Charged Higgs Searches in CMS, Part 2

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Introduction

- **Extended Higgs sector beyond 2HDM`s being probed with the CMS Experiment**

- **Focus in this talk on extensions via additional SU(2) <u>triplets</u> governing custodial symmetry**

  - **SU(2)xU(1) (1,0) representation (real triplet), (1,+/-2) representation complex triplet**

- **Offer complementary event signatures in the detector**

- **Doubly charged Higgs bosons appear**

- **Opposed to 2HDM, (doubly-)charged Higgs couples to W/Z bosons at tree-level**

CMS Searches Presented

- **Three CMS analysis being presented: <u>two 8 TeV results, one 13 TeV</u>**

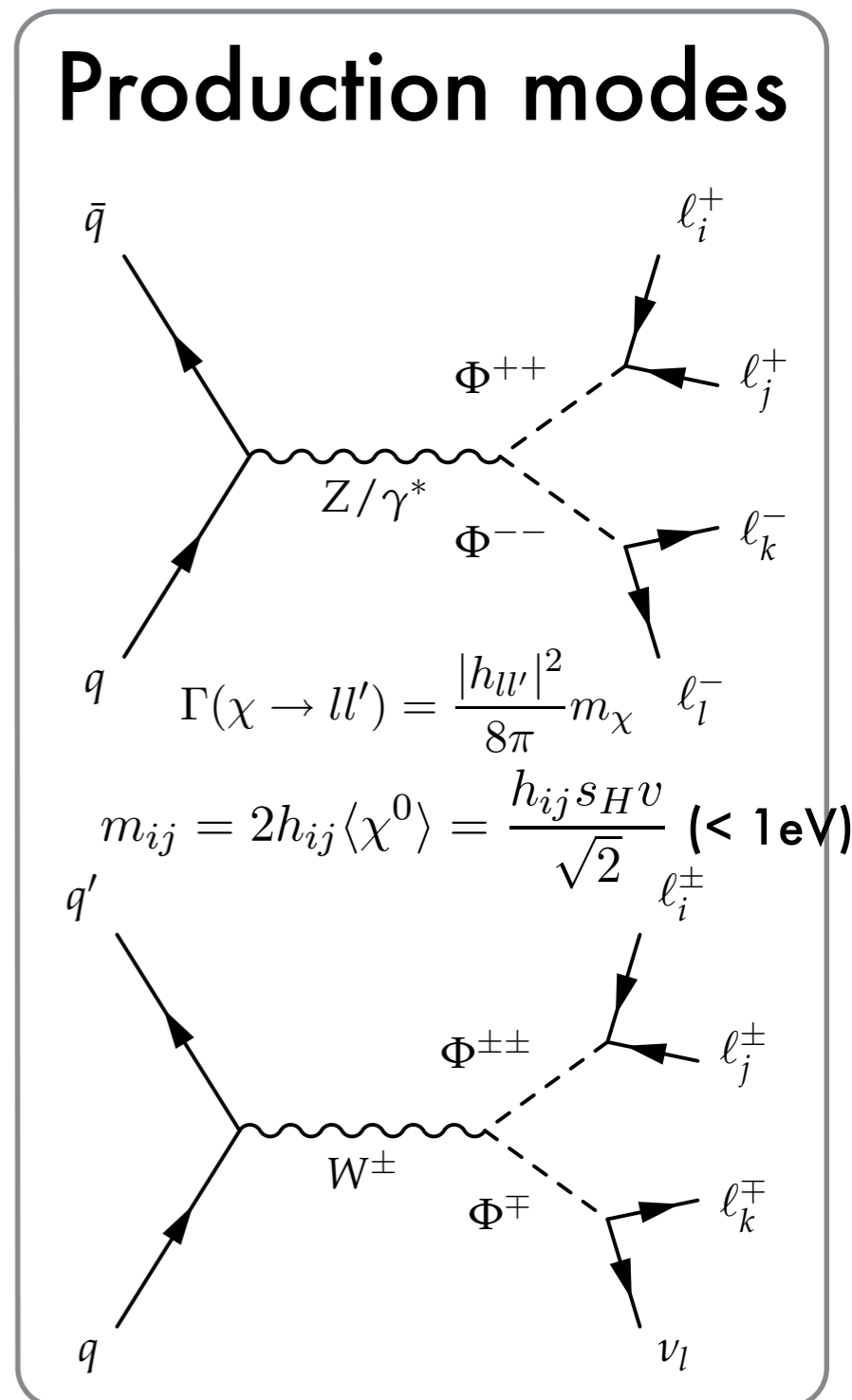| Run-1 Result at 8TeV CMS-PAS-HIG-14-039	Run-1 Result at 8TeV CERN-PH-EP-2014-250	Run-2 Result at 13TeV CMS-PAS-HIG-16-027
Search for a doubly-charged Higgs boson decaying into leptons	**Search for a doubly-charged Higgs decaying in to same-sign W pairs produced with VBF signature**	**Search for a charged Higgs decaying in WZ bosons produced with VBF signature**
Probing extension by complex Higgs triplet with small VEV (required by custodial symmetry, small boson couplings), typeII Seesaw mechanism, large Yukawa couplings	Probing extensions by real/ complex Higgs triplet with large VEV, arranged to preserve custodial symmetry Georgi-Machacek Model, General doubly-charged bosonic state coupling to bosons	Probing extensions by real/ complex Higgs triplet with large VEV, arranged to preserve custodial symmetry Georgi-Machacek Model, General charged bosonic state coupling to bosons

Doubly-Charged Higgs: Leptonic Decay

- **small triplet vev, larger Yukawa couplings**

  - <u>already performed at 7 TeV</u>, HERA, LEP, TeVatron, …

- **Search performed 19.7/fb at 8 TeV**

- **Search performed in 3,4 lepton final states**

  - **mutually exclusive, all lepton flavor final states (e, μ , τ→lνν)**

- **Event Pre-Selection:**
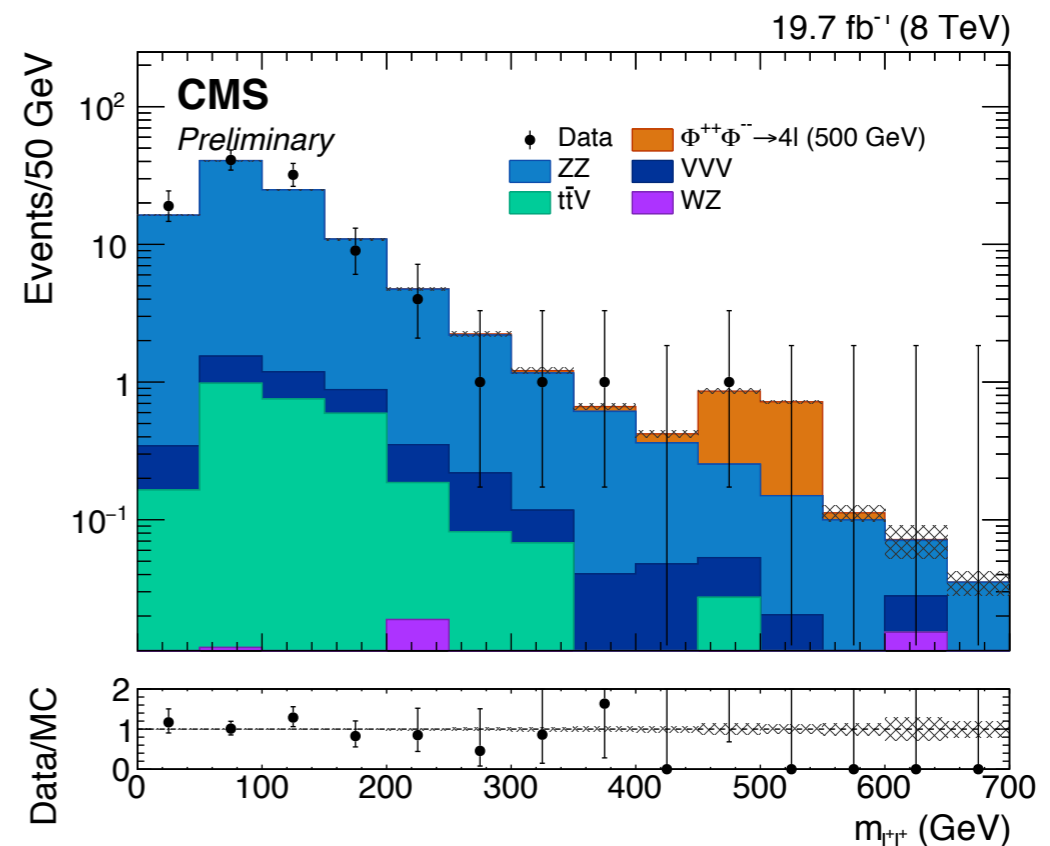
  - **di-lepton trigger, lepton-pT > 20GeV, letal<2.4**

Production modes

$$\Gamma(\chi \to ll') = \frac{|h_{ll'}|^2}{8\pi} m_\chi$$

$$m_{ij} = 2h_{ij}\langle \chi^0 \rangle = \frac{h_{ij} s_H v}{\sqrt{2}} \ (< 1\text{eV})$$

- **Then H++ mass dependent signal selection cuts applied**
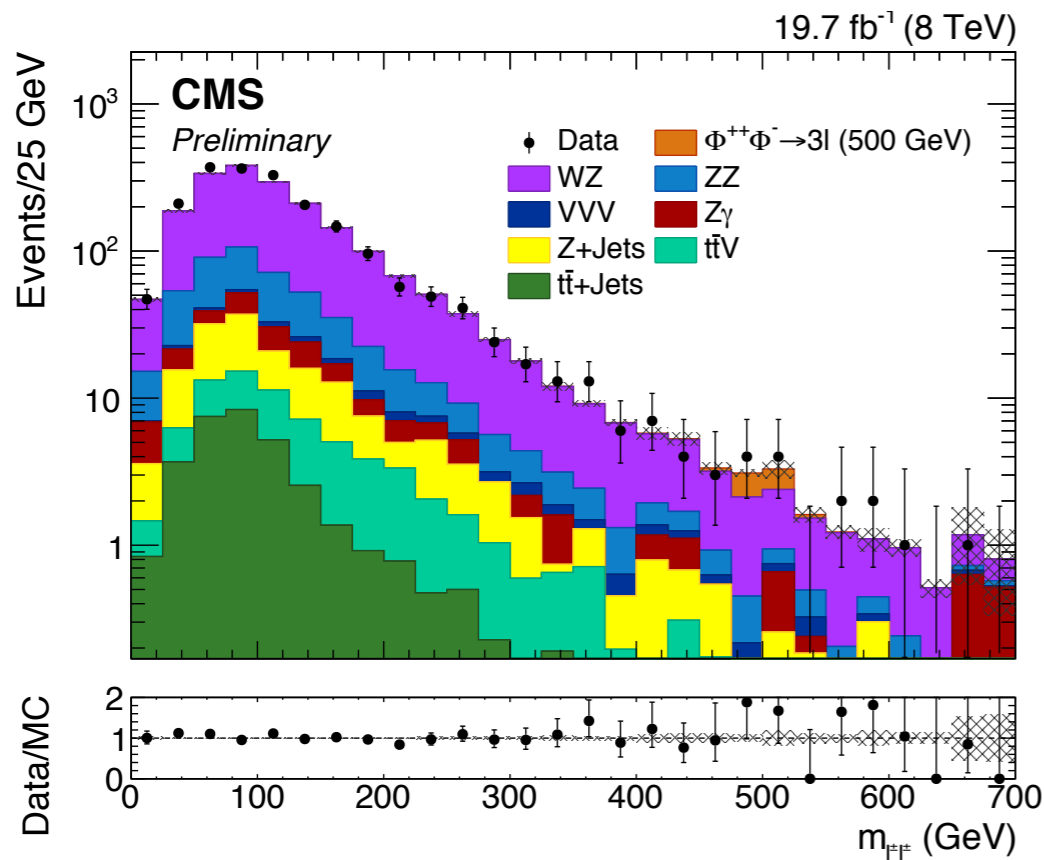
3 lepton category

4 lepton category

Signal Selection

- **Full selection:**
  mass dependent optimisation on discriminating variables

Variable		$ee, e\mu, \mu\mu$,BP1-4	$e\tau, \mu\tau$
$\|m(\ell^+\ell^-) - m_{Z_0}\|$ (GeV)	$>$	80	80
$s_T = \sum p_T^\ell$ (GeV)	$>$	$1.07 \cdot m_\Phi + 45$	$0.72 \cdot m_\Phi + 50$
$\Delta R_{\ell^\pm \ell^\pm} \begin{pmatrix} m_\Phi < 400 \, \text{GeV} \\ m_\Phi \geq 400 \, \text{GeV} \end{pmatrix}$	$>$	$m_\Phi/380 + 2.06$ $m_\Phi/1200 + 2.77$	$m_\Phi/380 + 1.96$ $m_\Phi/1000 + 2.6$
$m_{\ell^\pm \ell^\pm}$ (GeV)	$\in$	$(0.9 \cdot m_\Phi, 1.1 \cdot m_\Phi)$	$(0.5 \cdot m_\Phi, 1.1 \cdot m_\Phi)$

- **background estimation extrapolated from inverted mass cut sample after preselection**

| Variable		$ee, e\mu, \mu\mu$,BP1-4	$e\tau, \mu\tau$
$\|m(\ell^+\ell^-) - m_{Z_0}\|$ (GeV)	$>$	None	10
$s_T = \sum p_T^\ell$ (GeV)	$>$	$0.6 \cdot m_\Phi + 130$	$m_\Phi + 100$ or 400
$\Delta R_{\ell^\pm \ell^\pm}$	$>$	None	None
$m_{\ell^\pm \ell^\pm}$ (GeV)	$\in$	$(0.9 \cdot m_\Phi, 1.1 \cdot m_\Phi)$	$(0.5 \cdot m_\Phi, 1.1 \cdot m_\Phi)$
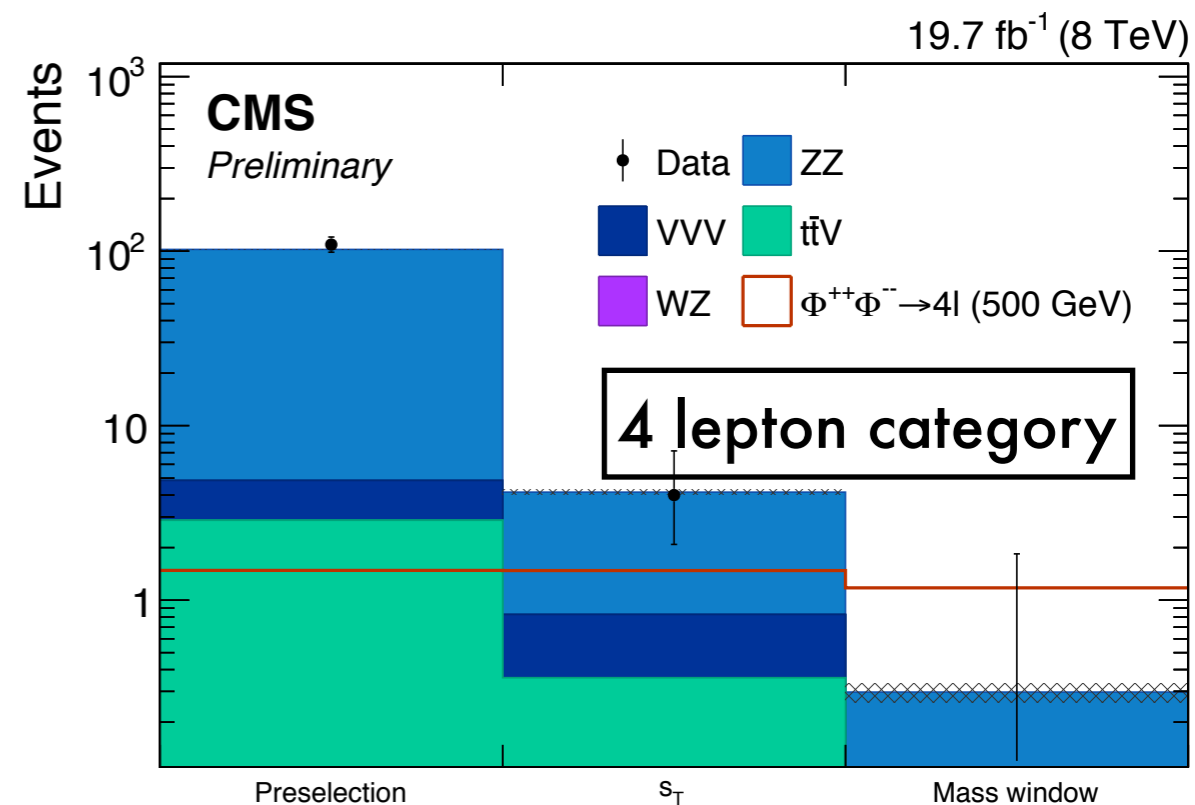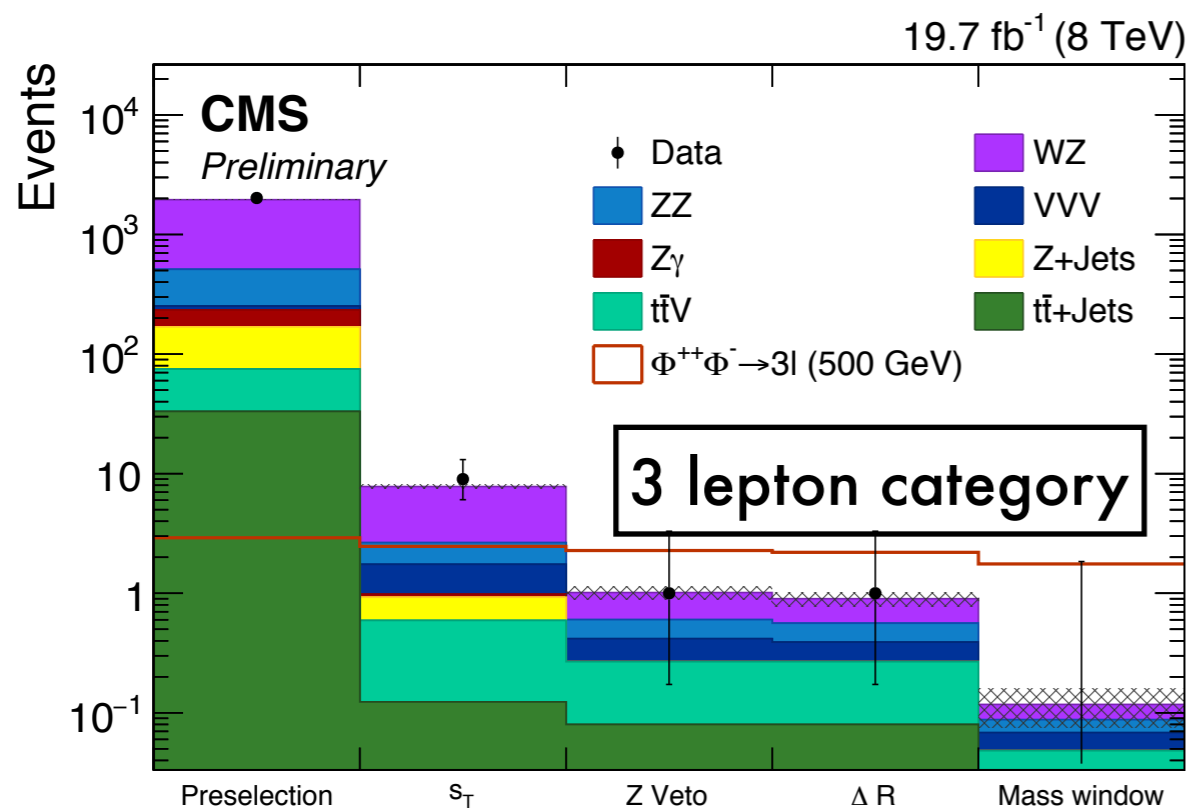
- **Benchmark scenarios defined for different neutrino hierarchy hypothesis**

Benchmark Point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	1/2	0	0	1/8	1/4	1/8
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

- **Model dependent and independent exclusion limits calculated**

- **H++ Masses from 400-600 GeV excluded**

  - **improved wrt 7 TeV excluded M < 450 GeV (ee, μμ)**
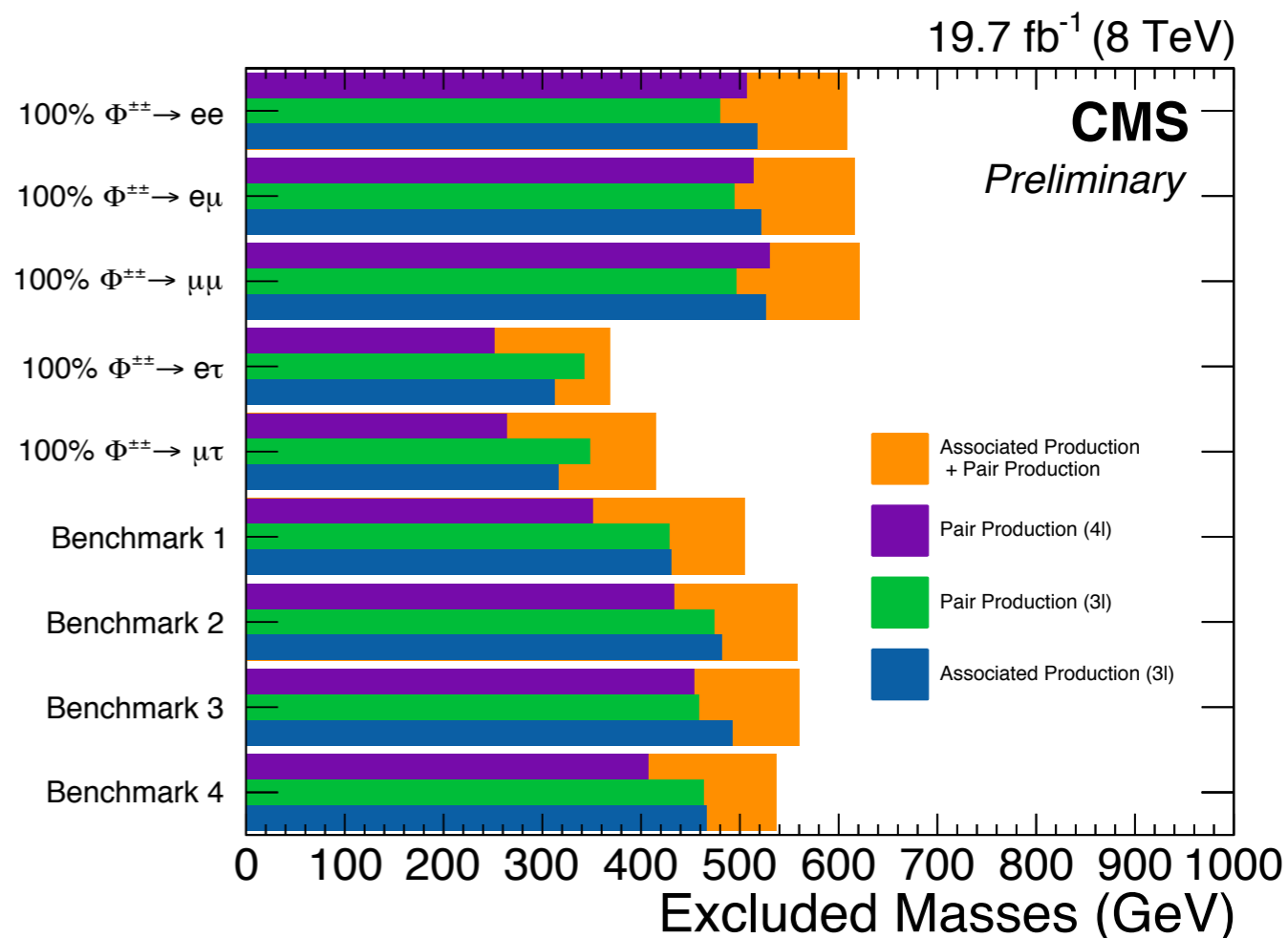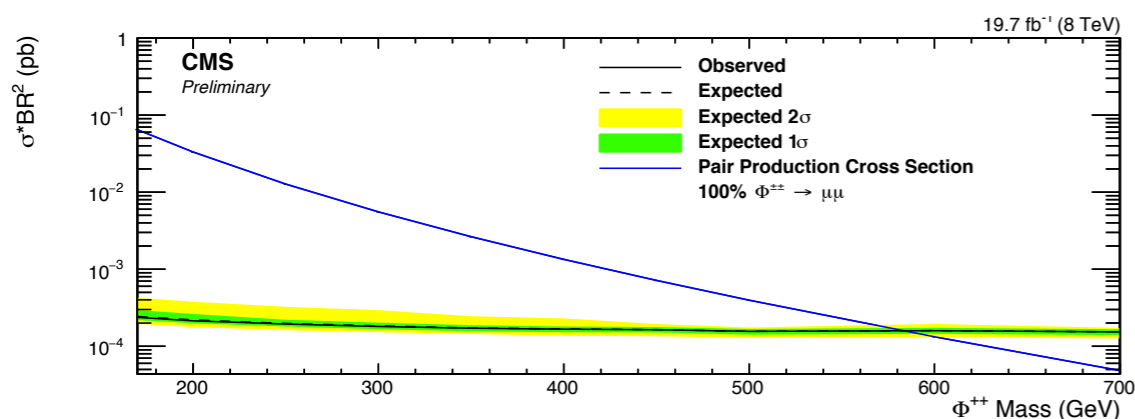
Doubly-Charged Higgs WW at 8 TeV

- **Analysis performed on 8 TeV dataset 19.7/fb**

  - **CERN-PH-EP-2014-250**

- **H++ WW coupling proportional to large VEV, real&complex triplet arranged to preserve custodial symmetry (Georgi-Machacek Model)**

- **probing doubly charged Higgs in custodial fiveplet, fermiophobic**

- **Search performed in same analysis as CMS VBS study, WW signal becomes background**

- **clean signature**

  - **VBF production: two high energetic forward jets**

  - **like sign leptons:** $\mu^{+}\mu^{+}\nu_{\mu}\nu_{\mu}jj,\ e^{+}e^{+}\nu_{e}\nu_{e}jj,\ e^{+}\mu^{+}\nu_{e}\nu_{\mu}jj$
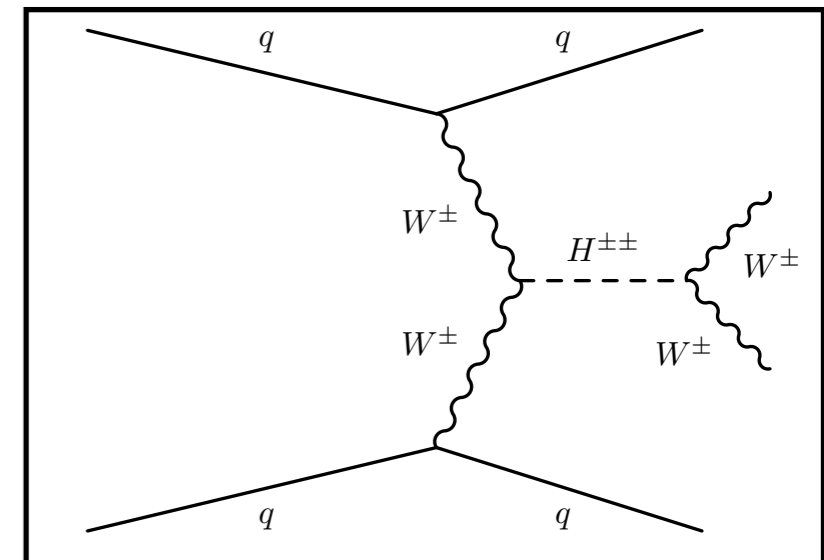
Event Selection

- **Event Selection:**

  - two same-sign leptons $|\eta|$ < 2.5, pT > 20 GeV (third lepton veto)

  - two jets $|\eta|$ < 4.5 , pT>30GeV

- **additional VBF Selection cuts:**
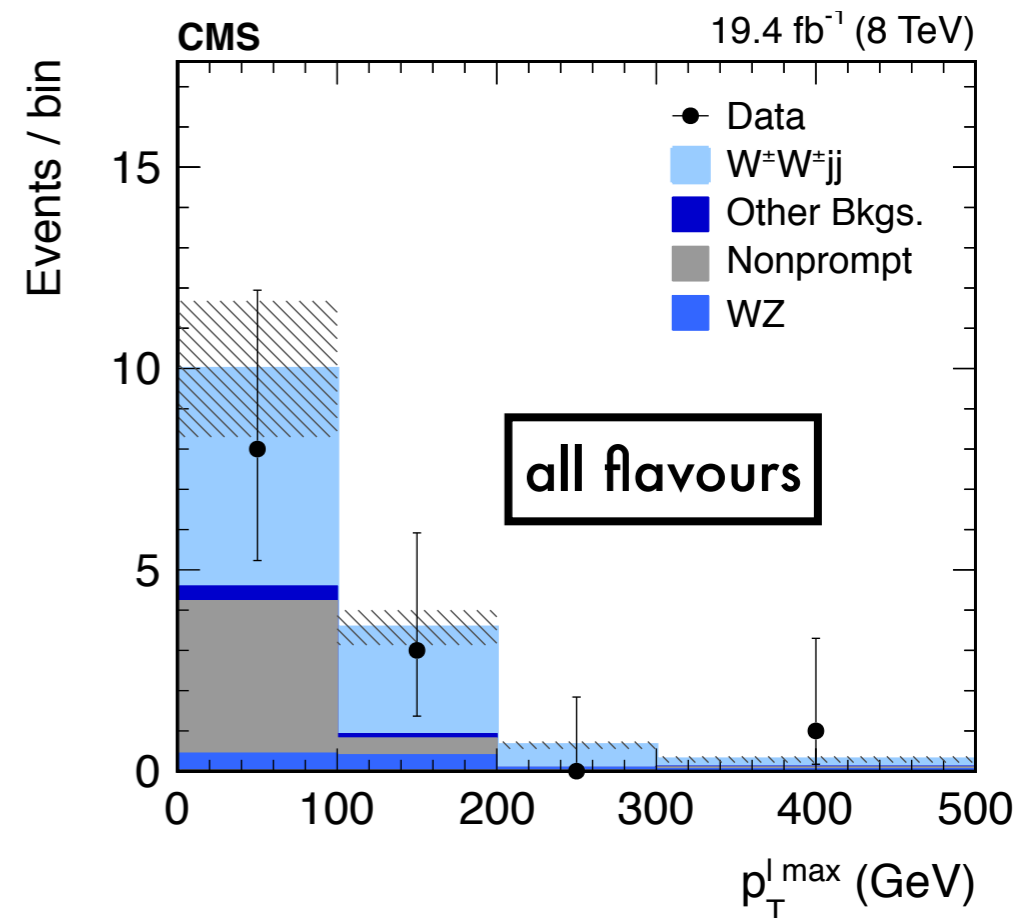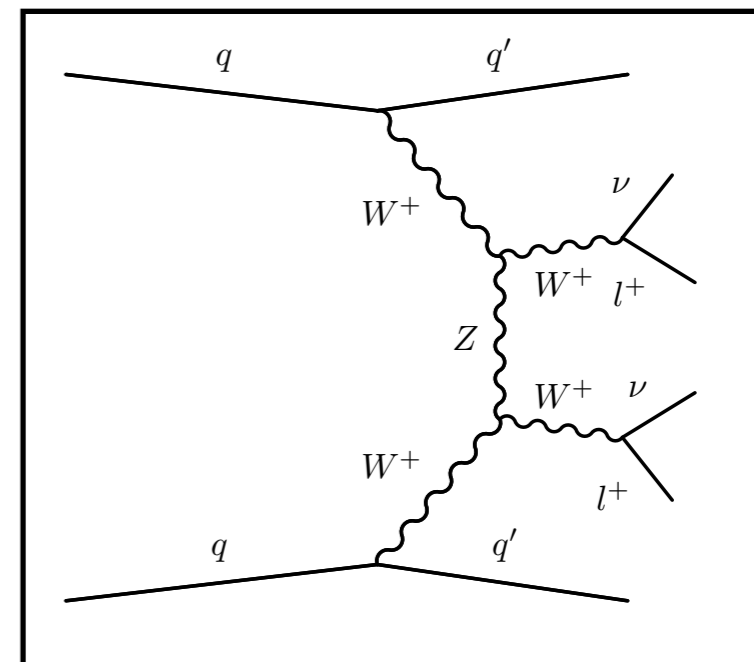
  - m(jj) > 500

- **Major backg**

  - WWjj, 70%, (estimated

  - Non Prompt

  - WZjj (estim

Signal Extraction

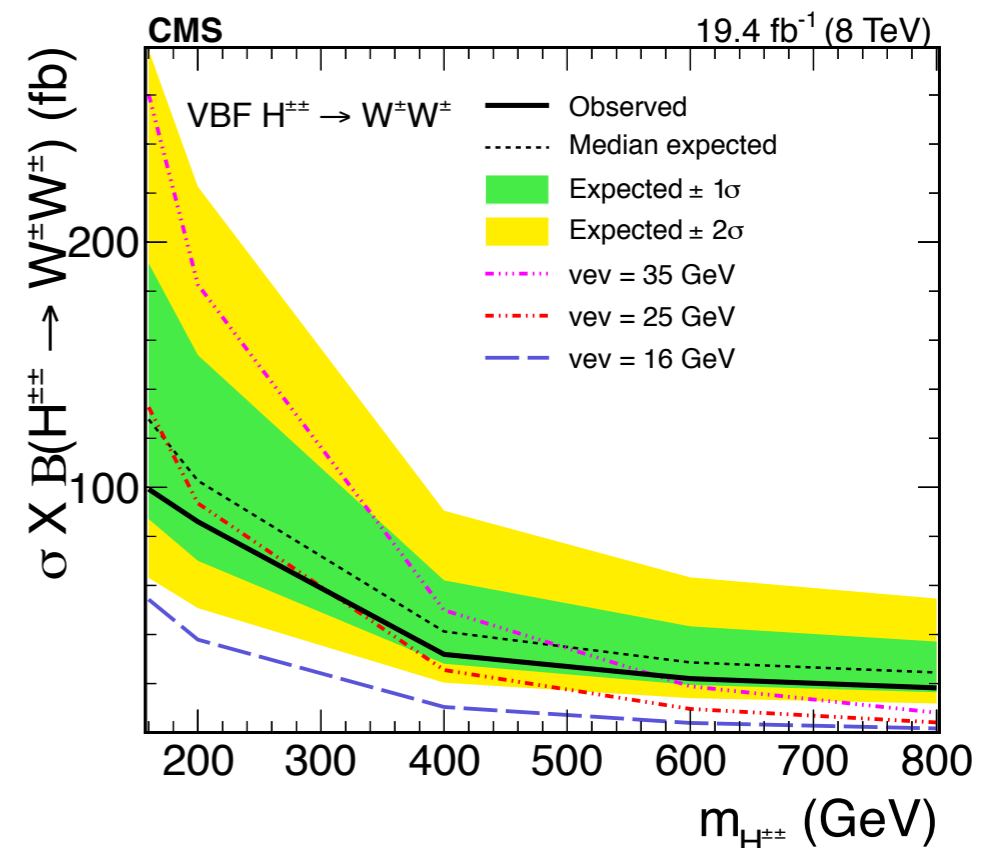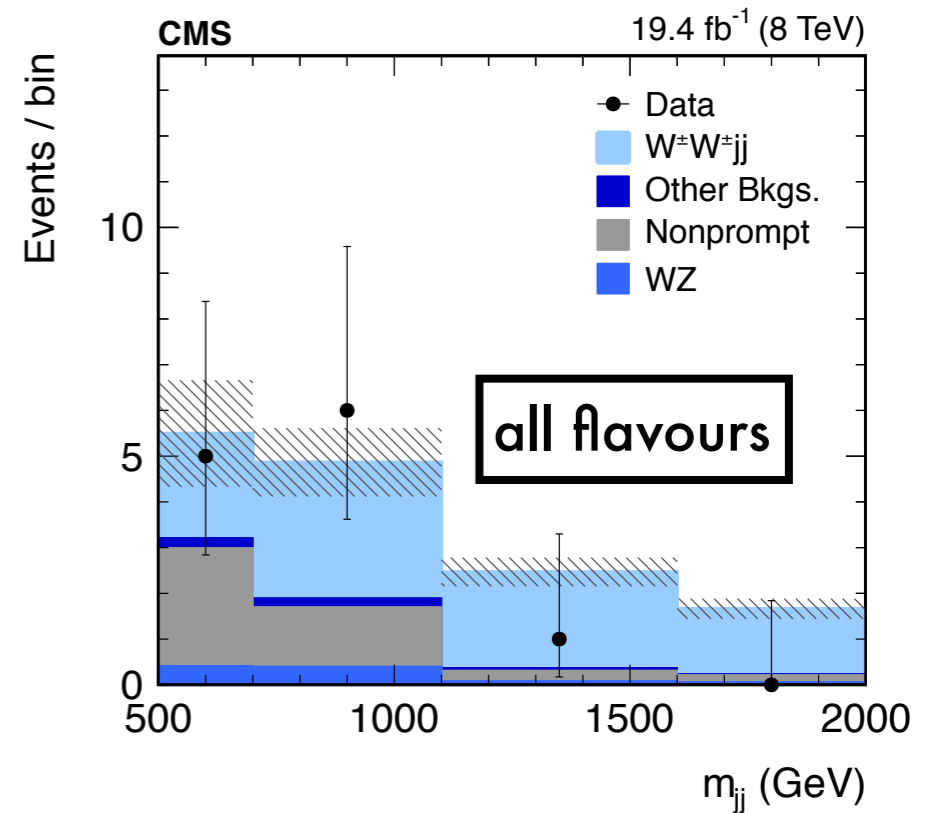- **Model independent limits on cross section times BR are derived**

  - LHCHXSWG-2015-001 and MG Model files did not exist back then

- **m(jj) distribution is used to extract signal**

- **Model independent limit to be converted into exclusion limit on VEV in Georgi-Machacek Model**

  - **essentially:** $\mathrm{BR}(H_5^{\pm\pm} \to W^\pm W^\pm) = 1$

Charged Higgs to WZ at 13 TeV

- **Search performed on 15.2 /fb at 13 TeV collected in 2015 and 2016**

 - PAS-HIG-16-027

- **Again Georgi-Machacek Model**

  - or vector-boson-philic charged particle

- **Consider fully leptonic final state**

  - small WZ BR but: clean, small irreducible background contributions, transverse mass used as discriminant for signal extraction

- **Signal produced according to recommended Model file provided:**

https://feynrules.irmp.ucl.ac.be/wiki/GeorgiMachacekModel
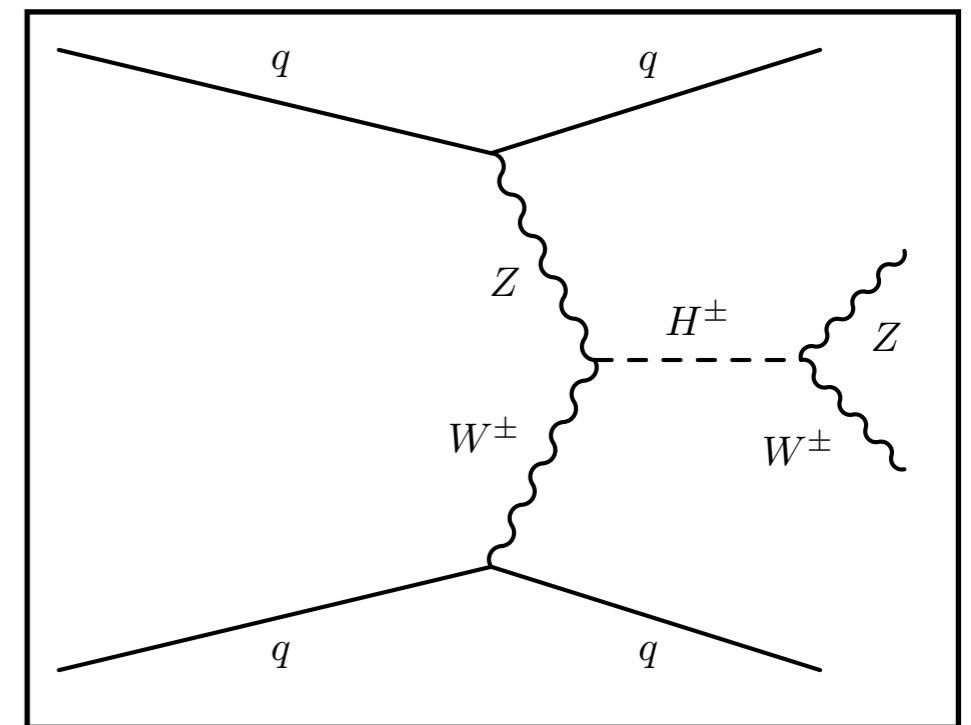
Event Selection

- **Requirements on event selection signal acceptance (10-15%):**

  - 3 leptons with pT>20/20/10 (4th lepton veto) (electrons, muons)

  - reconstructed Z candidates:
    |m(ll) - m(Z)| < 15 GeV (opposite-sign same-flavor)

  - VBF topology:
    two jets |etal < 4.5 , pT>30GeV, m(jj) > 500 GeV, dEta(jj) > 2.5

  - MET>30 GeV, reject top events (b-tagging veto)

- **Largest background from WZ process (EWK+QCD)**

- **followed by non-prompt leptons**

  - Z+jets, ttbar

Event Yields on 2016 dataset

Process	all flavor final-states
Data	53
WZ	34.5 ± 7.9
Non-prompt	8.8 ± 2.7
$Z\gamma$	1.0 ± 0.7
ZZ	1.6 ± 0.1
VVV	5.3 ± 0.5
Total Bkg.	51.3 ± 8.4

Background E

- **WZ+2Jets cross section at 13 TeV no**
  background:

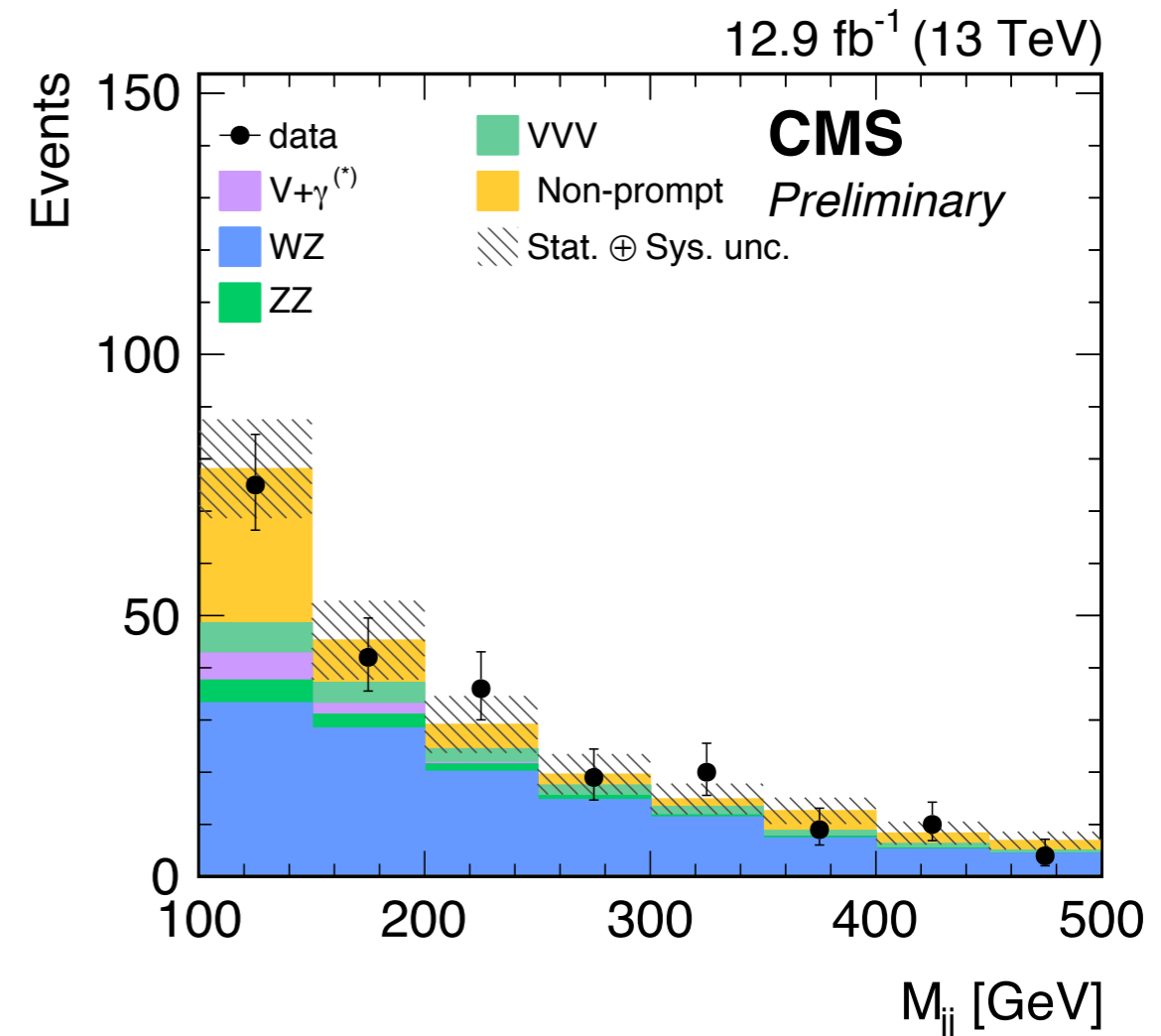 - QCD produced WZ normalisation obtai
    (EWK contribution estimated from simu

$$100 < m_{jj} < 500 \text{ GeV} \qquad |\Delta\eta_{jj}| < 2.5$$

signal contamination negligible

- **Non-Prompt lepton SM processes**
  estimated from fake-enriched
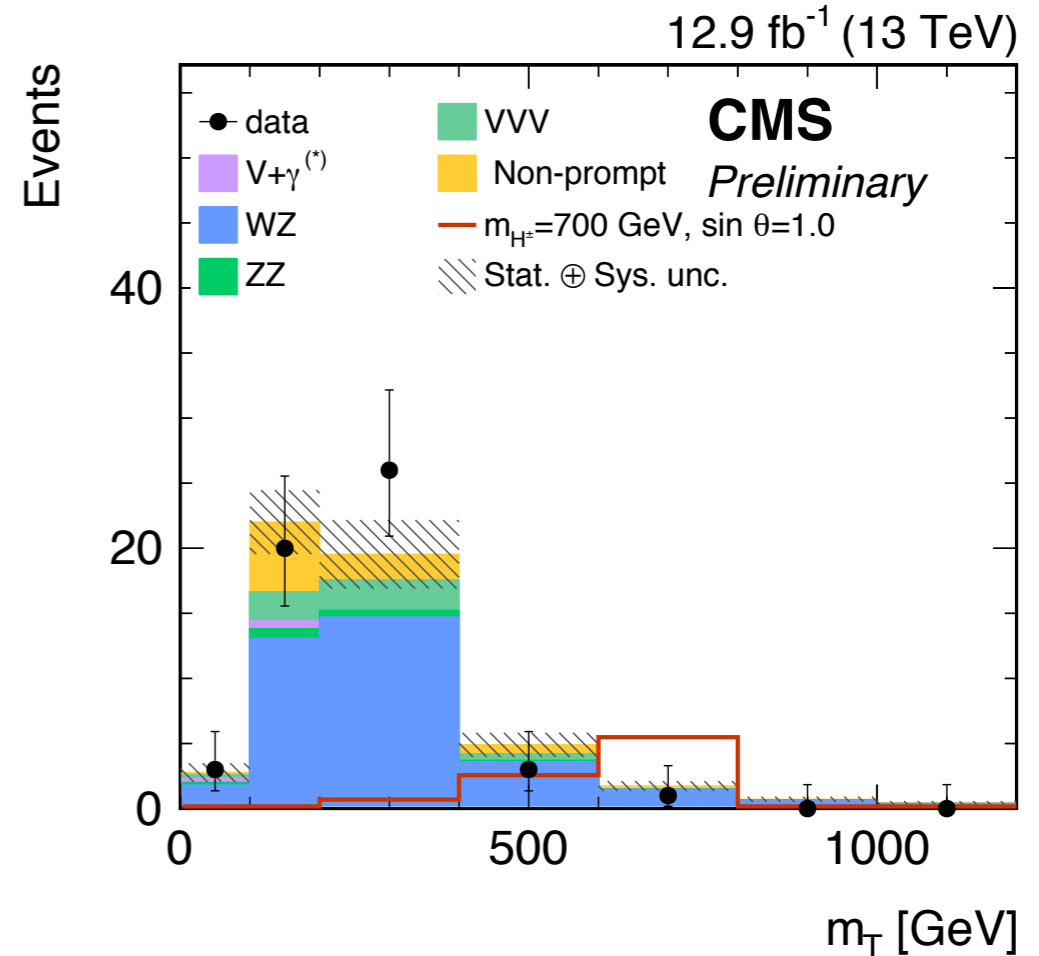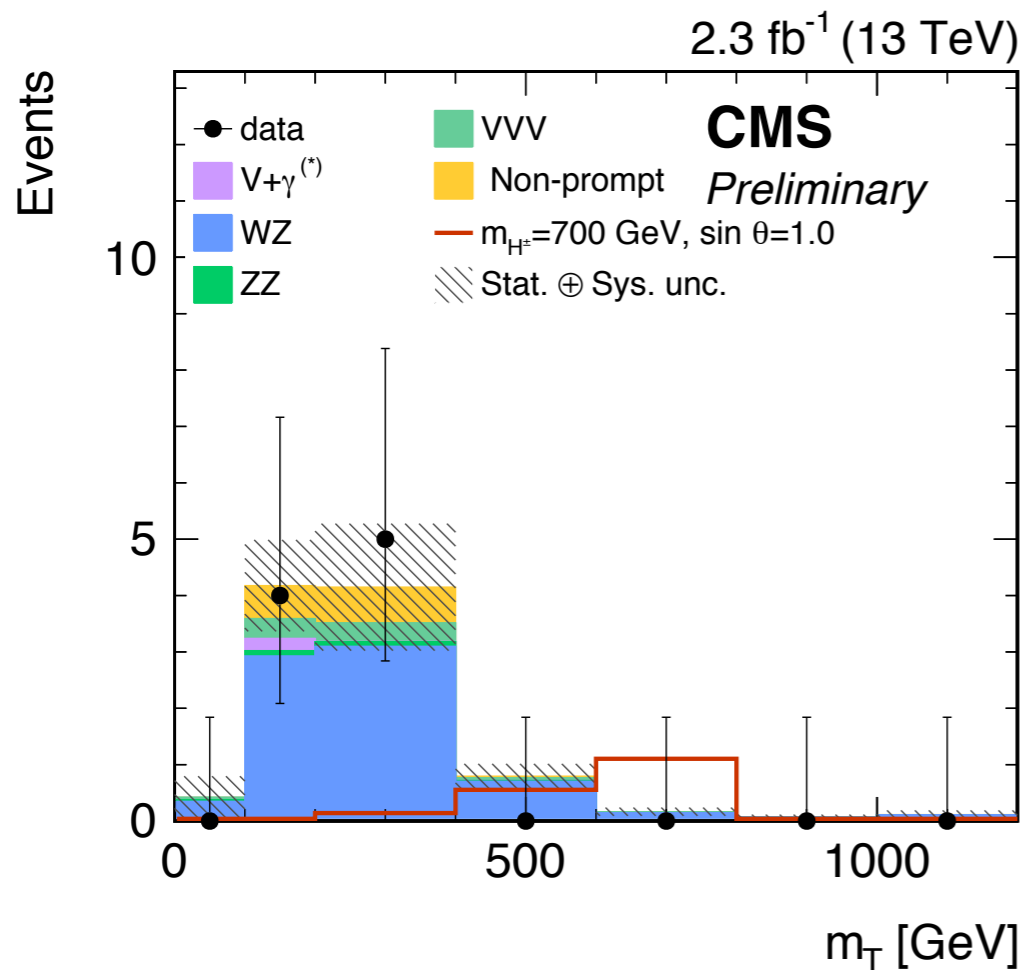 **(loose) lepton selection sample**

  - non-prompt lepton transfer factor
    estimated from di-jet sample

Signal Extraction

- **Simultaneous fit of transverse mass distributions obtained in 2015 and 2016 data-taking periods to extract signal**

  - different experimental conditions, uncorrelated uncertainties

$$m_T(WZ) = \sqrt{(E_T(W) + E_T(Z))^2 - (\mathbf{p_T}(W) + \mathbf{p_T}(Z))^2}$$

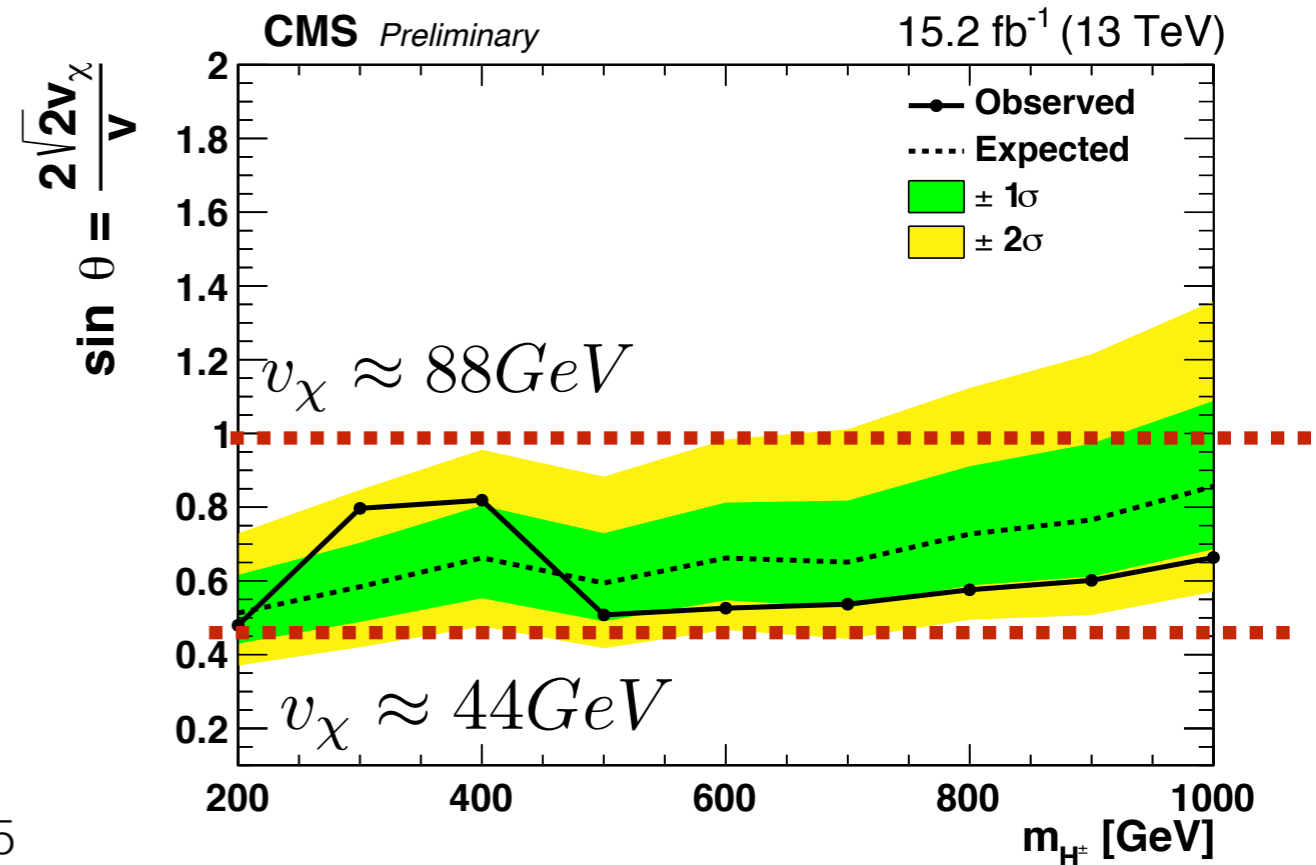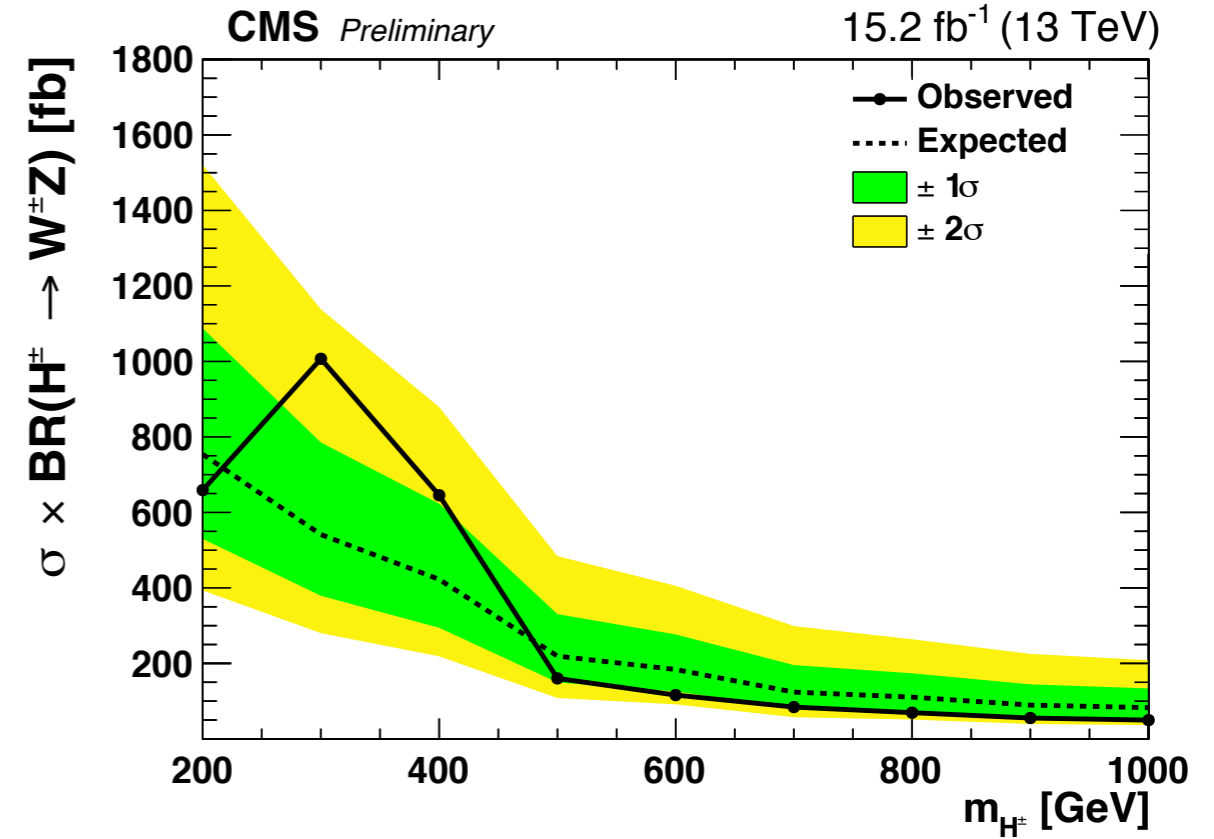- **Model independent limit on cross section time BR derived**

  - note: higher parton luminosities => larger SM contributions, but also larger signal cross section

- **Recommended cross sections from LHCHXSWG-2015-001**

-
$$\sigma(\text{VBF} \to H_5) = s_H^2 \sigma_1(\text{VBF} \to H_5)$$

Top-right plot: CMS *Preliminary* — 15.2 fb⁻¹ (13 TeV). $\sigma \times BR(H^\pm \to W^\pm Z)$ [fb] vs $m_{H^\pm}$ [GeV]. Observed, Expected, $\pm 1\sigma$, $\pm 2\sigma$.

Bottom-left plot: CMS *Preliminary* — 15.2 fb⁻¹ (13 TeV). $\sigma \times BR(H^\pm \to W^\pm Z)$ [fb] vs $m_{H^\pm}$ [GeV].

Bottom-right plot: CMS *Preliminary* — 15.2 fb⁻¹ (13 TeV). $\sin\theta = \dfrac{2\sqrt{2}v_\chi}{v}$ vs $m_{H^\pm}$ [GeV]. $v_\chi \approx 88 GeV$, $v_\chi \approx 44 GeV$.

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Summary

- **Active exploration of extended Higgs sectors via Higgs triplets**

- **Two searches for doubly charged Higgs bosons shown at 8 TeV**

  - Expect results for these searches at 13 TeV soon

- **Search for charged Higgs bosons decaying into WZ in fully leptonic final state at 13 TeV presented**

  - improved performance at low and high masses when compared to semi-leptonic final state

- **Searches for Higgs triplets can be combined and more final states added to improve sensitivity**

Additional Material

Theoretical Constraints on GM Model

- **Unitarity constraints on GM quintet mass and VEV**
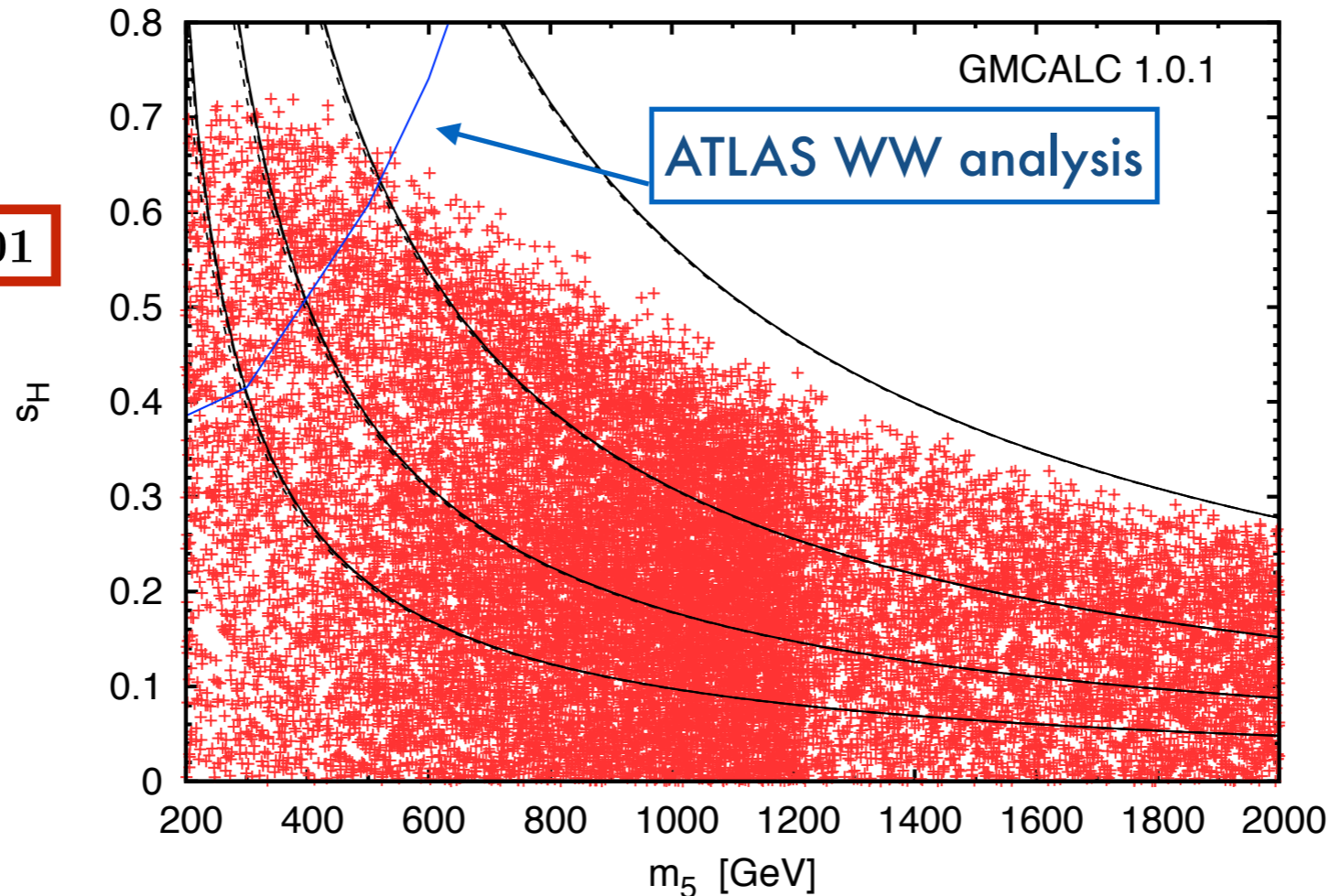
LHCHXSWG-2015-001

Logan, Zaro

FIG. 1. Allowed ranges of m_5 and s_H after imposing theoretical and indirect experimental constraints on the GM model. The red points are a parameter scan produced using GMCALC 1.0.1 [6]. Contours of the width-to-mass ratio of H_5^0 (solid black lines), $H_5^\pm$ (long-dashed black lines, indistinguishable from the solid lines) and $H_5^{\pm\pm}$ (short-dashed black lines), assuming that $BR(H_5 \to VV) = 1$. From top to bottom, $\Gamma(H_5)/m_5 = 0.10, 0.03, 0.01,$ and 0.003. The recast analysis in Ref. [11], which constrains the doubly-charged scalar H_5^{++}, excludes points above the blue curve.