Search for doubly charged Higgs boson decaying to same-sign W boson.

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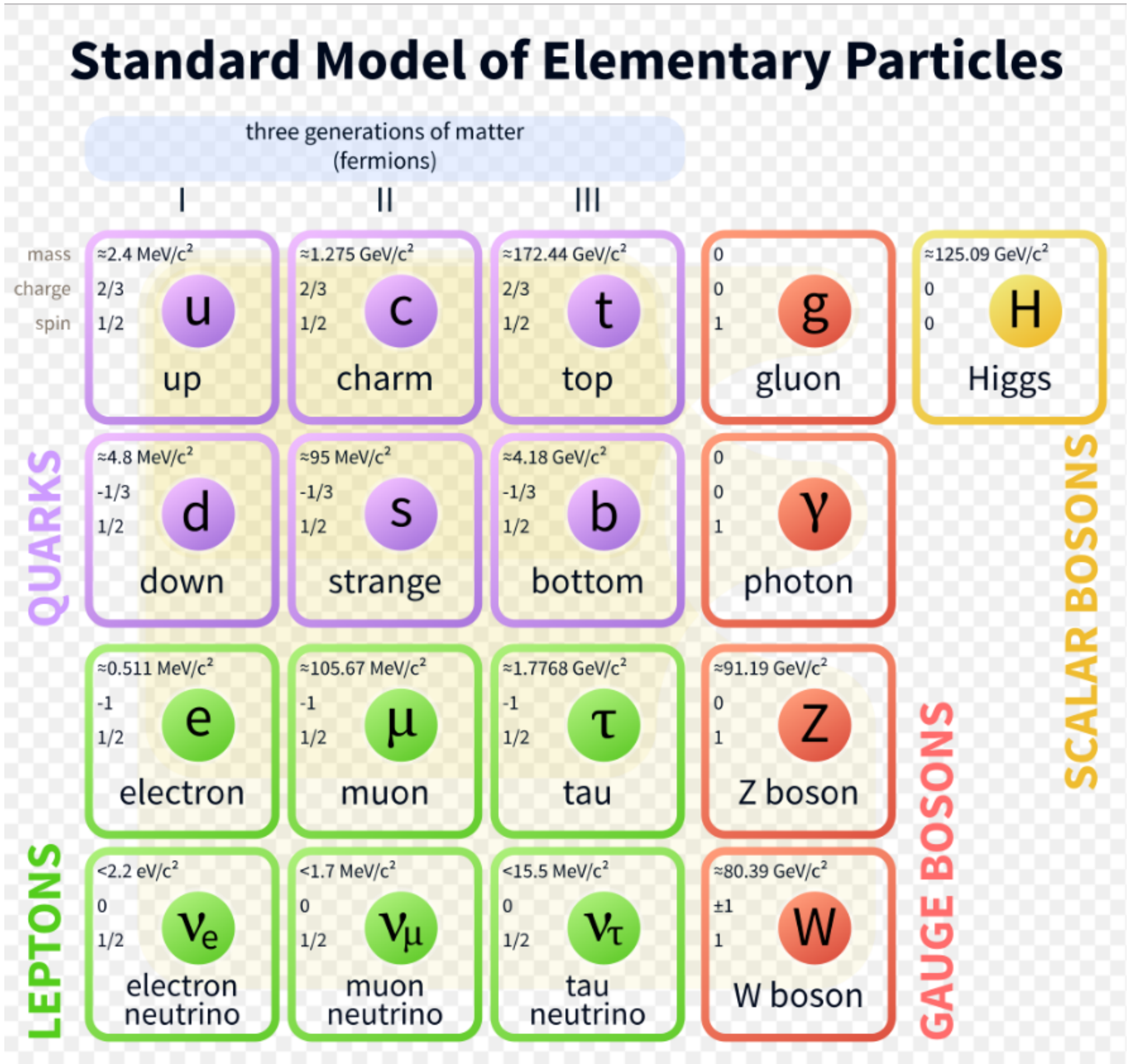
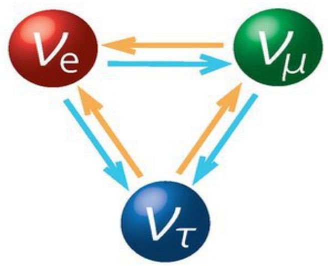
The Standard Model of Particle Physics



The Standard Model

- Field theory with a gauged symmetry
- Describes 3 of the 4 forces in nature
- Matter particles (fermions) and their interactions (bosons)
- Include a mechanism to generate masses of these particles

Motivation



- Neutrino oscillations is an incompleteness of the Standard Model.
- Can extending the scalar sector solve it?

Scalar Sector

The doublet triplet model(DTM) extends the scalar sector to include a hypercharge Y = 2 scalar triplet Δ, together with the SM scalar doublet.

$$\mathcal{L} = (D_\mu H)^\dagger (D^\mu H) + Tr(D_\mu \Delta)^\dagger (D^\mu \Delta) - V(H,\Delta) + \mathcal{L}_{Yukawa}$$

$$\mathcal{L}_{Yukawa} = \mathcal{L}^{SM}_{Yukawa} - Y_\nu L^T C \otimes i\sigma^2 \Delta L$$

$$V(H,\Delta) = -m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + m_\Delta^2 Tr(\Delta^\dagger \Delta)$$

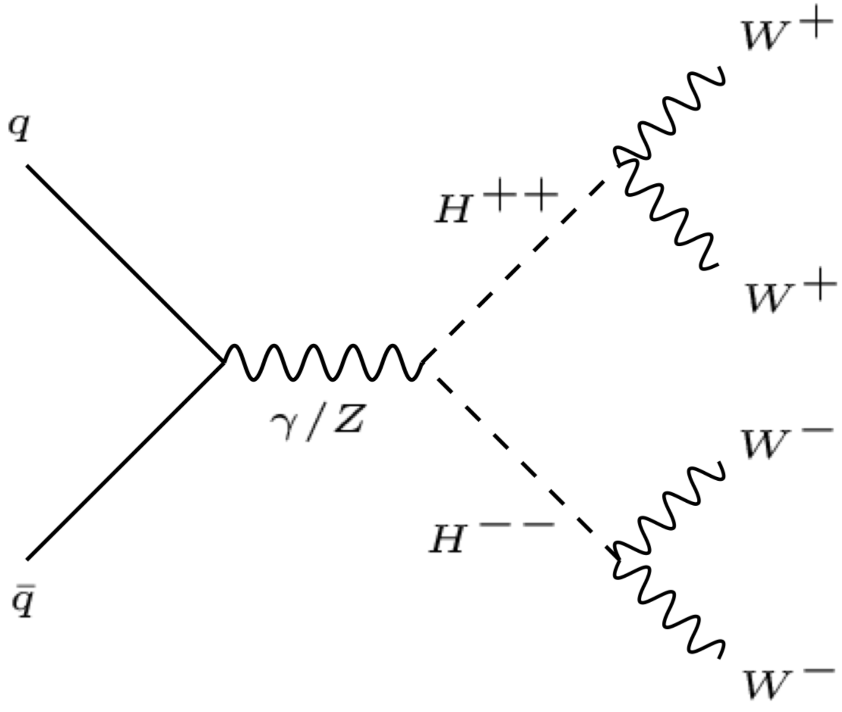
$$+[\mu(H^\dagger i\sigma^2 \Delta^\dagger H) + h.c.] + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) + \lambda_2 (Tr\Delta^\dagger \Delta)^2 + \lambda_3 Tr\left(\Delta^\dagger \Delta\right)^2$$

$$+\lambda_4 H^\dagger \Delta \Delta^\dagger H.$$

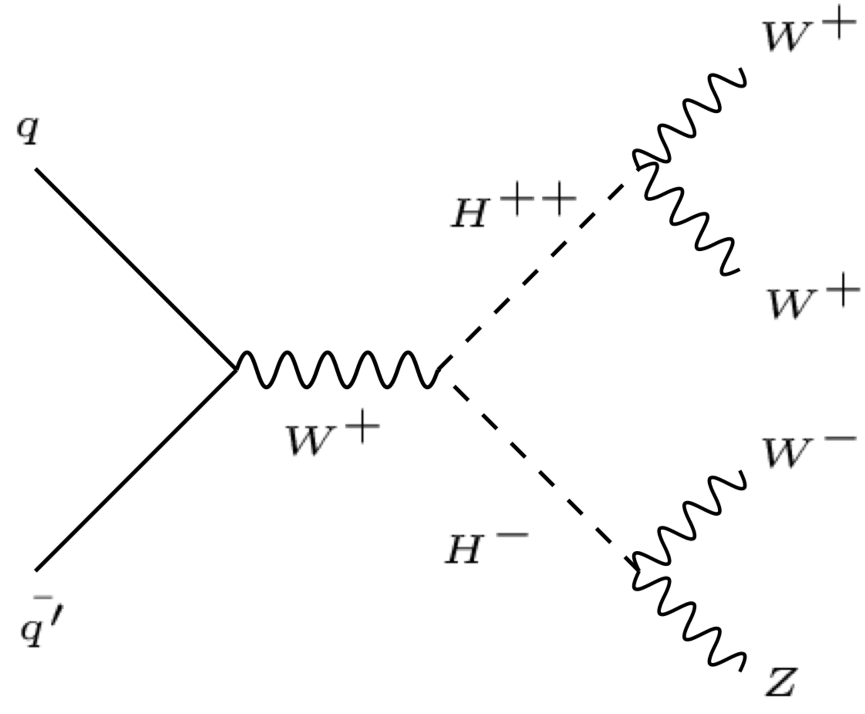
Type-II Seesaw Model

- An explaintion of the oscillations and finite mass of neutrinos.
- Predicting new scalars, some of which have mass in electroweak scale range.
- Electroweak Symmetry Breaking causes a mixing between these fields and results in 7 scalar bosons: $H^{\pm\pm}$, $H^\pm$, $\Lambda^0(CP\ odd)$, $H^0(CP\ even)$, $h^0(CP\ even)$

Production Mode



Pair Production



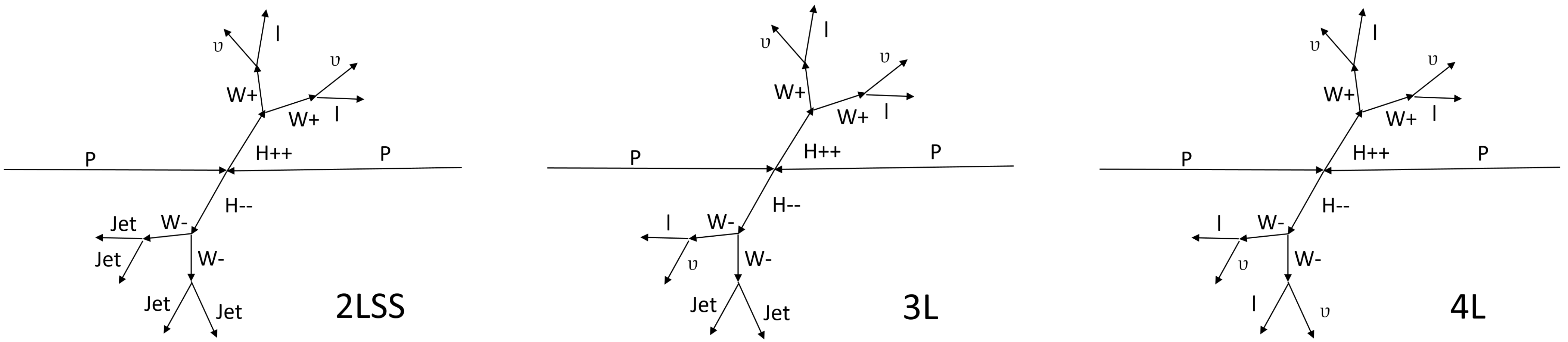
Associated Production

- Focus on the pair production mode: $pp \to \gamma^*, Z^* \to H^{\pm\pm}H^{\mp\mp}$
- Require $H^{\pm}$ heavier than the $H^{\pm\pm}$ by a few 100 GeV(Large λ_4) to suppress the associated production.
- Two decay mode:
  - $H^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$ (arxiv: 1710.09748) massed below 800 GeV have been excluded
  - $H^{\pm\pm} \to W^{\pm}W^{\pm}$ (This analysis)

Outline

Three channels according to different final states.

- Two same sign leptons, MET and four jets.
- Three leptons, MET and two jets.
- Four leptons, and MET.



- Consider different masses of $H^{\pm\pm}$, from 200 GeV to 700 GeV. (100 GeV step)
- 36.1 fb^{-1} data collected with $\sqrt{s}$ = 13 TeV during 2015 and 2016 are using in this analysis.

Lepton Definition

	Electrons		Muons	
Lepton candidate type	L	T	L	T
Lepton p_{T}	$p_{\mathrm{T}} > 10$ GeV		$p_{\mathrm{T}} > 10$ GeV	
Pseudo-rapidity	$\|\eta\| < 2.47$, not in crack $1.37 : 1.52$		$\|\eta\| < 2.5$	
Identification and isolation	*loose*	*tight*	*loose*	*tight*
Impact parameter longitudinal $\|z_0 \sin\theta\|$	< 0.5 mm	< 0.5 mm	< 0.5 mm	< 0.5 mm
Impact parameter transverse $\|d_0\|/\sigma(d_0)$	< 5	< 5	< 3	< 3

- Two types of lepton requirements are used for both electrons and muons:
- Tight (denoted by T) and Loose (denoted by L)
- The type L conditions are a subset of the type T conditions.

Overview of 2LSS channel

2LSS channel

$H^{\pm\pm}H^{\mp\mp} \to 4W \to \ell^{\pm}\ell^{\pm} + E_T^{\text{miss}} + 4jets$

Three sub channels: $ee, e\mu, \mu\mu$

Background

- Prompt background :
  WZ,ZZ and same-sign WW: Monte Carlo.
- Charge-MisID background :
  W^+W^- and Z+jets will contribute addition background by Charged MisID: Data-driven likelihood method.
- Fake background :
  Z+jets, W+jets and $t\bar{t}$: data-driven fake-factor method.

Event Pre-selection

Trigger requirement
Two T leptons with same sign , $p_T > 30$, 20 GeV respectively.
$\lvert M_{ll} \rvert <$80 GeV or $\lvert M_{ll} \rvert >$ 100 GeV for ee channel
No b-jet, MV2c10_70 working point
Njets $\geq$ 3
$E_{\mathrm{T}}^{\mathrm{miss}} >$ 70 GeV

Event Pre-Selection of the di-lepton same sign analysis

Trigger requirement:

- At least one lepton with P_T > 30 GeV matched to the single-lepton trigger signals

Fake Enriched region:

- At least one of the leptons is required to pass type L and fail type T

Fake Control region:

- $E_{\mathrm{T}}^{\mathrm{miss}} <$ 70 GeV

Charge Mis-identification

Likelihood Method

$$\ln \mathcal{L}(\varepsilon|N_{tot},N_{ss}) = \sum_{i,j} \ln \left[N^{i,j}_{tot}(\varepsilon_i+\varepsilon_j)\right] N^{i,j}_{SS} - N^{i,j}_{tot}(\varepsilon_i+\varepsilon_j) \quad (1)$$

- Rates of muon is negligible
- Rates of Type-T electrons are measured with T+T pair,with fine binning.
  $|\eta|$: 0, 0.6, 1.1, 1.37, 1.52, 1.7, 2.3, 2.47
  $P_T[GeV]$: 20, 60, 90, 130, 1000
- Rates of Type-L electrons are measured with L(not T)+T pair,
  with coarse binning:
  $|\eta|$: 0, 1.37, 1.52, 2.47
  $P_T[GeV]$: 20, 60, 1000
- Charge-MisID rates nominal results: $[0.021,9.921]$ in percent for T, while $[0.68,12.18]$ in percent for L electrons due to different bins.
- A systematic uncertainty of 30% is estimated from Monte Carlo samples due to Kinematic Difference

Fake Factor Method

- The fake factor is defined as ratio :

$$\theta_\ell = \frac{N_{\ell\ell}(Events\ of\ two\ T\ same{-}sign\ leptons)}{N_{\ell\not\ell}(Events\ of\ one\ T\ and\ one\ L\ non{-}T\ same{-}sign\ leptons)}$$

- Fake factors are measured in low E_T^{miss} region ($< 70 GeV$).
- Muon fake factor is measured in $\mu\mu$ channel.
- Electron fake factor is measured in $e\mu$ channel.

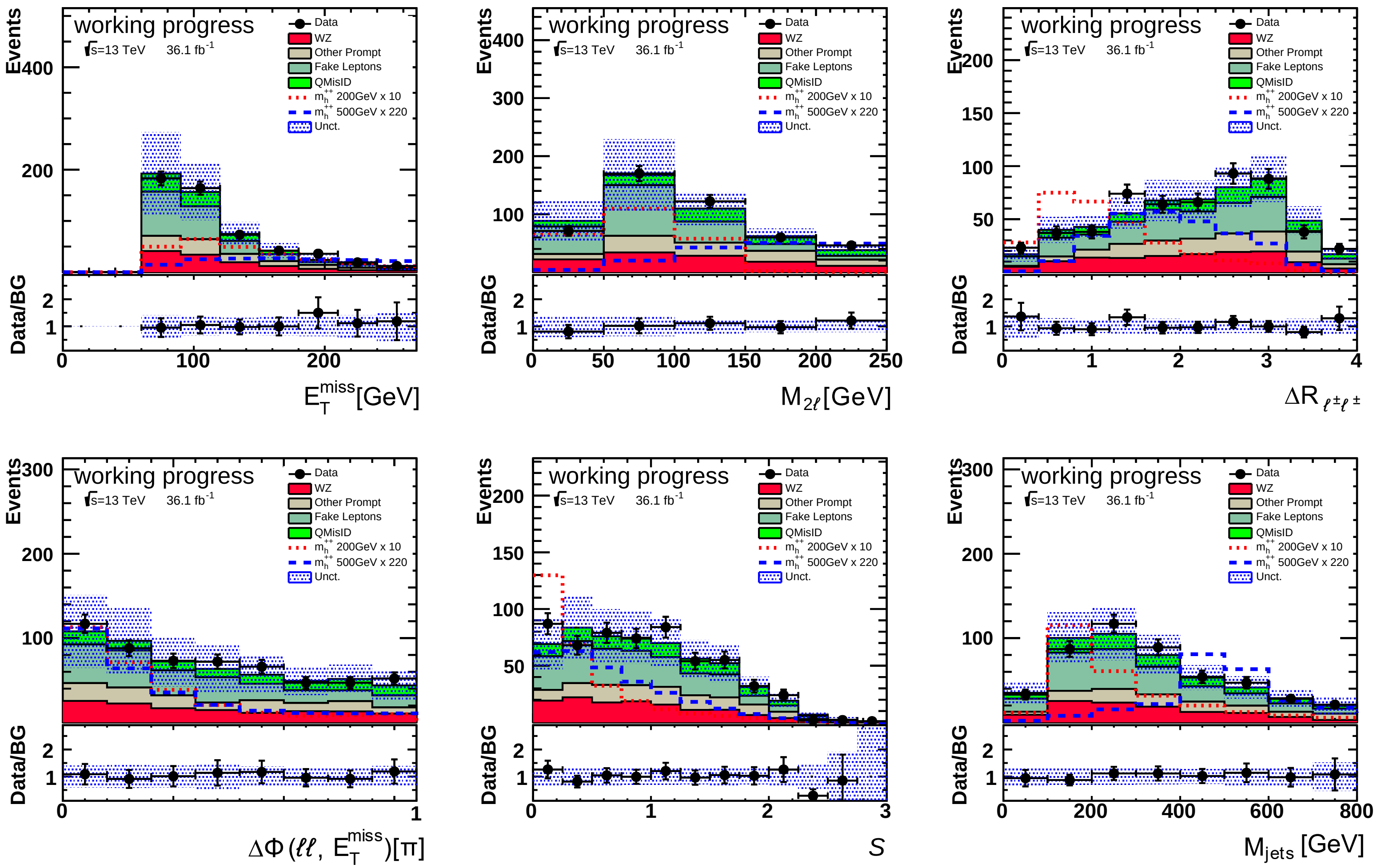
$$\theta_e = \frac{N_{\mu e}}{N_{\mu\not e}}(E_T^{miss} < 70\text{ GeV}) = \frac{N_{\mu e}^{Data} - N_{\mu e}^{\text{Prompt}\ SS} - N_{\mu e}^{\text{Q}MisId} - N_{\mu e}^{\text{F}akeMuon}}{N_{\mu\not e}^{Data} - N_{\mu\not e}^{\text{Prompt}\ SS} - N_{\mu\not e}^{\text{Q}MisId}}$$

$$\theta_\mu = \frac{N_{\mu\mu}}{N_{\mu\not\mu}}(E_T^{miss} < 70\text{ GeV}) = \frac{N_{\mu\mu}^{Data} - N_{\mu\mu}^{\text{Prompt}\ SS}}{N_{\mu\not\mu}^{Data} - N_{\mu\not\mu}^{\text{Prompt}\ SS}}$$

The measured muon fake factor is 0.14$\pm$0.03, and the measured electron fake factor is 0.48$\pm$0.07, where the uncertainties are only staticticał.
A systematic uncertainty of 50% is estimated from complementary control samples.

Discriminating Variables

- Six variables are used on top of pre-selection level to go to signal region
- E_T^{miss}, $\Delta R_{\ell\ell}$, $\Delta\Phi(\ell\ell, E_T^{miss})$, S, $M_{\ell\ell}$, M_{jets}
- Variable S: $S = \frac{rms(\phi_{\ell_1},\phi_{\ell_2},\phi_{E_T^{miss}}) * rms(\phi_{j1},\phi_{j2},\cdots)}{rms(\phi_{\ell_1},\phi_{\ell_2},\phi_{E_T^{miss}},\phi_{j1},\phi_{j2},\cdots)}$.



Overview of 3L channel

3L channel

- $H^{\pm\pm}H^{\mp\mp} \rightarrow 4W \rightarrow \ell^{\pm}\ell^{\mp}\ell^{\mp} + E_T^{\text{miss}} + 2jets$
- Two subchannel: SFOS0, SFOS1,2
- SFOS0: no same flavor opposite sign leptons
- SFOS1,2: presence of same-flavor opposite sign leptons

Background

Prompt background:

- WZ, ZZ: Monte Carlo

Fake background:

- : $t\bar{t}$, Z+jets: data-driven fake-factor method.

Definitions of regions

	Selection Criteria	Y	X	Z	T
A	Three leptons with $P_T^{0,1,2} > 10, 20, 20GeV$	$\surd$	$\surd$	$\surd$	$\surd$
B	$\|M_{01} - M_Z\| > 10$ GeV and $\|M_{02} - M_Z\| > 10$ GeV	$\surd$	$\surd$		$\surd$
*	$\|M_{01} - M_Z\| \leq 10$ GeV or $\|M_{02} - M_Z\| \leq 10$ GeV			$\surd$	
	$M_{01} > 15$ GeV and $M_{02} > 15$ GeV	$\surd$	$\surd$		$\surd$
	$MET > 30$ GeV		$\surd$		$\surd$
	$N_{\mathrm{jet}} >= 2$		$\surd$		$\surd$
*	$N_{\mathrm{jet}} = 1$	$\surd$			
*	$N_{\mathrm{jet}} >= 1$			$\surd$	
C	$N_{\mathrm{b-jet}} = 0$		$\surd$	$\surd$	
*	$N_{\mathrm{b-jet}} >= 1$				$\surd$

- Y: Region in which fake factors are measured.
- X: Pre-selection region used to optimize variables and reach the SR
- Z: Z-enriched region.
- T: Top enriched region.

Fake Factor Method

Fake Factor fomula

The fake factors are calculated in the YS and YF regions using the formula:

$$\theta_{e/\mu} = \frac{(Data - N_{prompt})_{xee/x\mu\mu}}{(Data - N_{prompt})_{xe\not{e}/x\mu\not{\mu}}}$$

Fake Contribution

$$N_{xe\mu} = \theta_e \times N_{x\mu\not{e}} + \theta_\mu \times N_{xe\not{\mu}}$$

$$N_{xee} = \theta_e \times N_{xe\not{e}}$$

$$N_{x\mu\mu} = \theta_\mu \times N_{x\mu\not{\mu}}$$

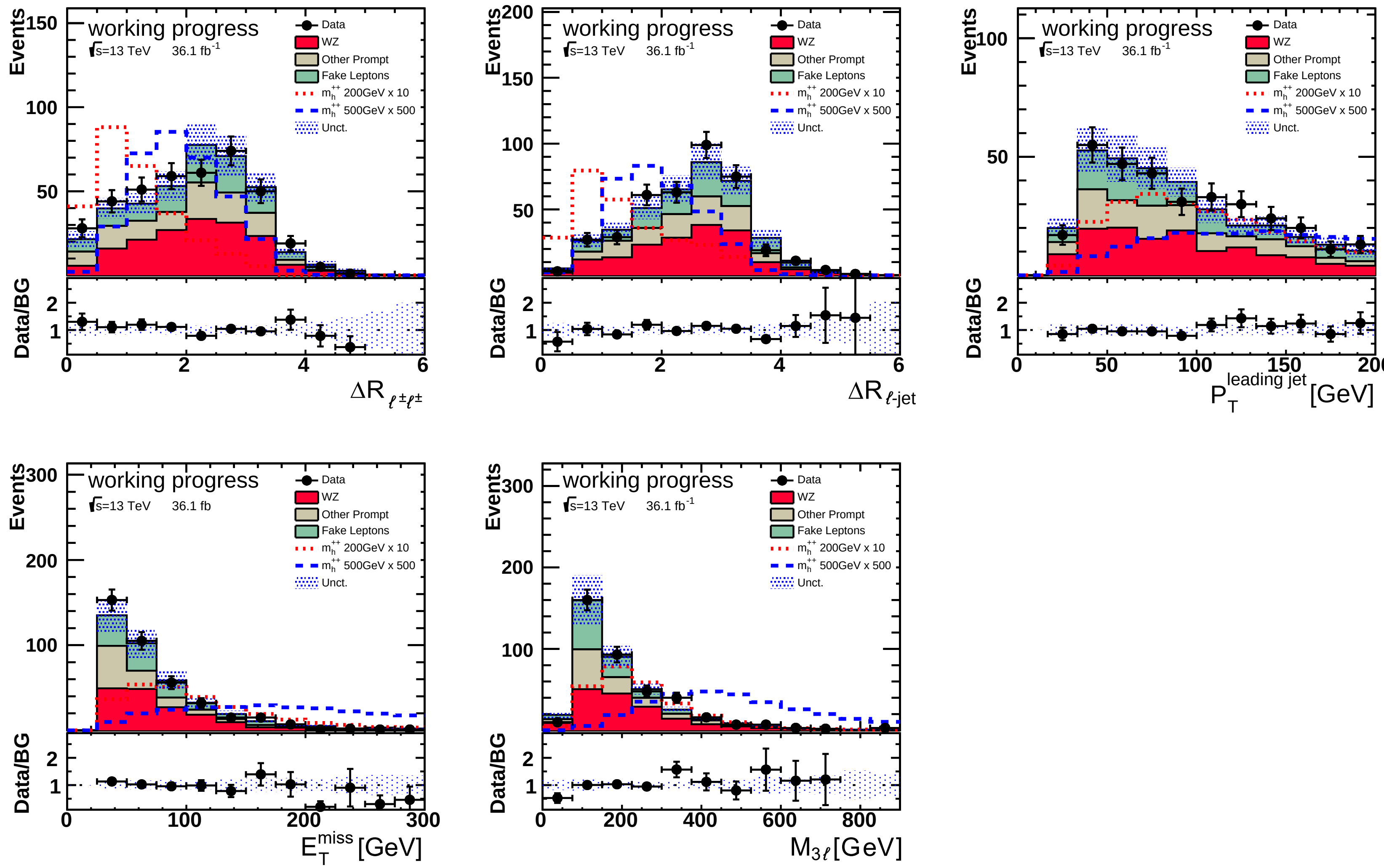
Fake Factor Result

The muon fake factor is found to be 0.17$\pm$0.06 and the electron fake factor is found to be 0.39$\pm$0.07, where the errors are statistical only.

A systematic uncertainty of 55%(for electrons) and 81%(for muons) is estimated from complementary control samples.

Discriminating variables

- Five variables are used on top of pre-selection level to go to signal region
- E_T^{miss}, $M_{3\ell}$, $P_T^{leading\ jet}$, $\Delta R_{\ell-jet}$, $\Delta R_{\ell^\pm\ell^\pm}$



Overview of 4L channel

4L channel

- $H^{\pm\pm}H^{\mp\mp} \rightarrow 4W \rightarrow \ell^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp} + E_T^{\text{miss}}$

background

- Prompt background: Monte Carlo
- Fake leptons: Process-dependent scale factors with Monte Carlo

Pre-Selection

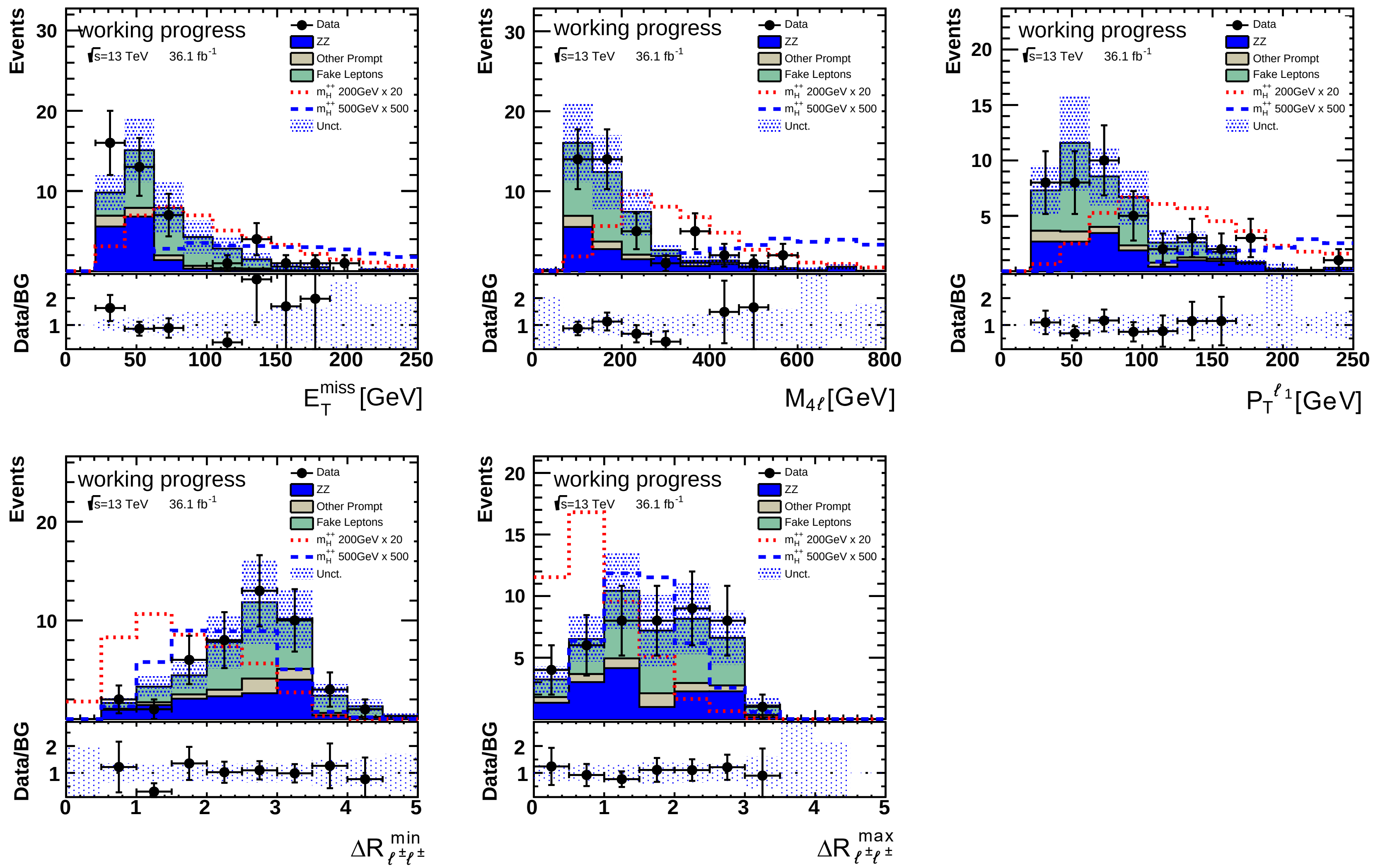
- 4 Leptons
- Zero total charge and trigger match
- $|M_{\ell^{\pm}\ell^{\mp} - M_Z}| > 10GeV$
- $M_{\ell^{\pm}\ell^{\mp}} > 12GeV$
- $E_T^{miss} > 30GeV$
- $N_{b-jet} = 0$

Control region to calculate fake scale factor

- Z+jets events (light-jet environment)
- ttbar events (heavy-jet environment)

Discriminanting variables

- Five variables are used on top of pre-selection level to go to signal region
- E_T^{miss}, $M_{4\ell}$, $P_T^{\ell 1}$, $\Delta R^{min}_{\ell^\pm \ell^\pm}$, $\Delta R^{max}_{\ell^\pm \ell^\pm}$



Systematics

Systematics included

- Theoretical uncertainties such as PDF, factorization scale and parton shower,~15% for signal.
- Uncertainty from cross section measurements, about 20~30%
- Uncertainty on luminosity,~3%.
- Uncertainty from data-driven background estimation, 50~80% for $2\ell ss$ and 3ℓ, ~50% for 4ℓ channel.
- Uncertainties due to detector simulation that affect the acceptance of signal region selection like uncertainty of Jet energy scales, vary from ~5% to ~40%.

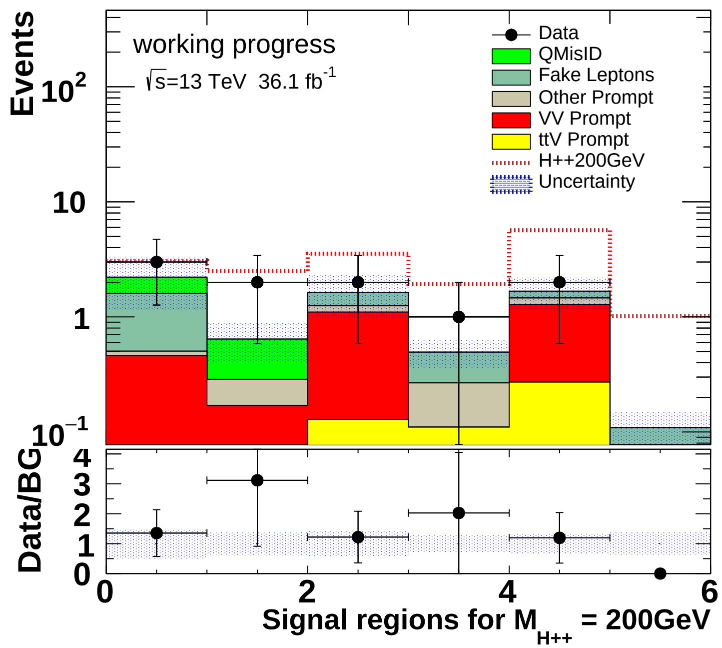
Summary

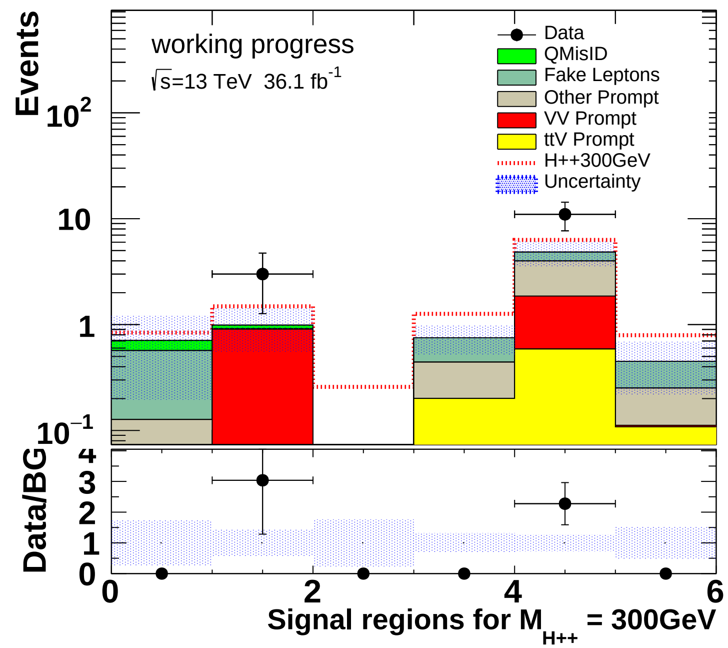
Channel	Prompt leptons	Fake leptons	Charge mis-Id
$2\ell ss$	Monte Carlo	Data-driven Fake Factor	Data-driven Likelihood
3ℓ	Monte Carlo	Data-driven Fake Factor	
4ℓ	Monte Carlo	MC : process-dependent scale factors	

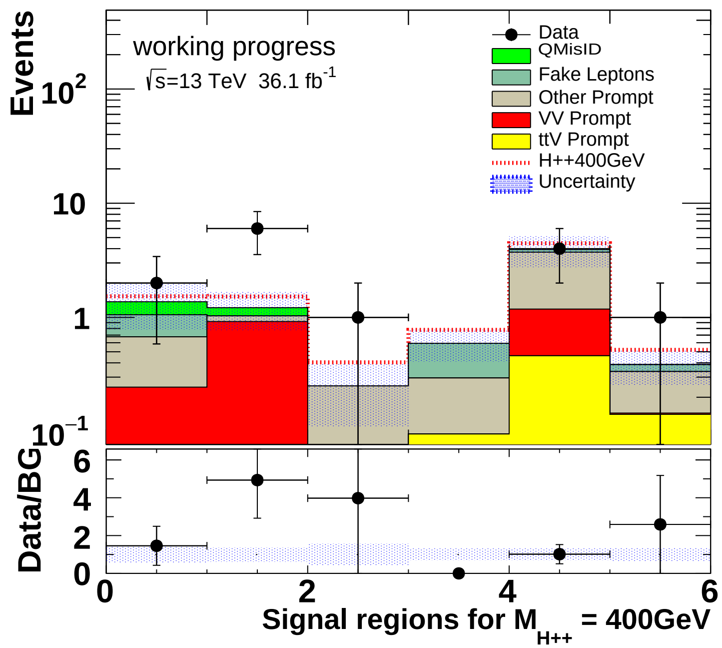
Signal

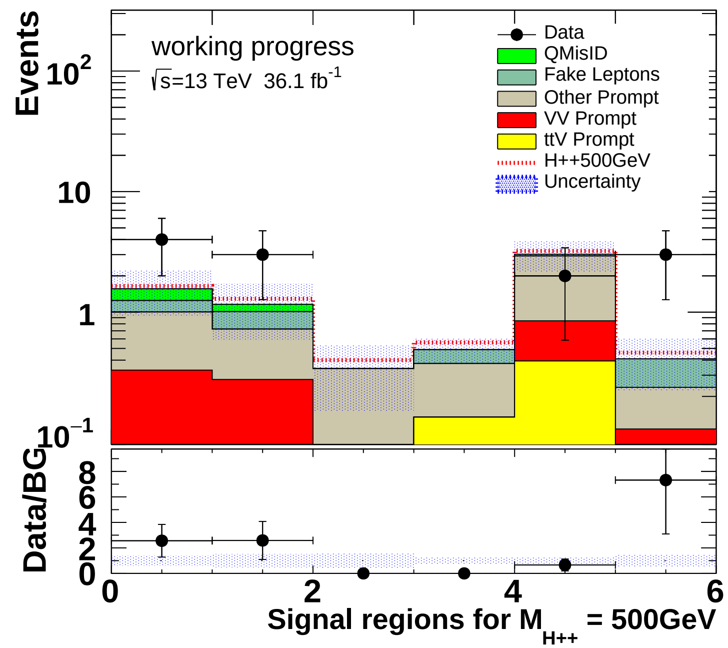
Use discriminant variables in each channel with MVA to optimized signal region cuts, while cuts are chosen to maximize significance.

Signal Region









Conclusion

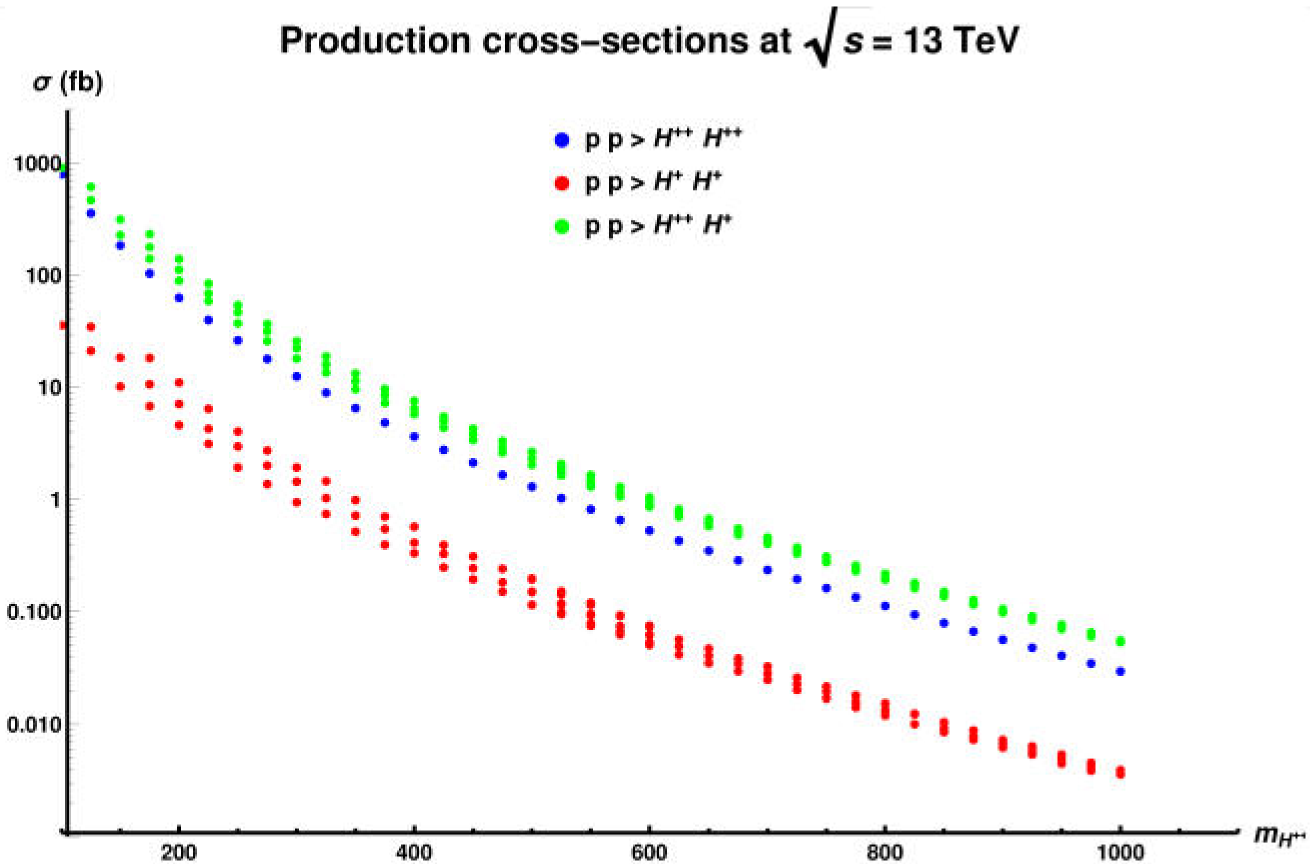
Status

- No significant signal observed.
- Will give a exclusion limit at 95% CL.
- Results to be published.

Plan

- Use full Run-2 data
- Use ChargeFlipTagger in ChargeMisID part.
- Use PromptLeptonIso(Veto) to improve Fake Estimate
- Search the applicability of boosted signature of W hadronic decays
- Associated production $pp \to W^{*+} \to H^{\pm\pm}H^{\mp}$

Back Up



For nearly degenerate charged Higgs bosons, cross-section of associated production twice as high as pair production.

Two possible decays of $H^{\pm}$:

- $\mathcal{BR}(H^{\pm} \to W^{\pm} Z) = 60\%$
- $\mathcal{BR}(H^{\pm} \to t\bar{b}) = 40\%$

Multi-lepton final states possible. Could enhance the sensitivity to the model.

Back Up