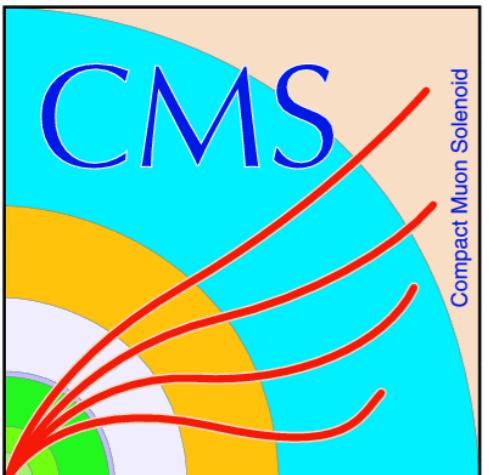


Search for MSSM Higgs boson and beyond at CMS

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on behalf of the CMS Collaboration

EPS-HEP2017
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Introduction

- ★ The discovery of the SM Higgs boson is not the only part of the Higgs physics program at the LHC experiments

- as the SM is known not to be complete

- ★ Many BSM theories with extended Higgs sector

- e.g. 2HDM and Higgs Triplet Model

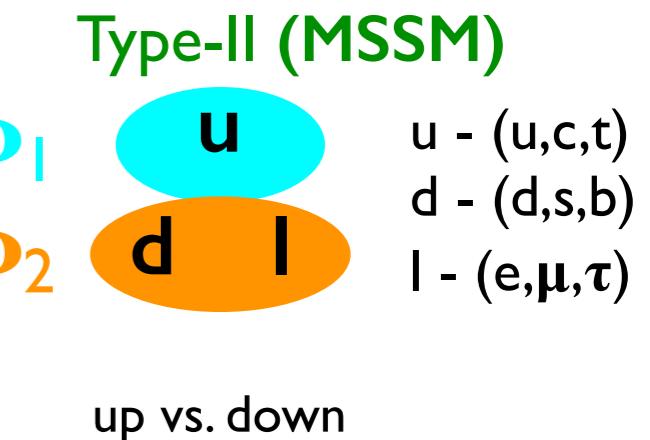
- ★ **Minimal Supersymmetric Standard Model (MSSM)**

H^+ , H^- , A (CP-odd), H and h (CP-even)

- m_A and $\tan\beta$ are two free parameters at tree level
 - $m_h^{\text{mod+}}$ scenario is a modification of $m_h^{\text{max+}}$ to have $m_h = 125 \pm 3^*$ GeV
 - hMSSM scenario trades the value $m_h = 125$ against radiative corrections

- ★ **Higgs Triplet Model** extends the SM with a scalar triplet ($\Phi = \Phi^{\pm\pm}, \Phi^\pm, \Phi^0$)

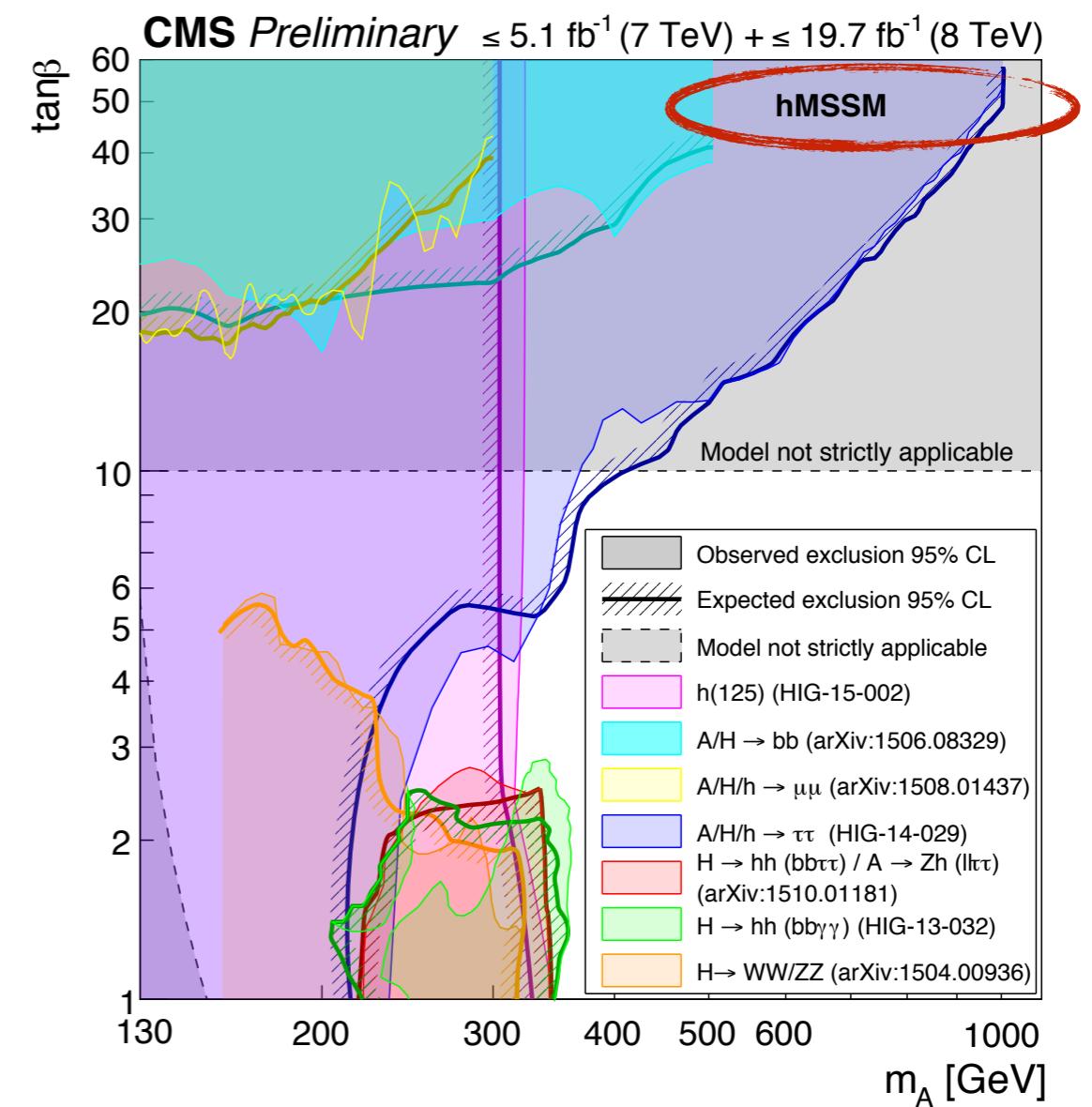
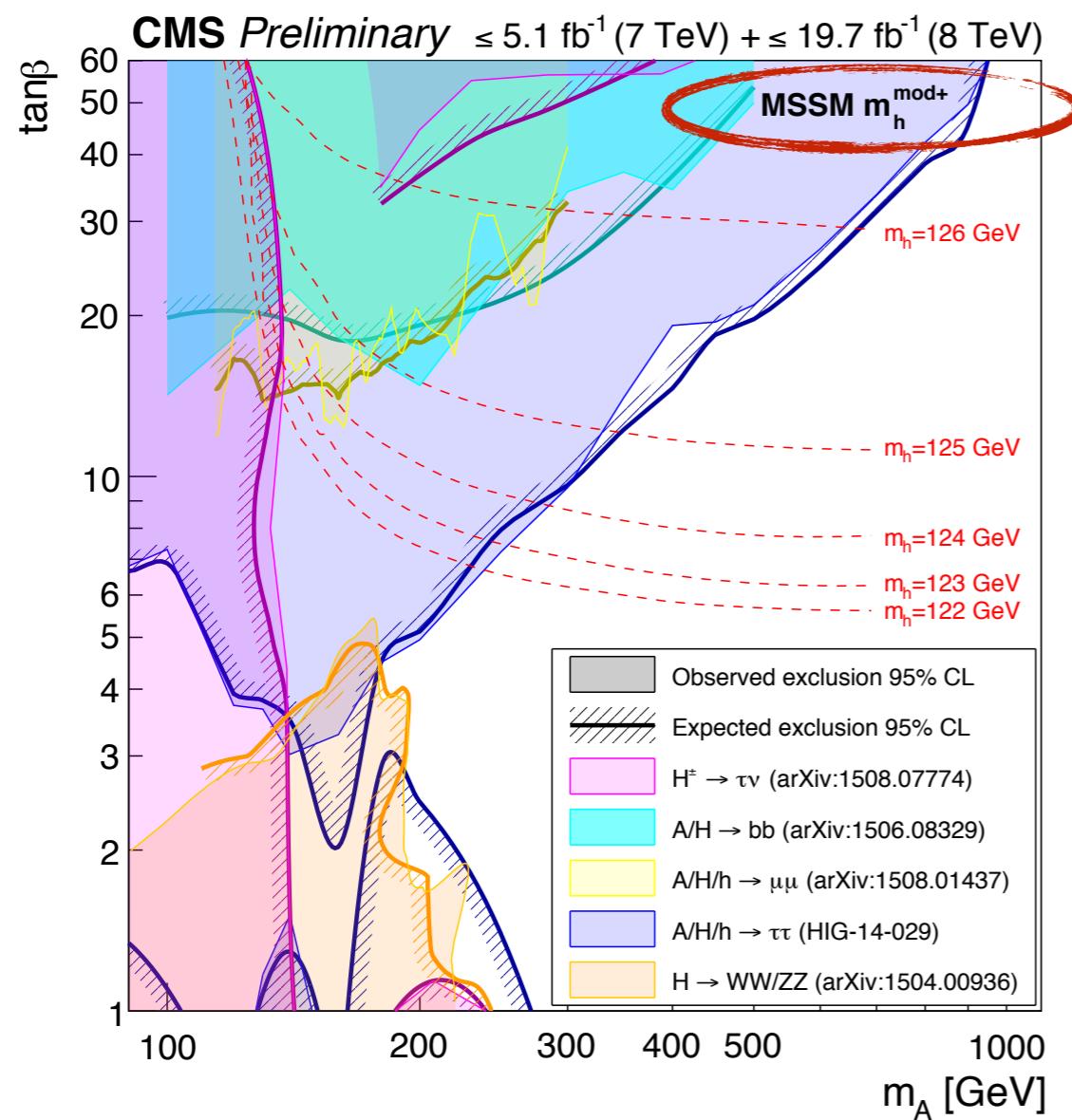
- allows fermiophobic Higgs boson, introduces neutrino masses etc.



* theoretical uncertainty

Run-I Recap

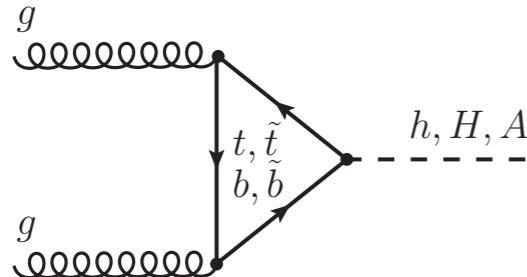
- ★ Searches for the Higgs sector of the MSSM performed during the LHC Run-I data
- ★ 95% CL exclusion contours in the MSSM $m_h^{\text{mod+}}$ and hMSSM scenarios



Neutral MSSM $H \rightarrow \tau\tau$

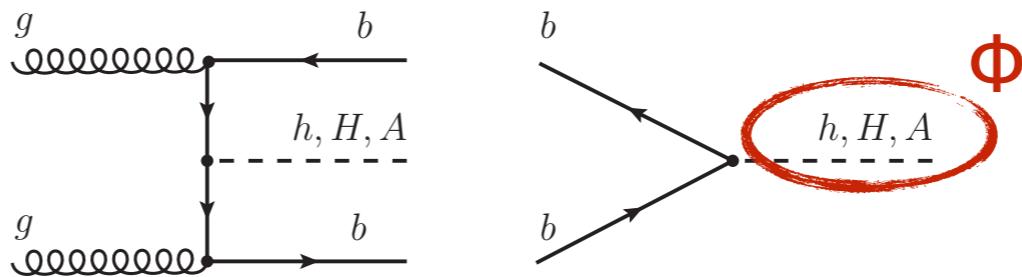
- ★ Combined 4 most sensitive channels : $e\mu, e\tau_h, \mu\tau_h, \tau_h\tau_h$ (τ_h = hadronic tau)
- ★ 2 categorization for two production modes

gluon fusion : no b-tag



enhanced at low $\tan\beta$

b association : b-tag



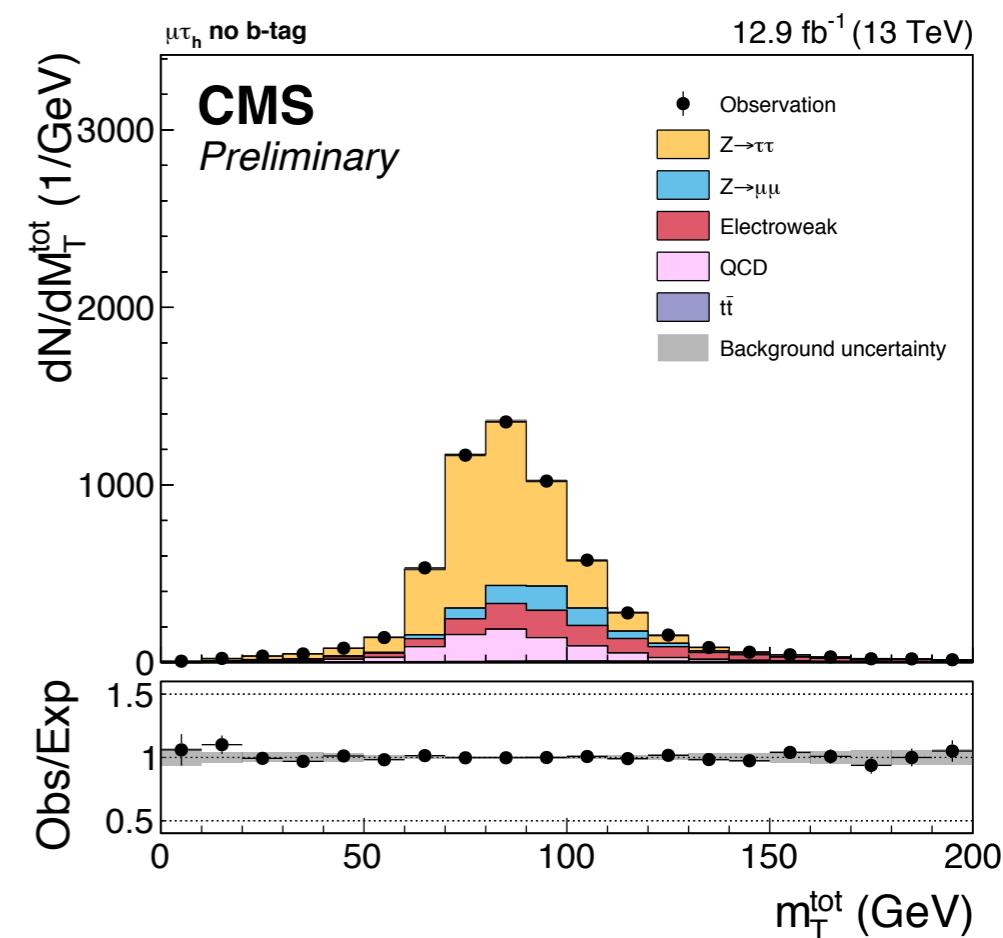
enhanced at high $\tan\beta$

- ★ Dominant backgrounds

- $Z \rightarrow \tau\tau, Z \rightarrow ll, W + \text{jets}, \text{QCD}$ and $t\bar{t}$

- ★ Total transverse mass for signal extraction (new!)

$$m_T^{\text{tot}} = \sqrt{m_T(E_T^{\text{miss}}, \tau_1^{\text{vis}})^2 + m_T(E_T^{\text{miss}}, \tau_2^{\text{vis}})^2 + m_T(\tau_1^{\text{vis}}, \tau_2^{\text{vis}})^2}$$

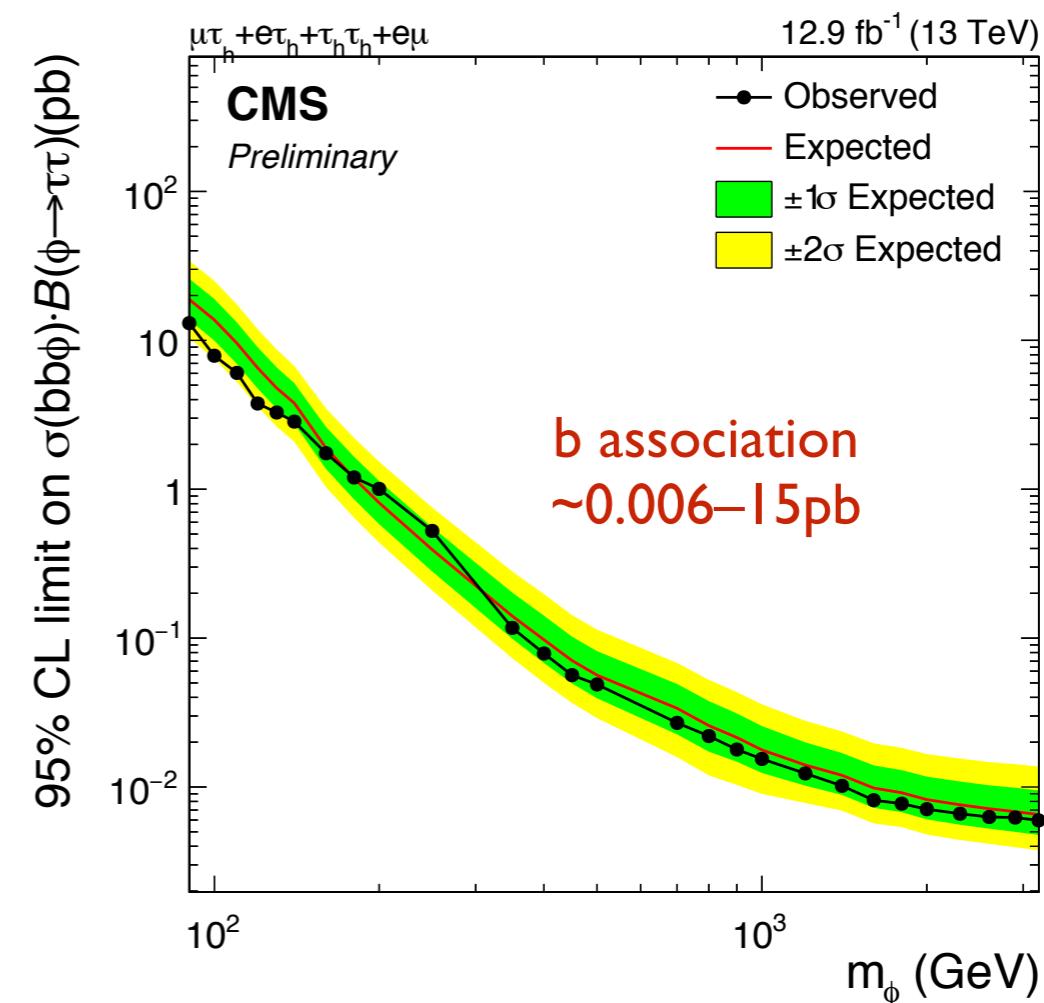
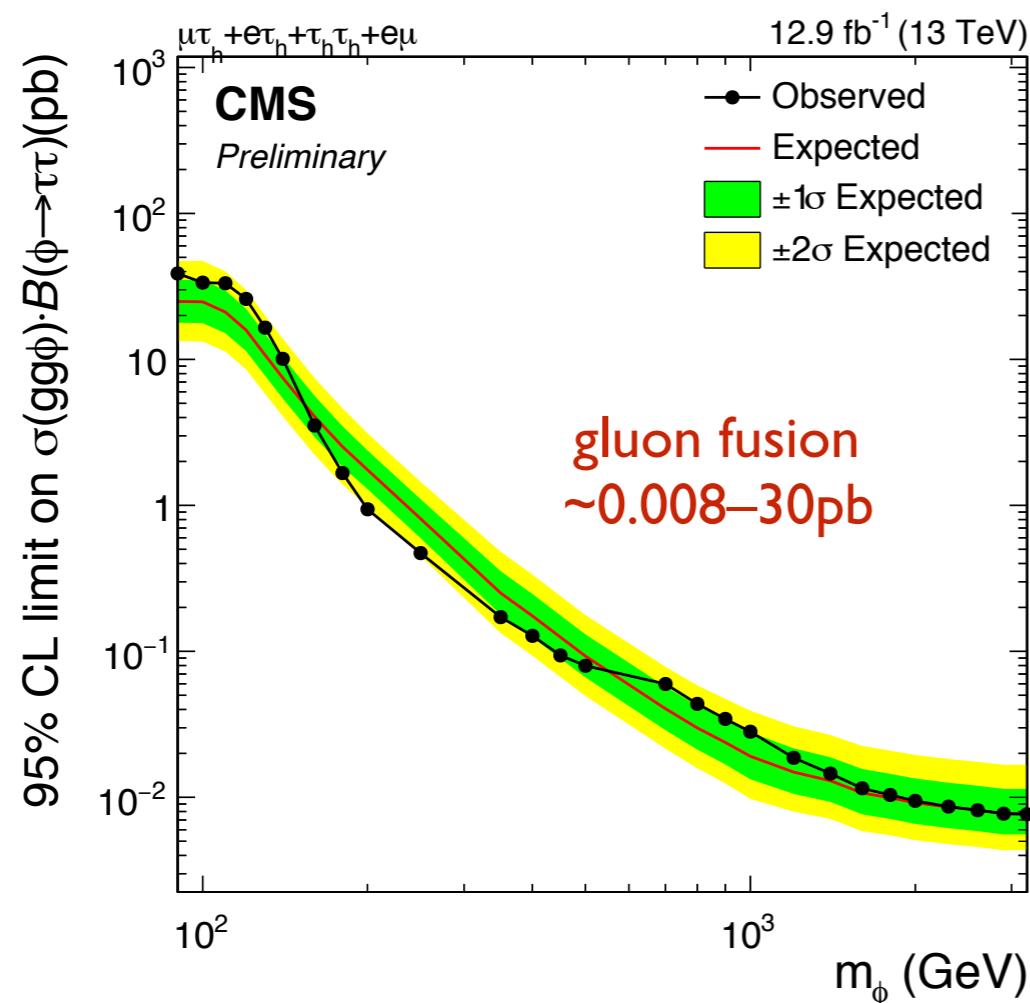


Neutral MSSM $H \rightarrow \tau\tau$

★ Systematic uncertainties

- normalization : $e/\mu \rightarrow \tau_h$ fake rate, ID/Isolation/trigger efficiencies, jet energy scale
- shape : lepton energy scale, high p_T tau ID efficiency, jet $\rightarrow \tau_h$ fake rate in $W+jets$

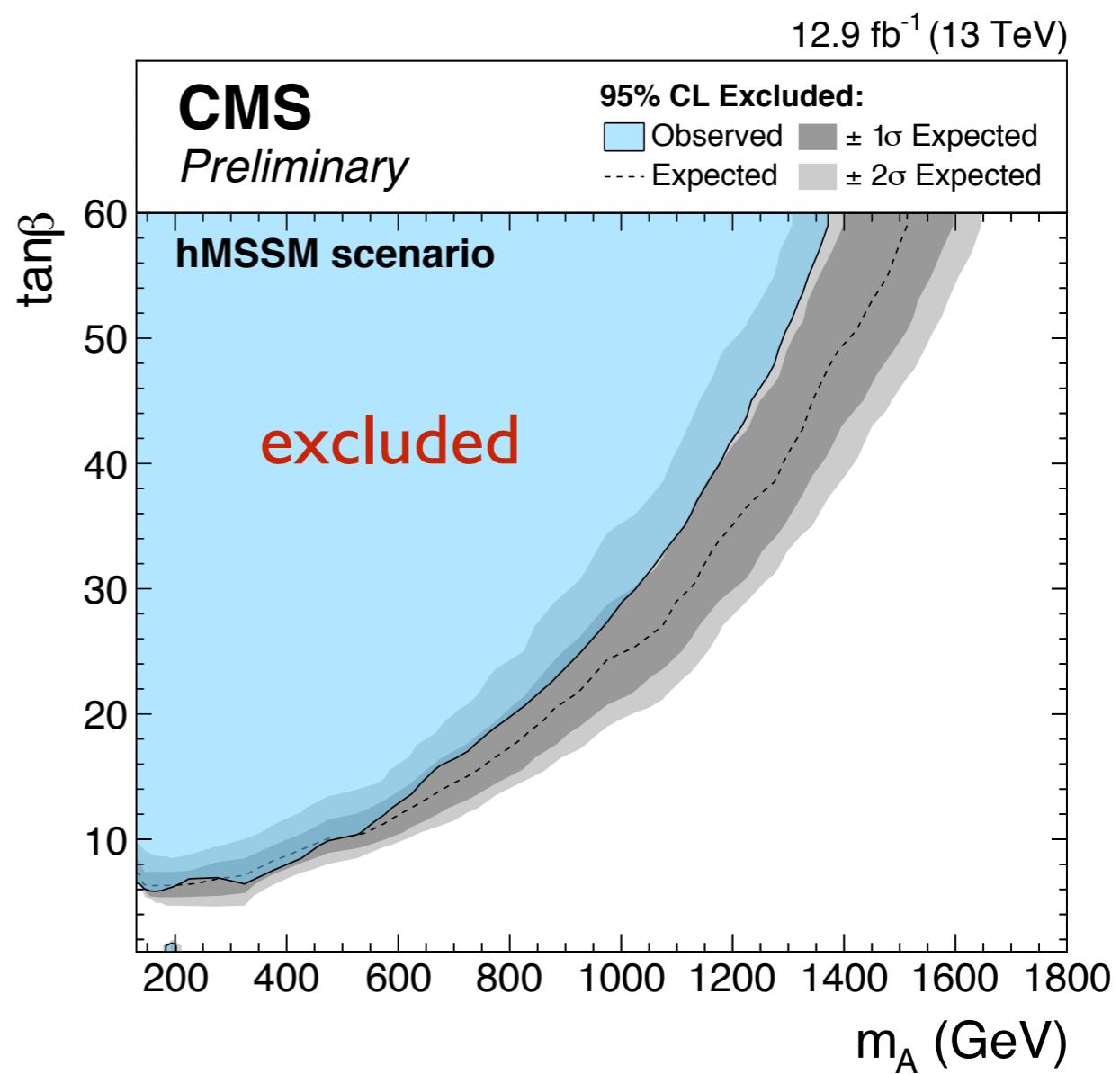
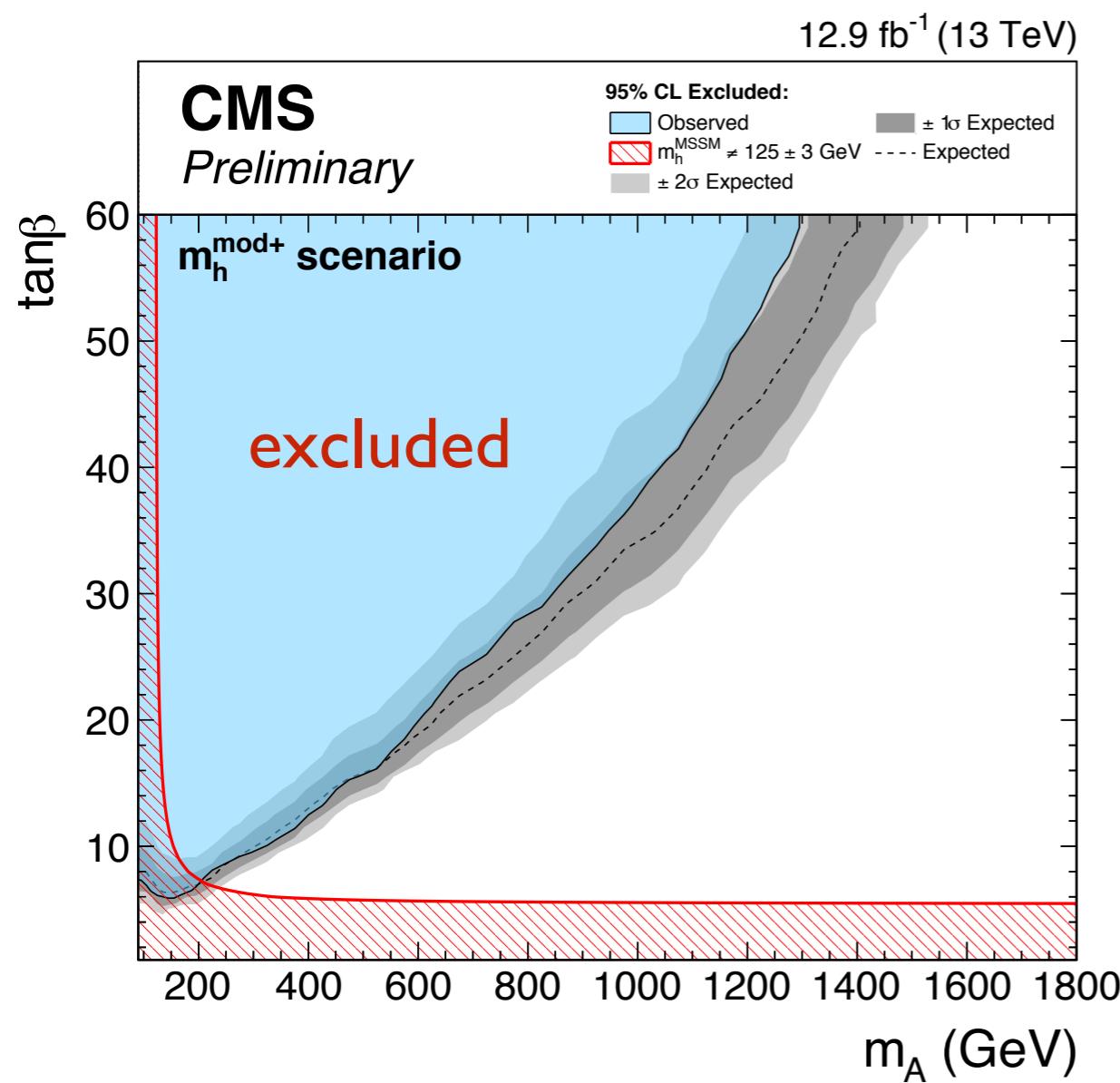
★ Model-independent upper limits on $\sigma \times B$ at 95% CL



no excess of signal is observed in mass range of $m_\phi = 90\text{GeV} - 3.2\text{TeV}$

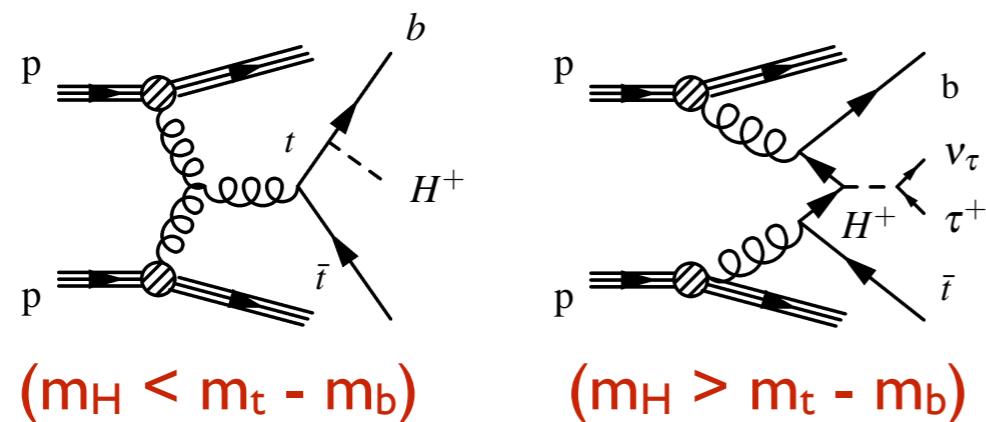
Neutral MSSM $H \rightarrow \tau\tau$

- ★ Interpretation in MSSM benchmark scenarios : $m_h^{\text{mod}+}$ and hMSSM
- ★ Exclusion upper limits at 95% CL in the m_A - $\tan\beta$ plane



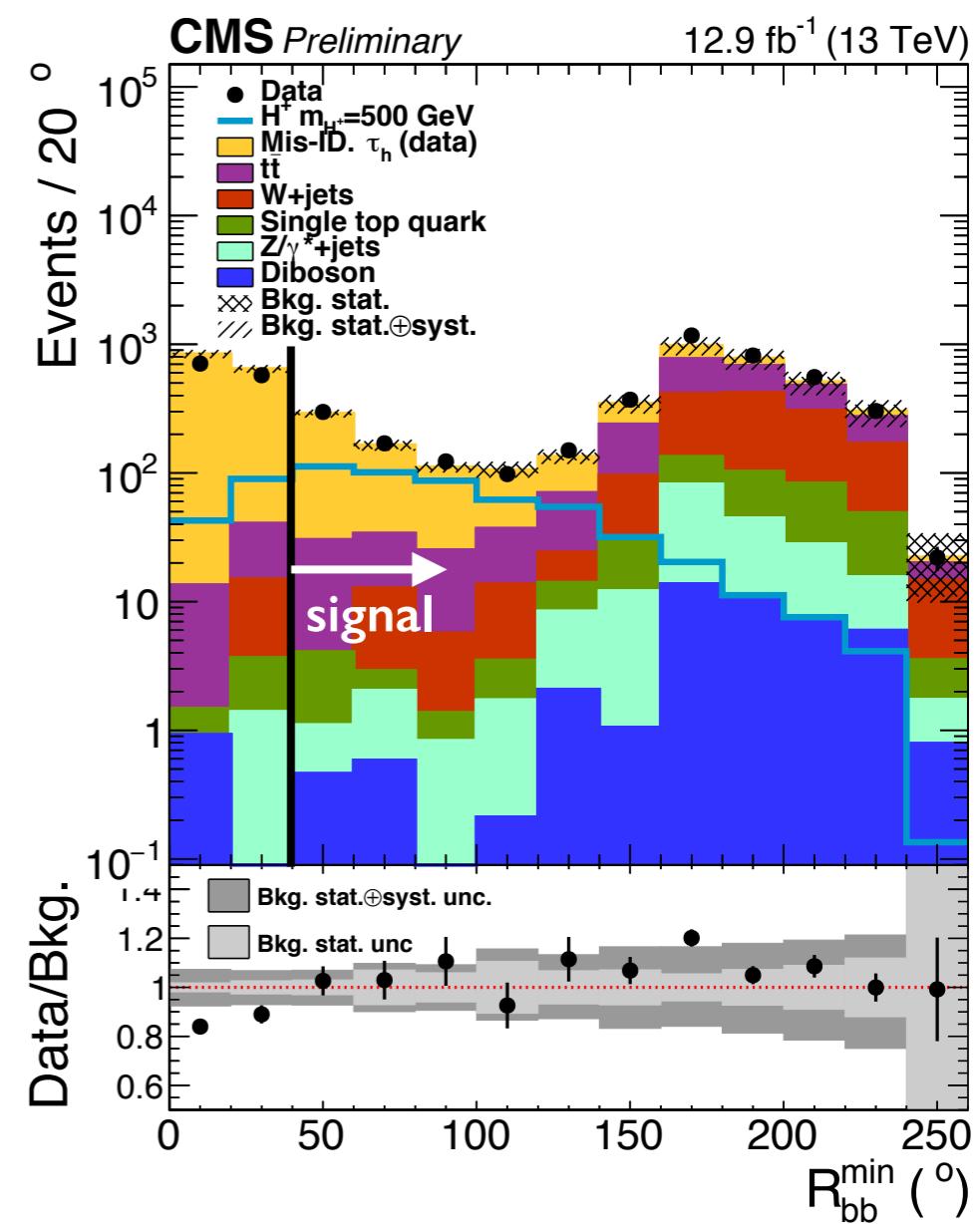
Charged MSSM $H^\pm \rightarrow \tau^\pm \nu$

- ★ Search for a charged Higgs boson in the fully hadronic tau channel (τ_h)
 - neutrinos only originate from H^\pm decay, thus m_T can be reconstructed



- ★ Main backgrounds
 - Fake tau (QCD multi-jet) : data-driven method
 - Genuine tau (EW+ttbar processes) : from MC
- ★ Angular cut to exploit differences between multi-jet background and signal

$$R_{bb}^{\min} = \min_{j \in j_1 \dots j_3} \sqrt{\Delta\phi(E_T^{\text{miss}}, j)^2 + (\pi - \Delta\phi(\tau_h, E_T^{\text{miss}}))^2}$$

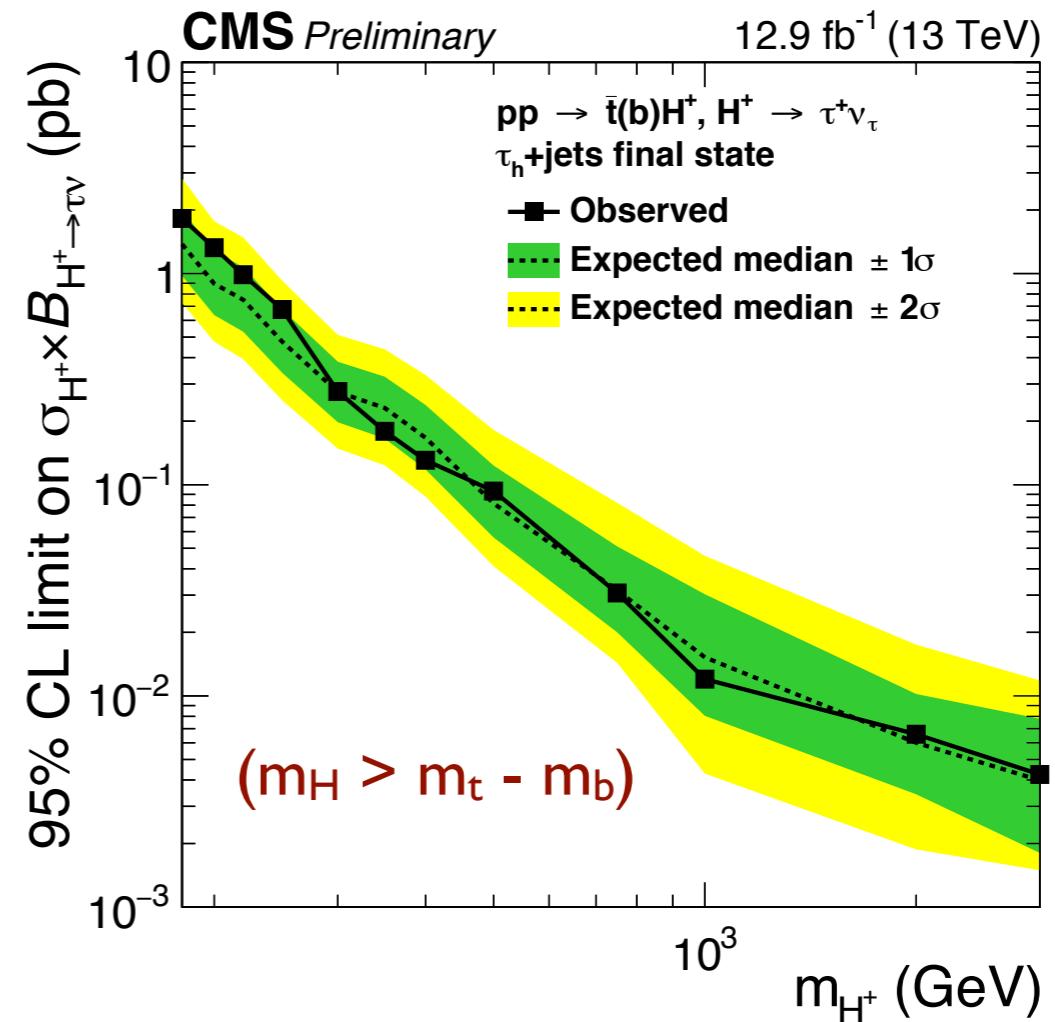
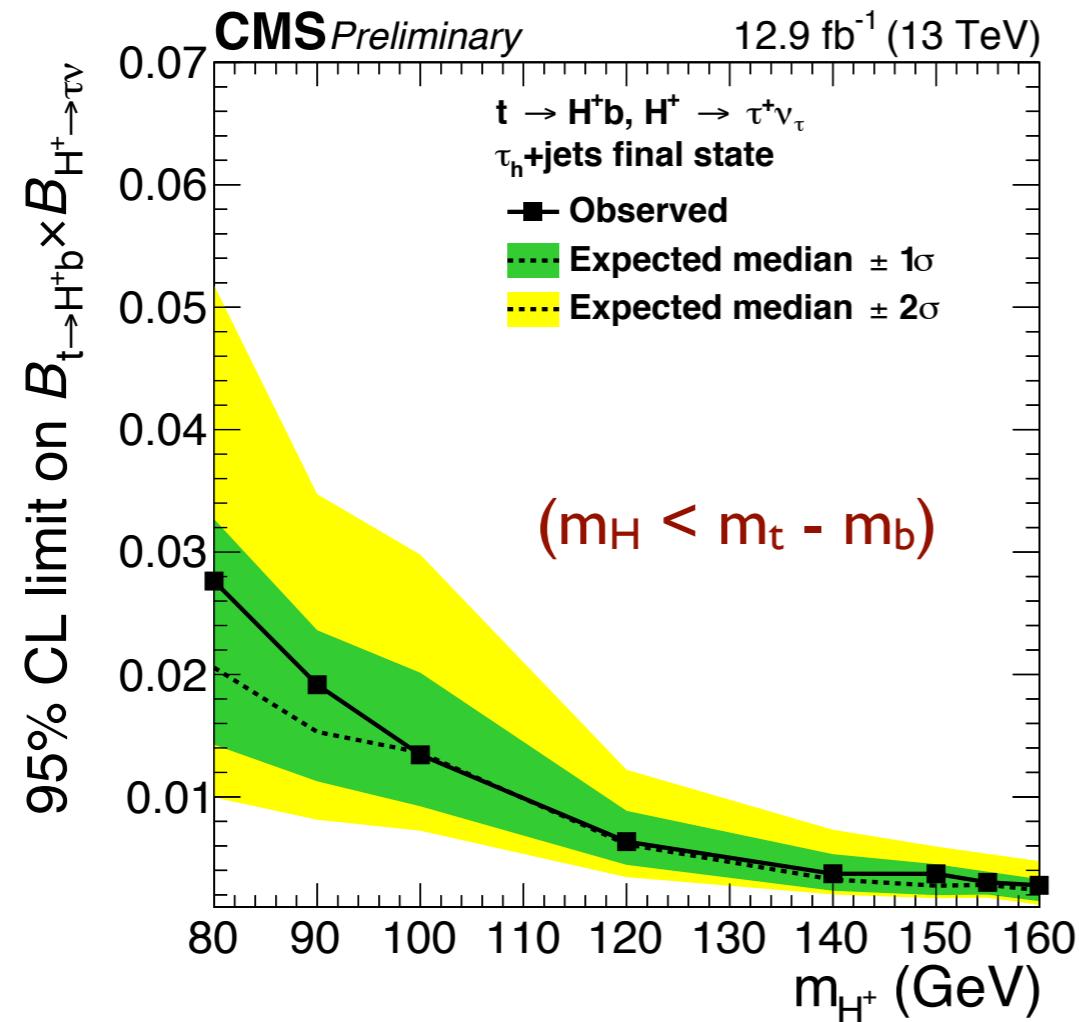


Charged MSSM $H^\pm \rightarrow \tau^\pm \nu$

- ★ Signal extraction from transverse mass of hadronic tau and missing E_T

$$m_T^2 = 2 \cdot p_T^{\tau_h} |E_T^{\text{miss}}| (1 - \cos \Delta\phi(E_T^{\text{miss}}, \tau_h))$$

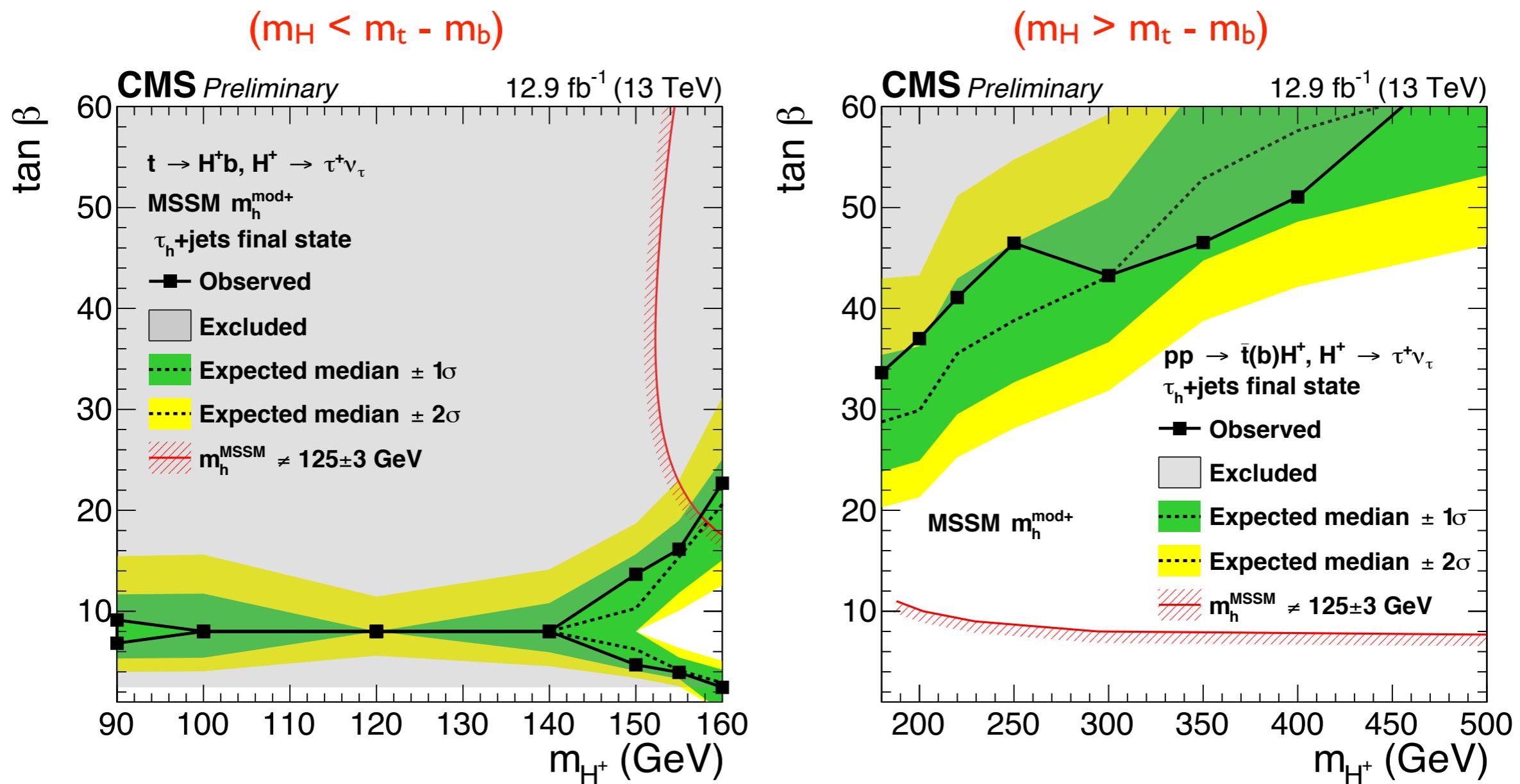
- ★ Model-independent upper limits at 95% CL on $B(t \rightarrow H^+ b) \times B(H^+ \rightarrow \tau^\pm \nu)$ for low mass and $\sigma \times B$ for high mass



no excess of signal is observed in mass range of $m(H^+) = 80\text{GeV} - 3\text{TeV}$

Charged MSSM $H^\pm \rightarrow \tau^\pm \nu$

- ★ Interpretation in the context of MSSM $m_h^{\text{mod+}}$ benchmark scenario
- ★ Exclusion upper limits at 95% CL in the $m(H^\pm)$ - $\tan\beta$ plane



Charged $H^\pm \rightarrow WZ$

- ★ In MSSM, couplings of H^\pm to W/Z are suppressed

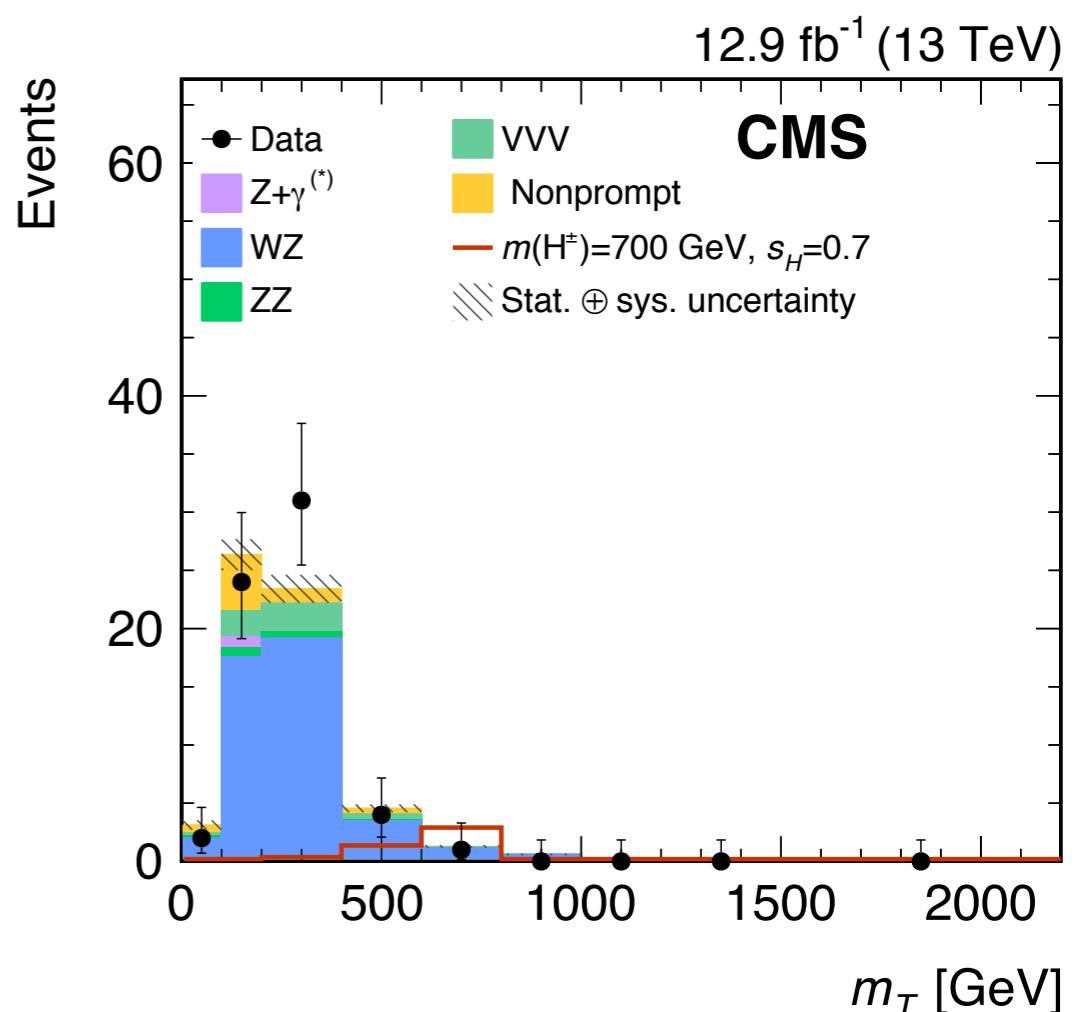
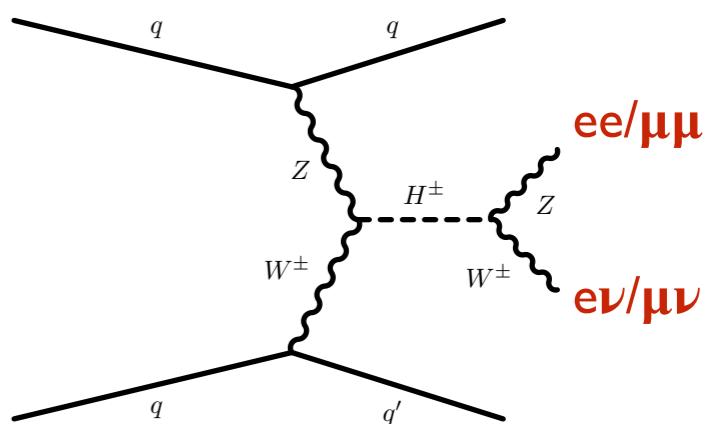
- ★ Fermiophobic H^\pm bosons appear in **Higgs Triple Model**
 - couplings to W and Z bosons at tree level
 - e.g. Georgi-Machacek (GM) model

- ★ VBF production of H^\pm and decays to WZ
 - 2 VBF jets ($\Delta\eta_{jj} > 2.5$, $M_{jj} > 500$ GeV)
 - ≥ 3 leptons and missing $E_T > 30$ GeV

- ★ Backgrounds
 - WZ (80%), VVV, ZZ, Z γ , Fake leptons

- ★ Signal extraction from transverse mass

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



Charged $H^\pm \rightarrow WZ$

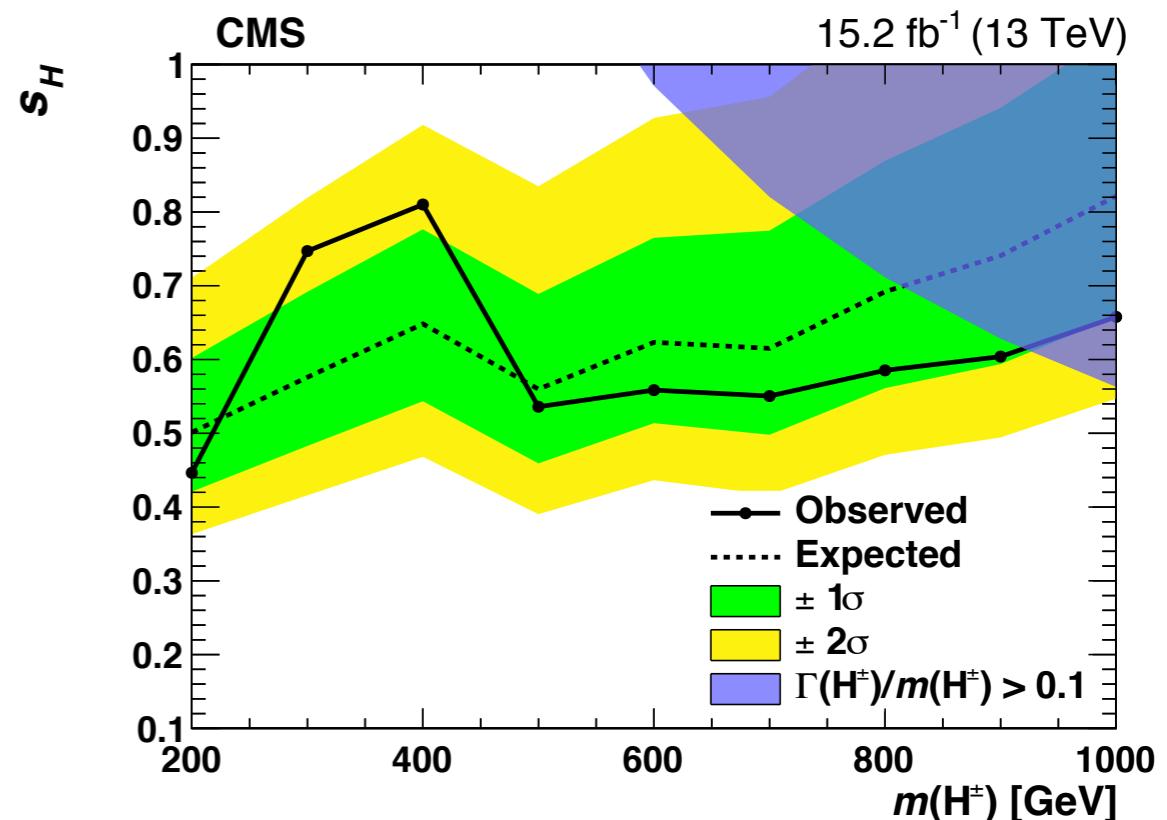
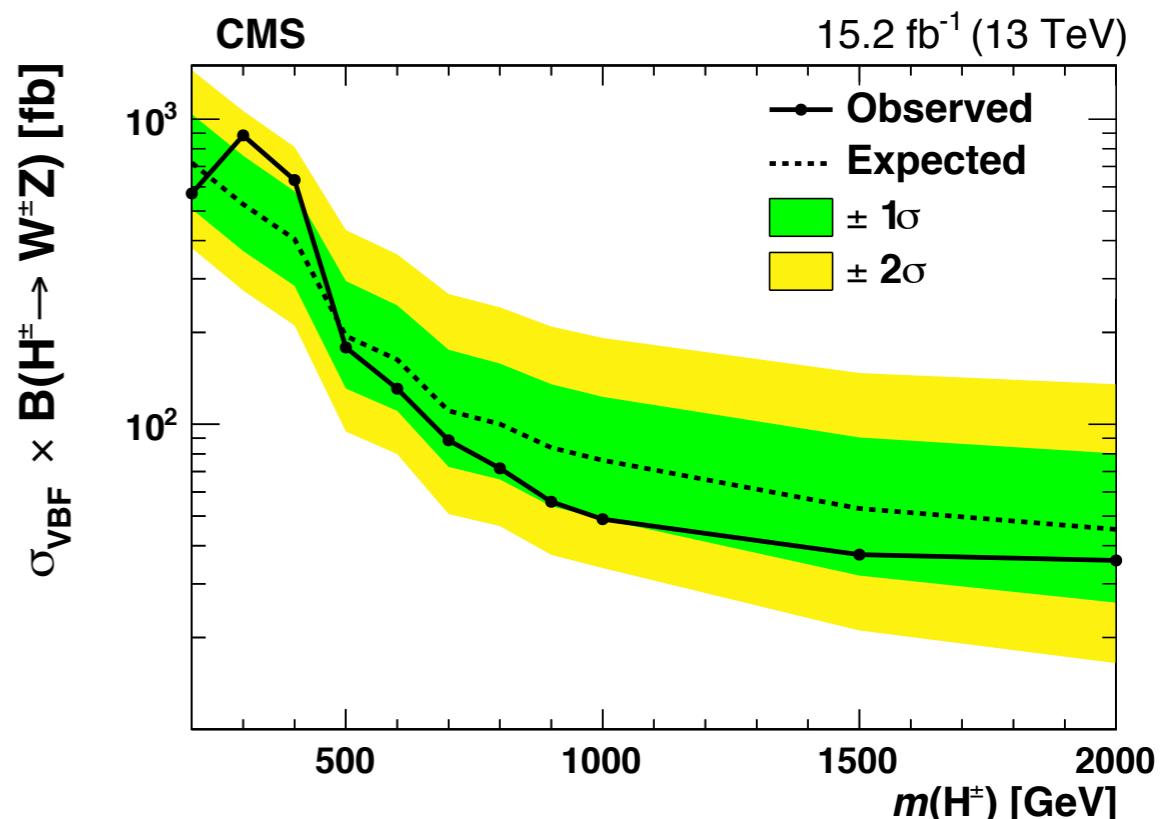
- ★ Combined 2015 and 2016 data
 - 13 TeV, $\int L dt = 15.2 \text{ fb}^{-1}$

- ★ Model-independent limits on $\sigma \times B$ at 95% CL
 - assuming narrow width resonance
 - $m(H^\pm) = 300 \text{ GeV} - 2 \text{ TeV}$

- ★ Interpretation in the GM model
 - exclusion limits on s_H as function of $m(H^\pm)$

$$s_H \equiv \sin \theta_H = \frac{2\sqrt{2}v_\chi}{v}$$

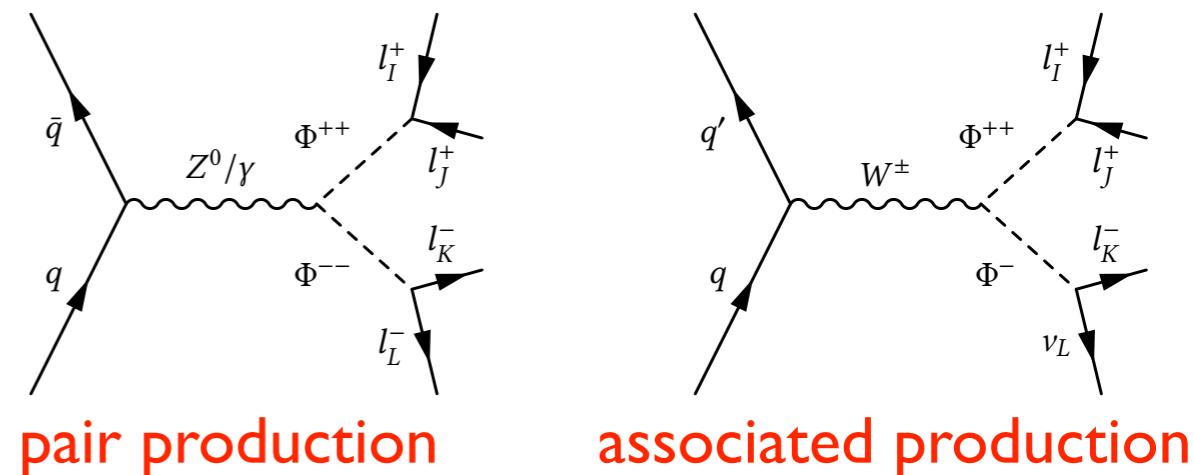
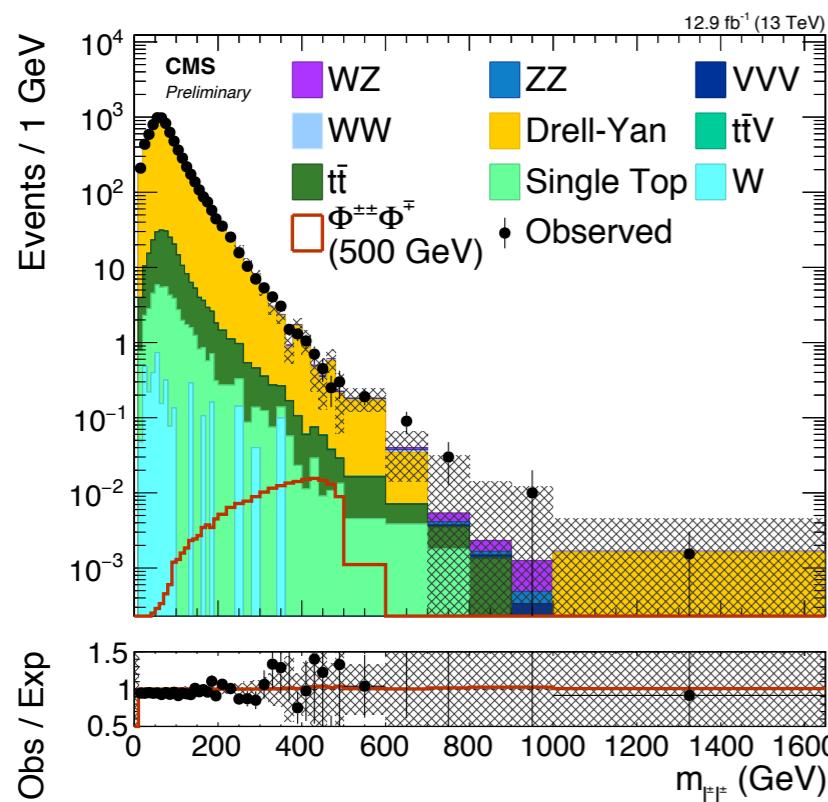
where v_χ and v are vevs of a complex triplet and the Higgs field, respectively



Doubly-Charged Higgs

- ★ The minimal Type-II seesaw mechanism extends Higgs sectors with a scalar triplet (Φ)
 - measuring BR would give access to neutrino parameters
 - specific to the left-handed doubly-charged Higgs boson

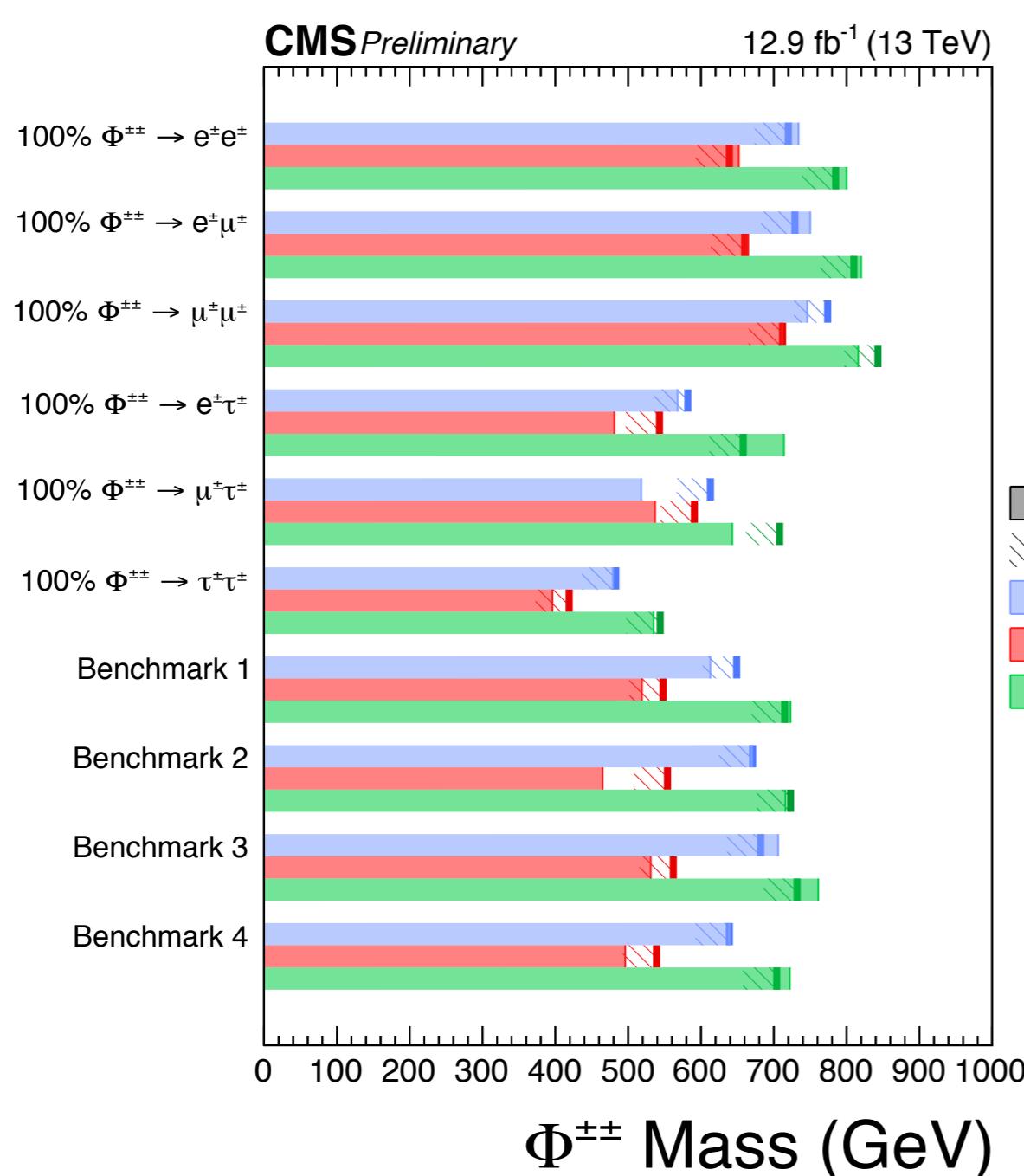
- ★ 3 leptons and 4 leptons final states
 - $\Phi^{\pm\pm} (100\%) \rightarrow ee, e\mu, \mu\mu, e\tau, \mu\tau, \tau\tau$
 - select events with charges +++, --+, +--



- ★ Signal extraction using 5 discriminating variables
 - S_T = scalar sum of lepton p_T ; difference between “best Z ” and “PDG Z ” mass; dR between same sign leptons; missing ET ; same sign invariant mass

- ★ Main uncertainties from background data-driven method

Doubly-Charged Higgs boson



- ★ Lower bounds on $\Phi^{\pm\pm}$ mass at 95% CL are set for 6 channels assuming 100% branching fractions
- ★ Limits also set for 4 benchmarks targeting several neutrino mass hypotheses

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

branching fraction scenarios of $\Phi^{\pm\pm}$

No evidence for a doubly-charged Higgs boson

Summary

- ★ The latest results using Run-2 LHC data on searches for BSM Higgs bosons at CMS have been presented
 - both neutral and charged Higgs bosons
- ★ No evidence for any BSM Higgs bosons is observed
 - sensitivity significantly increased after Run-I
- ★ Many new results to come with full 2016 data (36 fb^{-1}) soon!
- ★ Stay tuned!
 - <https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG>

Backup

Compact Muon Solenoid (CMS)

CMS DETECTOR

Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

STEEL RETURN YOKE
12,500 tonnes

SILICON TRACKERS
Pixel ($100 \times 150 \mu\text{m}$) $\sim 16\text{m}^2 \sim 66\text{M}$ channels
Microstrips ($80 \times 180 \mu\text{m}$) $\sim 200\text{m}^2 \sim 9.6\text{M}$ channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying $\sim 18,000\text{A}$

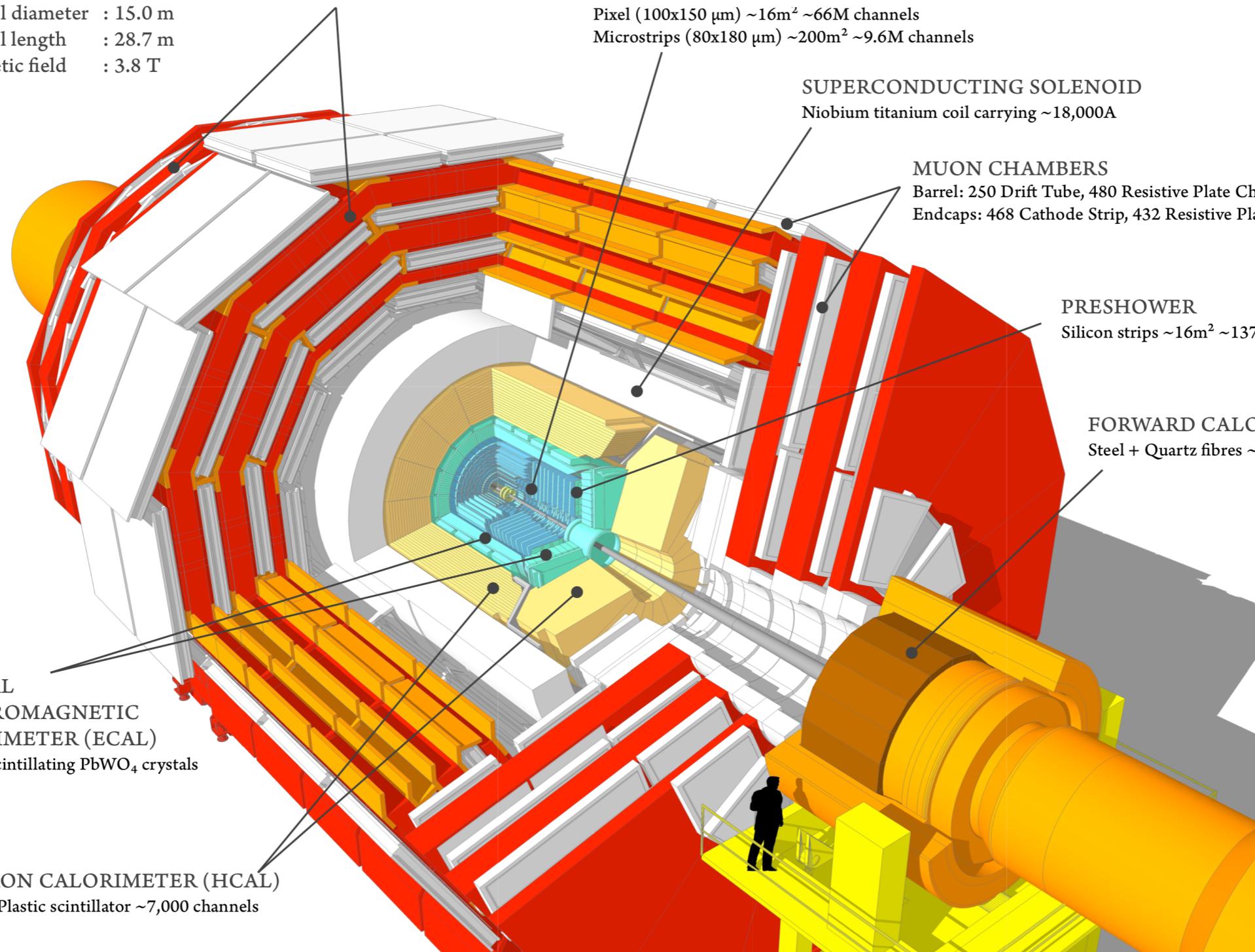
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers

PRESHOWER
Silicon strips $\sim 16\text{m}^2 \sim 137,000$ channels

FORWARD CALORIMETER
Steel + Quartz fibres $\sim 2,000$ Channels

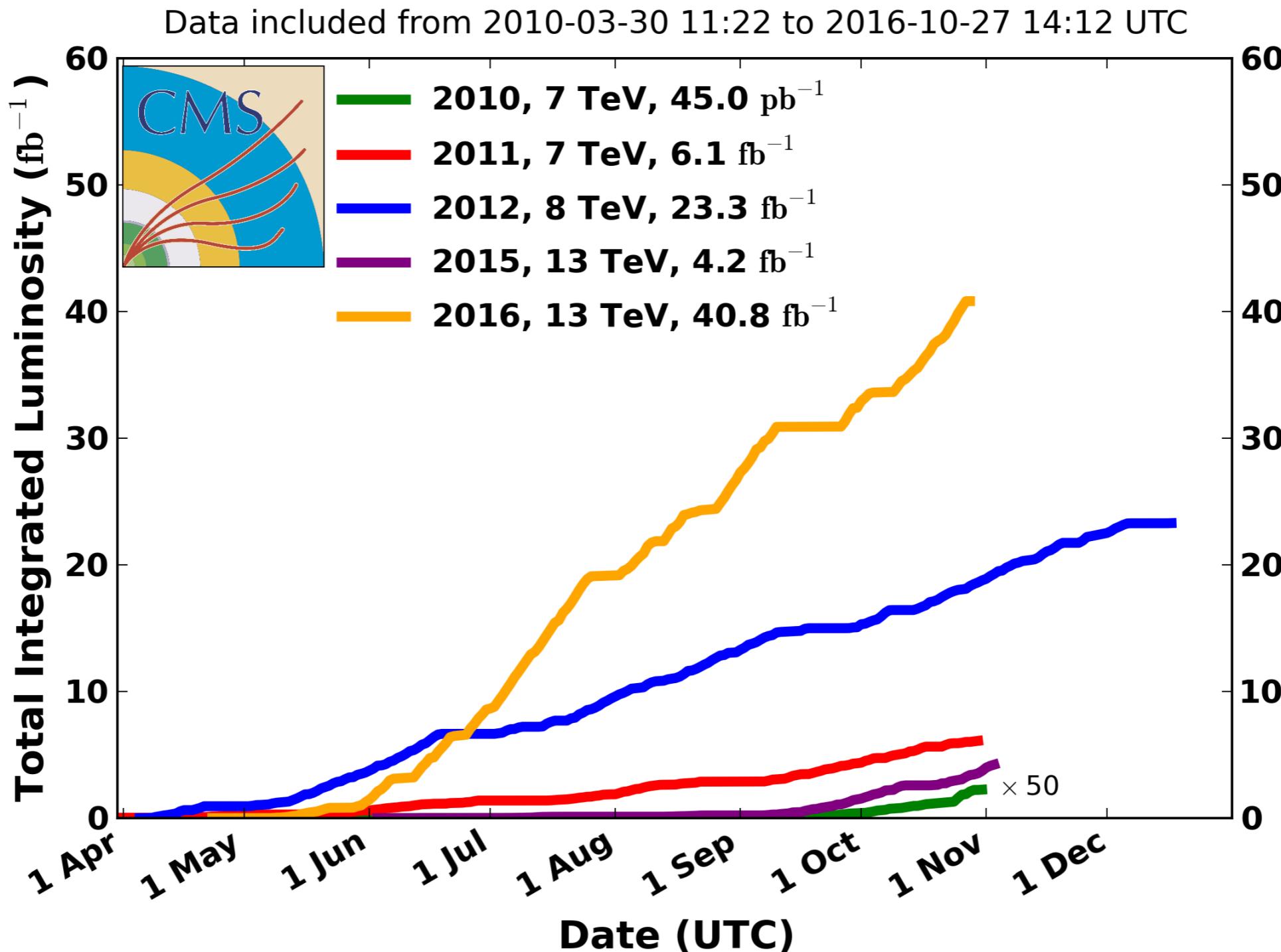
CRYSTAL
ELECTROMAGNETIC
CALORIMETER (ECAL)
 $\sim 76,000$ scintillating PbWO₄ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator $\sim 7,000$ channels



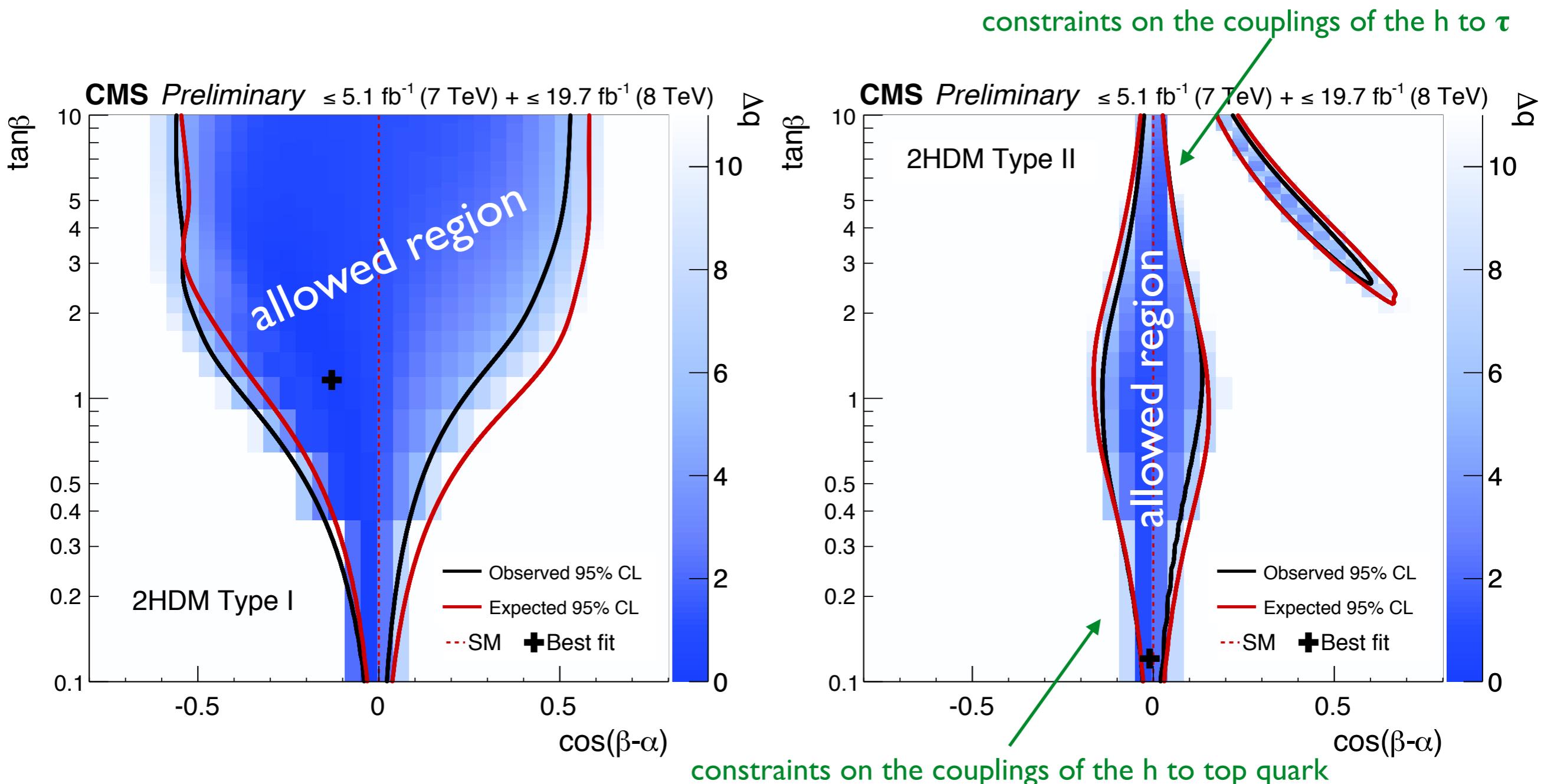
Luminosity 2011-2016

CMS Integrated Luminosity, pp



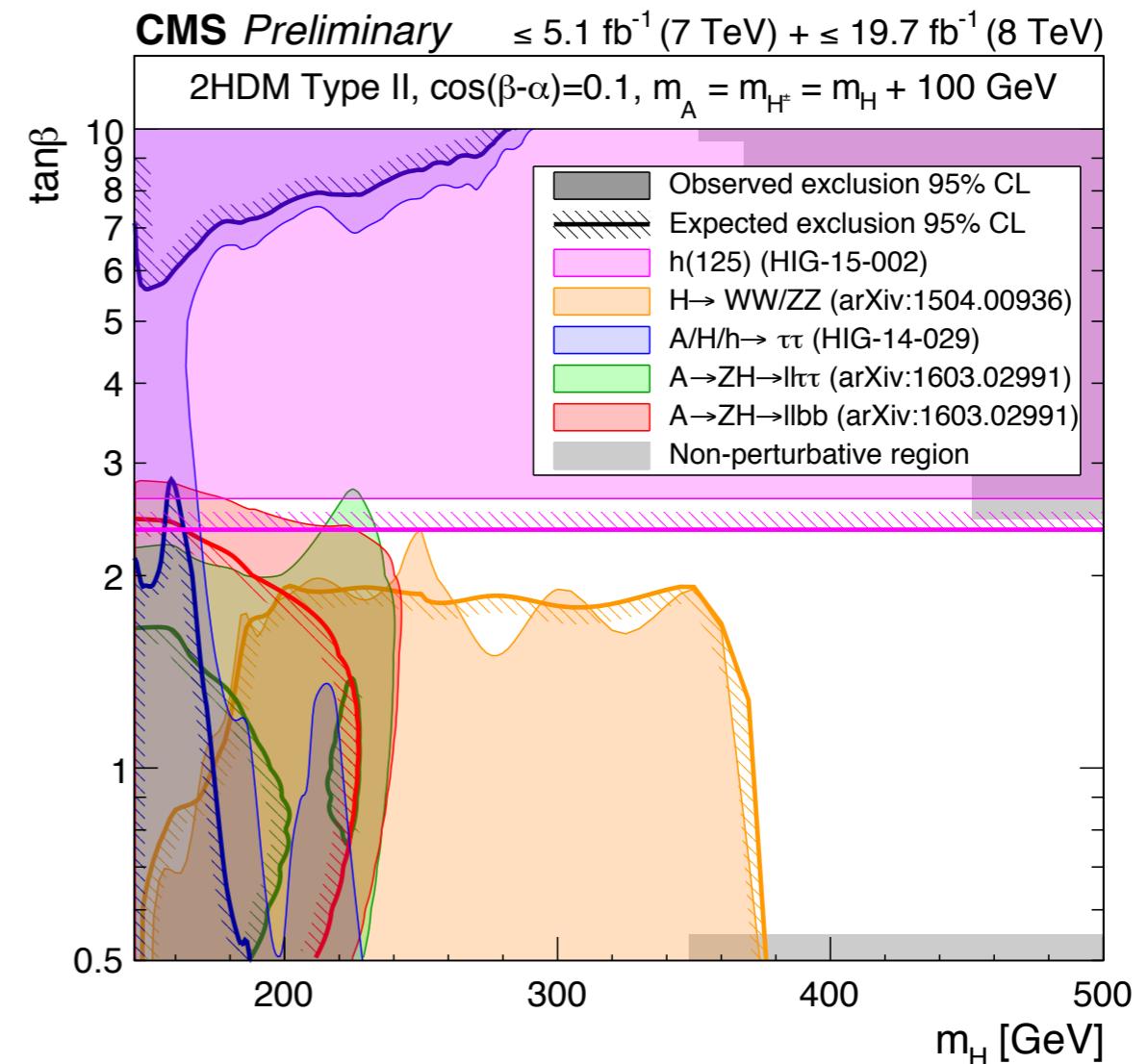
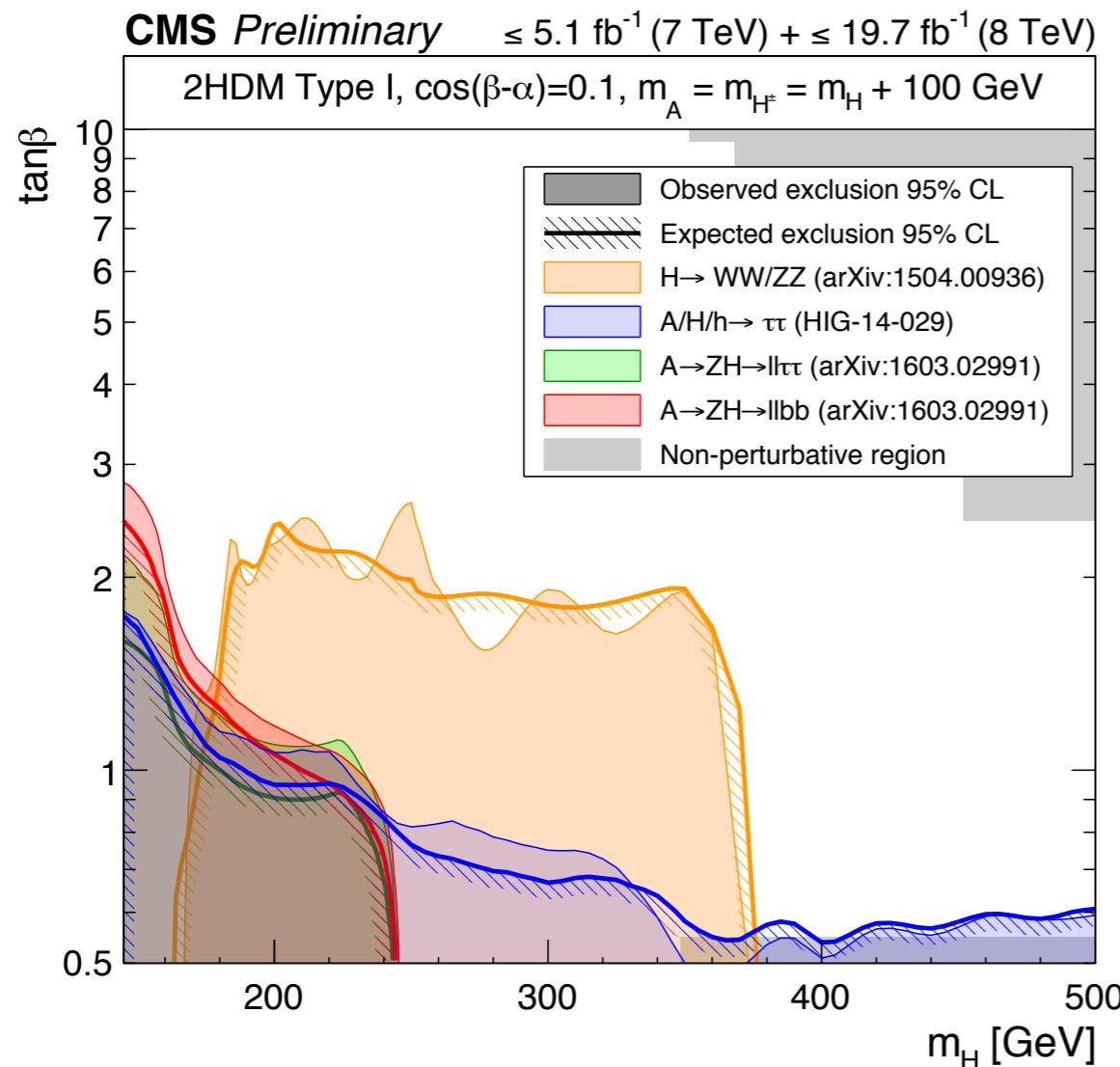
Run-I Indirect Searches

- ★ Constraints on 2HDM (Type-I and Type-II) in general
 - couplings of the SM Higgs boson (h or H^0) put strong constraints on 2HDM



Run-I Direct Searches

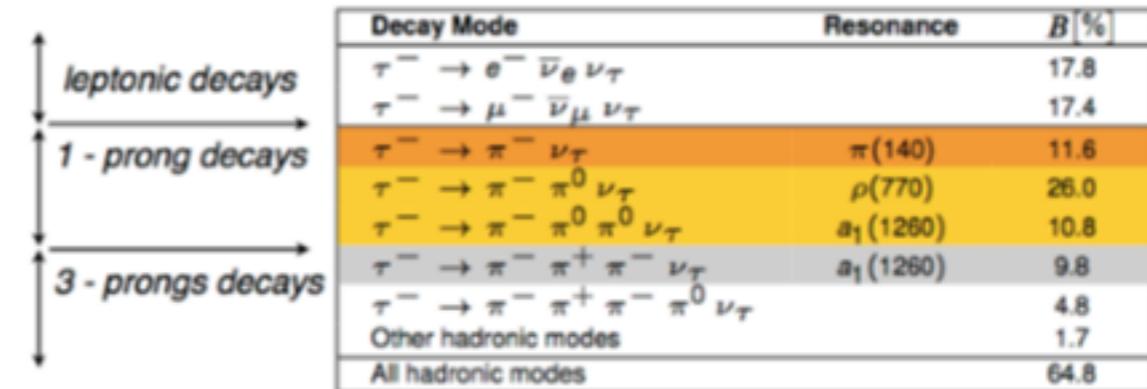
- ★ 95% CL exclusion contours in explicit 2HDM (Type-I and Type-II) scenarios



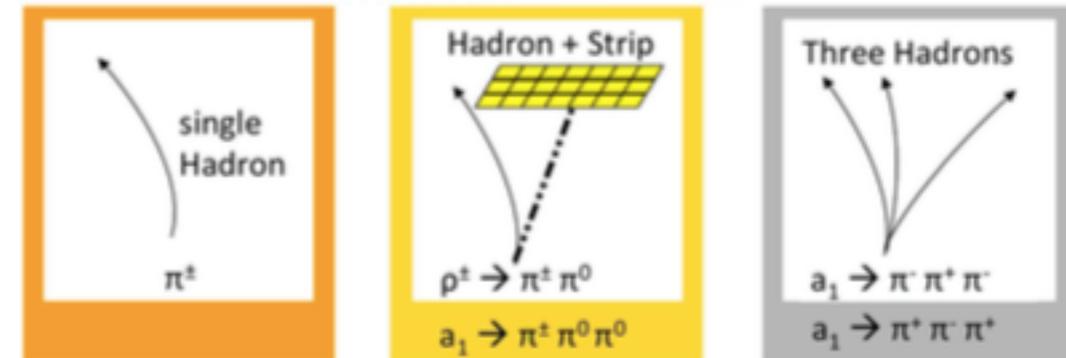
Tau Reconstruction

- ★ Leptonic decay → 35%: standard electron ID or Muon ID
- ★ Hadronic decay → 65%: hadron-plus-strip(HPS) algorithm

- ★ Hadronic taus reconstructed from a combination of charge hadron and strips of cluster of e/γ candidate



- ★ Tau mass reconstructed should be compatible with tau decay mode



- ★ MVA-based discriminators against jet and electron, cut-based discriminator against muon are used
- ★ New feature: in run-2, strip size adjusted dynamically!

MSSM $H \rightarrow \tau\tau$: Selection

	$\mu\tau_h$	$e\tau_h$	$\tau_h\tau_h$	$e\mu$
Trigger (threshold in GeV)	$\mu(22)$	$e(25)$	$\tau_h(35)$ & $\tau_h(35)$	$\mu(8)$ & $e(23)$ or $\mu(23)$ & $e(12)$
Offline selection	$p_T^\mu > 23$ GeV, $ \eta^\mu < 2.1$ $p_T^{\tau_h} > 30$ GeV, $ \eta^{\tau_h} < 2.3$	$p_T^e > 26$ GeV, $ \eta^e < 2.1$ $p_T^{\tau_h} > 30$ GeV, $ \eta^{\tau_h} < 2.3$	$p_T^{\tau_h} > 40$ GeV, $ \eta^{\tau_h} < 2.1$ $p_T^{\tau_h} > 40$ GeV, $ \eta^{\tau_h} < 2.1$	$p_T^\mu > 10(24)$ GeV, $ \eta^\mu < 2.4$ $p_T^e > 13(24)$ GeV, $ \eta^e < 2.5$
Additional ID	Medium ID	MVA ID 80%	-	Medium ID MVA ID 80%
Isolation	$I_\mu^{rel} < 0.15$ MVA Medium	$I_e^{rel} < 0.1$ MVA Medium	MVA Tight	$I_\mu^{rel} < 0.2$ $I_e^{rel} < 0.15$
Impact parameter (cm)	$d_{xy}^\mu < 0.045$ $d_z^\mu < 0.2$ $d_z^{\tau_h} < 0.2$	$d_{xy}^e < 0.045$ $d_z^e < 0.2$ $d_z^{\tau_h} < 0.2$	$d_z^{\tau_h} < 0.2$	$d_{xy}^{\mu/e} < 0.045$ $d_z^{\mu/e} < 0.2$
Lepton vetoes	No loose $\mu^+\mu^-$ pair with $p_T^\mu > 15$ GeV	No loose e^+e^- pair with $p_T^e > 15$ GeV	-	No additional loose e with $p_T > 10$ GeV and $ \eta < 2.5$ No additional loose μ with $p_T > 10$ GeV and $ \eta < 2.4$

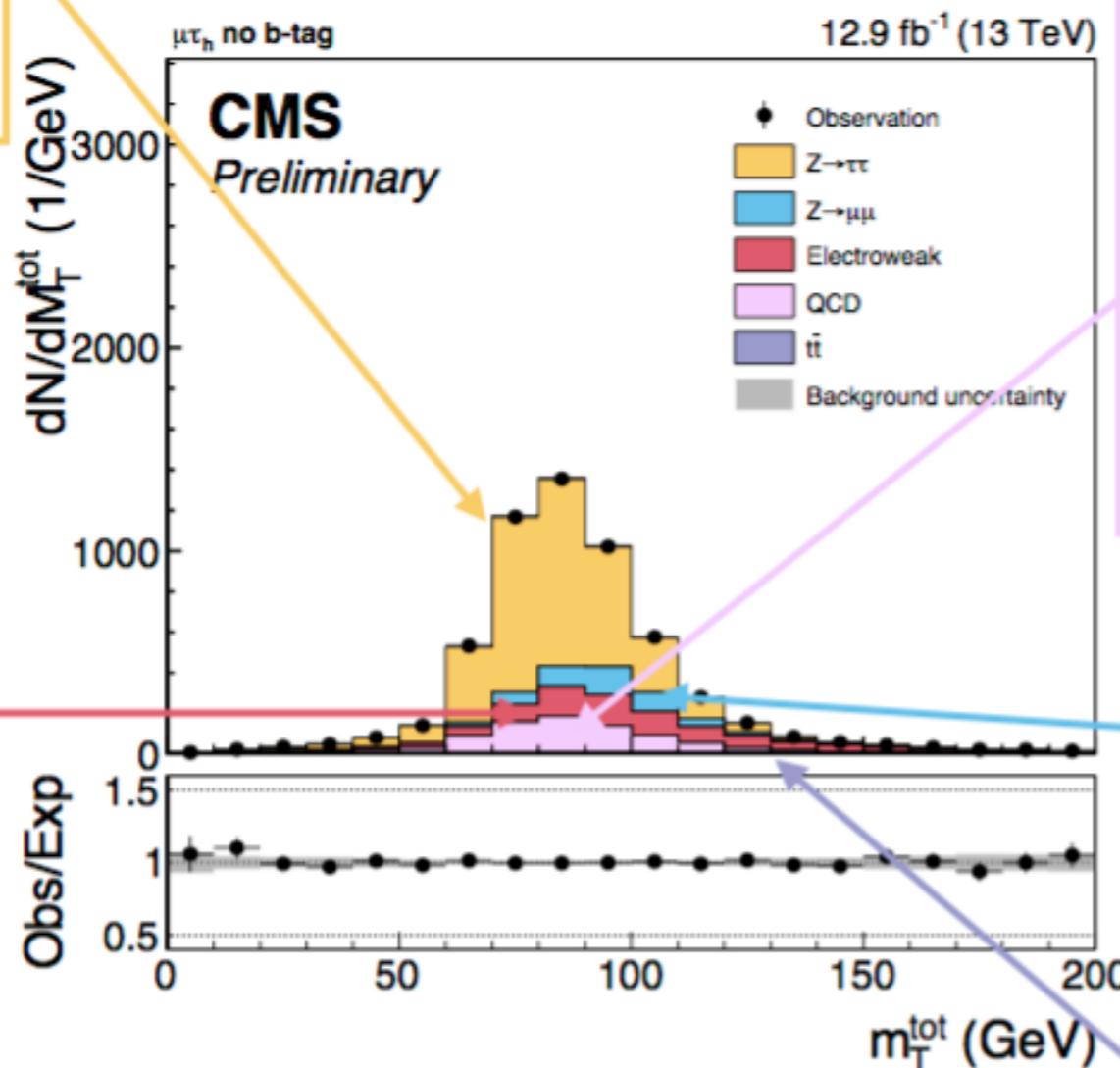
★ Additional cuts

- to reduce $W+jets$, cut on $m_T < 40$ (50) GeV for $\mu\tau_h(e\tau_h)$
- to reduce ttbar in $e\mu$, $D_\zeta > -20$ GeV where $D_\zeta = P_\zeta - 1.85 \cdot P_\zeta^{\text{vis}}$

$$P_\zeta = (\vec{p}_T^e + \vec{p}_T^\mu + \vec{p}_T^{\text{miss}}) \cdot \frac{\vec{\zeta}}{|\vec{\zeta}|} \quad \text{and} \quad P_\zeta^{\text{vis}} = (\vec{p}_T^e + \vec{p}_T^\mu) \cdot \frac{\vec{\zeta}}{|\vec{\zeta}|},$$

MSSM $H \rightarrow \tau\tau$: Backgrounds

Z $\rightarrow\tau\tau^*$: Norm and shape from MC, with data-driven correction applied



W+Jets:**
 $\mu_{\text{Th}}, e_{\text{Th}}$: Norm from high m_T control region
shape from MC
 $\text{ThTh}, e\mu$: Norm and shape from MC

QCD:** Fully data-driven
 $\mu_{\text{Th}}, e_{\text{Th}}, e\mu$: Norm from SS with other backgrounds subtracted, and OS/SS ratio applied, **shape** from SS
ThTh: Norm from OS region with loosened isolation (SR excluded), scale factor loose \rightarrow tight isolation (measured in equivalent SS regions) applied.
Shape from OS region with loosened isolation

Z $\rightarrow ll$: Norm and shape from MC

*Control regions included in fit for this background, affecting the post-fit normalisation of **all channels**
** Control regions included in fit for this background affecting the post-fit normalisation of the μ_{Th} and e_{Th} channels only

ttbar: Norm and shape from MC, with data-driven corrections

$H^\pm \rightarrow \tau^\pm \nu$: Selection

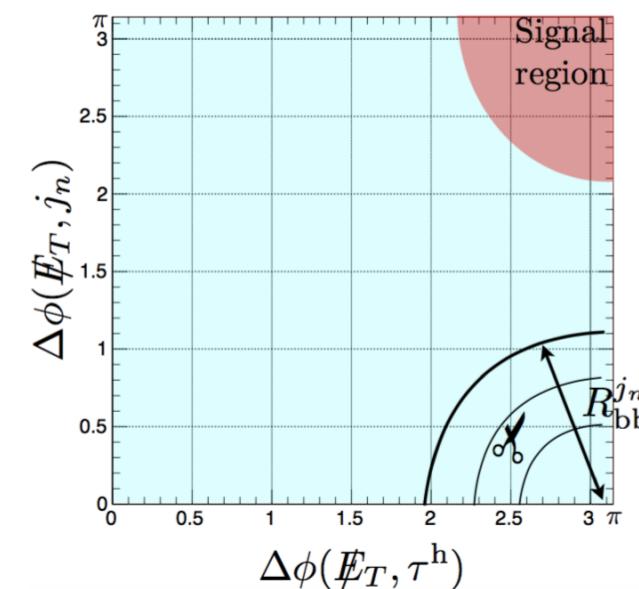
- ★ Tau (hadronic)
 - $p_T > 60$ GeV (50 GeV for light mass search)
 - $|\eta| < 2.1$
 - leadTrack $p_T > 30$ GeV
 - decayMode: 1 prong
 - byLooseCombinedIsolation
 - against electron
 - against muon

- ★ MET
 - MET > 100 GeV (90 GeV for light mass search)
 - MET Filters
 - PF MET
 - Type-I Corrections

- ★ B-jets
 - $p_T > 30$ GeV, $|\eta| < 2.5$
 - Loose WP CSV
 - $N \geq 1$

- ★ Jets
 - $p_T > 30$ GeV, $|\eta| < 4.7$
 - Loose Jet ID
 - Jet Energy corrections
 - $N \geq 3$

- ★ Lepton veto
 - $\mu(e)$
 - $p_T > 10 (15)$ GeV, $|\eta| < 2.5$
 - Loose (Veto) WP
 - Isolation $< 20 (15)$ % p_T



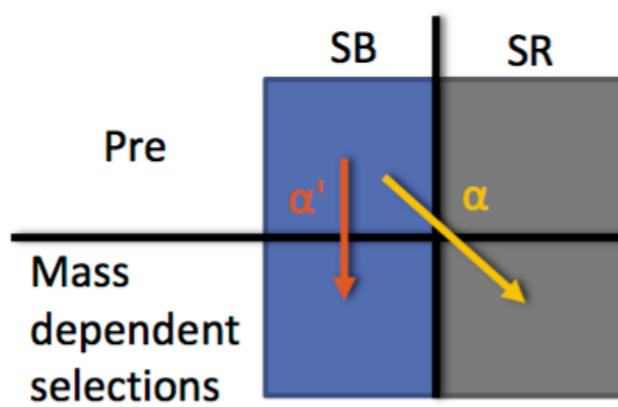
Doubly-Charged Higgs

- ★ Analysis categories are separated by the number of taus associated to the $\Phi^{\pm\pm}$
- ★ Background estimation is modified based on category
 - all light leptons or categories with a real Z decaying to light leptons are estimated full from MC
 - others are estimated with a combination of MC and data-driven via the fake efficiency method
- ★ Fake background estimation (non-prompt)
 - tight-to-loose method
- ★ Background estimation in the final signal region is performed using an alpha sideband method
 - Alpha and alpha prime defined as below and estimated with MC (+DD)
 - N_{pre} : preselection with the NOT (mass window OR other mass dependent selections) applied
 - N_{SB} : with mass dependent selections and the NOT of the mass window
 - N_{SR} : with the AND of the mass dependent selections and the mass window
 - The contribution N^{exp} is then estimated from data in the preselection

$$\alpha = \frac{N_{SR}}{N_{pre}} \quad \alpha' = \frac{N_{SB}}{N_{pre}}$$

$$N_{SR}^{exp} = \alpha \cdot (N_{pre}^{Data} + 1)$$

$$N_{SB}^{exp} = \alpha' \cdot (N_{pre}^{Data} + 1)$$



Doubly-Charged Higgs boson

★ Signal extraction using 5 discriminating variables

3 leptons

Variable	ee, e μ , $\mu\mu$	e τ , $\mu\tau$	$\tau\tau$
S_T	$> 0.99 \cdot m_{\Phi^{++}} - 35 \text{ GeV}$	$> 1.15 \cdot m_{\Phi^{++}} + 2 \text{ GeV}$	$> 0.98 \cdot m_{\Phi^{++}} + 91 \text{ GeV}$
$ m_{\ell^+\ell^-} - m_Z $	$> 10 \text{ GeV}$	$> 20 \text{ GeV}$	$> 25 \text{ GeV}$
E_T^{miss}	–	$> 20 \text{ GeV}$	$> 50 \text{ GeV}$
$\Delta R(\ell^\pm\ell'^\pm)$	–	< 3.2	$< m_{\Phi^{++}}/380 + 1.86 \quad (m_{\Phi^{++}} \leq 400)$ $< m_{\Phi^{++}}/750 + 2.37 \quad (m_{\Phi^{++}} > 400)$
Mass window	$[0.9 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}] \text{ GeV}$	$[0.4 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}] \text{ GeV}$	$[0.3 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}] \text{ GeV}$

4 leptons

Variable	ee, e μ , $\mu\mu$	e τ , $\mu\tau$	$\tau\tau$
S_T	$> 1.23 \cdot m_{\Phi^{++}} + 54 \text{ GeV}$	$> 0.88 \cdot m_{\Phi^{++}} + 73 \text{ GeV}$	$> 0.46 \cdot m_{\Phi^{++}} + 108 \text{ GeV}$
$ m_{\ell^+\ell^-} - m_Z $	–	$> 10 \text{ GeV}$	$> 25 \text{ GeV}$
$\Delta R(\ell^\pm\ell'^\pm)$	–	–	$< m_{\Phi^{++}}/1400 + 2.43$
Mass window	$[0.9 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}] \text{ GeV}$	$[0.4 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}] \text{ GeV}$	$[0.3 \cdot m_{\Phi^{++}}, 1.1 \cdot m_{\Phi^{++}}] \text{ GeV}$

★ 4 benchmark points targeting several neutrino mass hypotheses

- BP1: tri-bi-maximal normal hierarchy
- BP2: tri-bi-maximal inverted hierarchy
- BP3: degenerate mass spectrum of 0.2 eV
- BP4: equal branching fractions