Searches for charged Higgs bosons at CMS

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for CMS experiment

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Beyond the SM Higgs sector

- **Theoretical motivation for an extended Higgs sector is broad:** coupling constant unification, CP violation, neutrino masses, hierarchy problem…
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Doublet models

- Add another doublet → **two Higgs-Doublet Models** (2HDM)
  - 5 scalar bosons: h, H, A, **H^+, H^-**
  - Classes of models (no FCNCs):

Type I (Fermiophobic)

$\Phi_1^{d} \Phi_2^{u}$
e

Type II (MSSM-like)

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Type X (Lepton-specific)

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Type Y (Flipped)

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Triplet models

- Addition of scalar triplet(s)
  - **Georgi-Machacek model**: add one real and one complex SU(2) triplet
- H^+ phenomenology different from the doublet models
  - **H^+WZ couplings** at tree level
  - Double-charged Higgs bosons **H^{++}**

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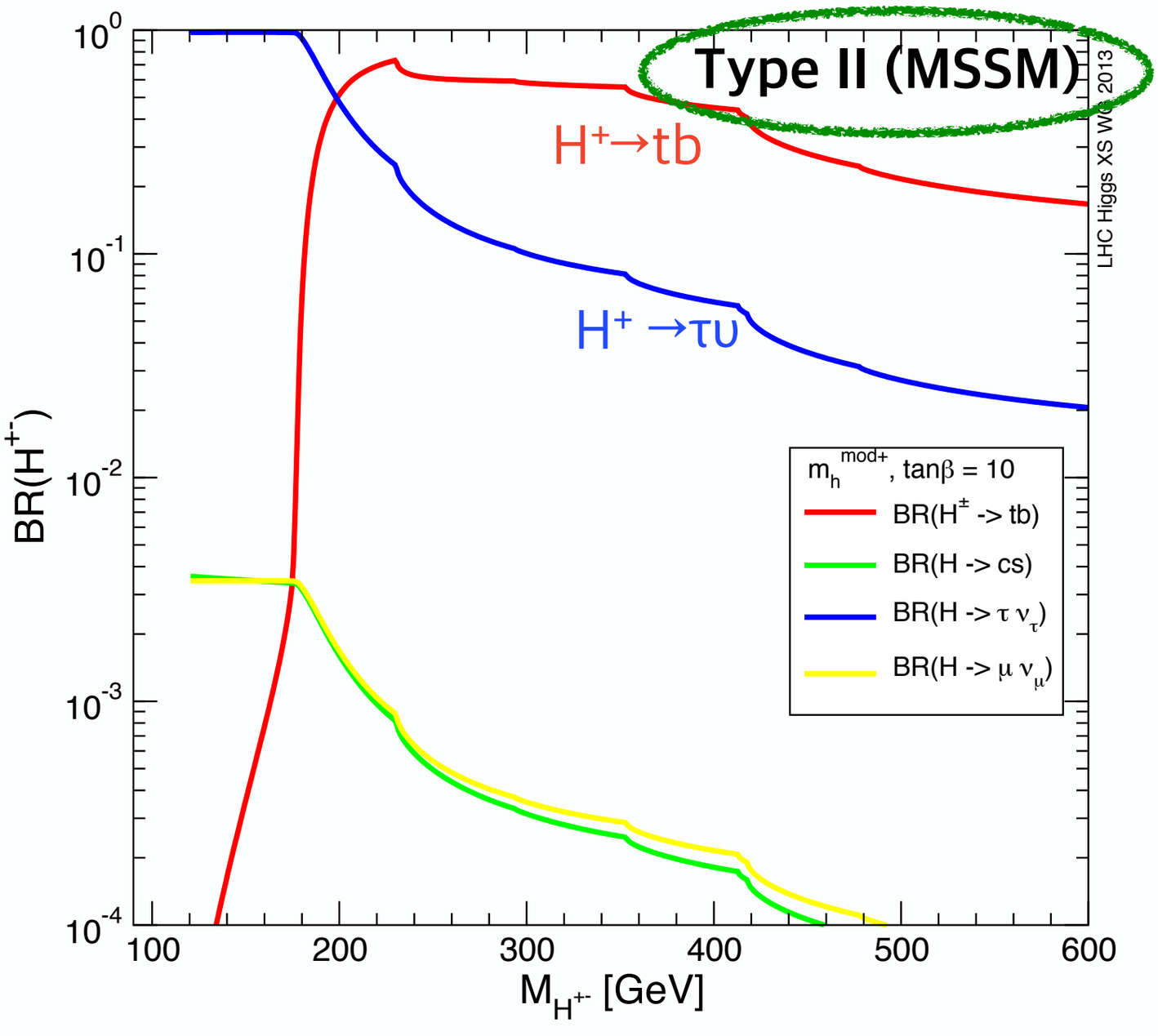
Experimental signatures for H^+

- H^+ production and decay are **model-dependent**
  → Different searches constrain different scenarios



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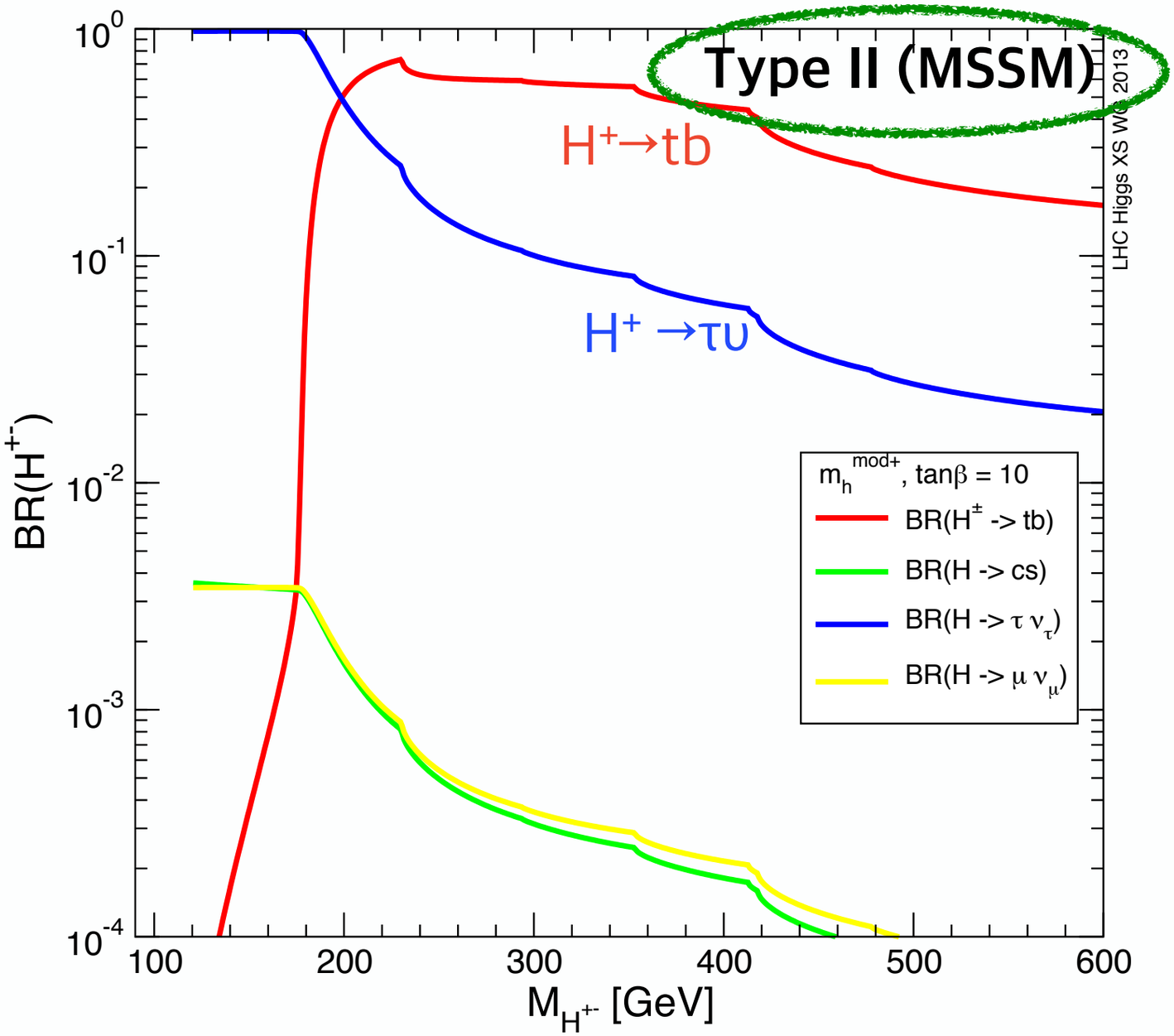

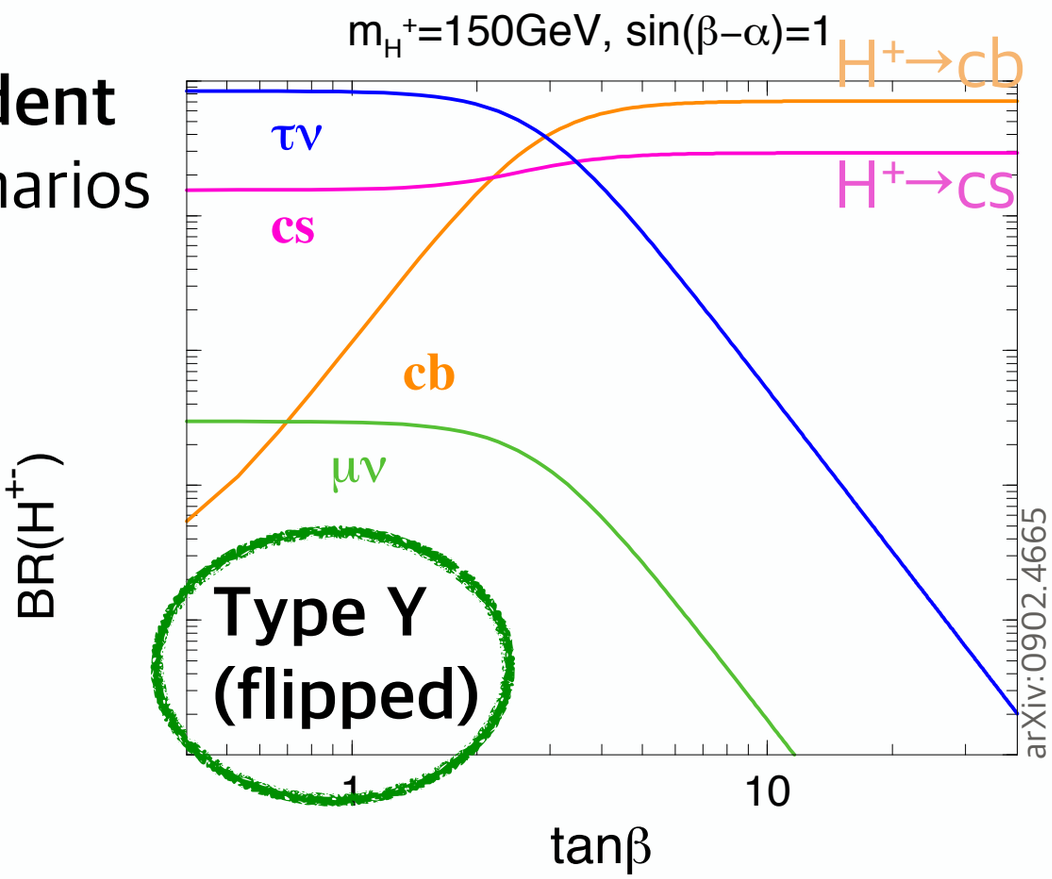

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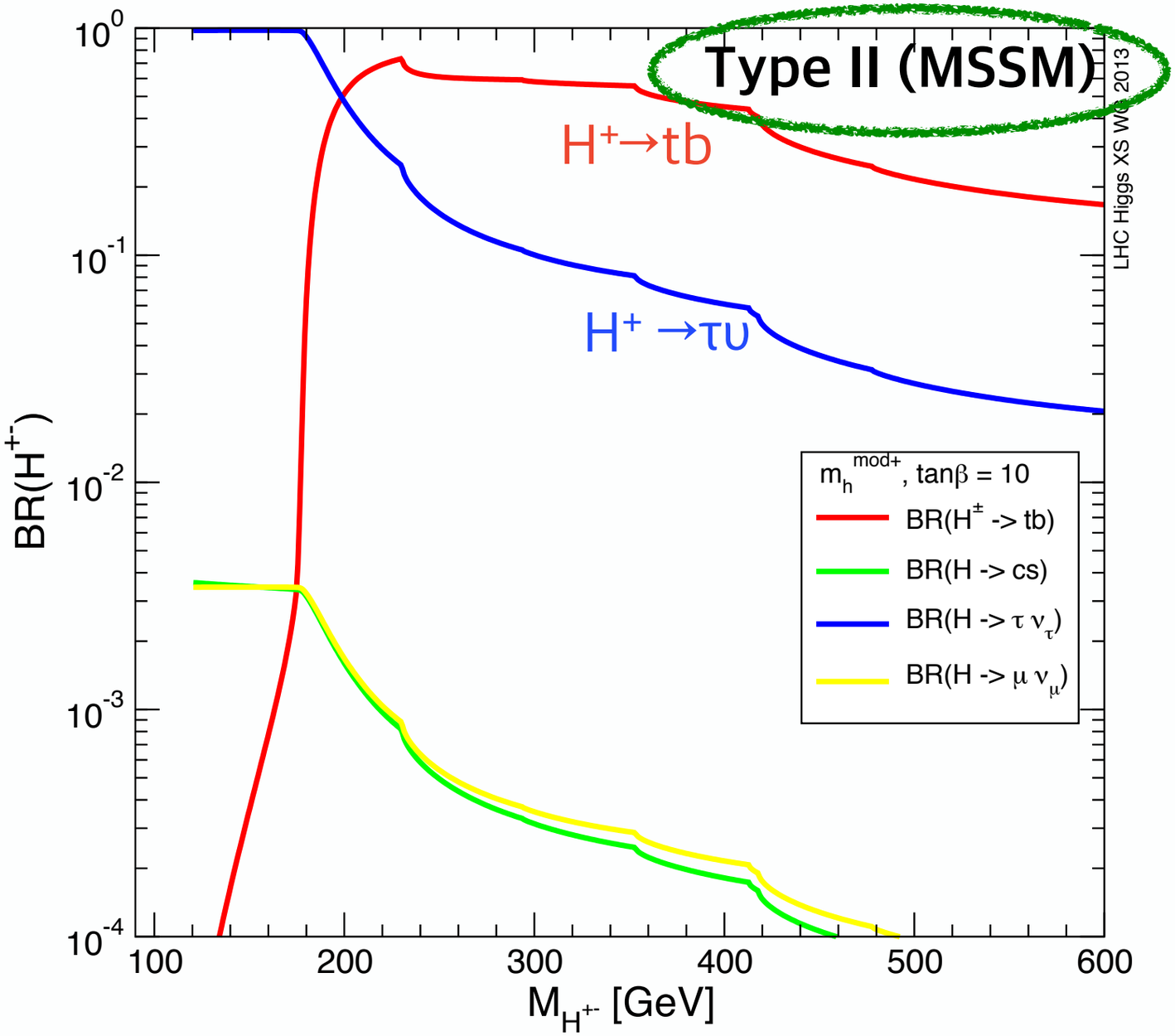
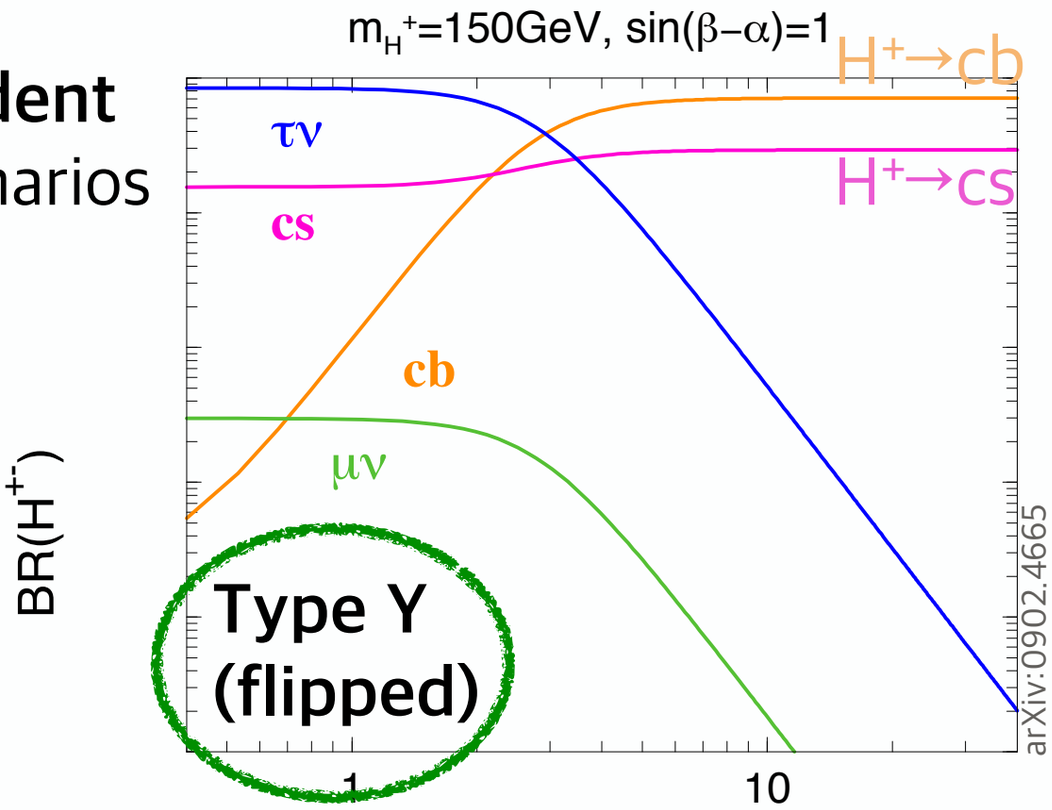
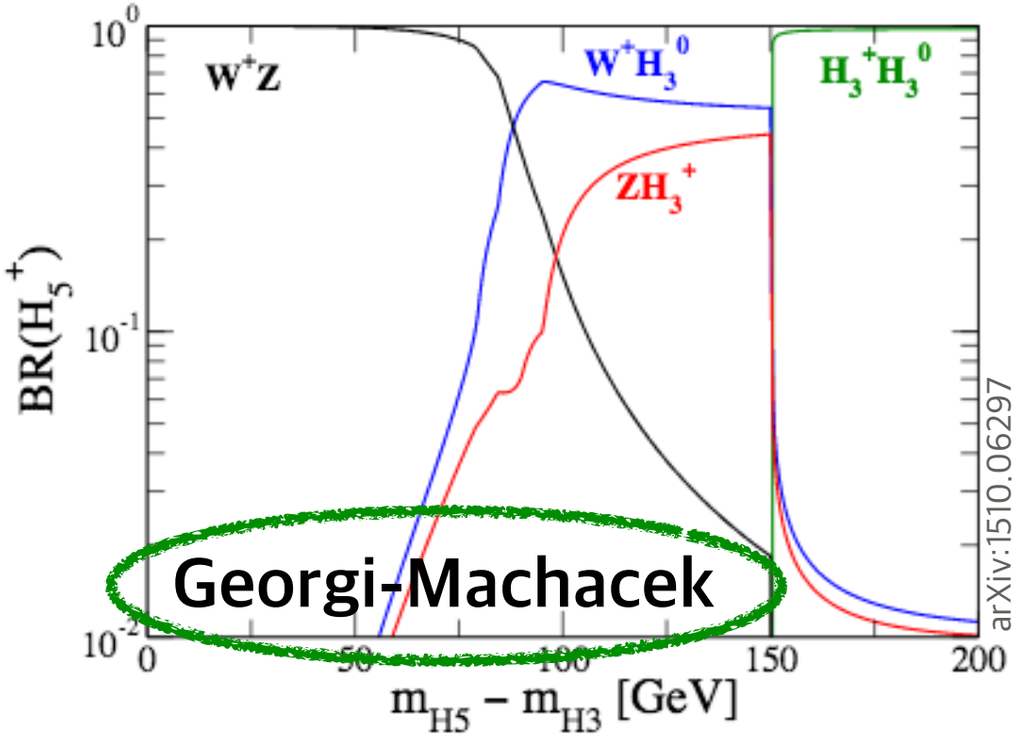
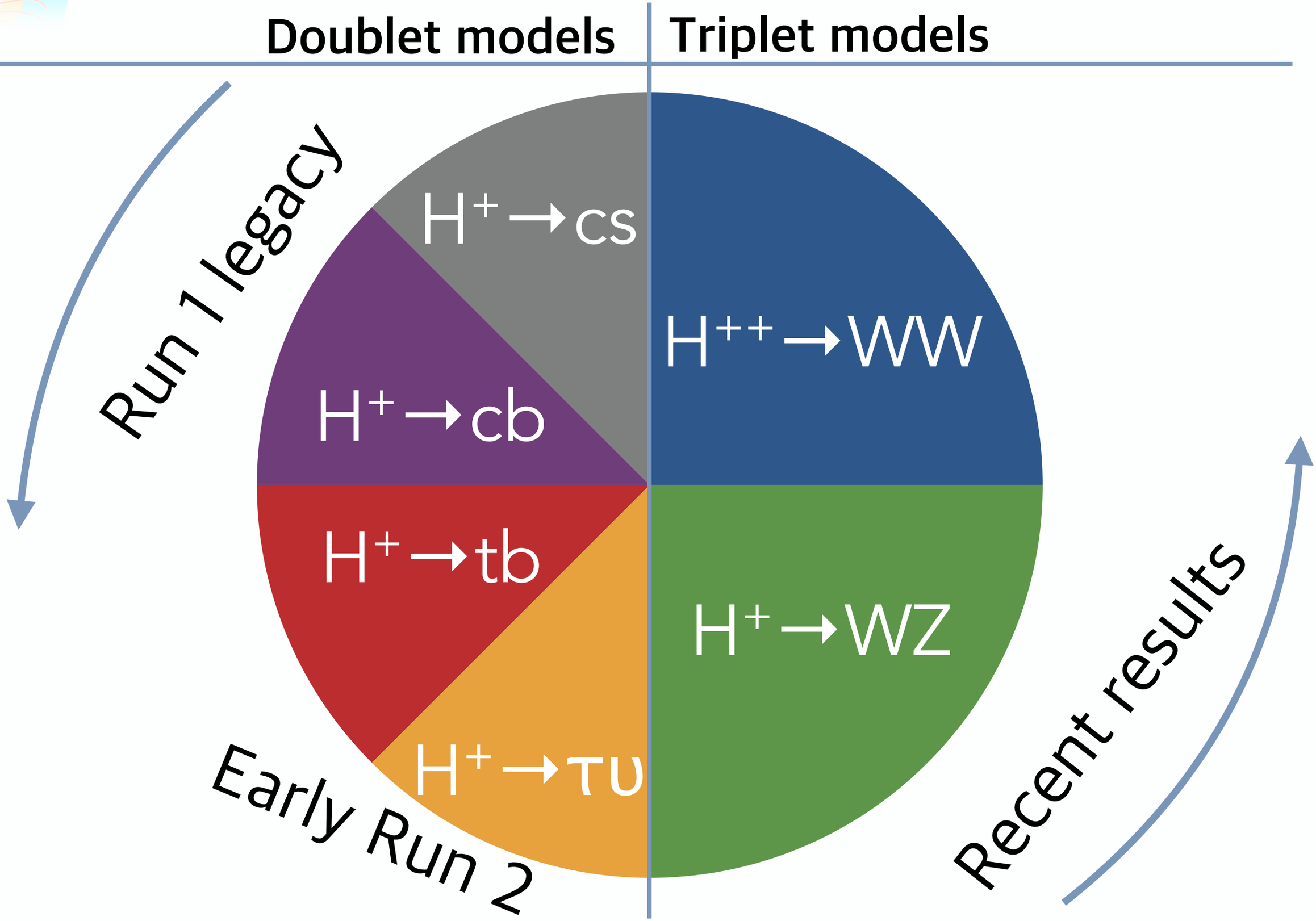


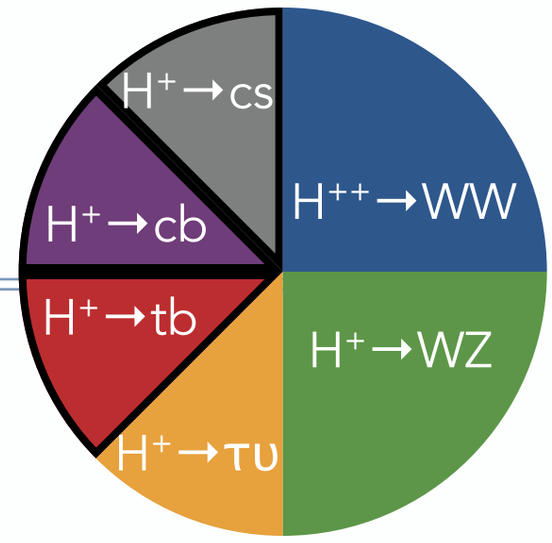




Overview


Doublet models
Triplet models
Run 1 legacy
$H^+ \to cs$
$H^+ \to cb$
$H^+ \to tb$
$H^+ \to \tau\nu$
$H^{++} \to WW$
$H^+ \to WZ$
Early Run 2
Recent results

Run 1 legacy



- Run 1 was fruitful in terms of H^+ results - some examples here
  - Many exclusion limits still competitive
  - **Model-independent limits** can be interpreted as constraints on parameter spaces of **specific scenarios**

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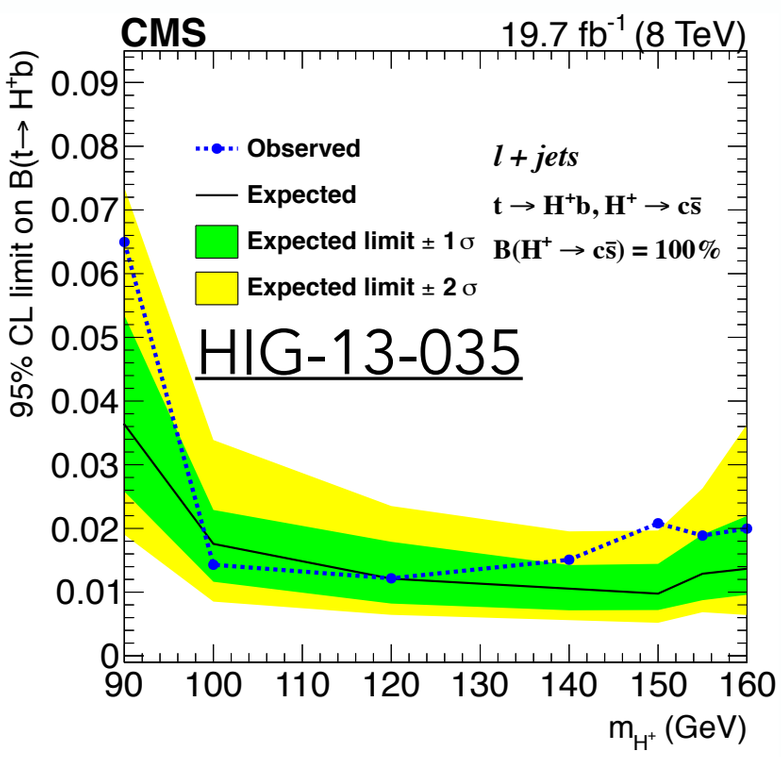

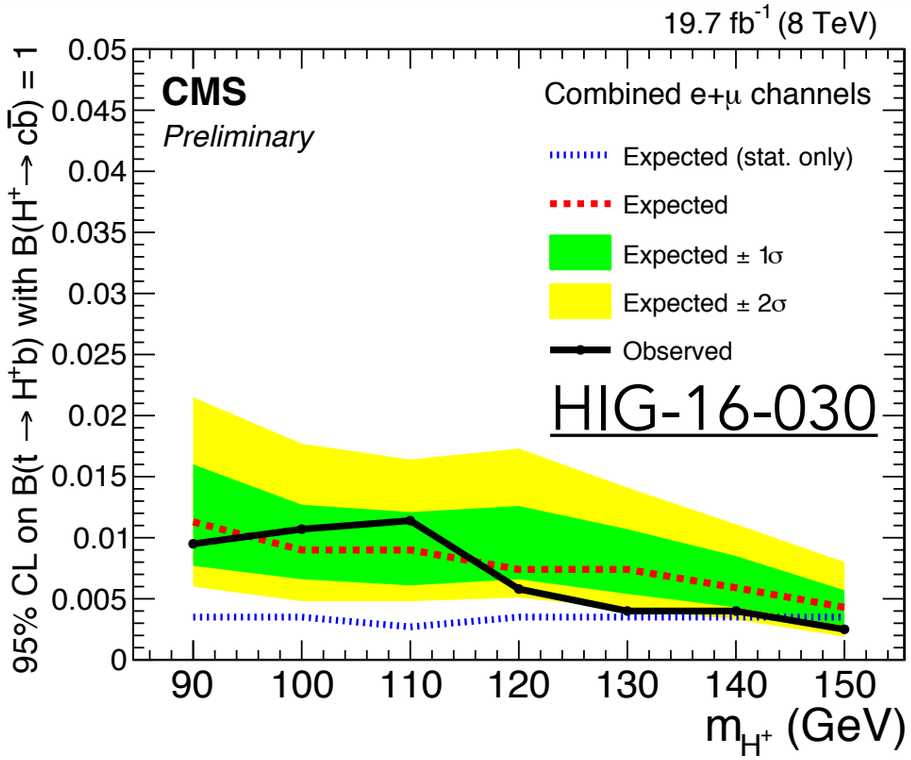

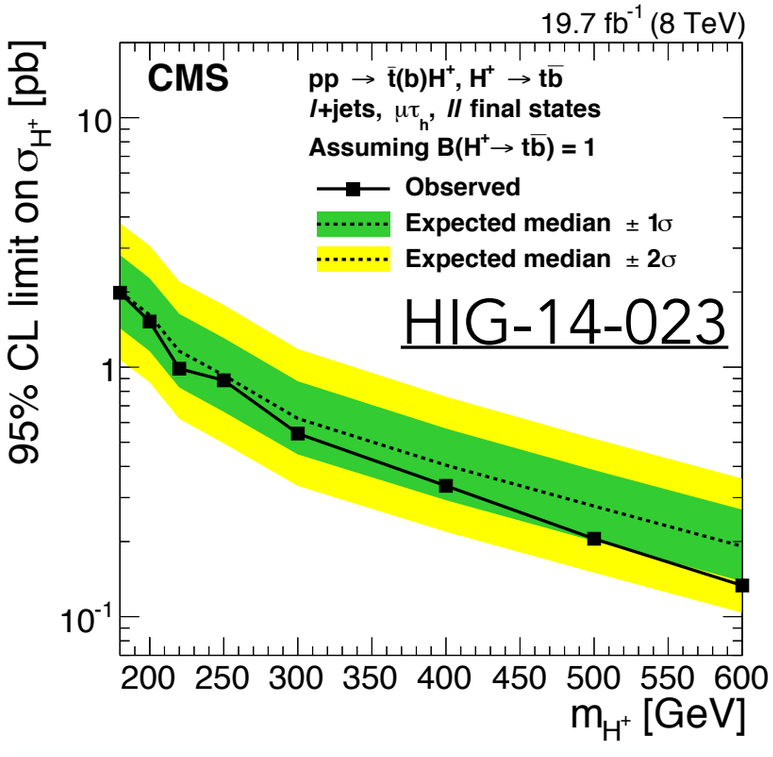

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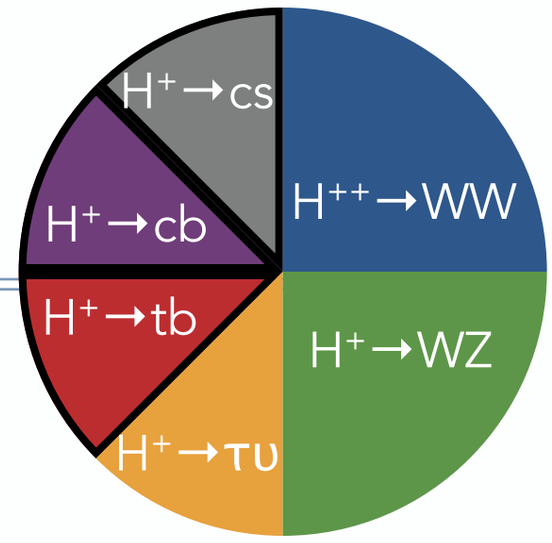

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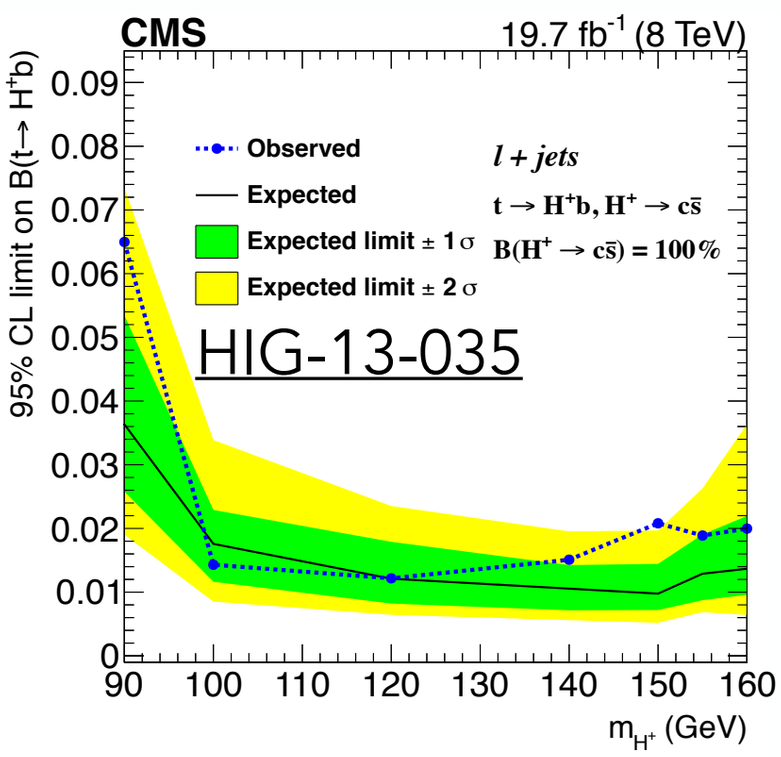
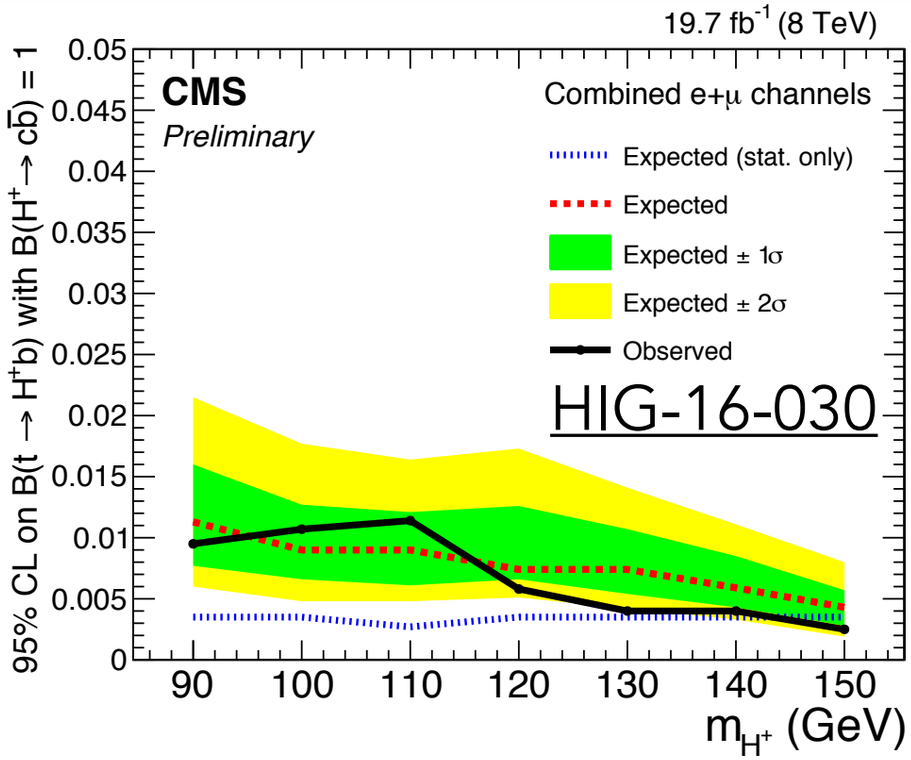
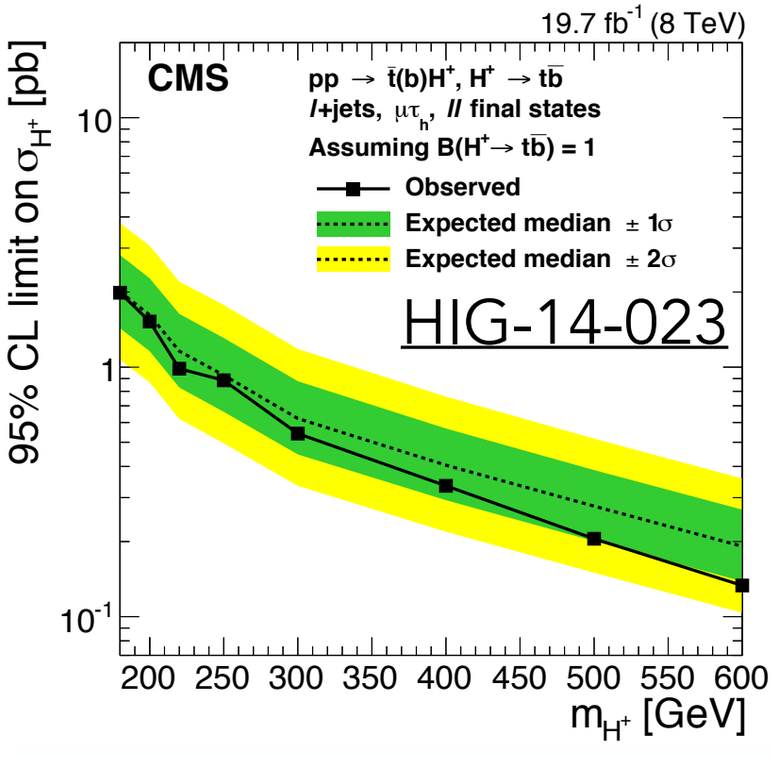
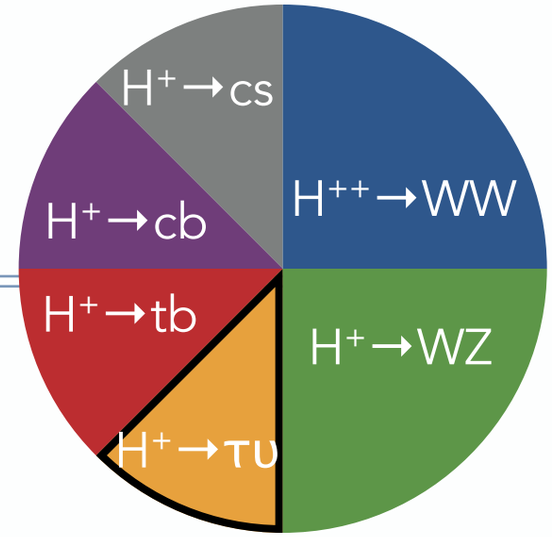






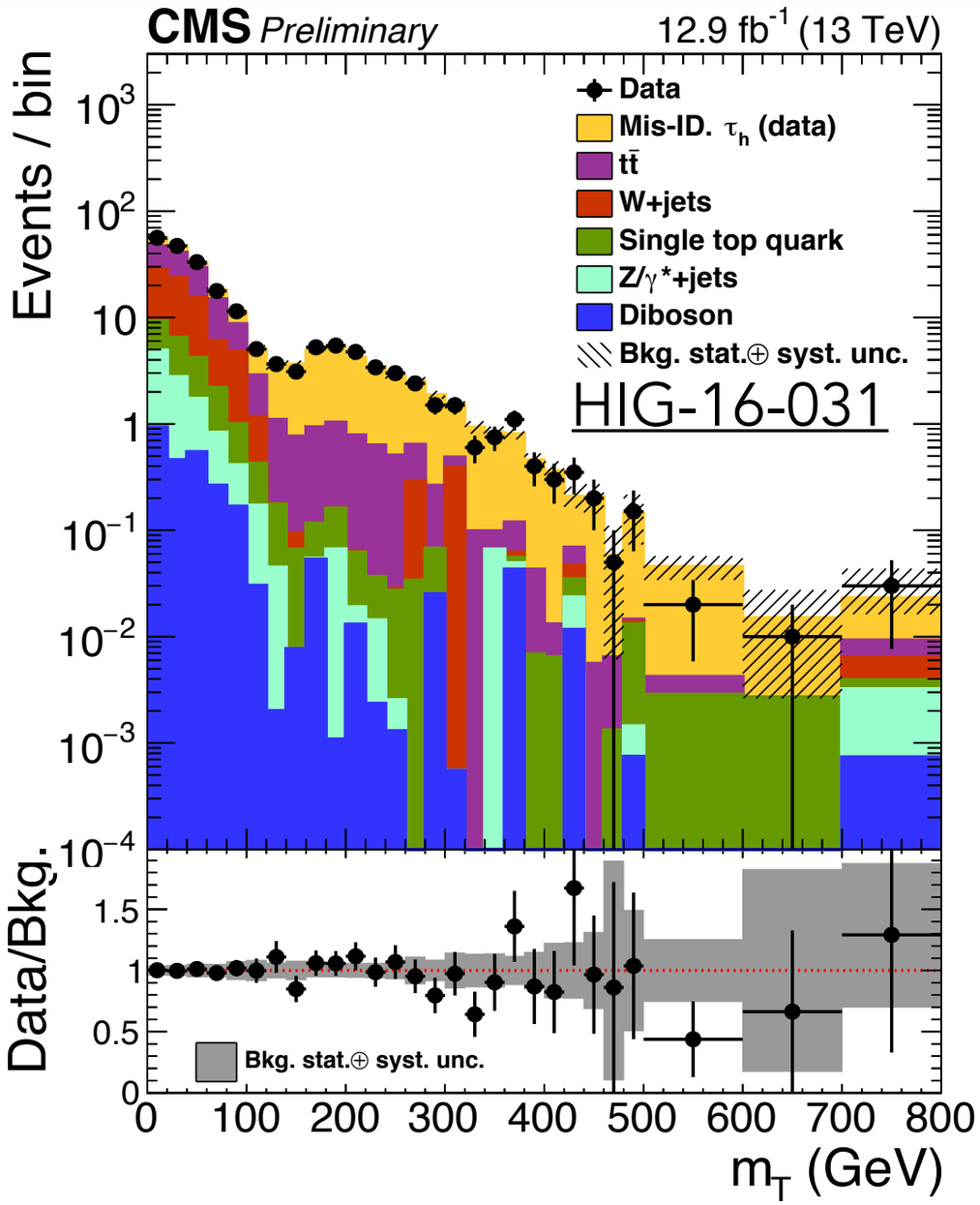
- Work on Run 2 dataset continues with improved analysis methods
  - Decreasing stat. uncertainties require good control of systematic effects

Run 2: $H^+ \to \tau\nu$



- Reconstruct the τν transverse mass in the fully hadronic final state:

$$m_{\mathrm{T}} = \sqrt{2 p_T^{\tau_{\mathrm{h}}} E_T^{\mathrm{miss}} \left(1 - \cos(\Delta\phi(E_T^{\mathrm{miss}}, \tau_{\mathrm{h}}))\right)}$$



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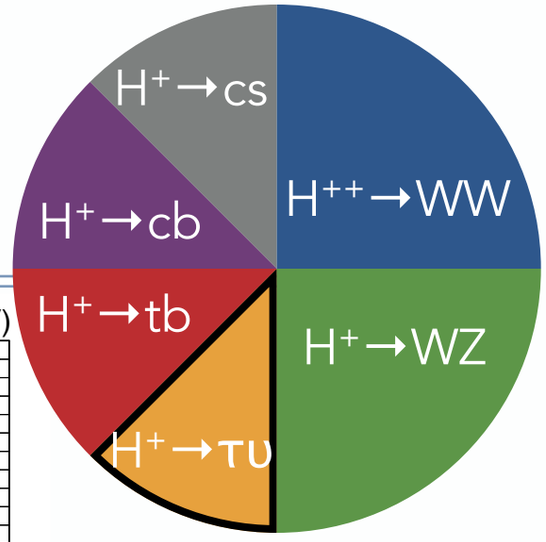

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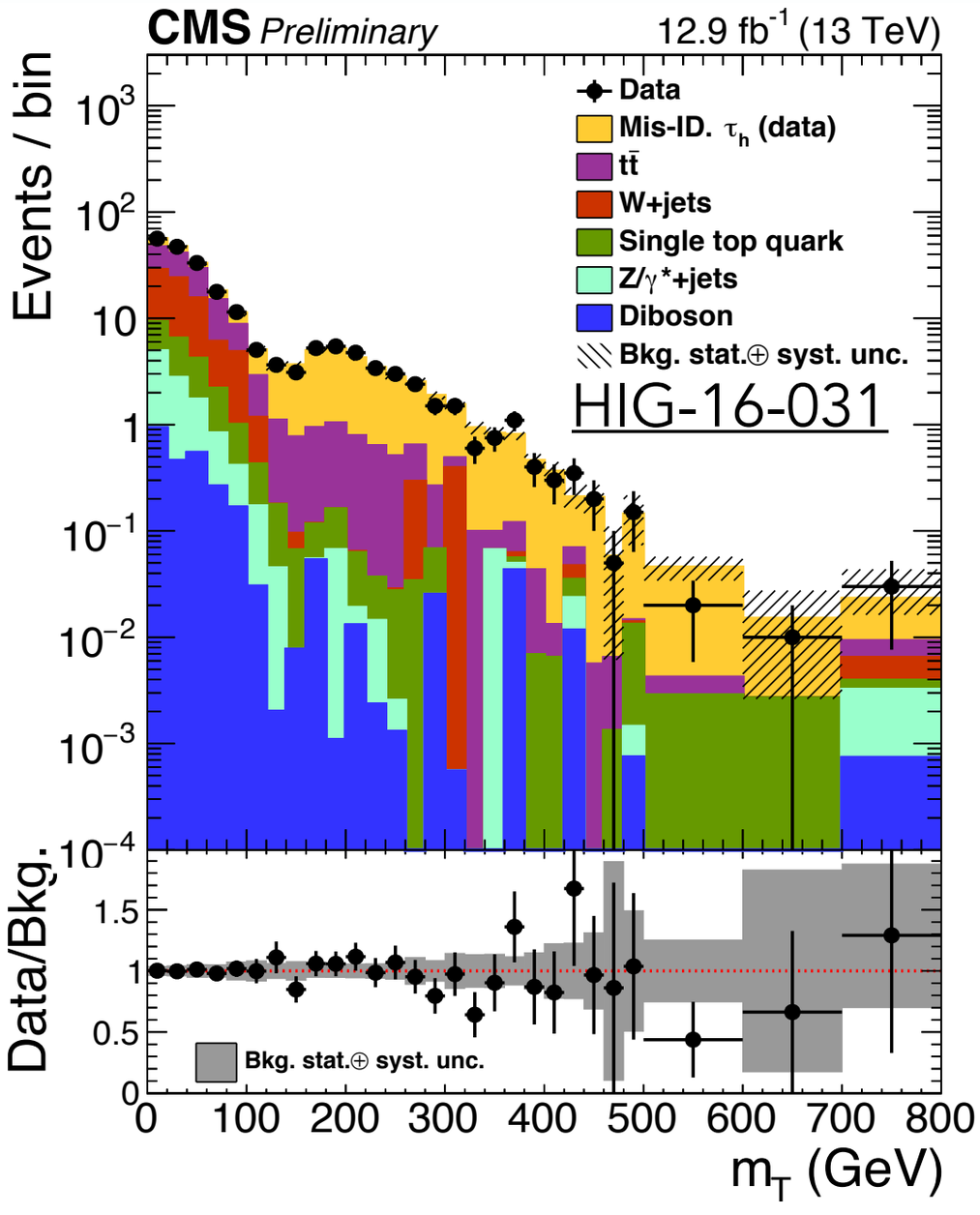
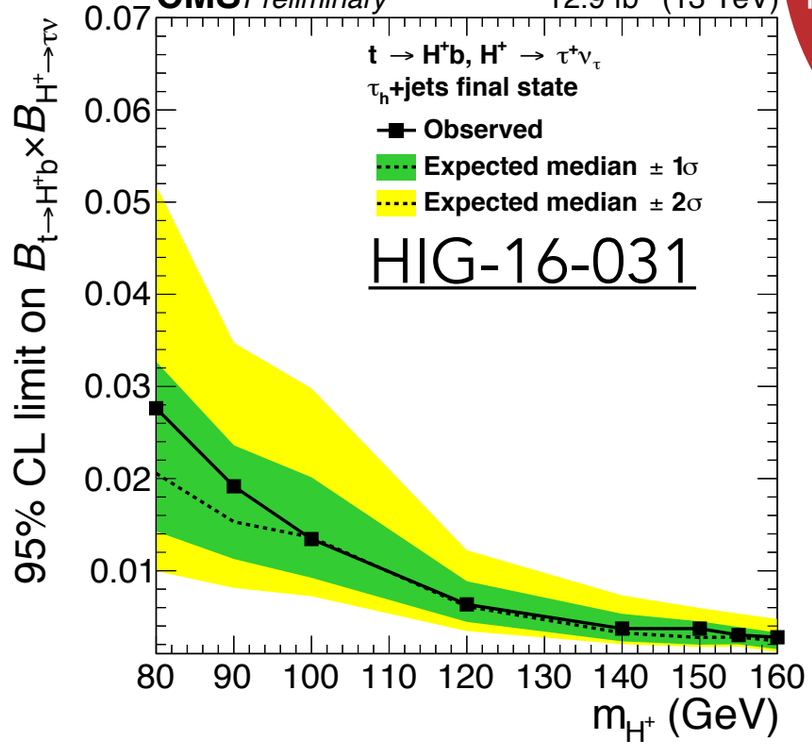
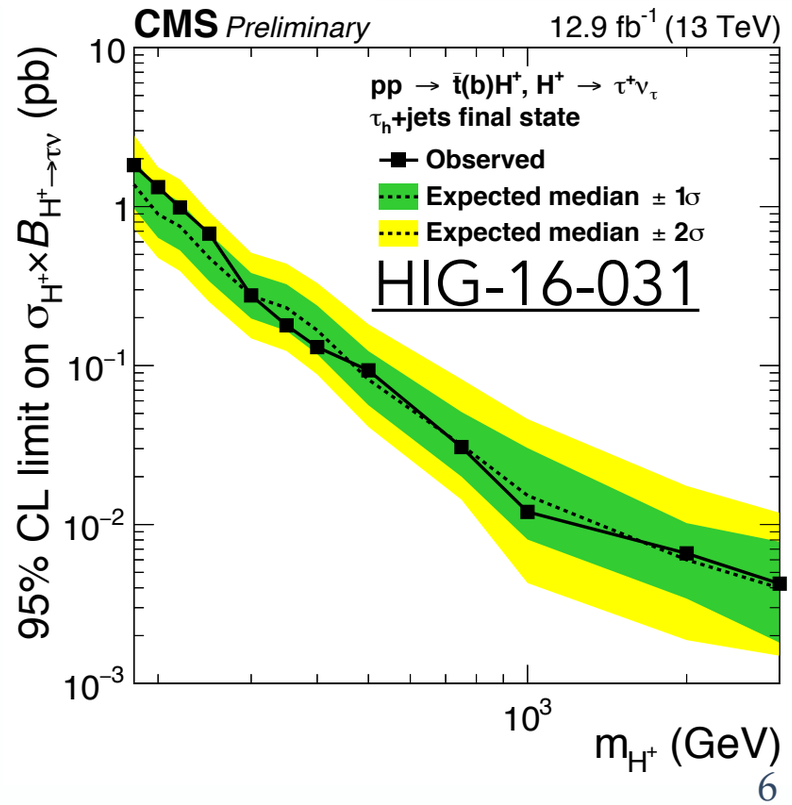
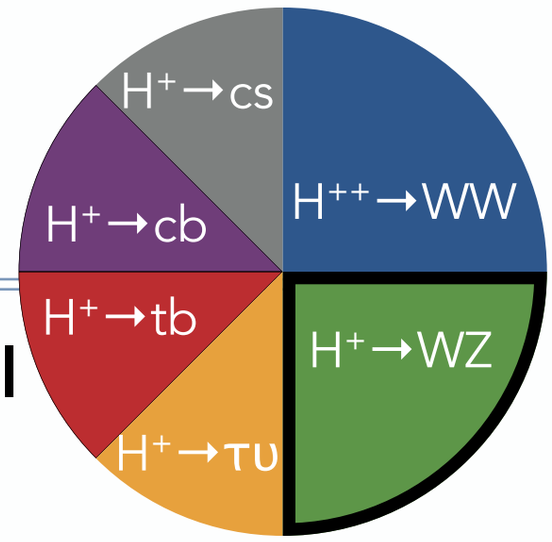




- Extract 95% CL limits by binned ML fit

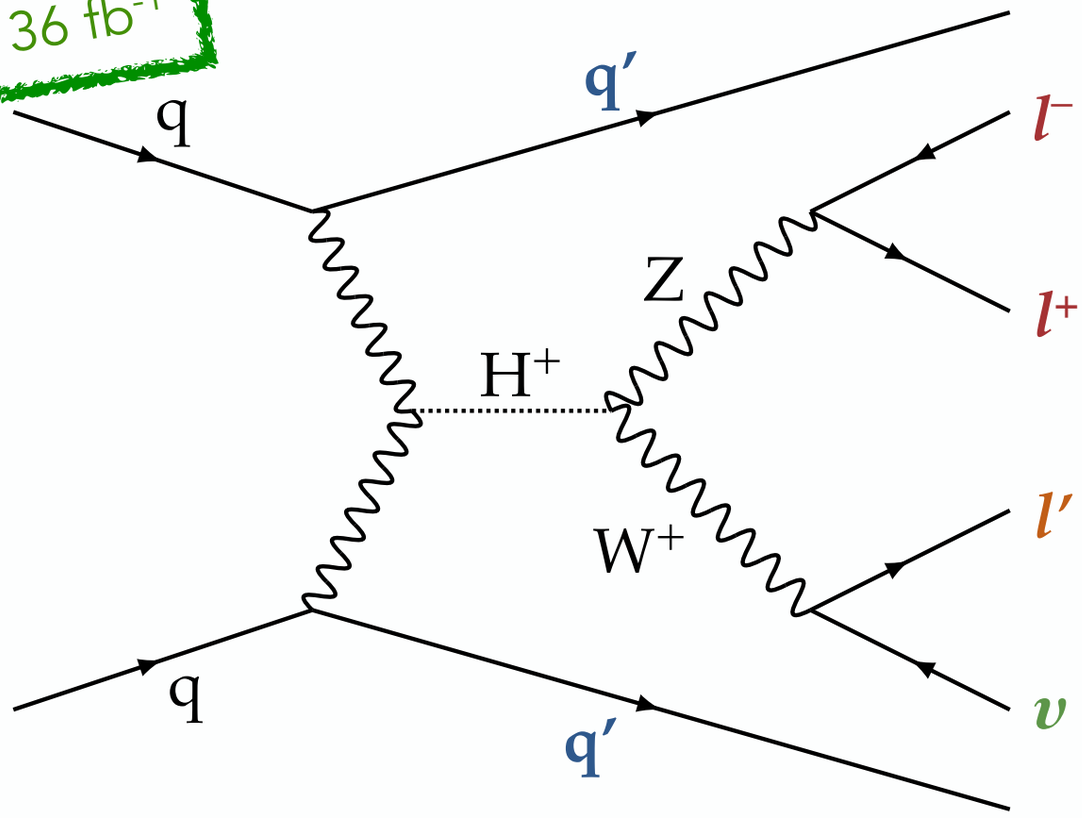


Triplet models: $H^+ \to WZ$



NEW
36 fb^{-1}

VBF H^+ production predicted by Georgi Machacek model



Event selection

- **Z**: ***l*⁺*l*⁻ pair**: $p_T > 25$ GeV (15 GeV), $|m_{ll}-m_Z| < 15$ GeV
- **W**: **3rd lepton *l'***, $p_T > 20$ GeV and $p_T^{miss} > 30$ GeV
- **Two AK4 jets:** $p_T > 30$ GeV, $|\eta|<4.7$, $\Delta R_{j,l}>0.4$, $m_{jj} > 500$ GeV, $\Delta\eta_{j1,j2}>2.5$,

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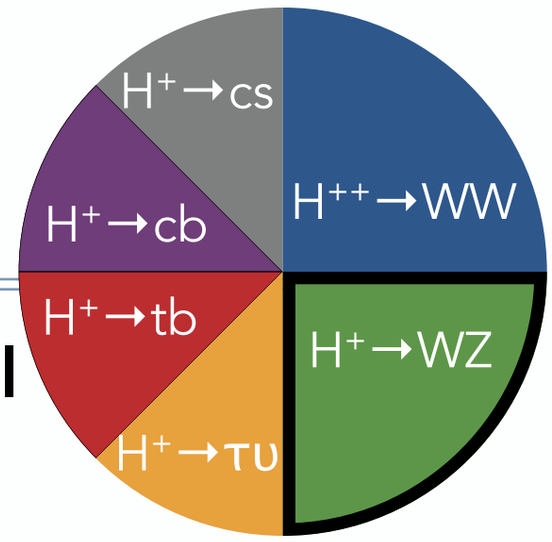

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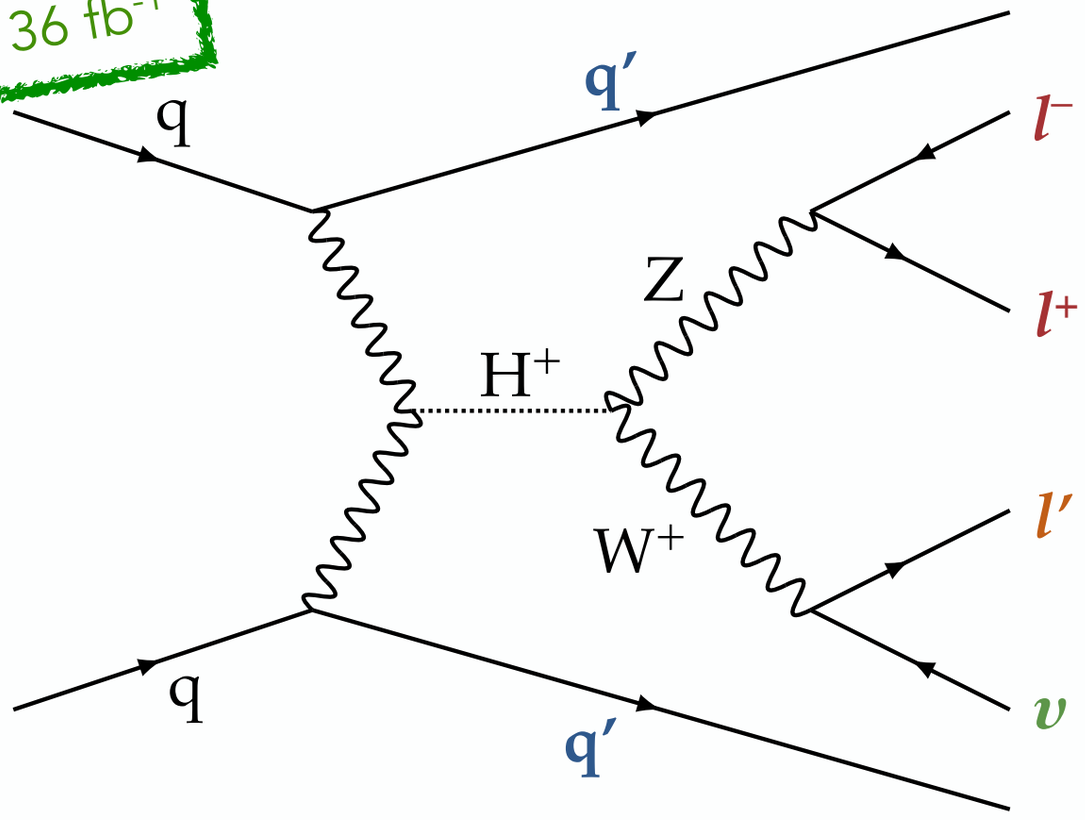

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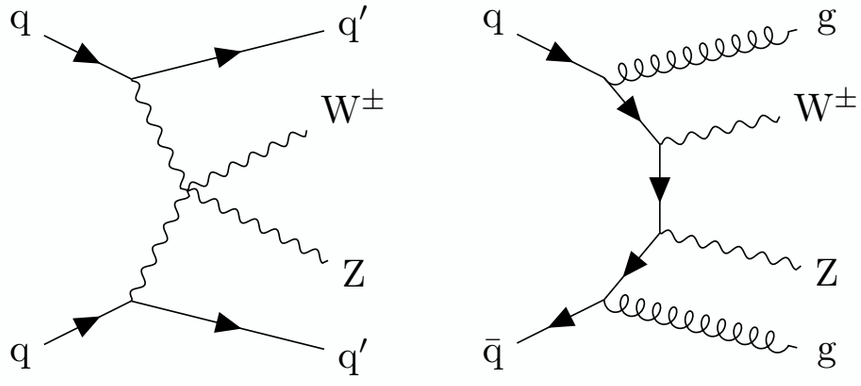
Additional selections to suppress backgrounds

- **4th lepton veto** (p_T > 10 GeV)
- **b jet veto** (p_T > 30 GeV, $|\eta|<4.7$) against $t\bar{t}$
- **m_{ll} > 4 GeV** (for all lepton pairs), against coll. emission and low-m_{ll} resonances
- **m_{3l} > 100 GeV** against Z+FSR

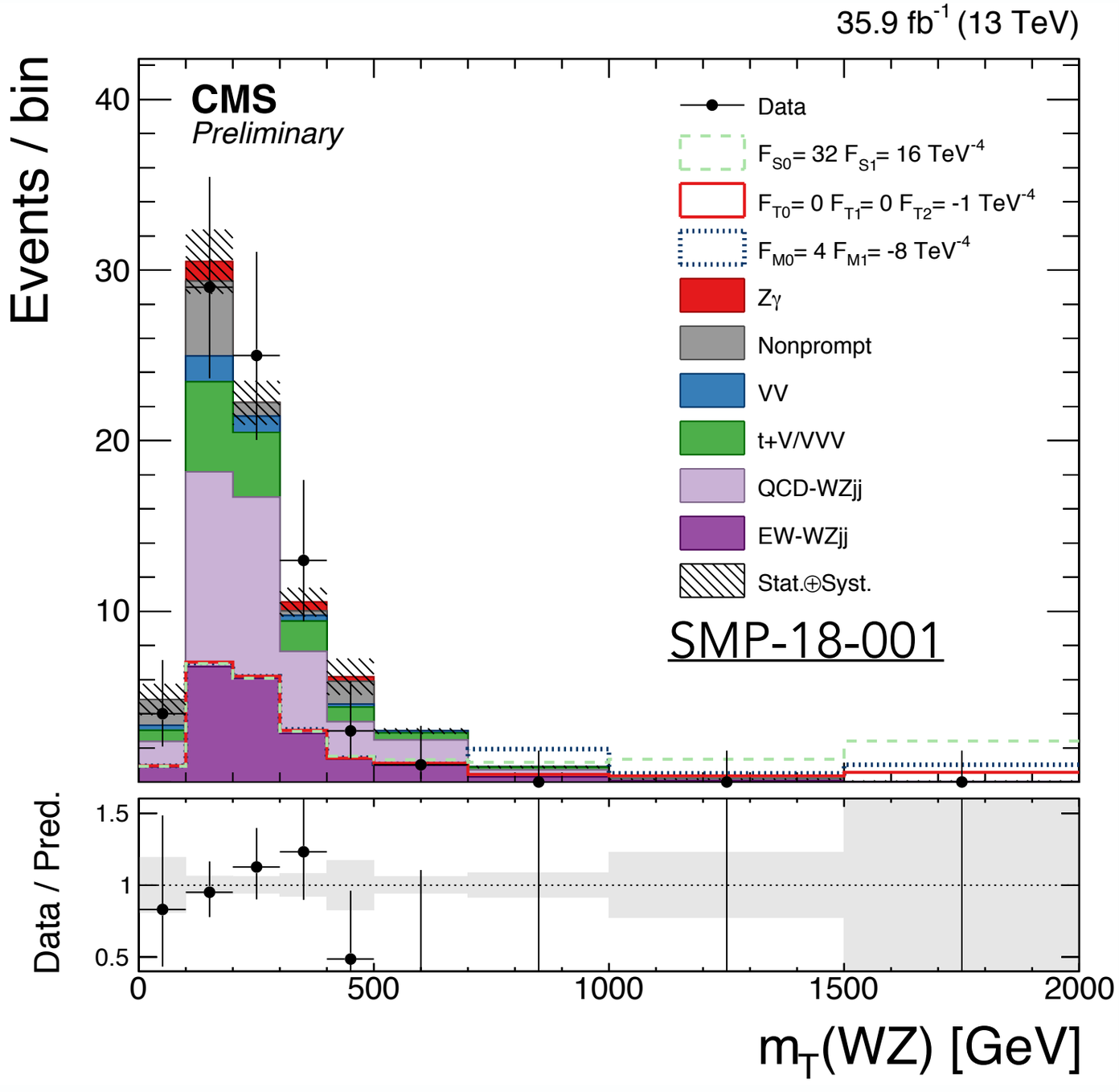


Irreducible backgrounds: SM WZjj

Triplet models: $H^+ \rightarrow WZ$

NEW 36 fb^{-1}

- Reconstruct WZ **transverse mass** $m_T^2(\mathrm{WZ}) = (E_T(\mathrm{W}) + E_T(\mathrm{Z}))^2 - (\vec{p}_T(\mathrm{W}) + \vec{p}_T(\mathrm{Z}))^2$
  → ML fit to extract limits on H^+ production cross section



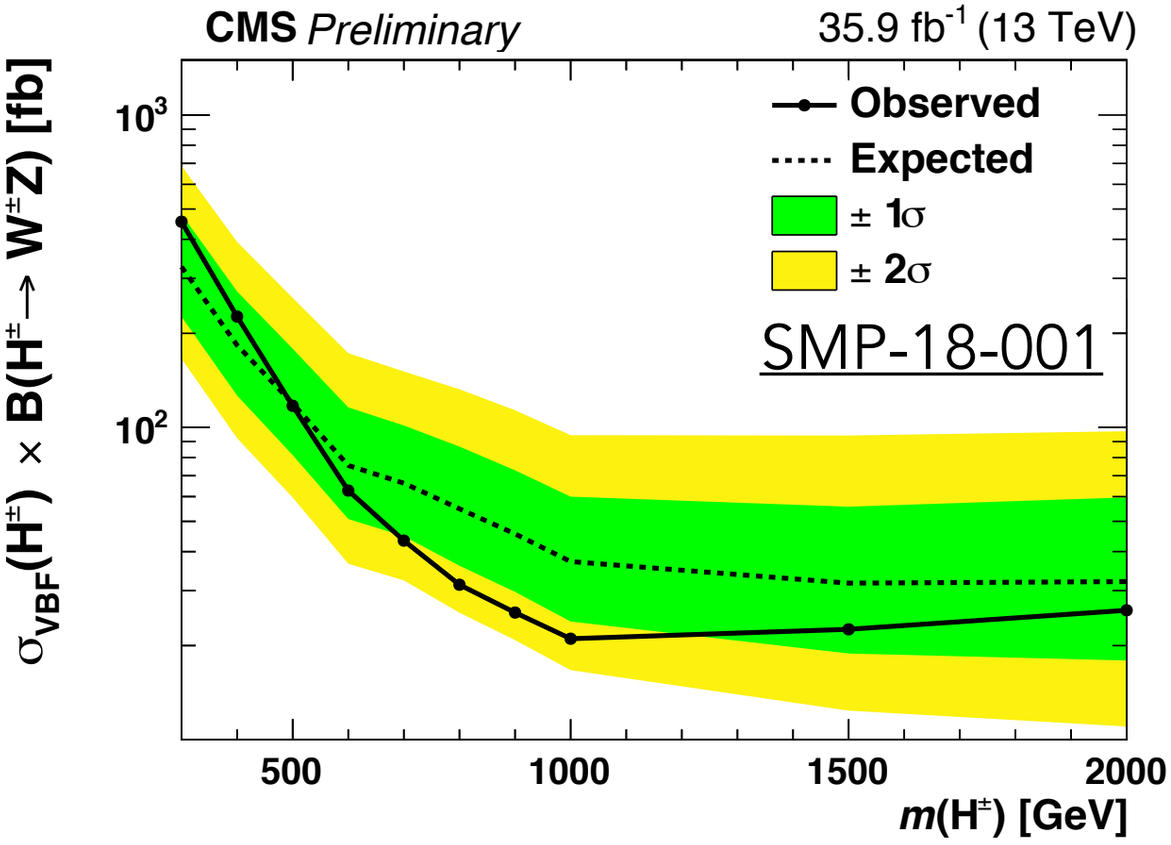
Background estimation

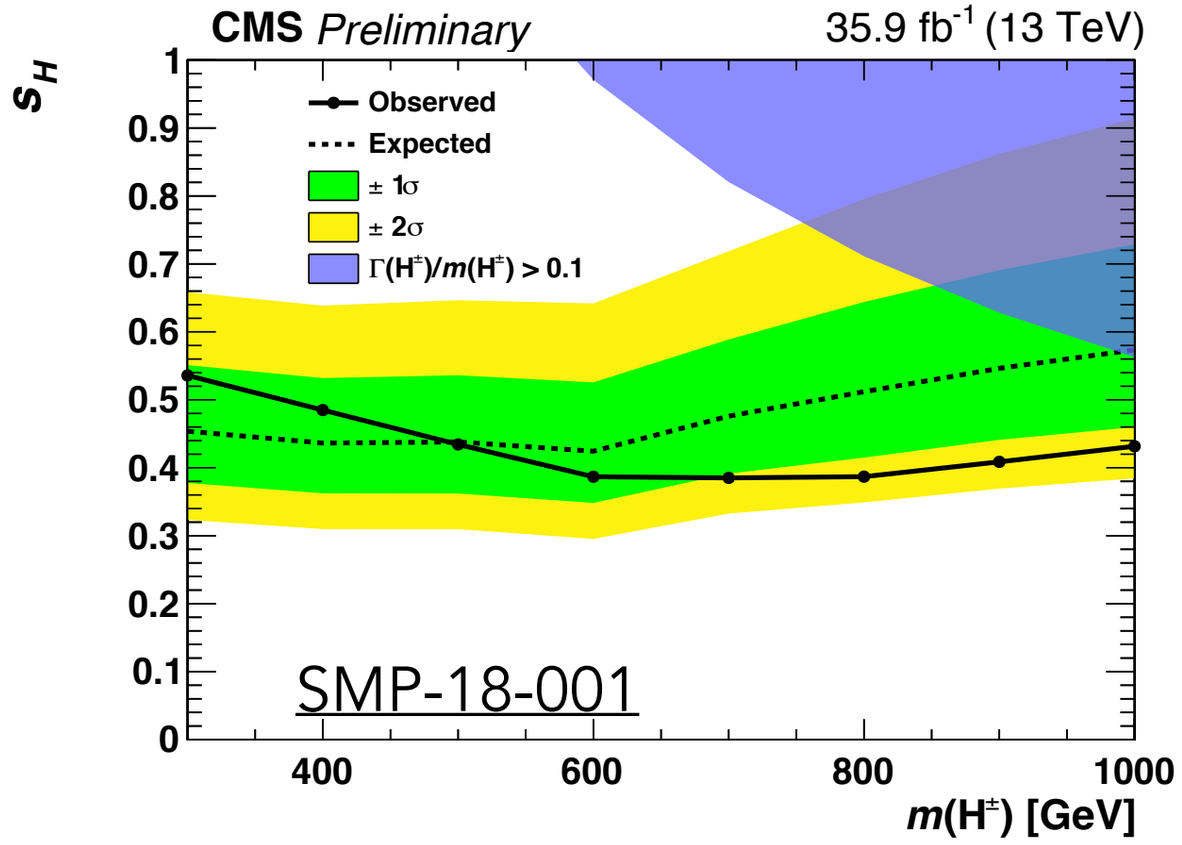
- **Prompt lepton backgrounds** (**EW/QCD WZjj**, **top**, **VV**, **Zγ**) estimated from **simulation**
  - **QCD WZjj**: normalization from a control region (mjj > 100 GeV and invert m_{jj} or $\Delta\eta_{j1,j2}$ cut)
- **Nonprompt lepton background** estimated from **data**

Limits also set on anomalous quartic gauge couplings in terms of **effective field theory** (EFT) operators

Triplet models: $H^+ \rightarrow WZ$

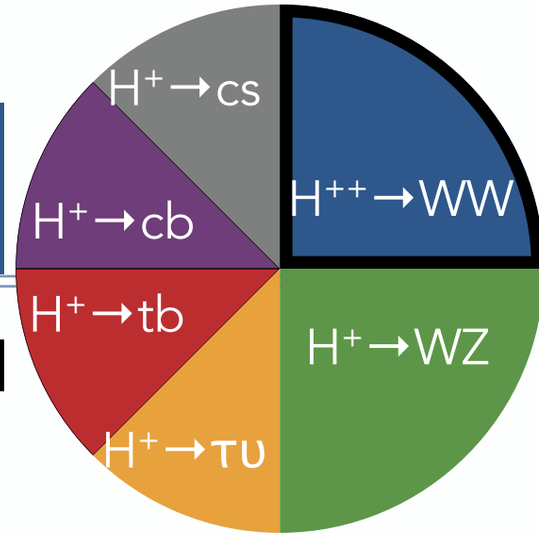
NEW 36 fb^{-1}





- 95% upper limits on $\sigma_{VBF} \times B(H^+ \rightarrow WZ)$ extracted using CL_s criterion
  - H^+ assumed to have a **narrow intrinsic width**
- Limits interpreted in **Georgi-Machacek model**, as a function of $\mathbf{m_{H+}}$ and $\mathbf{s_H}$
  - $\mathbf{s_H^2}$ is the W/Z mass fraction generated by VEV of the triplets
- **Blue region** not allowed theoretically

Triplet models: $H^{++} \rightarrow WW$



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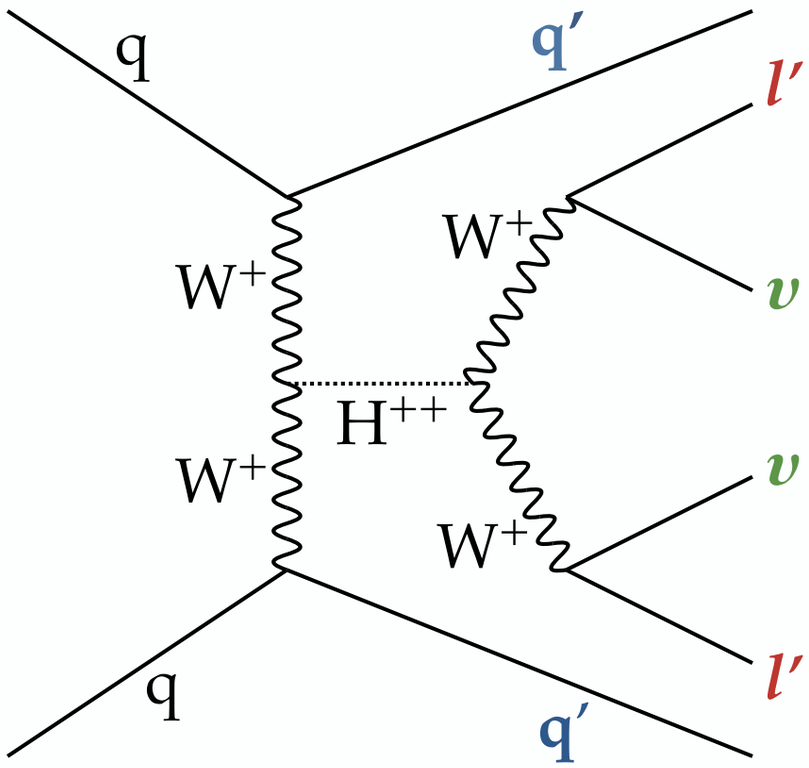
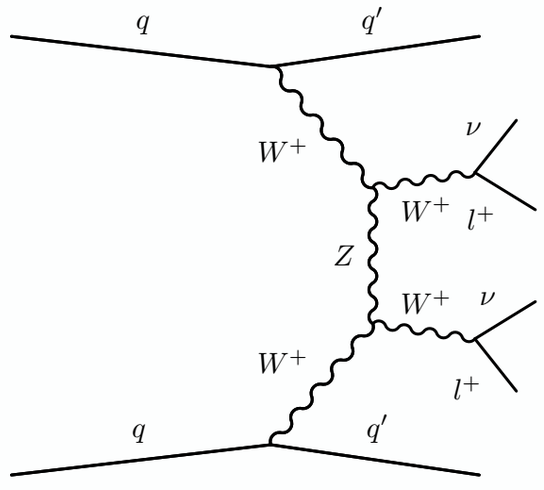


Event selection

- **Two isolated same-sign leptons**
  - p_T > 25 GeV or p_T >20 GeV
  - $|\eta|$ < 2.5 (2.4) for electrons (muons)
- p_T^{miss} **> 40 GeV**
- **Two AK4 jets** (p_T > 30 GeV, $|\eta|$<5) and m_{jj} > 500 GeV
- $\max(z_l^*) < 0.75$, $z_l^* = |\eta_l - (\eta_{j1}+\eta_{j2})/2| / |\Delta\eta_{j1j2}|$



Irreducible background:
SM W^+W^+ production

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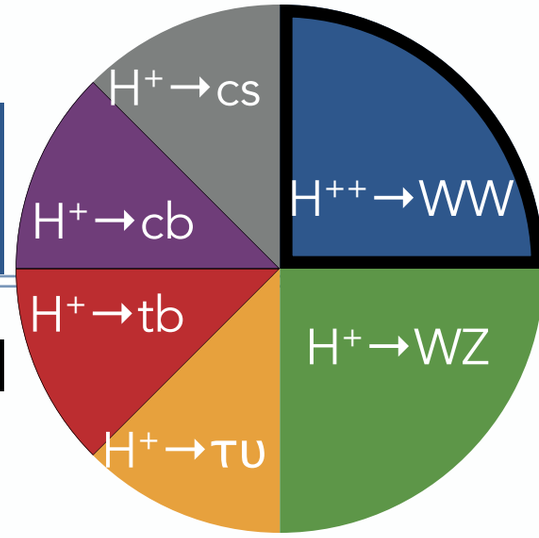

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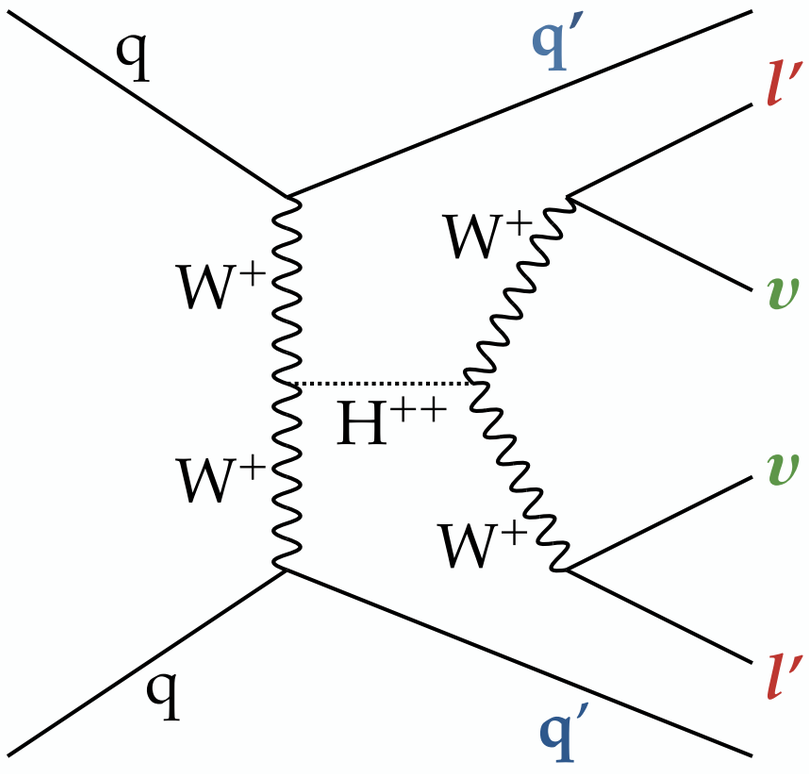

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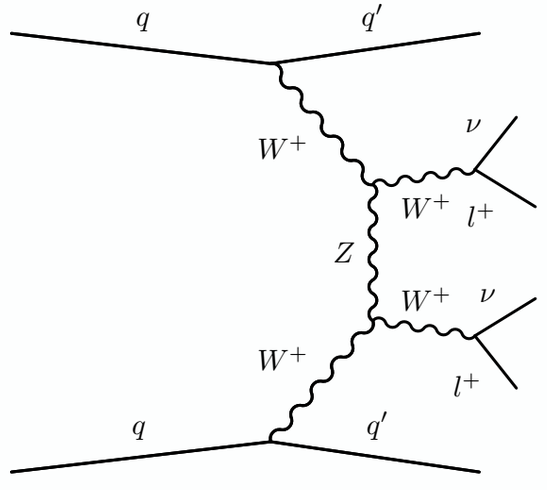
Additional selections to suppress backgrounds

- **m_{ll} > 20 GeV** against nonprompt leptons
- **b jet veto** against $t\bar{t}$
- **Z veto** ($m_{ll}-m_Z$ > 15 GeV) against Drell-Yan
- **3rd lepton veto** (p_T > 10 GeV) against WZ
- **τ_h veto** (p_T > 18 GeV) against WZ



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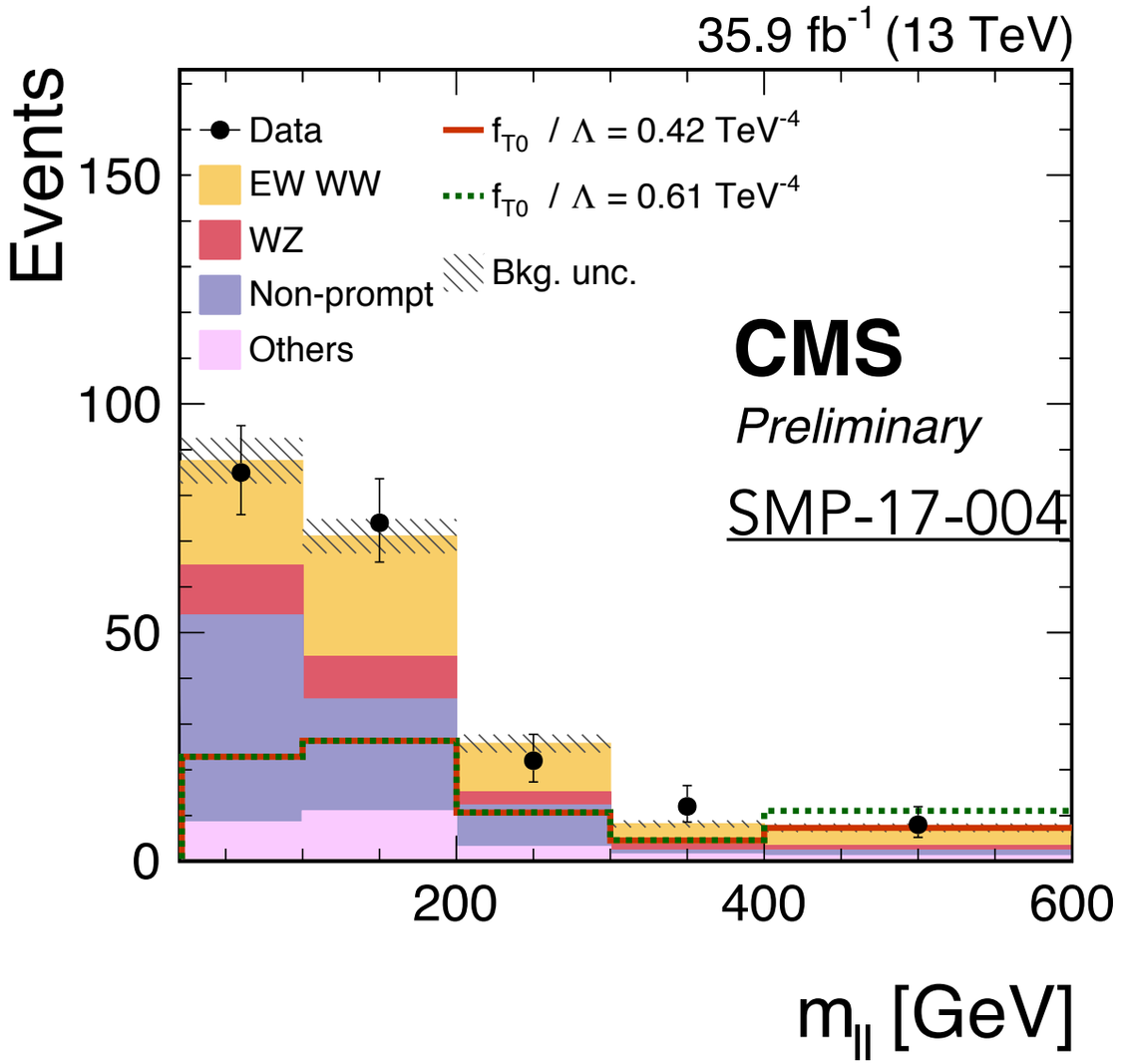
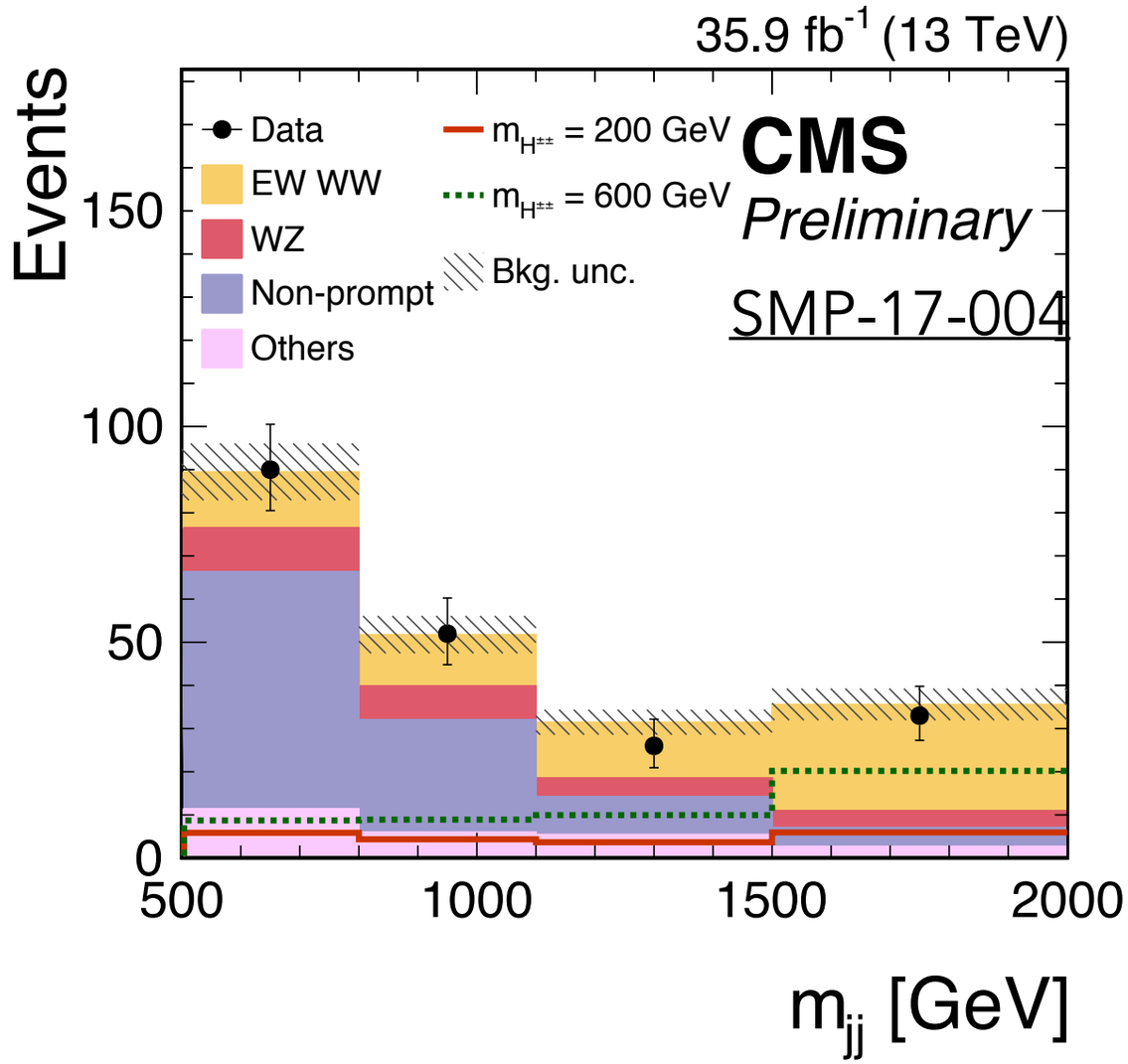
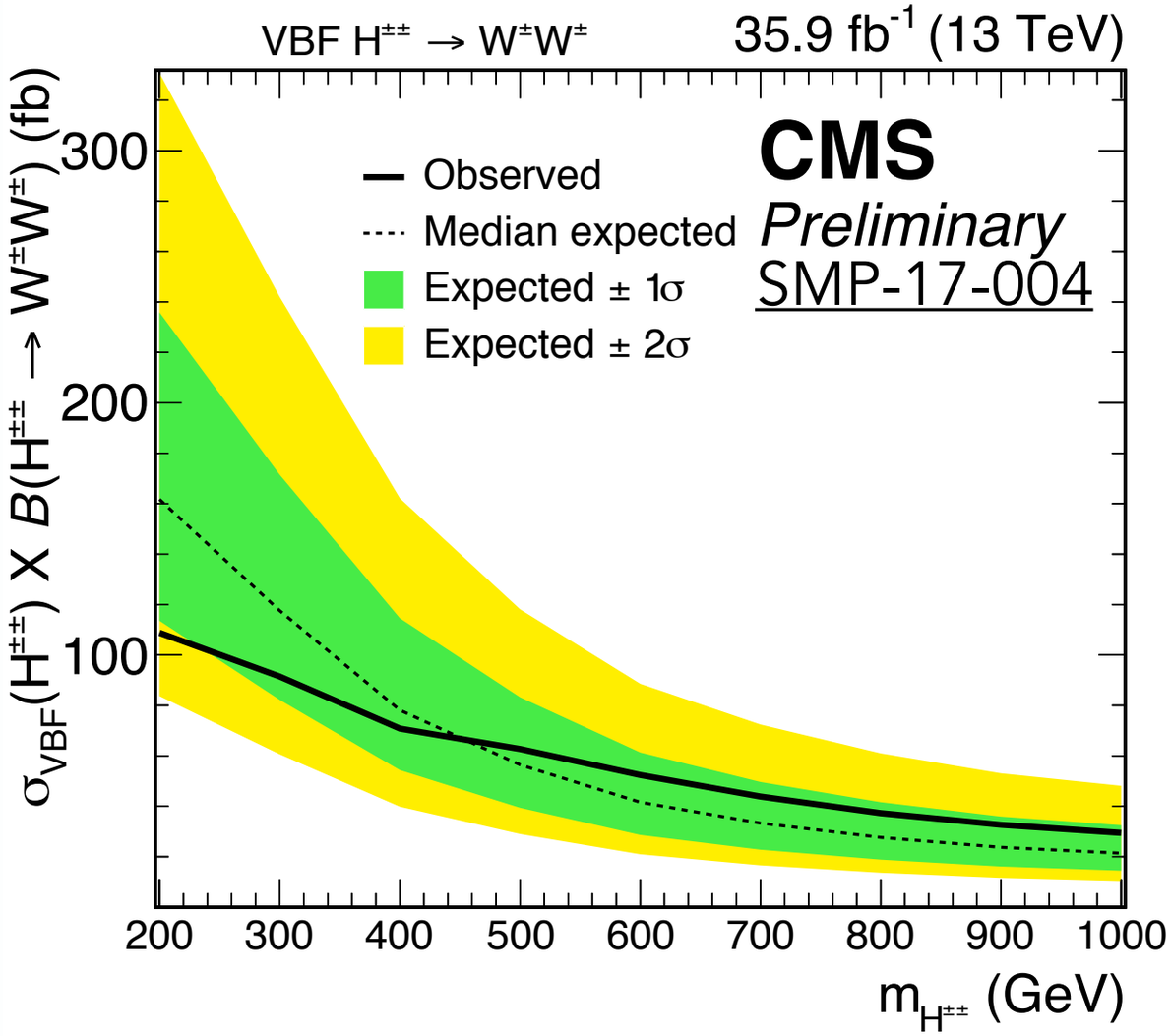




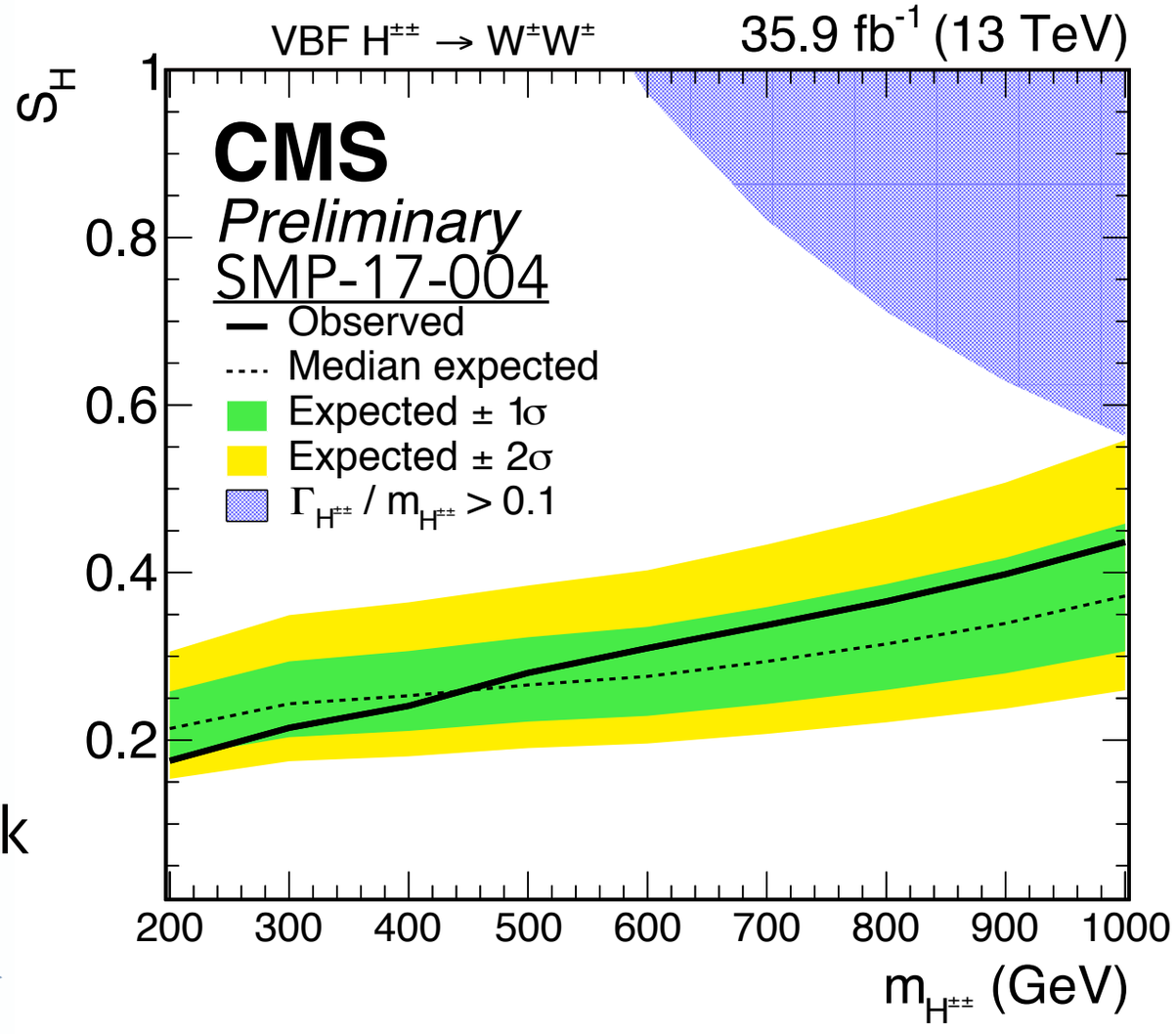
- **Simultaneous fit to (m_{ll},m_{jj})** 2D distribution **and m_{jj} in WZ control region**
- Non-prompt lepton background estimated from **data**
- WW, WZ and other backgrounds from **simulation** (corrections from data)
  - WZ normalized using **WZ control region** (3 leptons, $|m_{ll} - m_Z| < 15$ GeV)

Triplet models: $H^{++} \rightarrow WW$

36 fb^{-1}



- 95% model-independent limits extracted using CL_s criterion

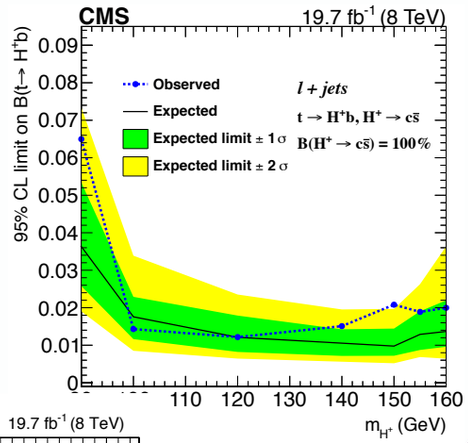


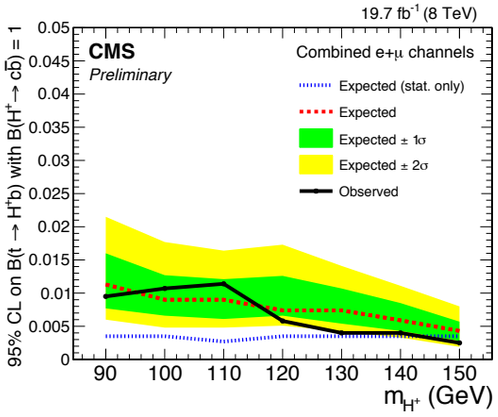
- Limits interpreted in Georgi-Machacek model, as a function of m_{H++} and s_H

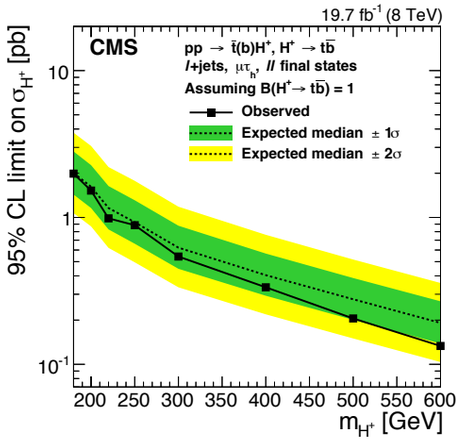
- **Blue region** not allowed theoretically

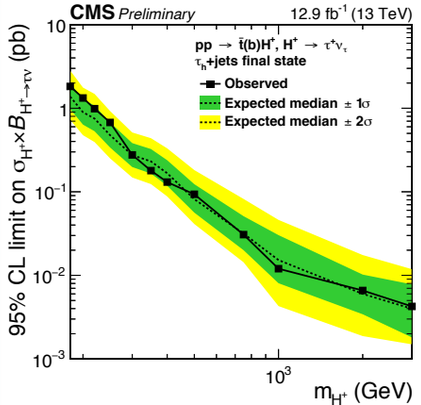
Summary

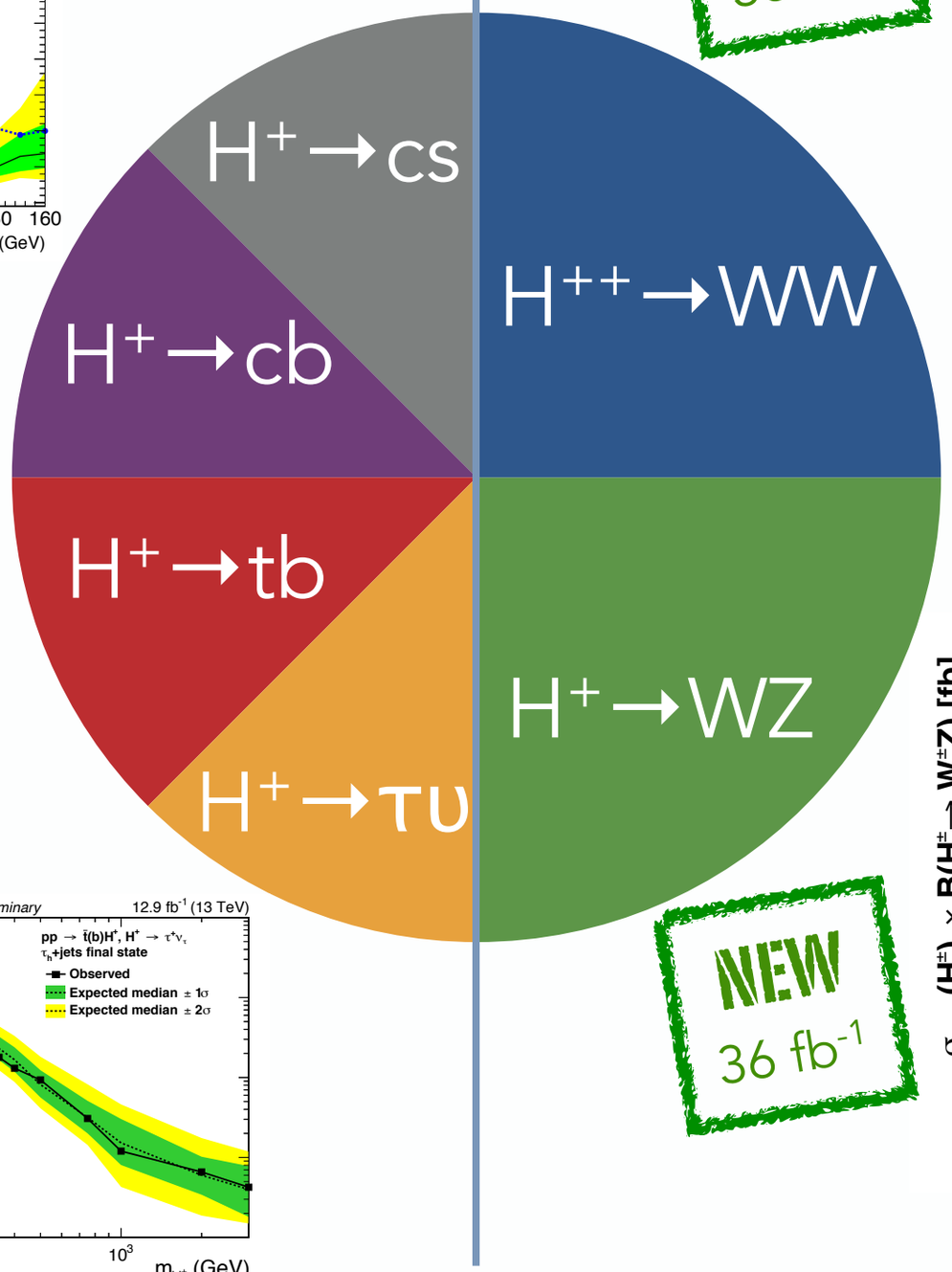
Doublet models





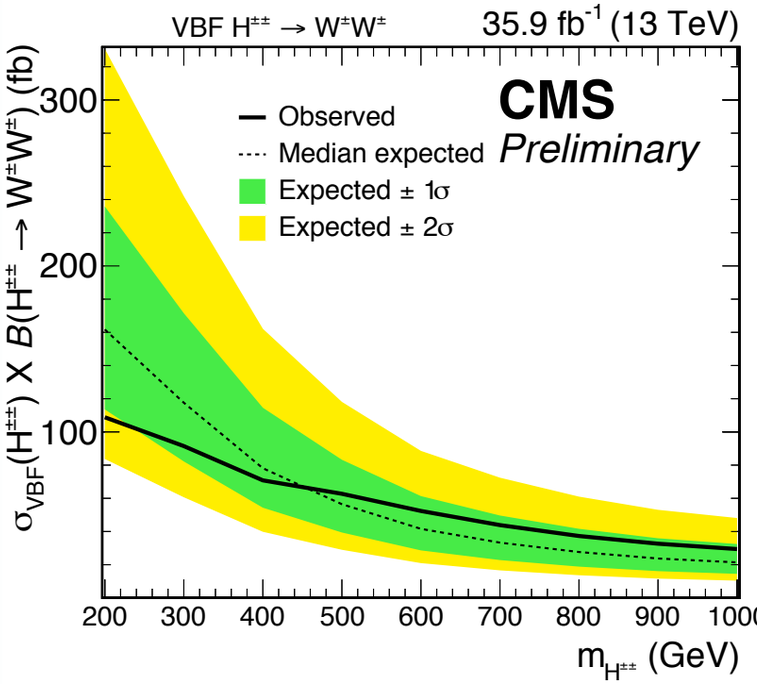




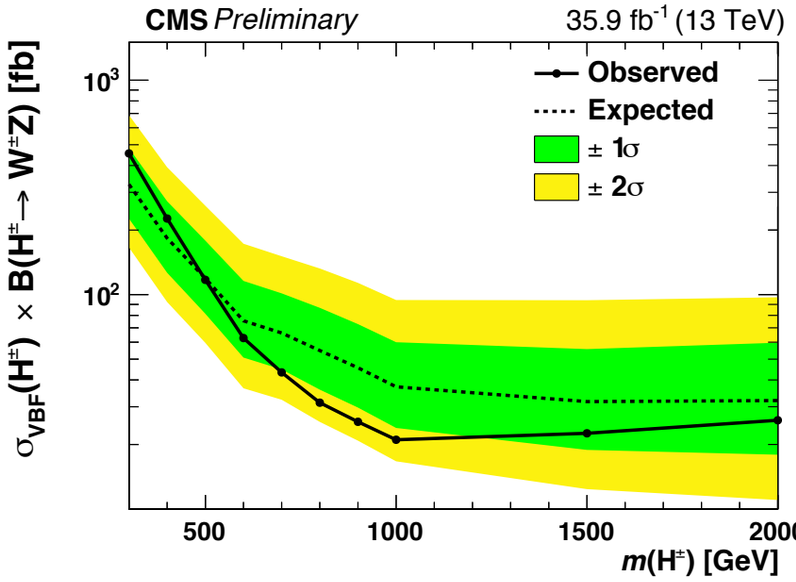


Triplet models

36 fb-1

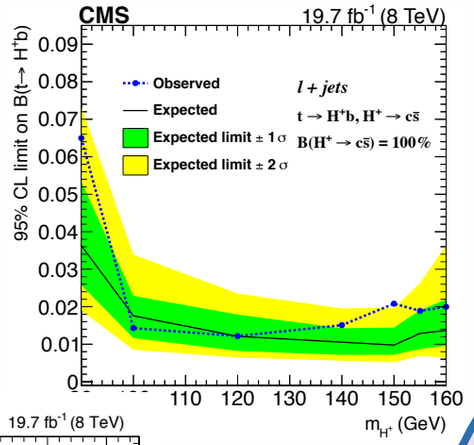


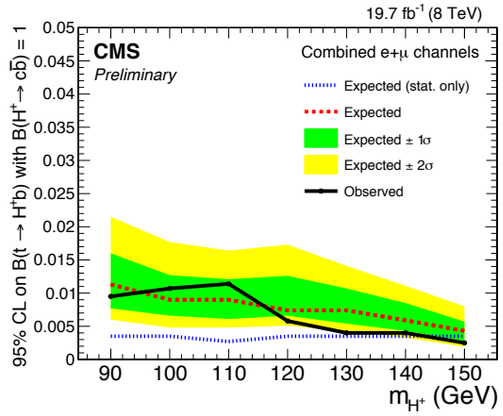
NEW
36 fb-1

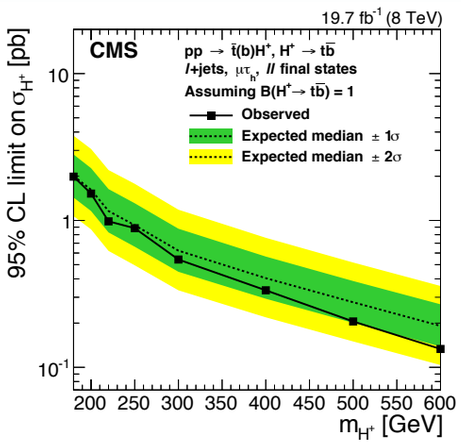


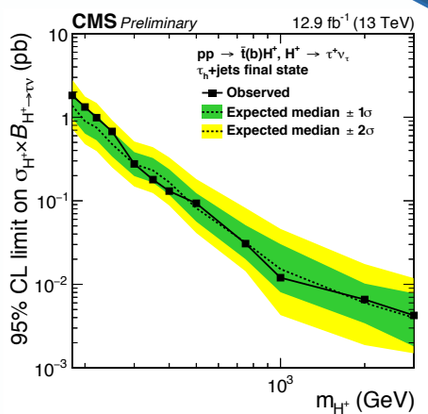
Summary

Doublet models



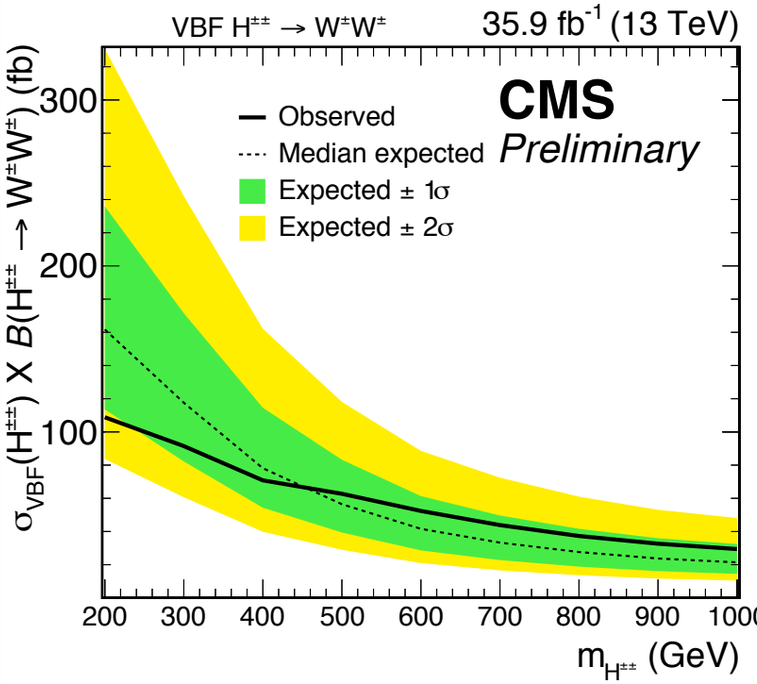




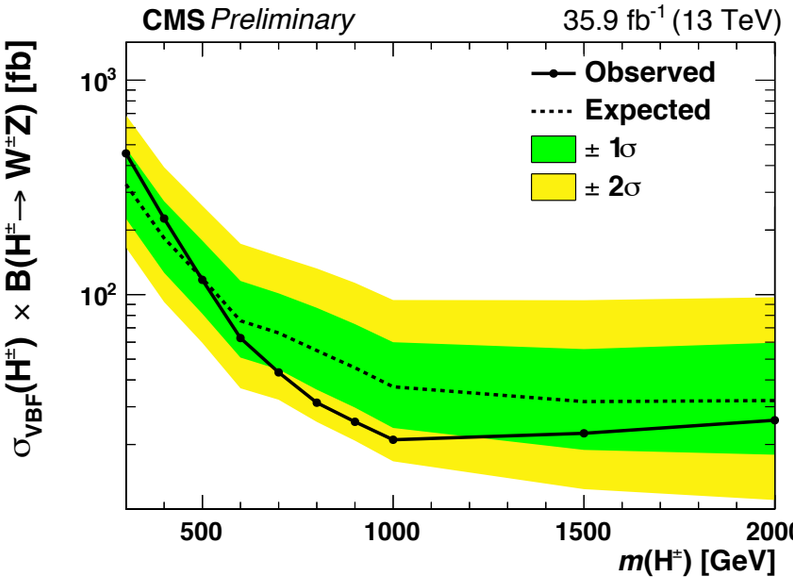


Triplet models

36 fb^{-1}



NEW
36 fb^{-1}



Run 2 continues…

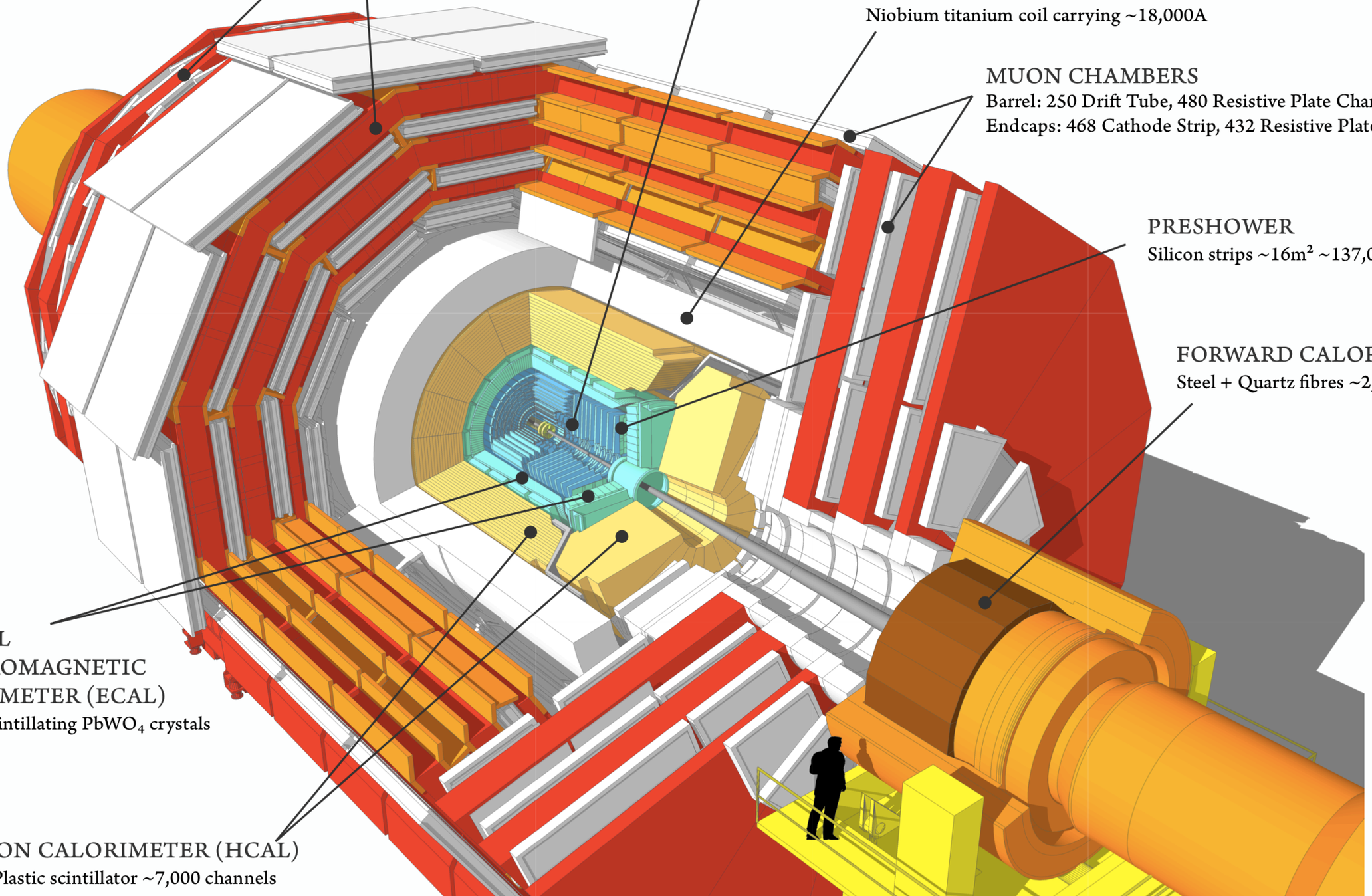
More H$^+$ results will follow!

Back-up slides

CMS detector

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 (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels

SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A

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

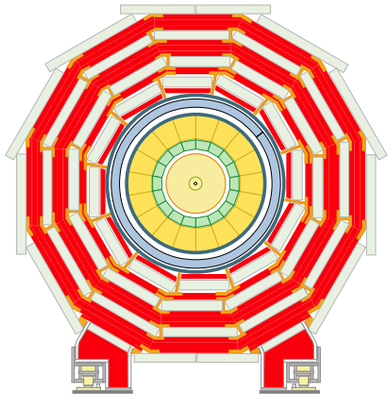
PRESHOWER
Silicon strips ~16m² ~137,000 channels

FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels

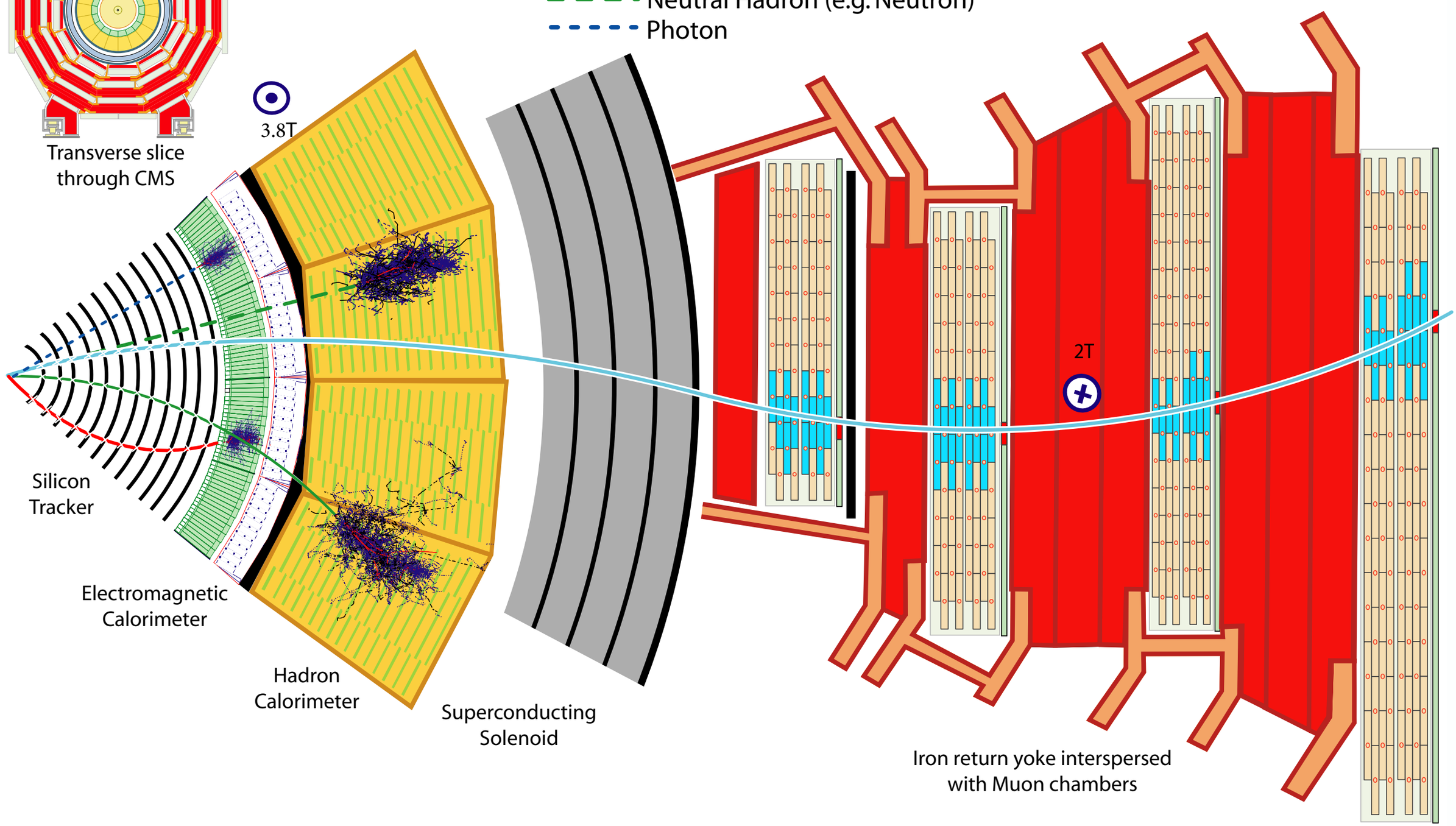
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating $PbWO_4$ crystals

HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

CMS detector



Transverse slice through CMS



Georgi-Machacek model

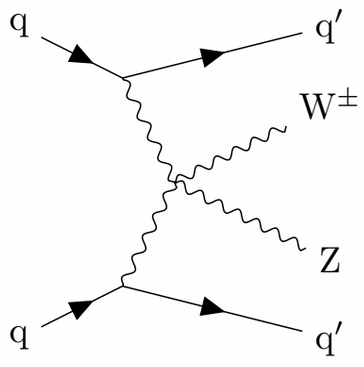
- Scalar sector of the Standard Model (SM) is extended by **addition of one complex and one real SU(2) triplet**
  - H. Georgi and M. Machacek, Nucl. Phys. B 262, 463 (1985)
- **A custodial SU(2) symmetry** is imposed upon the scalar potential, so that **ρ=1 is at tree level**
  → agreement with EWK precision data

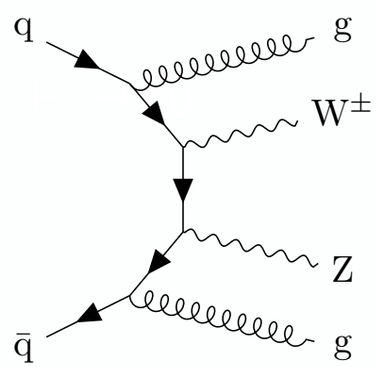
$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 + \dots$$

- Model used as implemented in MG5_aMC –
  - Doublet and triplet VEVs constrained to obtain the observed W and Z masses

$H^+ \rightarrow WZ$: Trigger & background estimation

Trigger: OR of single lepton and dilepton triggers, ~100% efficiency





Normalization of QCD WZjj background

- Normalization from **control region**, (10% syst. uncert)

Nonprompt lepton background measurement

- ”Nonprompt lepton” = a **lepton inside jets** or a **jet mis-id. as an isol. lepton**
- Tight-to-loose method:
  - **Select control sample of leptons with loose ID/isolation** requirements
  - **Estimate the probability** that a loose lepton is misidentified as a tight one using a **dijet sample enriched in nonprompt leptons**
  - **Apply** this probability (as a function of **lepton flavor, p_T, η**) to control sample to estimate the resulting contribution to the signal region
- Method **validated** in tt and Drell-Yan enriched control regions
  → **30% syst. uncertainty**

$H^+ \rightarrow WZ$: Systematic uncertainties

- **Jet energy scale** and jet **energy resolution**
- **QCD RF scale** & **PDF** uncertainties for simulated (prompt lepton) backgrounds
- **QCD WZjj normalization** (10%)
- **Nonprompt lepton background normalization** (30%)
- **Statistical uncertainty of control sample** for nonprompt lepton background estimation
- **Lepton energy scale** and **efficiency** (~3%)
- **Luminosity** (2.5%)
- **b mistagging** probability
- **p_T^{miss} energy scale**
- **Pileup** reweighting
- **Lepton ID/isolation** efficiency
- **Trigger** efficiency

$H^{++} \rightarrow WW$: Background estimation

Trigger: OR of single lepton and dilepton triggers, ~100% efficiency

Nonprompt lepton background measurement

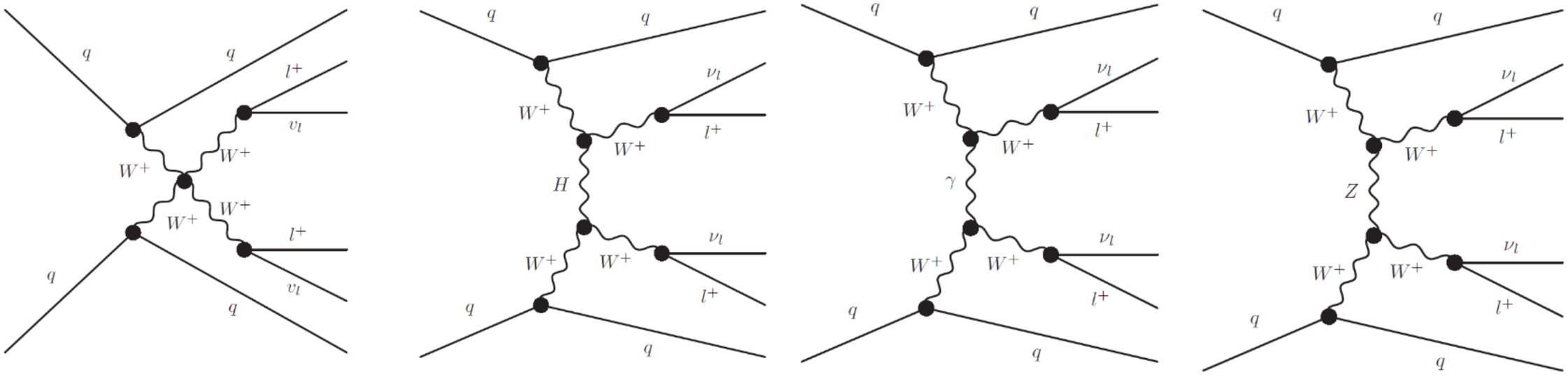
- Using tight-to-loose method

Charge misassignment background

- Probability from simulation + scale factors to data

Normalization of (simulated) WZ background

- Using the WZ control region, derive scale factors as a function of mjj



$H^{++} \rightarrow WW$: Systematic uncertainties

source	EW WW	QCD WW	DPS WW	ZZ	WZ	Wrong sign	VVV	Non-prompt	Wγ
Luminosity	2.5	2.5	2.5	2.5	-	2.5	2.5	-	2.5
Lepton efficiency	3.6	3.6	3.6	3.6	-	3.6	3.6	-	3.6
Momentum resolution	1.0	1.0	1.0	1.0	-	1.0	1.0	-	1.0
Trigger efficiency	1.0	1.0	1.0	1.0	-	1.0	1.0	-	1.0
Pile-up	0.5-2.0	0.5-2.0	0.5-2.0	0.5-2.0	-	0.5-2.0	0.5-2.0	-	0.5-2.0
b-tagging	0.5-3.0	0.5-3.0	0.5-3.0	0.5-3.0	-	0.5-3.0	0.5-3.0	-	0.5-3.0
JES	1.0-7.0	1.0-7.0	1.0-7.0	1.0-7.0	-	1.0-7.0	1.0-7.0	-	1.0-7.0
JER	1.0-3.0	1.0-3.0	1.0-3.0	1.0-3.0	-	1.0-3.0	1.0-3.0	-	1.0-3.0
PDF	1.0-5.0	1.0-5.0	1.0-5.0	1.0-4.0	-	-	-	-	-
EWK-QCD interference	1.0-4.0	-	-	-	-	-	-	-	-
QCD scales EWK	3.0-12.0	-	-	-	-	-	-	-	-
QCD scales VVV	-	-	-	-	-	-	10-25.0	-	-
QCD scales ZZ	-	-	-	3.0-10.0	-	-	-	-	-
WZ normalization	-	-	-	-	20.0-40.0	-	-	-	-
Wrong sign normalization	-	-	-	-	-	1.0-3.0	-	-	-
Non-prompt normalization	-	-	-	-	-	-	-	30.0	-
Statistics	2.0-7.0	10.0-20.0	15.0-70.0	1.0-17.0	1.0-15.0	7.0-60.0	10.0-70.0	10.0-90.0	30.0-90.0