Searches for charged Higgs bosons in *pp* collisions with the CMS and ATLAS detector

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on behalf of the ATLAS and CMS collaborations

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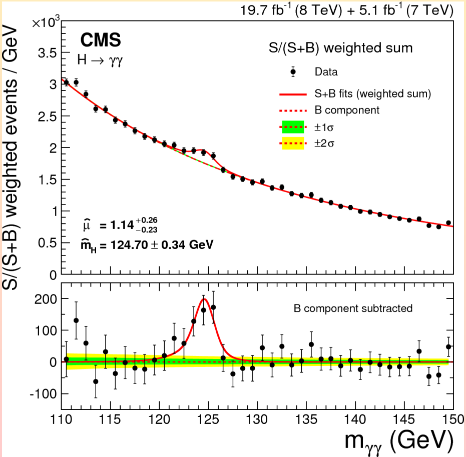
LHCP 2015 - St. Petersburg, Aug 31→Sep 6

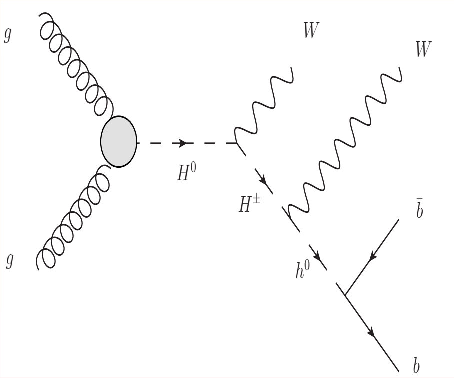
- A Higgs boson compatible with the SM one has been found at the LHC
  it might not be the only one!
- Multi-Higgs models might explain experimental observations
  - **Baryon asymmetry:** explicit and spontaneous CP violation.
  - **Dark matter:** dark matter candidates from doublets w/out a VEV
  - **Neutrino oscillations:** masses generated at $\geq$ 1 loop
- Minimal Supersymmetric Standard Model (MSSM) is the minimal extension: h, H, A, H^+, H^-
  - One characteristic parameter: $tan\beta$ (ratio of VeVs of neutral Higgses)
  - **After** $h(125)$**, Higgs sector can be described using only** $m_{\mathrm{H}+}$ **and** $tan\beta$**: `hMSSM` [1]**
  - No prediction $\rightarrow$ need to scan full parameter phase space



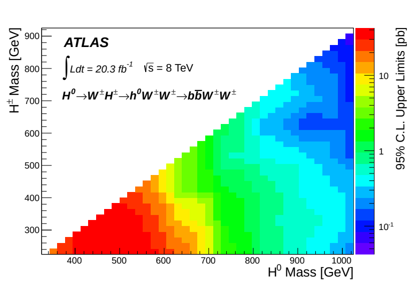
- The discovery of a charged Higgs boson would be an unequivocal signal of new physics
- Main charged Higgs boson search channels
  - Vector boson fusion/decay
    - Cascade decays involving $h^0(125)$
    - VBF production, decay to $\mathrm{W}^{\pm}\mathrm{Z}$
  - Top quark production and decay
    - In top quark decays if $m_{\mathrm{H}\pm} < m_{top}$
    - Associated production $\mathrm{t(b)H}^+$ if $m_{\mathrm{H}\pm} > m_{top}$

Multi-Higgs boson cascade
Phys. Rev. D 89, 032002 [2]

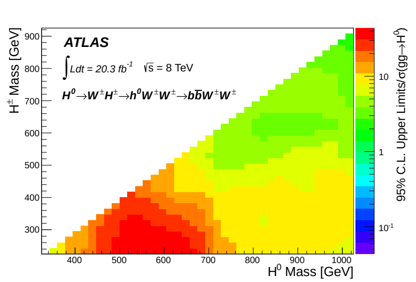
- Assume $\mathrm{h}(125)$ Higgs boson, and no particular model for additional bosons
- $(\mathrm{W} \to \ell\nu)(\mathrm{W} \to \mathrm{q}\bar{\mathrm{q}}')\mathrm{b}\bar{\mathrm{b}}$ final states
- **Selection:** $\geq$ 4 jets (2 of them b-tagged), 1 lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$
- **Background determination:** BDT trained for each signal mass using variables from cascade decay



Better exclusion limits at high mass

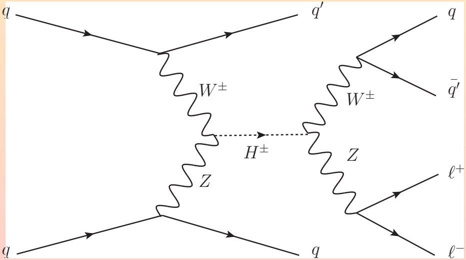


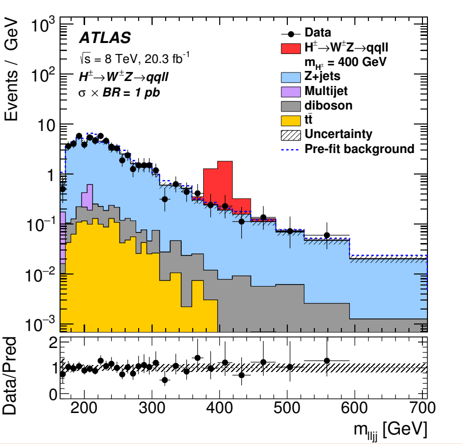
Observed limits greater than NNLO ($gg \to H^0$ at SM rate) for all mass points



- Decay allowed at tree level in Higgs Triplet Models
- Search for $(Z \to \ell^+\ell^-)(W \to q\bar{q}')q\bar{q}'$ final states and M_{H^+} [200, 1000] GeV

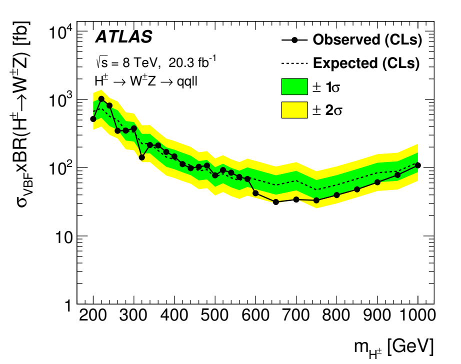
- $\geq$ 4 jets
  - 2 non-b-tagged jets in opposite hemispheres
  - 2 highest p_T remaining jets: assumed $W \to q\bar{q}'$
  - $60 < m_{q\bar{q}'} < 95$ GeV
- $= 2$ isolated leptons ($e^\pm$,$\mu^\pm$)
  - $83 < m_{\ell\ell} < 99$ GeV





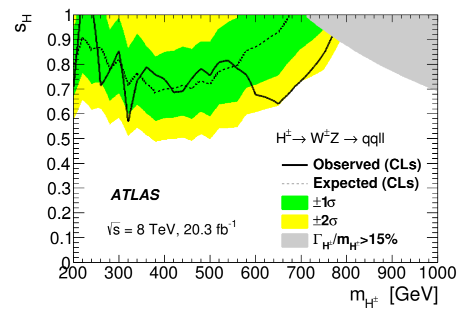
$\mathrm{H}^{\pm} \to \mathrm{W}^{\pm}\mathrm{Z}$ in vector boson fusion - 2/2
[Phys. Rev. Lett. 114, 231801 (2015)] [3]

Exclusion limits



- Observed limits on $\sigma_{VBF} \times \mathcal{B}(\mathrm{H}^{\pm} \to \mathrm{W}^{\pm}\mathrm{Z})$ vary between 31 – 1020 fb
- 6 times better than ATLAS inclusive WZ search for $m_{\mathrm{H}^{\pm}} < 800$ GeV

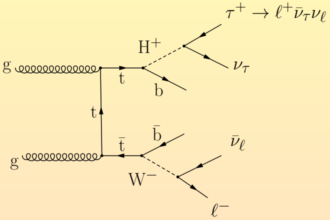
Interpretation in Higgs triplet model

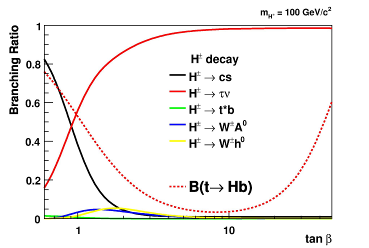


- Georgi-Machacek triplet model
- s_H^2: fraction of m_{W}^2 and m_{Z}^2 generated by the triplet v.e.v.
- $s_H^2 \propto$ cross section and $H^{\pm}$ width
- $\mathcal{B}(\mathrm{H}^{\pm} \to \mathrm{W}^{\pm}\mathrm{Z}) = 1$ assumed (predicted to be very high when above $\mathrm{W}^{\pm}\mathrm{Z}$ threshold)

Searching for charged Higgs using top quarks

- H^+ can be produced after top quark decays if $M_{\mathrm{H}^+} < M_t - M_b$
- Tau or charmed final states expected depending on $tan\beta$

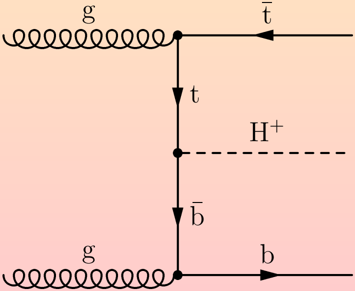




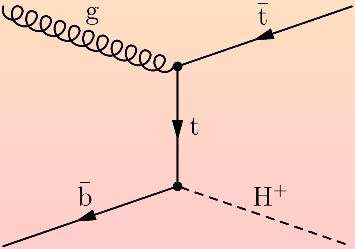
(from `D0 Note 5715-CONF`)

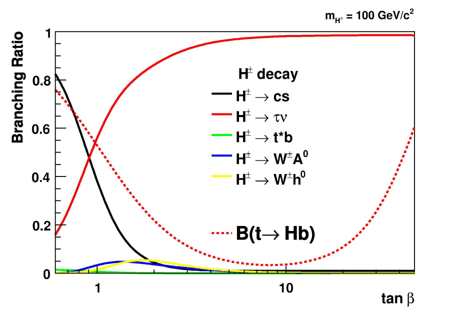
- H^+ can be produced in association with top quarks if $M_{\mathrm{H}^+} > M_t - M_b$

4FS similar to ttH production



5FS dominates (similar to tW production)

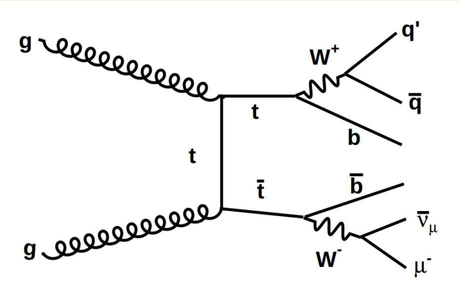


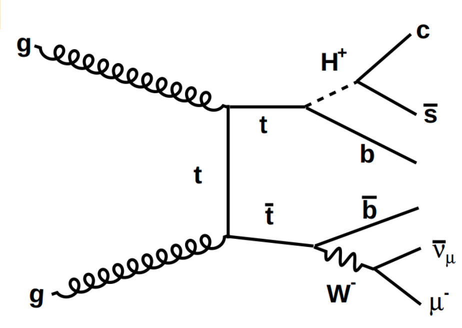


(from D0 Note 5715-CONF)

Searching for a light H^+

$tan\beta < 1$: search with $c\bar{s}$ final states





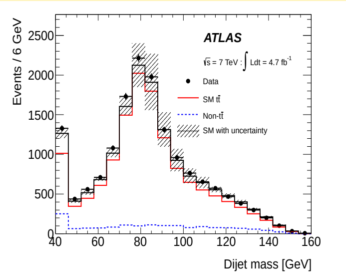
(Plots from [9])

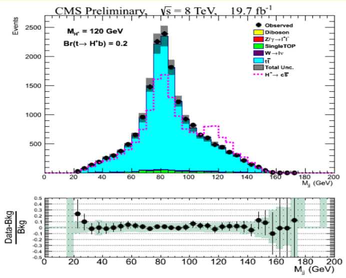
Light H^+ w/ $tan\beta < 1$: $c\bar{s}$ decay mode in ℓ+jets final state

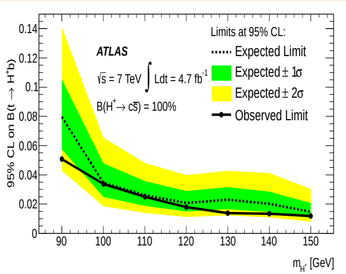
- **Selection (ATLAS):** $= 1$ lepton (e, μ), ≥ 4 jets, ≥ 2 b-tagged jets, E_T^{miss}, $M_T(\ell, E_T^{miss})$
- **Selection (CMS):** ≥ 1 lepton, veto additional loose leptons, ≥ 4 jets, ≥ 2 b-tagged jets, E_T^{miss}
- **W/Z mass reconstruction:** separate signal from $t\bar{t}$ main background through final state reconstruction

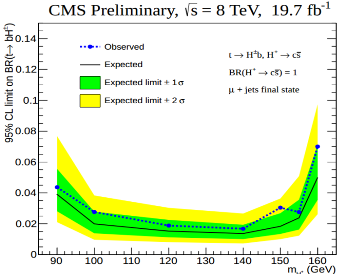
Eur. Phys. J. C, 73 6 (2013) 2465 [4]

CMS-HIG-13-035 [9]



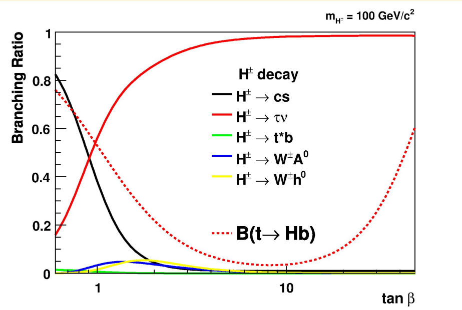




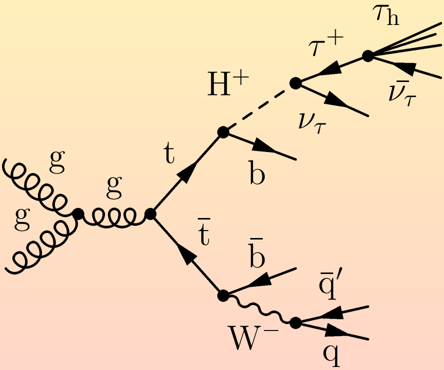


Searching for a light $\mathrm{H}^{\pm}$ when $tan\beta > 1$

- For $m_{\mathrm{H}^+} < m_{top}$, $\mathrm{H}^+ \rightarrow \tau^+\nu_\tau$ decay mode is dominant for any $tan\beta$
- The most sensitive final state is τ_h+jets
- $\mu\tau_h$ final state contributed at 7 TeV [7], but is not competitive at 8 TeV



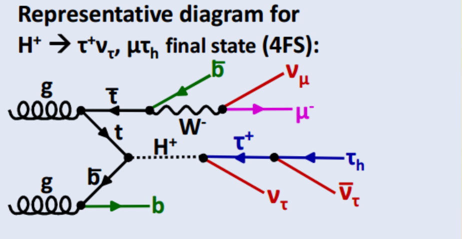
(from D0 Note 5715-CONF)

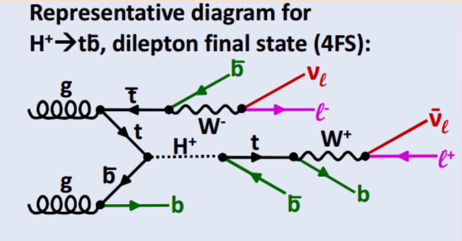


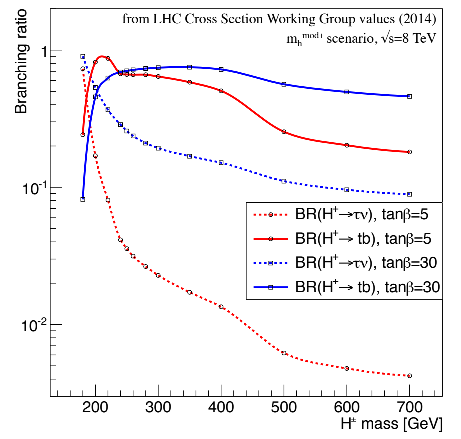
(From [8])

Searching for a heavy $\mathrm{H}^{\pm}$

- In most of the MSSM models, $\frac{\mathcal{B}(\mathrm{H}^+\to t\bar{b})}{\mathcal{B}(\mathrm{H}^+\to\tau^+\nu_\tau)} > 5$ for $\tan\beta > 8$
- $\mathrm{H}^+ \to t\bar{b}$ decay mode probed via $\mu\tau_h$, dilepton, and ℓ+jets final states
  - Extra b-jet multiplicity and changes in $\mathrm{t\bar{t}}$ kinematics and acceptance enhance sensitivity to H^+ in production of $t\bar{b}$
- $\mathrm{H}^+ \to \tau^+\nu_\tau$ decay mode probed mainly via τ_h+jets ($\mu\tau_h$ and dilepton far less sensitive, ℓ+jets not studied)

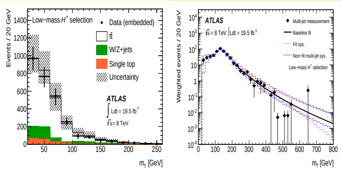


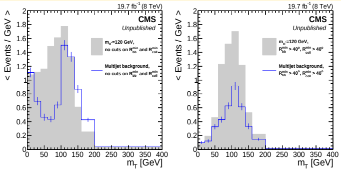


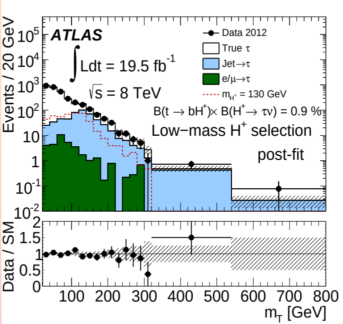


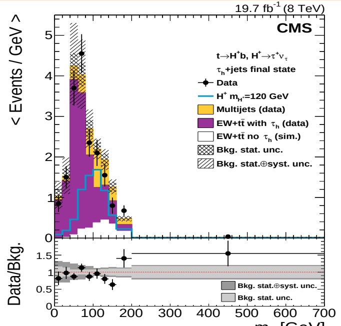
τ_h+jets final state

- **CMS (arXiv:1508.07774 [8]):** 1 τ_h, $\geq$ 3 jets, veto leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$
- **ATLAS (JHEP03 (2015) 088 [5]):** 1τ_h, $\geq$ 4(3) jets (low(high)-mass), veto leptons, $\geq$ 1 b-tagged jets, $E_{\mathrm{T}}^{\mathrm{miss}}$
- **Dominant backgrounds (EWK and multijets):** measured from data
- **Multijet background control:** via fit in control region (ATLAS, CMS) and angular cuts (CMS)
- **Model independent:** decay modes other than $\mathrm{H}^+ \to \tau^+\nu_\tau$ included in data driven estimate







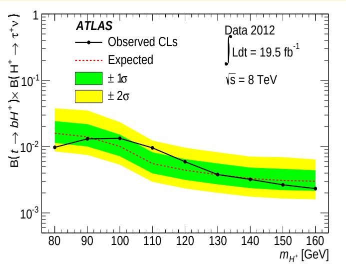


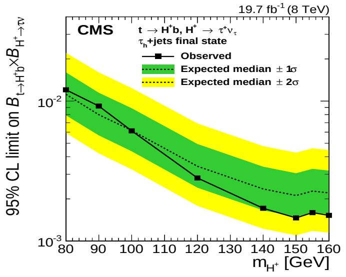
τ_h+jets final state - results

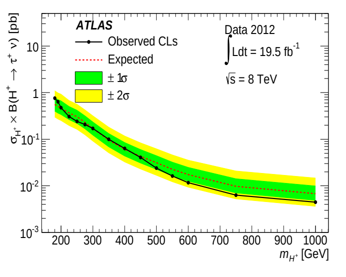
- CMS has better sensitivity in the central mass range $m_{\mathrm{H}^+} = 90 - 400$ GeV
- ATLAS has better sensitivity for $m_{\mathrm{H}^+} < 90$ GeV and in the high mass range $m_{\mathrm{H}^+} > 400$ GeV

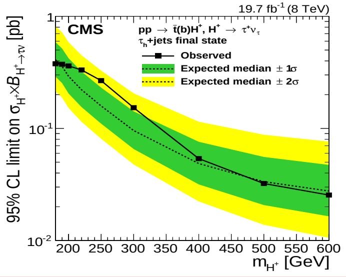
JHEP03 (2015) 088 [5]

arXiv:1508.07774 [8]







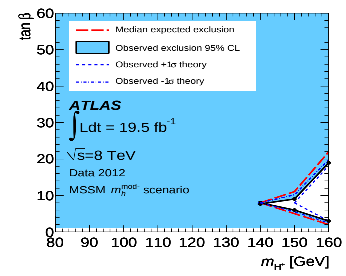


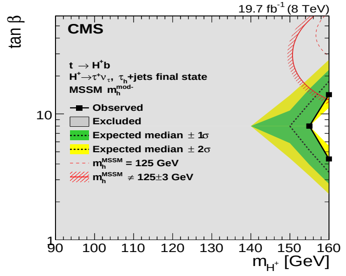
τ_h+jets final state - interpretations

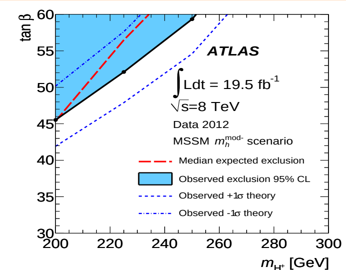
- Model-independent upper limits are computed for $\mathcal{B}(t \to \mathrm{H}^+ b) \times \mathcal{B}(\mathrm{H}^+ \to \tau\nu)$
- Limits are then interpreted as exclusion region in $(m_{\mathrm{H}^+} - tan\beta)$ plane for the m_{h}^{mod-} scenario
- Not much space left available in the parameter space for low mass. $tan\beta \leq 1$ excluded for $m_{\mathrm{H}^+} < 250$ GeV

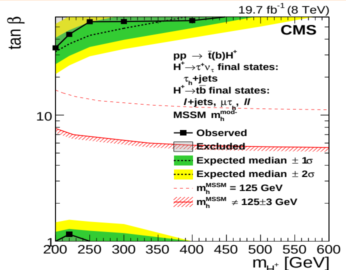
JHEP03 (2015) 088 [5]

arXiv:1508.07774 [8]



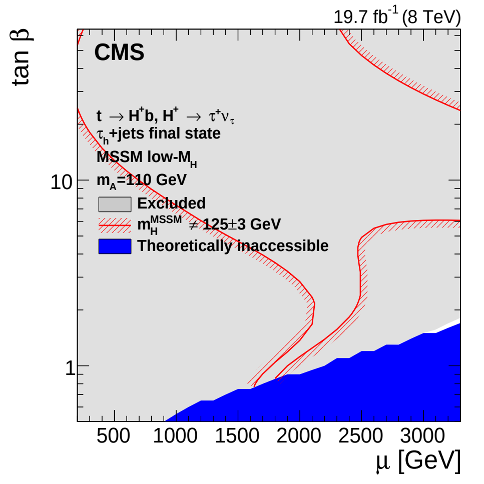






- Low-M_{H} scenario with $m_A = 110$ GeV completely excluded (CMS [8])
- Completely excluded also by ATLAS [5]

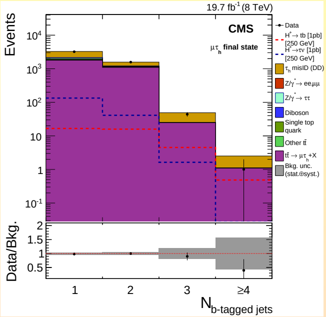
arXiv:1508.07774 [8]



$\mu\tau_h$ and ℓ+jets final states (CMS: arXiv:1508.07774 [8])

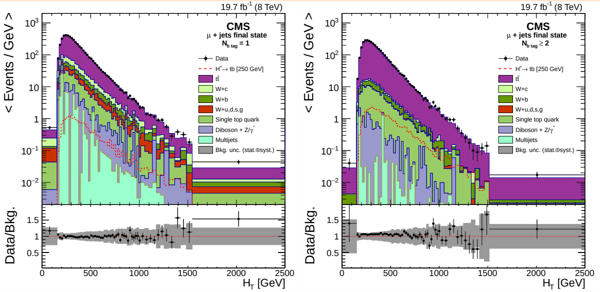
- $\mu\tau_h$ **final state:** more sensitive to $\mathrm{H}^+ \to \tau^+\nu_\tau$ decay mode
  - **Offline selection:** 1 isolated muon, veto loose leptons, $\geq$ 2 jets, E_T^{miss}, $\geq$ 1 b-tags, $1\tau_h$, opposite sign
  - **Backgrounds:** misidentified τ_h component estimated from data
  - Improved estimation of the tau fake rate by fully accounting for quark/gluon composition in the sample

N_{b-tags}: better sensitivity for $\mu\tau_h$



- ℓ**+jets final state:** sensitive to $\mathrm{H}^+ \to t\bar{b}$ decay mode
  - **Selection:** 1 lepton (e, μ), $\geq$ 2 jets, $\geq$ 1 b-tagged jets, $E_\mathrm{T}^{\mathrm{miss}} \geq 20$ GeV
  - **Backgrounds:** $\mathrm{t\bar{t}}$, $\mathrm{W} + \mathrm{c}/b$, W+light flavours determined via simultaneous fit from data
  - Insensitive to the $\mathrm{H}^+ \to \tau^+\nu_\tau$ decay mode

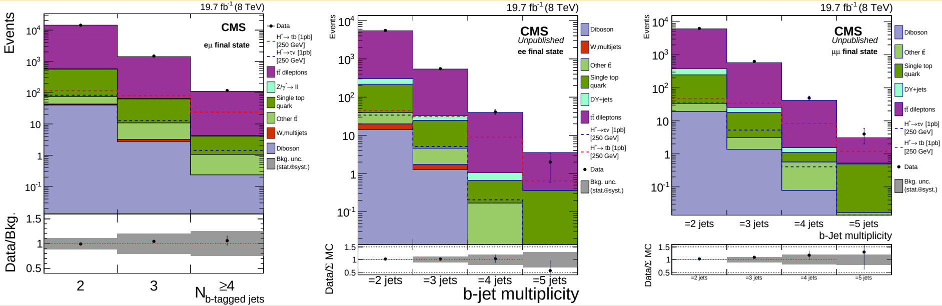
H_T, split in $= 1/\geq 2$ b-tags: better sensitivity for ℓ+jets



Dilepton final state (CMS: arXiv:1508.07774 [8])

- More sensitive to $\mathrm{H}^+ \to t\bar{b}$ decay mode
  - **Selection:** 1$e\mu$ pair, $\geq$ 2 jets, veto low $e\mu$ masses, opposite sign
  - **Backgrounds:** large irreducible $\mathrm{t\bar{t}}$, minor single top and Drell-Yan contamination
  - **Tighter $N_{b\ tags}$ requirement** yields better sensitivity to $\mathrm{H}^+ \to t\bar{b}$ decay mode than the $\mu\tau_h$ final state

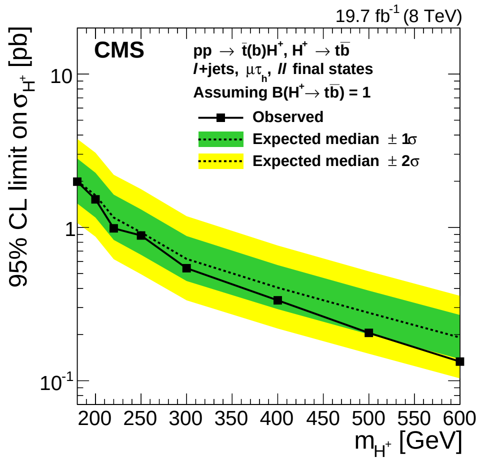
N_{b-tags}: better sensitivity for dilepton



Single-contributing channel approach: $\mu\tau + e\mu + ee + \mu\mu + \ell$+jets
CMS: arXiv:1508.07774 [8]

- Each channel is allowed to contribute exclusively
- Assume that one of them has $\mathcal{B} = 1$ and the other has $\mathcal{B} = 0$
- First direct search ever for $\mathrm{H}^+ \to tb$ decay mode (CMS)

arXiv:1508.07774 [8]



Summary

- Charged Higgs boson searched for in a large spectrum of production/decay modes
- Vector boson fusion/decay and cascade decays involving $h(125)$
  - $\sigma(gg \to \mathrm{H}^0) \times \mathcal{B}(\mathrm{H}^0 \to \mathrm{W}^\mp \mathrm{H}^\pm \to \mathrm{W}^\pm \mathrm{W}^\mp \mathrm{h}^0 \to \mathrm{W}^\pm \mathrm{W}^\mp \mathrm{b\bar{b}}) \leq 0.065 - 43$ pb (ATLAS [2])
  - $\sigma_{VBF} \times \mathcal{B}(\mathrm{H}^\pm \to \mathrm{W}^\pm \mathrm{Z}) \leq 31 - 1020$ fb (ATLAS [3])
- Charged Higgs boson in top quark production/decay modes
- $\mathrm{H}^+ \to \mathrm{c\bar{s}}$ decay mode: Low $tan\beta$: $\mathcal{B}(\mathrm{t} \to \mathrm{H}^+\mathrm{b}) \leq 4 - 2\%$ (ATLAS [4], CMS [9])
- $\mathrm{H}^+ \to \tau^+\nu_\tau$ decay mode: τ_h+jets final state has the best sensitivity
  - Low m_{H^+}: $\mathcal{B}(\mathrm{t} \to \mathrm{H}^+\mathrm{b}) \times \mathcal{B}(\mathrm{H}^+ \to \tau^+\nu_\tau) \leq 1 - 0.1\%$ (ATLAS [5], CMS [8])
  - ATLAS more sensitive in the tails, CMS more sensitive for $m_{\mathrm{H}^+} = 90 - 400$ GeV
- $\mathrm{H}^+ \to t\bar{b}$ decay mode: first direct search ever for this decay mode (CMS [8])
  - $\sigma(pp \to \bar{\mathrm{t}}(\mathrm{b})\mathrm{H}^+) \leq 4 - 0.5$ pb (assuming $\mathcal{B}(\mathrm{H}^+ \to t\bar{b}) = 1$)
- $\mathrm{H}^+ \to \tau^+\nu_\tau$ and $\mathrm{H}^+ \to t\bar{b}$ results interpreted in MSSM scenarios
  - Phase space for m_{h}^{max} and $m_{\mathrm{h}}^{mod\pm}$ severely constrained
  - $tan\beta \leq 1$ ruled out for $m_{\mathrm{H}^+} < 250$ GeV
  - low-M_{H} scenario completely ruled out (ATLAS [5], CMS [8])
- Charged Higgs not found (yet ☺): stay tuned for 13 TeV new exciting searches!

THANKS FOR THE ATTENTION!

Awesome russian cat from a cafeteria 5 minutes from here

References I

Djouadi, A., Maiani, L., Moreau, G., Polosa, A., Quevillon, J., Riquer, V.
The post-Higgs MSSM scenario: habemus MSSM?
The European Physical Journal. C, Particles and Fields, 73(12), 2650.
[doi:10.1140/epjc/s10052-013-2650-0]

ATLAS Collaboration,,
Search for a multi-Higgs-boson cascade in $W^+W^-b\bar{b}$ events with the ATLAS detector in pp collisions at $\sqrt{s} = 8 \text{ TeV}$
Phys. Rev. D, 89 032002. [doi:10.1103/PhysRevD.89.032002]

ATLAS Collaboration,
Search for a Charged Higgs Boson Produced in the Vector-Boson Fusion Mode with Decay $H^\pm \to W^\pm Z$ using pp Collisions at $\sqrt{s} = 8 \text{ TeV}$ with the ATLAS Experiment
Phys. Rev. Lett. 114, 231801 (2015). [doi:10.1103/PhysRevLett.114.231801]

ATLAS Collaboration,
Search for a light charged Higgs boson in the decay channel $H^+ \to c\bar{s}$ in $\mathrm{t\bar{t}}$ events using pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ with the ATLAS detector
The European Physical Journal C 73 6 (2013) 2465.
[doi:10.1140/epjc/s10052-013-2465-z]

ATLAS Collaboration,
Search for charged Higgs bosons decaying via $chiggspm \to \tau^\pm \nu$ in fully hadronic final states using pp collision data at $\sqrt{s} = 8 TeV$ with the ATLAS detector
Journal of High Energy Physics 03 (2015) 88. [doi:10.1007/JHEP03(2015)088]

References II

CMS Collaboration.

Search for a light charged Higgs boson in top quark decays in *pp* collisions at $\sqrt{s} = 7$ *TeV*

Journal of High Energy Physics, 07 (2012) 143.

CMS Collaboration

Updated search for a light charged Higgs boson in top quark decays in *pp* collisions at $\sqrt{s} = 7$ *TeV*

CMS-PAS-HIG-12-052, [CDS:1502246]

CMS Collaboration,

Search for a charged Higgs boson in pp collisions at $\sqrt{s} = 8$ TeV

Submitted to J. High Energy Phys.. [arXiv:1508.07774]

CMS Collaboration

Search for H^{+} to cs-bar decay

CMS-PAS-HIG-13-035, [CDS:1728343]

Roy, D.P.

Looking for the charged Higgs boson

doi Mod. Phys. Lett, A19, 1813-1828, 2004 [arXiv:hep-ph/0406102]

CMS Collaboration

8 TeV Jet Energy Corrections and Uncertainties based on 19.8 fb^{-1} of data in CMS

CMS-DP-2013-033, [CDS:1627305]

References III

CMS Collaboration
Jet Energy Corrections and Uncertainties. Detector Performance Plots for 2012.
CMS-DP-2012-012, [CDS:1460989]

CMS Collaboration
CMS Particle Flow and Tau Identification Results
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsPFT

CMS Collaboration
Performance of quark/gluon discrimination in 8 TeV pp data
CMS-PAS-JME-13-002, [CDS:1599732]

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