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

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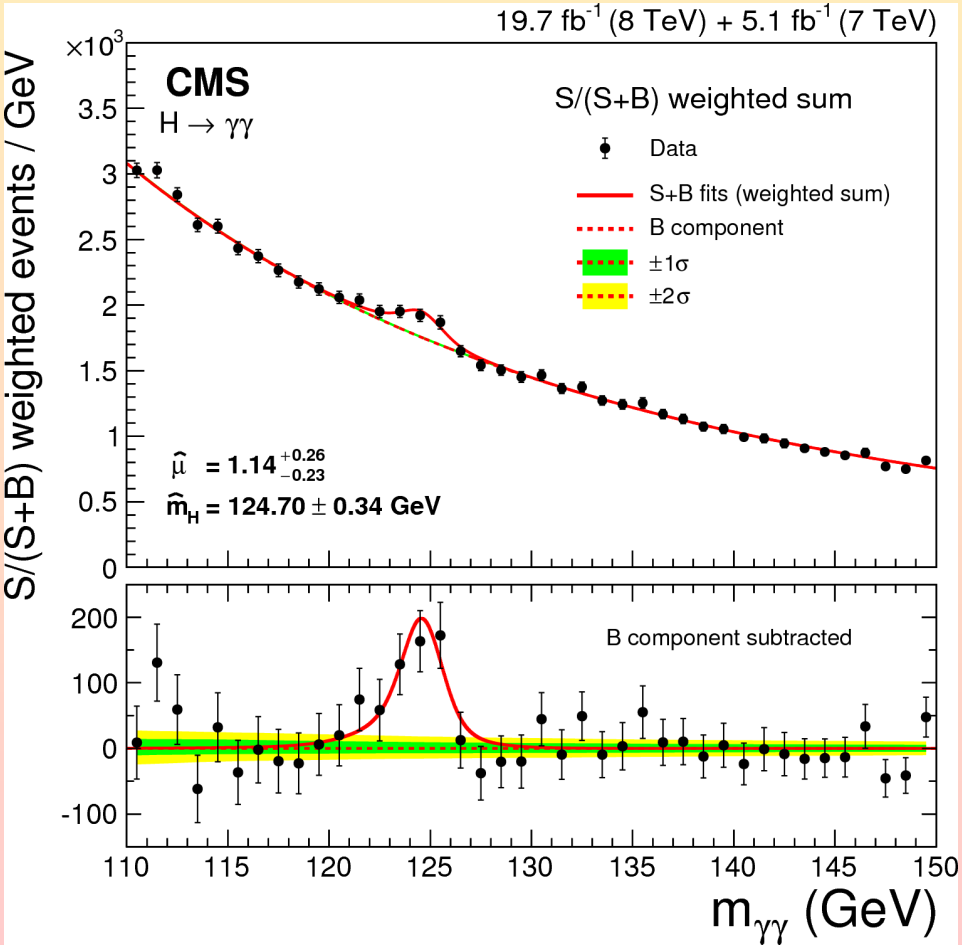
Jornadas do LIP 2016, Braga

Outline

- 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_{H^+} **and** $tan\beta$**:** `hMSSM` **[1]**
  - No prediction $\rightarrow$ need to scan full parameter phase space

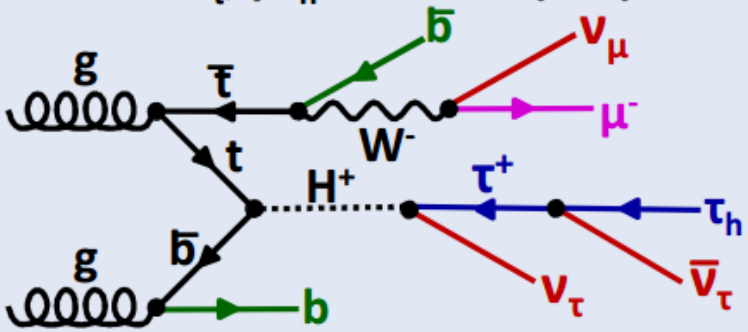


- The discovery of a charged Higgs boson would be an unequivocal signal of new physics
- Main charged Higgs boson search channels
  - Vector boson fusion/decay
    - Cascade decays involving $h^0(125)$
    - VBF production, decay to $\mathrm{W}^{\pm}\mathrm{Z}$
  - Top quark production and decay
   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

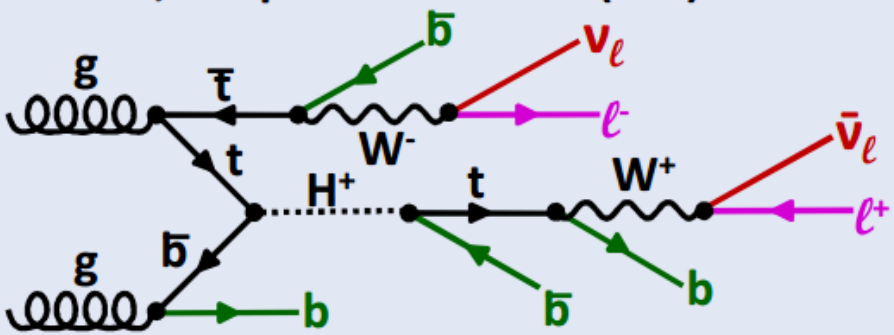
Searching for a heavy ($m_{H^\pm} > m_{top}$) charged Higgs boson

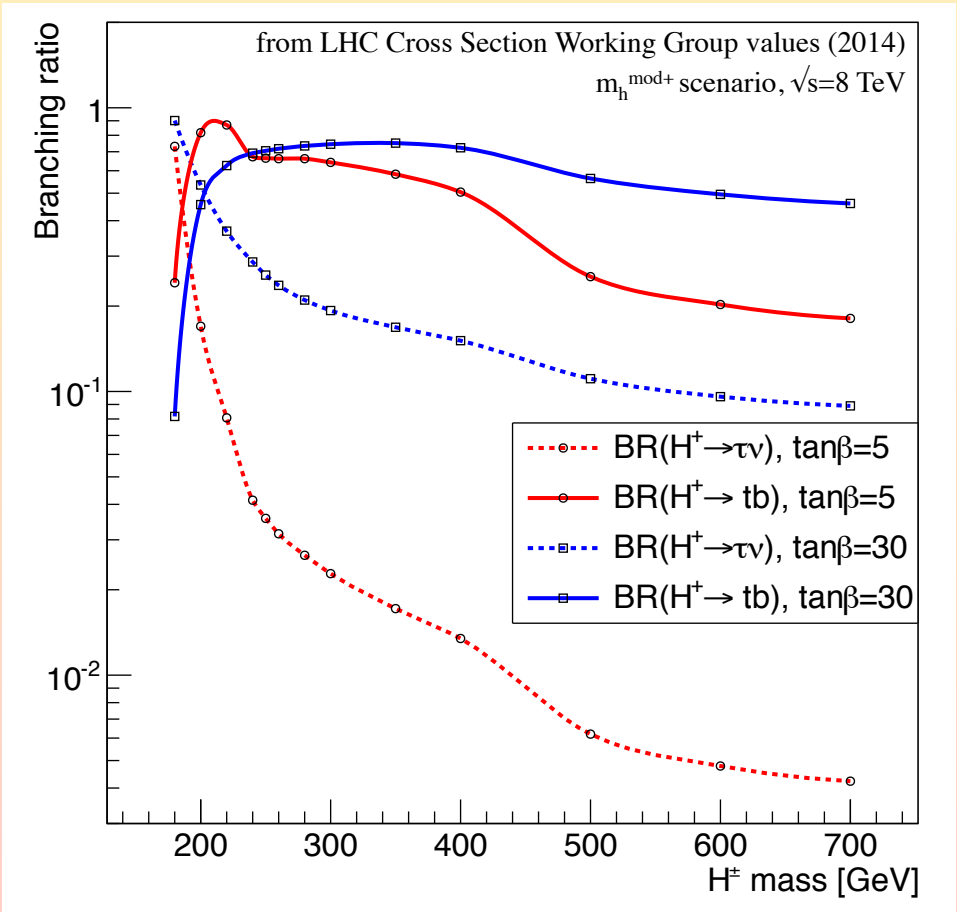
- In most of the MSSM models, $\frac{\mathcal{B}(H^+ \to t\bar{b})}{\mathcal{B}(H^+ \to \tau^+ \nu_\tau)} > 5$ for $tan\beta > 8$
- $H^+ \to t\bar{b}$ decay mode probed via $\mu\tau_h$, dilepton, and ℓ+jets final states
  - Extra b-jet multiplicity and changes in $t\bar{t}$ kinematics and acceptance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

Representative diagram for
$H^+ \to \tau^+\nu_\tau$, $\mu\tau_h$ final state (4FS):



Representative diagram for
$H^+ \to t\bar{b}$, dilepton final state (4FS):





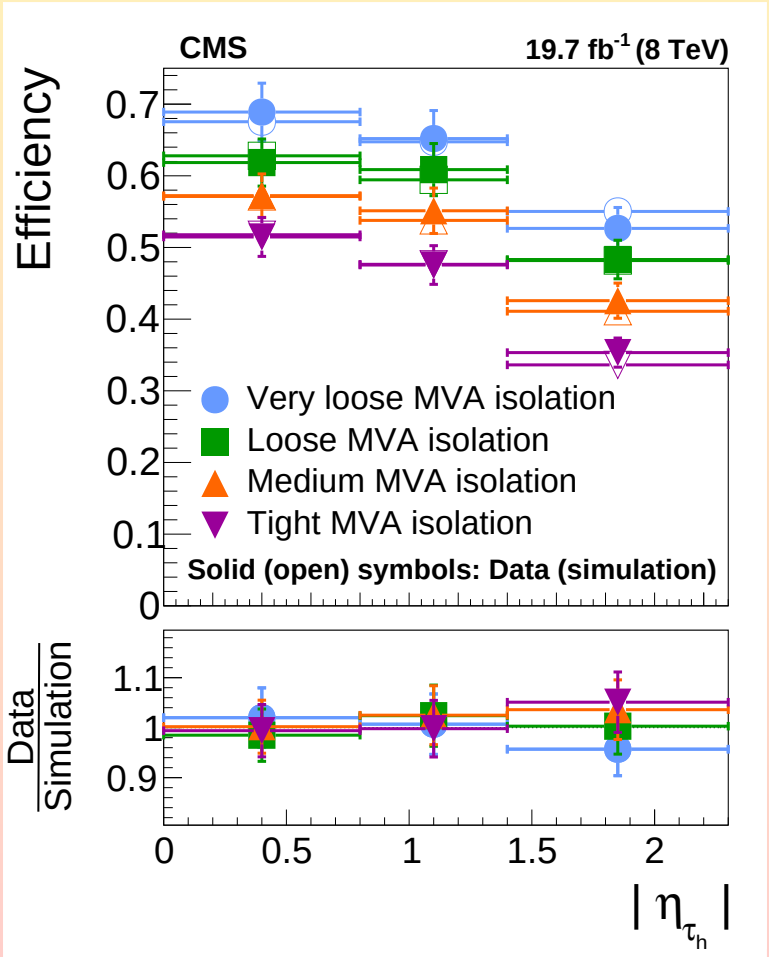
Tau identification (JINST 11 (2016) no.01, P01019 [2])

- Leptonically decaying taus ($\mathcal{B} = 35\%$) are indistinguishable from electrons and muons
- Hadronically decaying taus, τ_h, ($\mathcal{B} = 65\%$) are separable from jets
  - Signature: narrow jets containing 1 or 3 $\pi^{\pm}$ and 0, 1, or 2 π^0
  - Intermediate decays via ρ and a_1 identifiable via mass cuts
- Reconstruct hadrons (pixel+calorimeters), and γs (η-ϕ clustering in "strips")

Challenges

- Reject $e \to \tau_h$ fakes
  - Appears as iso track + calo, like 1-p τ_h
- Reject $\mu \to \tau_h$ fakes
  - Relatively easier (muon chambers!)
- Huge jet$\to \tau_h$ background
- τ_h candidates are collimated
  - $\pi^{\pm}$s and γs from π^0

Decay mode	Res.	Branching frac. (%)
$\tau^- \to e^- \bar{\nu}_e \nu_\tau$		17.8%
$\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$		17.4%
$\tau^- \to h^- \nu_\tau$		11.5%
$\tau^- \to h^- \pi^0 \nu_\tau$	$\rho^-(770)$	26.0%
$\tau^- \to h^- \pi^0 \pi^0 \nu_\tau$	$a_1^-(1260)$	9.5%
$\tau^- \to h^- h^+ h^- \nu_\tau$	$a_1^-(1260)$	9.8%
$\tau^- \to h^- h^+ h^- \pi^0 \nu_\tau$		4.8%
Other modes with hadrons		3.2
All modes containing hadrons		64.8

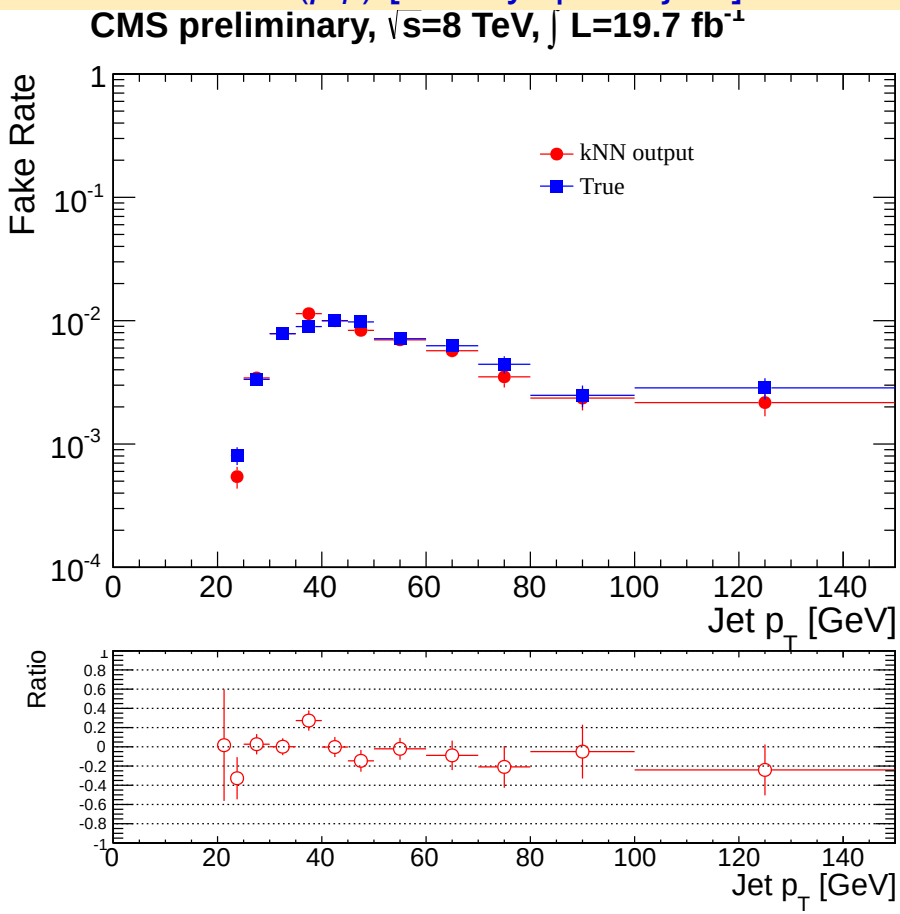


Jet$\rightarrow \tau_h$ misidentification rate estimate (JHEP 1511 (2015) 018 [10])

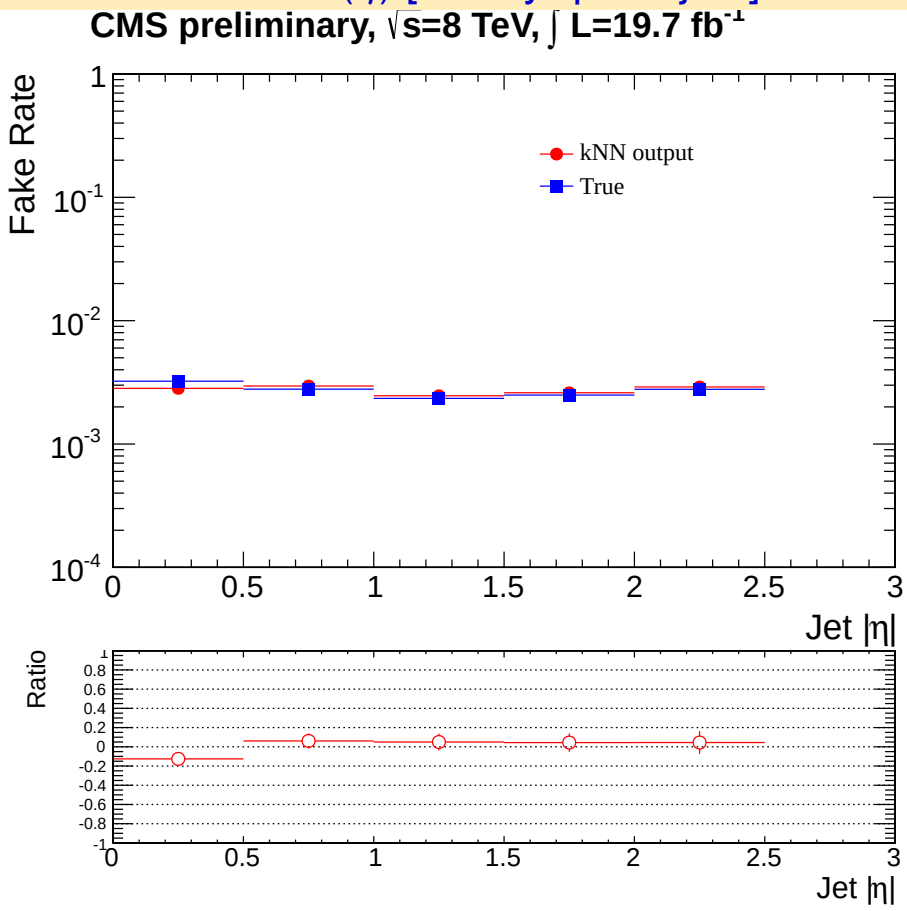
MADE IN LIP

- Use dedicated samples to perform a data-driven estimate for μ+jets events faking $\mu\tau_h$ events
- Compute fake rates for 8 *TeV* using `k-Nearest-Neighbours` algorithm
  - Classify jet as tau fake according to local density of tau fakes in features space
- Account for the quark/gluon jets compositions of the samples from MC
- Improved median for the estimate of the fake events, and reduced uncertainty by $\sim 35\%$

Fake rate (p_T) [mainly quark jets]

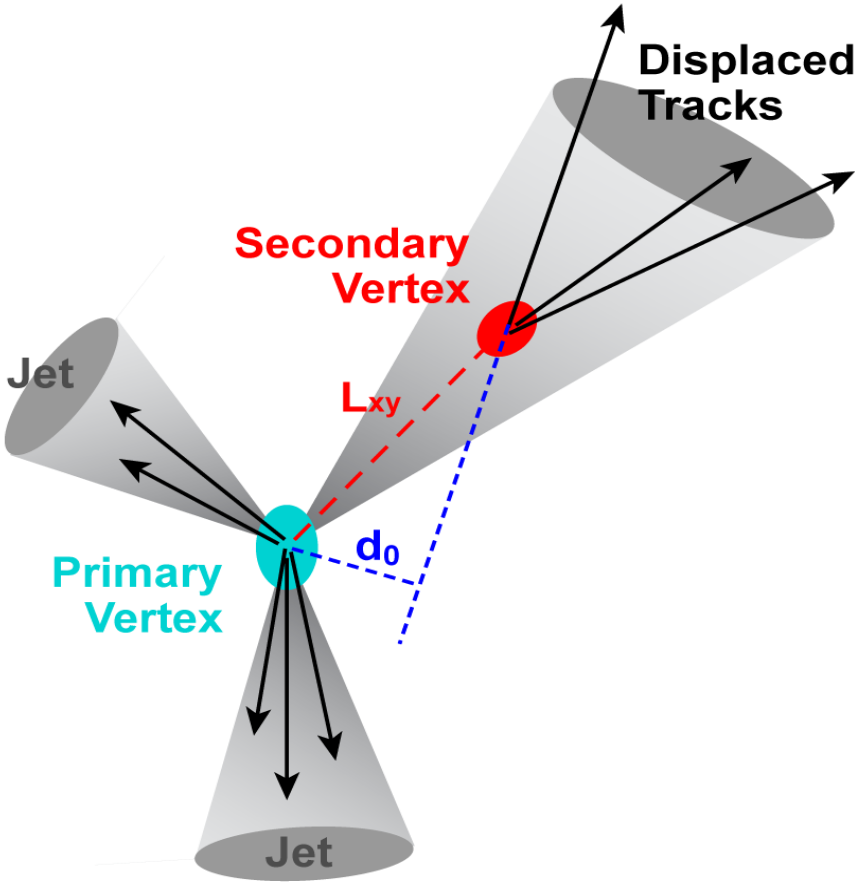


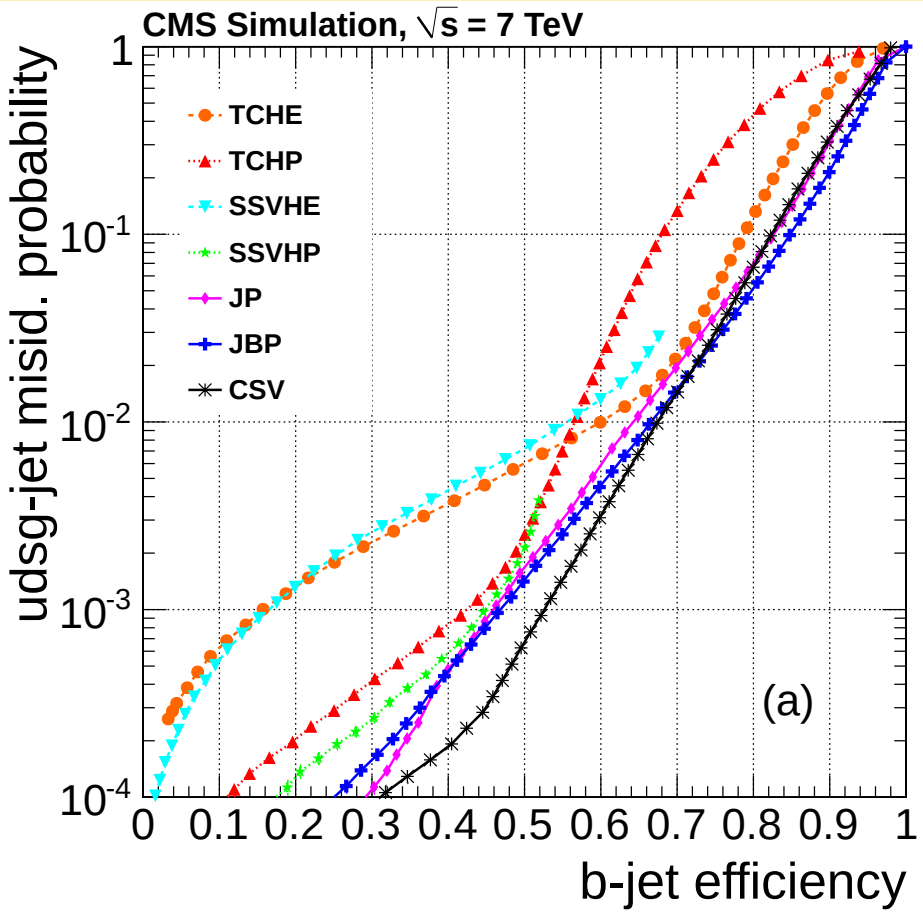
Fake rate (η) [mainly quark jets]



b-tagging (JINST 8 (2013) P04013 [3])

- Crucial for discriminating final states from decays of multiple top quarks
- Discriminating power coming mainly from the long ($\sim$ 1.6 ps lifetime)
  - Tracks multiplicity and track impact parameter
  - Presence of reconstructed secondary vertices (SV), and mass of the SV
- Selecting a mistag rate of 1% yields a b-tagging efficiency of $\sim$ 70% (for the CSV algorithm)

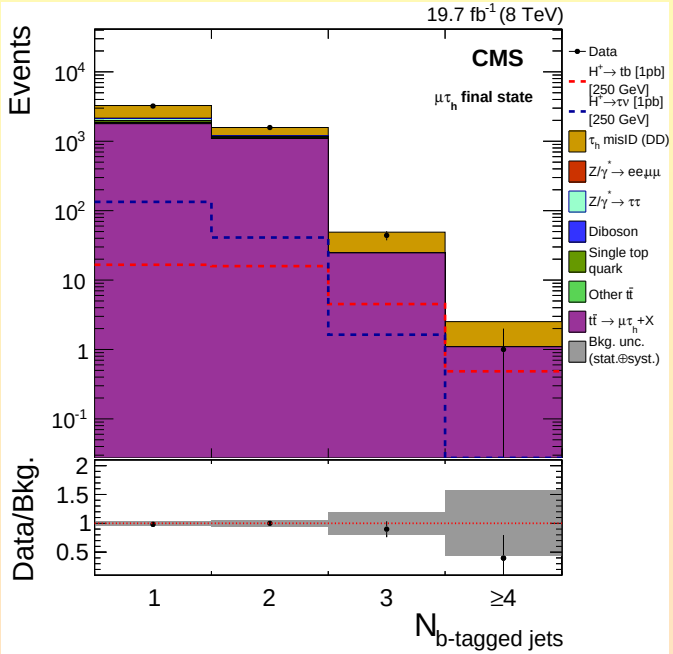




$\mu\tau_h$ and ℓ+jets final states (JHEP11(2015),018 [10])

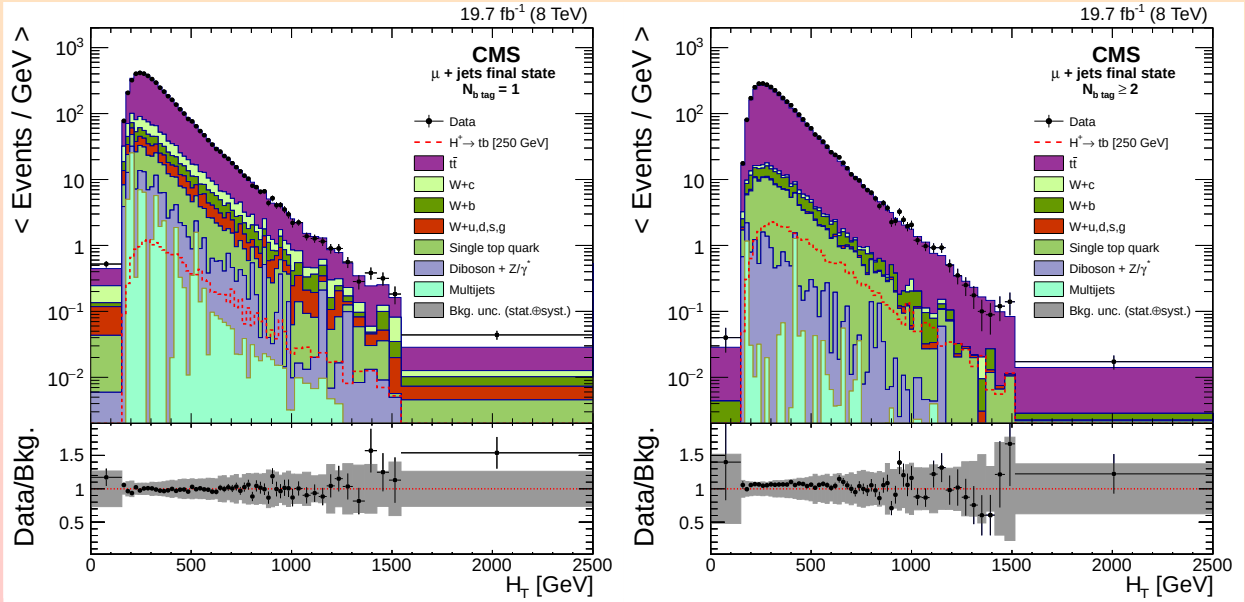
- $\mu\tau_h$ **final state:** more sensitive to $H^+ \to \tau^+\nu_\tau$ decay mode
  - **MADE IN LIP**
  - **Offline selection:** 1 isolated muon, veto loose leptons, $\geq$ 2 jets, E_T^{miss}, $\geq$ 1 b-tags, 1τ_h, opposite sign
  - **Backgrounds:** misidentified τ_h component estimated from data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

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



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

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



Dilepton final state (JHEP11(2015),018 [10])

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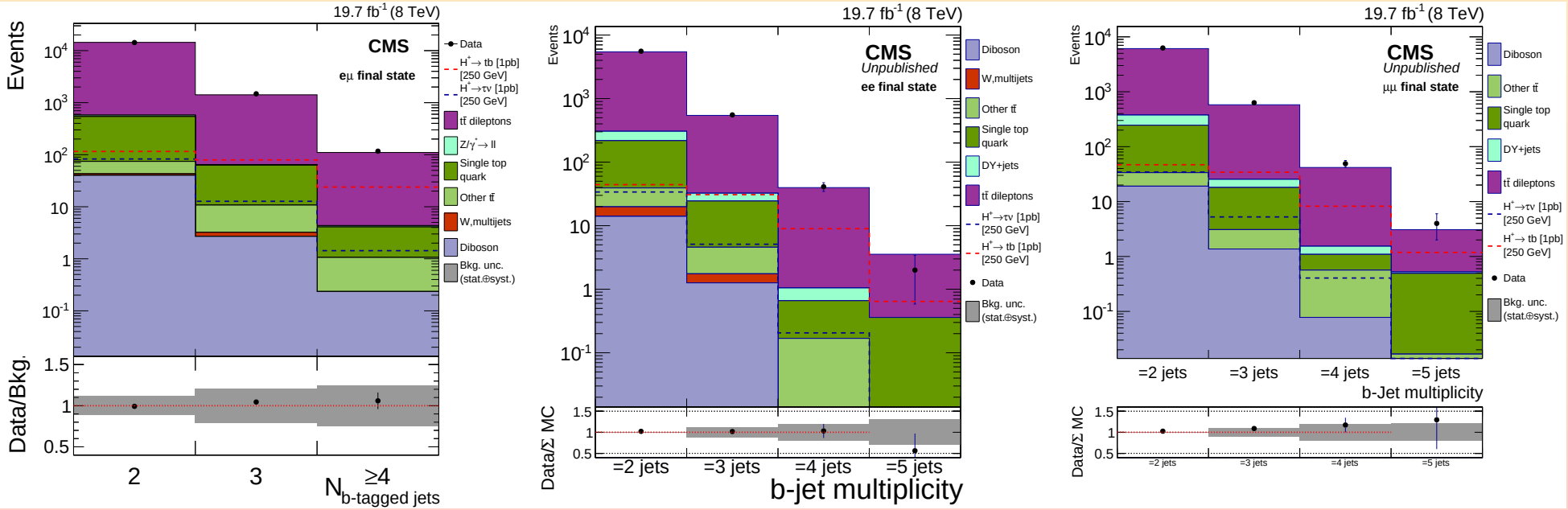
- More sensitive to $H^+ \to t\bar{b}$ decay mode
  - **Selection:** 1$e\mu$ pair, $\geq$ 2 jets, veto low $e\mu$ masses, opposite sign
  - **Backgrounds:** large irreducible $t\bar{t}$, minor single top and Drell-Yan contamination
  - **Tighter $N_{b\ tags}$ requirement** yields better sensitivity to $H^+ \to t\bar{b}$ decay mode than the $\mu\tau_h$ final state
- First public result for a $H^+ \to t\bar{b}$ direct search (CMS-HIG-13-026, Sep 2014)
- First published result for a $H^+ \to t\bar{b}$ direct search (combined with $\mu\tau_h$ and ℓ+jets, JHEP11(2015),018)

N_{b-tags}: better sensitivity for dilepton

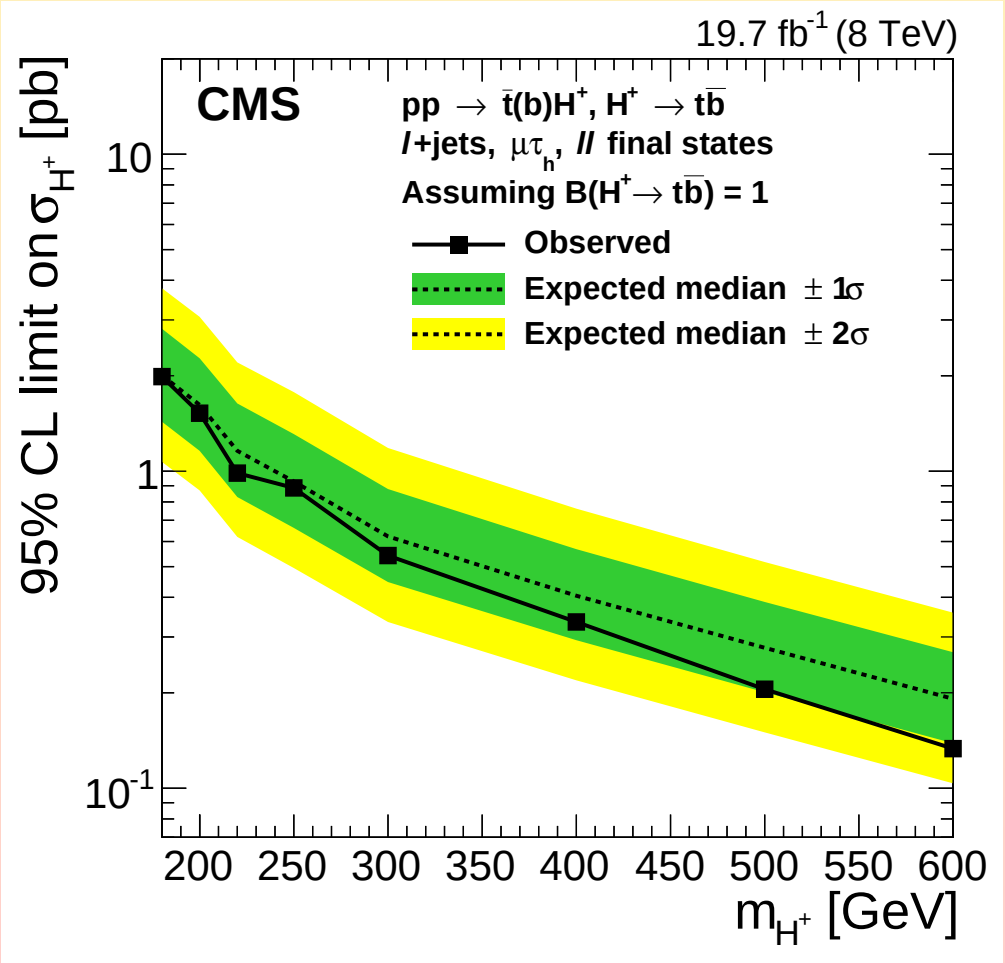


Combination of $\mu\tau + e\mu + ee + \mu\mu + \ell$+jets JHEP11(2015),018 [10]

MADE IN LIP

- Assume $H^+ \to t\bar{b}$ decay only
- First published $H^+ \to t\bar{b}$ direct search ever

JHEP11(2015),018 [10]



Summary

- Charged Higgs boson searched for in top quark production/decay modes
- $H^+ \to t\bar{b}$ decay mode: first direct search ever for this decay mode (CMS [10])
  - **MADE IN LIP**
  - $\sigma(pp \to \bar{t}(b)H^+) \leq 4 - 0.5$ pb (assuming $\mathcal{B}(H^+ \to t\bar{b}) = 1$)
- Charged Higgs not found (yet ☺): stay tuned for 13 TeV new exciting searches!
  - Started last summer by hosting two very-very-awesome summer students to apply multivariate analysis methods to simulation!

THANKS FOR THE ATTENTION!

And for these awesome 4 years :)

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]

CMS Collaboration
Reconstruction and identification of τ lepton decays to hadrons and ν_τ at CMS
J. Inst, 11(2016), P01019. [doi:10.1088/1748-0221/11/01/P01019]

CMS Collaboration,
Identification of b-quark jets with the CMS experiment
J. Inst, 8(2013), P04013. [doi:10.1088/1748-0221/8/04/P04013]

ATLAS Collaboration„
Search for a multi-Higgs-boson cascade in $W^+W^-b\bar{b}$ events with the ATLAS detector in pp collisions at $\sqrt{s} = 8$ 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 $\sqrt{s} = 8$ TeV with the ATLAS Experiment
Phys. Rev. Lett. 114, 231801 (2015). [doi:10.1103/PhysRevLett.114.231801]

References II

ATLAS Collaboration,

Search for a light charged Higgs boson in the decay channel $H^+ \to c\bar{s}$ in $t\bar{t}$ events using pp collisions at $\sqrt{s} = 7$ 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]

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
J. High Energy Phys., 11(2015), 018. [doi:10.1007/JHEP11(2015)018]

References III

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]

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

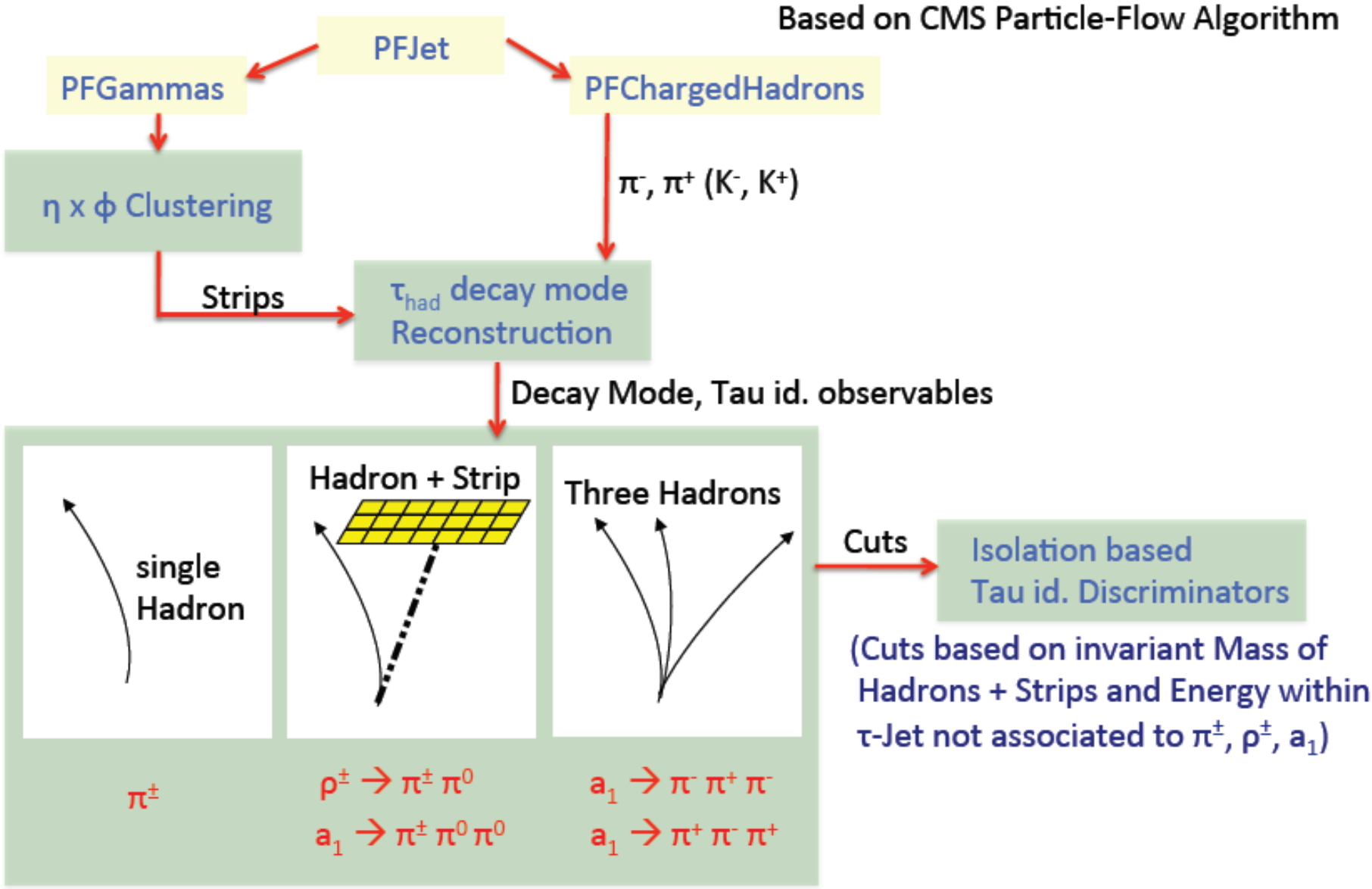
Performance of quark/gluon discrimination in 8 TeV pp data

CMS-PAS-JME-13-002, [CDS:1599732]

BACKUP SLIDES

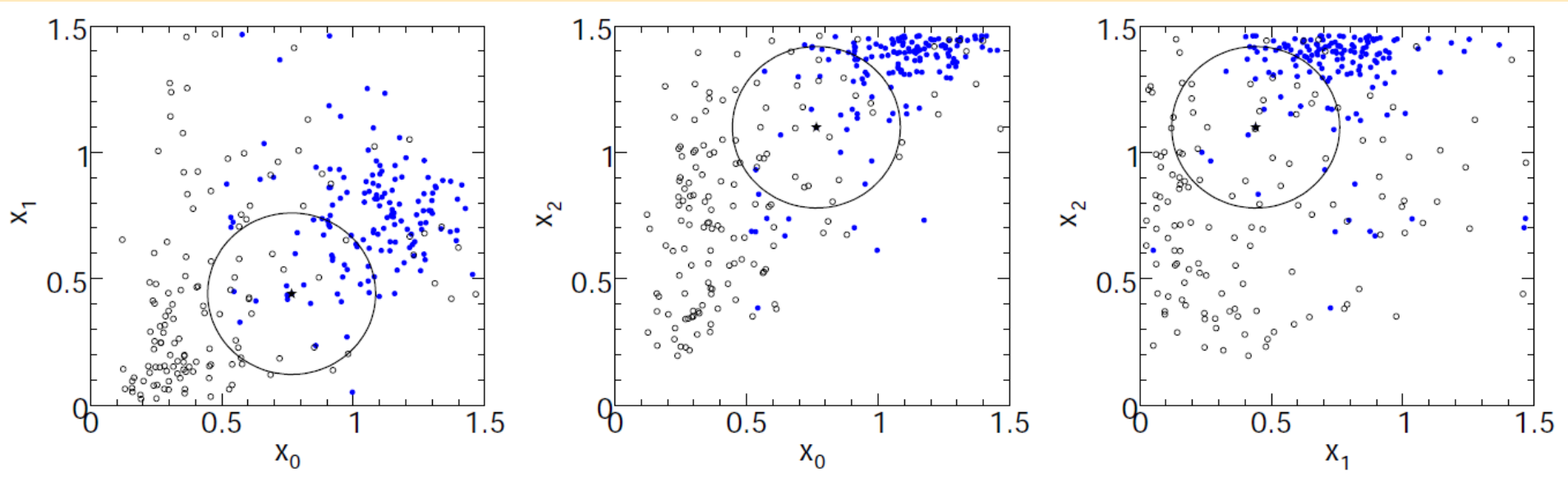
Tau identification - details of the reconstruction

- Hadron-Plus-Strips (HPS) Algorithm



kNN method for jet $\rightarrow \tau_h$ probability

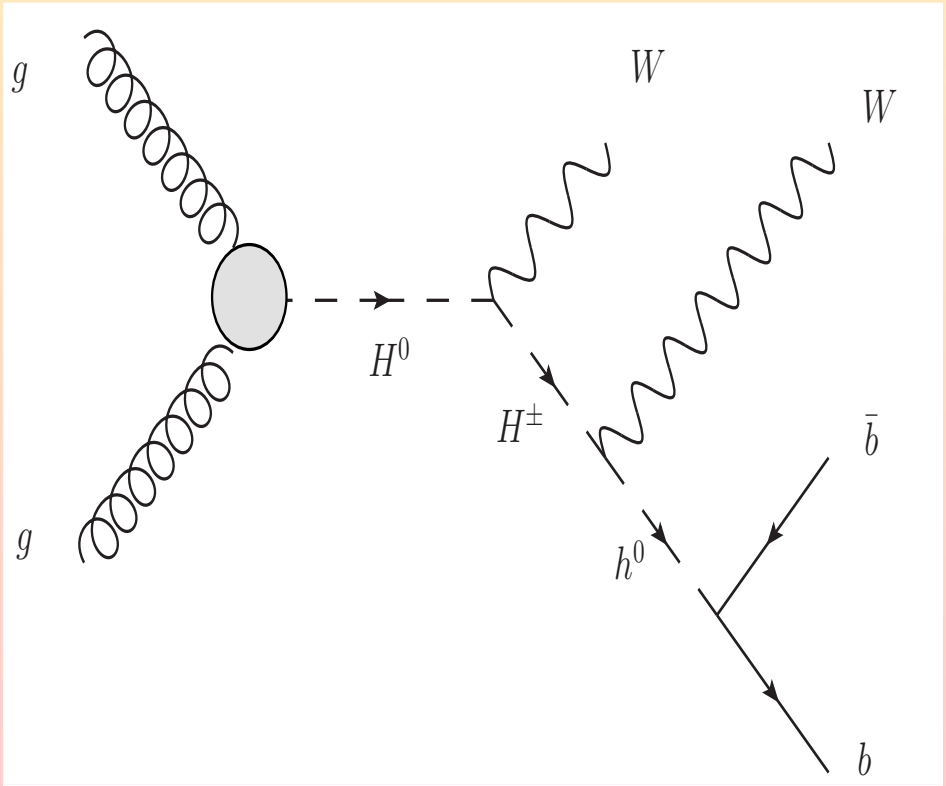
- **k-Nearest-Neighbours algorithm:**
  - Phase space: $(p_T^{jet}, |\eta|^{jet}, R^{jet})$
  - Training set of jets from dedicated real-τ_h-free samples
  - Classify jets near a reconstructed τ_h as fakes
  - Obtain probability of faking a $\tau_h \propto$ number of fakes in the nearest 20 jets
  - Extract a weights matrix $P(p_T^{jet}, |\eta|^{jet}, R_{jet})$
  - Estimate in g/q-jets dominated samples and average the resulting probability



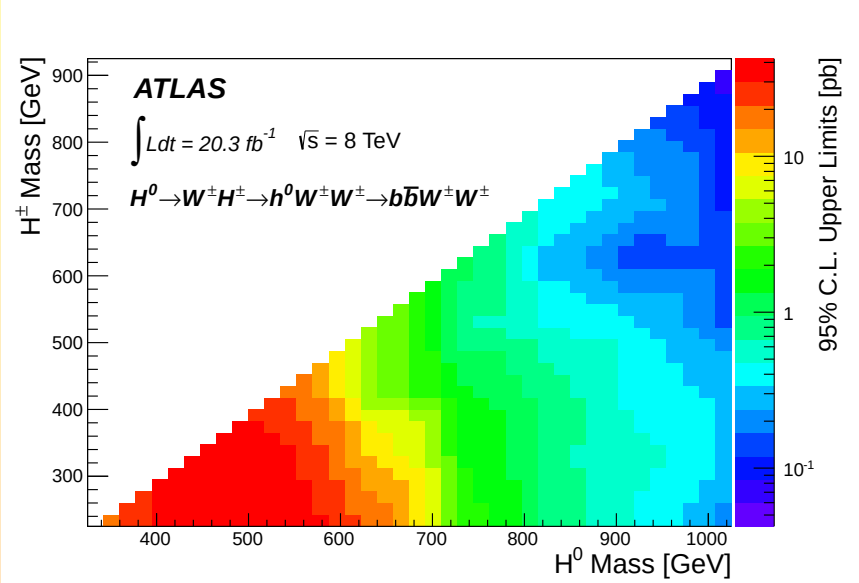
(from TMVA Users Guide)

Multi-Higgs boson cascade
Phys. Rev. D 89, 032002 [4]

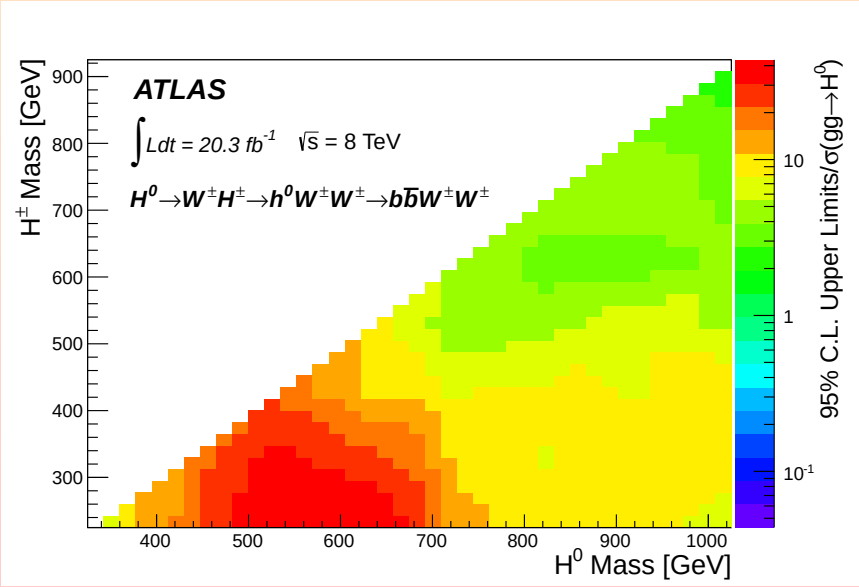
- Assume $\mathrm{h}(125)$ Higgs boson, and no particular model for additional bosons
- $(\mathrm{W} \to \ell\nu)(\mathrm{W} \to \mathrm{q}\bar{\mathrm{q}}')\mathrm{b}\bar{\mathrm{b}}$ final states
- **Selection:** $\geq$ 4 jets (2 of them b-tagged), 1 lepton, $E_{\mathrm{T}}^{\mathrm{miss}}$
- **Background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

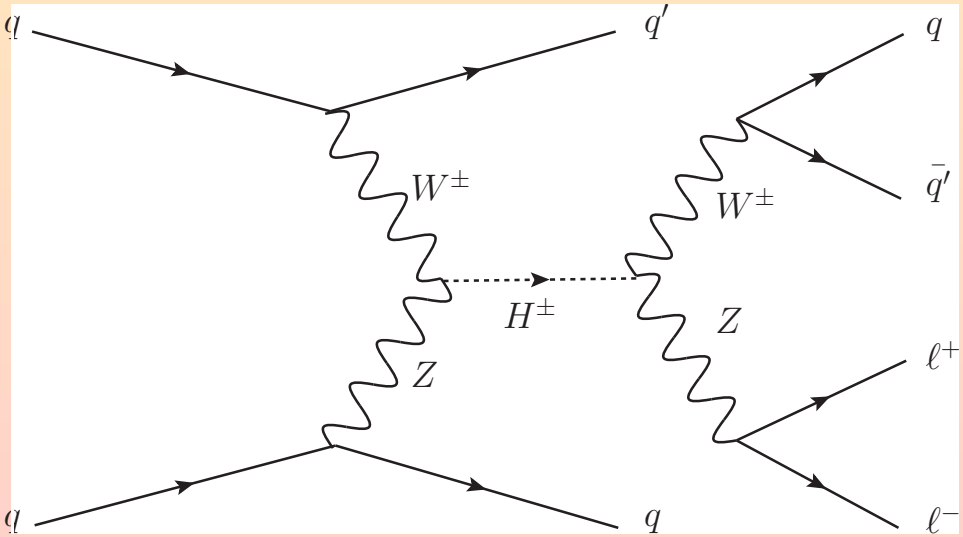


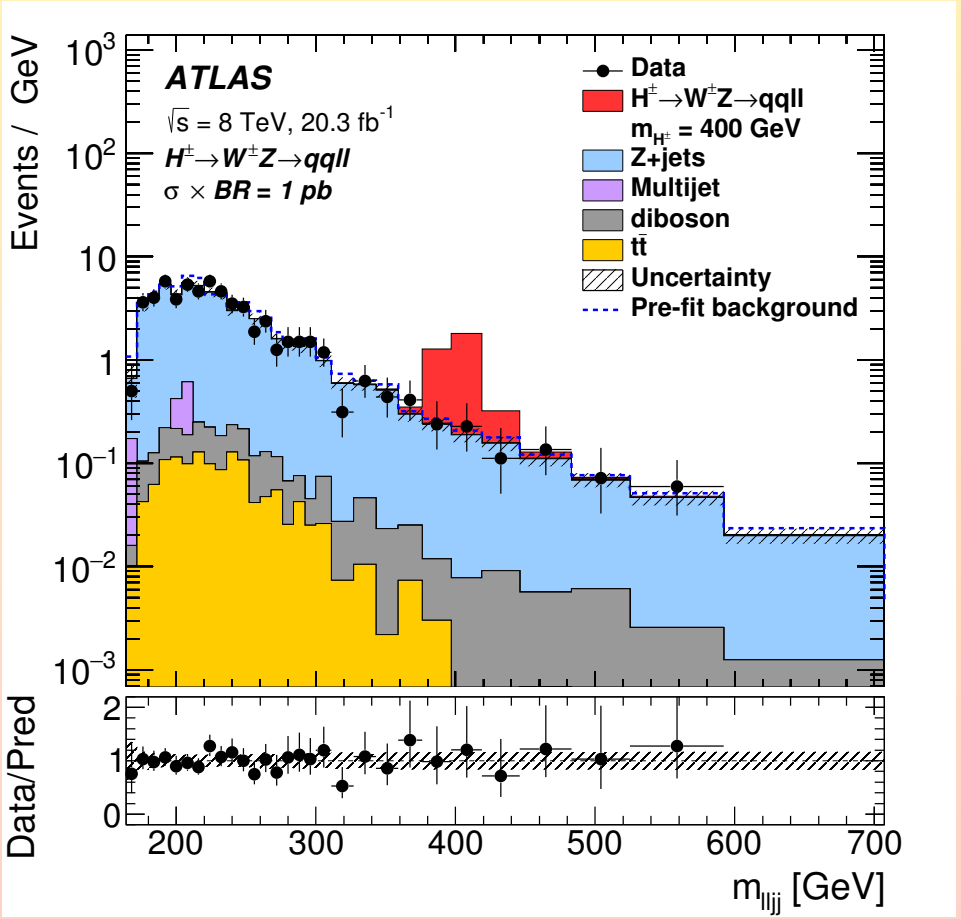
$H^{\pm} \to W^{\pm}Z$ in vector boson fusion - 1/2

Phys. Rev. Lett. 114, 231801 (2015) [5]

- 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

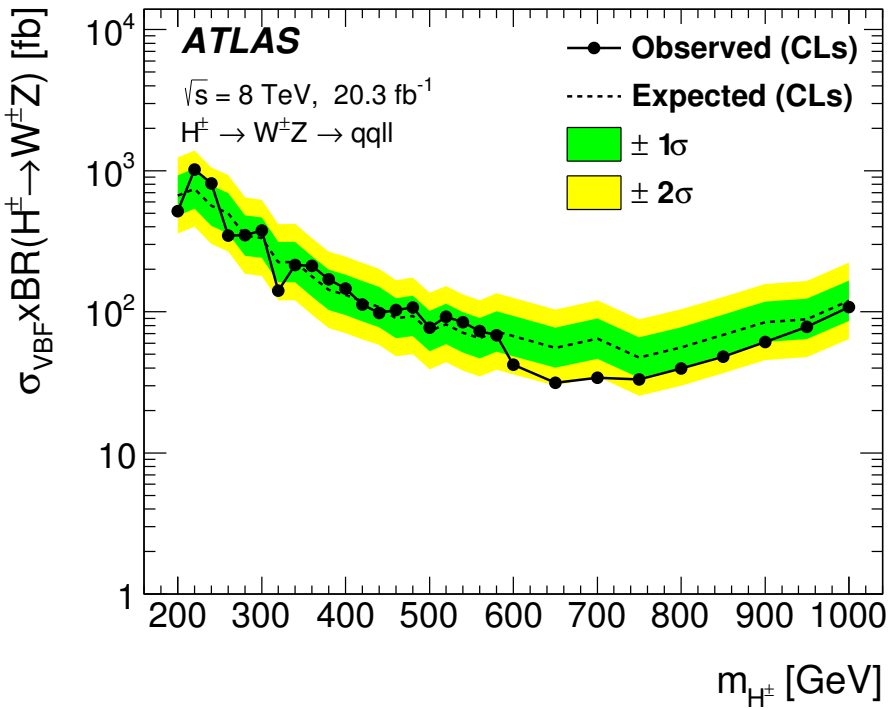




$H^{\pm} \to W^{\pm}Z$ in vector boson fusion - 2/2

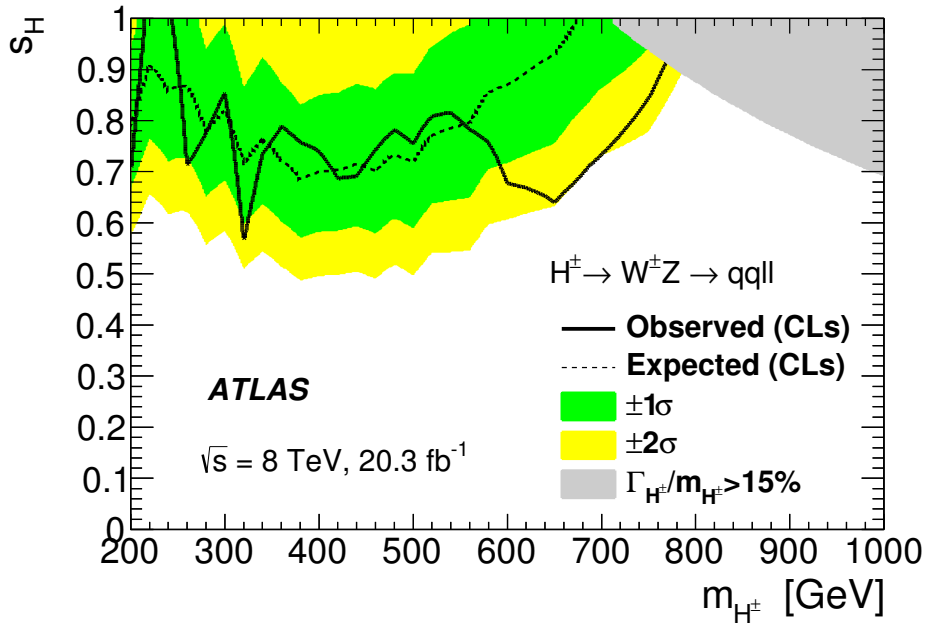
Phys. Rev. Lett. 114, 231801 (2015) [5]

Exclusion limits



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

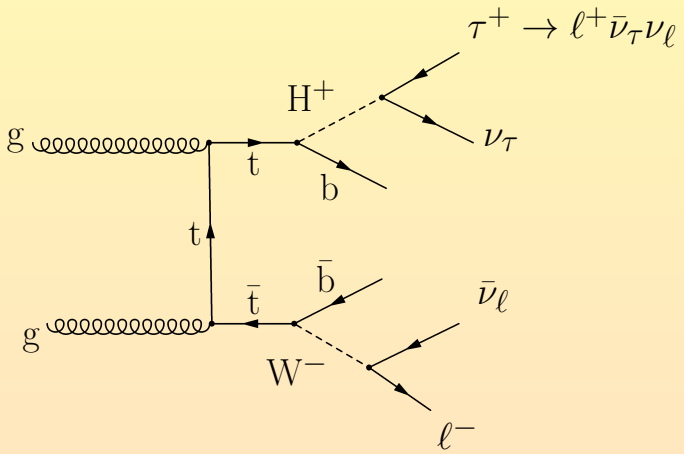
Interpretation in Higgs triplet model

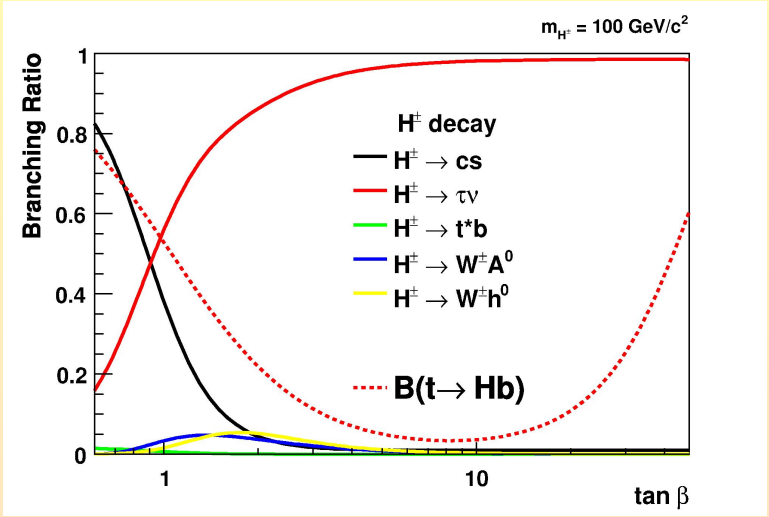


- Georgi-Machacek triplet model
- s_H^2: fraction of m_W^2 and m_Z^2 generated by the triplet v.e.v.
- $s_H^2 \propto$ cross section and $H^{\pm}$ width
- $\mathcal{B}(H^{\pm} \to W^{\pm}Z) = 1$ assumed (predicted to be very high when above $W^{\pm}Z$ threshold)

Searching for charged Higgs using top quarks

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

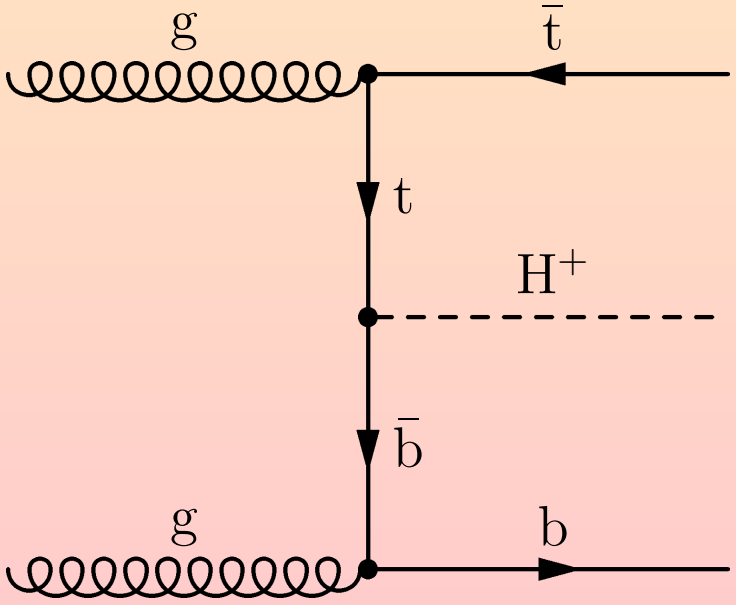




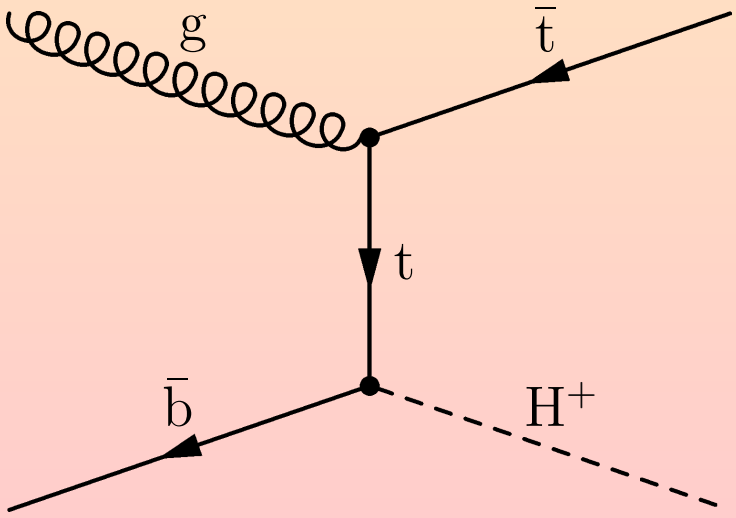
(from `D0 Note 5715-CONF`)

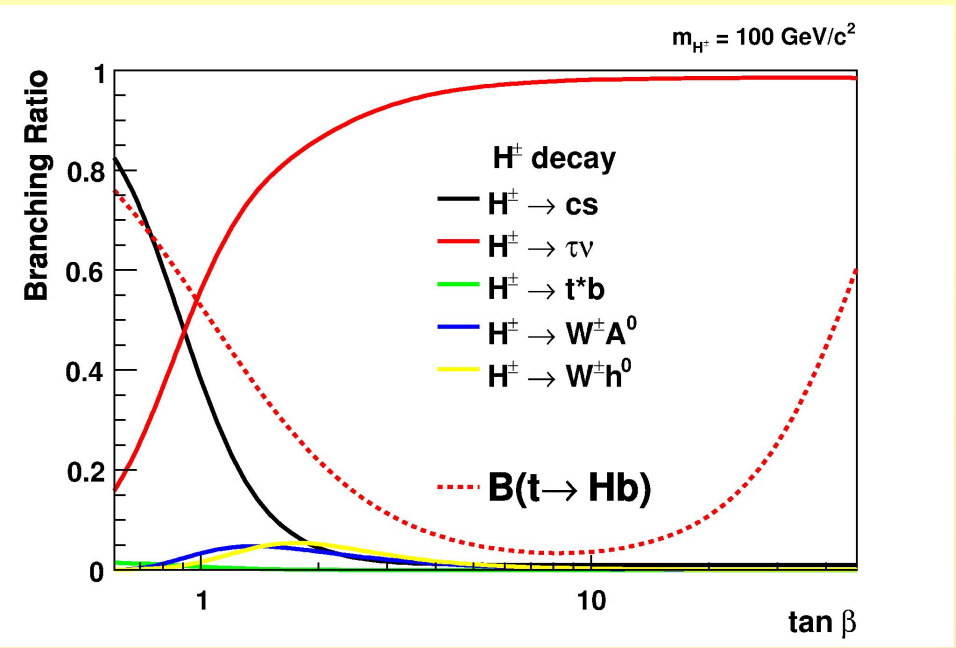
- H^+ can be produced in association with top quarks if $M_{H^+} > M_t - M_b$

4FS similar to ttH production



5FS dominates (similar to tW production)

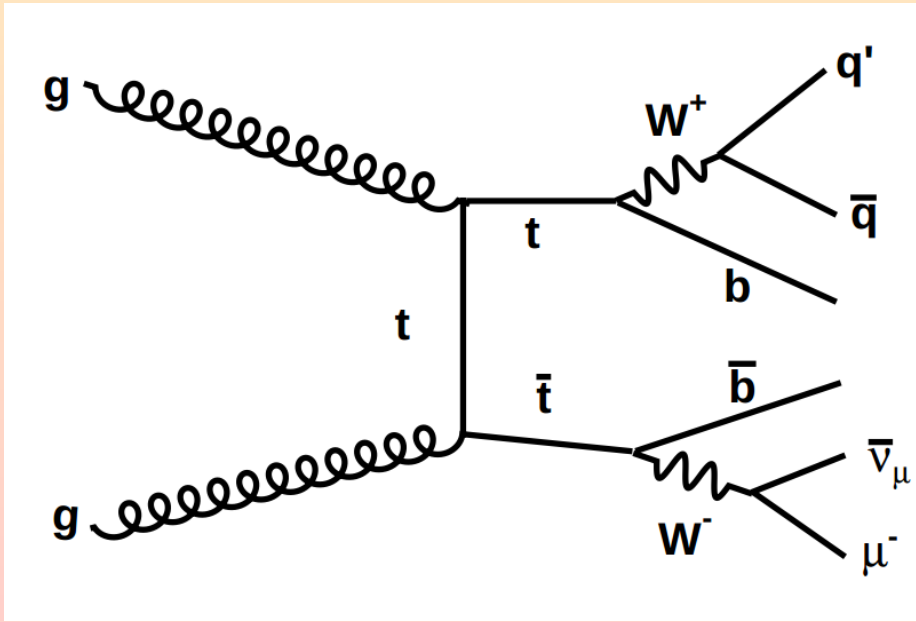


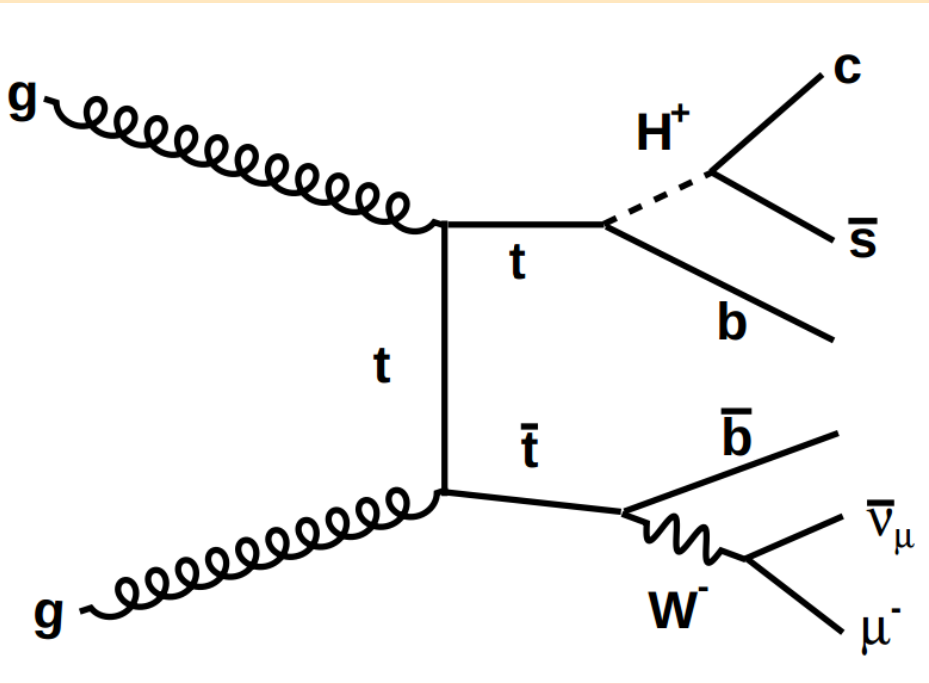


(from D0 Note 5715-CONF)

Searching for a light H^+

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



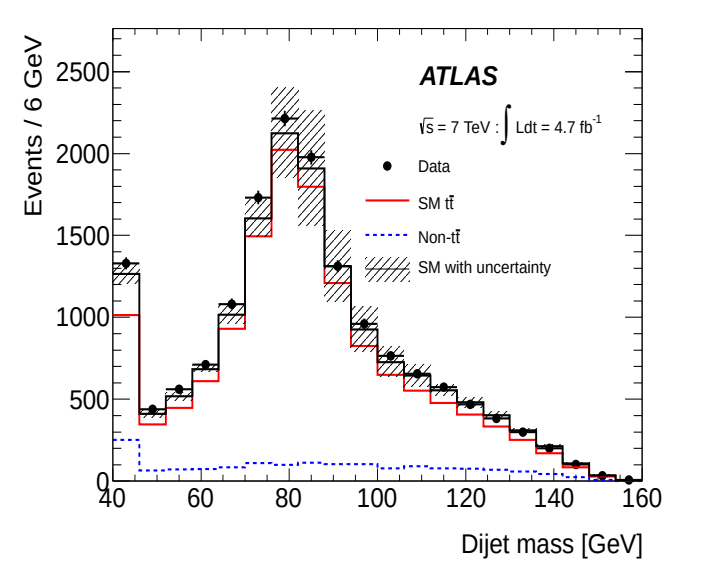


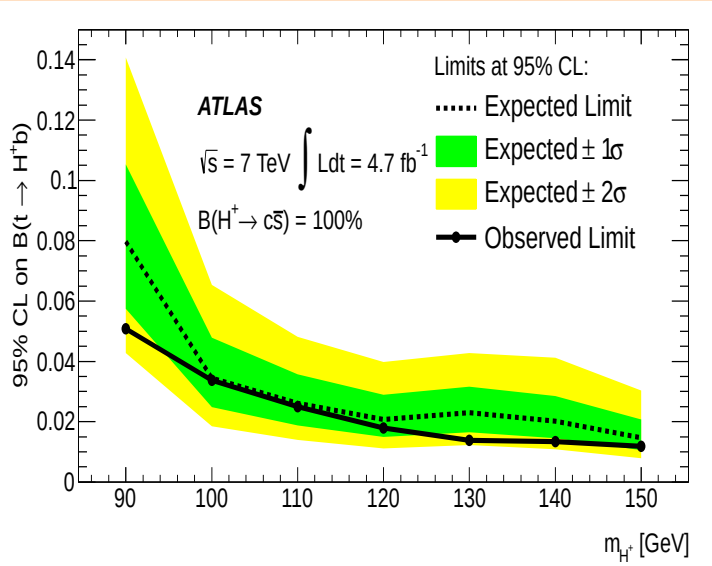
(Plots from [11])

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

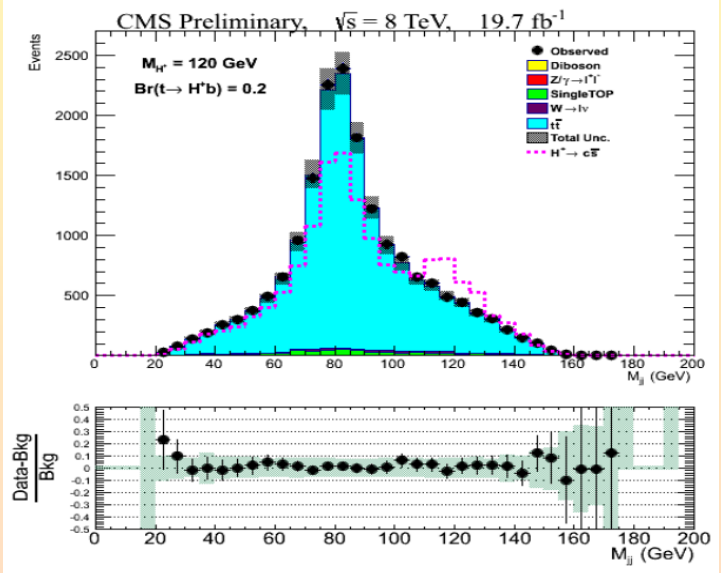
- **Selection (ATLAS):** $=$ 1 lepton (e, μ), $\geq$ 4 jets, $\geq$ 2 b-tagged jets, E_T^{miss}, $M_T(\ell, E_T^{miss})$
- **Selection (CMS):** $\geq$ 1 lepton, veto additional loose leptons, $\geq$ 4 jets, $\geq$ 2 b-tagged jets, E_T^{miss}
- **W/Z mass reconstruction:** separate signal from $t\bar{t}$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

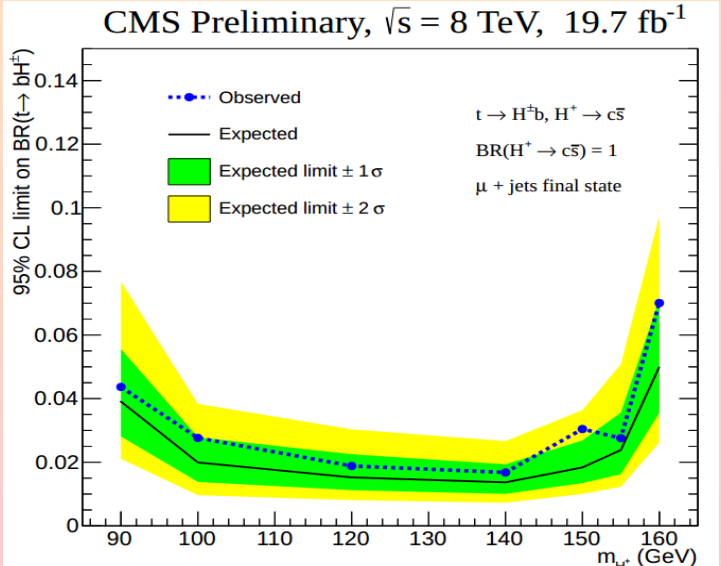
Eur. Phys. J. C, 73 6 (2013) 2465 [6]





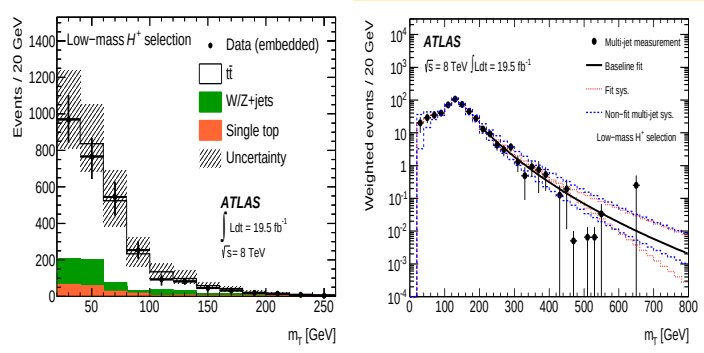
CMS-HIG-13-035 [11]

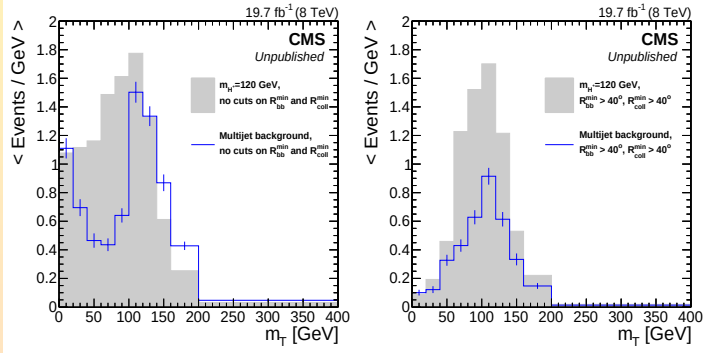


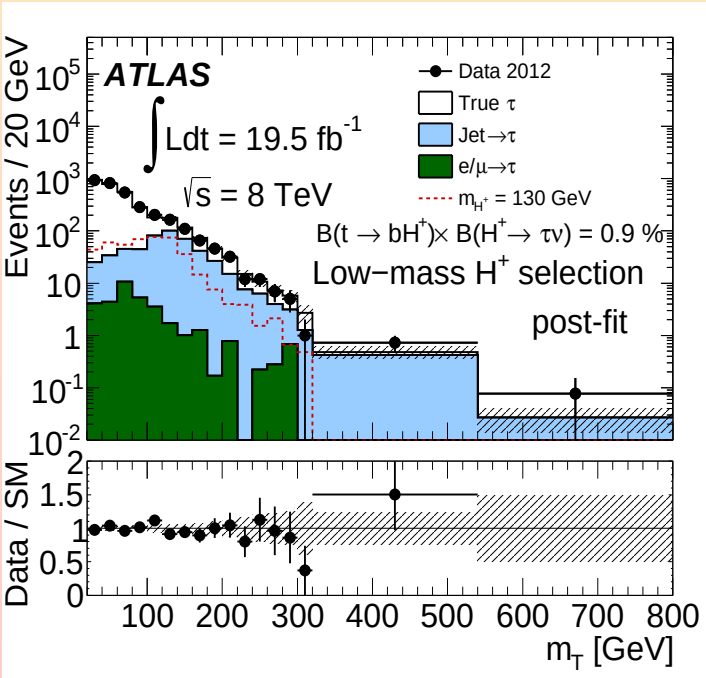


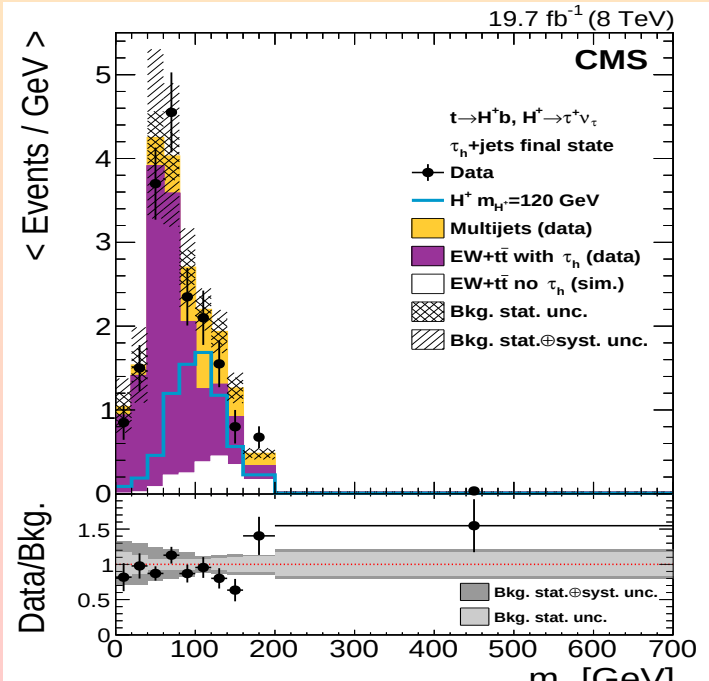
τ_h+jets final state

- **CMS (arXiv:1508.07774 [?]):** 1 τ_h, $\geq$ 3 jets, veto leptons, $E_{\mathrm{T}}^{\mathrm{miss}}$
- **ATLAS (JHEP03 (2015) 088 [7]):** 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





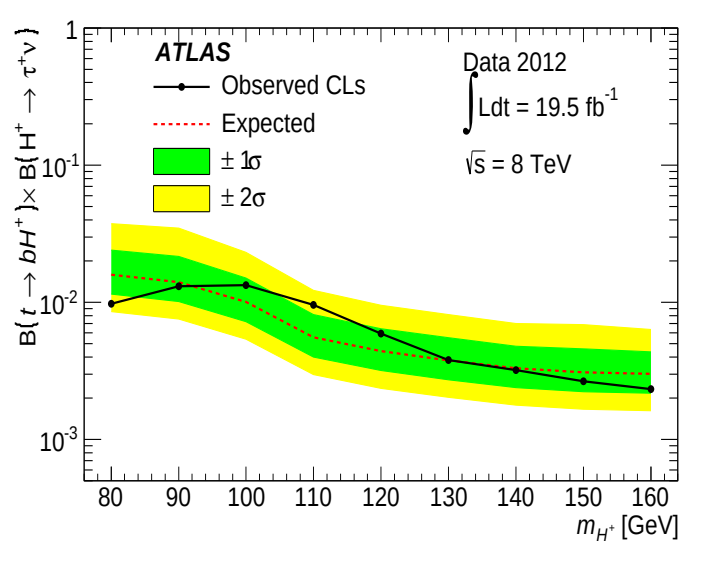


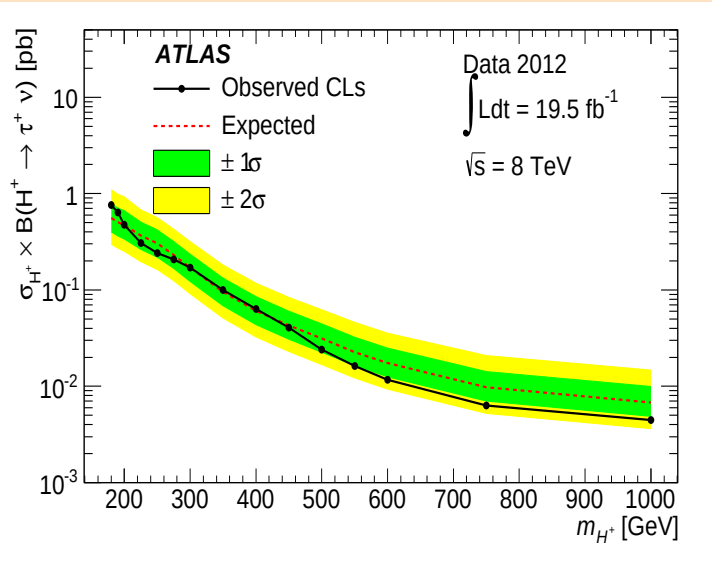


τ_h+jets final state - results

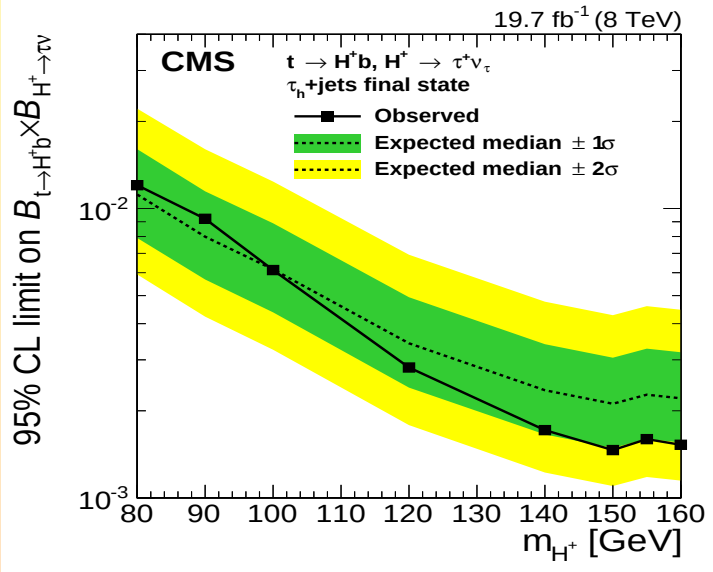
- CMS has better sensitivity in the central mass range $m_{H^+} = 90 - 400$ GeV
- ATLAS has better sensitivity for $m_{H^+} < 90$ GeV and in the high mass range $m_{H^+} > 400$ GeV

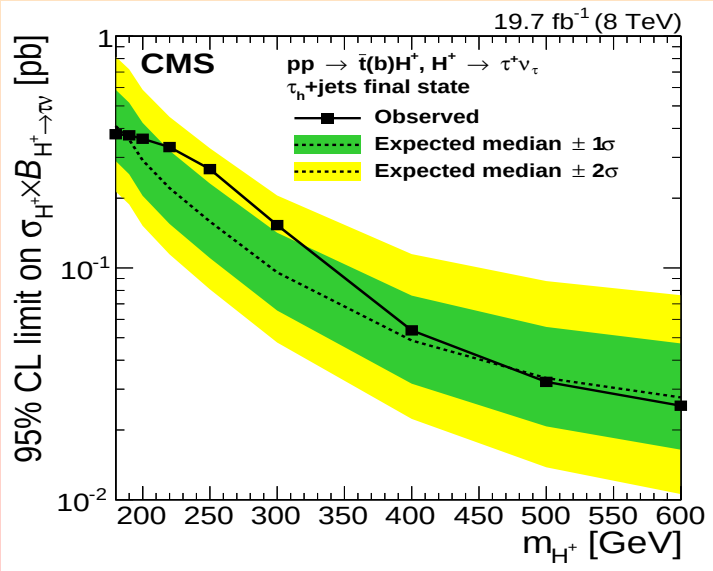
JHEP03 (2015) 088 [7]





arXiv:1508.07774 [?]

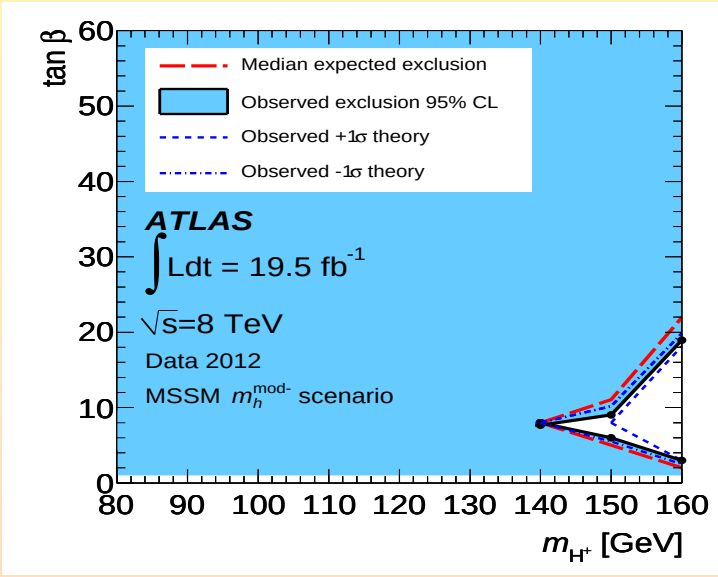


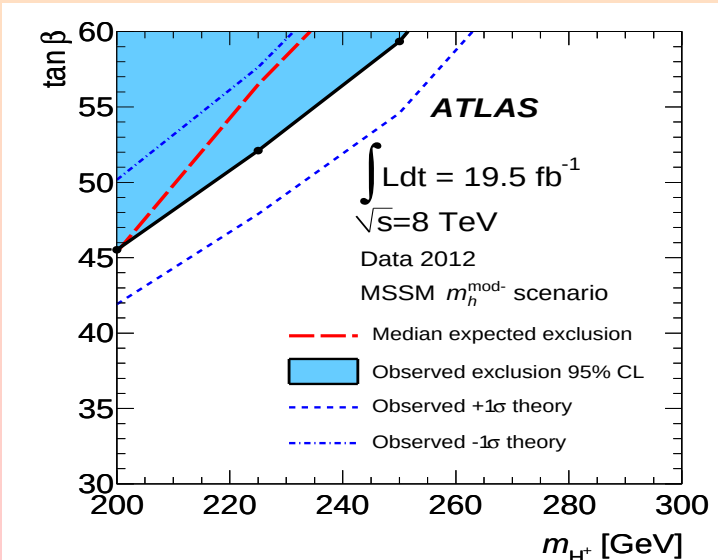


τ_h+jets final state - interpretations

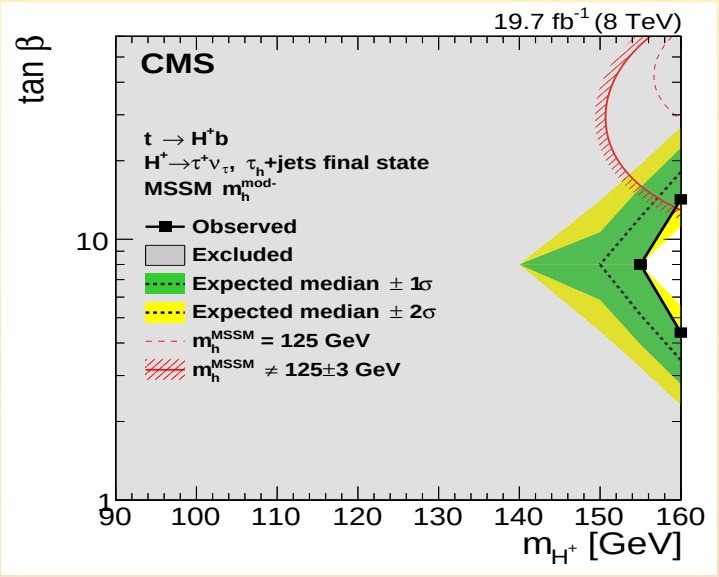
- Model-independent upper limits are computed for $\mathcal{B}(t \to \mathrm{H}^+ b) \times \mathcal{B}(\mathrm{H}^+ \to \tau\nu)$
- Limits are then interpreted as exclusion region in ($m_{\mathrm{H}^+} - tan\beta$) plane for the m_h^{mod-} scenario
- Not much space left available in the parameter space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

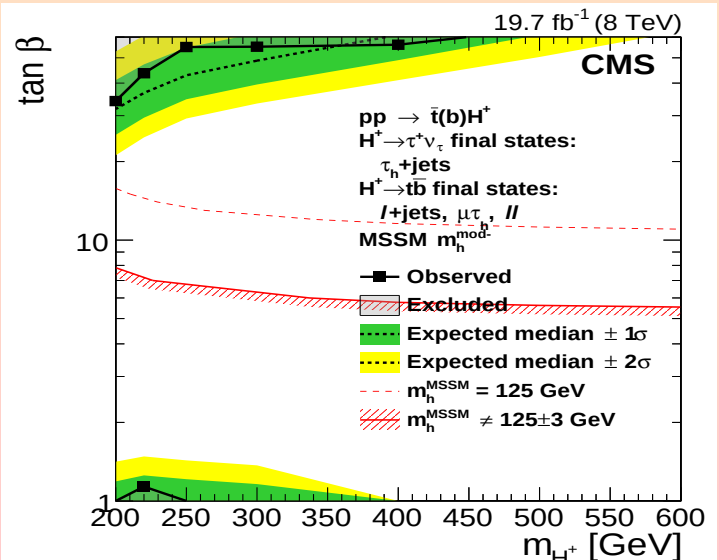
JHEP03 (2015) 088 [7]





arXiv:1508.07774 [?]





τ_h+jets final state results - interpretations

- Low-M_H scenario with $m_A = 110$ GeV completely excluded (CMS [**?**])
- Completely excluded also by ATLAS [7]

arXiv:1508.07774 [**?**]