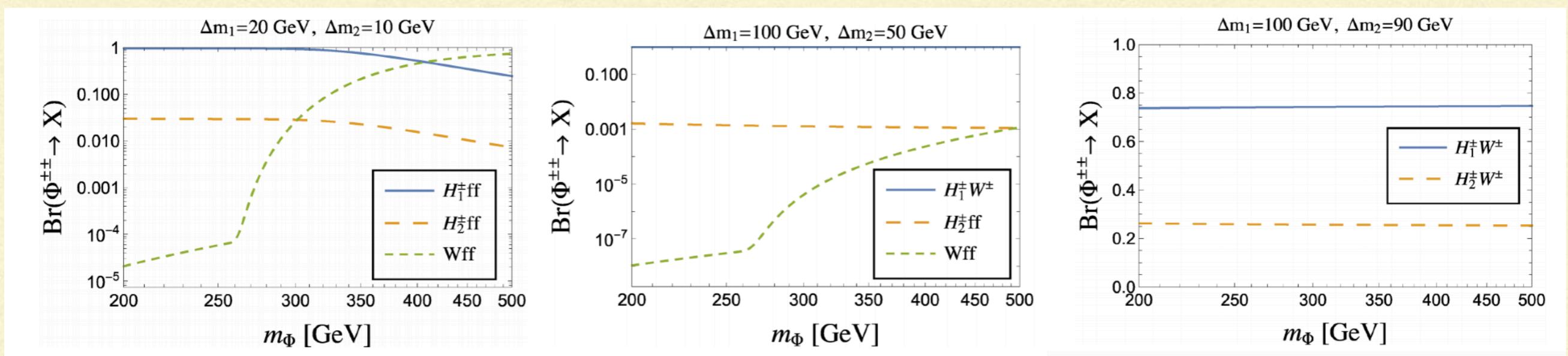
Backup Slides

Decay of charged scalars

Singly charged $H_{1,2}^\pm$ ($\Delta m = m_{H_2} - m_{H_1}$)

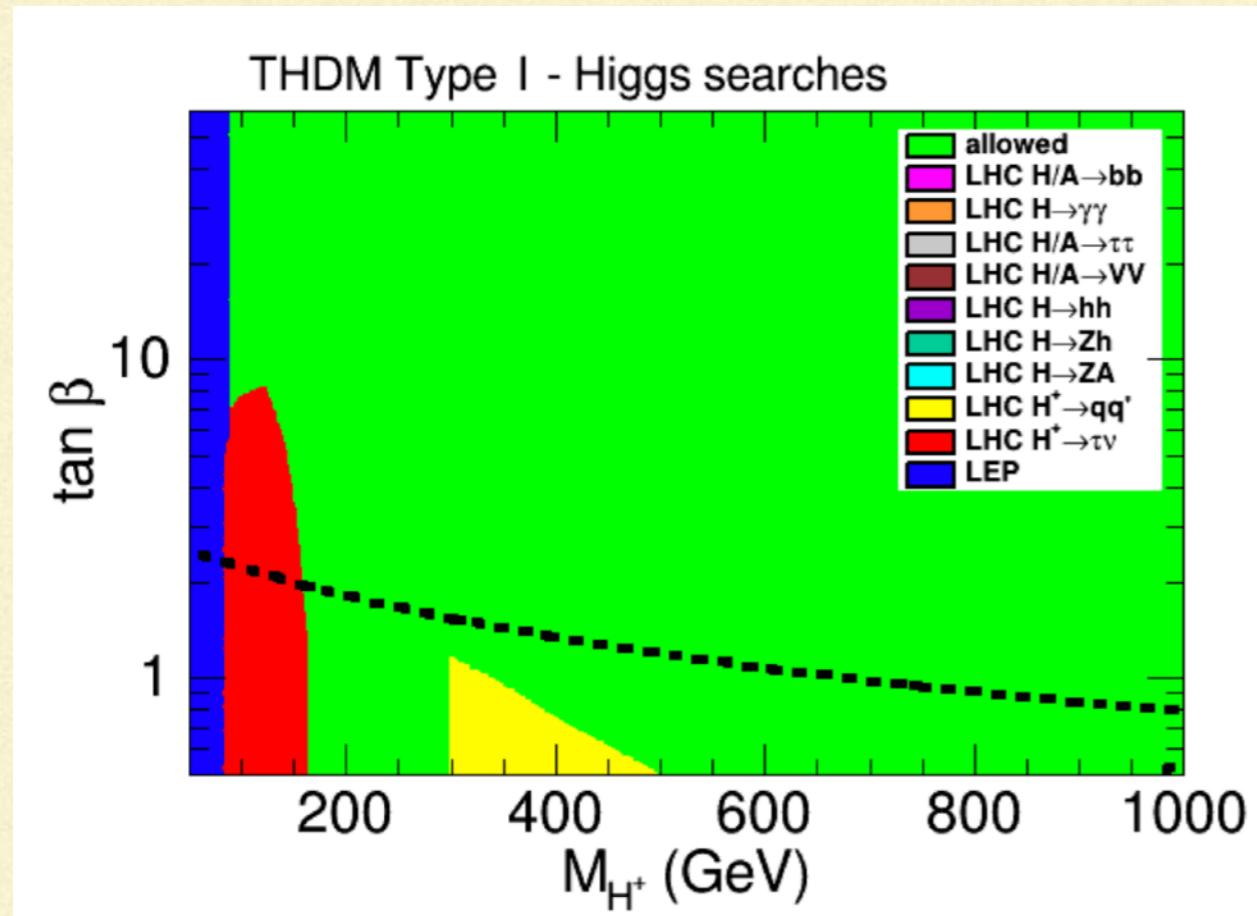


Doubly charged $\Phi^{\pm\pm}$ ($\Delta m_1 = m_\Phi - m_{H_1}$, $\Delta m_2 = m_\Phi - m_{H_2}$)



Constraints for singly charged scalars $H_{1,2}^\pm$

$$-\frac{\sqrt{2}}{\nu} \left\{ V_{ij} \bar{u}_i (m_{u_i} P_L + m_{d_j} P_R) d_j + m_{\ell_i} \bar{\nu}_i P_R \ell_i \right\} (\cos \chi H_1^+ - \sin \chi H_2^+) + \text{h.c.}$$



In the heavy mass region, most stringent bound is from flavor experiments. (black dashed line)

In the light mass region, stringent bounds are from LHC Run2 or LEP.

Figure from A. Arbey, et al, Eur.Phys.J(2018)

We have also confirmed our two scenarios satisfy the constraints from latest search of $H^\pm \rightarrow tb$ ([arXiv:2102.10076\[hep-ex\]](https://arxiv.org/abs/2102.10076)) and $H^\pm \rightarrow \tau\nu$ ([JHEP07\(2019\)142](https://doi.org/10.1007/JHEP07(2019)142)).