Charged Higgs and LFV Higgs decays at the LHC

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Direct LHC searches for charged Higgs and Lepton Flavour Violation Higgs:

$H^+ \rightarrow \tau\nu$

$H^+ \rightarrow cb$

$H \rightarrow e\mu$

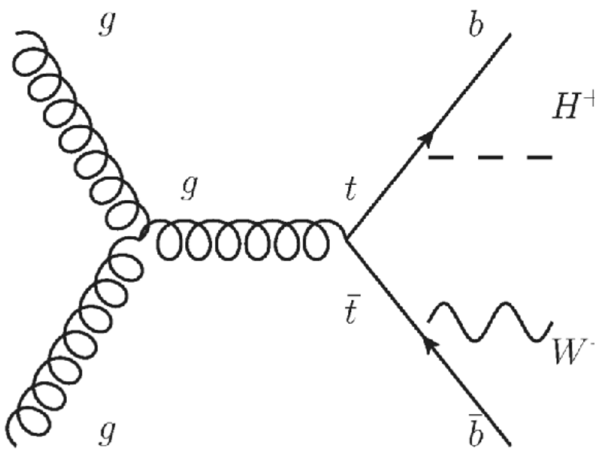
$H \rightarrow \tau e$

$H \rightarrow \tau\mu$

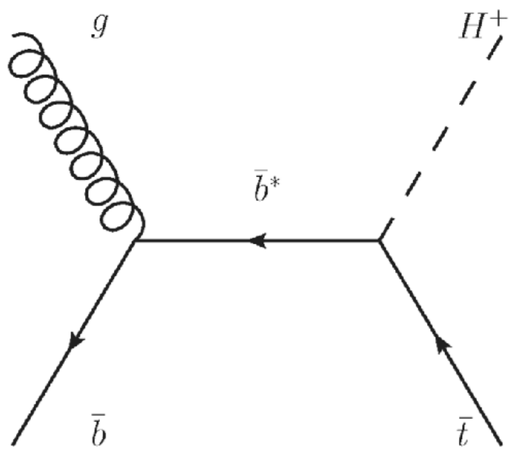
Charged Higgs

Higgs couplings to fermions might be modified in case of an extended Higgs sector (MSSM, 2HDM, etc etc) where a charged Higgs is predicted.

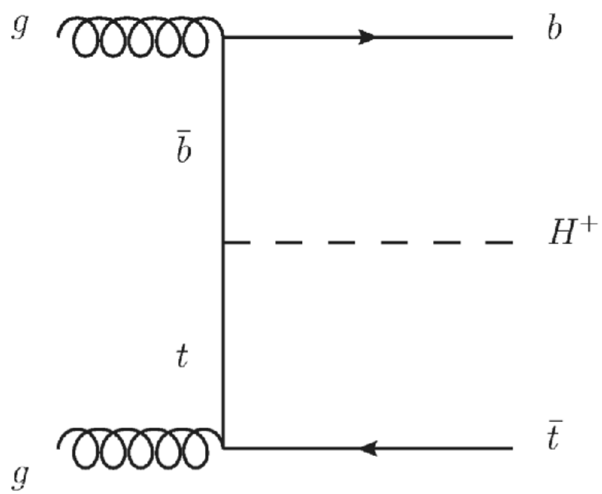
Charged Higgs bosons are primarily produced in decays of (low-mass) or in association with (high-mass) a top quark:



$m_{H+} < m_{top}$



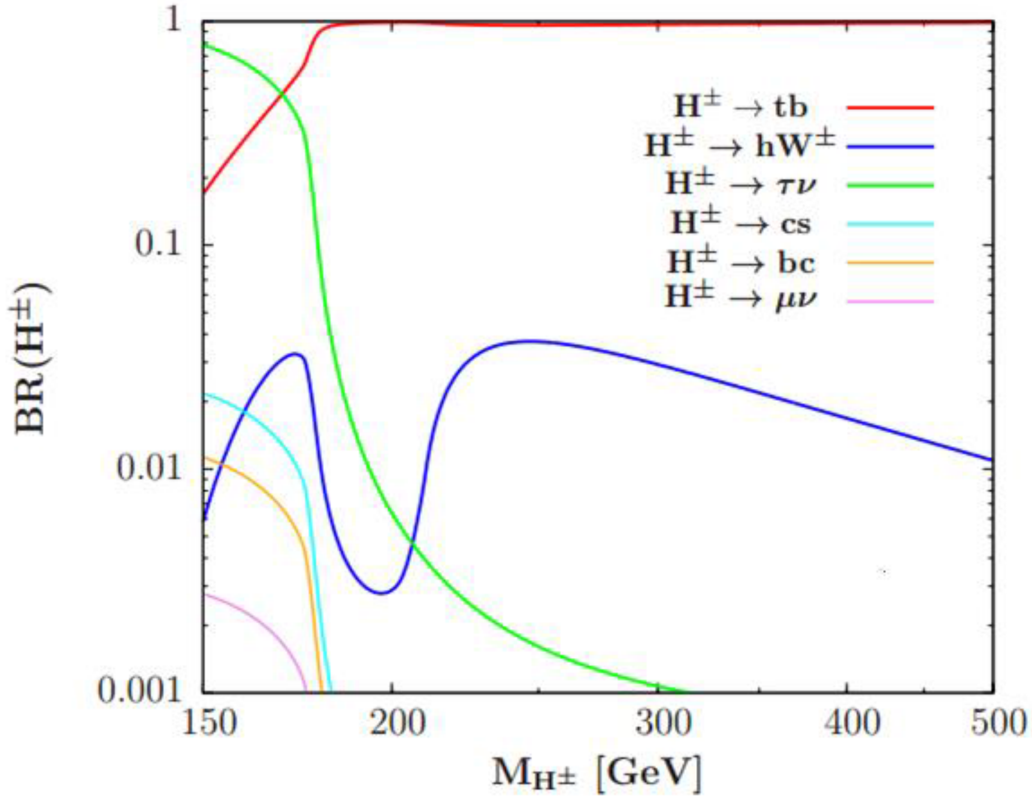
$m_{H+} > m_{top}$, 5FS



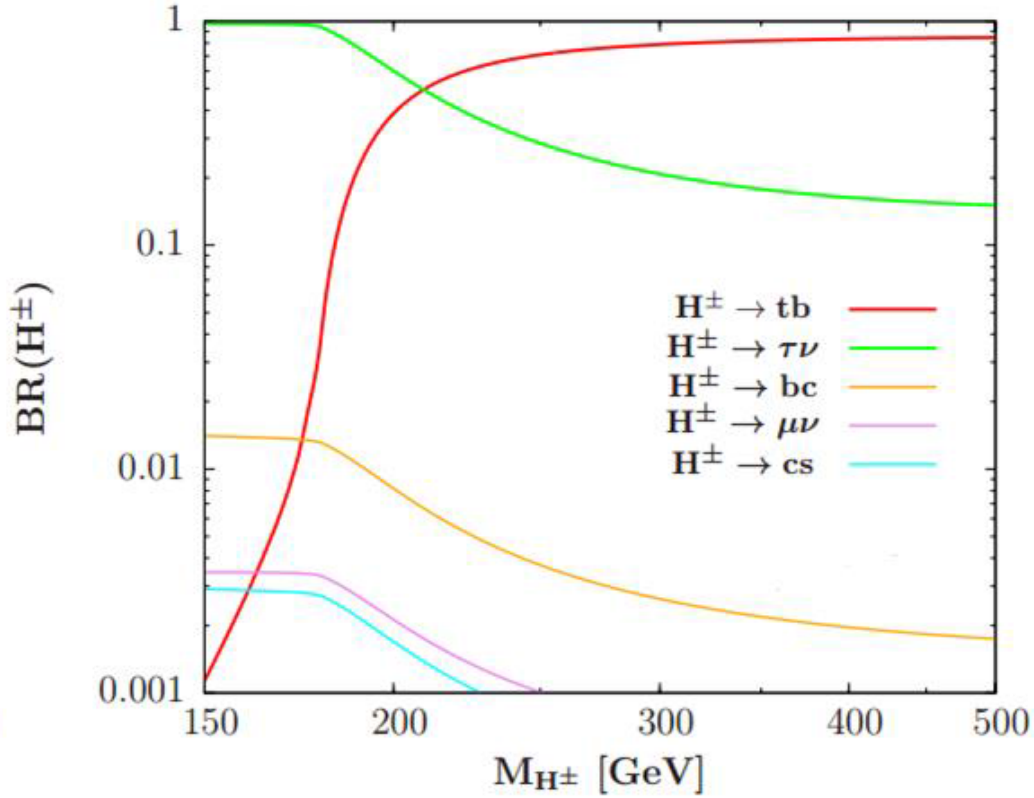
$m_{H+} > m_{top}$, 4FS

Charged Higgs decay modes

$\tan\beta = 2$

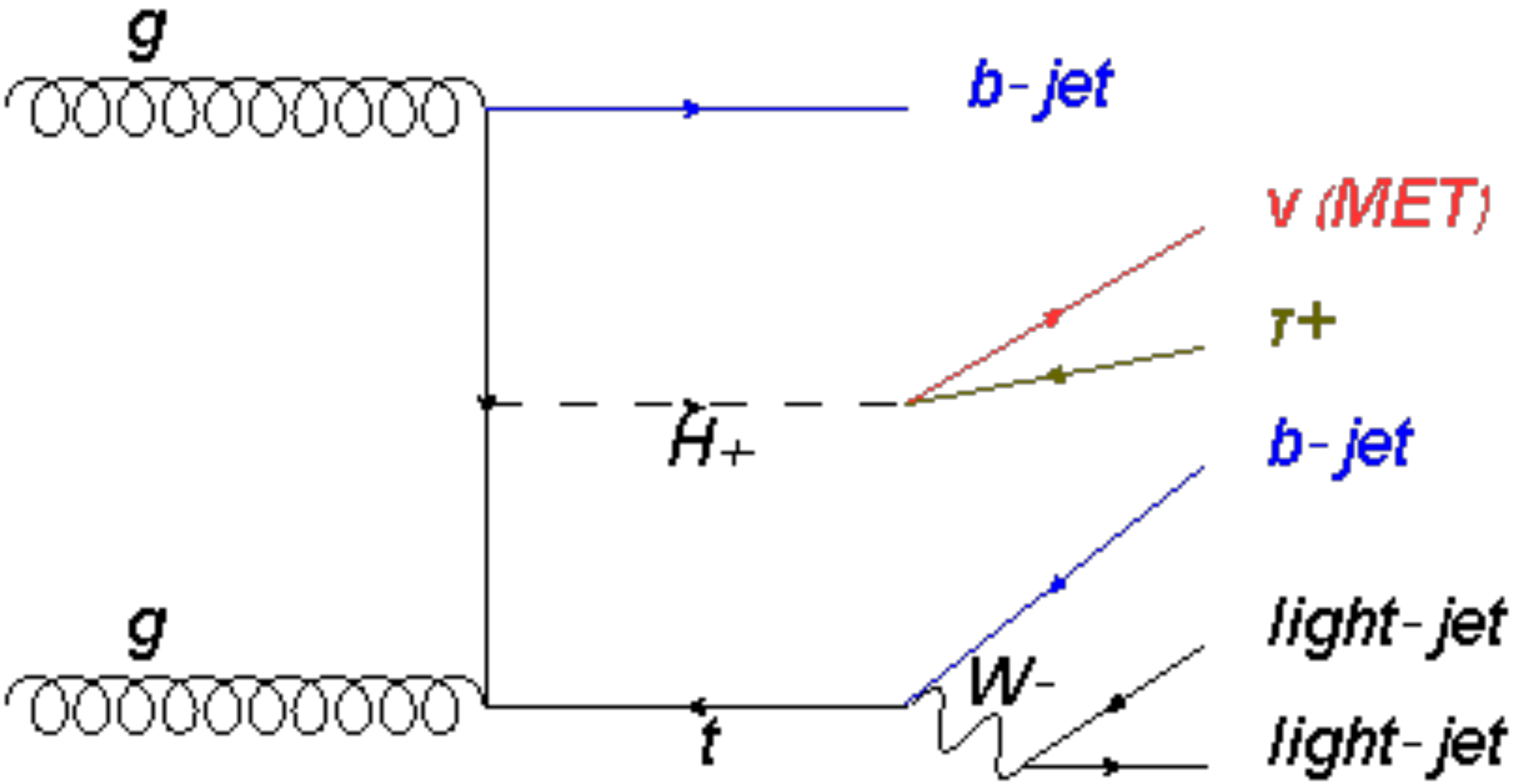


$\tan\beta = 30$

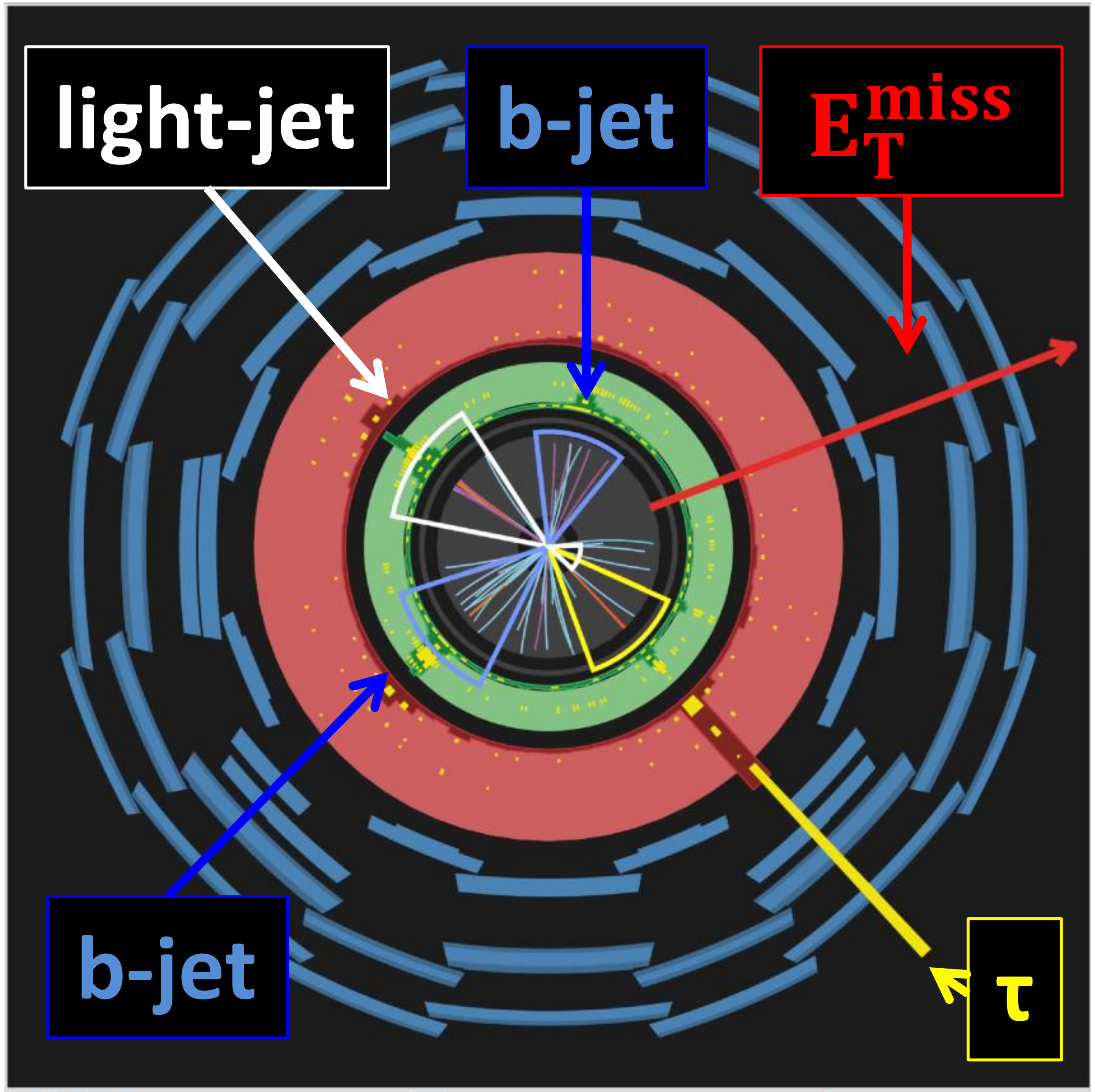


A. Djouadi, L. Maiani, A. Polosa, J. Quevillon, V. Riquer (**arXiv:1502.05653**)

$H^+ \to \tau\,\nu$

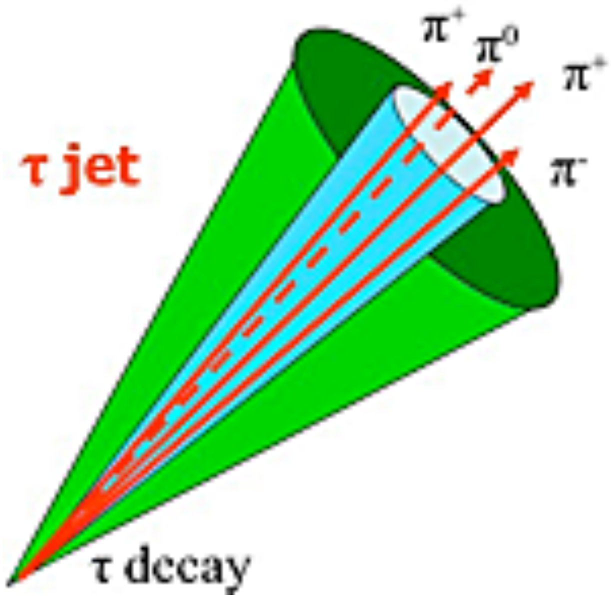


$H^+ \rightarrow \tau\, \nu$



τ @ LHC

decay modes	branching fraction (%)
leptonic modes	
$\tau^{\pm} \to e^{\pm}\nu_e\nu_\tau$	17.4
$\tau^{\pm} \to \mu^{\pm}\nu_\mu\nu_\tau$	17.9
hadronic modes	64.7%
$\tau^{\pm} \to \pi^{\pm}\nu_\tau$	10.9
$\tau^{\pm} \to \pi^{\pm}\pi^{0}\nu_\tau$	25.5
$\tau^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}\nu_\tau$	9.3
$\tau^{\pm} \to \pi^{\pm}\pi^{0}\pi^{0}\pi^{0}\nu_\tau$	1.0
$\tau^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}\nu_\tau$	9.3
$\tau^{\pm} \to \pi^{\pm}\pi^{\pm}\pi^{\mp}\pi^{0}\nu_\tau$	4.6

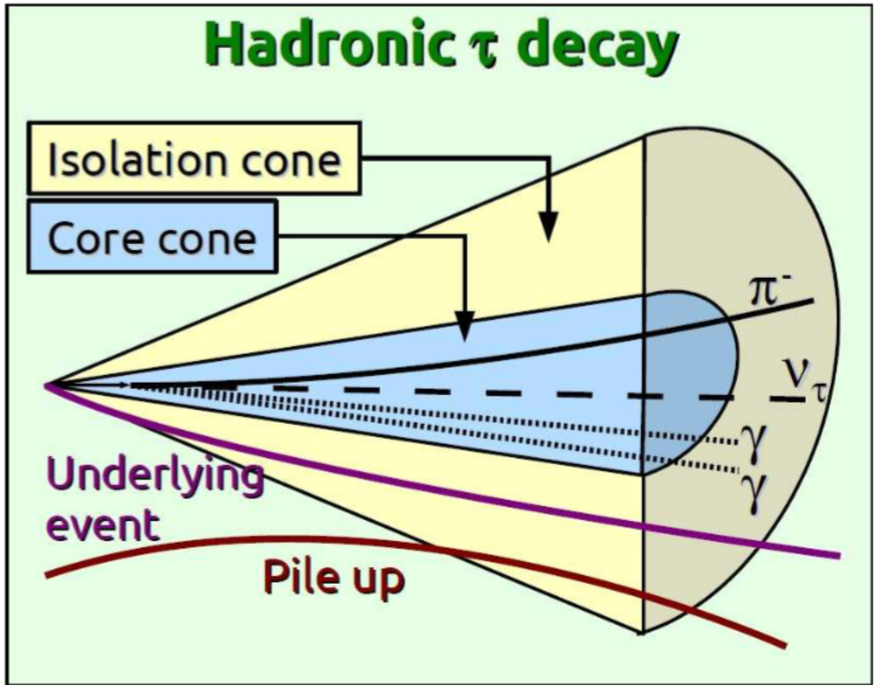


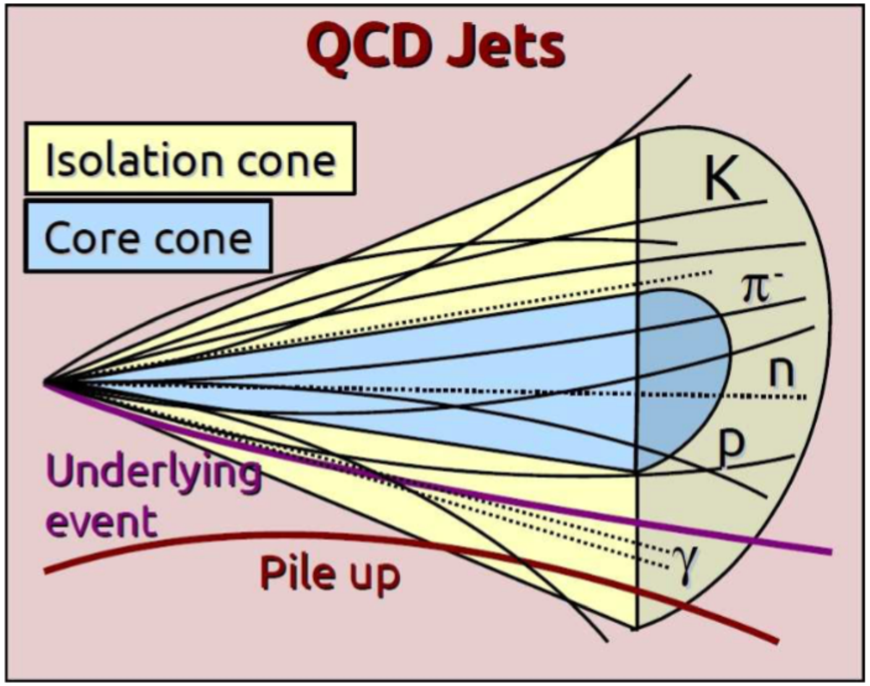
Specific mix of $\pi^{\pm}$ and π^{0}:

Reconstruction & ID:

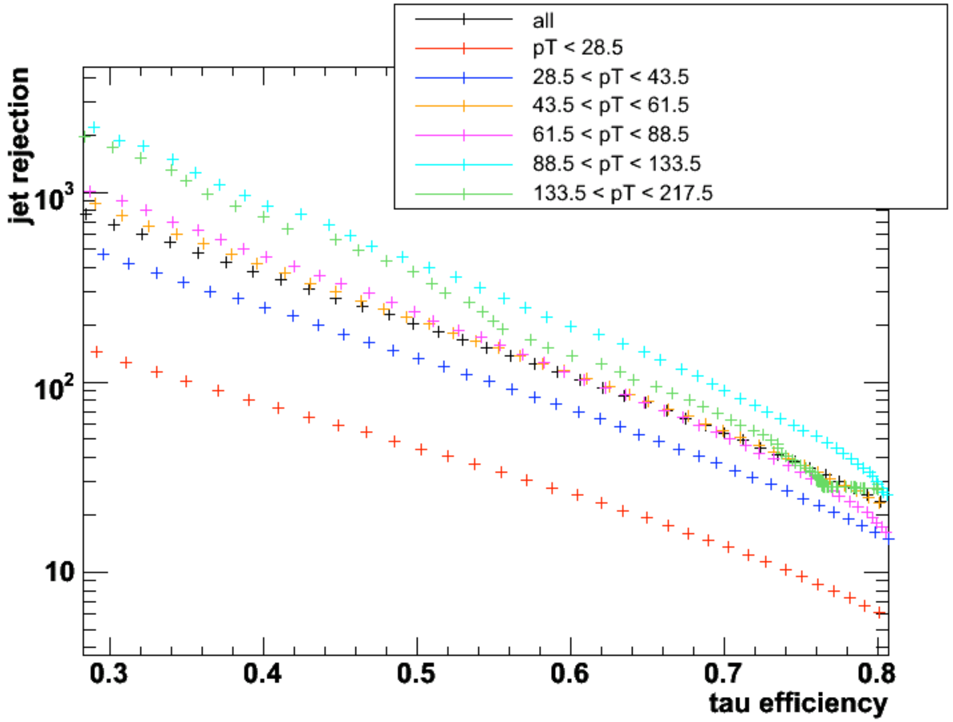
- τ reconstruction seeded by anti-k_T jets
- Identification criteria (BDT)

τ @ LHC



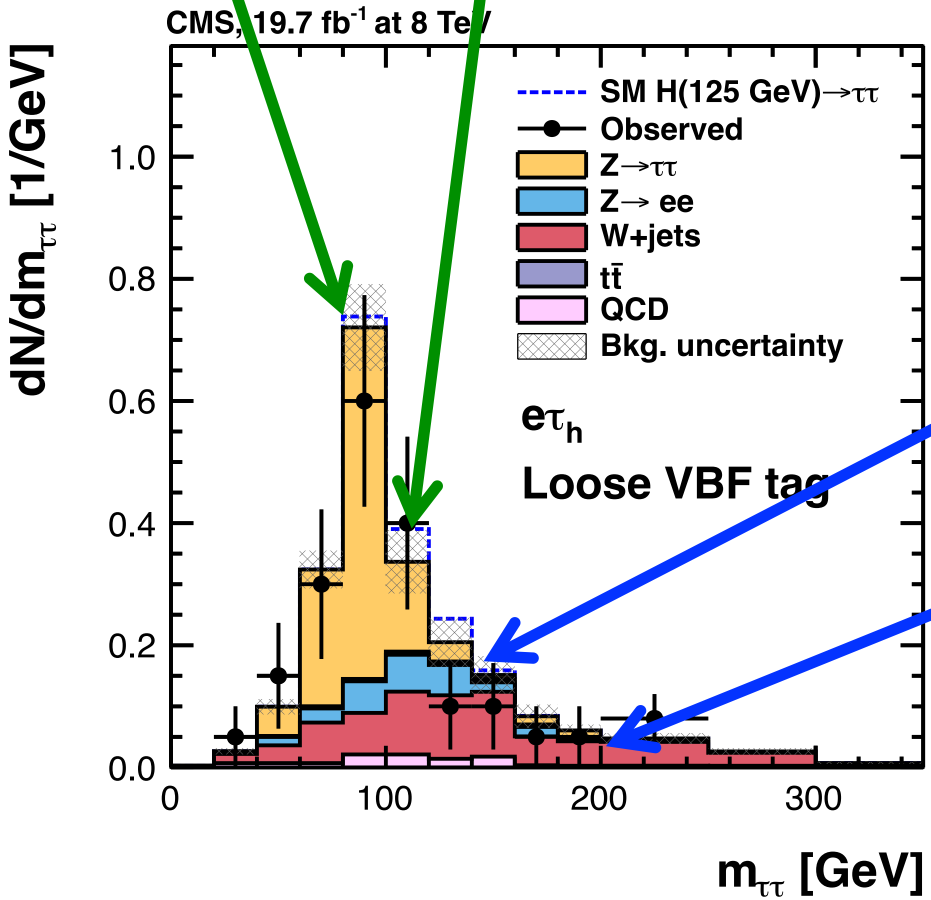


- Very collimated
  - 90% of the energy is contained in a 'cone' of radius R=0.2
- Low charged track multiplicity
  - One, three prongs
- Hadronic, EM energy deposition
  - Charged pions
  - Photons from π^o



τ @ LHC

Signal: reconstruction of genuine hadronic taus (τ_h)



Backgrounds:

Rejection of fake τ_h from electrons / muons

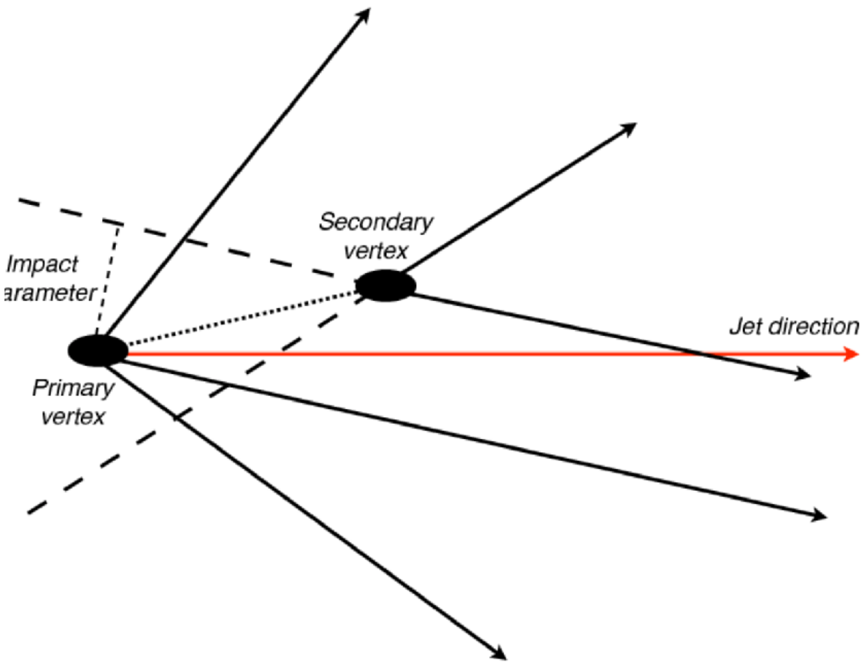
Rejection of fake τ_h from QCD jets

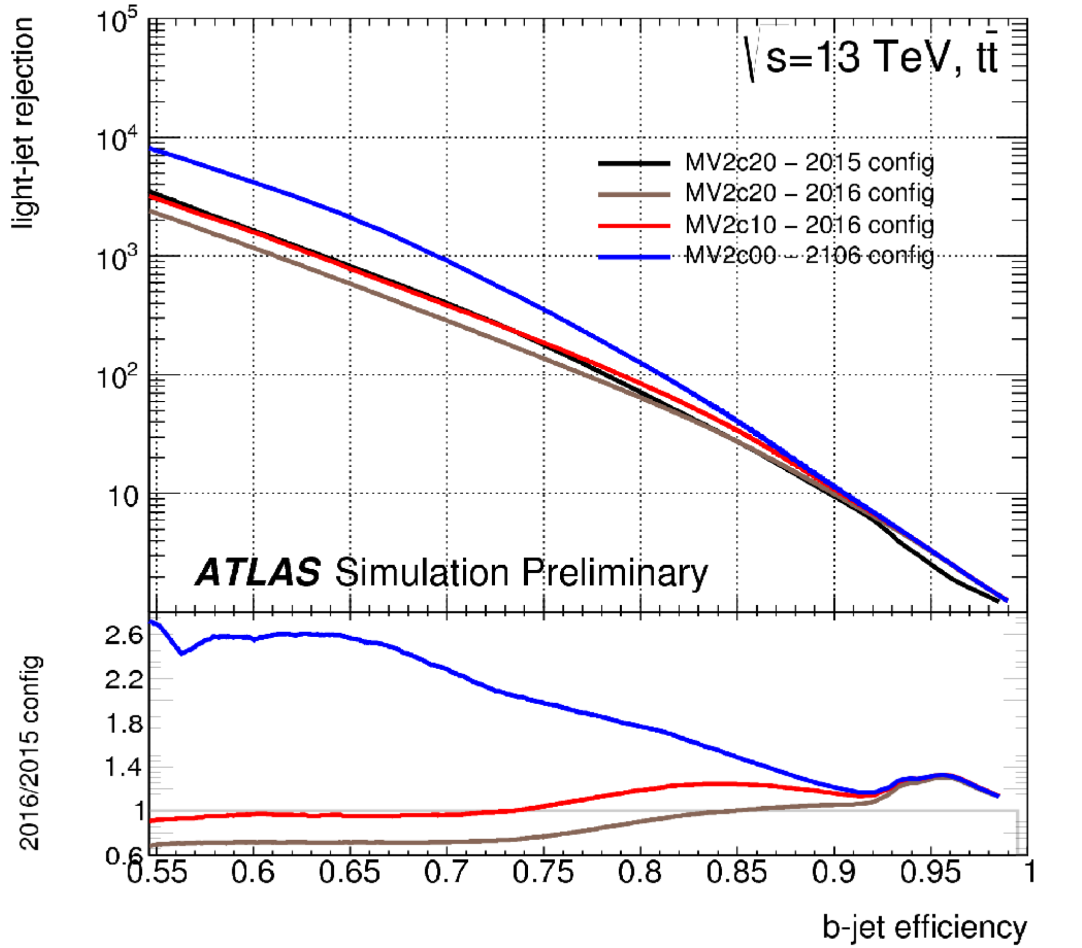
+ efficient trigger selection

+ rejection of pileup (LHC currently features up to ~40 collisions / bunch crossing)

+ reliable description of data using simulation

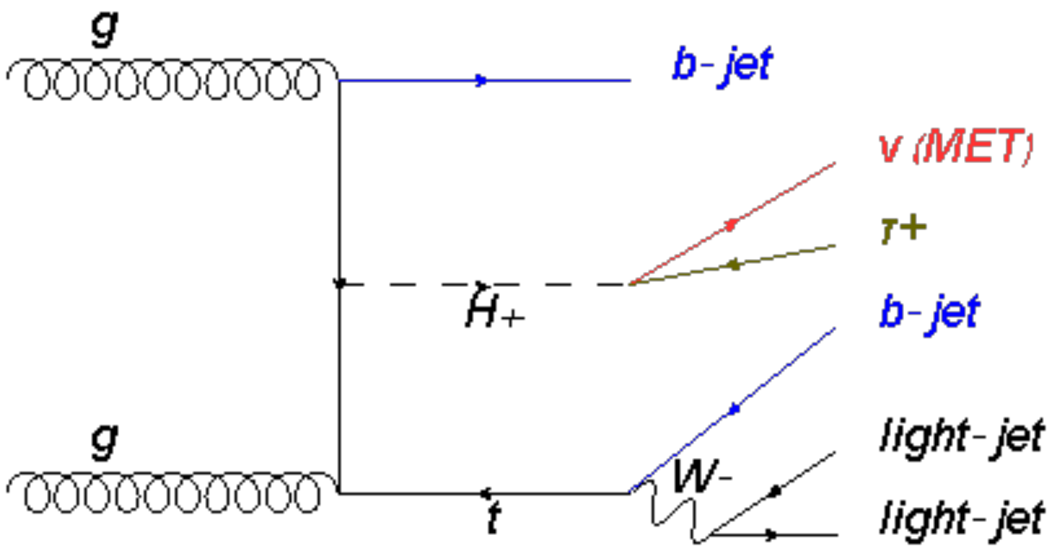
b-jet @LHC





Impact parameters + secondary and tertiary vertices + invariant mass are used for b-tagging combined for the MVA-based ID: " = 70% and c- or light-jet rejection of 10/400.

$H^+ \rightarrow \tau\, \nu$ event selection



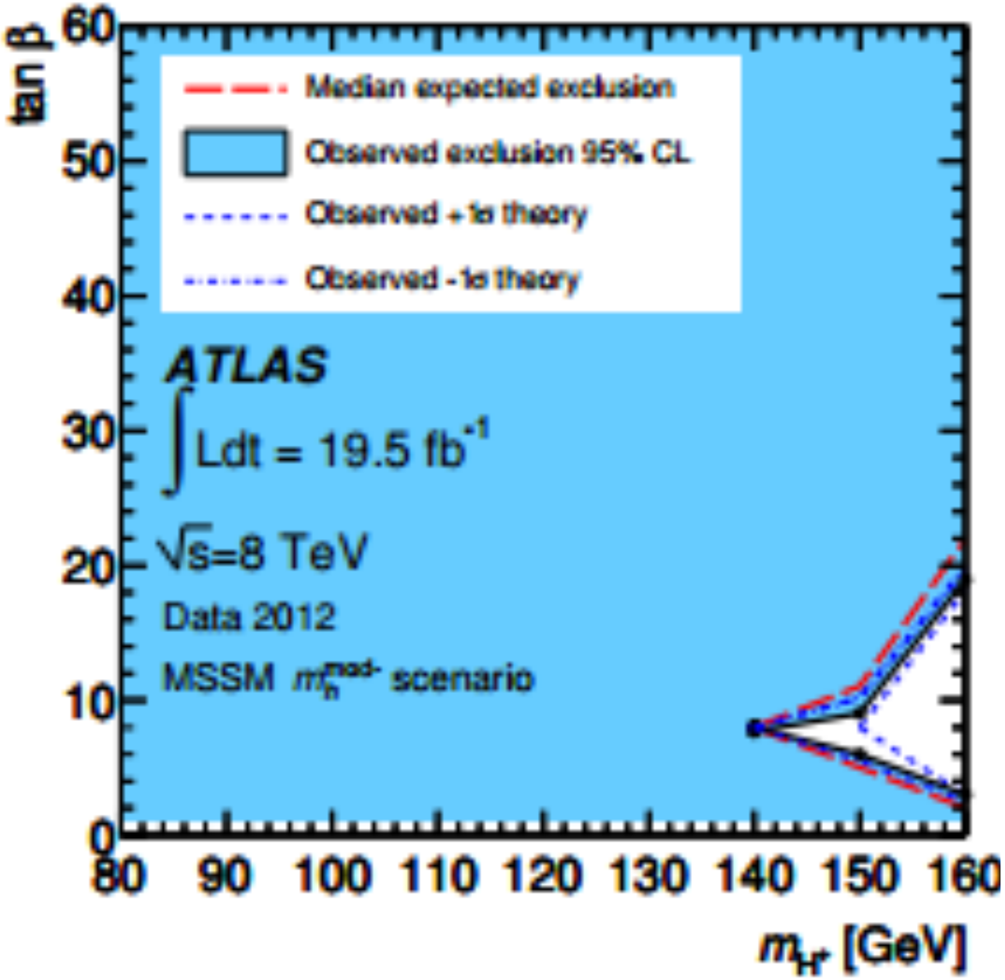
Missing transverse energy trigger (threshold at 70 (90) GeV for 2015 (2016))

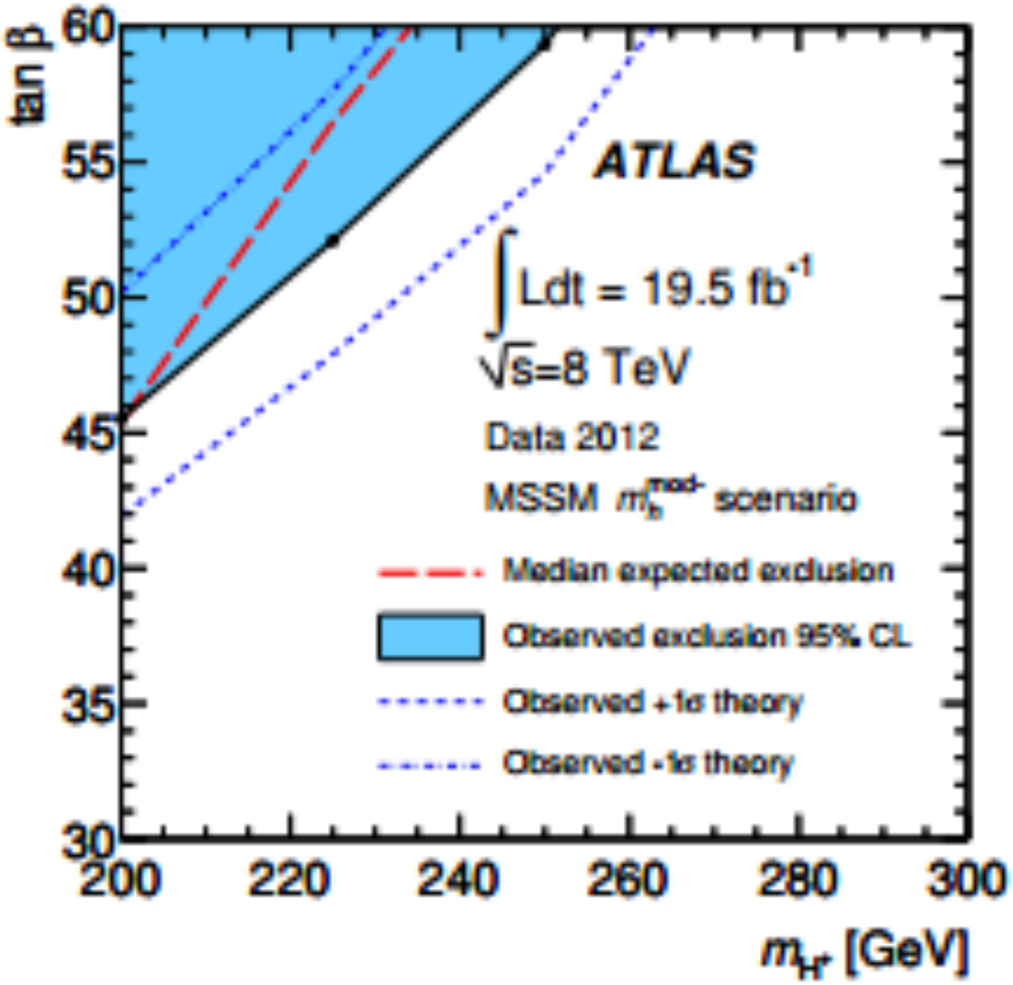
High missing transverse energy (>150 GeV)

Three or more jets with at least one is b-tagged jet (p_T >25GeV, b-tag)

Veto electrons or muons (p_T > 20 GeV)

$H^+ \to \tau\nu$ @ 8 TeV Results

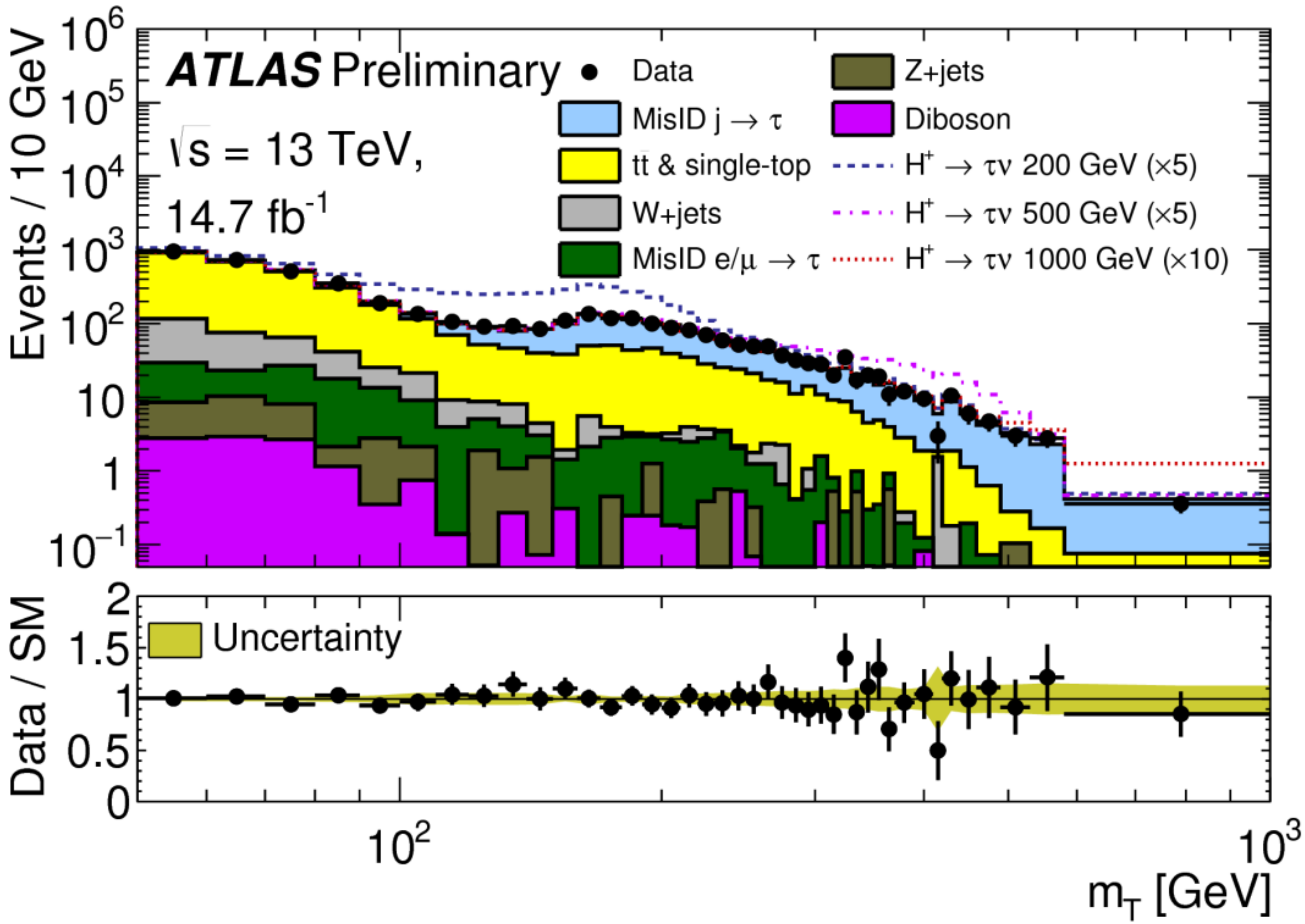




95% C.L limits on $Br(t \to bH^+)$ in the range 0.2-1.3%, assuming $Br(H^+ \to \tau\nu) = 100\%$;

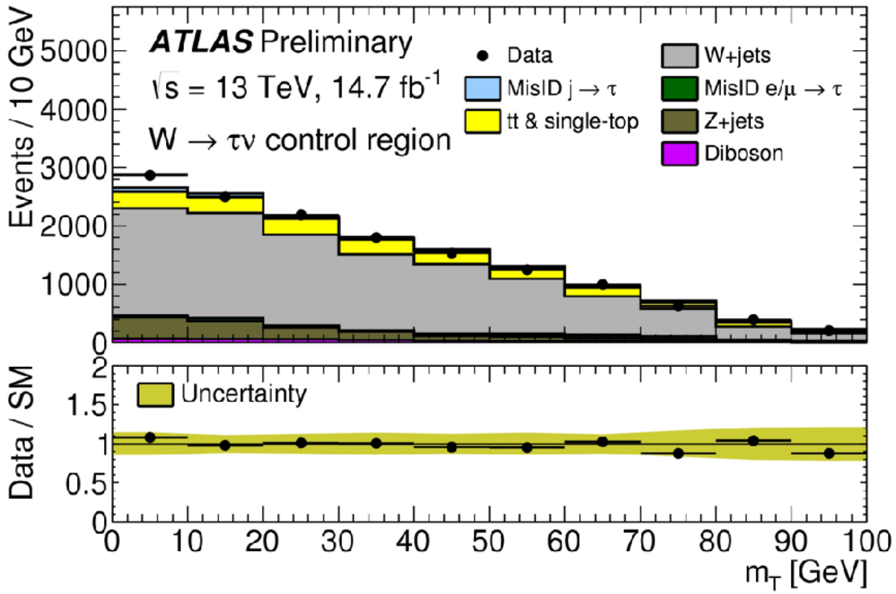
$H^+ \rightarrow \tau \nu$ event selection

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



$H^+ \to \tau\nu$ background

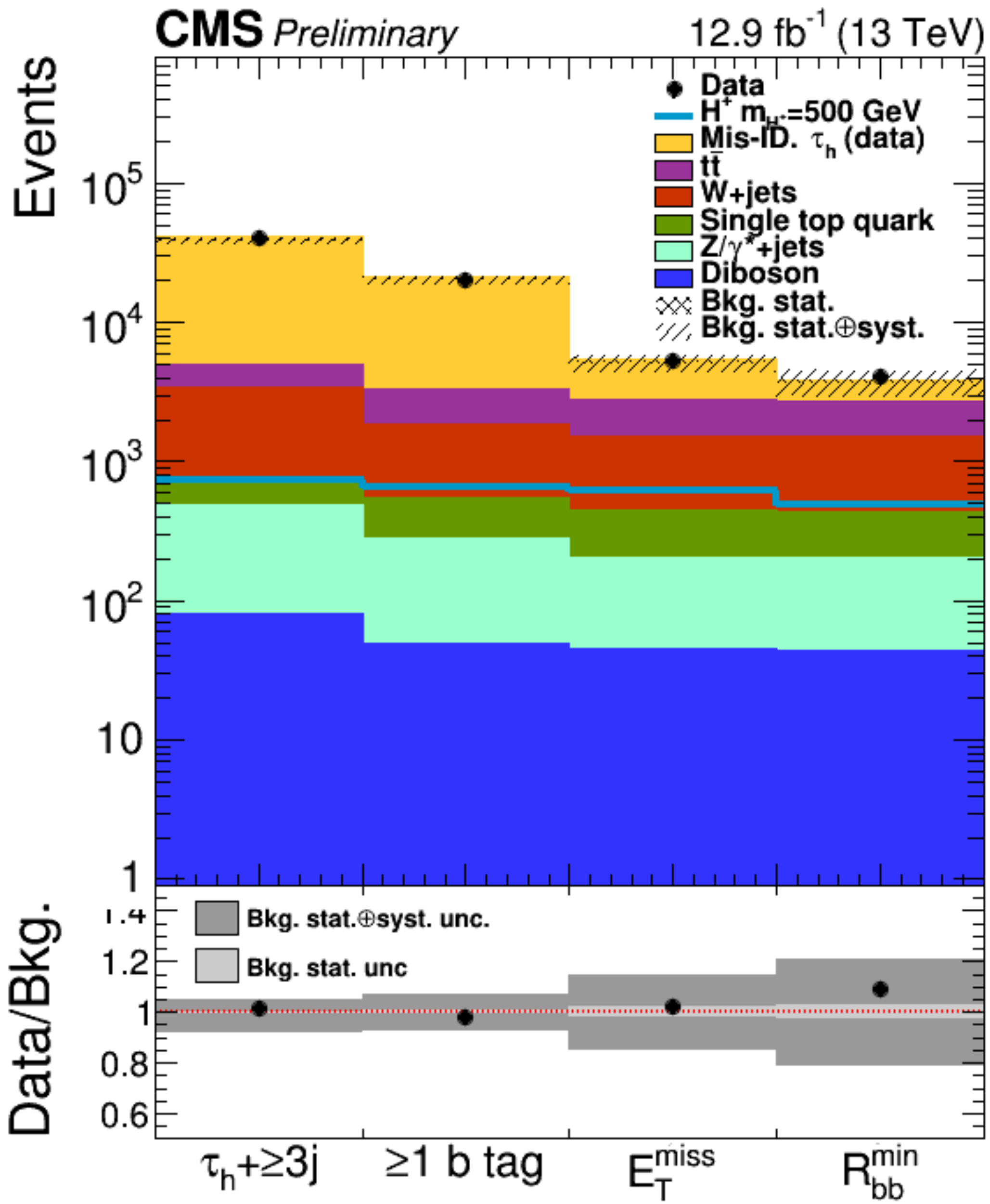
ttbar, single top, Drell-Yan, di-boson with a real tau: from simulation + data normalisation



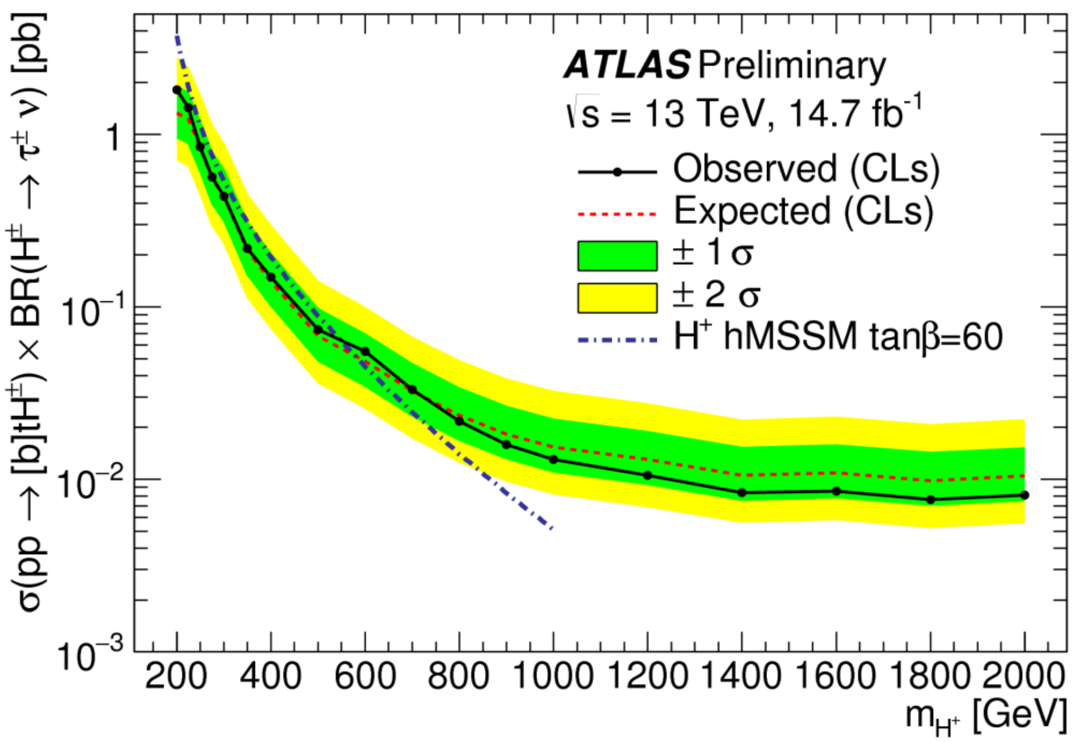
W+jets from embedding in Run1 and for Run2 as above

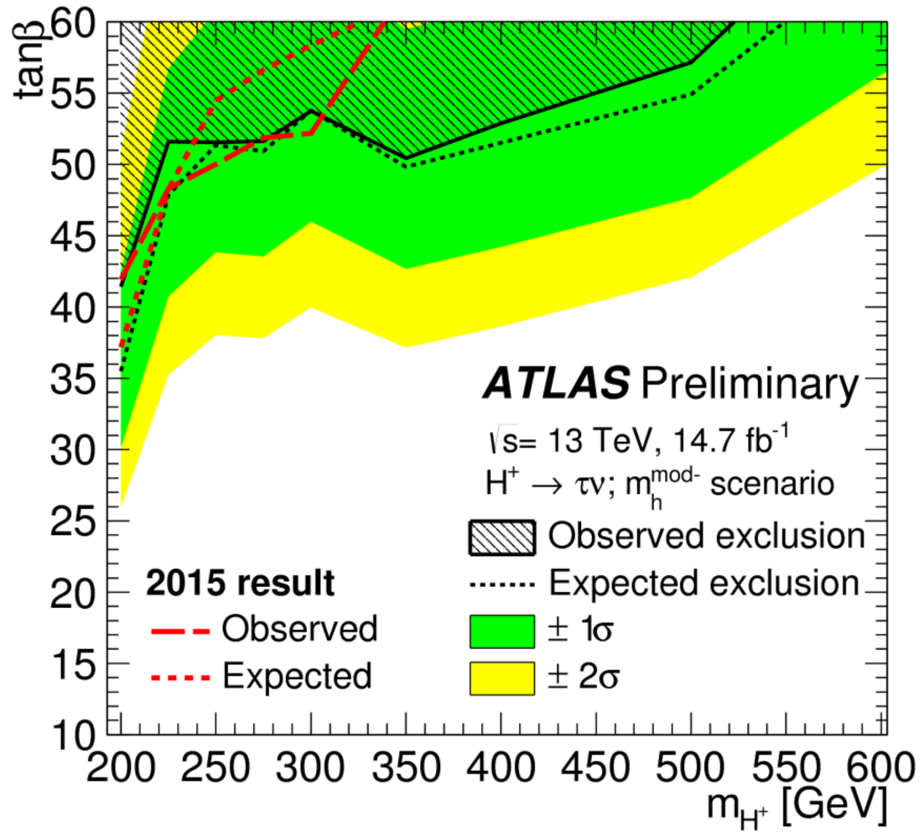
fake taus: from data from data

m_{H+} = 180–3000 GeV



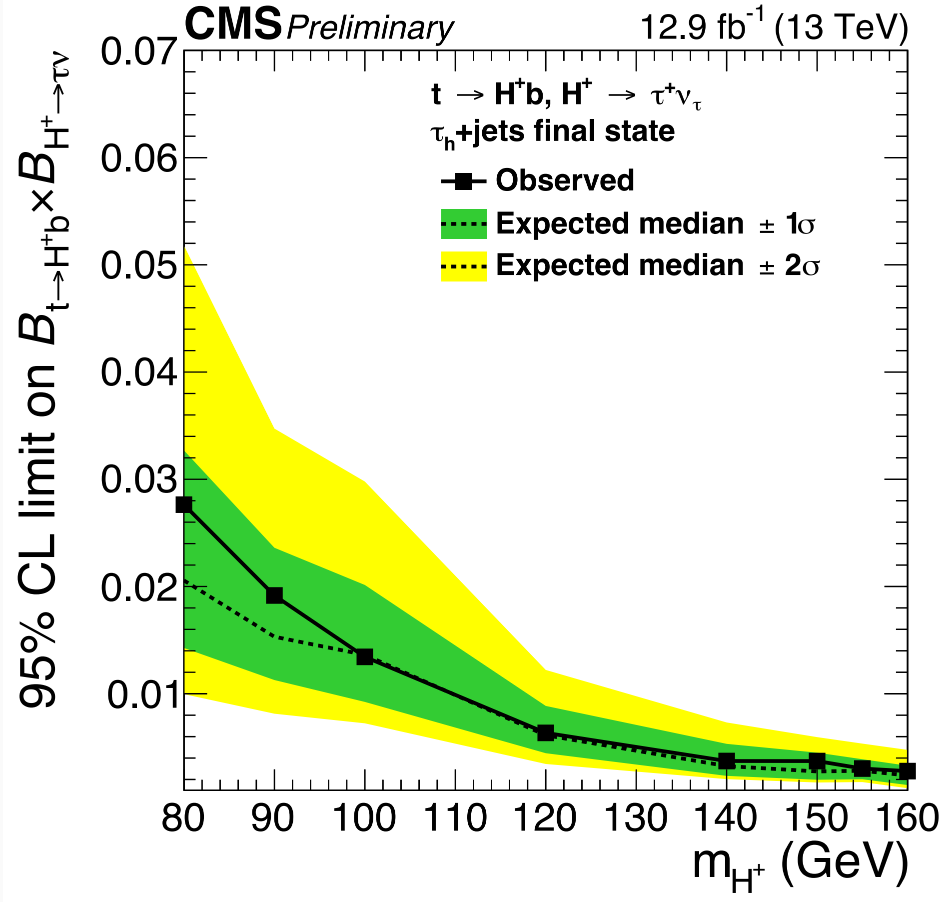
$H^+ \rightarrow \tau\, \nu$ @ 13 TeV





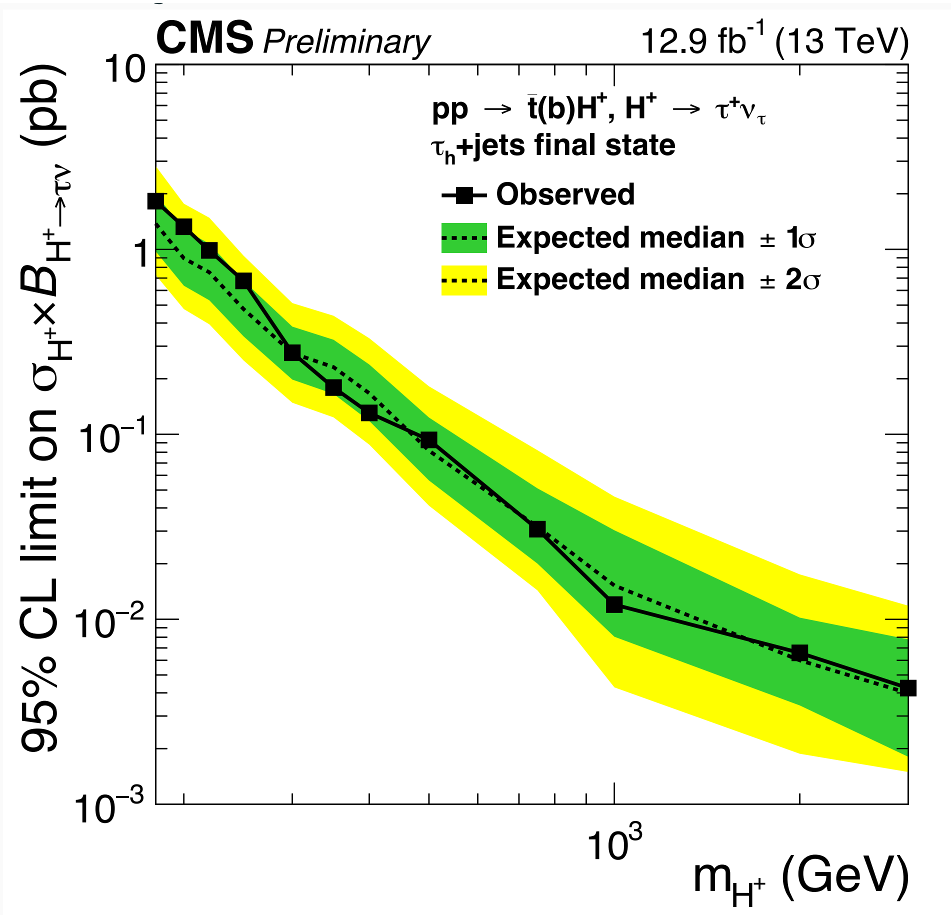
For 14.7 fb^{-1} @ 13 TeV, in mass range of m_H = 200-2000 GeV, upper limits were set in range of 2.0 pb^{-1} to 8fb^{-1}

$H^+ \to \tau\,\nu$ @ 13 TeV



$m_{\mathrm{H}^+} =$ 80–160 GeV

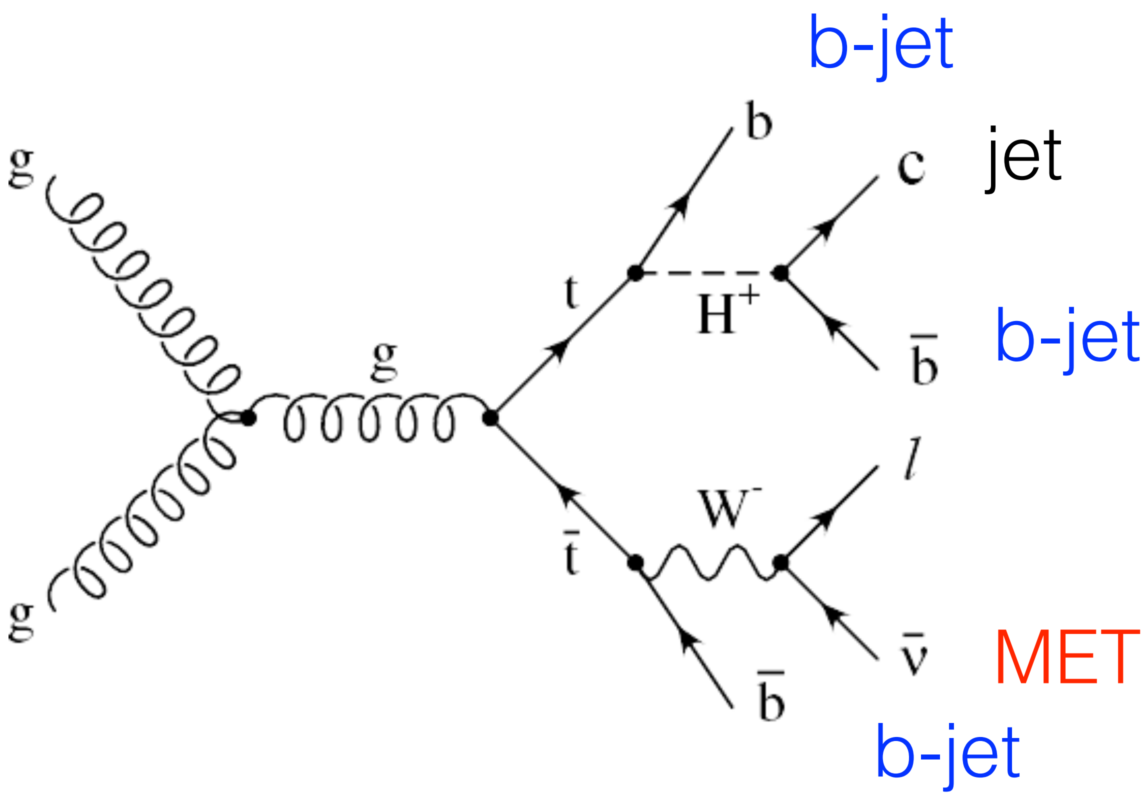
Observed limit: 2.8–0.28%



$m_{\mathrm{H}^+} =$ 180–3000 GeV

Observed limit: 1.8–0.0042 pb

$H^+ \rightarrow bc$ event selection

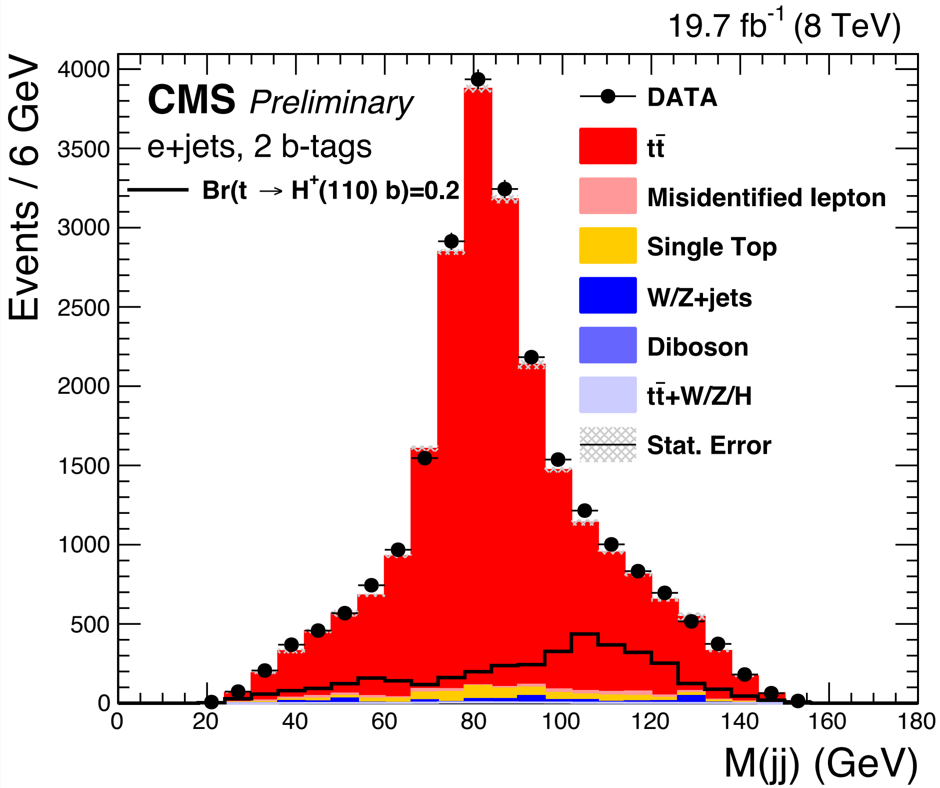


- Missing transverse energy trigger (threshold at 20 GeV)
- Four or more jets with at least two b-tagged (p_T >30GeV, b-tag)
- One electron or muon (p_T threshold of 20 GeV)

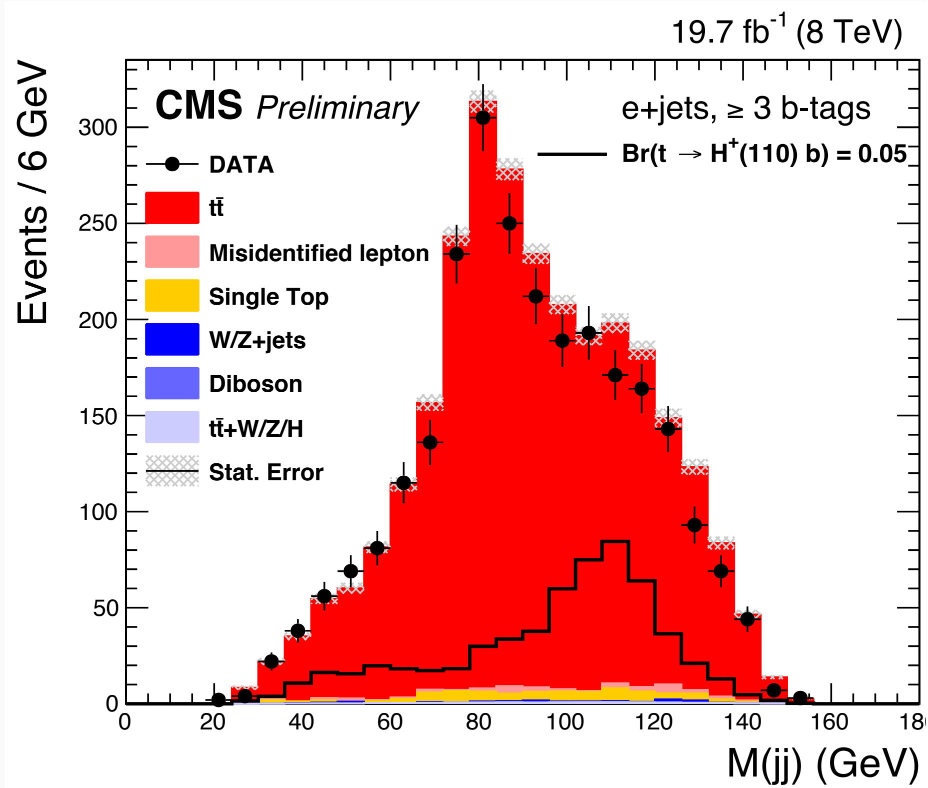
H+ → bc event selection @8 TeV

Limits extracted from dijet invariant mass M(jj)

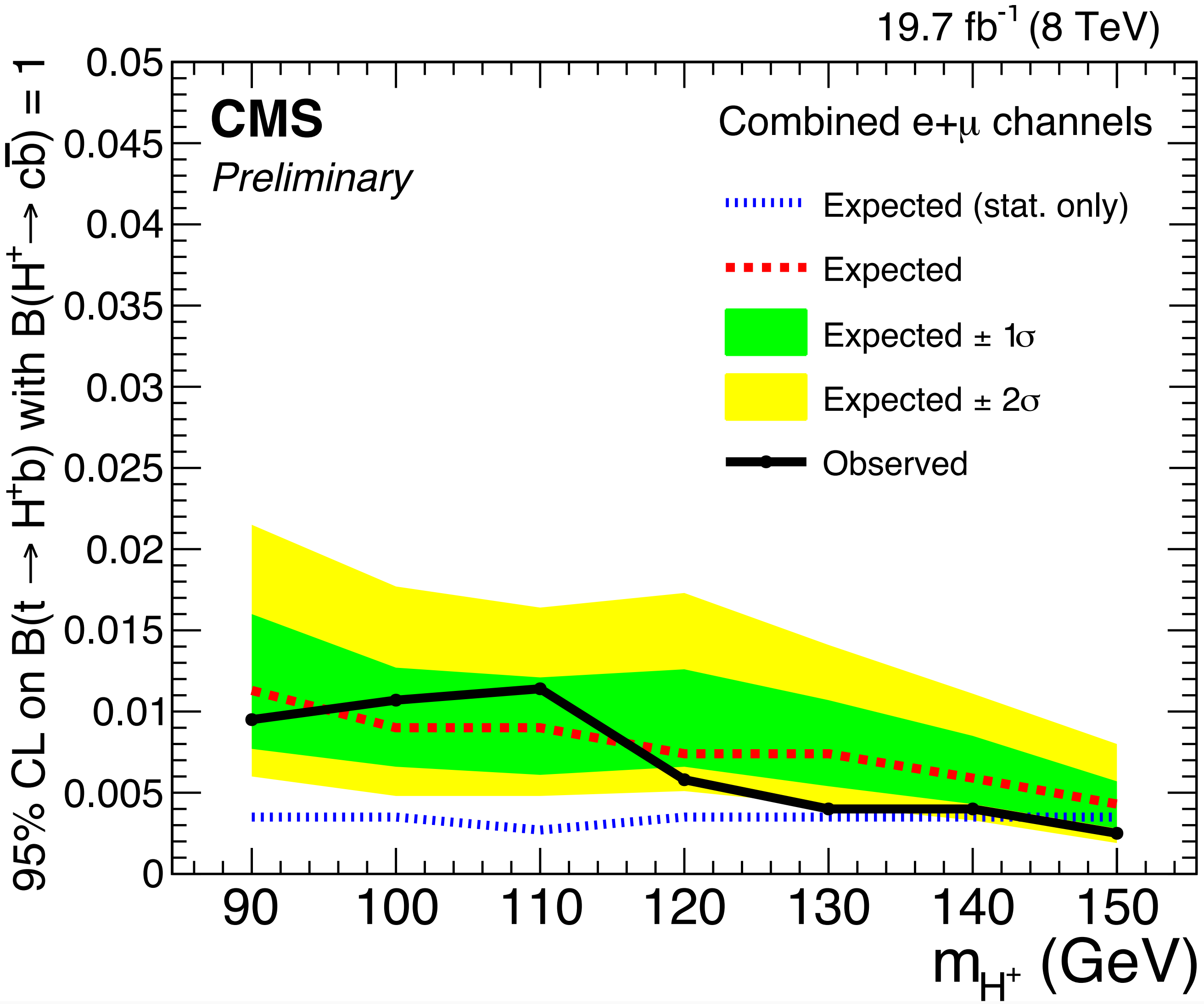
e+jets, 2 b jets



e+jets, $\geq$ 3 b jets

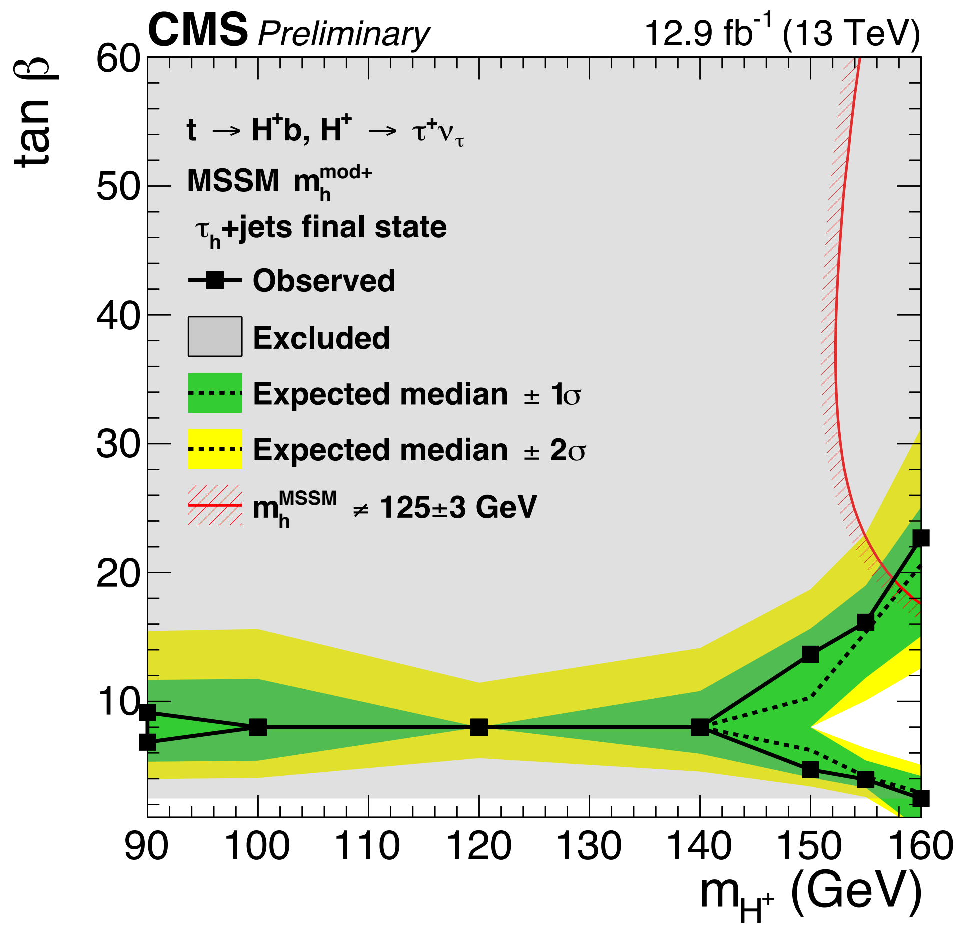


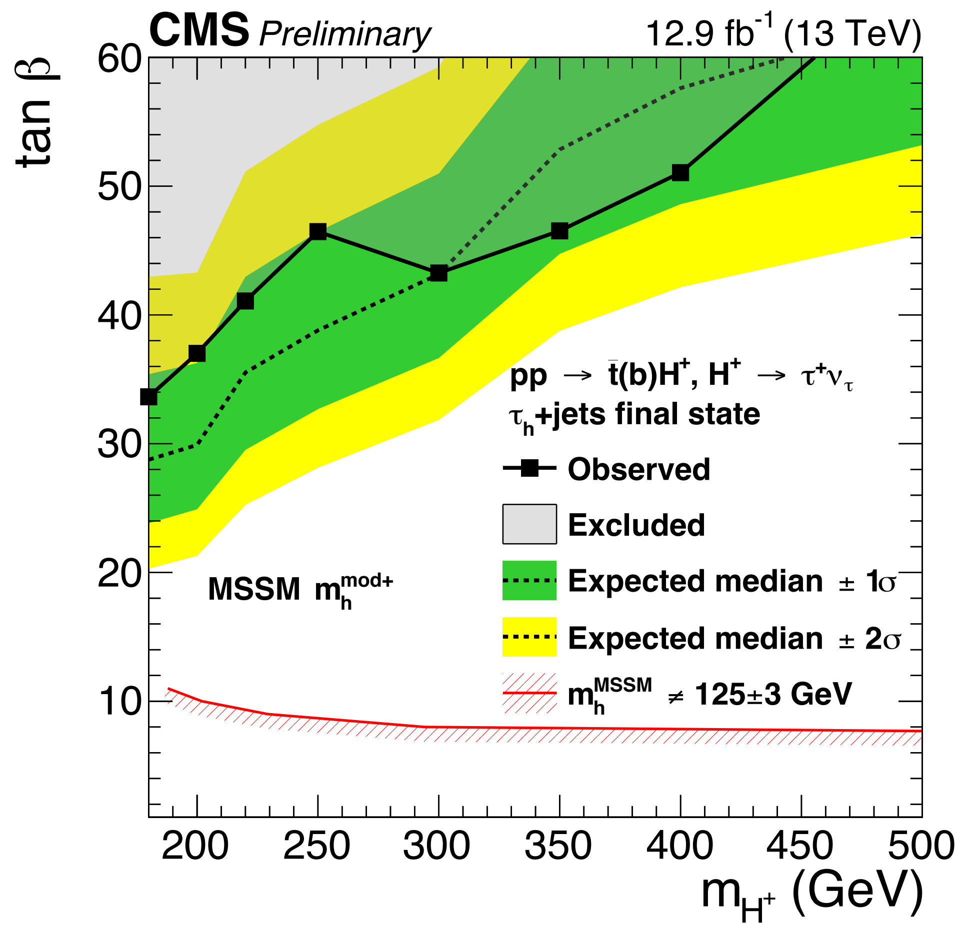
$H^+ \to bc$ @ 13 TeV



Observed limit between 1.1-0.4 % assuming that $Br(H^+ \to cb) = 100\%$

$H^+ \to bc$ MSSM interpretation





LFV in Higgs decays

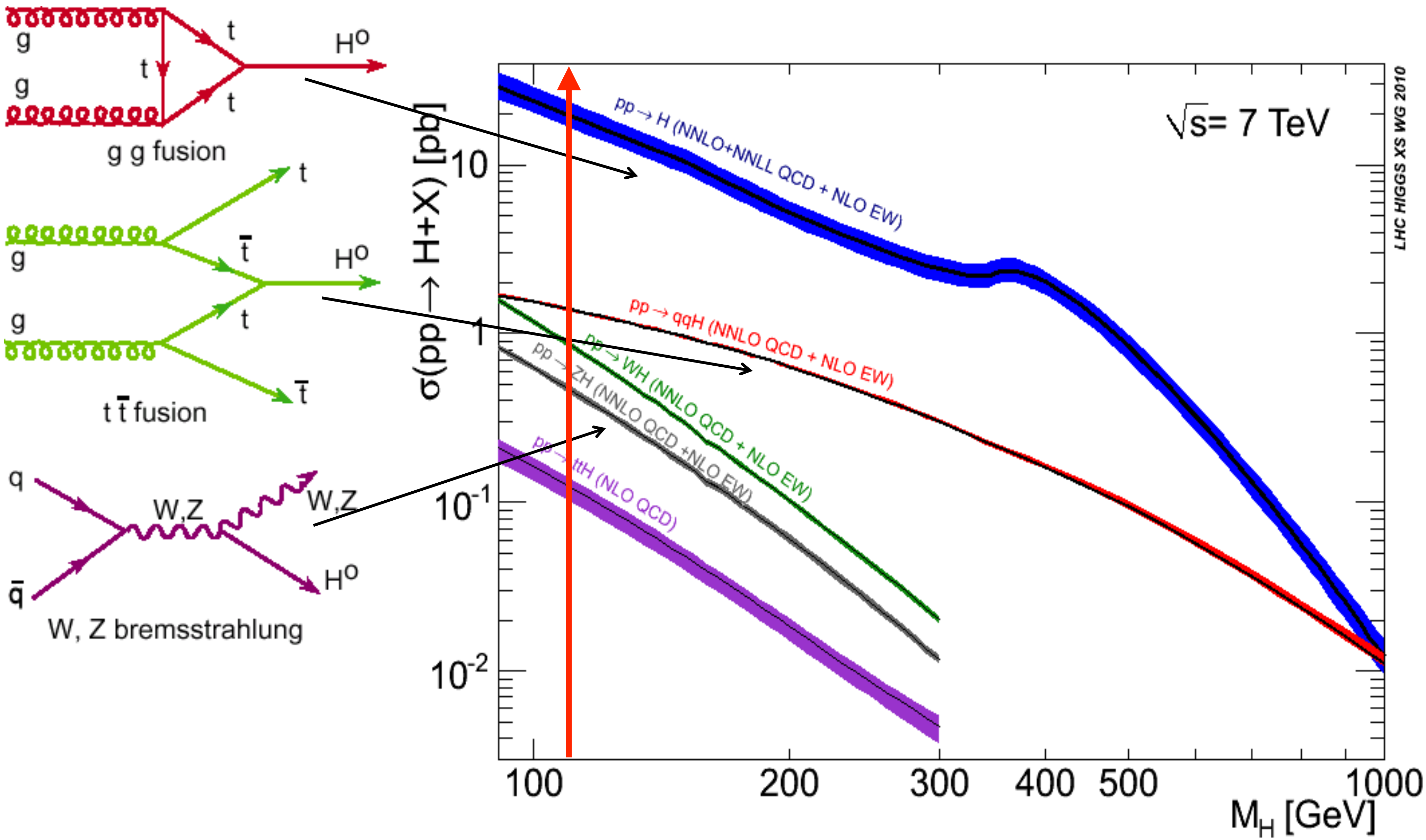
LFV couplings to the Higgs possible, e.g. if SM only valid to finite scale Λ

$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

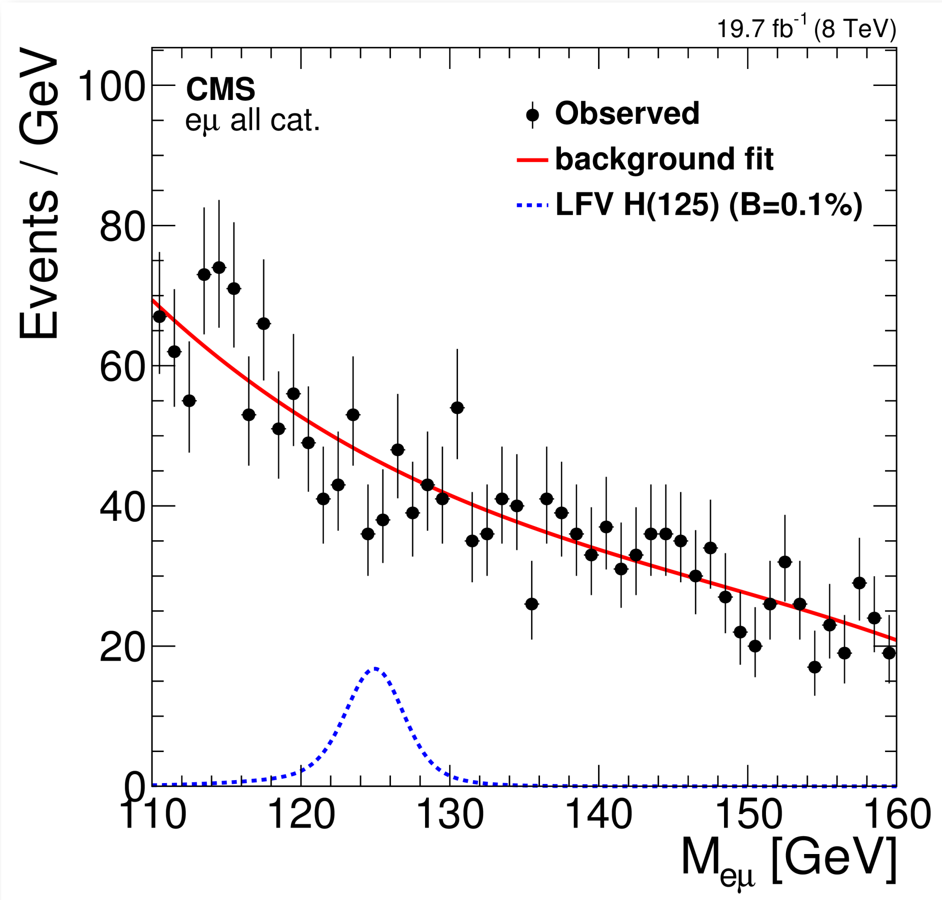
LFV Higgs couplings would allow processes like $\mu \to e$, $\tau \to \mu$ and $\tau \to e$ via a virtual Higgs boson

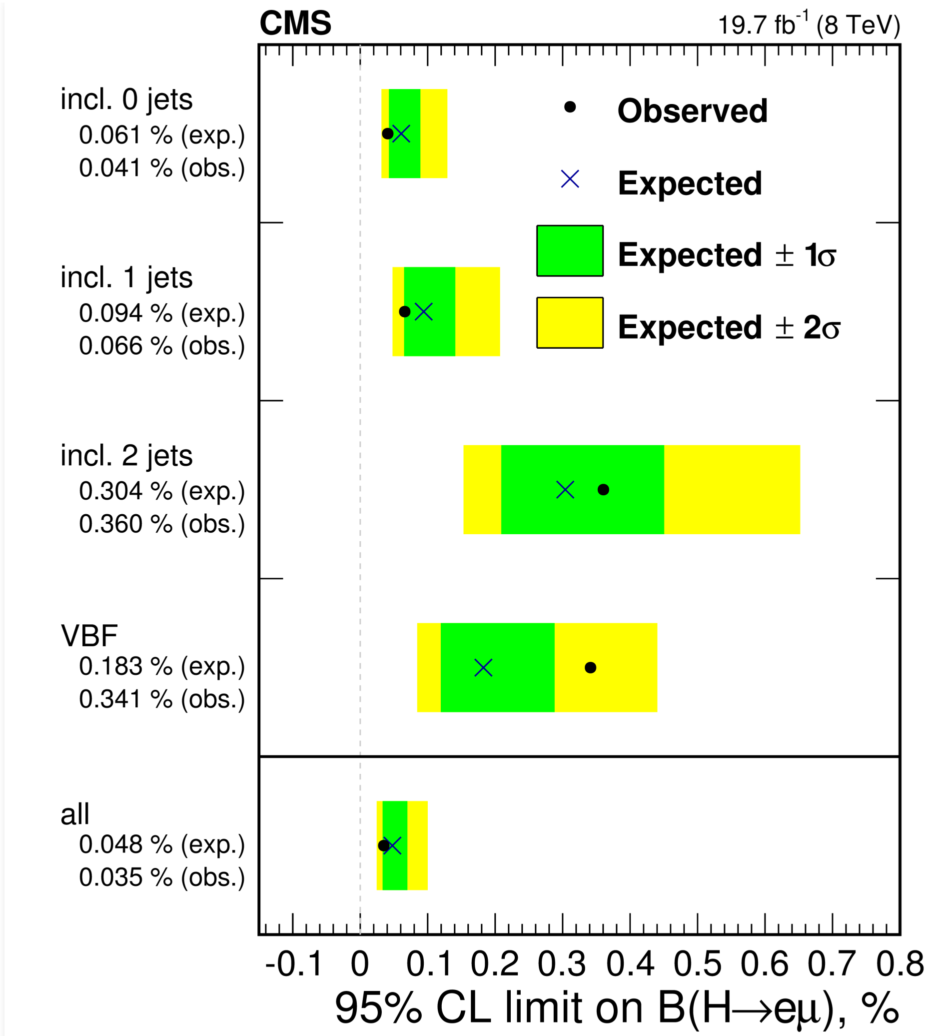
- $\mathcal{B}(H \to e\mu) < \mathcal{O}(10^{-8})$ @ 95% CL from $\mu \to e\gamma$
- $\mathcal{B}(H \to e\tau/\mu\tau) < \mathcal{O}(10\%)$ @ 95% CL from $\tau \to e\gamma/\mu\gamma$ and e/μ g-2 measurements
- $\mathcal{B}(H \to e\tau/\mu\tau) < 13\%$ @ 95% CL from theoretical reinterpretation of $H \to \tau\tau$ search results from ATLAS

Higgs production at the LHC



Results: $H \to e\mu$





Signal: Sum of two Gaussians

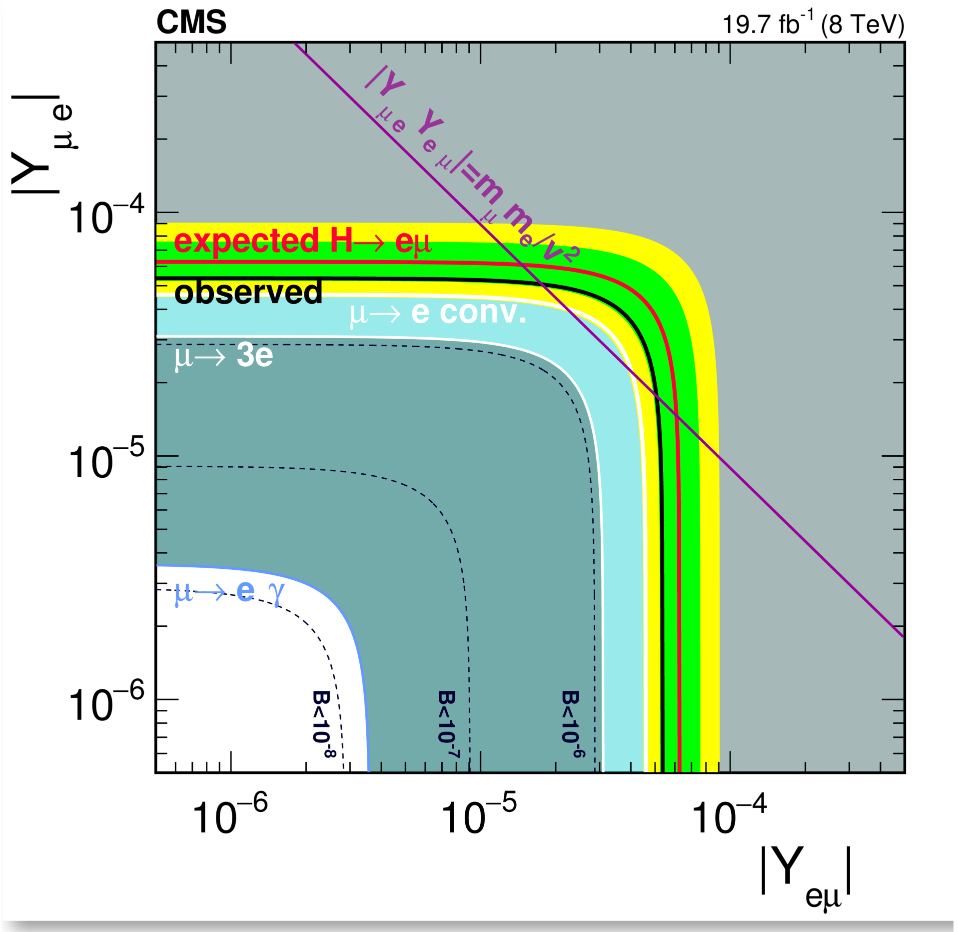
$\mathcal{B}(H \to e\mu) < 0.035\%$ @ 95% CL

Background: fit with 4th order Polynomial

tested also power law or exponential functions

Limits on flavour violation Yukawa couplings

$$\sqrt{|Y_{\ell\ell'}|^2 + |Y_{\ell\ell'}|^2} \propto \frac{\mathcal{B}(H \to \ell\ell')}{1 - \mathcal{B}(H \to \ell\ell')}$$



$$\sqrt{|Y_{e\mu}|^2 + |Y_{\mu e}|^2} < 5.4 \cdot 10^{-4}$$

Search strategy for H → e/μ τ

Lepton selection

↓

Categorisation:

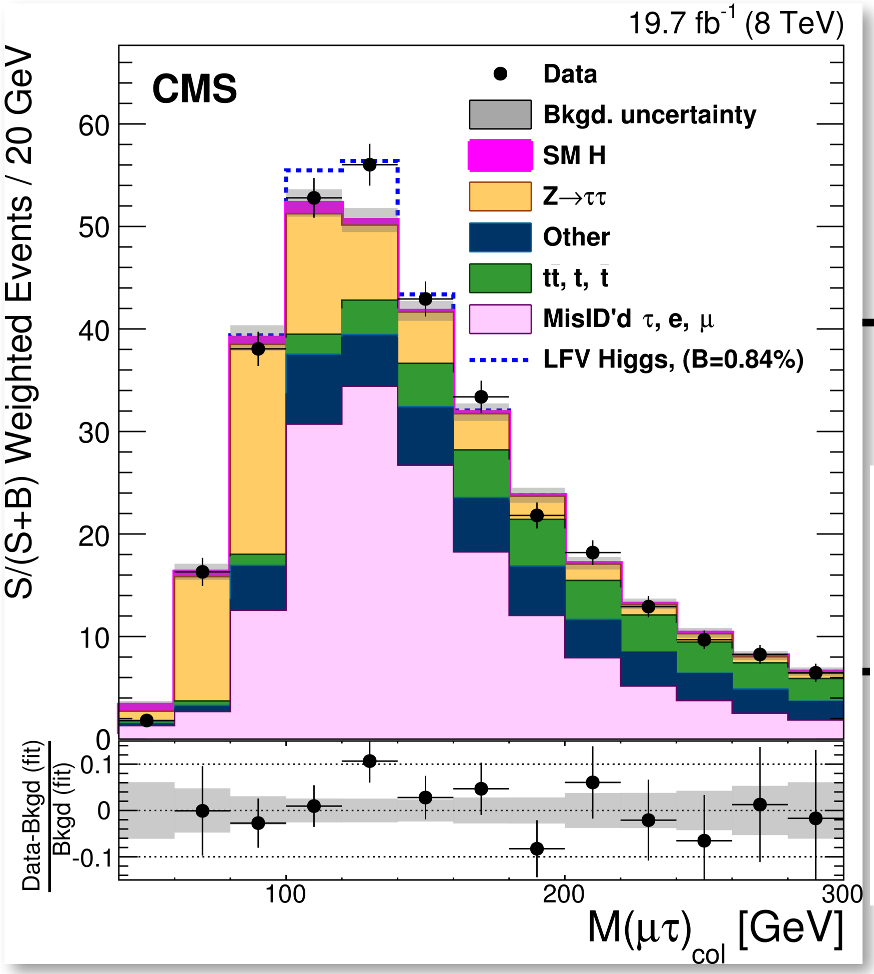
CMS: 0-jet, 1-jet, VBF
ATLAS: background type

↓

Calculate $m_{\ell\ell'}$

↓

Background suppression



→

Determine $\mathcal{B}(H \to \ell\ell')$

Background Estimation

<u>$Z \to \tau\tau$</u>

Embedding: measure $Z \to \mu\mu$ in data and replace μ by simulated τ

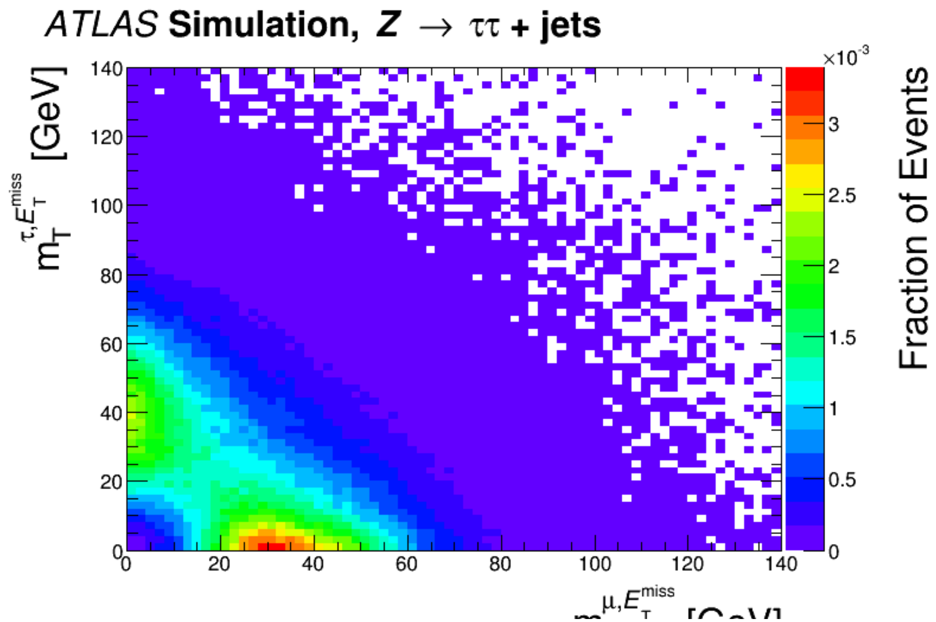
<u>Misidentified leptons</u>

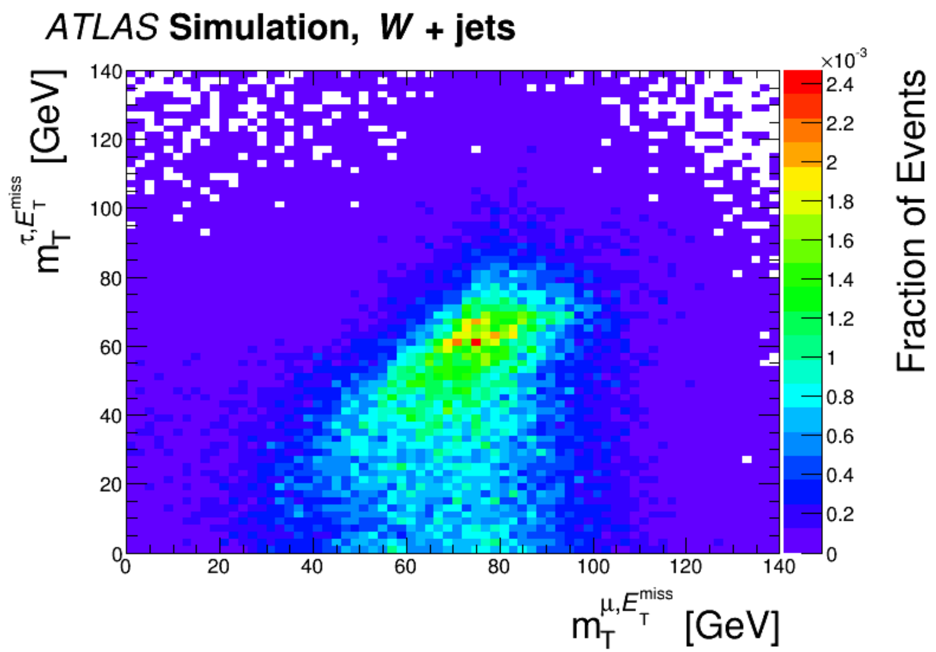
From data with various techniques

<u>Top-pair and W+jets</u>

Shape from simulation but normalization from data

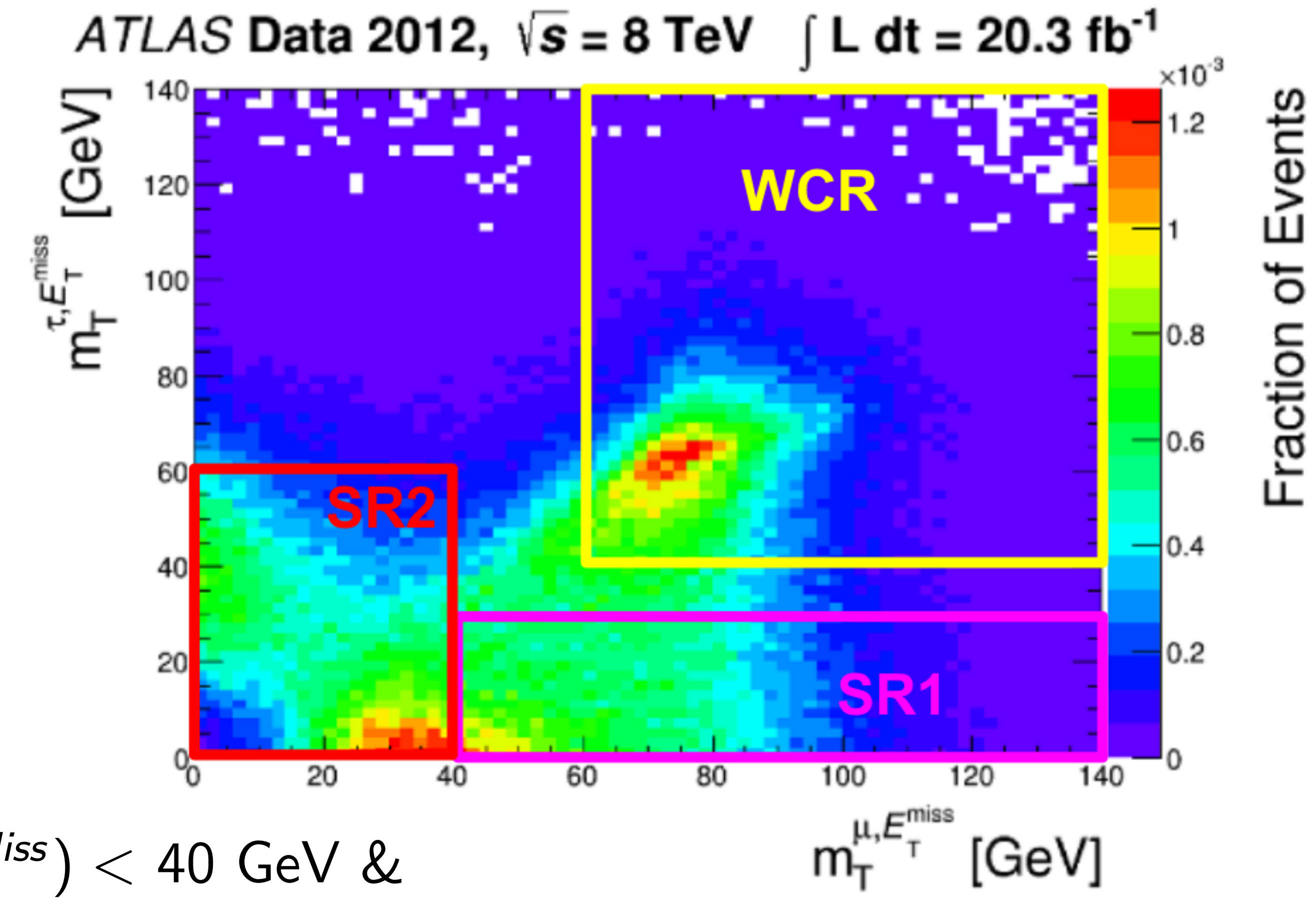
<u>Others backgrounds</u> from simulation





Signal (run1)

$$m_{T} = \sqrt{2p_T^{\ell_1}\left(p_T^{\ell_2} + E_T^{miss}\right)(\cosh\Delta\eta - \cos\Delta\phi)}.$$



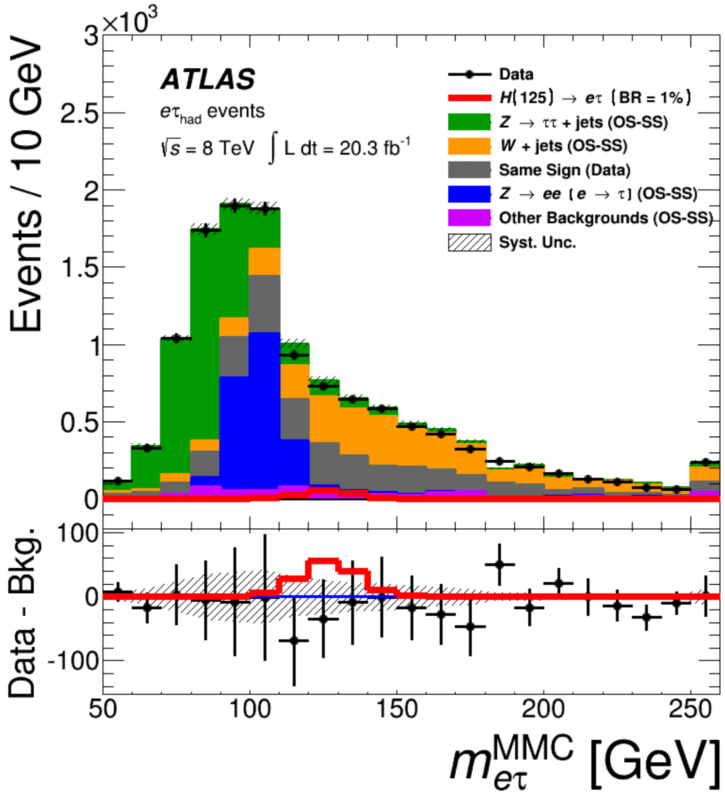
SR2: $m_T(\mu, E_T^{Miss}) < 40$ GeV & $m_T(\tau_{had}, E_T^{Miss}) < 60$ GeV

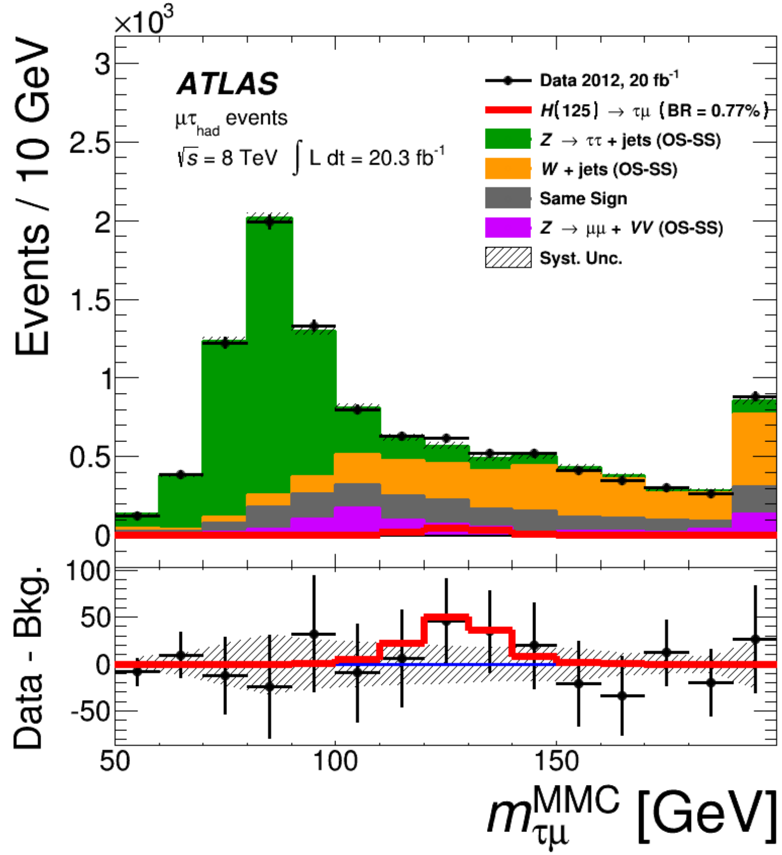
dominant bkgd Z+jets

SR1: $m_T(\mu, E_T^{Miss}) > 40$ GeV & $m_T(\tau_{had}, E_T^{Miss}) < 30$ GeV

dominant bkgd W+jets

m_T distribution (Run1)



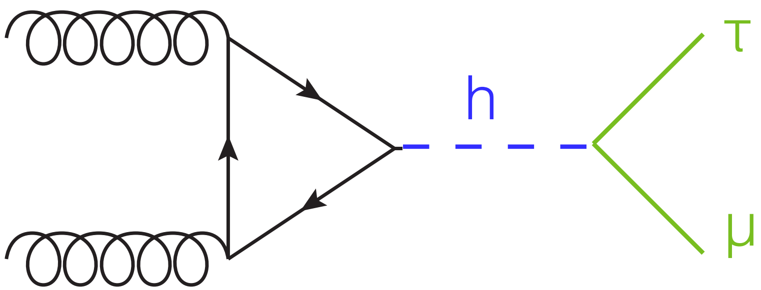


ATLAS: Br(H → e/μτ) at 1.81 & 1.85% @ 95% CL, respectively

CMS: Br($H \to e\tau$) <0.69%@95%CL for μτ see next slides

CMS: H → μτ Run2

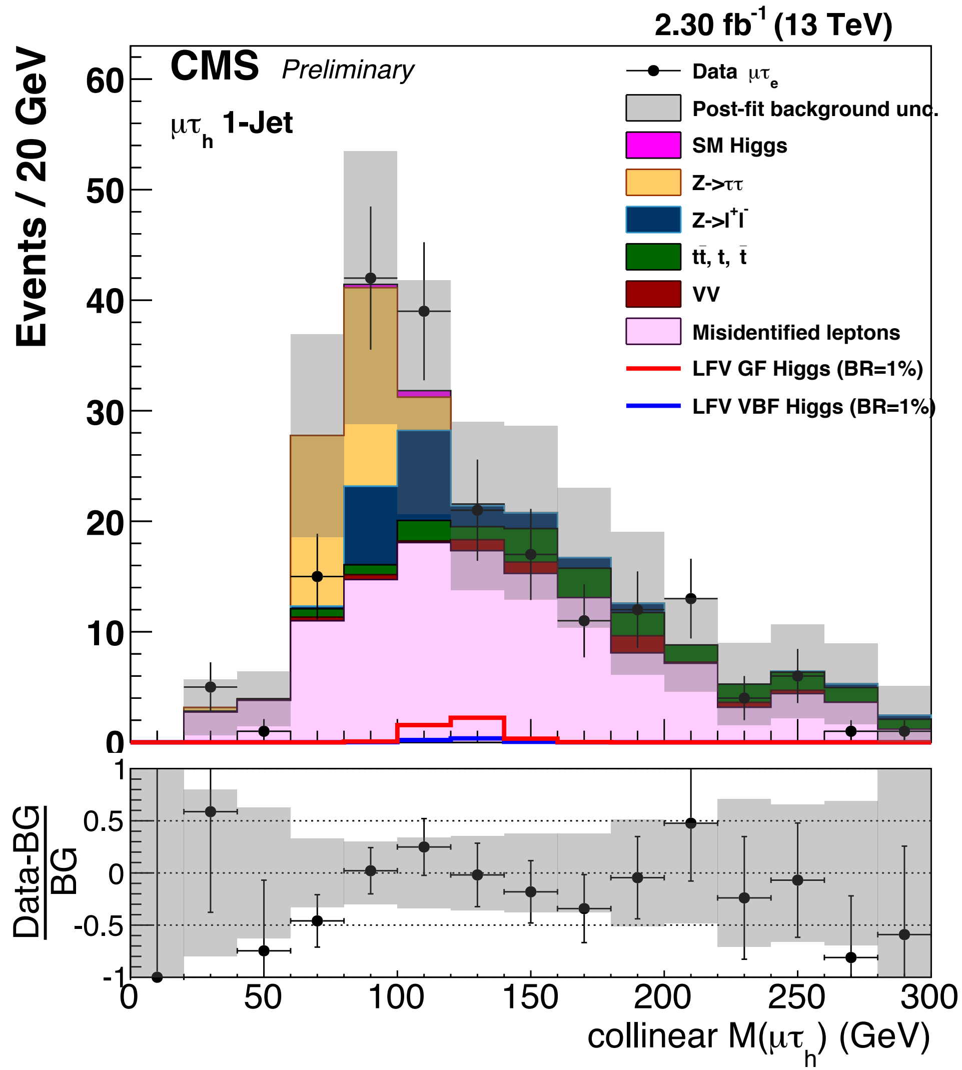
Signal



see JHEP 03 (2013) 26. arXiv: 1209.1397

2 channels ($\ell\tau_{\ell'}$, $\ell\tau_{had}$)
and 3 categories (0-1-2 Jets)

Large backgrounds
Template fits to the collinear mass distribution

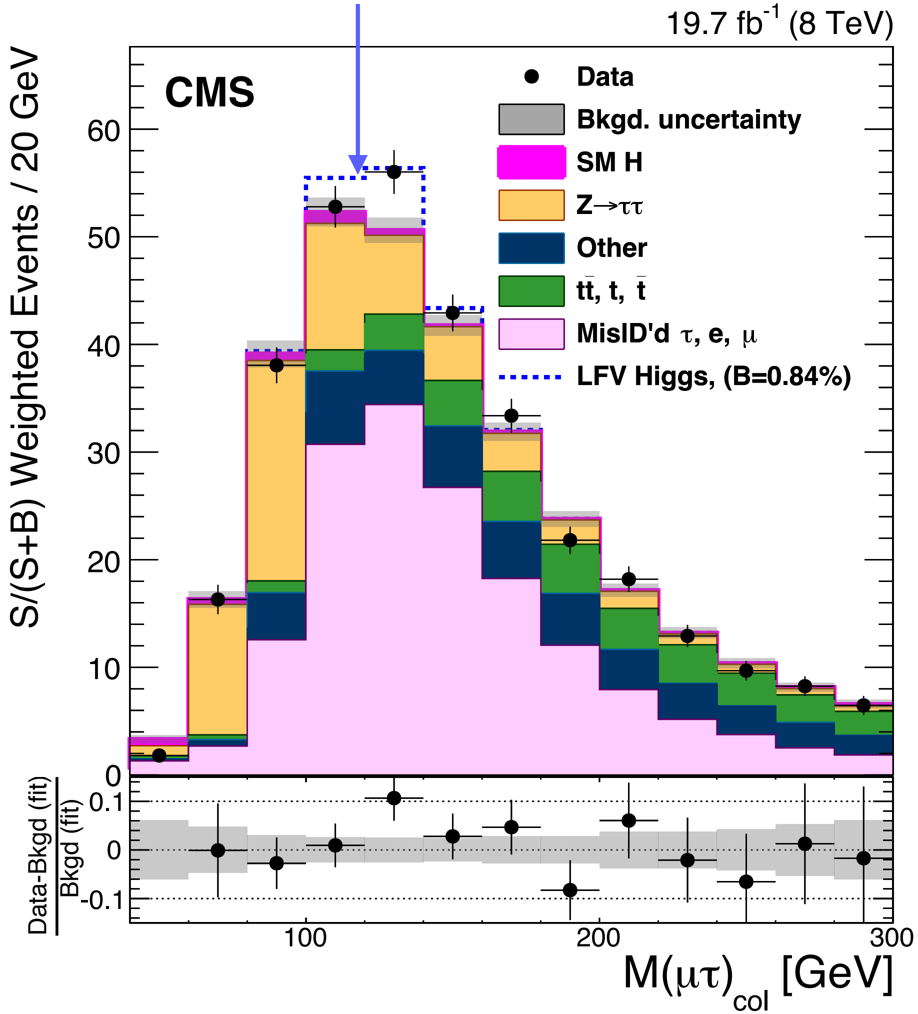


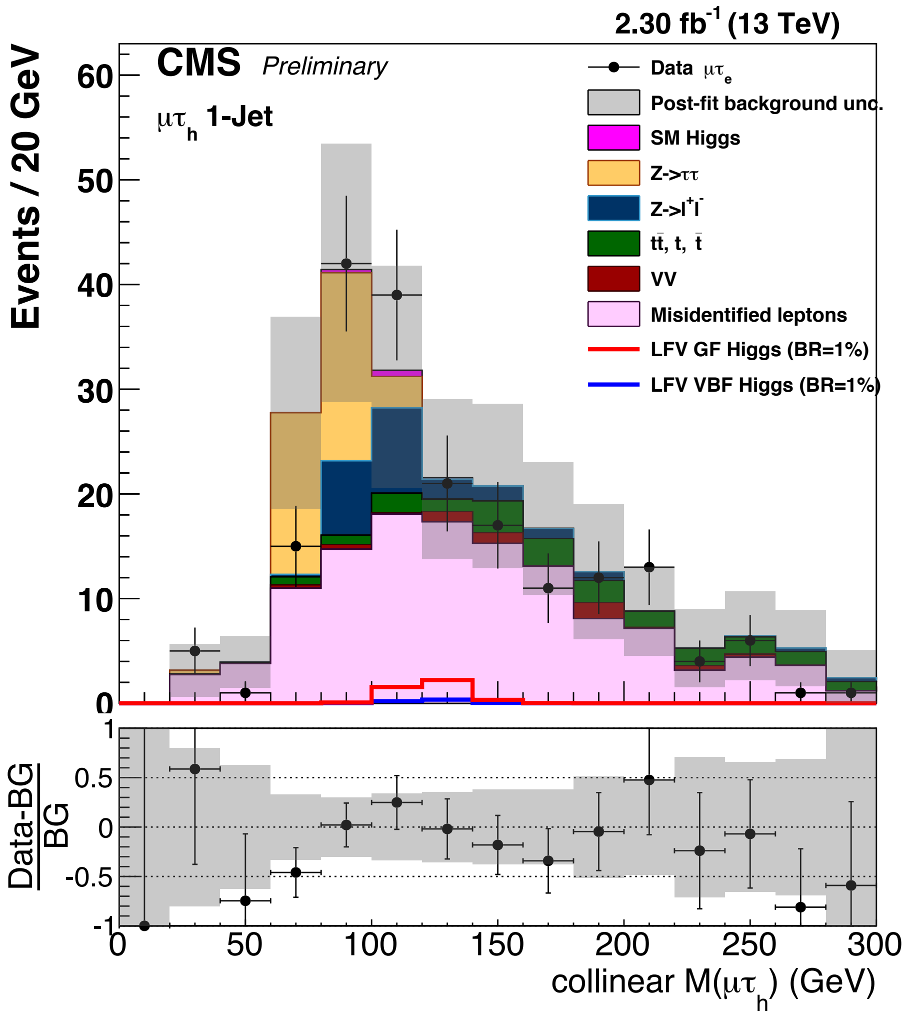
13 TeV: Br(H→μτ)<1.20% (1.62% expected)

H → μτ Run2 vs Run1

Excess in μτ at 8 TeV

No excess observed at 13 TeV in 2015 data, but not sensitive enough to exclude the 8TeV result



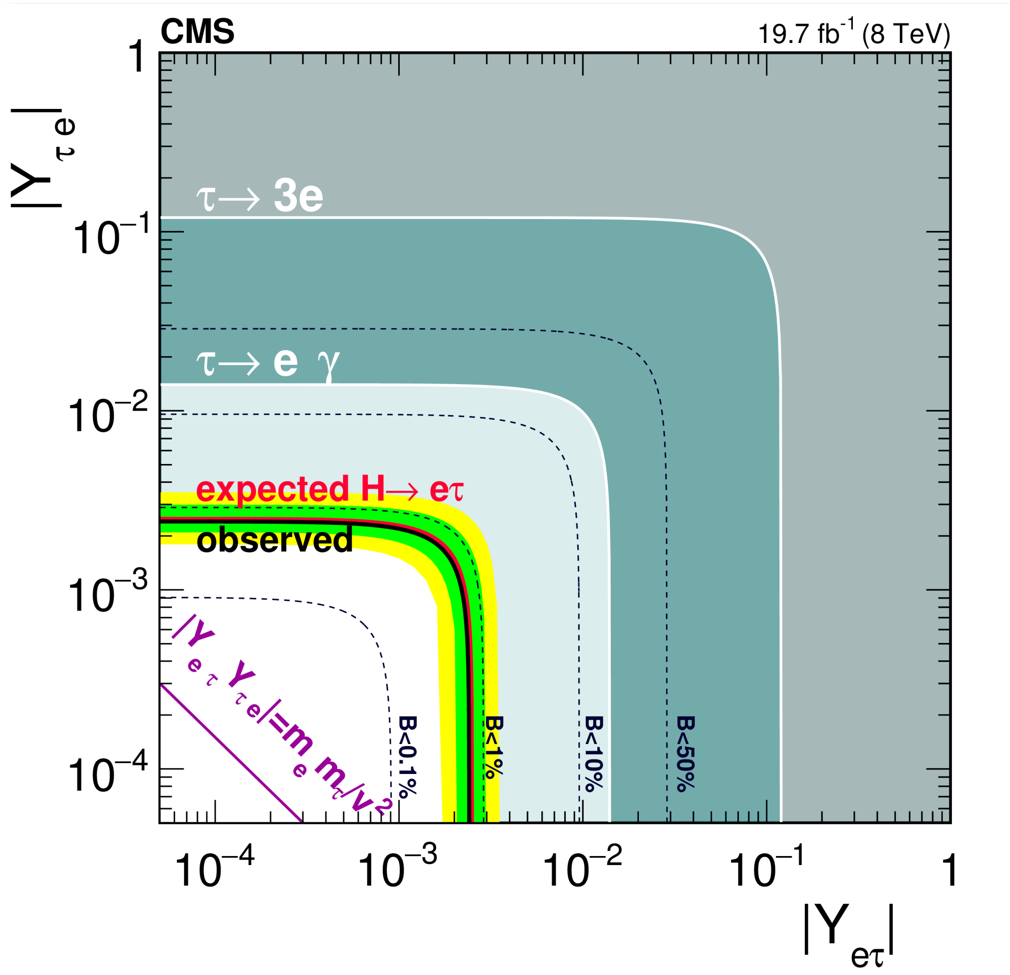


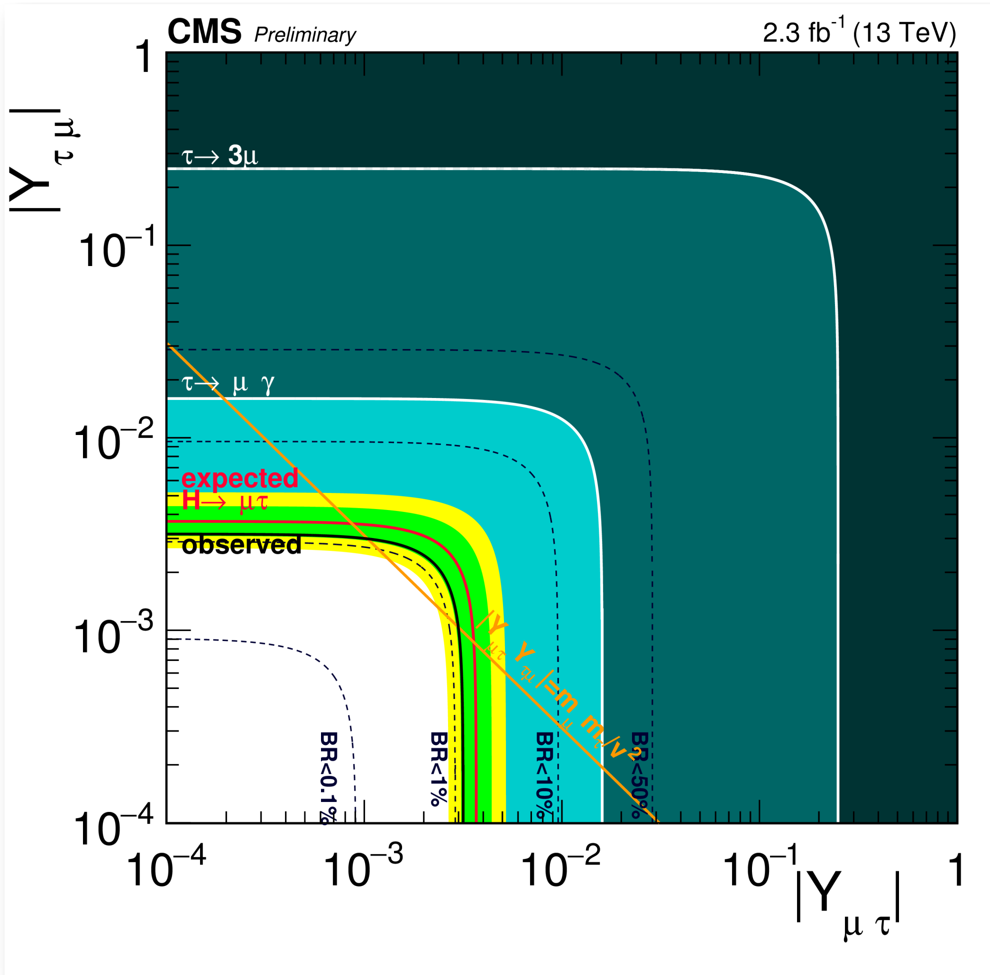
13 TeV: Br(H→μτ)<1.20% (1.62% expected)

8 TeV: Br(H→μτ)<1.51% (0.75% expected)

Limits on flavour violation Yukawa couplings

$$\sqrt{|Y_{\ell\ell'}|^2 + |Y_{\ell\ell'}|^2} \propto \frac{\mathcal{B}(H \to \ell\ell')}{1 - \mathcal{B}(H \to \ell\ell')}$$

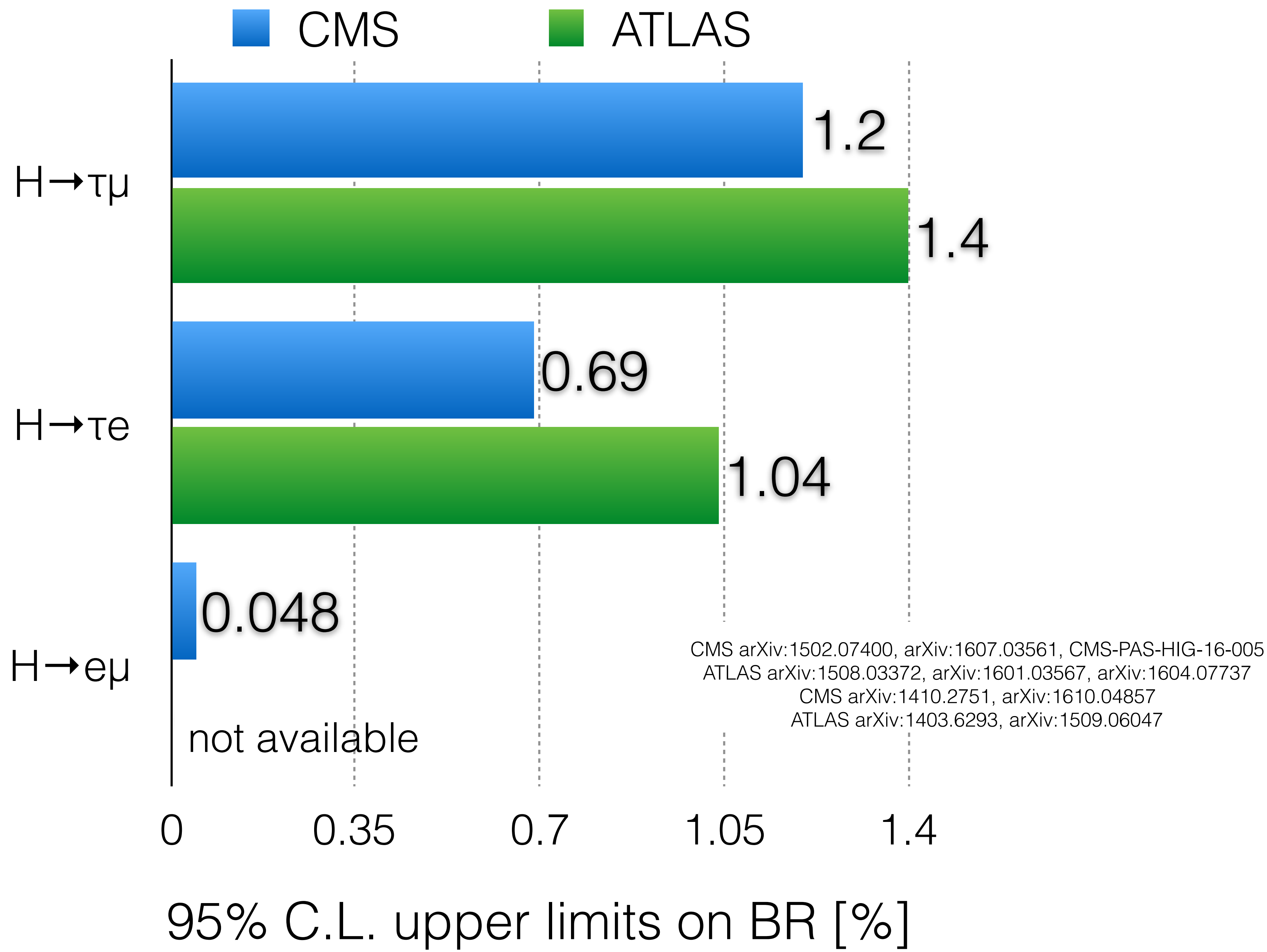




$$\sqrt{|Y_{e\tau}|^2 + |Y_{\tau e}|^2} < 2.4 \cdot 10^{-3}$$

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.16 \cdot 10^{-3}$$

Lepton Couplings



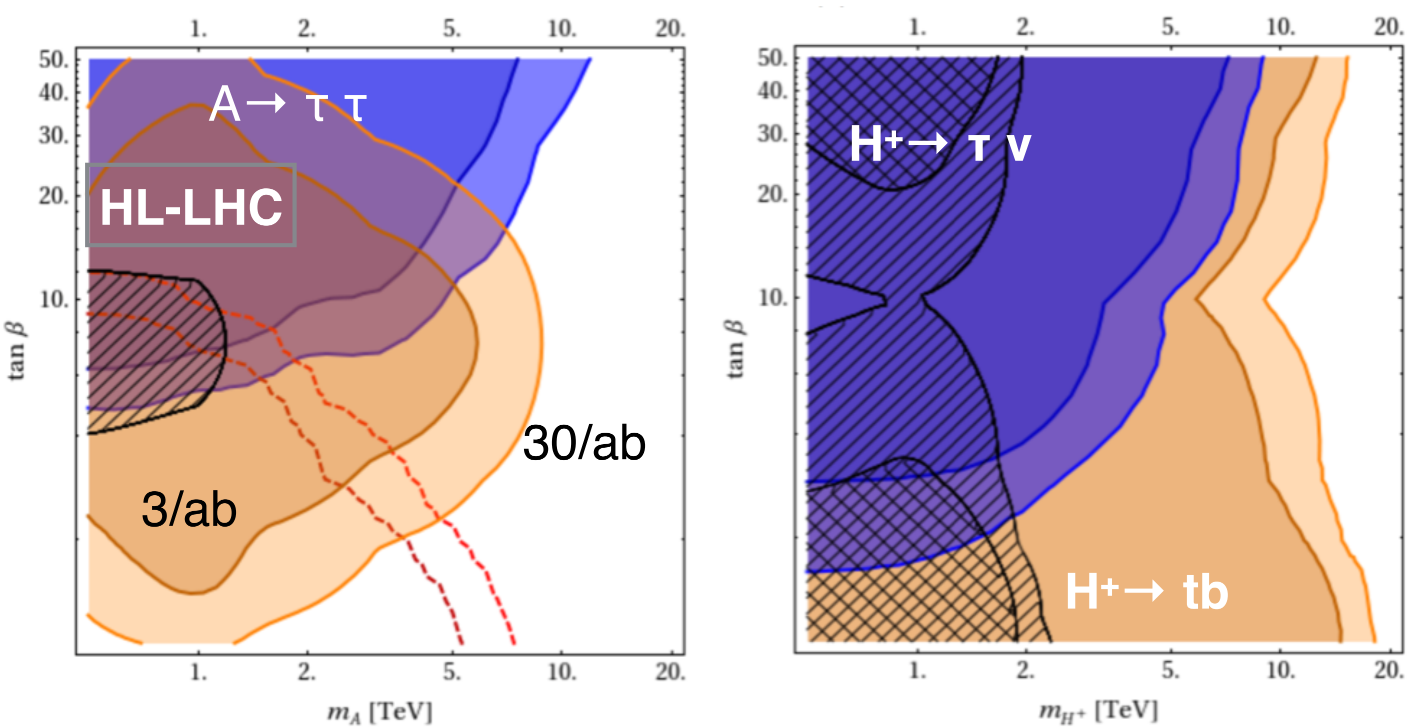
Outlook

A lot of activity in those analysis and significant improvement are expected with full Run2 dataset (expecting about 200 fb^{-1} to be recorded)

We specie much more stronger limits as most of the analyses are limited by statistics.

New methods are being developed as we understand more data.

HL-LHC and proposed future —> TeV region

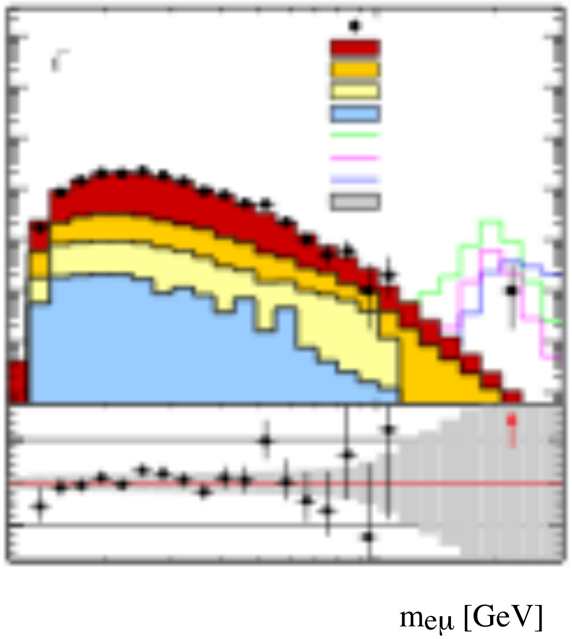


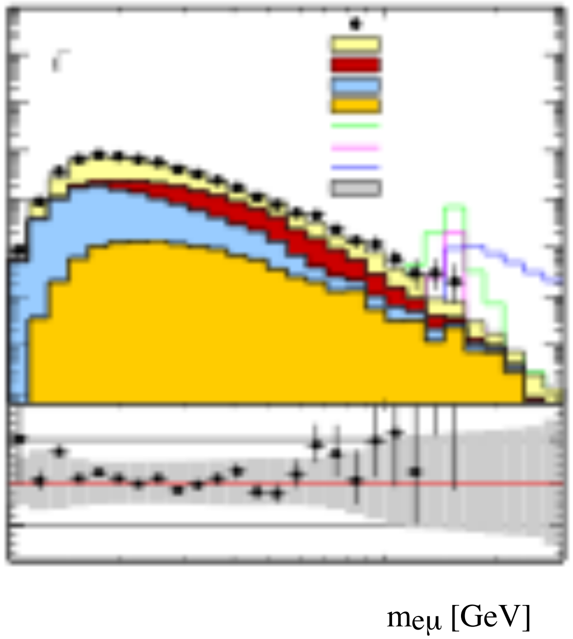
(c) Exclusion reach for neutral Higgs

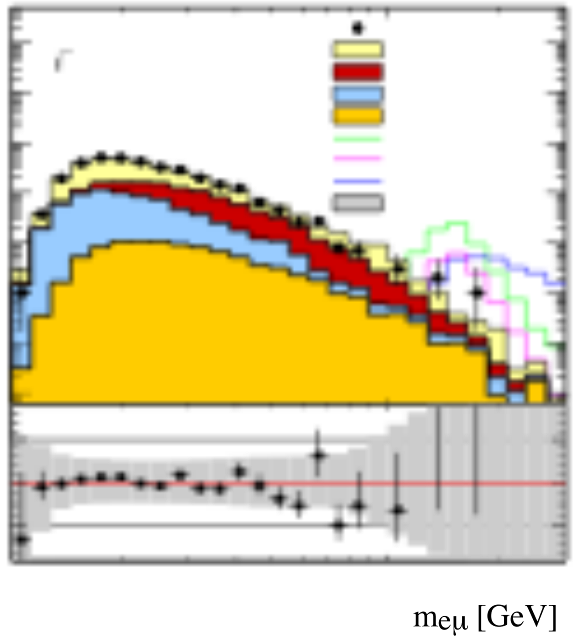
(d) Exclusion reach for charged Higgs

Backup

LFV high mass







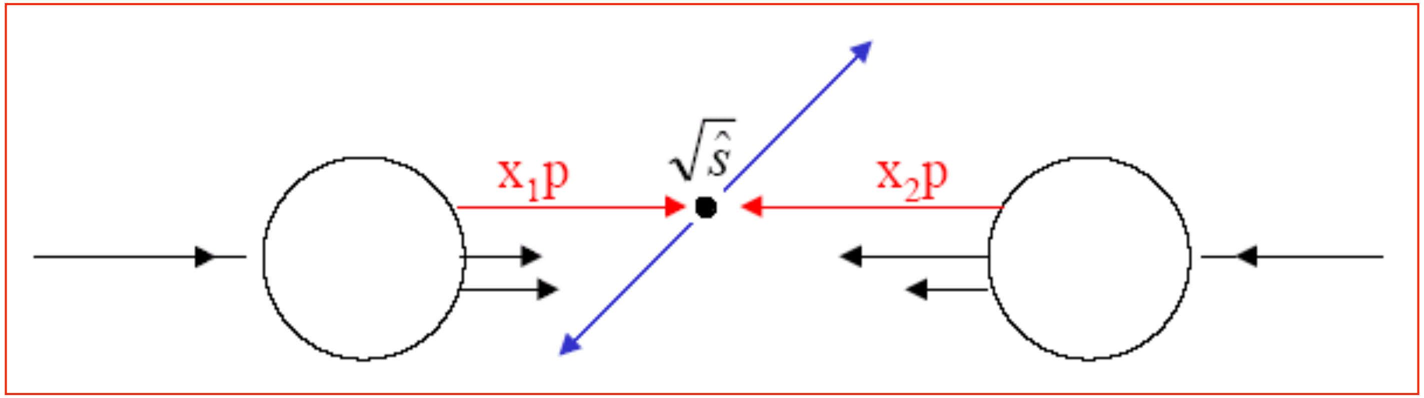
Slight excess found at high mass in the eτ channel

Mirrored by a deficit in the μτ channel

Overall, no significant deviations found from SM expectation, but the 2.1 TeV eμ event has attracted some attention (arXiv:1606.06696)

Higg sproduction in pp collisions

$\sqrt{\hat{s}} = \sqrt{x_1 x_2 s}$ $\qquad 0 < x < 1$ $\qquad$ Bjorken Scaling



$$\sigma = \sum_{a,b} \int dx_1 dx_2 f_a(x_1, Q^2) f_b(x_2, Q^2) \hat{\sigma}_{a,b}(x_a, x_b)$$

Momentum distribution of partons in protons

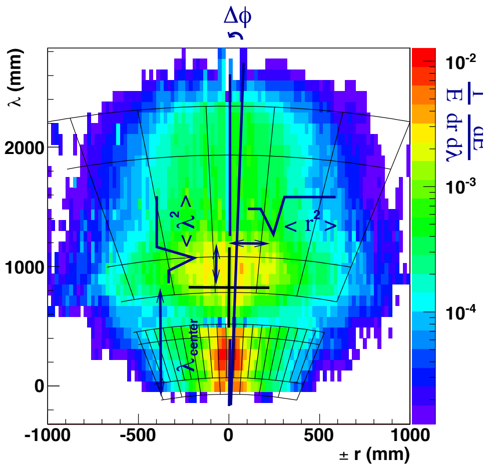
Parton cross section

Reco & ID:

- Tau reconstruction seeded by anti-k_T jets
- Identification based on:
    - Shower profile, isolation properties, etc.

Energy measurement :

- Based on energy depositions inside 0.2 cone
- ..using noise suppressed Topo Clusters
- ..calibrated to the *local hadronic scale* (LC)



Local hadron calibration in a nutshell:

- Each cluster classified in its hadronic/EM like shape => p^{EM}
- Calibration accounts for *non-compensation*, *dead material*, *out-of-cluster* effects
    - Advantage: Distinct treatment of different decay products
      => improves resolution

(had.) Tau reconstruction seeded by anti-k_t jets

Identification based on shower profil

- A final calibration brings the object to the tau energy scale (TES):
    - accounting for *object specific* effects
        - e.g.: out-of-cone, underlying event, etc.
        - correcting for pile-up effects

$$E_{Tau} = C_{\text{TES}} \cdot \sum_{\Delta R<0.2} E^{LCW}_{cluster}$$