Searches for Charged Higgs Bosons at CMS

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CMS Collaboration

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Motivation

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- The SM has only one Higgs boson, but we know SM is not the final word
  - Motivation for an extended model is broad: **hierarchy problem, dark matter**, **baryon asymmetry & CP violation**, **neutrino masses**…
  - H_{125} constrains but allows a more complex Higgs sector
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  → **5 different Higgs bosons**
    - Neutral, CP-even **h** (light) and **H** (heavier)
    - Neutral, CP-odd **A**
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CP-conserving 2HDMs without FCNCs

Type I (Fermiophobic) $\Phi_1^d \Phi_2^u$

Type II (MSSM-like) $\Phi_{1_e}^d \Phi_2^u$

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$H^{\pm}$ Production at the LHC

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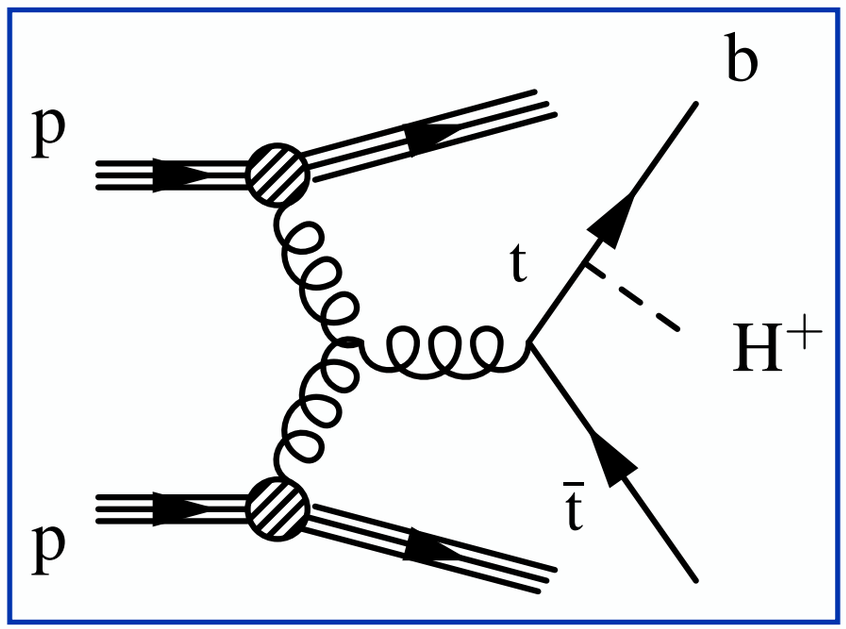

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"**diresonant**"
top production

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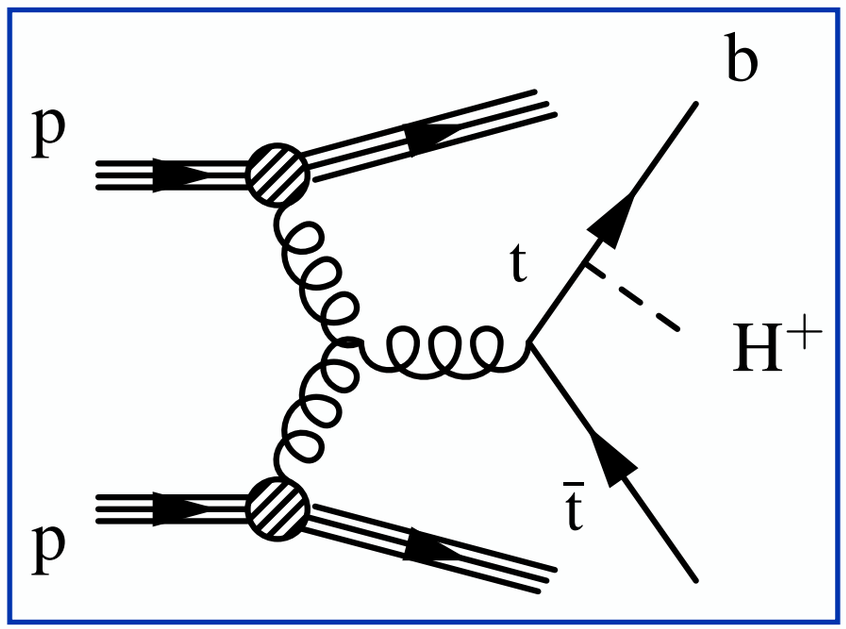

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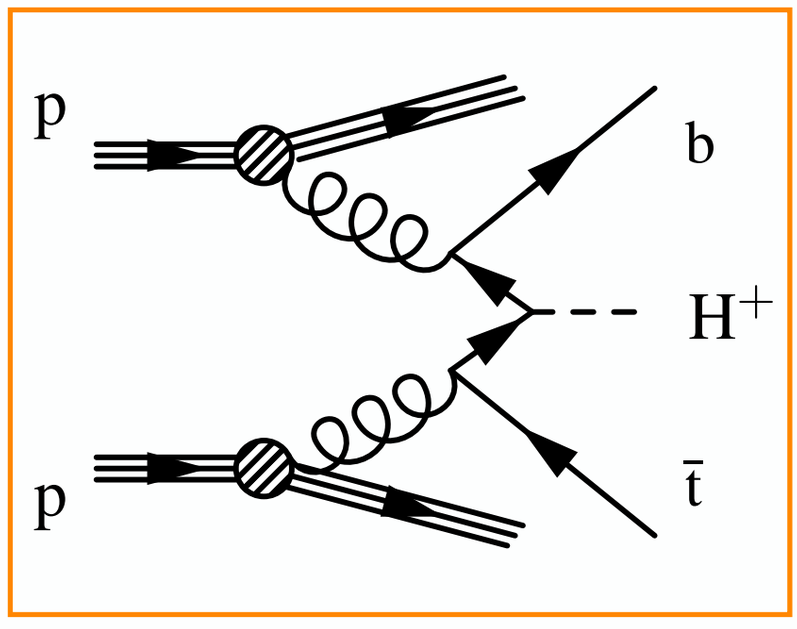

Heavy $H^{\pm}$ ($m_{H+} > m_t - m_b$):
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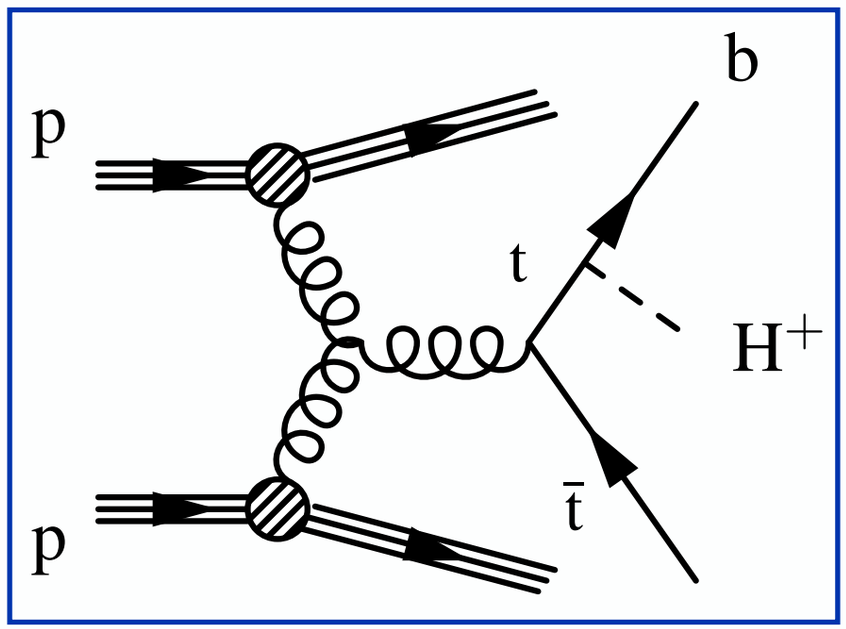

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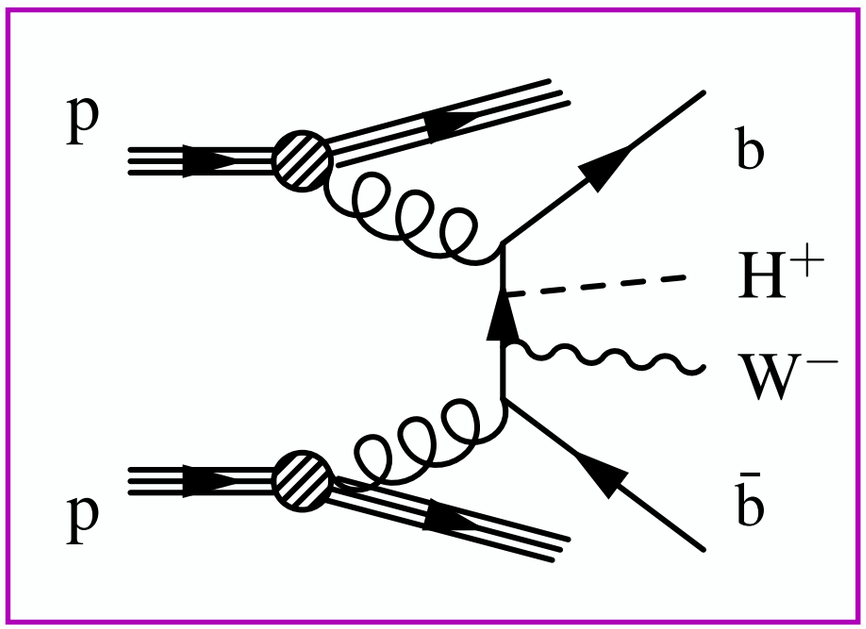
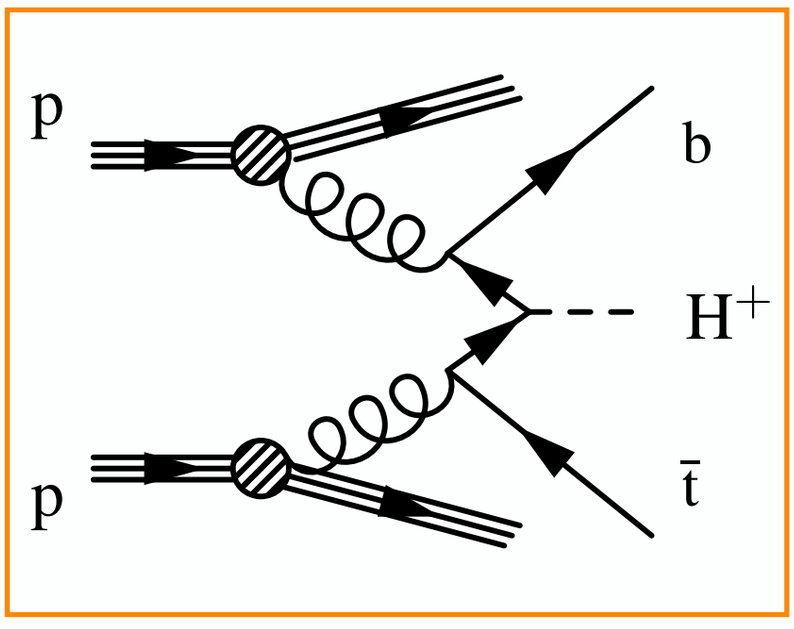


Intermediate $H^{\pm}$ ($m_{H+} \sim m_t$):
interference with the
"**nonresonant**" mode



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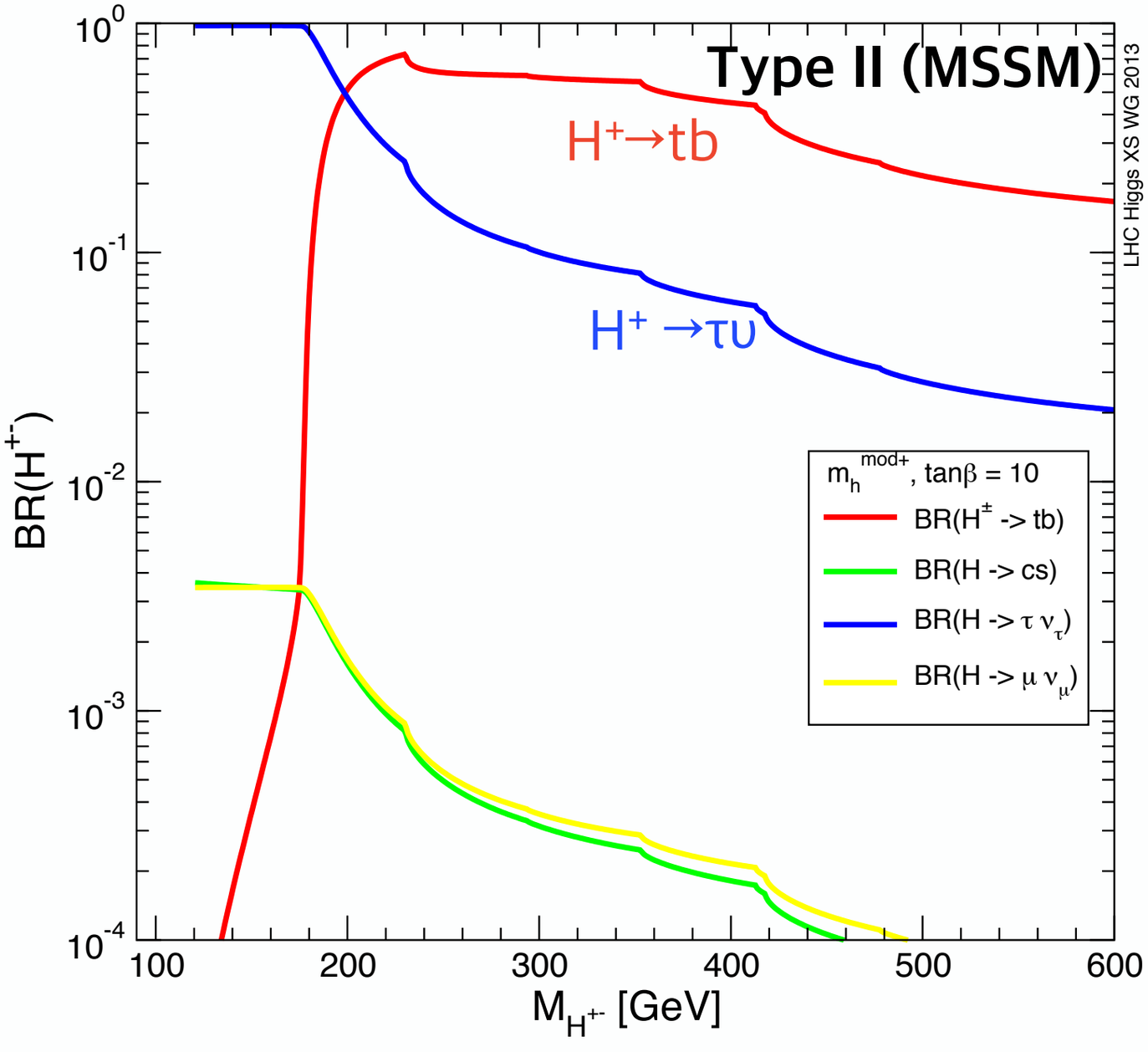
Experimental signatures for $H^{\pm}$

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



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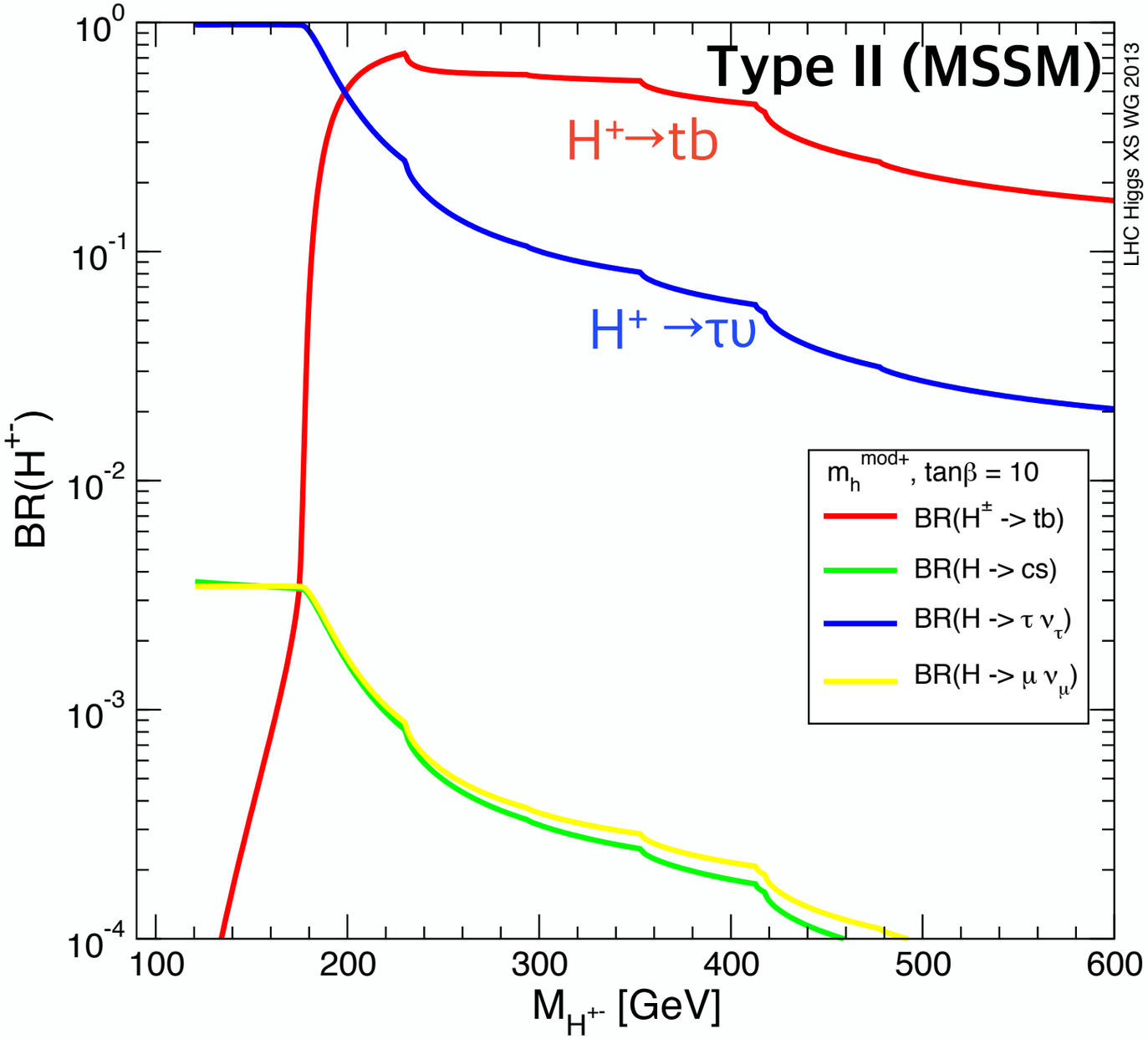

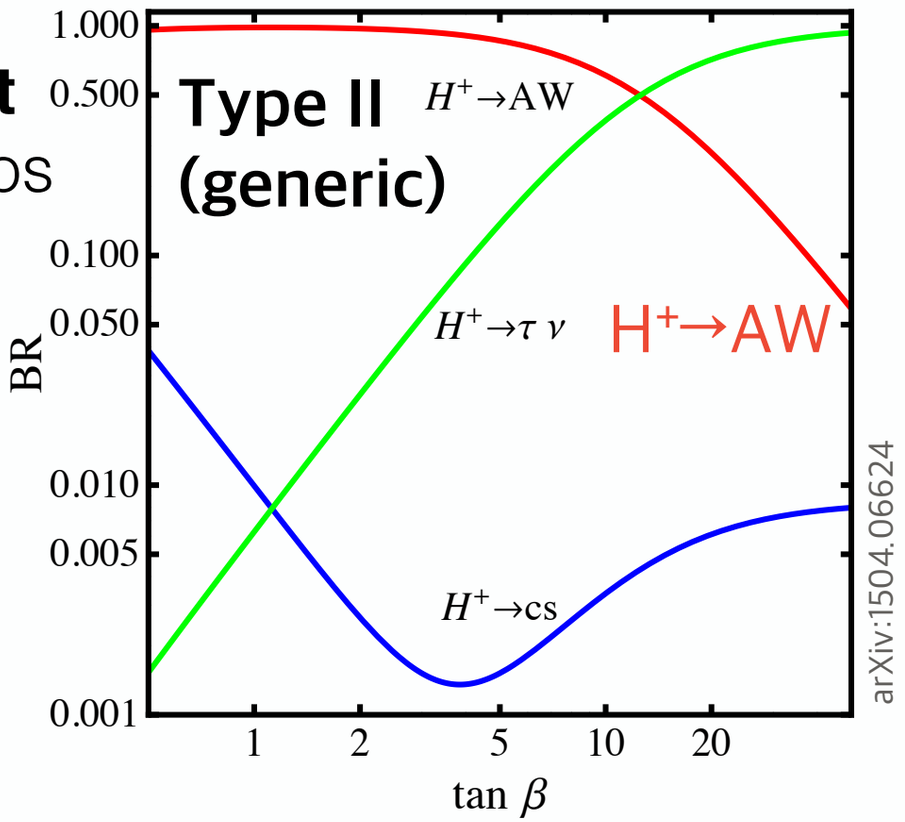

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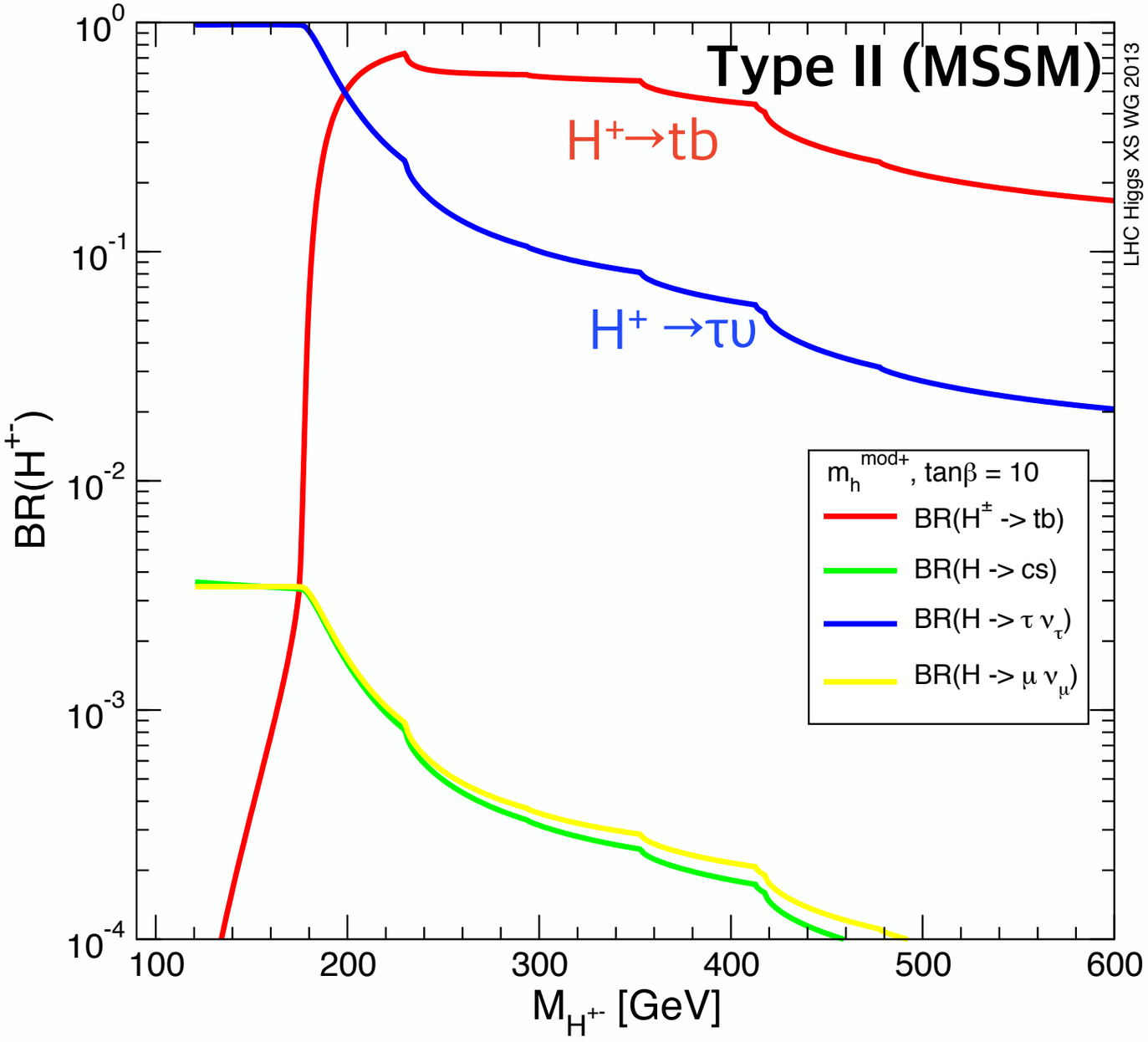

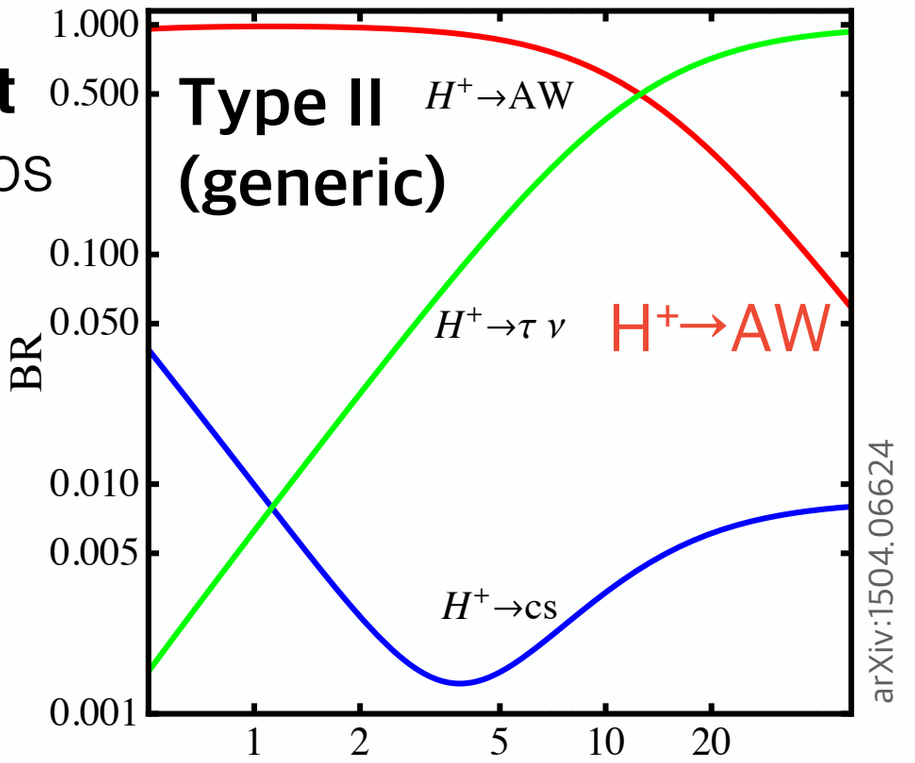

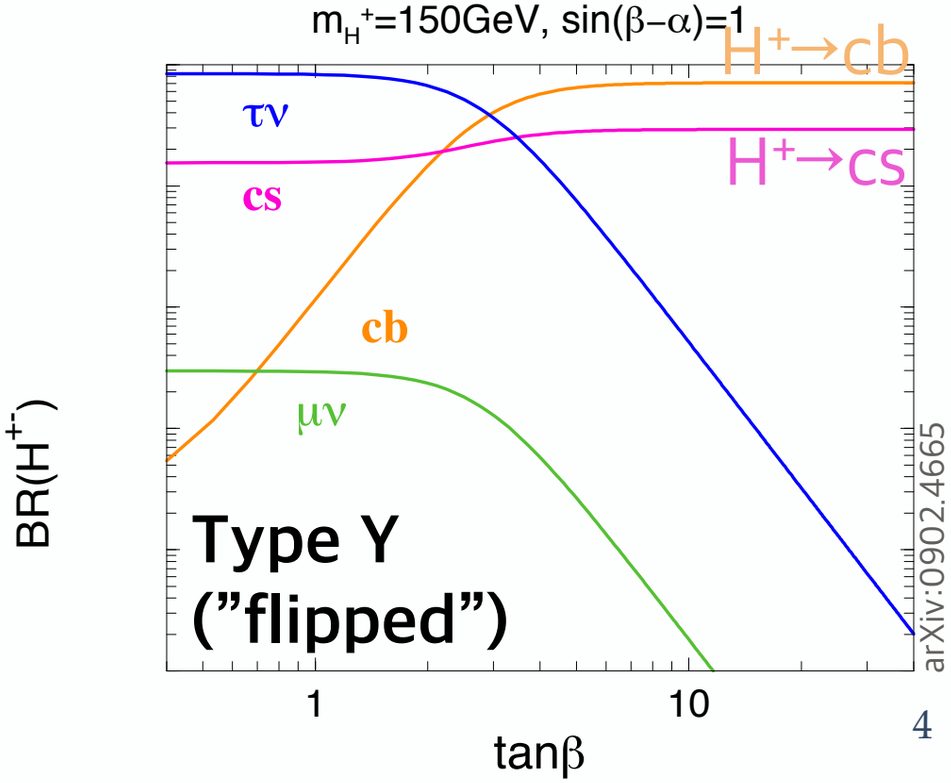

CMS 2HDM $H^{\pm}$ search program

	Light $H^{\pm}$ ($m_{H^{\pm}} < m_t$)	Heavy $H^{\pm}$ ($m_{H^{\pm}} > m_t$)
LHC Run 1 (7–8 TeV)	$H^{\pm}\rightarrow\tau\upsilon$, semileptonic & fully hadronic HIG-14-023	$H^{\pm}\rightarrow\tau\upsilon$, semileptonic & fully hadronic HIG-14-023
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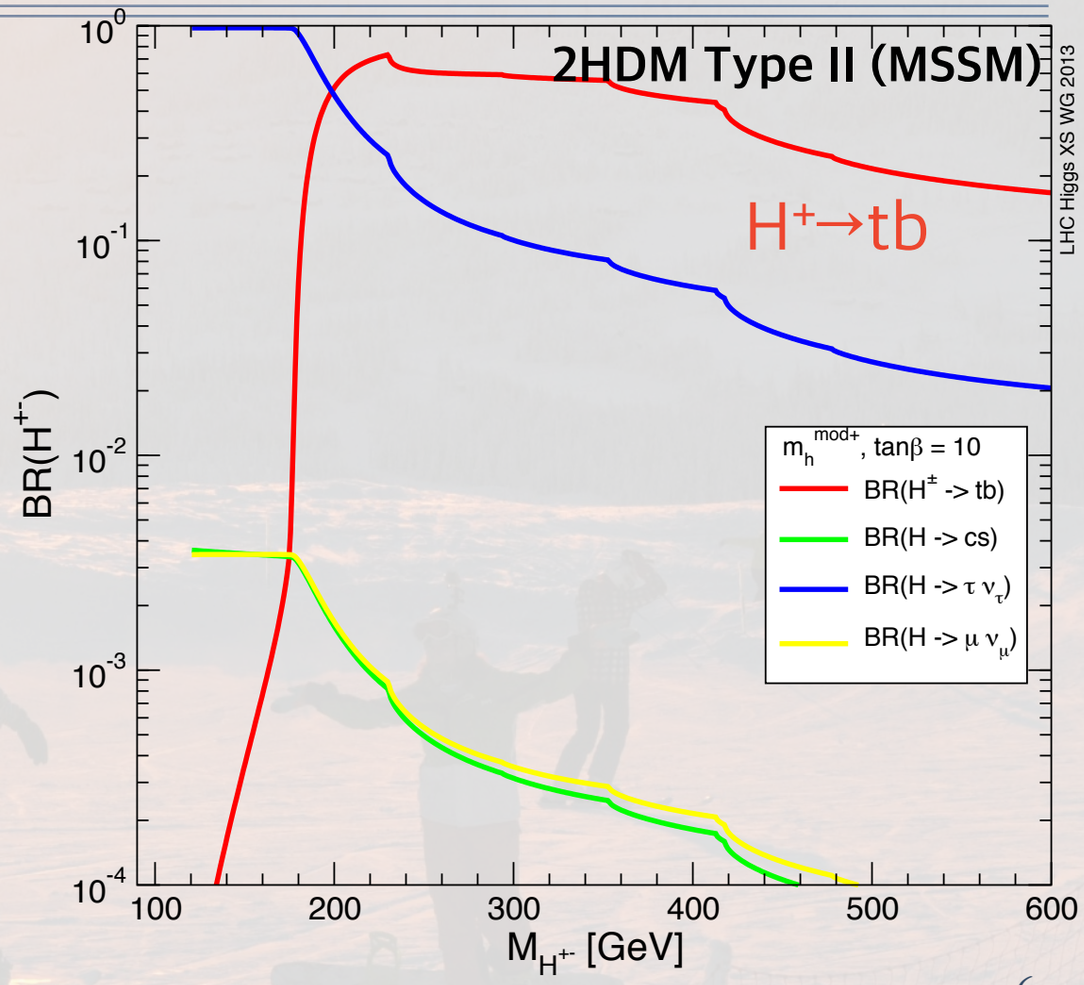
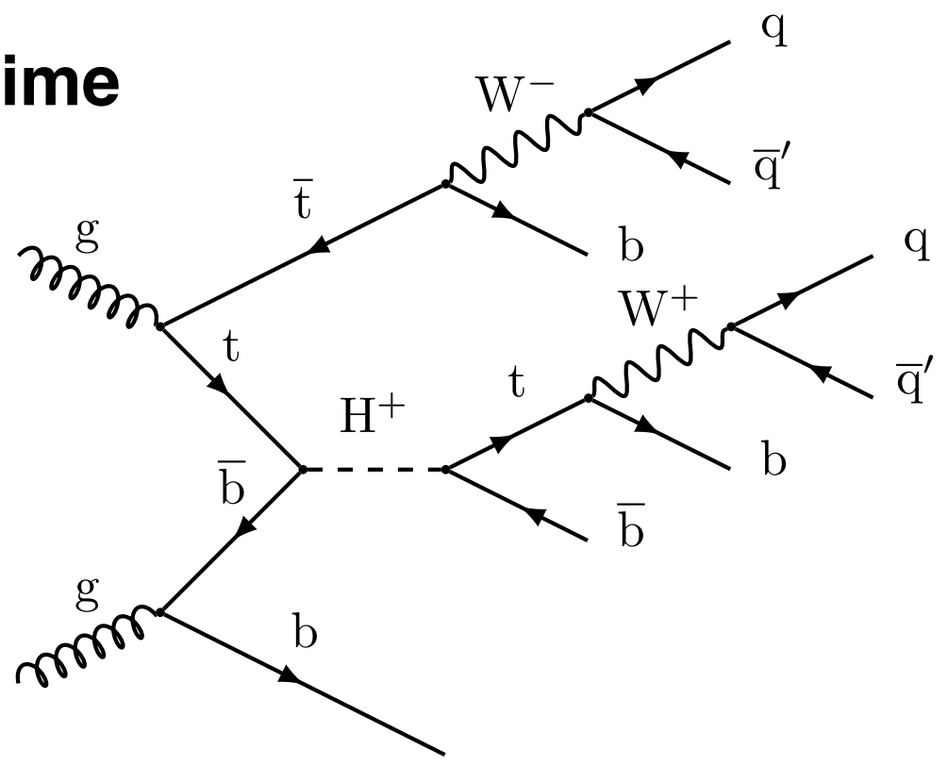


$H^{\pm} \rightarrow tb$: Hadronic final state

- Hadronic final state analyzed **for the first time**
  - Large branching fraction
  - No $p_T^{miss} \rightarrow m_{H\pm}$ can be reconstructed
  - Challenges: combinatorics, QCD multijet background



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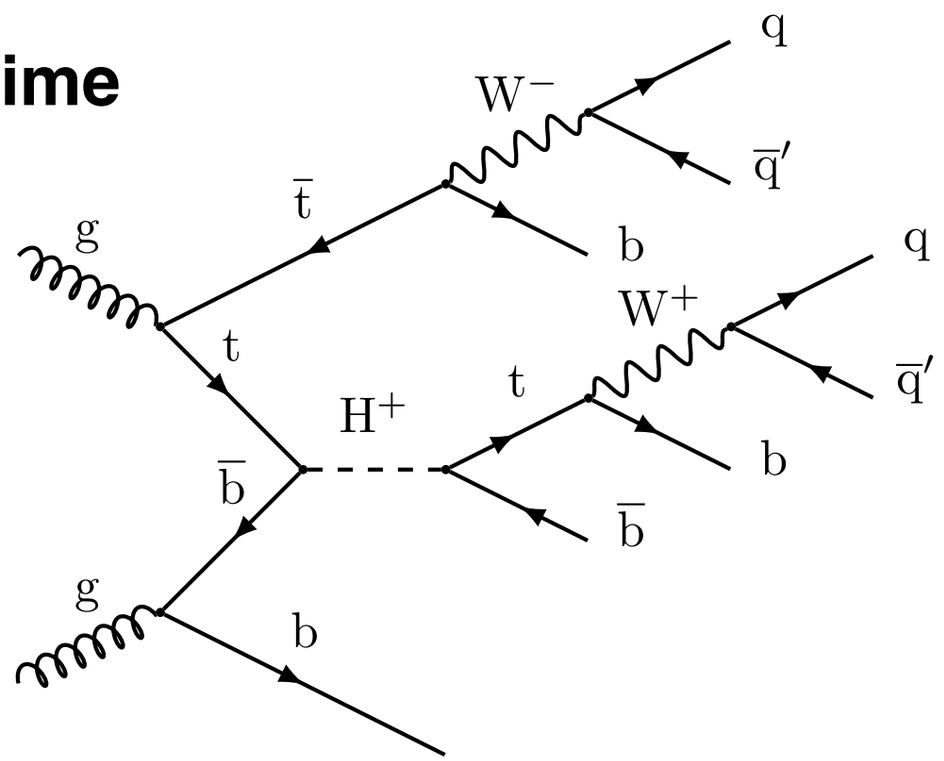

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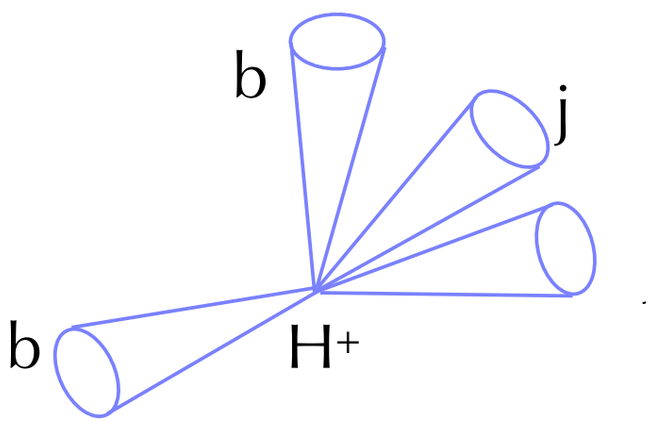
$H^{\pm}$ from **four AK4 jets** (BDT)



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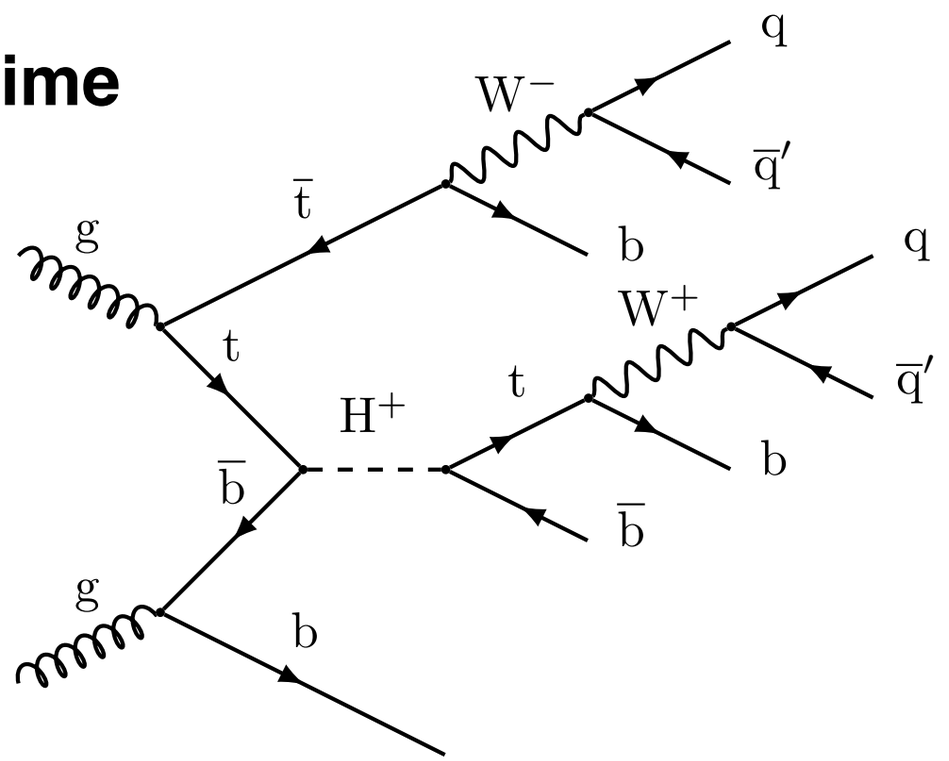

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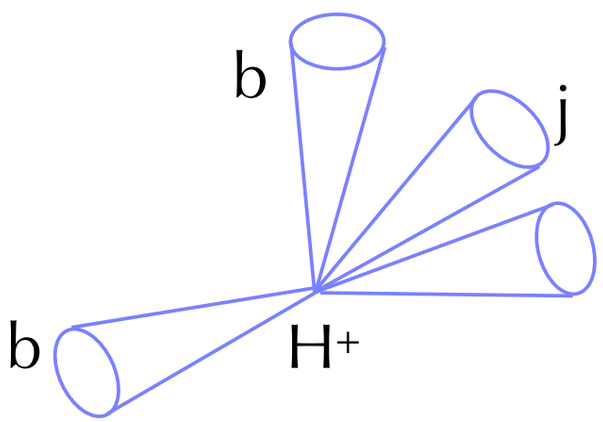
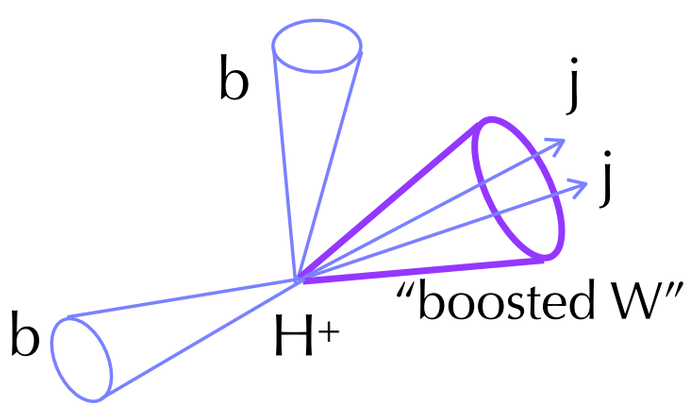
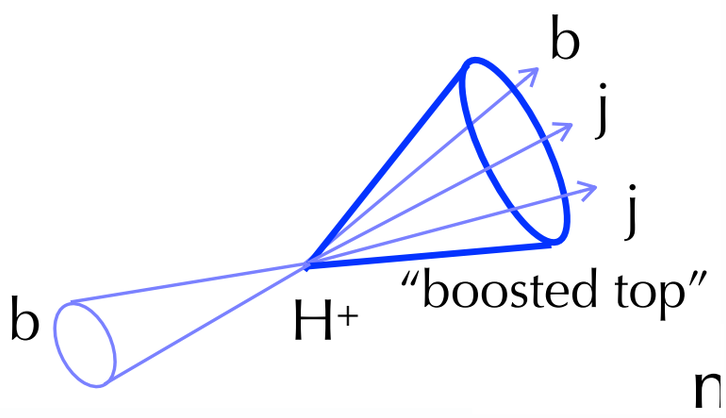
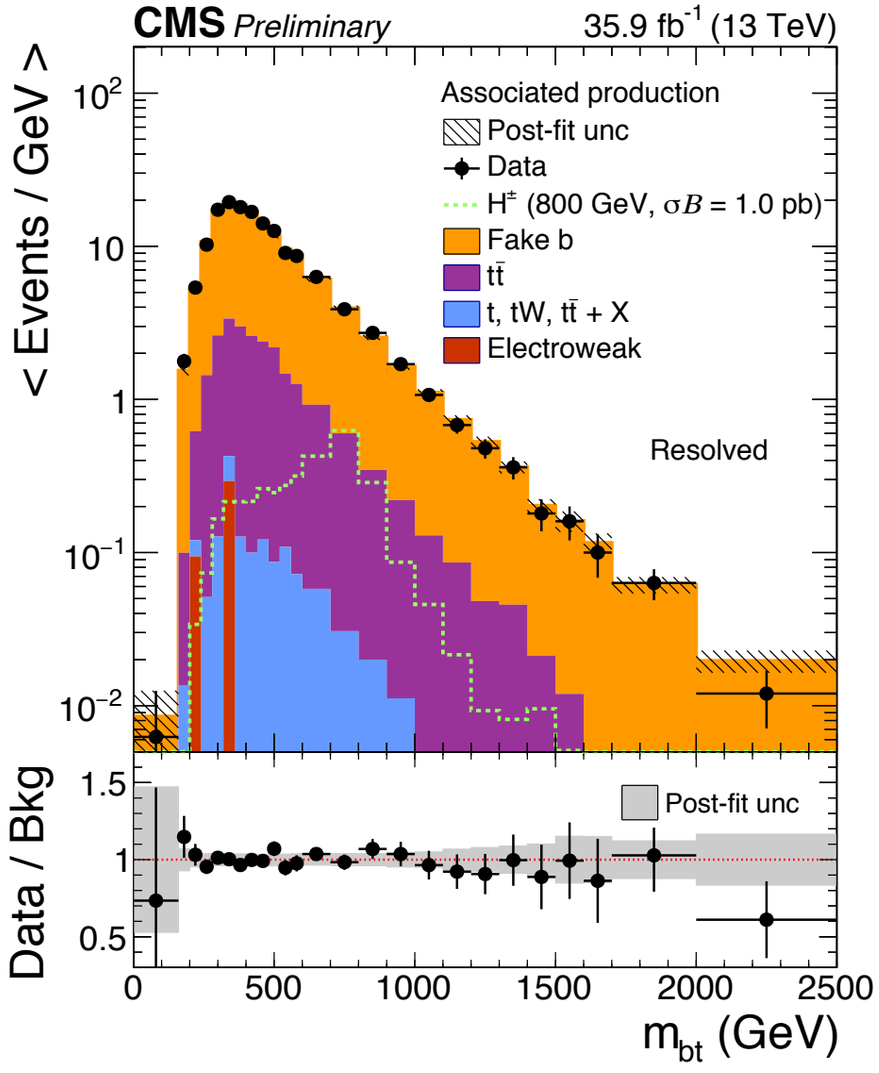


"Boosted" analysis: $H^{\pm}$ reconstructed from
AK8 W jet and two AK4 b jets or **AK8 top jet** and AK4 b jet





$H^{\pm} \rightarrow tb$: Hadronic results



- Resolved analysis: **m(tb) distribution** used to extract limits

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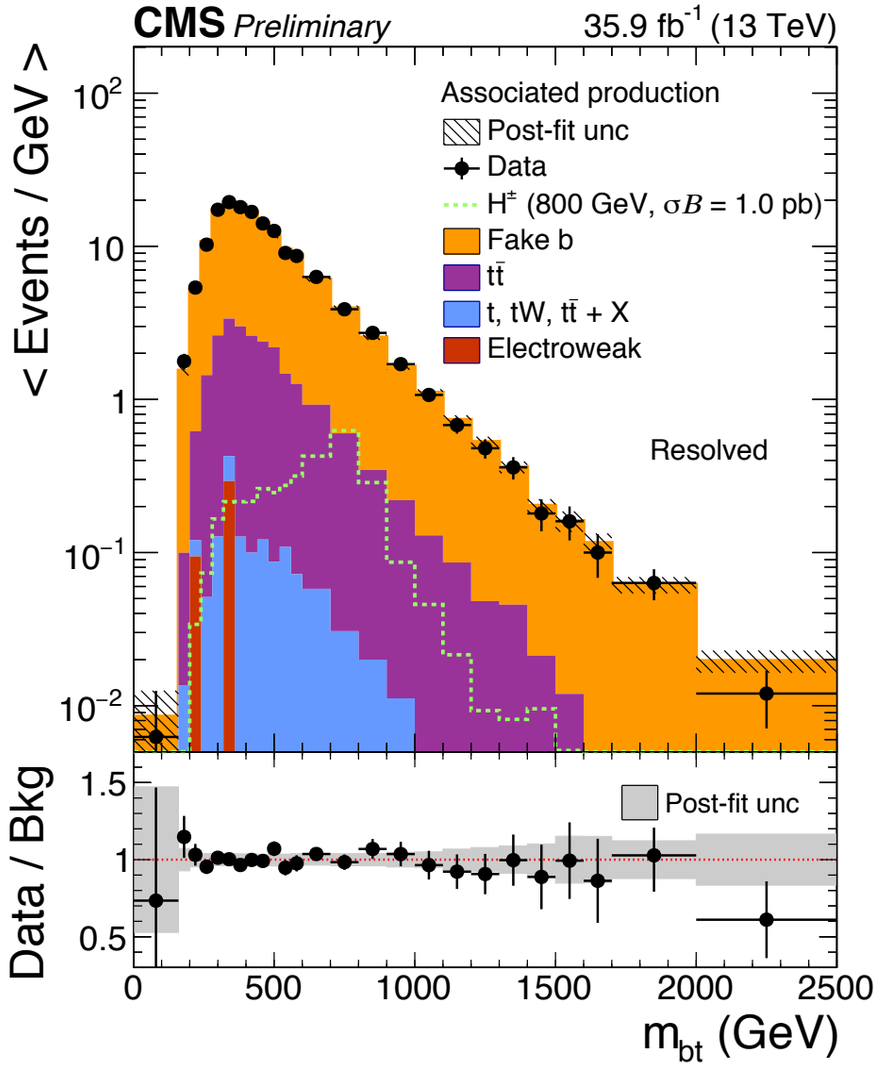

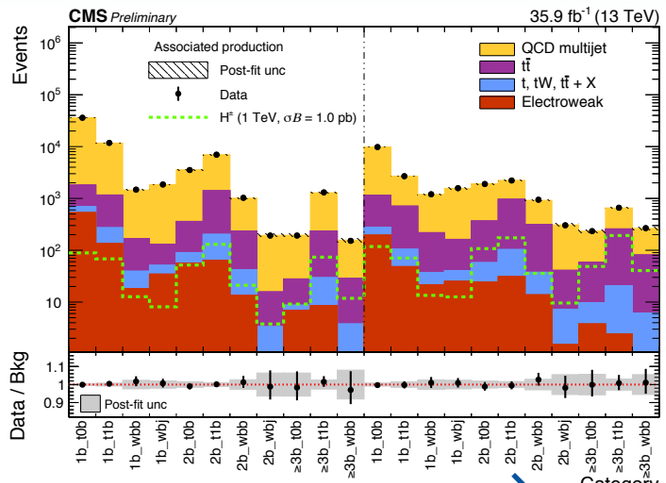

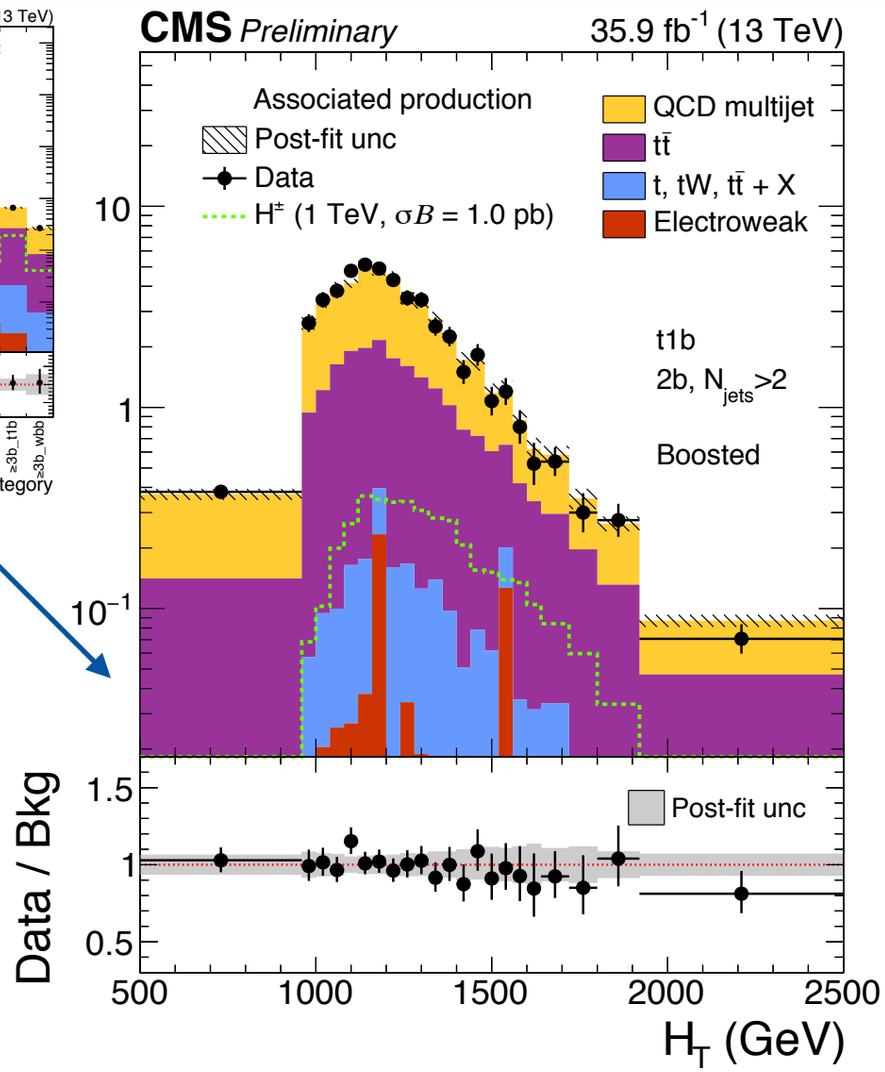

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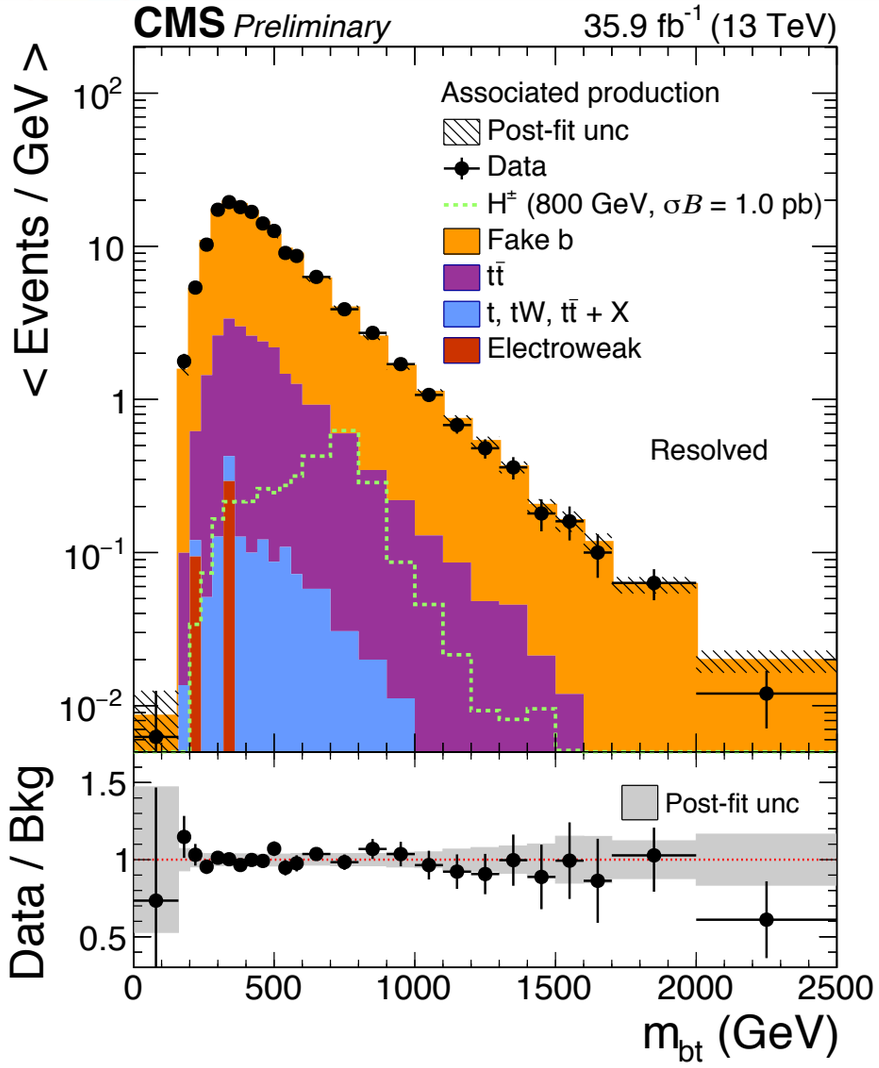

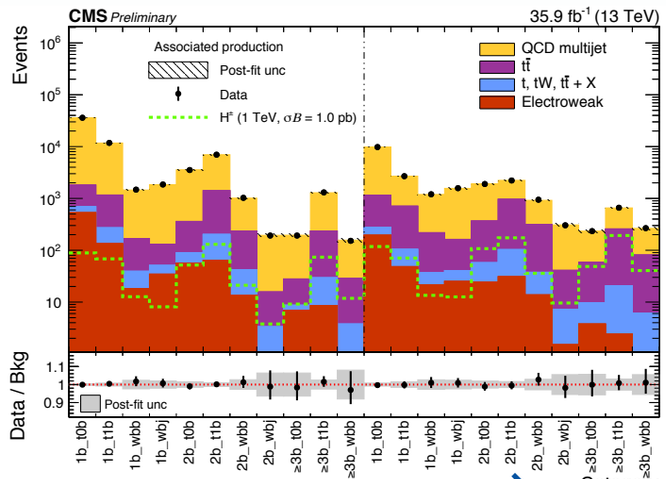

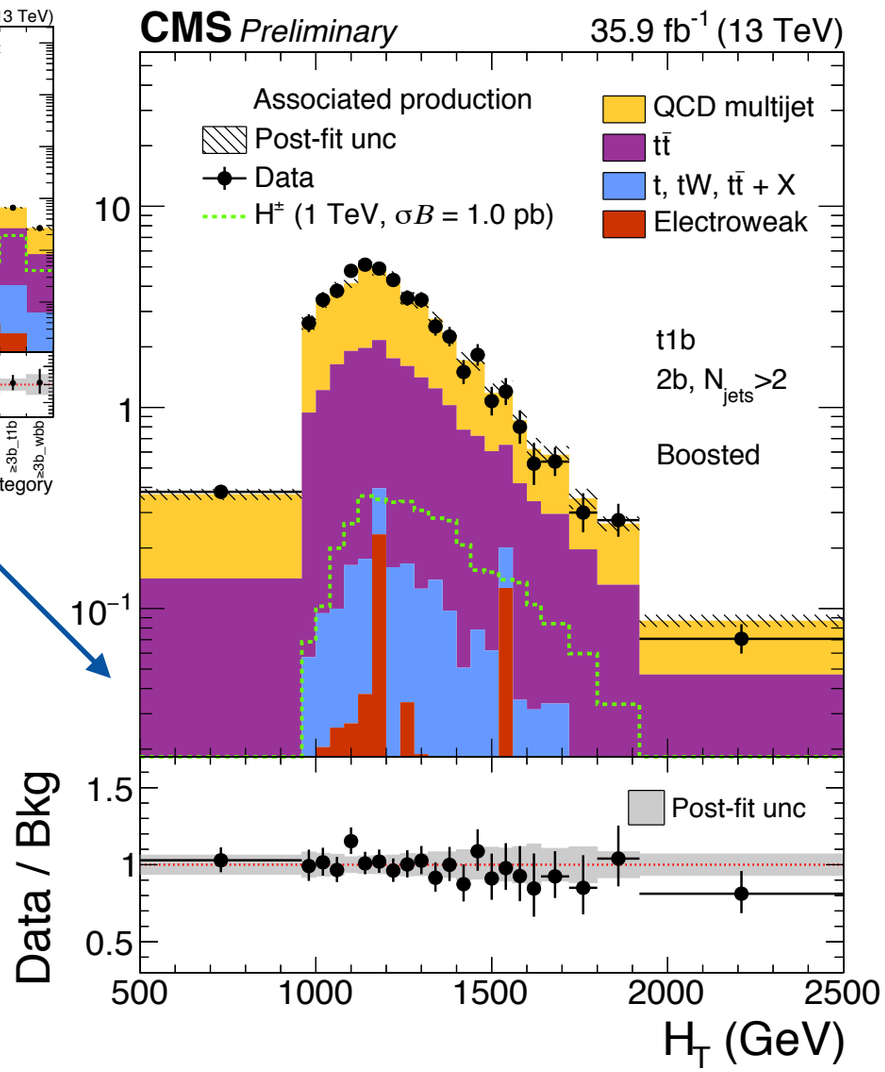

- Resolved analysis: **m(tb) distribution** used to extract limits

- Boosted analysis: **H_T distributions** in several categories used to extract limits

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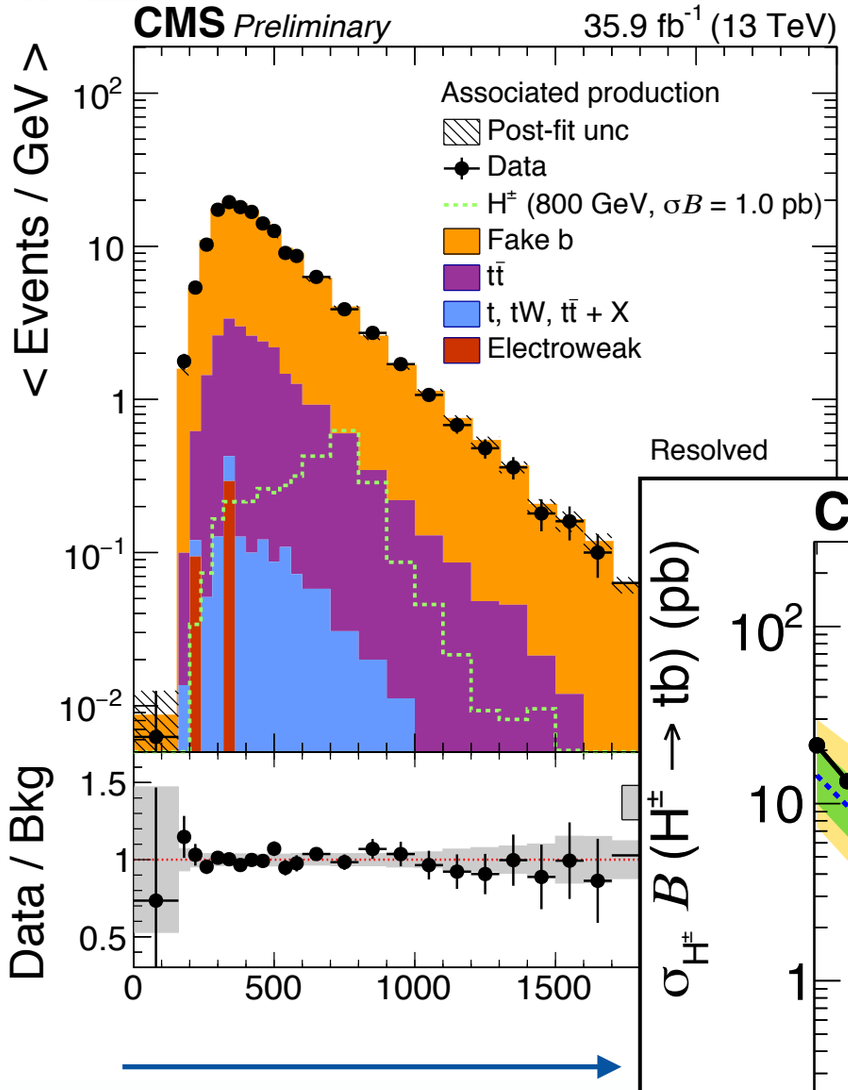

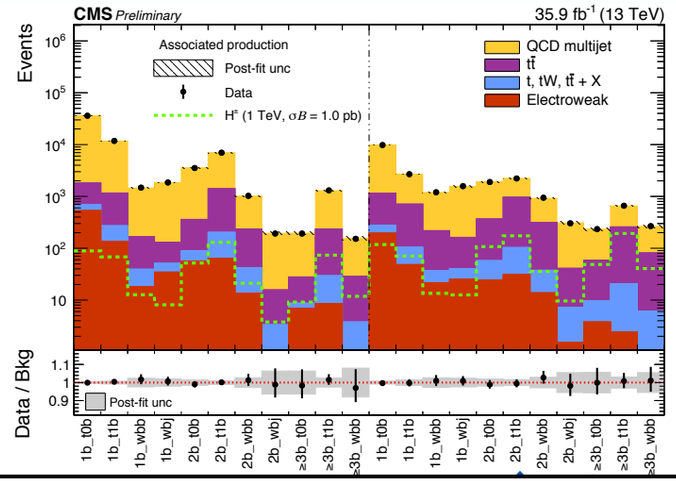

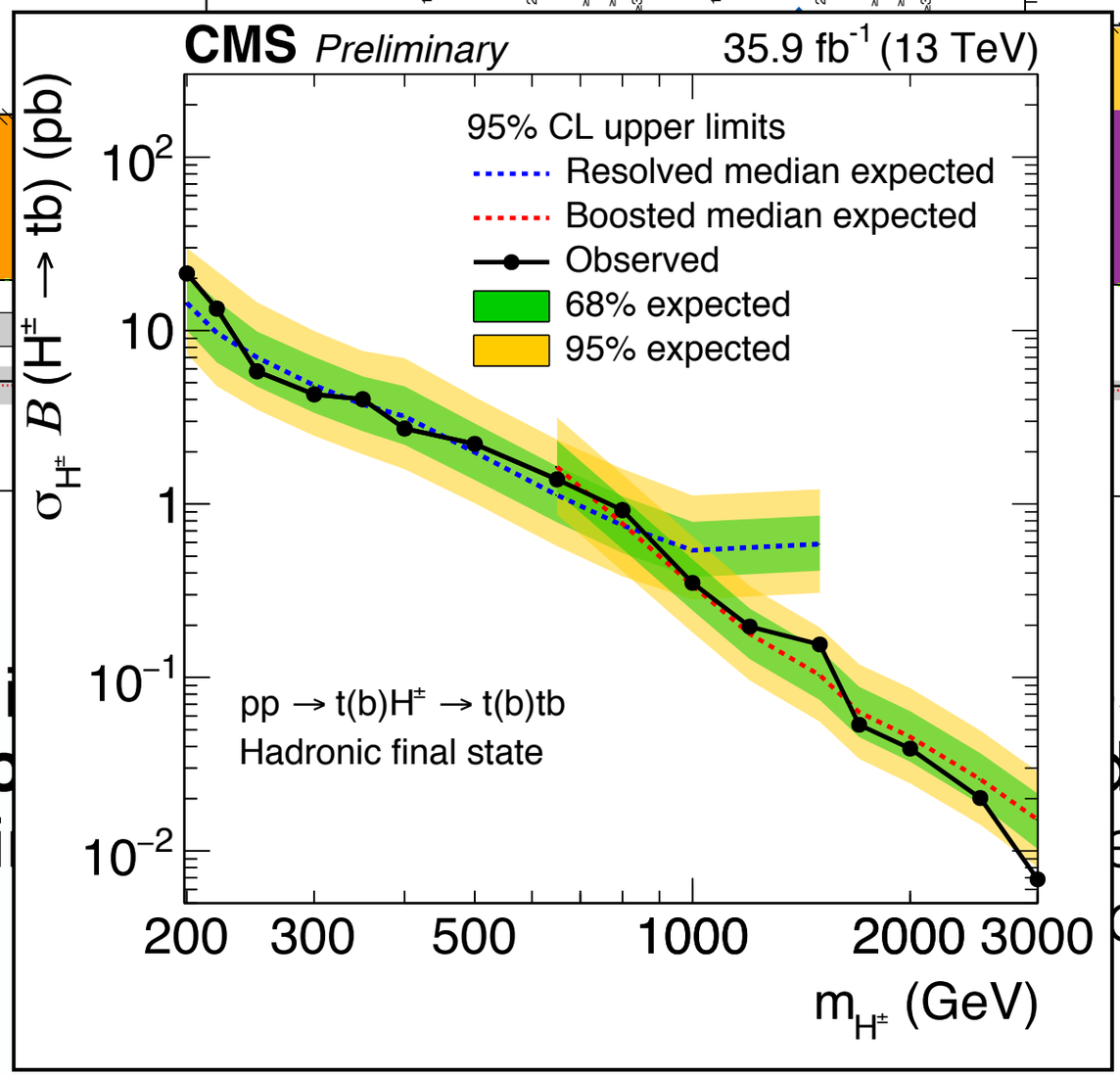

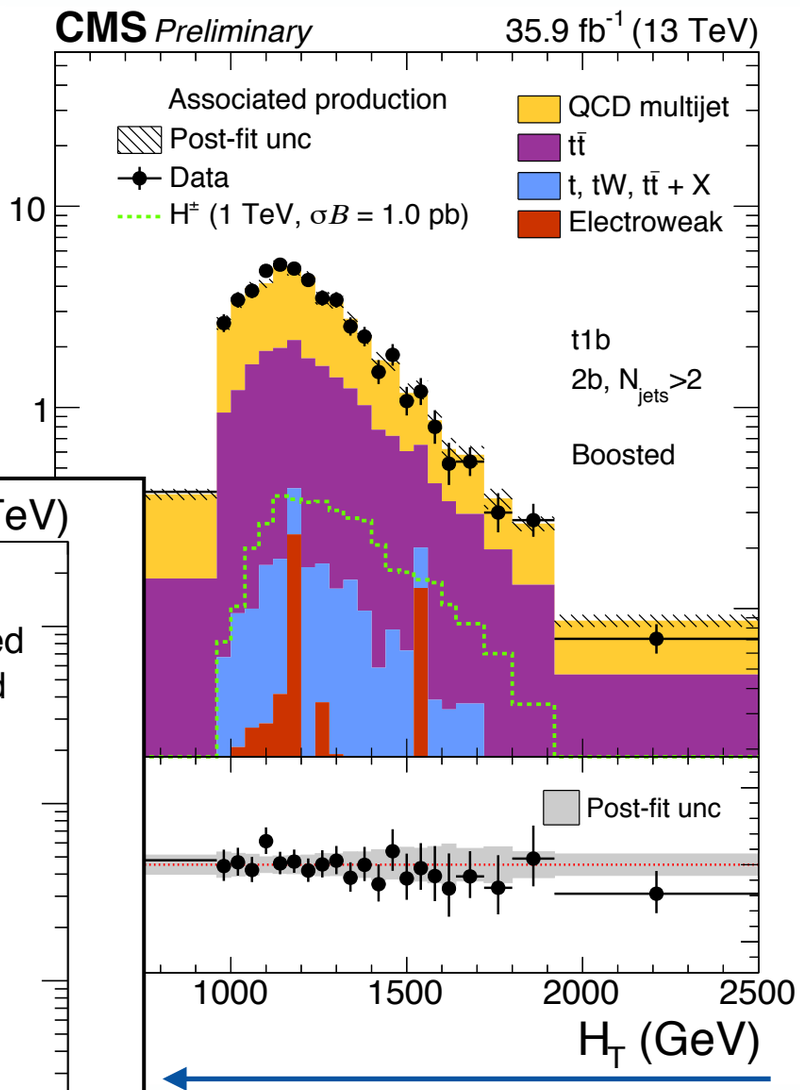

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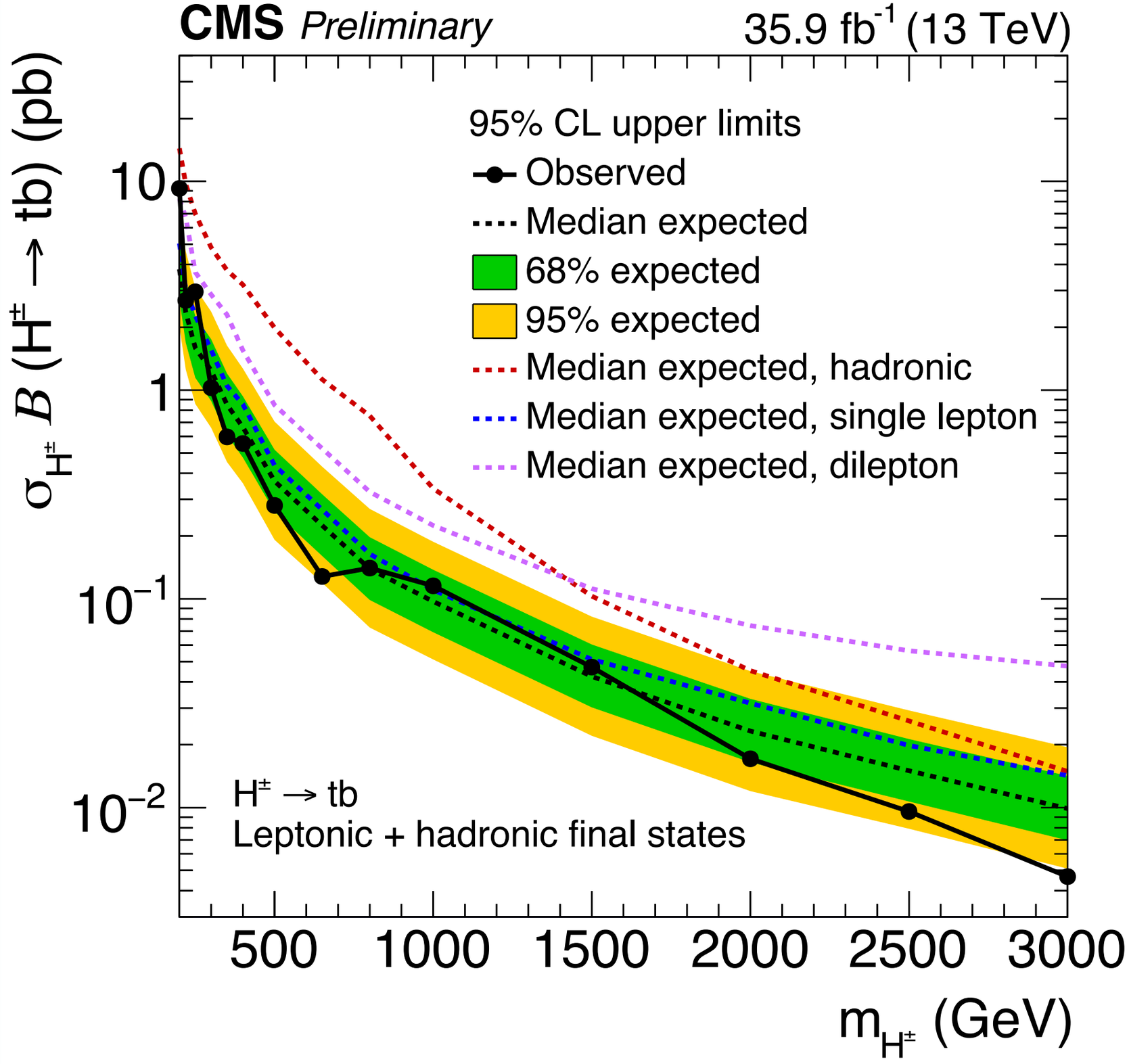
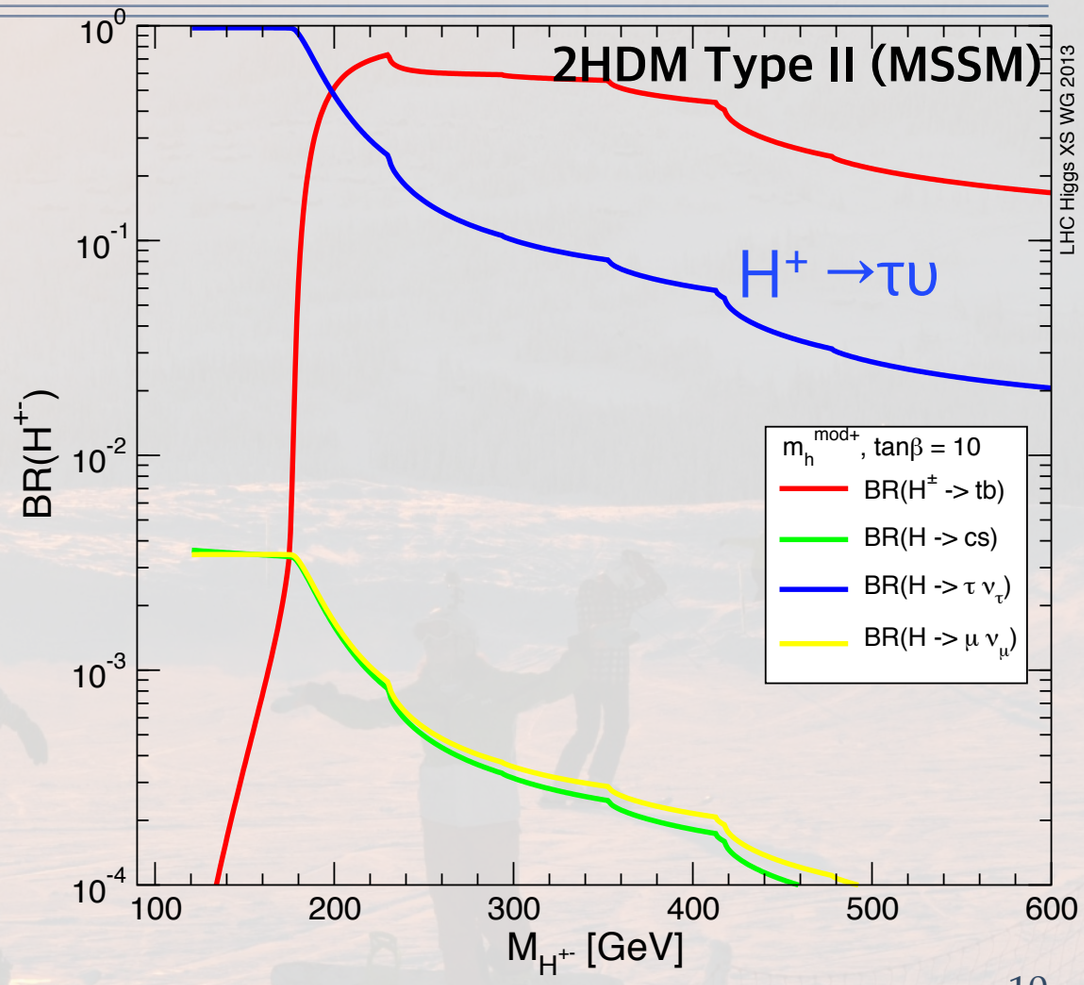
$H^{\pm} \rightarrow tb$: Combined results



$H^{\pm} \rightarrow \tau\upsilon$

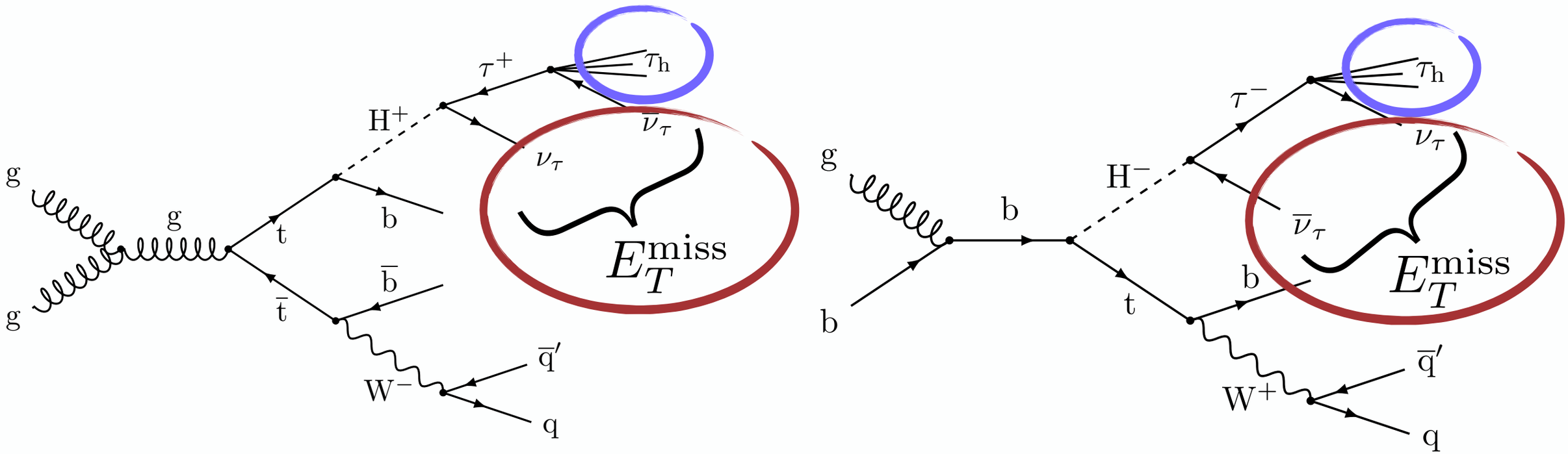


$H^{\pm} \rightarrow \tau\nu$: Strategy

- The τν channel is sensitive as it allows the reconstruction of the **transverse mass** of the τν system:

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

- Production changes with mass, but the final state remains similar



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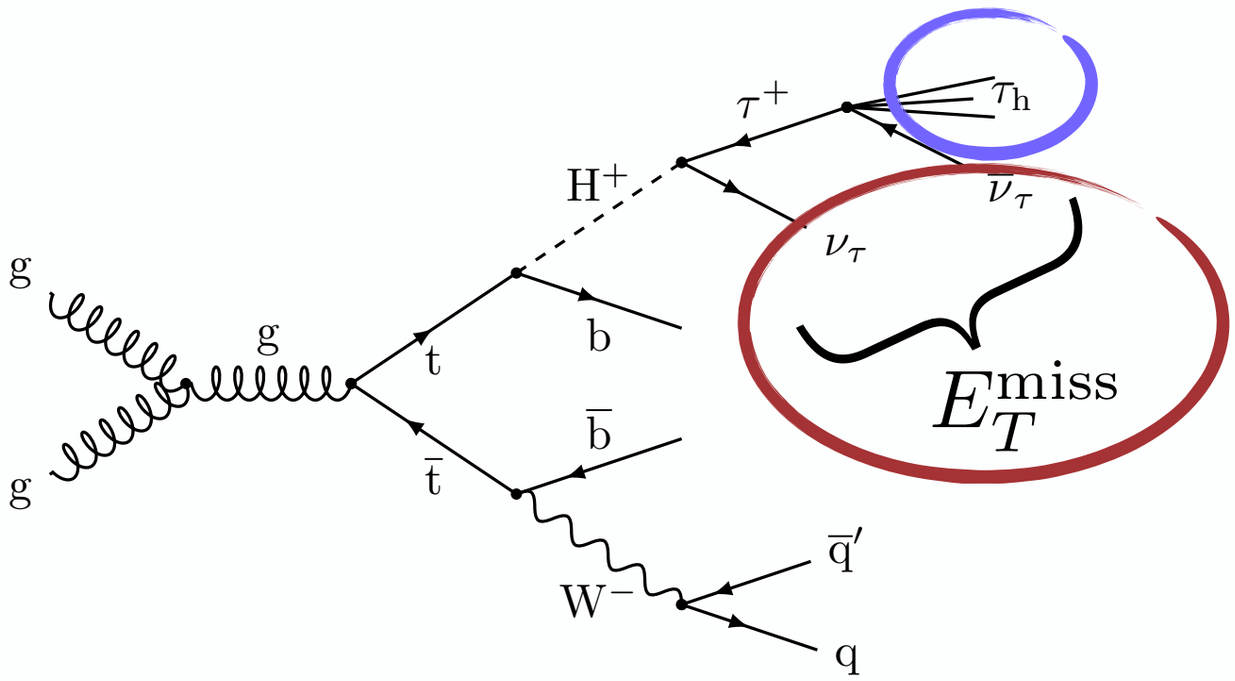
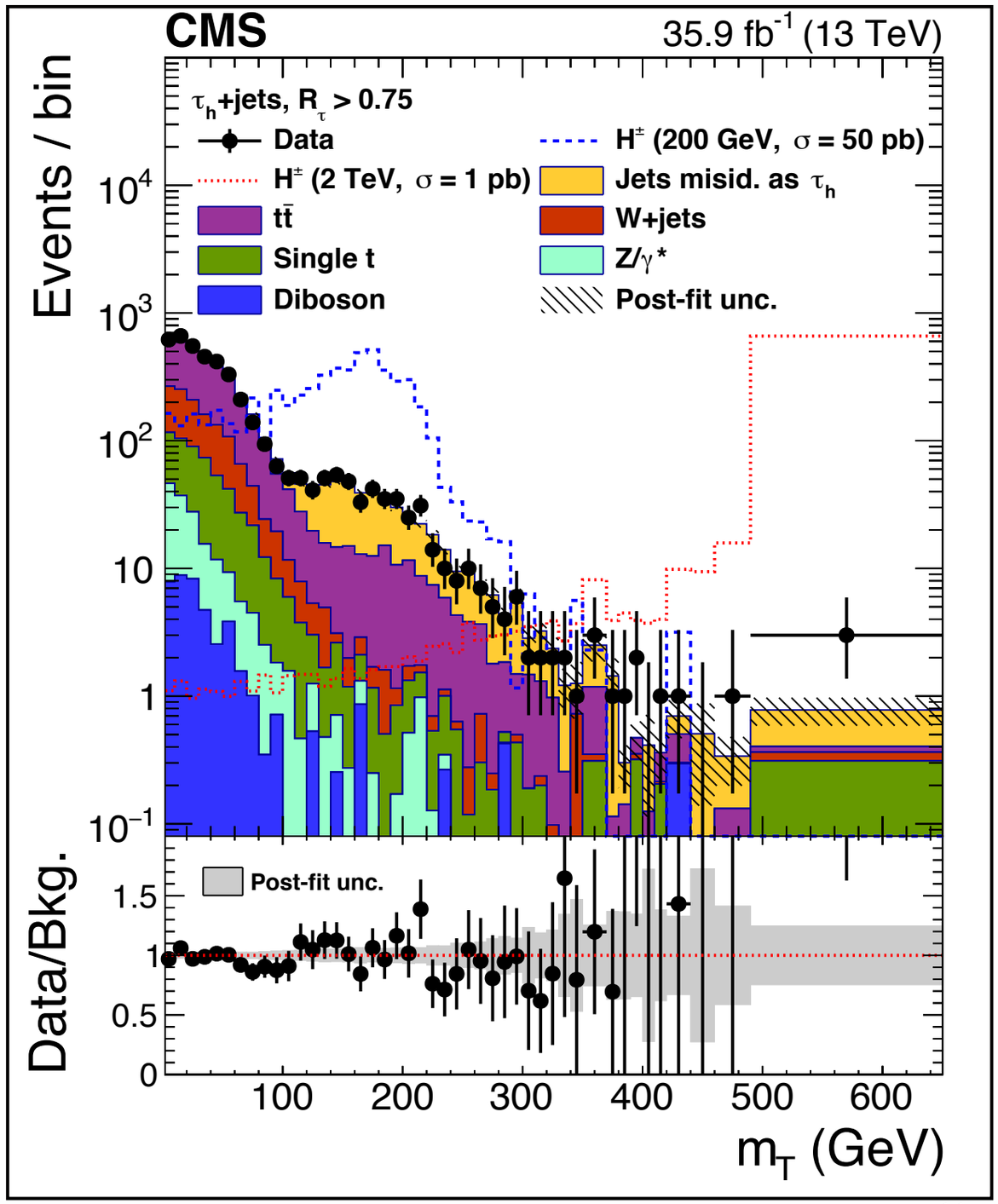
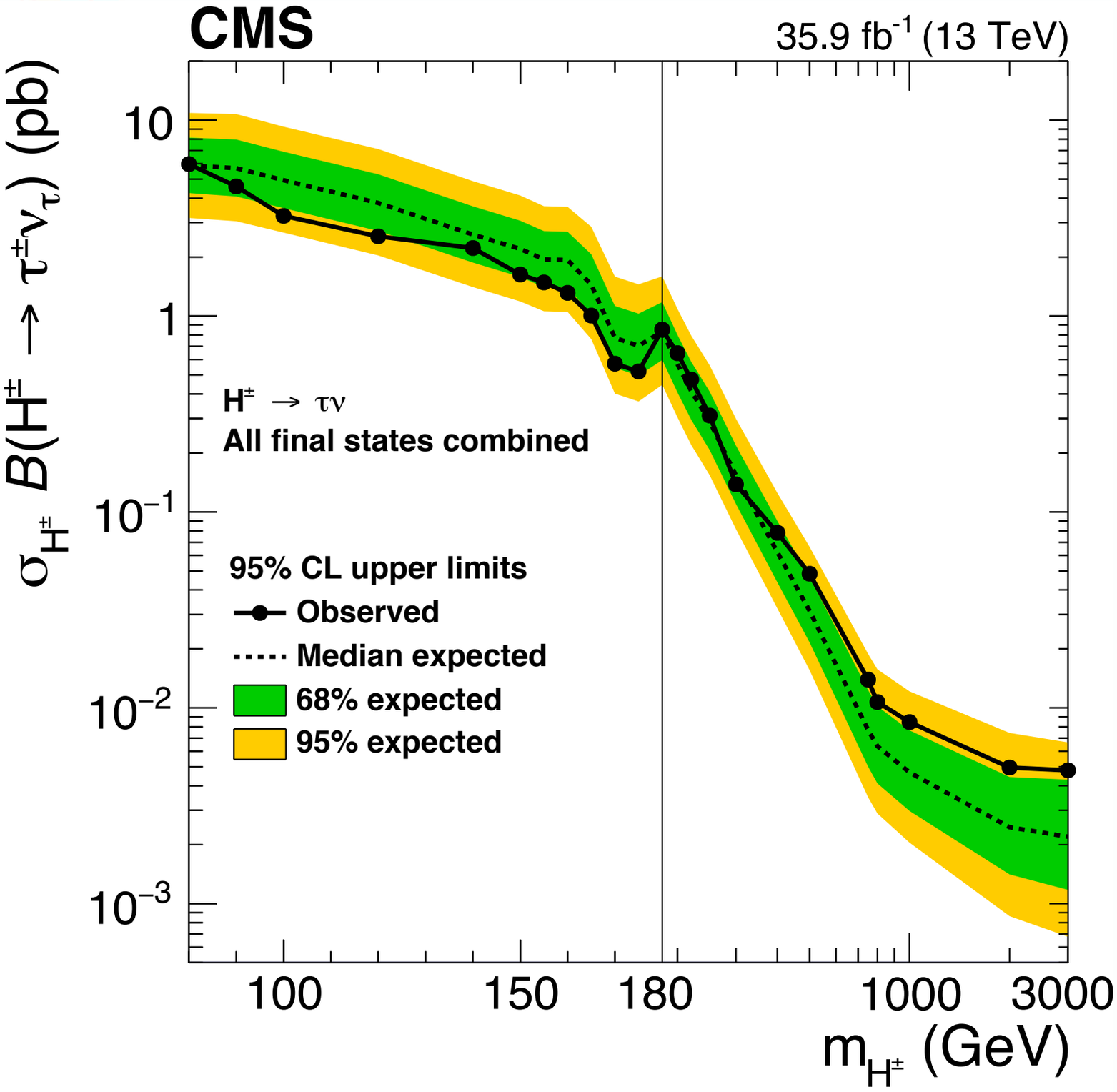


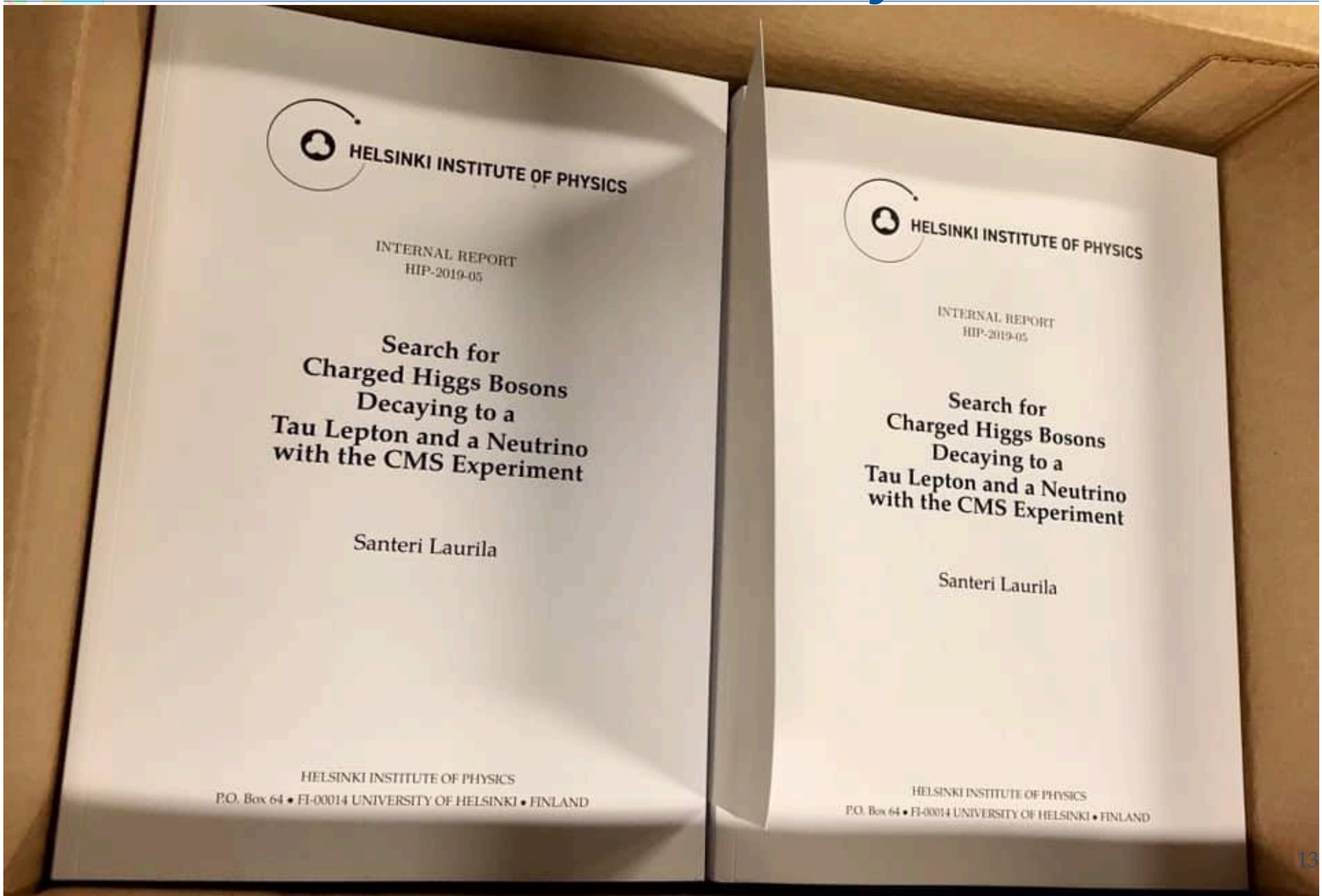


$H^{\pm} \rightarrow \tau\nu$: Results

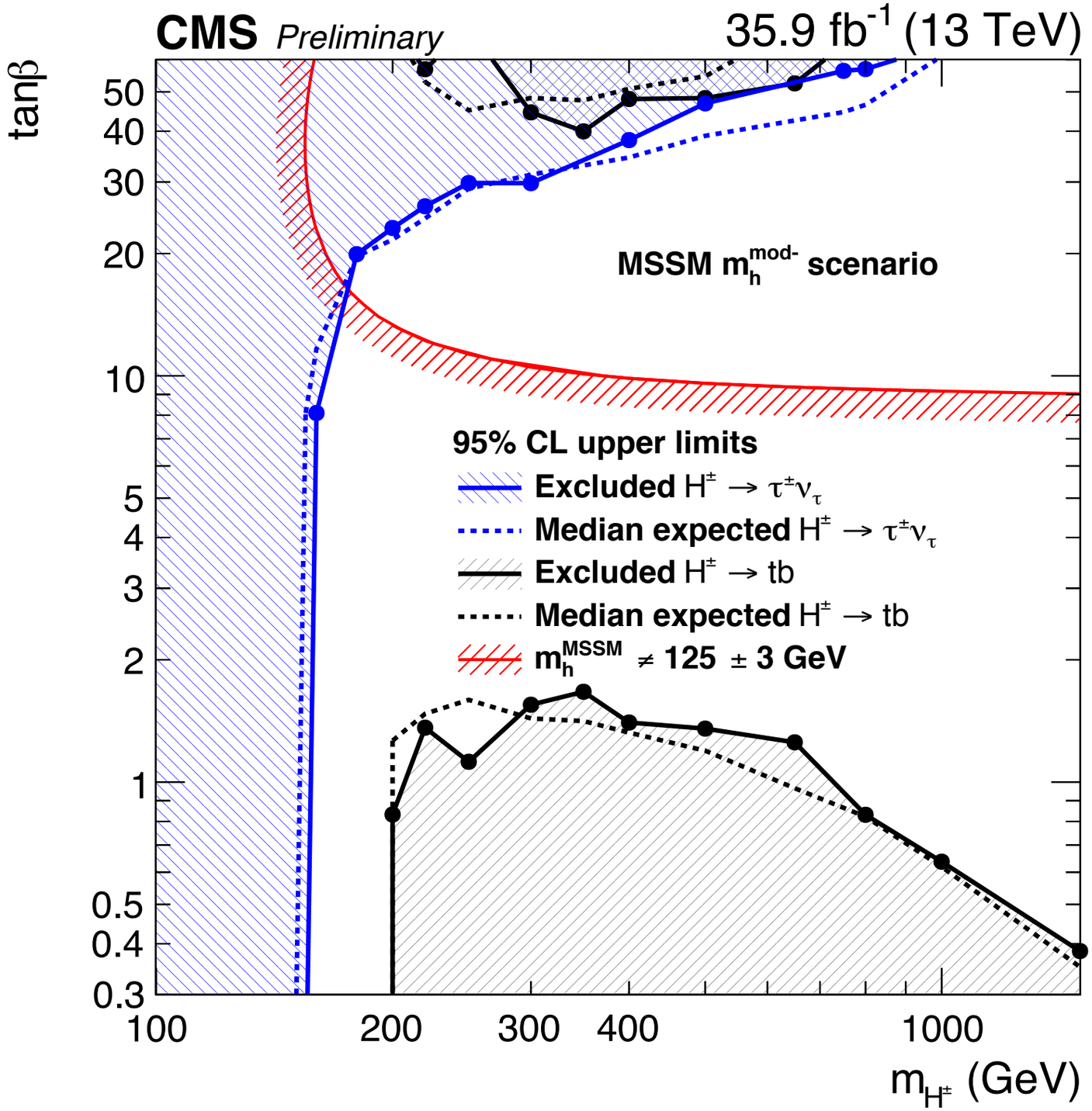


- **Sensitivity improved** up to a factor of 3 compared to the Run-1 legacy result
- **Mass range extended** from 600 GeV to 3 TeV
- **$m_{H+} \sim m_t$ included** for the first time at CMS

$H^{\pm} \rightarrow \tau\nu$: Details in my thesis

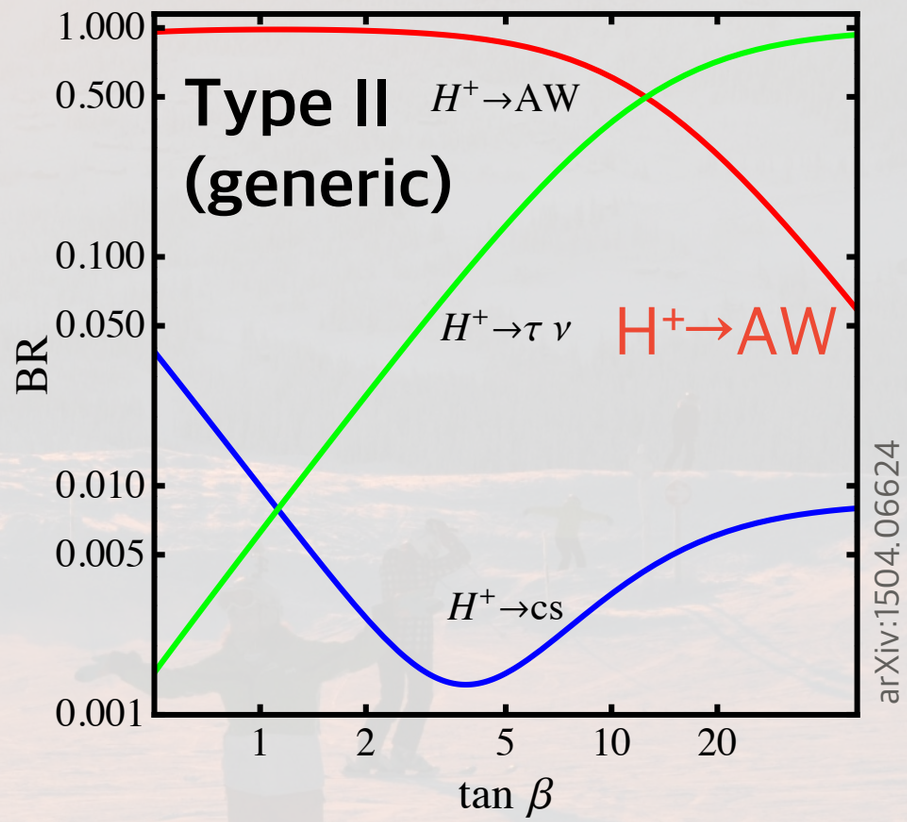


$H^{\pm} \to \tau\nu$ & $H^{\pm} \to tb$ combined



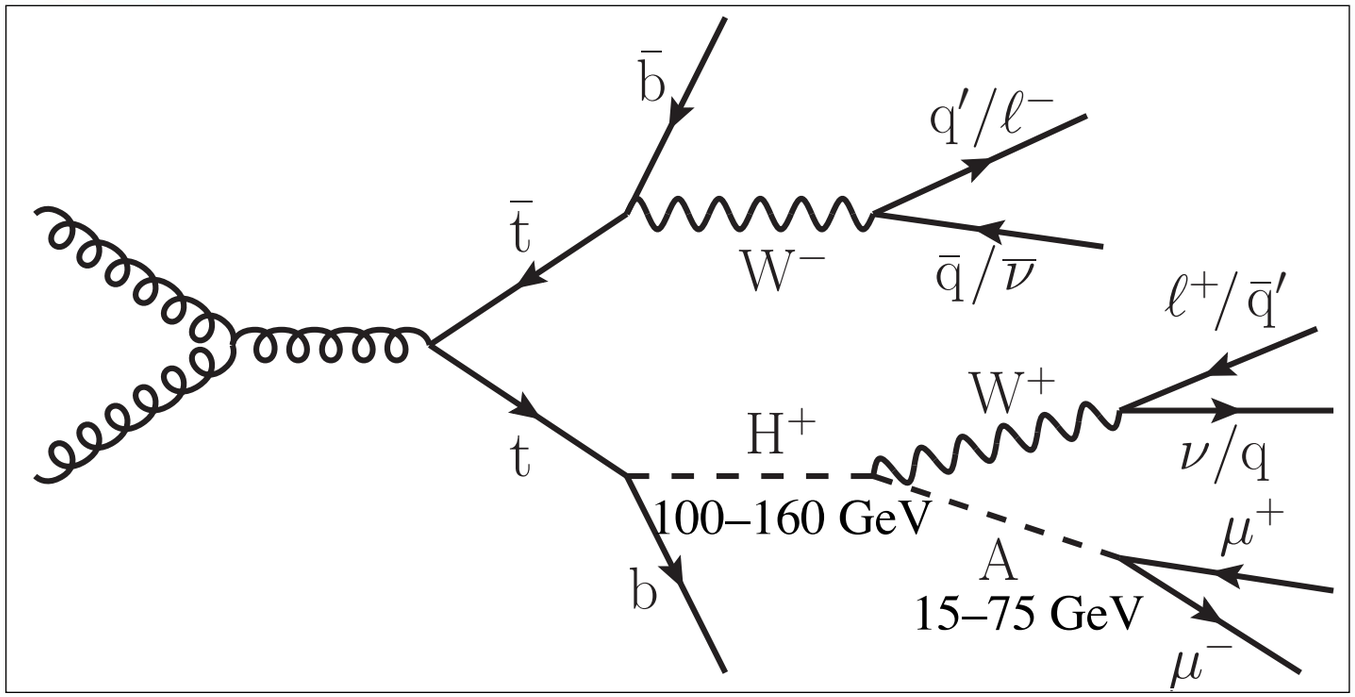
- Comparison of limits from the **ττ** and **tb** channels and from properties of H_{125}

$H^{\pm} \rightarrow W^{\pm} A,\ A \rightarrow \mu\mu$



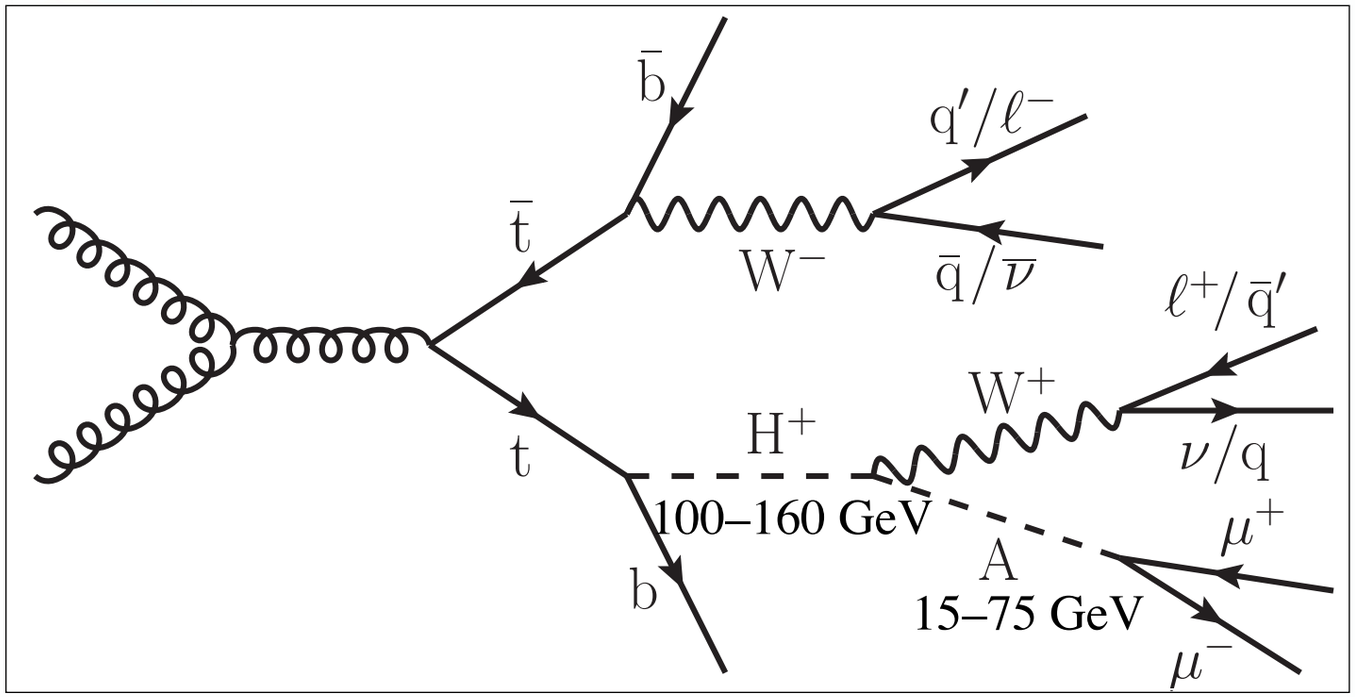
arXiv:1504.06624

$H^{\pm} \rightarrow W^{\pm}A,\ A \rightarrow \mu\mu$



- The first search for **$H^{\pm} \rightarrow W^{\pm}A$** at the LHC
- $B(A \rightarrow \mu\mu) \lesssim 10^{-3}$, but low-$p_T$ **muons perform well** in terms of trigger & identification **efficiency**, **resolution** and **pileup robustness**

$H^{\pm} \rightarrow W^{\pm}A,\ A \rightarrow \mu\mu$



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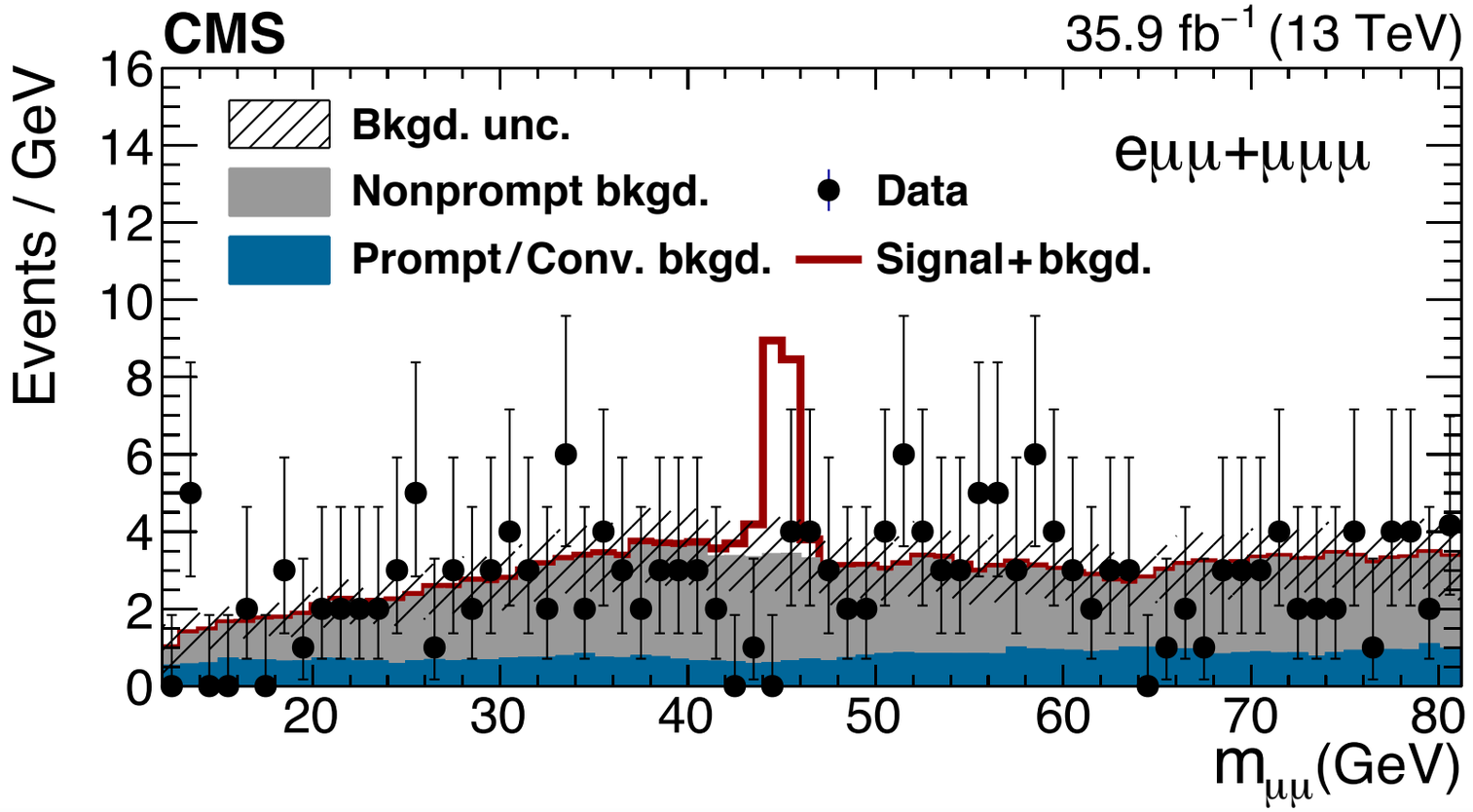
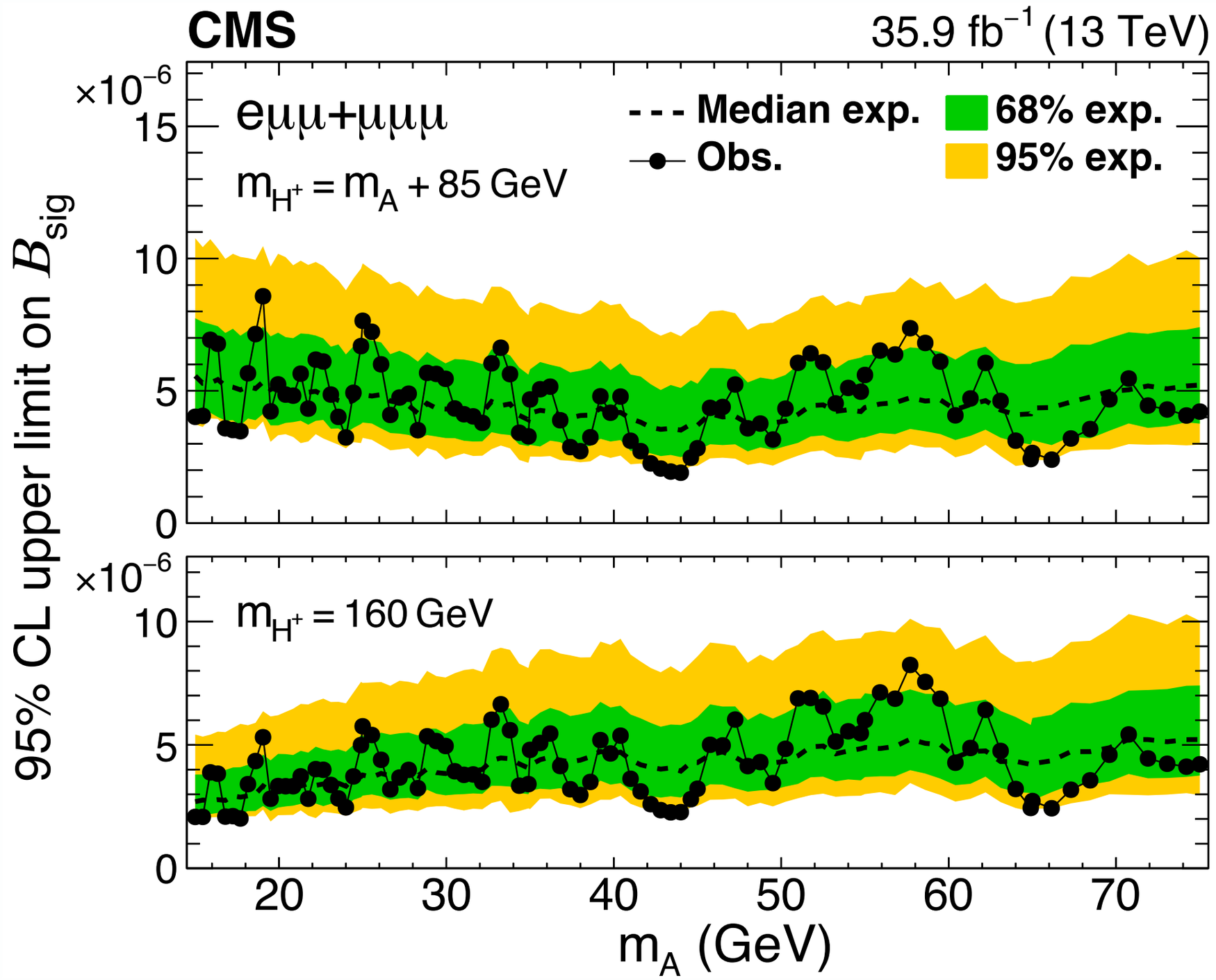
- **m($\mu\mu$) reconstructed** and **used to extract limits**



$H^{\pm} \rightarrow W^{\pm}A$, $A \rightarrow \mu\mu$: Results

- Limits on $B(t \rightarrow bH^{\pm})B(H^{\pm} \rightarrow W^{\pm}A)B(A \rightarrow \mu\mu)$ set **for the first time**



Summary & Outlook

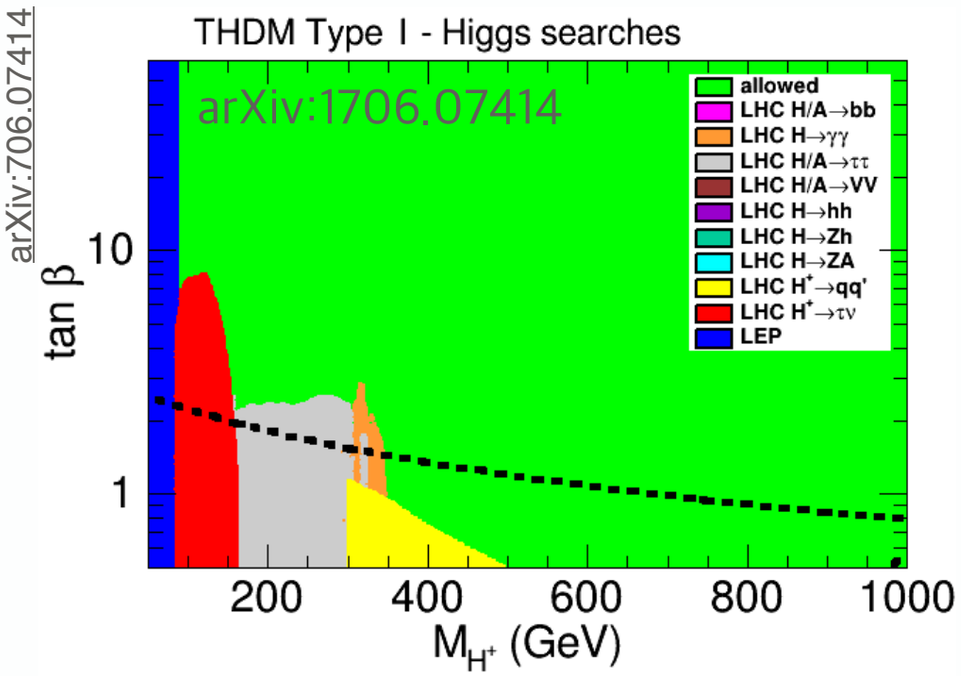
- CMS has a broad search program for charged Higgs bosons
- Several results are out based on 2016 data (36 fb^{-1}), including…
  - The first search for **$H^{\pm}\rightarrow W^{\pm}A$** at the LHC
  - Most extensive **$H^{\pm}\rightarrow \tau^{\pm}u$** search to date, including $m_{H\pm}\sim m_{top}$
  - First look at the fully hadronic final state of the **$H^{\pm}\rightarrow tb$** channel
- **Full Run 2 data** (140 fb^{-1}) is now being analyzed
- **Run 3** and **HL-LHC** coming up, happy searching continues!

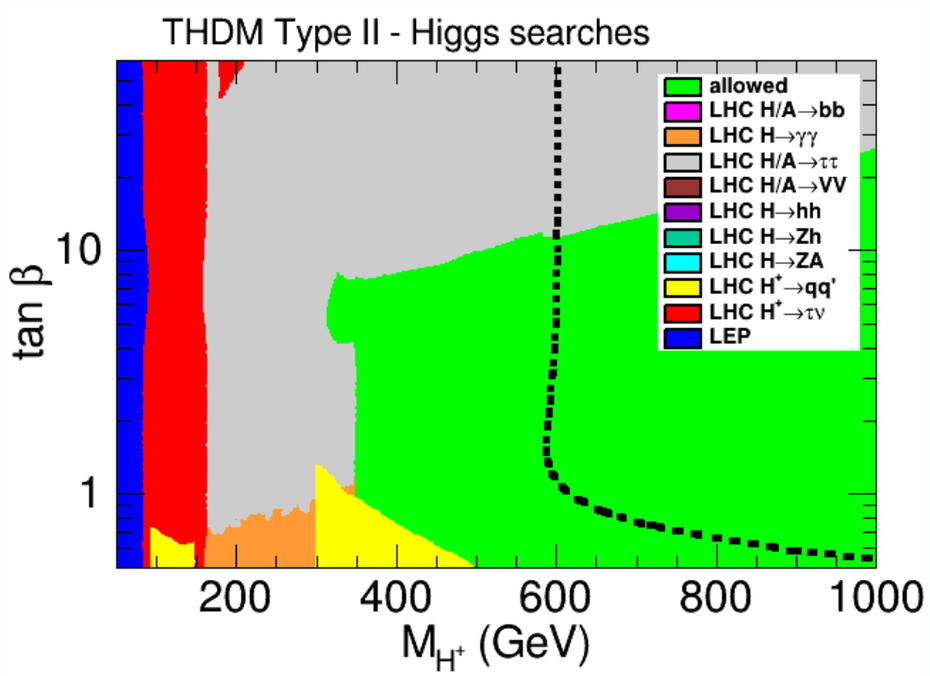
Thank you!

Back-up

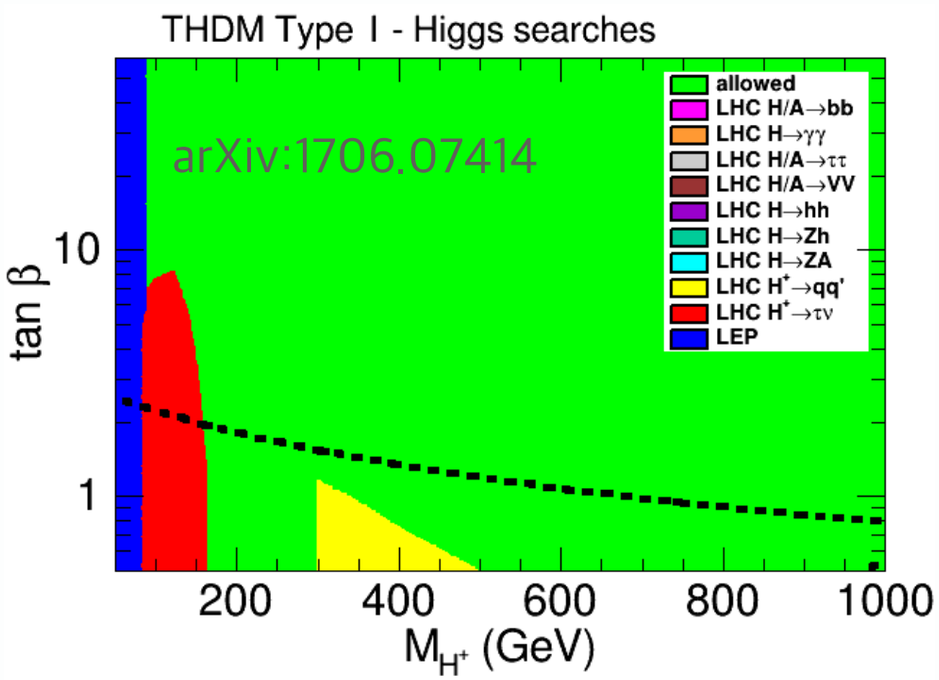
Previous Searches & Constraints

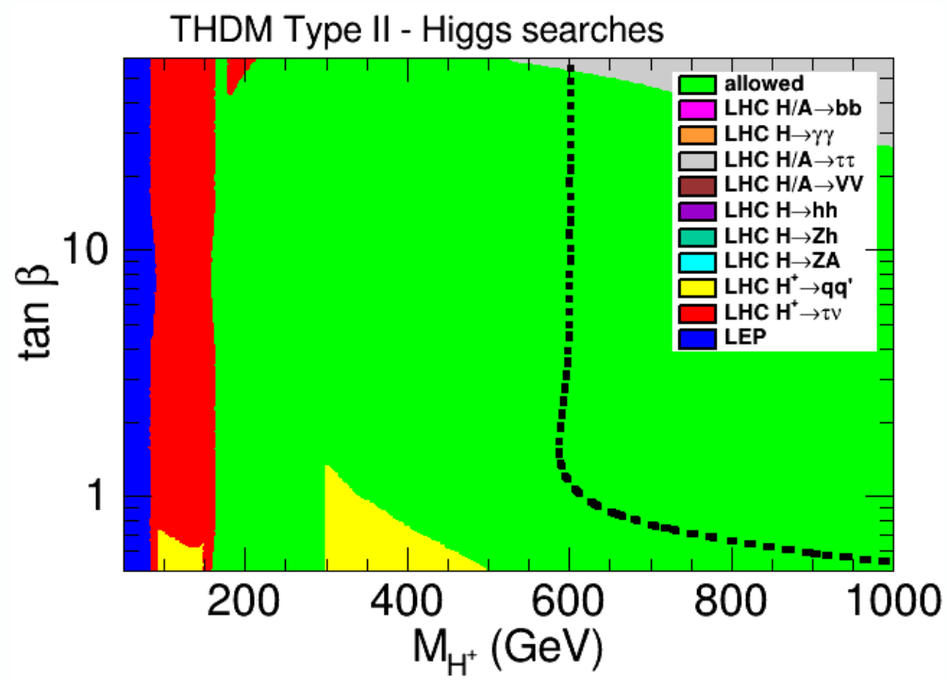
- Assuming MSSM-like relation between Higgs boson masses:





- Assuming m(H) = m(A) = 1 TeV:

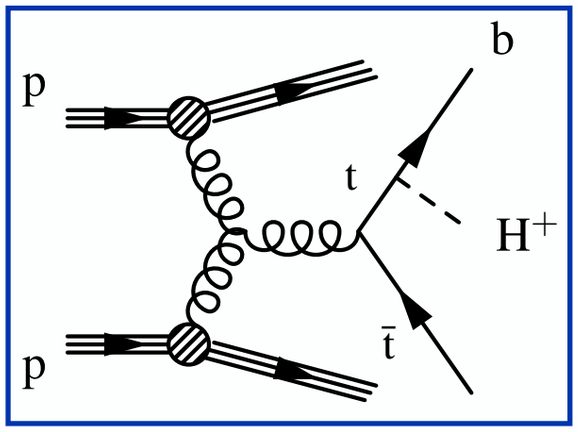


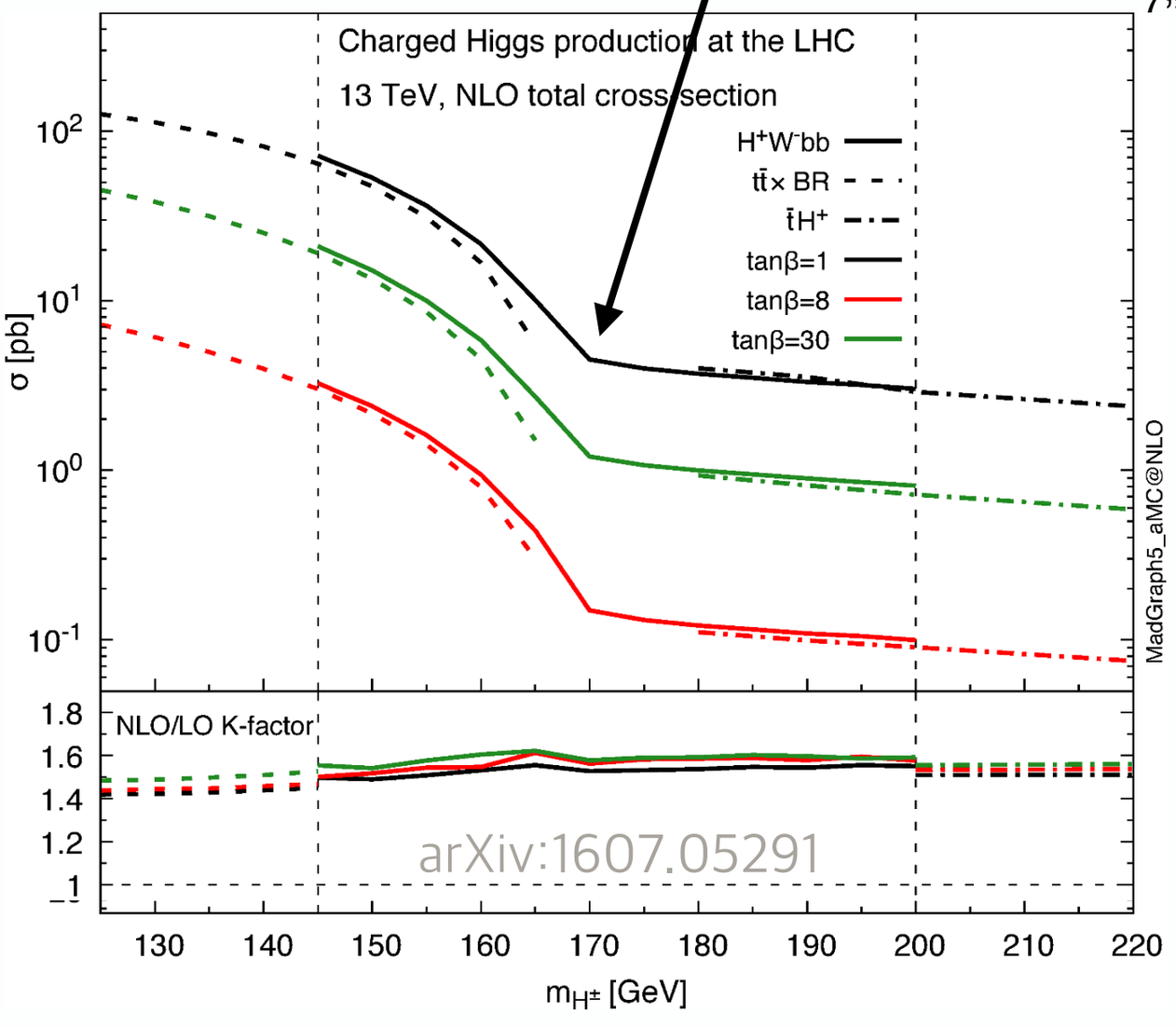


$H^{\pm}$ Production at the LHC

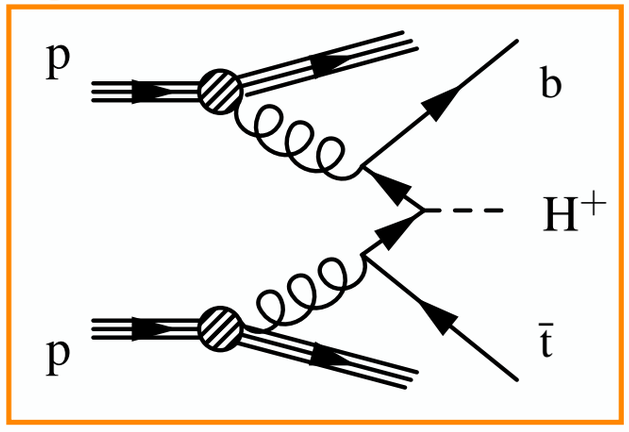
- **$H^{\pm}$ production mode** depends on its mass: $m_{H^+} = m_t - m_b$

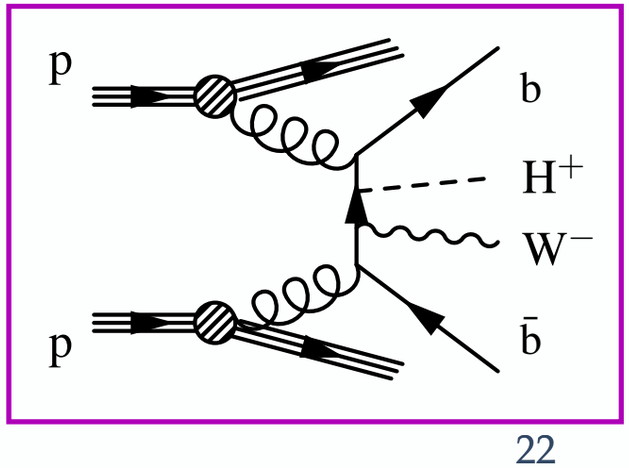
Light $H^{\pm}$ ($m_{H^+} < m_t - m_b$) dominantly produced in top quark decays (”**diresonant**” top production)





Heavy $H^{\pm}$ ($m_{H^+} > m_t - m_b$) dominantly produced in association with top quark (’”**single-resonant**” mode)

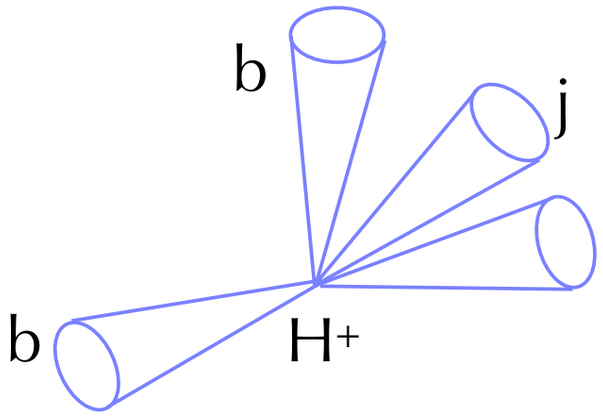




In **intermediate region** ($m_{H^+} \sim m_t$) the two processes **interfere** with the ”**nonresonant**" mode

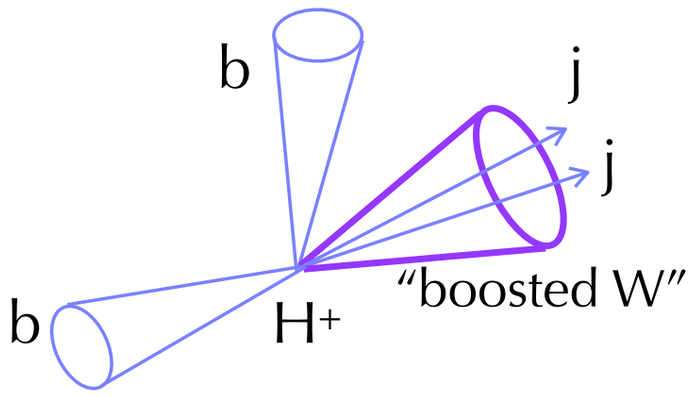
$H^{\pm} \rightarrow tb$: Hadronic final state

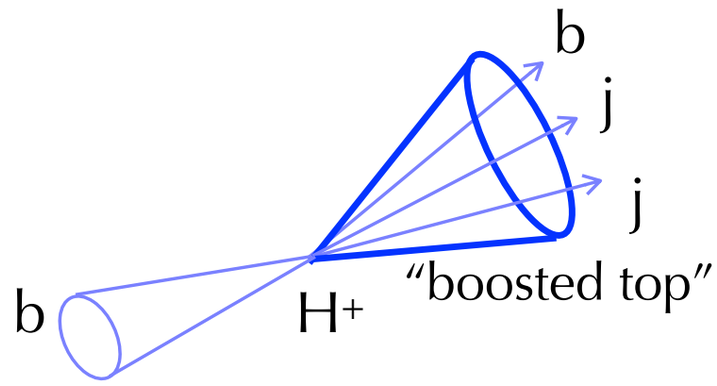
"Resolved" analysis



- BDT trained to **reconstruct top candidates from 3 AK4 jets**, requiring m(bjj)<400 GeV
- ≥7 jets, ≥3 b-jets, 2 top candidates
- $m_{H^{\pm}}$ reconstructed as m(tb) using the leading top quark and the leading free b-jet
- Dominating background with misidentified b jets estimated from a control region

"Boosted" analysis

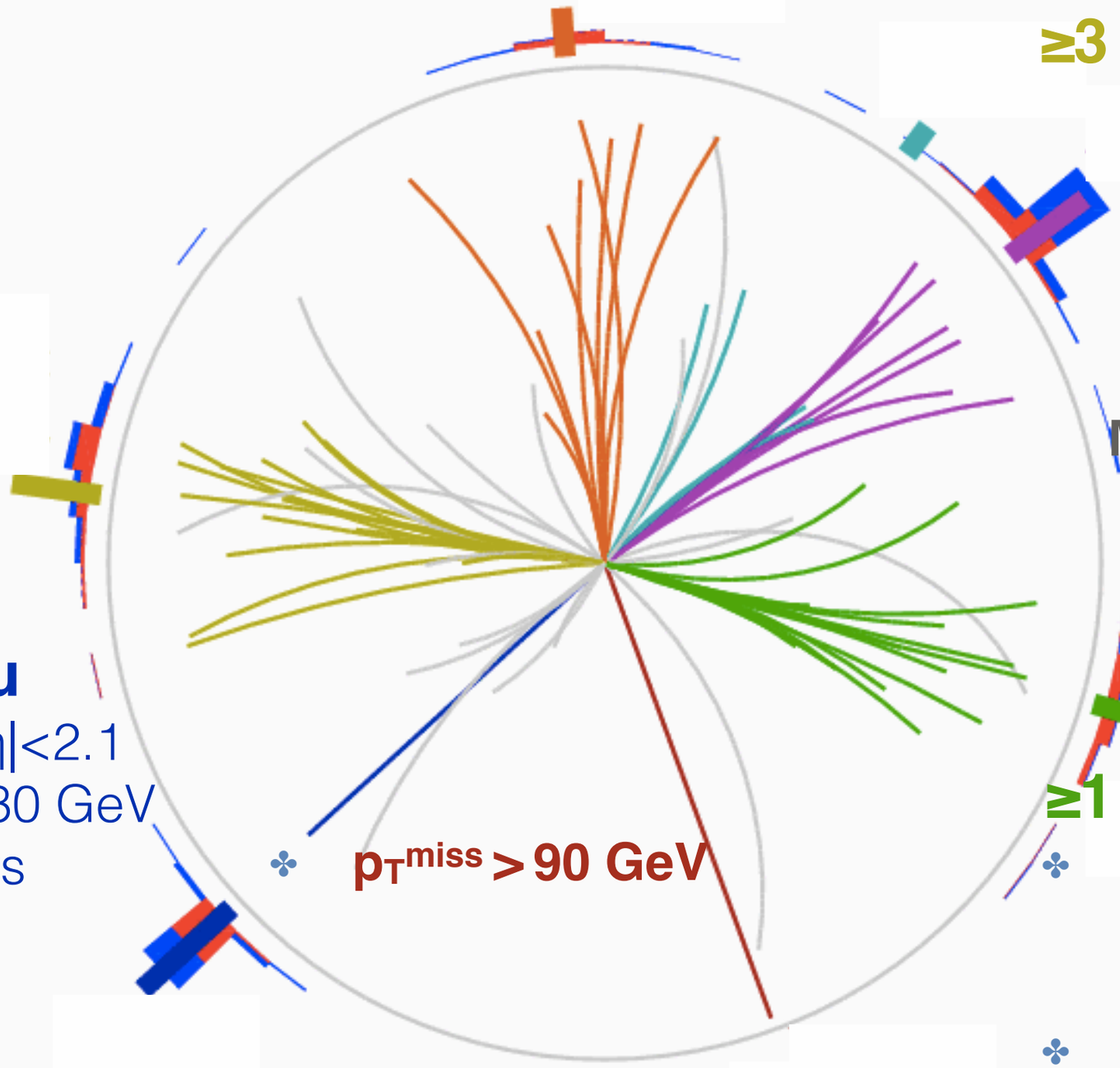




- W's and top quarks identified as AK8 jets
  - Soft-drop algorithm removes soft and wide-angle radiation
  - Jet mass, subjet b-tagging and N-subjettiness ratios τ_3/τ_2 and τ_2/τ_1 used to identify W and top candidates
- Extensive categorization based on the number of "top jets", "W jets", AK4 jets and b-jets
- $m_{H^{\pm}}$ used to define a **mass window** around the signal peak, sidebands used for QCD background estimation

$H^{\pm} \rightarrow \tau\nu$: Hadronic event selection

Tau + p_T^{miss} cross trigger + **offline selection** to target the hadronic final state:



Electron veto
- p_T >15 GeV
- $|\eta|$<2.5

≥3 hadronic jets
- p_T > 30 GeV
- $|\eta|$ < 4.7

Muon veto
- p_T > 10 GeV
- $|\eta|$<2.5

≥1 hadronic tau
- p_T > 50 GeV, $|\eta|$<2.1
- $p_T^{\text{leading track}}$ > 30 GeV
- 1-prong decays
- MVA-based ID & isolation

- **p_T^{miss} > 90 GeV**

≥1 b-jets
- b-tagging with Combined Secondary Vertex method (CSVv2)
- $|\eta|$ < 2.5

$H^{\pm} \rightarrow \tau\nu$: Background suppression

$H^{\pm}$ is a scalar while $W^{\pm}$ is a vector boson

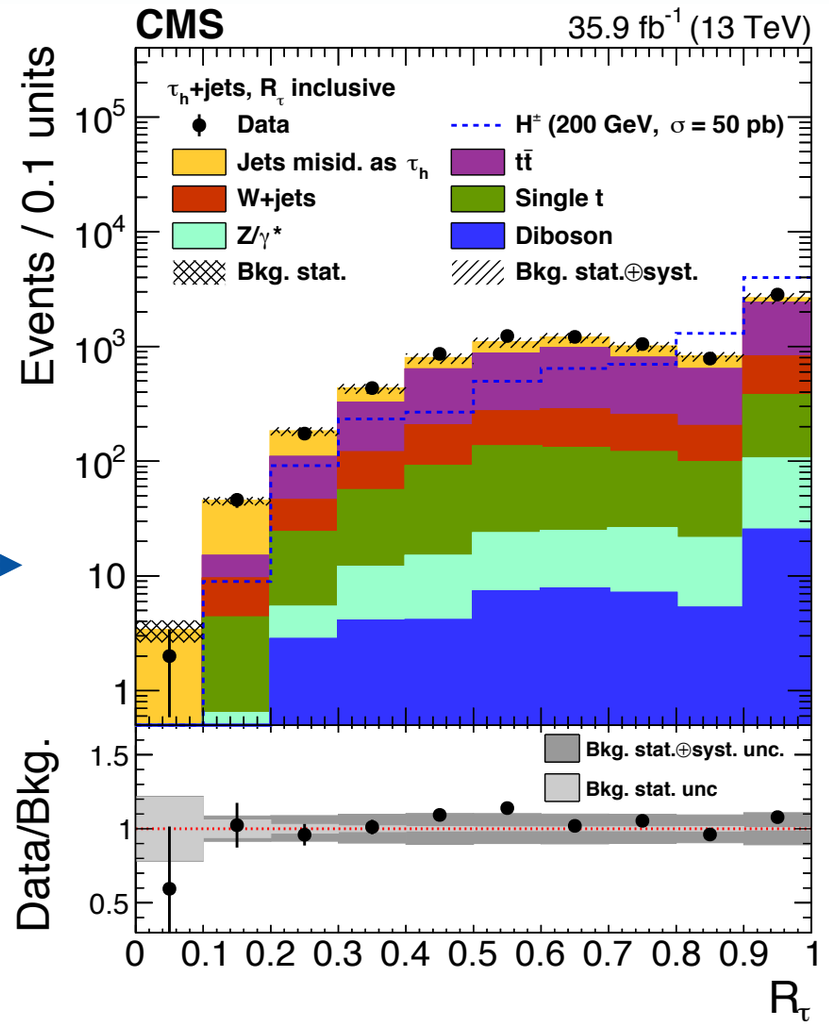
→**Different helicities** reflected in $\mathbf{R_T}$

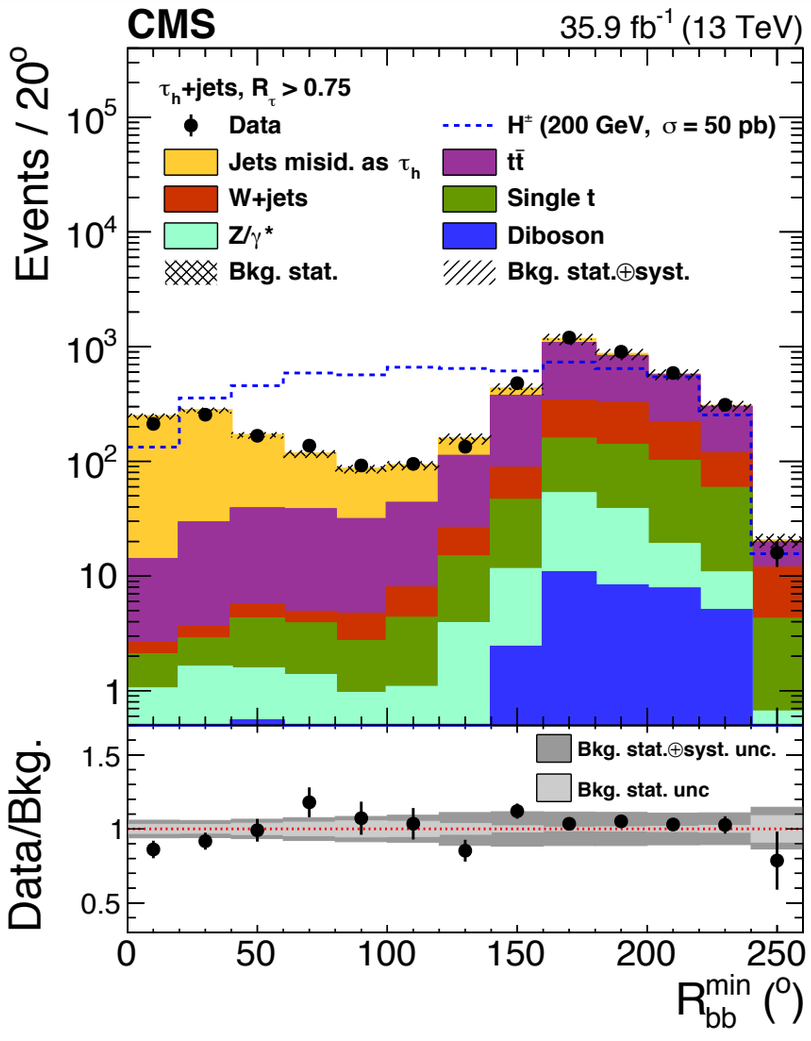
=**p(leading charged hadron)/p(τ_h)**

that has good discrimination power

→**Perform analysis in two categories**

divided by $\mathbf{R_T = 0.75}$

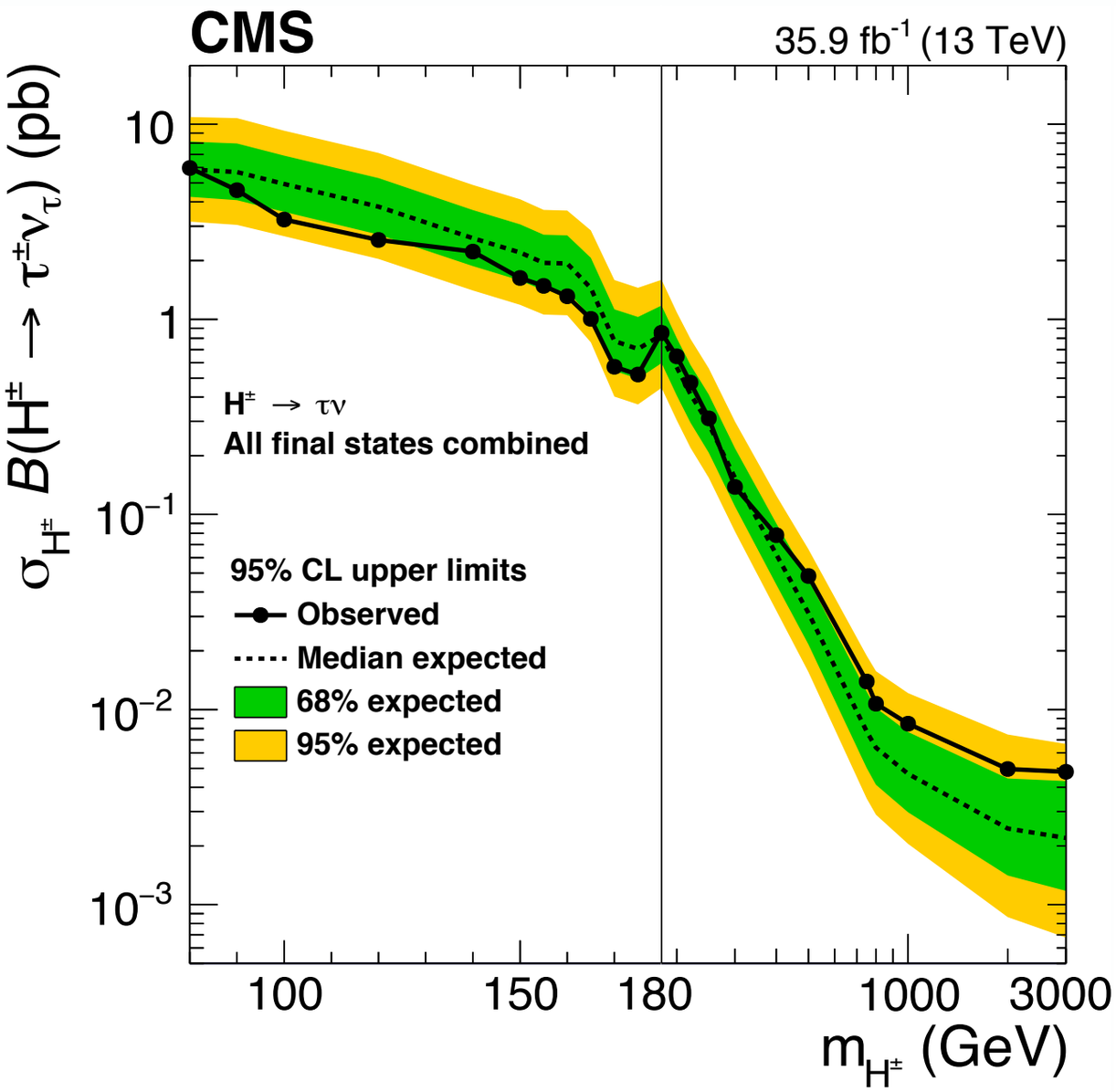




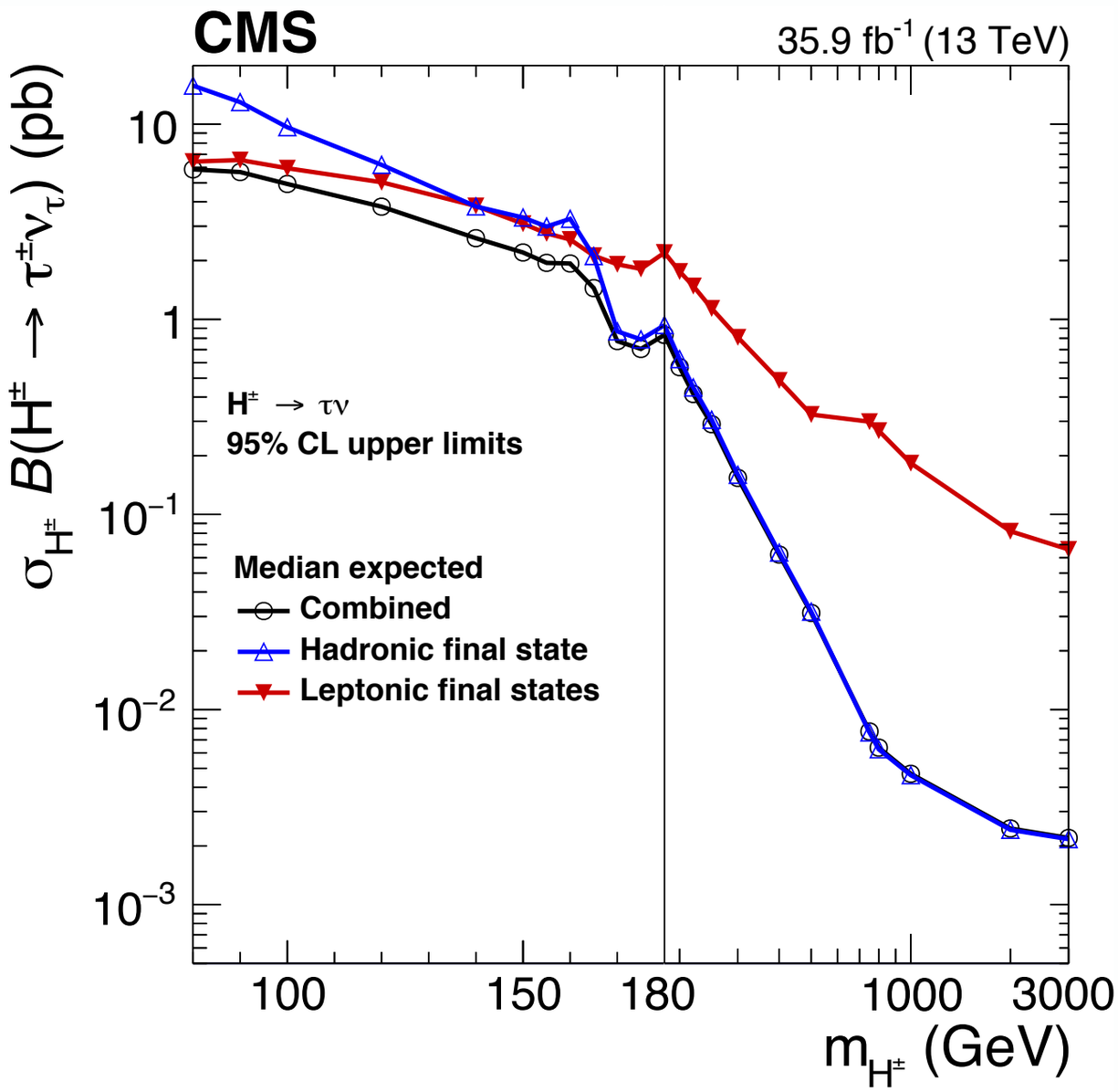
QCD multijet background supressed with $\mathbf{R_{bb}^{min} \geq 40^o}$ where

$$R_{\mathrm{bb}}^{\mathrm{min}} = \min_{n} \left\{ \sqrt{\left(180^\circ - \Delta\phi(\tau_{\mathrm{h}}, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})\right)^2 + \left(\Delta\phi(\mathrm{jet}_n, \vec{p}_{\mathrm{T}}^{\,\mathrm{miss}})\right)^2} \right\}$$

$H^{\pm} \rightarrow \tau\nu$: Combined results



- 95% CL upper limits on H+ production with **hadronic and leptonic final states combined**



- Expected median limits from the **leptonic** and **hadronic** final states separately and **combined**