Search for charged Higgs Bosons with the ATLAS detector

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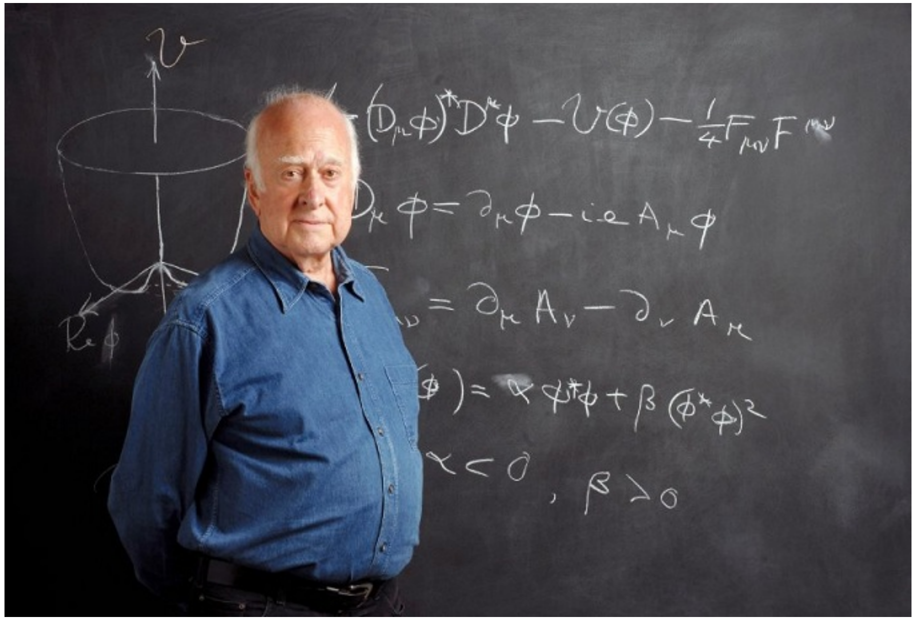
Motivation

- After the discovery of the 125 GeV Higgs resonance the SM is complete.
- As many things remain unexplained in the SM, BSM theories are very plausible, as SUSY.
- An extended Higgs sector is very common in most BSM theories.
- 2HDM (Minimal extension giving rise to charged scalars): Two complex scalar doublets with 5 Higgs bosons:
  - 2 CP-even Higgs bosons (h,H), one of which is the discovered 125 GeV resonance
  - 1 CP-odd pseudoscalar (A)
  - Two charged Higgs bosons ($H^{\pm}$)



$\tan\beta$ is the ratio of the vacuum expectation values (vev) of the two doublets and α is the mixing angle between the two CP-even Higgs bosons.

MSSM is a special case of 2HDM: “type II” with fixed mixing between h and H.

Motivation

- More complex extensions: Add Higgs triplet to SM

10 Higgs bosons,

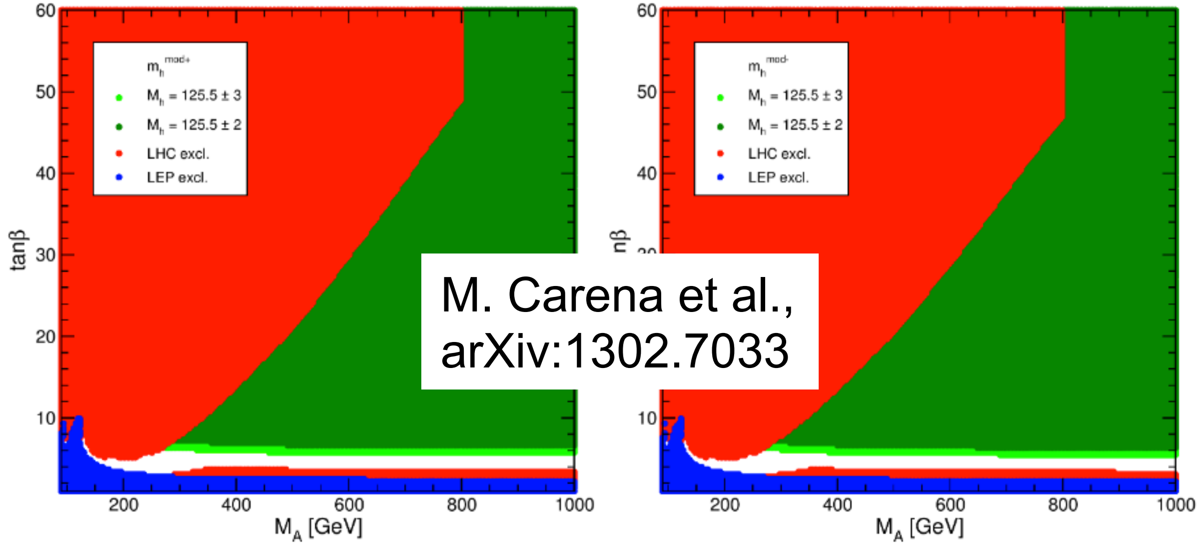
4 charged $H^{\pm}$, $H^{\pm\pm}$ (Doubly charged Higgs bosons)

Other extensions with $H^{\pm\pm}$:

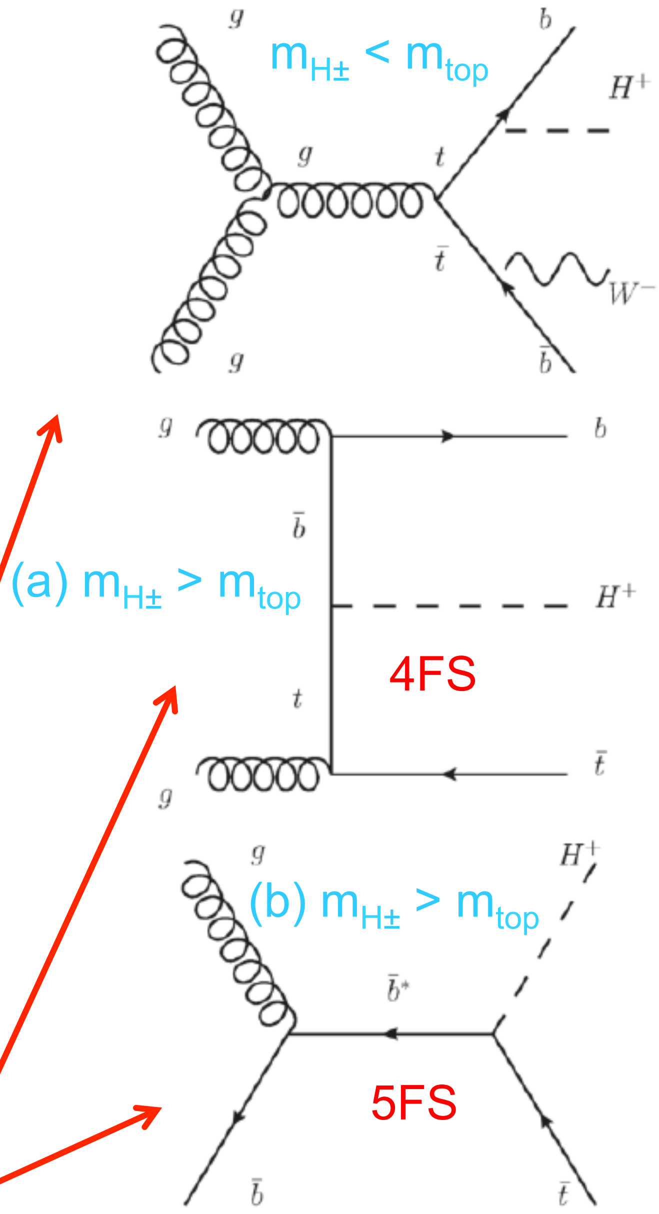
- left-right symmetric models,
- little Higgs model,
- type-II see-saw models,
- Georgi-Machacek model.
- Scalar singlet dark matter,
- Zee-Babu neutrino mass model.

ATLAS search for H±

- The m_A-tanβ plane in the m_h^{mod+} (left) and m_h^{mod-} (right) scenarios.
  The colors show exclusion regions from LEP (blue) and the LHC (red), and the favoured region $M_h = 125.5 \pm 2(3)$ GeV (green).



M. Carena et al., arXiv:1302.7033



- The decay $H^\pm \rightarrow \tau\nu$ is relevant in a large parameter range, specially for low $m_{H\pm}$ (below m_{top})
- For $m_{H\pm}$ above m_{top} (searches presented here) $H^\pm \rightarrow tb$ is the predominant decay

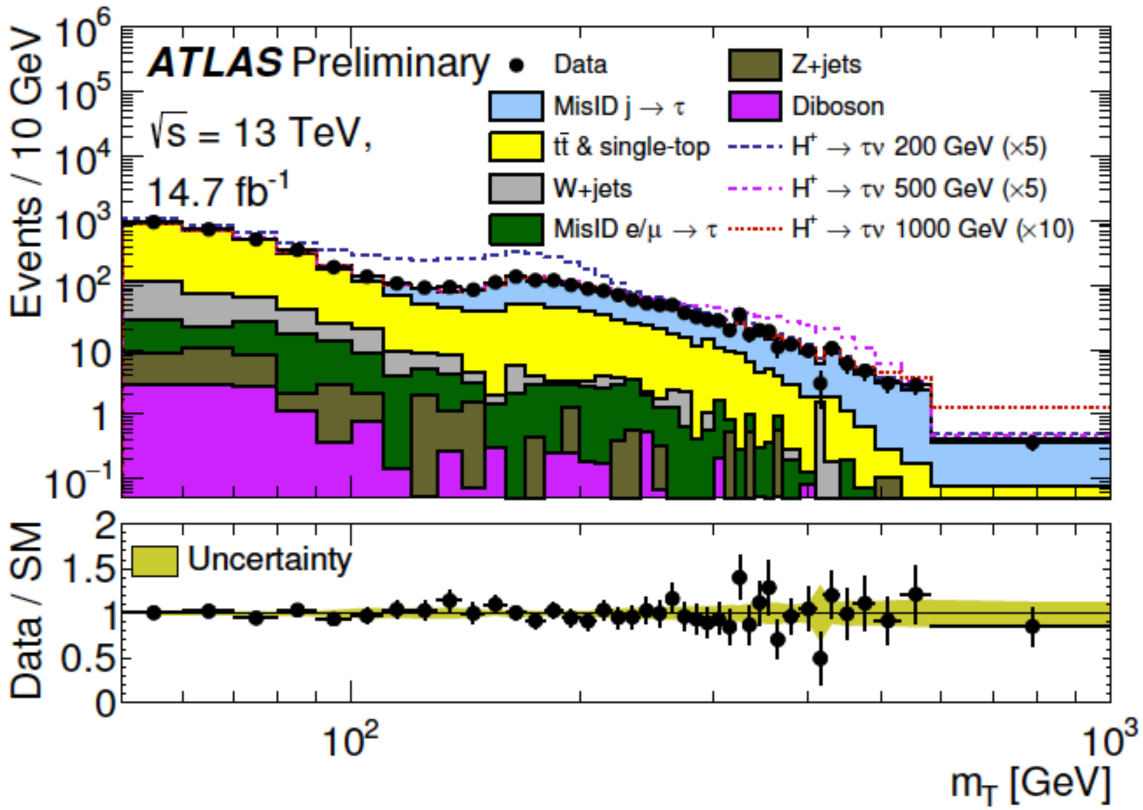
Search for $H^{\pm} \rightarrow \tau\nu$

14.7 fb^{-1} @ 13 TeV
ATLAS-CONF-2016-088

- Strategy:
  - "tau+jets" channel: one hadronic τ and jets from the hadronic top.
  - $200 \leq m_{H+} \leq 2000$ GeV
  - Discriminating variable

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi_{\tau, E_{\mathrm{T}}^{\mathrm{miss}}})}$$

- Signal selection:
  - E_T^{miss} trigger
  - 1 hadronic τ (p_T > 40 GeV)
  - ≥ 3 jets (p_T>25 GeV), of which ≥ 1b-tagged (70% eff).
  - Veto e, μ
  - E_t^{miss} > 150 GeV

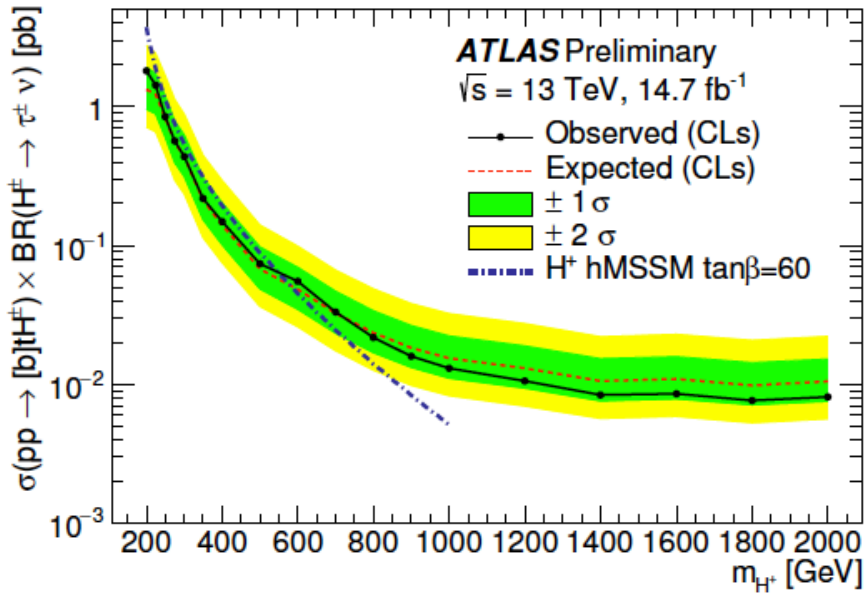


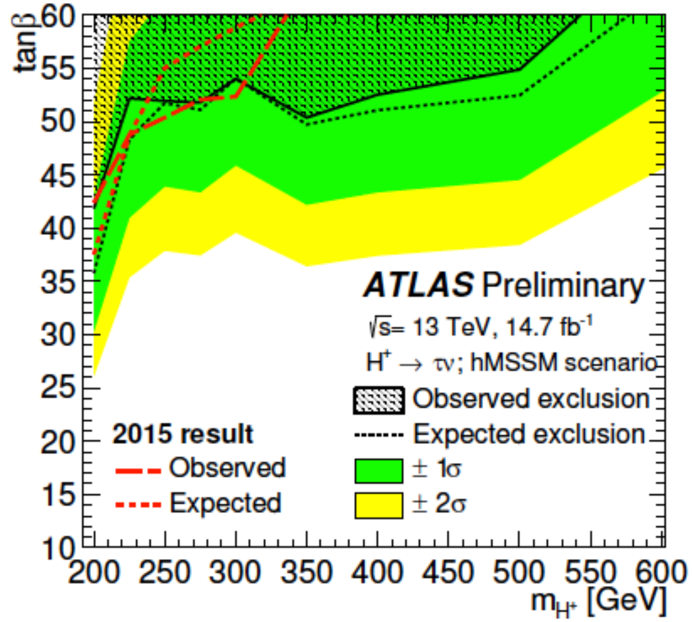
- Backgrounds:
  - True τ:
    - ttbar, W+jets from simulation with normalization validated in CR from data,
    - Z+jets, di-boson from simulation.
  - Fake τ's:
    - Mis-ID jets, from data using "fake factor" method,
    - Mis-ID e, μ, shape from simulation, normalization from data.

Search for $H^{\pm} \to \tau\nu$

14.7 fb^{-1} @ 13 TeV
ATLAS-CONF-2016-088

- Systematic uncertainties:
  - Fake factors and τ mis-ID (specially at high m_{H+})
  - ttbar modelling (specially at low m_{H+})
  - reconstruction of jets, τ, luminosity.
- Profile likelihood fit to m_T.
- No deviation from expected background.
- Upper CLs limits on the cross-section (model-independent) on top.
  The cross-section times Branching fraction limit ranges from 2.0 to 0.008 pb.
- Interpretation in hMSSM (Djouadi et al, arXiv: 1502.05653) on bottom.
  Values of tanβ in the range 42-60 are excluded for $m_{H\pm}$= 200 GeV.
  Masses of $H^{\pm}$ in the range from 200 to 540 GeV is excluded at tanβ=60.



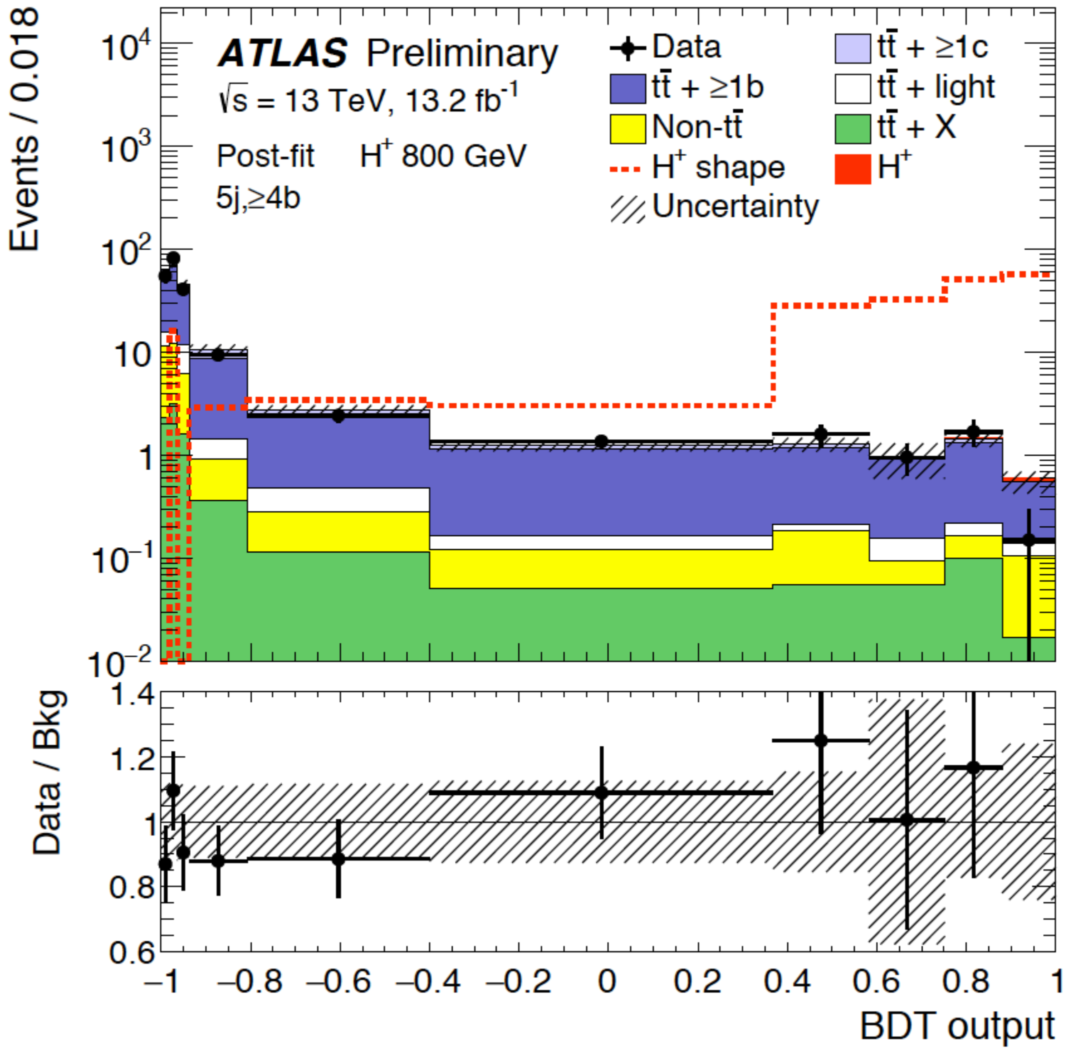


Search for H±–>tb

13.2 fb^{-1} @ 13 TeV
ATLAS-CONF-2016-089

- Strategy:
  - "l+jets" channel: one lepton and jets from the hadronic top.
  - $300 \leq m_{H+} \leq 1000$ GeV
  - Fitted variable: BDT in Signal Regions (SR), H_T^{had} (scalar sum of p_T of all jets) in Control Regions (CR).
- Signal selection:
  - 1 e or μ ($p_T > 25$ GeV)
  - ≥ 4 jets (p_T>25 GeV), of which ≥ 2b-tagged (70% eff).
- Main background: ttbar+≥1b.
- Based on jet and b-jet multiplicity, various SR and CR.

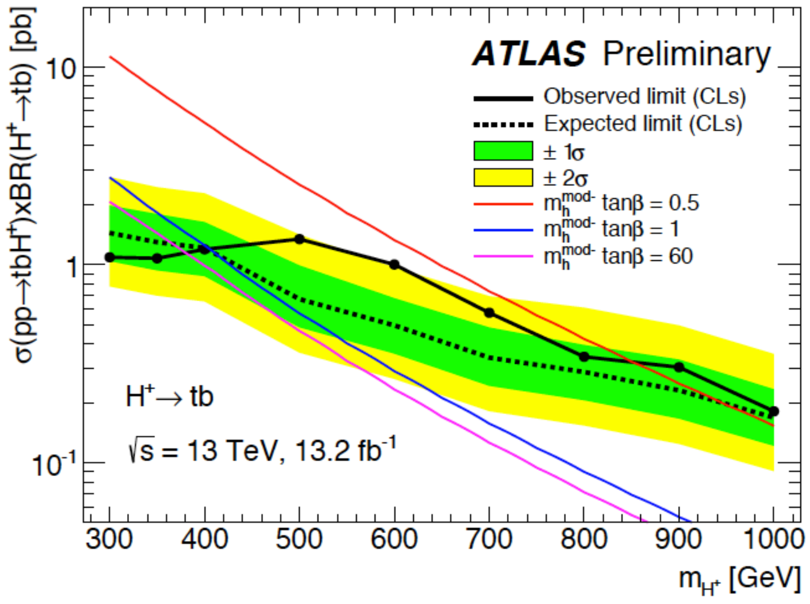
	2b	3b	≥4b
4j	CR	CR	
5j	CR	SR	SR
≥6j	CR	SR	SR

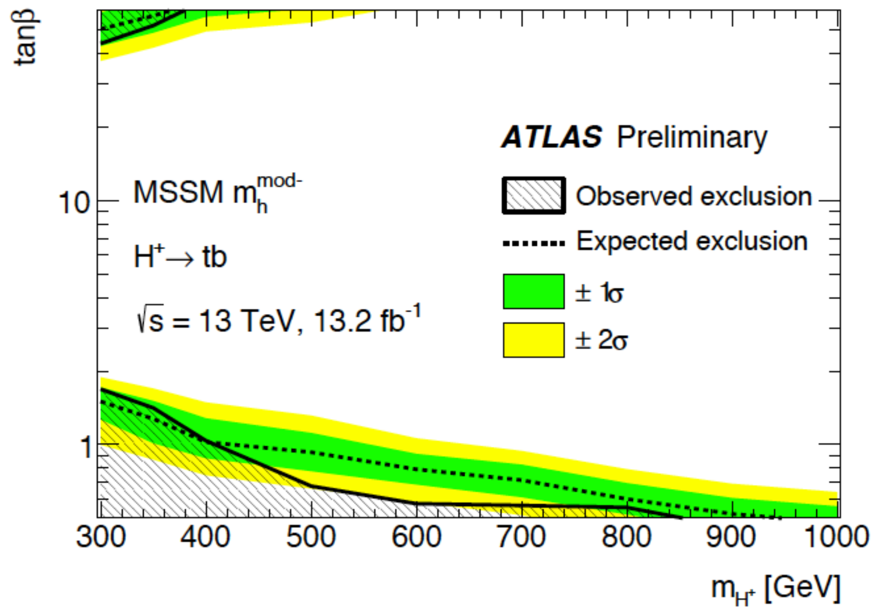


Search for H±–>tb

13.2 fb^{-1} @ 13 TeV
ATLAS-CONF-2016-089

- Simultaneous profile likelihood fit in SR (BDT output) and CR (H_T^{had}).
  ttbar ≥+1c, ttbar ≥1b norm free in fit.
- Major systematic uncertainties:
  - ttbar+heavy flavour modelling,
  - jet flavour tagging,
  - jet energy scale and resolution.
- No significant excess found.
- CLs limits:
  -Model-independent as a function of m_{H+} (top-right).
  -Interpretation in MSSM m_h^{mod-} on bottom-right.
  -In this scenario the light CP-even Higgs boson can be interpreted as the LHC signal in large parts of the M_H-tanβ plane.

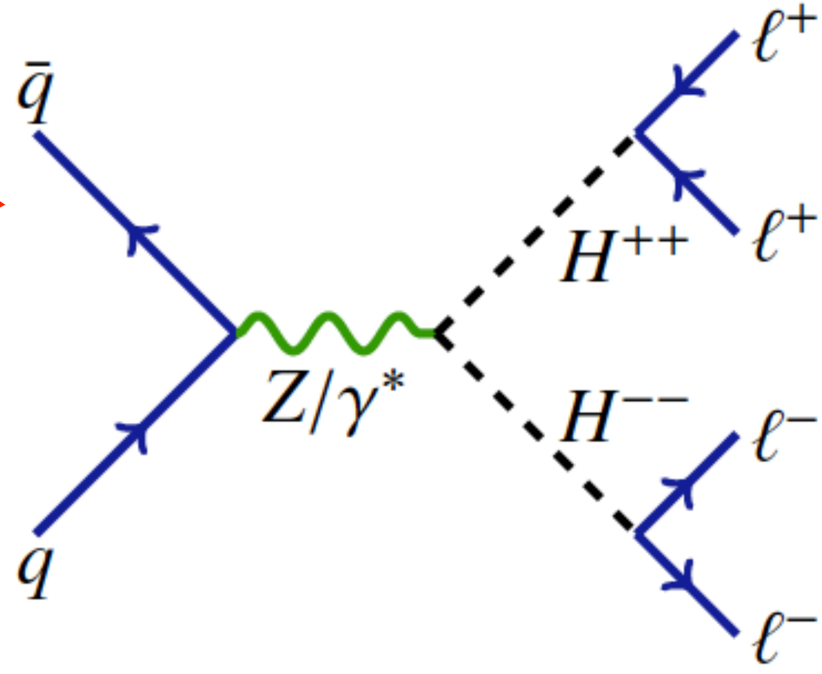




Search for $H^{\pm\pm} \to l^+l^+l^-l^-$

36.1 fb^{-1} @ 13 TeV
CERN-EP-2017-198,
arXiv: 1710.09748v1

- Doubly charged Higgs bosons $H^{\pm\pm}$ can arise in a large variety of BSM theories.
- Feynman diagram for $pp \to H^{++} H^{--} \to l^+l^+ l^-l^-$ production where $l^\pm l^\pm = e^\pm e^\pm$, $e^\pm\mu^\pm$ or $\mu^\pm\mu^\pm$.
- $H^{\pm\pm} \to l^\pm l^\pm$, $H^{\pm\pm} \to \tau^\pm\tau^\pm$ or $H^{\pm\pm} \to W^\pm W^\pm$, depending on $m_{H\pm\pm}$ and vacuum expectation value (vev) of the neutral Higgs triplet.
  At low $m_{H\pm\pm}$ and vev $H^{\pm\pm} \to l^\pm l^\pm$ dominates.
- Masses studied: $250 \leq m_{H\pm\pm} \leq 1300$ GeV



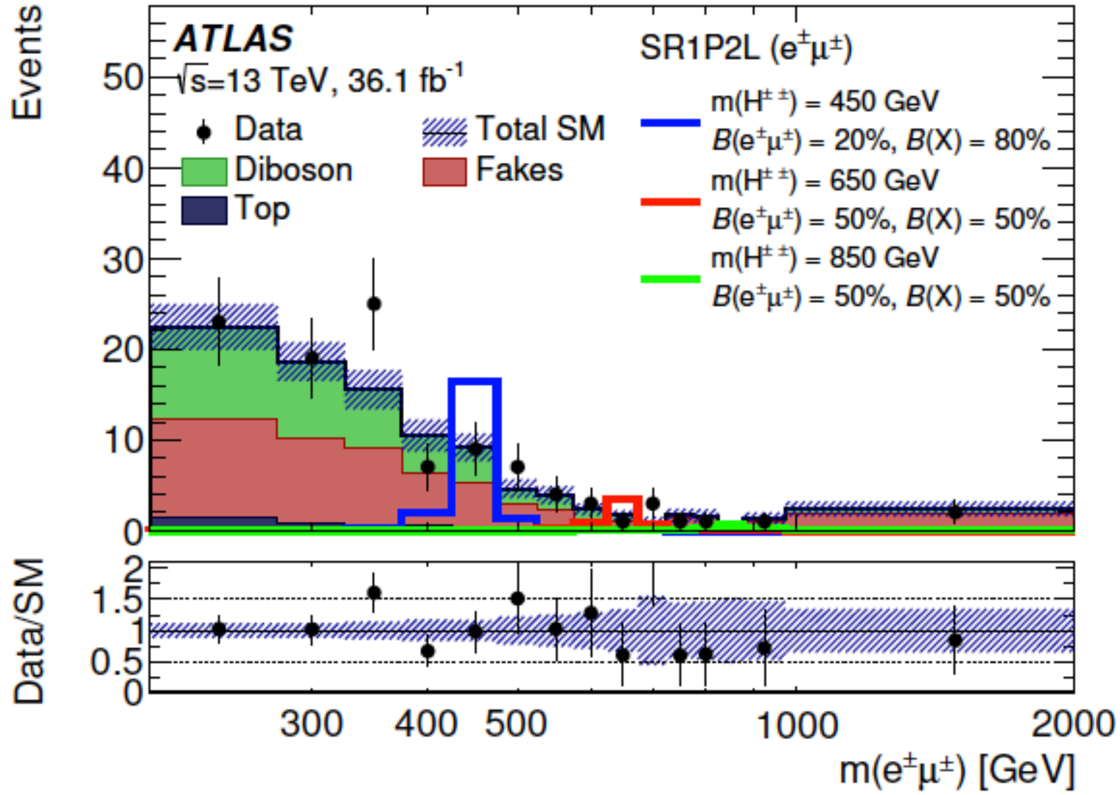
Drell-Yan process in this analysis

arXiv: 1710.09748v1
submitted to EPJC 26 Oct

$H^{\pm\pm} \to l^+l^+l^-l^-$ analysis

36,1 fb^{-1} @ 13 TeV
CERN-EP-2017-198,
arXiv: 1710.09748v1

- Backgrounds:
  - Z+V, ttbar+V (V=Z,W) produce prompt leptons. Estimated with simulation.
  - Z, ttbar, WW,… produce prompt leptons plus charged mis-ID. Estimated with simulation, data-driven correction factors.
  - "Fakes": non-prompt or mis-reconstructed leptons (multijets,…). Estimated with data, "fake factor" method.



- Selection:
  - 2, 3 or 4 leptons (e or μ),
  - b-jet veto, Z veto,
  - ΔR and p_T of lepton pairs.

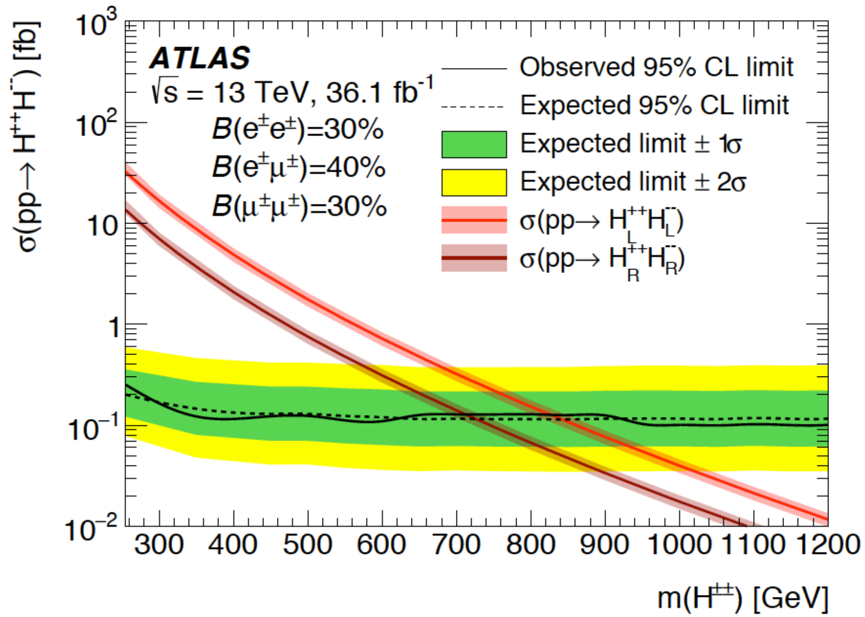
- Signal regions:
  - 1 same-sign pair,
  - 1 same-sign pair 3 leptons,
  - 2 same-sign pairs.

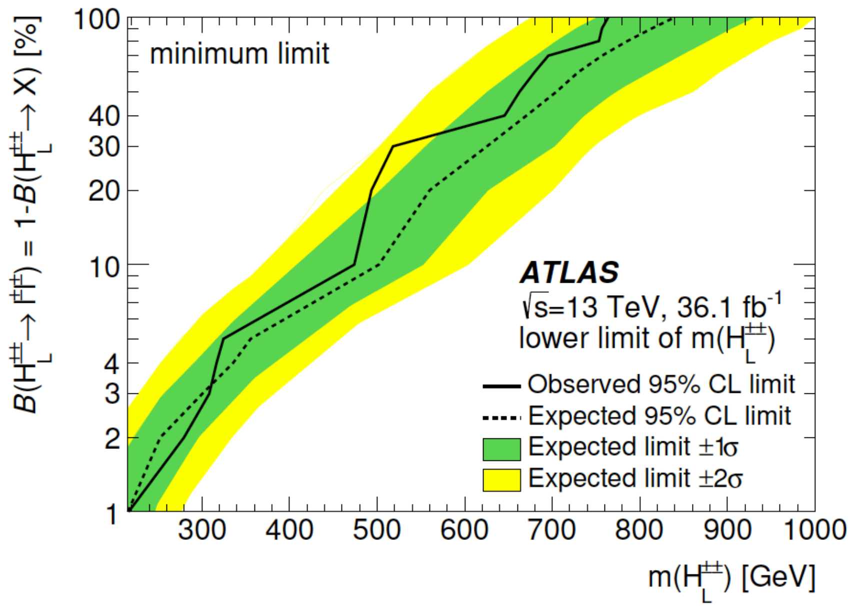
- Control regions:
  - opposite-charge control region,
  - diboson control region,
  - diboson in four-lepton regions.

$H^{\pm\pm} \to l^+l^+l^-l^-$ Results

ATLAS-CONF-2017-053, arXiv: 1710.09748v1

- Uncertainties:
  - Fake factor method.
  - Statistical uncertainty.
  - Theory description, …
- Maximum-likelihood fit to $m(l^{\pm}l^{\pm})$ (2 or 3 l) or $M=0.5 \times (m^{++} + m^{--})$ (4l).
- No significant excess found.
- Set 95% upper cross-section CLs limits.
- Top-right: Upper limit on cross-section for $B(e^{\pm}e^{\pm}) = 30\%$, $B(e^{\pm}\mu^{\pm}) = 40\%$, $B(\mu^{\pm}\mu^{\pm}) = 30\%$.
- Bottom-right: observed minimum limit on $m_{H\pm\pm}$ with only coupling to left-handed leptons is 760 for $B(H^{\pm\pm} \to l^{\pm}l^{\pm}) = 100\%$





Conclusions

- No evidence for charged Higs Boson yet.

- Big portion of parameter space still to be covered.
  - Control better systematics,
  - More statistics will help.

- For the coming months expect public results with Run2 data on both H^{+}-> $\tau\nu$, H^{+} -> tb, H^{+} -> $W^{+}Z$ and $H^{\pm\pm}$ -> $W^{\pm}W^{\pm}$.
  - New search channels,
  - Extensive use of MVA,
  - New mass search regime,
  - Factor 2 more statistics.

Back-up

Low $m_{H\pm}$ search (e.g. $H^+ \to \tau\nu$)

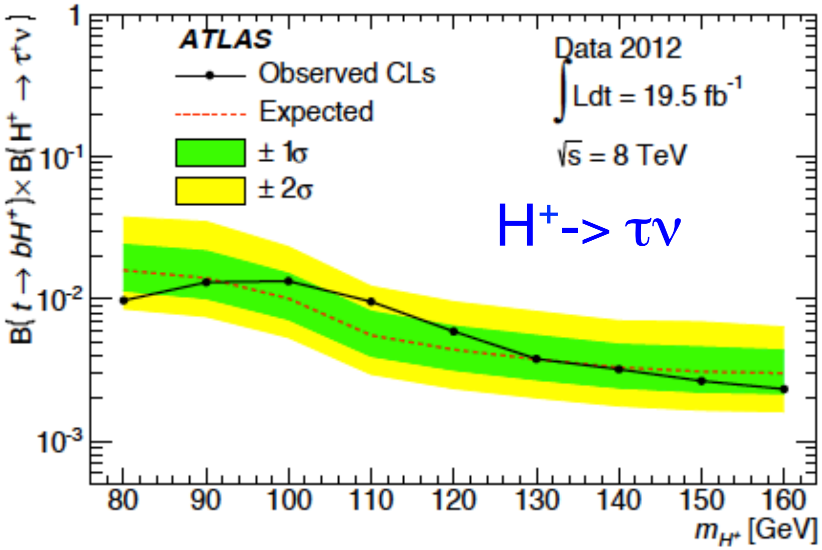
20 fb^{-1} @ 8 TeV
JHEP03 (2015) 088, JHEP03(2016) 127, Phys. Rev. Lett. 114, 231801 (2015)

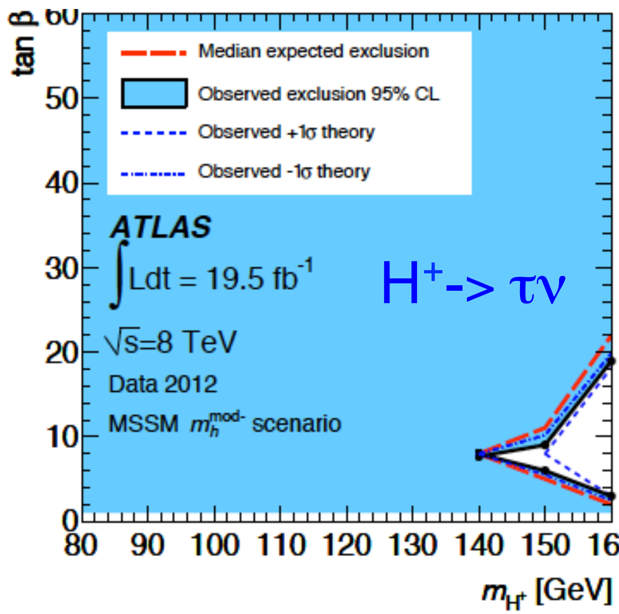
- Strategy:
  - "tau+jets" channel: one hadronic τ, b-jets and light jets from the W decay
  - $80 \le m_{H+} \le 160$ GeV,
    $200 \le m_{H+} \le 1000$ GeV
  - Discriminating variable

$$m_T = \sqrt{2 p_T^{\tau} E_T^{miss} (1 - \cos \Delta\phi_{\tau, E_T^{miss}})}$$

- Signal selection:
  - $\tau + E_T^{miss}$ trigger
  - 1 hadronic τ ($p_T > 40$ GeV)
  - $\ge$ 4 jets (p_T>25 GeV),
    of which $\ge$ 1b-tagged (70% eff).
  - Veto e, μ
  - $E_t^{miss} > 65$ GeV

- Top-right: model independent limit on $B(t \to bH^+) \times B(H^+ \to \tau\nu)$ as function of m_{H+} for the low-mass search.
  Bottom-right: exclusion limits with m_h^{max} scenario.





BSM theories with H^+ bosons

- Two Higgs doublets models (2HDM)
  - A.G. Akeroyd et al., *Prospects for charged Higgs searches at the LHC*, (2016), arXiv: 1607.01320 [hep-ph]
  - J.F. Gunion and H.E. Haber, *The CP conserving two Higgs doublet model: The Approach to the decoupling limit*, Phys. Rev. **D67** (2003) 075019, arXiv:hep-ph/0207010 [hep-ph]
  - G.C. Branco et al., *Theory and phenomenology of two-Higgs doublet models*, Phys. Rev. **516** (2012), arXiv: 1106.0034 [hep-ph]
- Models containing Higgs triplets
  - T.P. Cheng and L.F. Li, *Neutrino Masses, Mixings and Oscillations in SU(2)xU(1) Models of Electroweak Interactions*, Phys. Rev. **D22** (1980) 2860
  - J. Schechter and J.W.F. Valle, *Neutrino Masses in SU(2)xU(1) Theories*, Phys. Rev. **D22** (1980) 2227
  - G. Lazarides, Q. Shafi and C. Wetterich, *Pronton Lifetime and Fermion masses in an SO(10) Model*, Nucl. Phys. **B181** (1981) 287
  - R. N. Mohapatra and G. Senjanovic, *Neutrino Masses and Mixings in Gauge Models with Spontaneous Parity Violation*, Phys. Rev. **D23** (1981) 165
  - M. Magg and C. Wetterich, *Neutrino Mass Problem with Spontaneous Parity Violation*, Phys. Lett. **B94** (1980) 61

BSM theories with $H^{\pm\pm}$ bosons (1/3)

- Left-right symmetric (LRS) models
  - J.C. Pati and A. Salam, *Lepton Number as the Fourth Color*, Phys. Rev. D10 (1974) 275. Erratum: Phys. Rev. **D11** (1975) 703
  - R.N. Mohapatra and J.C. Pati, *Left-Right Gauge Symmetry and an Isoconjugate Model of CP Violation*, Phys. Rev. **D11** (1975) 566
  - G. Senjanovic and R.N. Mohapatra, *Exact Left-Right Symmetry and Spontaneours Violation of Parity*, Phys. Rev. **D12** (1975) 1502
  - P.S. Bhupal Dev, R. N. Mohapatra and Y. Zhang, *Displaced photon signal from a possible light scalar in minimal left-right seesaw model*, Phys. Rev. **D95** (2017) 115001, arXiv: 1612.09587 [hep-ph]
  - D. Borah and A. Dasgupta, *Observable lepton number violation with predominantly Dirac nature of active neutrinos*, JHEP**01** (2017) 072, arXiv: 1609.04236 [hep-ph]
- Higgs triplet models
  - J.E. Cieza Montalvo, N.V. Cortez, J.Sa Borges and M.D. Tonasse, *Searching for doubly charged Higgs bosons at the LHC in a 3-3-1 mode*l, Nucl. Phys. **B756** (2006) 1. Erratum: Nucl. Phys. **B796** (2008) 422, arXiv: hep-ph/0606243
  - J.F. Gunion, R. Vega and J. Wudka, *Higgs triplets in the standard model*, Phys. Rev. **D42** (1990) 1673
- Little Higgs model
  - N. Arkani-Hamed et al., *The Minimal Moose for a Little Higgs*, JHEP**08** (2002) 021, arXiv: hep-ph/0206020

BSM theories with $H^{\pm\pm}$ bosons (2/3)

- Type-II see-saw models
  - M. Muhlleitner and M. Spira, *Note on doubley charged Higgs pair production at hadron colliders*, Phys. Rev. **D68** (2003) 117701, arXiv: hep-ph/0305288
  - A.G. Akeroyd and M. Aoki*, Single and pair production of doubley charged Higgs bosons at hadron colliders*, Phys. Rev. **D72** (2005) 035011, arXiv: hep-ph/0506176
  - A. Hektor, M. Kadastik, M. Muntel, M. Raidal and L. Rebane, *Testing neutrino masses in little Higgs models via discovery of doubly charged Higgs at LHC*, Nucl. Phys. **B787** (2007) 198, arXiv: 0705.1495 [hep-ph]
  - P. Fileviez Perez, T. Han, G.Y. Huan. T. Li and K. Wang, *Testing a neutrino mass generation mechanism at the Large Hadron Collider*, Phys. Rev. **D78** (2008) 071301, arXiv: 0803.3450 [hep-ph]
  - W. Chao, Z.G. Si, Z. Z. Xing and S. Zhou, *Correlative signatures of heavy Majorana neutrinos and doubly-charged Higgs bosons at the Large Hadron Collider*, Phys. Lett. **B666** (2008) 451, arXiv: 0804.1265 [hep-ph]
- Georgi-Machacek model
  - H. Georgi and M. Machacek, *Double Charged Higgs Bosons*, Nucl. Phys. **B262** (1985) 463
- Scalar singlet dark matter
  - S. Bhattacharya, S. Jana and S. Nandi, *Neutrino masses and scalar singlet dark matter*, Phys. Rev. **D95** (2017) 055003, arXiv: 1609.03274 [hep-ps]

BSM theories with $H^{\pm\pm}$ bosons (3/3)

- Zee-Babu neutrino mass model (16-18)
  - A. Zee, *Quantum Numbers of Majorana Neutrino Masses*, Nucl. Phys. **B264** (1986) 99
  - K.S. Babu, *Model of ``Calculable'' Majorana Neutrino Masses*. Phys. Lett. **B203** (1988) 132
  - M. Nebot, J.F. Oliver, D. Palao and A. Santamaria, *Prospects for the Zee-Babu Model at the CERN LHC and low energy experiments*, Phys. Rev. **D77** (2008) 093013, arXiv: 0711.0483 [hep-ph]

Common parameters of 2HDM

- Four Higgs masses (m_H, m_h, m_A, $m_{H\pm}$)
  - m_H or m_h = 125 GeV
- Ratio of the vacuum expectation values of the two doubles, $\tan\beta = v_2/v_1$.
- Mixing angle between H and h, α.

2HDM Type	Doublet coupled to up-type quarks	Doublet coupled to down-type quarks	Doublet coupled to leptons
Type I	Φ_2	Φ_2	Φ_2
Type II	Φ_2	Φ_1	Φ_1
Lepton-specific	Φ_2	Φ_2	Φ_1
Flipped	Φ_2	Φ_1	Φ_2