Searches for Rare/BSM Top Decays at the LHC

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Introduction

- ATLAS and CMS conduct searches for new physics through deviation of top quark decays from the Standard Model.

- This presentation will show recent results for rare/BSM top quark decays from ATLAS and CMS, specifically in the search for the **charged Higgs Boson** and **Flavor Changing Neutral Currents (FCNC)**.

Charged Higgs Boson

Evidence of non-zero branching ratio for $t \rightarrow H^+ b$

ATLAS

$H \rightarrow c\bar{s}$ channel

$H \rightarrow \tau \upsilon$ channel

CMS

$H \rightarrow \tau \upsilon$ channel

Rare/BSM Decays: FCNC

Evidence of non-zero branching ratio for $t \rightarrow q(Z/\gamma/g)$ or involving new particles

ATLAS

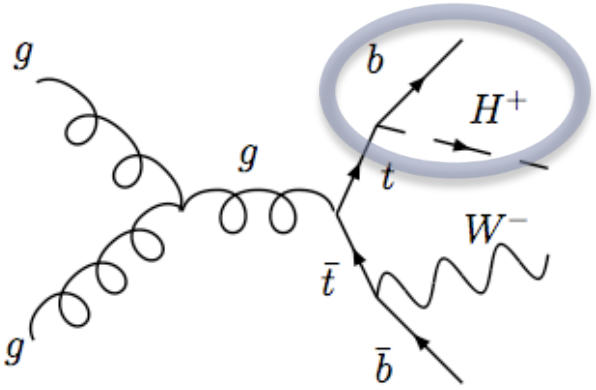
$t \rightarrow qZ$ and $gq \rightarrow t$

CMS

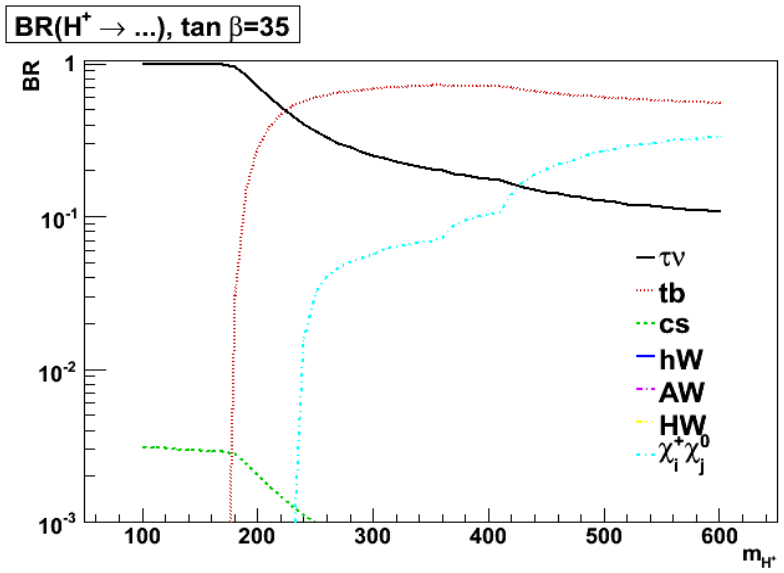
$T \rightarrow tZ$

Search for the Charged Higgs in Top Decays

- **In models with two Higgs doublet fields:**
  - There are 5 physical Higgs bosons (A, H, h, $H^{+/-}$)
- **Models with charged Higgs bosons include:**
  - SUSY models such as MSSM and some extensions
- **For a light charged Higgs boson ($H^+ < m_t$), some top pairs will decay to H^+bWb**



Charged Higgs Decays in the MSSM



- At tree level, the Higgs sector of the MSSM is described by **two parameters**:
  - $\mathbf{m_{H+}}$, the charged Higgs boson mass
  - **tan(β),** the ratio of the vacuum expectation values.
- For **tan(β) < 1**, $c\bar{s}$ is an important decay mode
  - BR($H^+ \rightarrow cs$) ≈ 40% for m_{H+} = 130 GeV
- For **tan(β) > 3**, $H^+ \rightarrow \tau\ \nu$ dominates the decays

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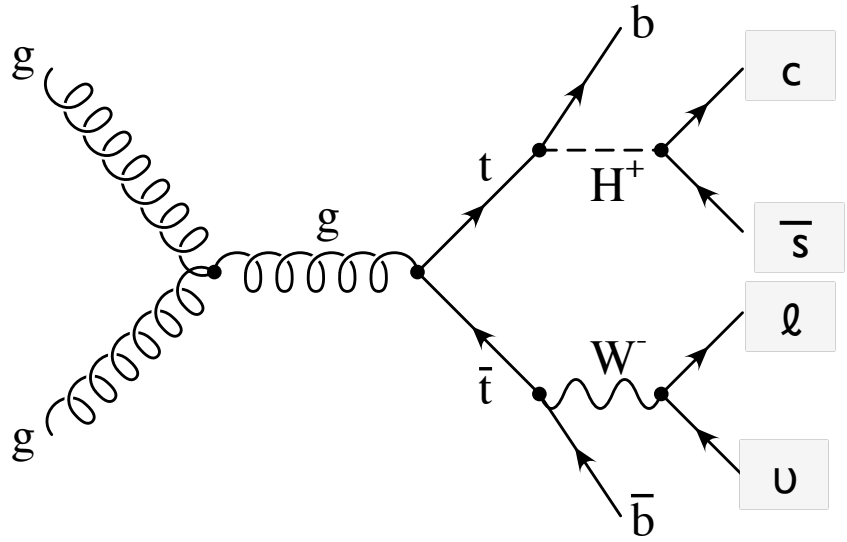
Charged Higgs Search: $H^+ \rightarrow c\bar{s}$

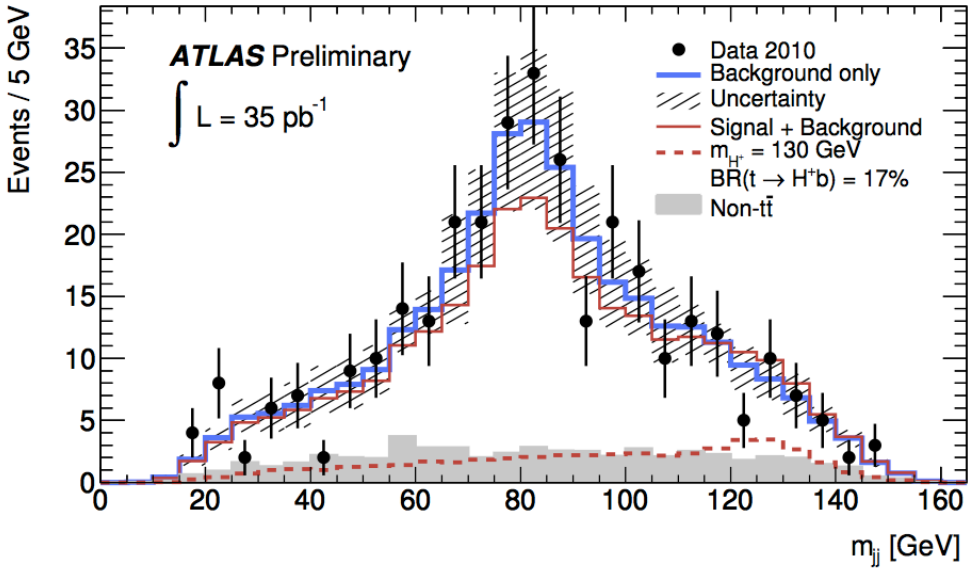
- The analysis searches for a final state the same as the "lepton+jets" final state of top pair decays.
  - The charged Higgs boson decays into two light jets
  - The W boson decays into an electron or muon and neutrino



- ***How is this distinguished from SM decays?***
  - 2-jet mass peaks at H^+ mass, not W mass
  - Reduced # of events in "lepton+jets" states (due to fully hadronic $tt \rightarrow H^+bH^-b$ decay)

Charged Higgs Search: $H^+ \rightarrow c\bar{s}$

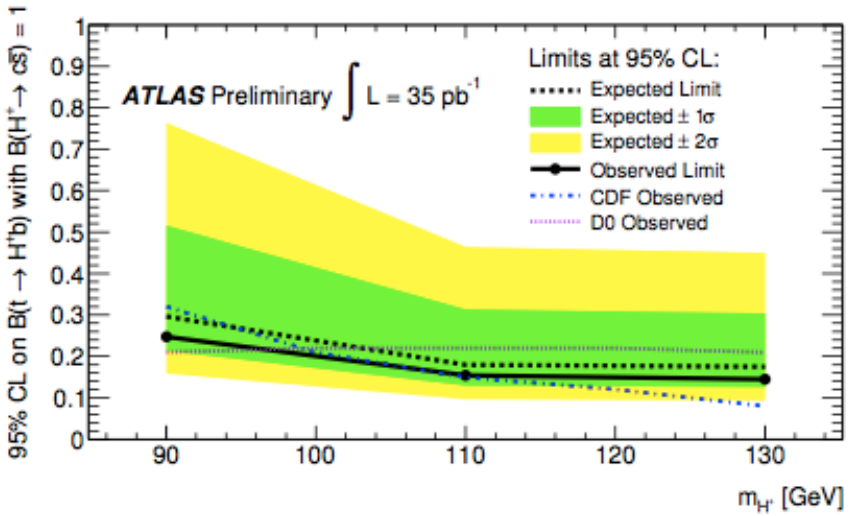
- **Event selection for the analysis**
  - Exactly **one high P_t lepton** (electron or muon)
  - At least **4 high P_t jets**
  - **High MET** (>20/30 GeV for muon/electron)
  - M_T(e,MET) > 25 GeV for the electron channel
  - $M_T(\mu$,MET)+MET > 60 GeV for the muon channel
  - At least **one identified b-jet**, using a secondary vertex algorithm



Charged Higgs Search: $H^+ \rightarrow cs$

- Most background is from **SM tt**, with small contributions from **single top**, **W/Z+jets**, **diboson** and **QCD multijets**.
- The 2 jets from H^+ are identified using a kinematic fitter
  - The assignment of reconstructed jets are varied
  - The b-jet + W/H systems are constrained to have the measured top quark mass within σ_{top} = 1.5 GeV
  - The best combination is found by minimizing a χ^2 for each assignment.
- **Limits were calculated using CL_s procedures**

Source	# of Events (stat+syst)	
Channel	Muon	Electron
Data	193	130
SM $t\bar{t} \rightarrow W^+bW^-\bar{b}$	156^{+24}_{-29}	106^{+16}_{-20}
W/Z + jets	17 ± 6	9 ± 3
Single top	7 ± 1	5 ± 1
Diboson	0.30 ± 0.02	0.20 ± 0.02
QCD multijet	11 ± 4	6 ± 3
Total Expected (SM)	191^{+26}_{-30}	127^{+17}_{-21}
$\mathcal{B}(t \rightarrow H^+b) = 10\%$:		
$t\bar{t} \rightarrow H^+bW^-\bar{b}$	20^{+3}_{-4}	14^{+2}_{-2}
$t\bar{t} \rightarrow W^+bW^-\bar{b}$	127^{+19}_{-23}	86^{+13}_{-16}
Total Expected ($\mathcal{B}$ = 10%)	181^{+21}_{-25}	120^{+14}_{-17}



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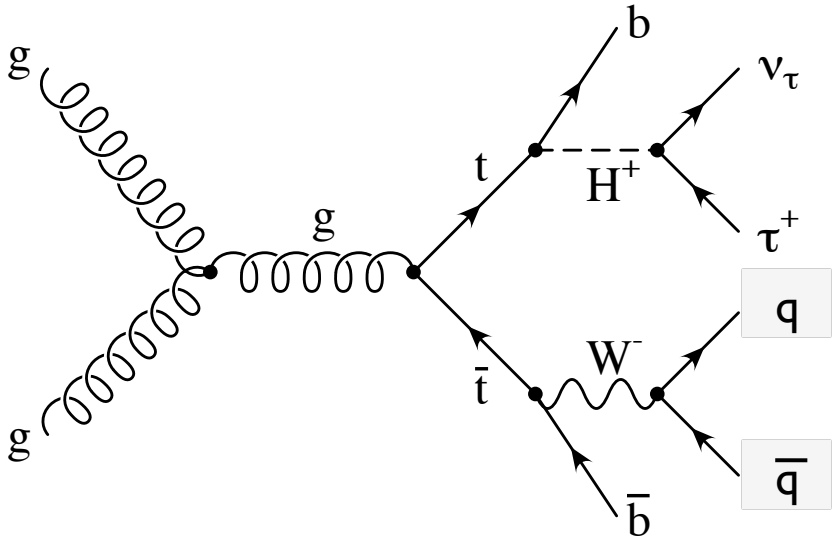
Charged Higgs Search: $H^+ \rightarrow \tau\ \upsilon$

- The most recent result for Charged Higgs from ATLAS is in the channel **$H^+ \rightarrow \tau\ \upsilon$**.
- This analysis searches for the "tau+jets" final state.
  - The H^+ decays into a **hadronically-decaying τ lepton**
  - The W boson decays into light quarks



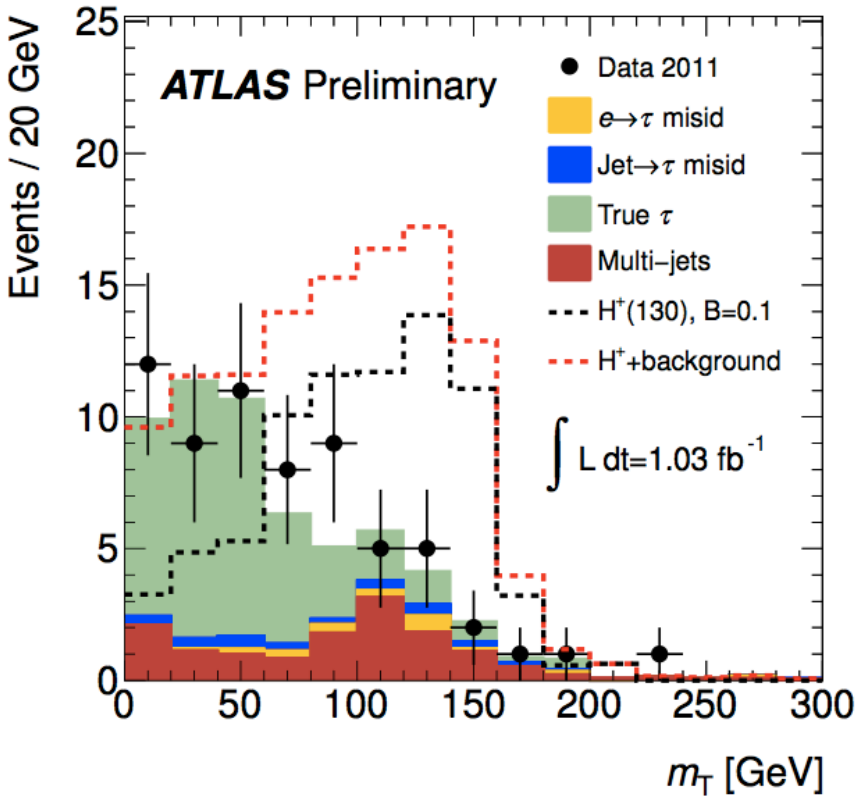
- ***What would give evidence for BSM physics?***
  - In many scenarios, BR($H^+ \rightarrow \tau\ \upsilon$) ≈ 100%.
  - An excess in "tau+jets" events over SM expectation could indicate a nonzero BR($t \rightarrow H^+ b$)

Charged Higgs Search: $H^+ \rightarrow \tau\ \upsilon$

- **Event selection for the analysis**
  - At least **four high P_t jets**
  - Exactly **one high P_t hadronic** τ
  - No identified electrons or muons
  - MET > 40 GeV
  - MET Significance, $\dfrac{MET}{0.5\sqrt{\Sigma E_T}}$ > 8 $GeV^{1/2}$
  - Reconstructed mass of the highest P_t combination of qqb satisfies 120 GeV < M(qqb) < 240 GeV

Charged Higgs Search: $H^+ \rightarrow \tau\ \upsilon$

- The final discriminating variable of the analysis, used in the limit setting process, is **$M_T(\tau$,MET)**.
  - In the case of the SM background, this is related to the W boson mass
  - In the case of the BSM signal, this is related to the charged Higgs boson mass
- Background contributions in the $M_T(\tau$,MET) distribution are from data-driven methods

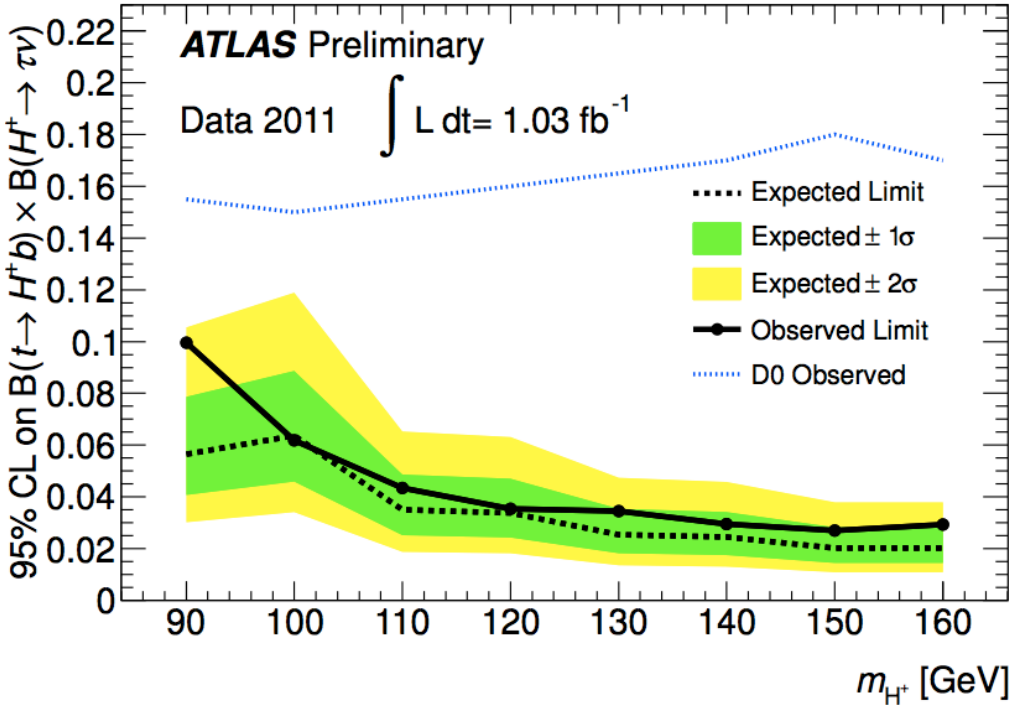


Events From:

	true τ jets	jet $\rightarrow \tau$ mis-id	$e \rightarrow \tau$ mis-id	multi-jet	expected (sum)	data
$m_T > 40$ GeV	21 ± 5	2.4 ± 0.7	1.9 ± 0.2	12 ± 5	37 ± 7	43

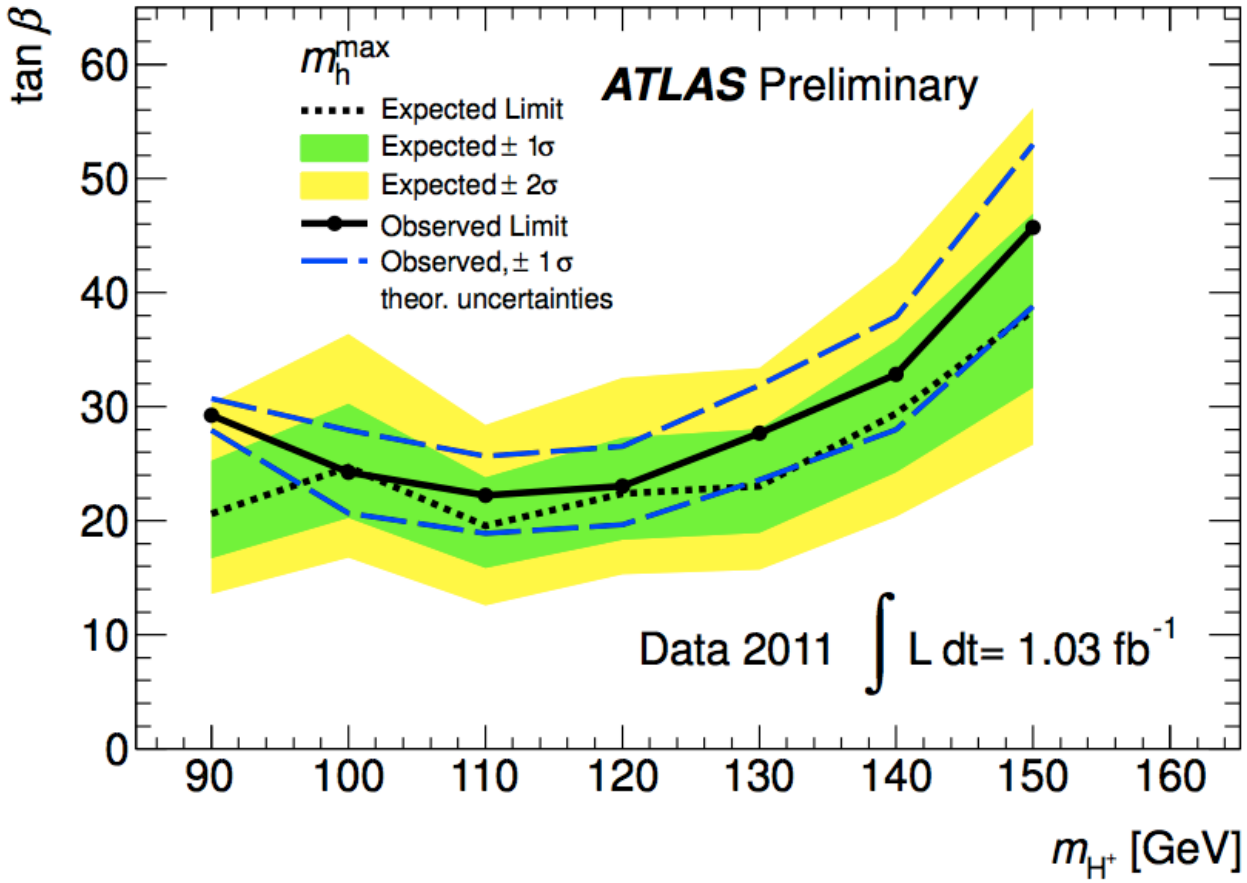
Charged Higgs Search: $H^+ \rightarrow \tau\ \upsilon$

- Exclusion limits are set on the product of the branching ratios **BR($t \rightarrow bH+$) X BR($H+ \rightarrow \tau\ \upsilon$)**, by rejecting the signal hypothesis at the 95% confidence level applying the CL_s procedure.
- Systematic uncertainties in shape and normalisation are incorporated via nuisance parameters.



Charged Higgs Search: $H^+ \rightarrow \tau\ \upsilon$

- Exclusion limits are also set on the m_{H+}-tan(β) plane of the m_h-max scenario of the MSSM.



CMS PAS HIG-11-008

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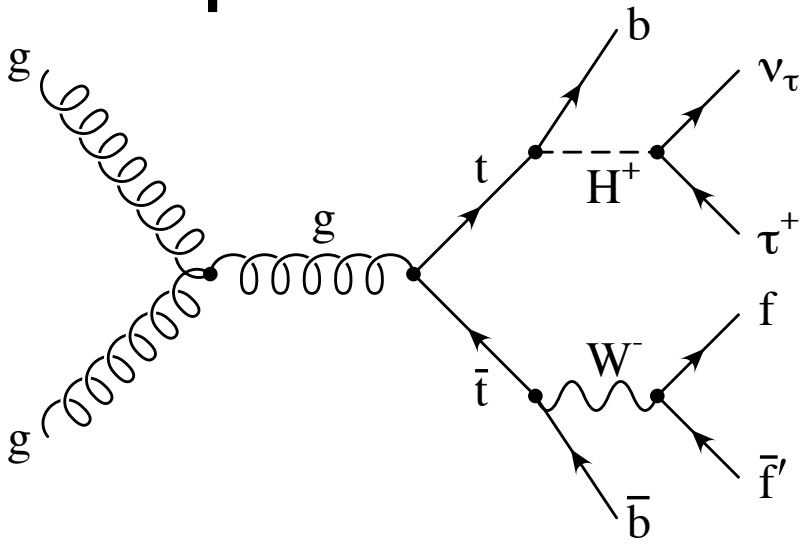
Charged Higgs Search: $H^+ \rightarrow \tau\ \upsilon$

- The CMS search for charged Higgs from top quark decays focuses on three channels.
- One channel is a decay with an electron, muon, b-jets and associated neutrinos in the final state.
- In two channels, H^+ decays into a **hadronically-decaying τ lepton.** The channels are defined by the W boson decay:

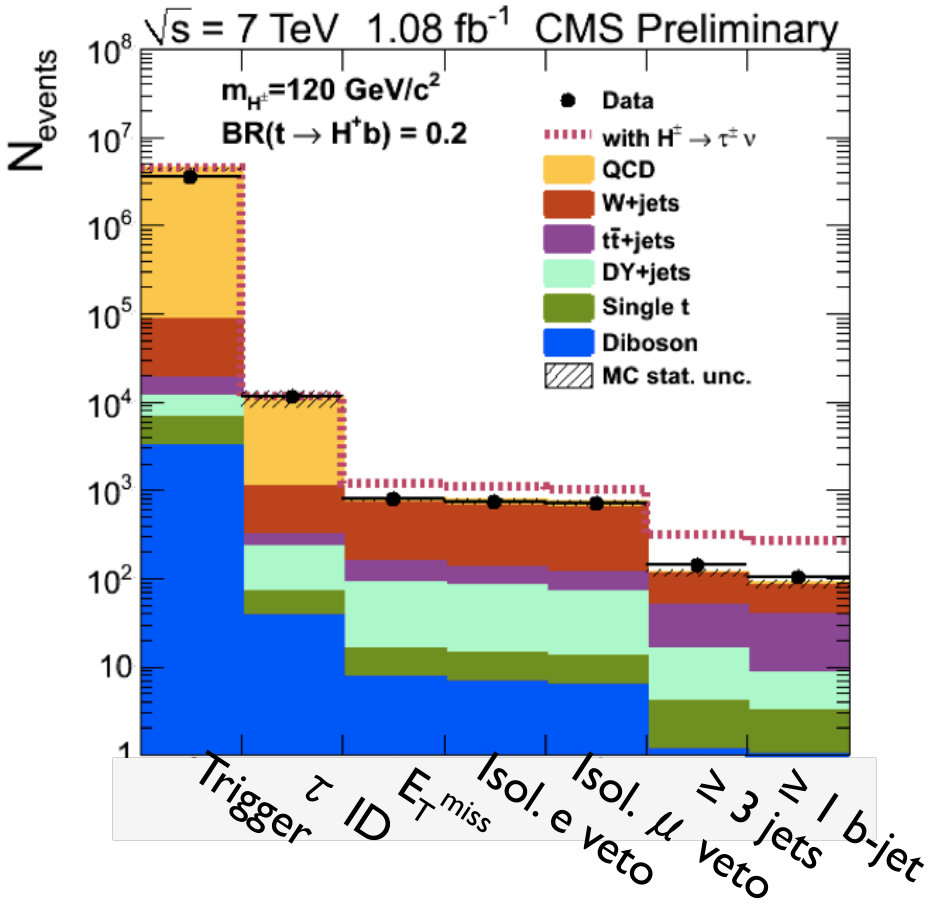


- W boson decays into a muon ("μ + τ")
- W boson decays into quarks ("fully hadronic")

- **BSM physics would be indicated by an excess of events in "H+" channels or a lack of events in the SM channel.**

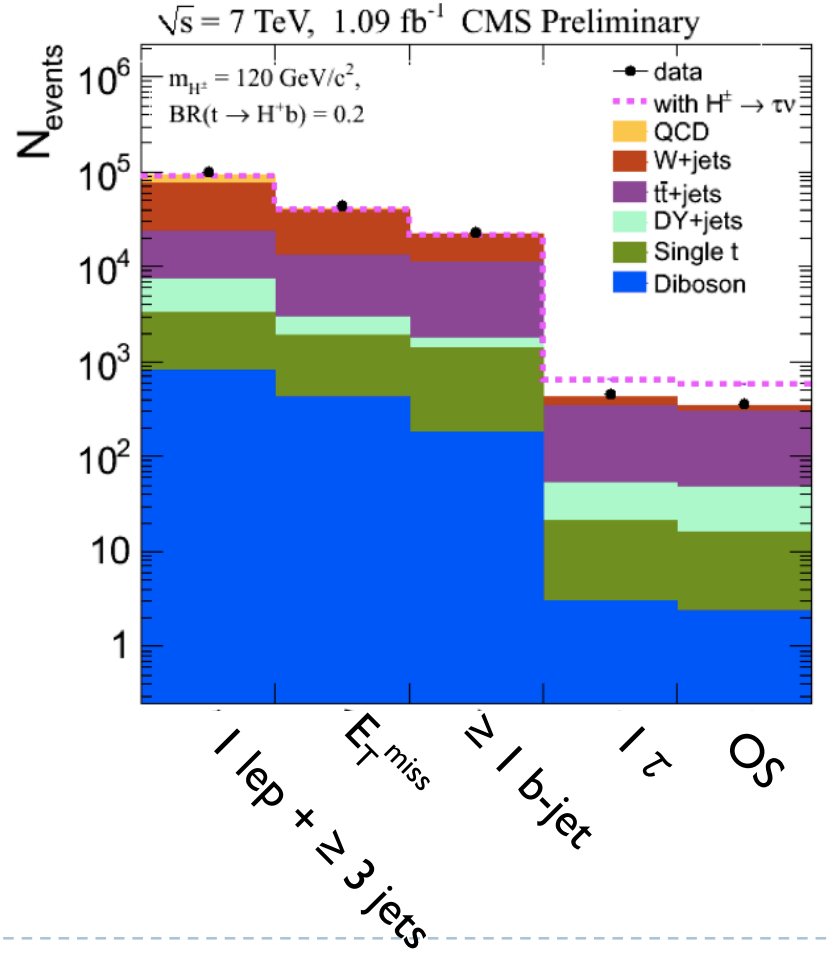
Charged Higgs Search: $H^+ \rightarrow \tau\ \upsilon$,"Fully Hadronic" Channel

- **Event selection**
  - Exactly **one high Pt hadronic** τ
  - At least **3 high P_t jets**
  - At least one b-tagged jet
  - No identified leptons (e/ μ)
  - MET > 70 GeV



Charged Higgs Search: $H^+ \rightarrow \tau \upsilon$, "$\mu + \tau$" Channel

- **Event selection**
  - Exactly **one high P_t hadronic τ**
  - Exactly **one high P_t μ**
  - At least **2 high P_t jets**
  - At least one b-tagged jet
  - MET > 40 GeV



Charged Higgs Search: $H^+ \rightarrow \tau \upsilon$, "$\mu + \tau$" and "Fully Hadronic" Channel

- Results for the "Fully Hadronic" Channel

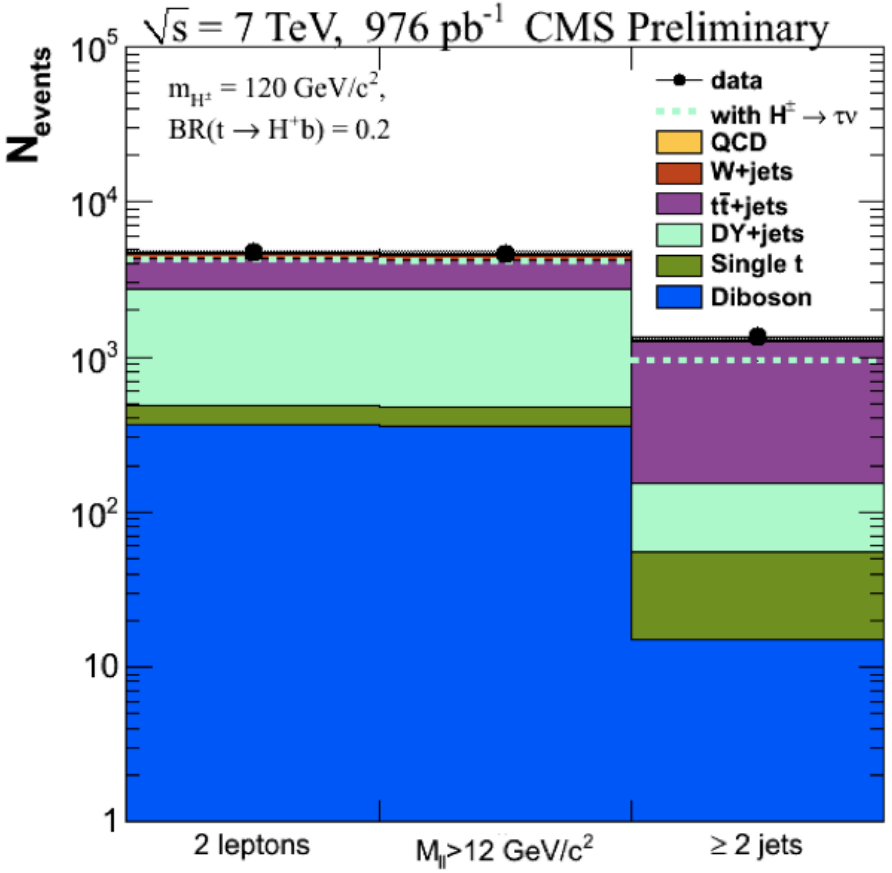
Source	$N_{events} \pm stat. \pm syst.$
HH+HW, $m_{H^\pm} = 120\ GeV/c^2$, BR=0.2	$121 \pm 6 \pm 39$
QCD multi-jets	7.5 ± 0.5 (stat.+syst)
EWK+$t\bar{t}$ τ	$71 \pm 5 \pm 16$
EWK+$t\bar{t}$ τ fakes	$3.5 \pm 0.8 \pm 1.0$
Total expected from the SM	$82 \pm 5 \pm 16$
Data	104

- Results for the "$\mu + \tau$" Channel

Source	$N_{events} \pm$ stat. $\pm$ syst.
HH+HW, m_{H^+}=120 GeV/c^2, BR=0.2	$323 \pm 8.7 \pm 67$
τ fakes	$163.0 \pm 9.7 \pm 17.3$
$t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b\ \tau\nu b$	$152.7 \pm 2.8 \pm 35.0$
$t\bar{t} \rightarrow WbWb \rightarrow \ell\nu b\ \ell\nu b$	$13.2 \pm 0.8 \pm 3.5$
$Z/\gamma^* \rightarrow ee, \mu\mu$	$0.7 \pm 0.5 \pm 0.5$
$Z/\gamma^* \rightarrow \tau\tau$	$30.9 \pm 3.6 \pm 6.0$
Single top	$13.8 \pm 0.7 \pm 2.1$
VV	$2.4 \pm 0.2 \pm 0.4$
Total expected from the SM	$376.7 \pm 10.8 \pm 39.7$
Data	361

Charged Higgs Search: $H^+ \rightarrow \tau\ \upsilon$, "μ +e" Channel

- **Event selection**
  - Exactly **one high P_t e**
  - Exactly **one high P_t μ**
  - At least **2 high P_t jets,** separated from the leptons
  - M_{ll} > 12 GeV/c^2



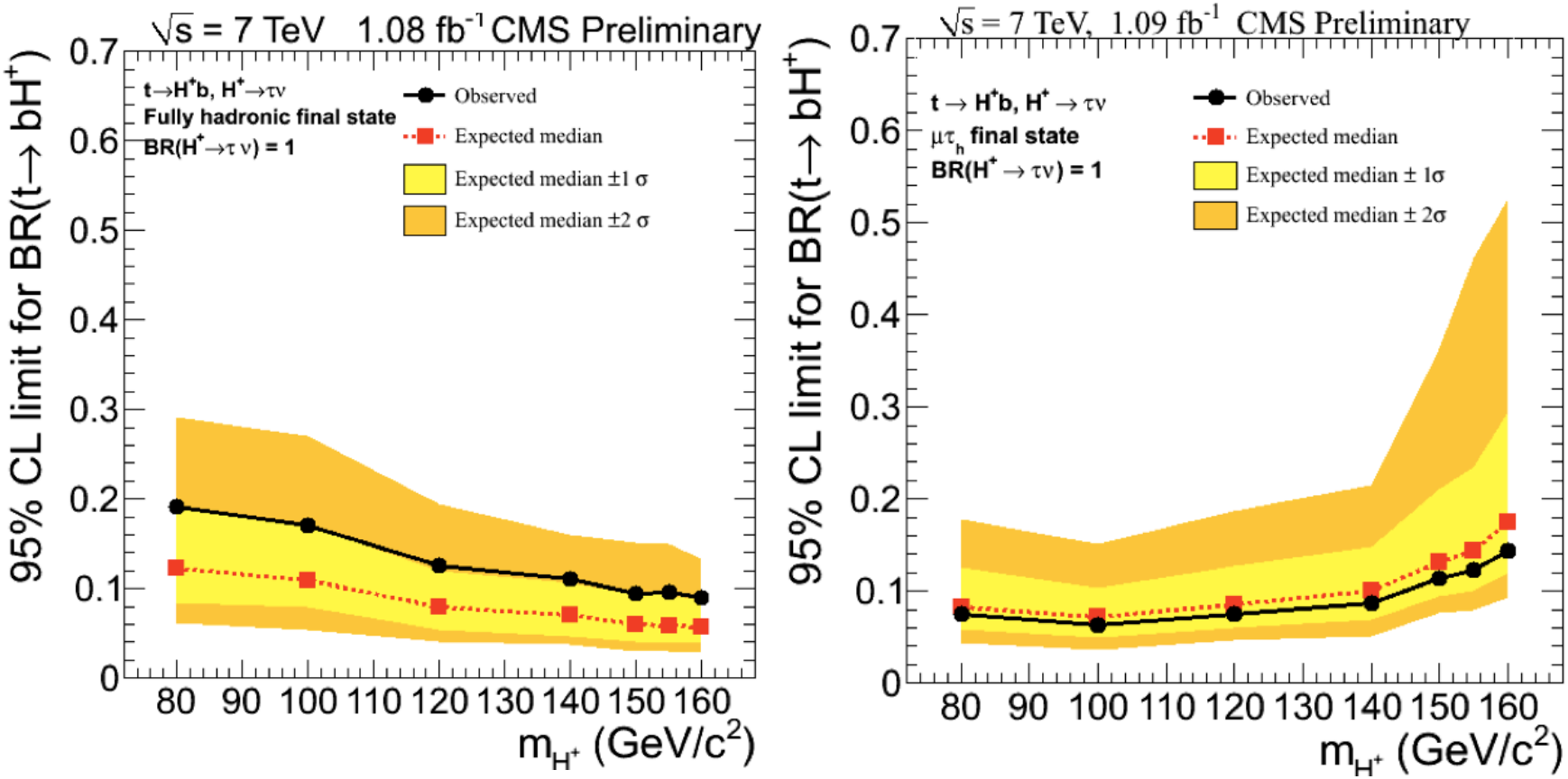
Charged Higgs Search: $H^+ \rightarrow \tau \upsilon$, "$\mu$ +e" Channel

- The resulting event numbers are:

Source	$N_{events} \pm$ stat. $\pm$ syst.
HH+HW, m_{H^+}=120 GeV/c^2, BR=0.2	$219 \pm 7 \pm 43$
$t\bar{t}$	$1094 \pm 6 \pm 219$
$Z/\gamma^* \rightarrow ll$	$98 \pm 3 \pm 12$
W+jets	$18 \pm 3 \pm 2$
Single top	$40 \pm 1 \pm 4$
VV	$14.7 \pm 0.4 \pm 1$
Total expected from SM	$1264 \pm 7 \pm 219$
Data	1340

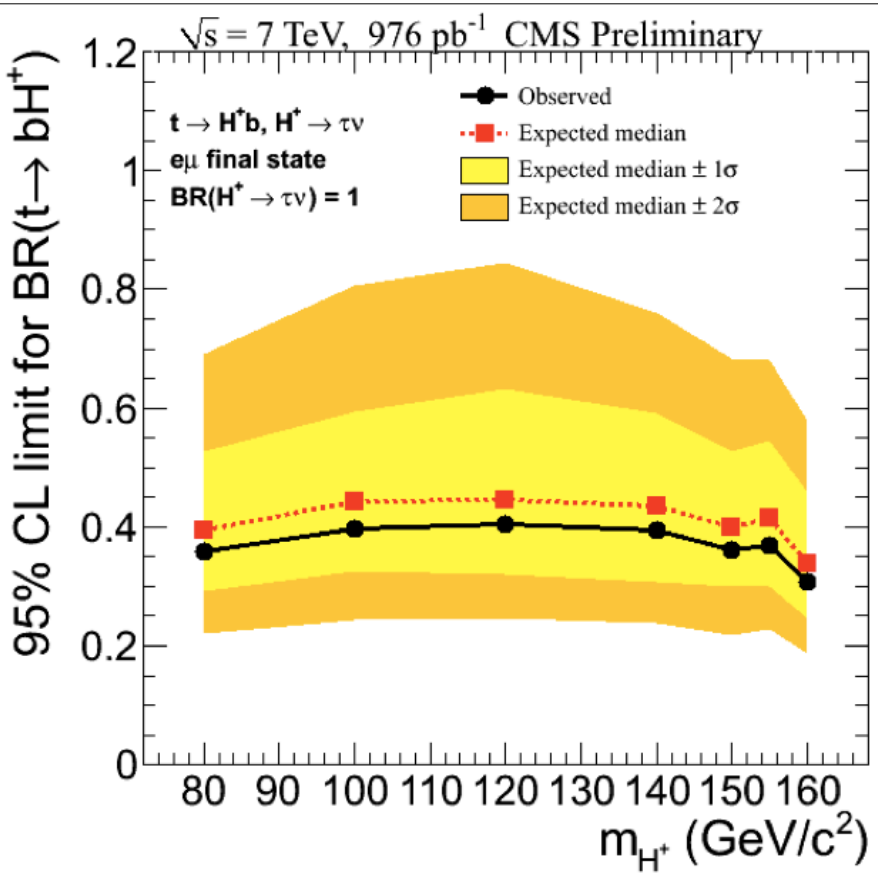
Charged Higgs Search: $H^+ \rightarrow \tau \upsilon$, CMS

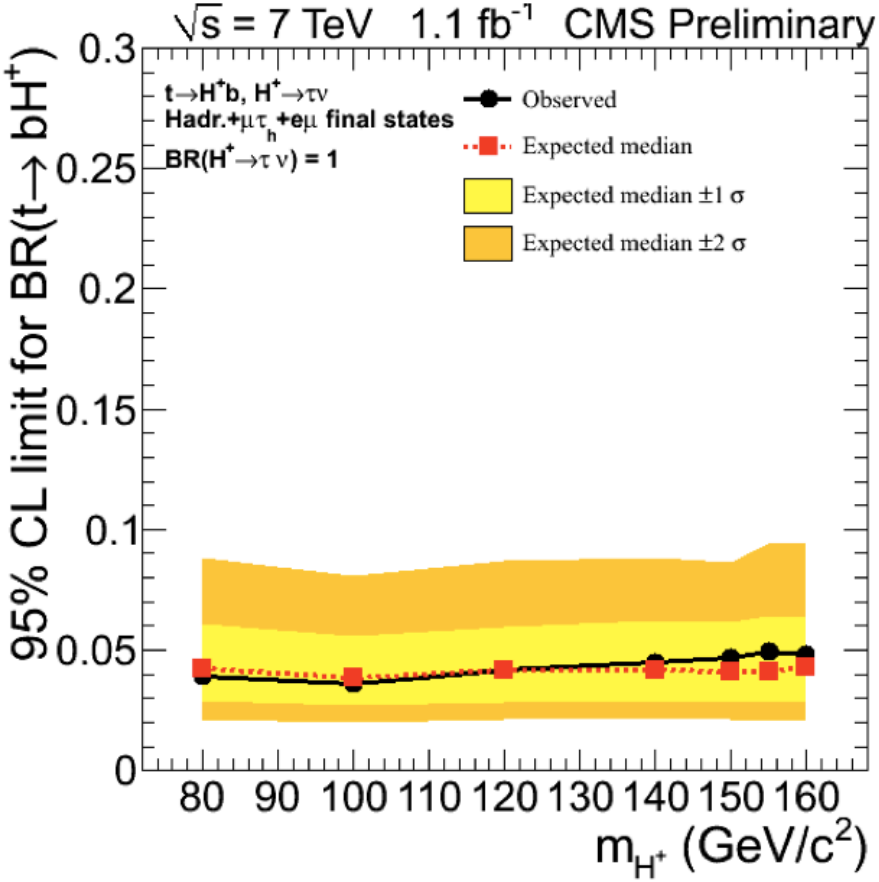
- Limits on BR($t \rightarrow H^+ b$) for the "fully hadronic" and "$\mu + \tau$" channels



Charged Higgs Search: $H^+ \rightarrow \tau\ \upsilon$, CMS

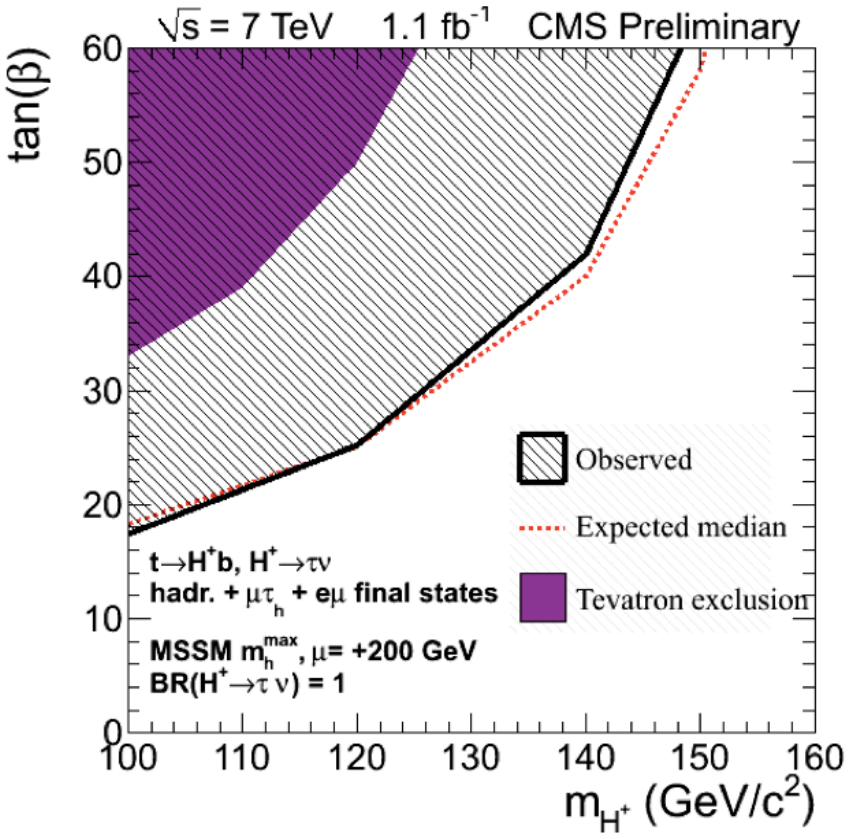
- Limits on BR($t \rightarrow H^+b$) for the "μ +e" channel and the combined limit of all channels.





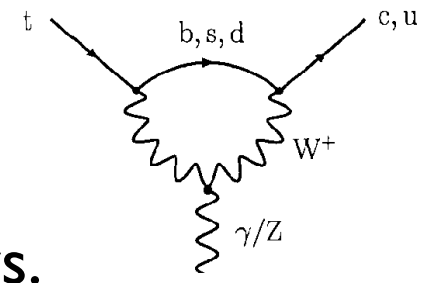
Charged Higgs Search: $H^+ \rightarrow \tau \upsilon$, CMS

- A CLs method is used to obtain the upper limit at 95% C.L. on the excess (lack) of the events compared to the Standard Model expectation.
- To the right is the resulting limit of the combined analysis on the m_{H+}-tan(β) plane of the MSSM m_h-max scenario



Search for Flavor Changing Neutral Currents (FCNC) in Top Decays

- Top quark FCNC are **absent at tree-level** in the Standard Model, and are **highly suppressed** by the GIM mechanism.
  - They are only present in the SM through loop corrections.
- Several BSM physics models predict **higher branching ratios** for FCNC top quark decays.
  - Quark-Singlet Models, Two-Higgs-Doublet Models, MSSM, SUSY with R-parity violation, Topcolour-assisted Technicolour.
- Possible channels for top quark FCNC are:
  - $t \rightarrow Z\ q$
  - $t \rightarrow g\ q$
  - $t \rightarrow \gamma\ q$



SM FCNC

ATLAS-CONF-2011-061

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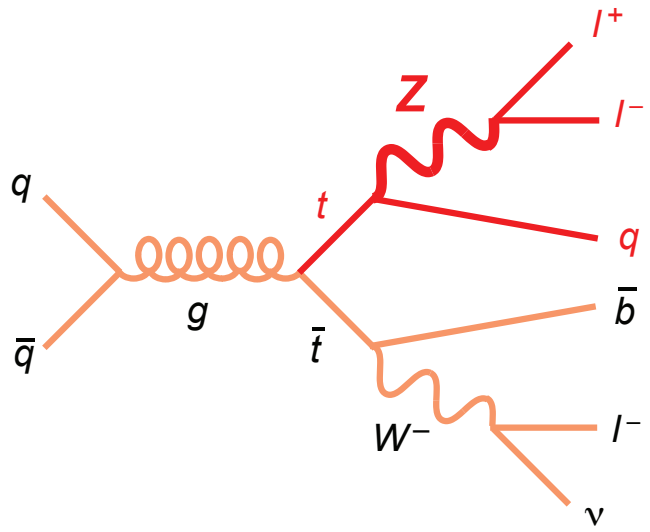
Top Quark FCNC - t→Z q

- One channel in the ATLAS search for FCNC in top quark decays consists of:
  - One top decaying into a Wb, the dominant SM mode
  - One top decaying via t→Z q

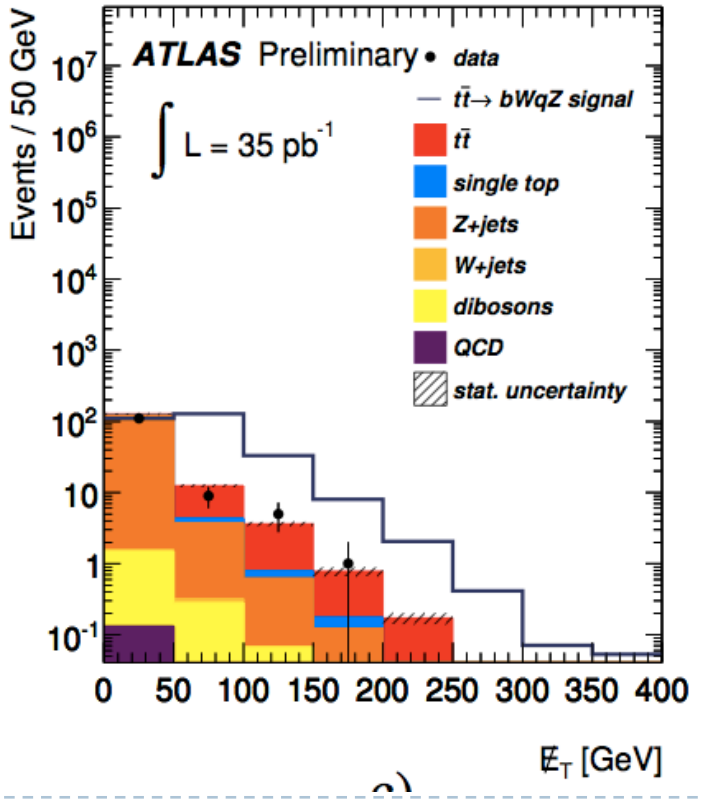
- To reduce QCD multi-jet and W+jets backgrounds, only the case where both the Z boson and the W boson decay leptonically (Z→ee/ μ μ , W→e ν / μ ν) are considered.

- **Thus, the signal contains:**
  - 3 isolated leptons
  - 2 jets
  - Missing Transverse Energy



Top Quark FCNC - t→Z q

- **Event selection**
  - Exactly **3 leptons**
    - Two of same flavor and opposite charge
  - At least **2 jets**
  - MET > 20 GeV
  - No identified photons
  - Plot shows MET distribution, after all selection except only requiring 2 leptons.



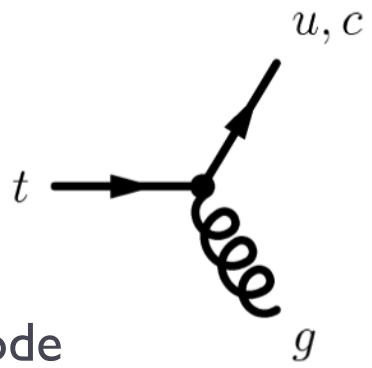
Top Quark FCNC - t→Z q

- The results after the event selection are consistent with SM expectations
- No evidence for the top decay t→qZ is found
- Limits on the BR(t→qZ) are calculated using a modified frequentist likelihood method, and the results are shown in the table below.

Selection	Final selection	
Channel	e	μ
W+jets	0.00 ± 0.08	0.00 ± 0.08
Z+jets	0.10 ± 0.08	0.02 ± 0.01
Dibosons	0.08 ± 0.01	0.11 ± 0.01
$t\bar{t}$	0.05 ± 0.02	0.04 ± 0.02
Single-top	0.00 ± 0.00	0.00 ± 0.00
Expected background	0.23 ± 0.11	0.17 ± 0.08
Data	0	1
Signal Efficiency	$(8.53 \pm 0.09)\%$	$(11.96 \pm 0.11)\%$

	observed	(-1σ)	expected	$(+1\sigma)$
with systematics	17%	9%	12%	16%

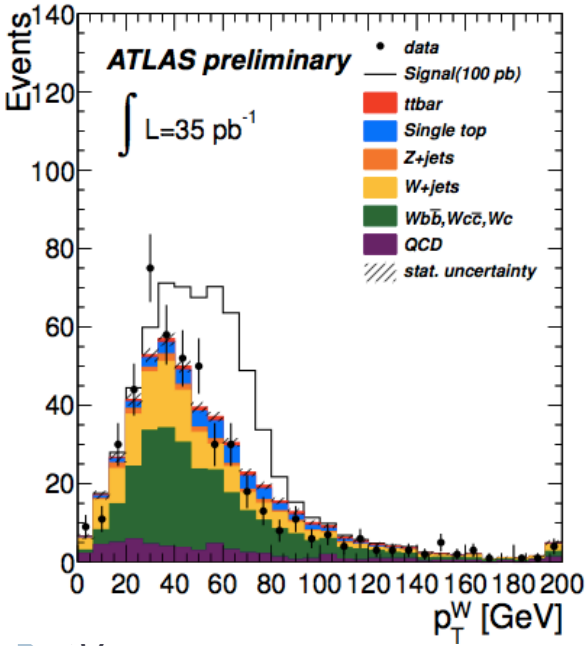
Top Quark FCNC - gq→t

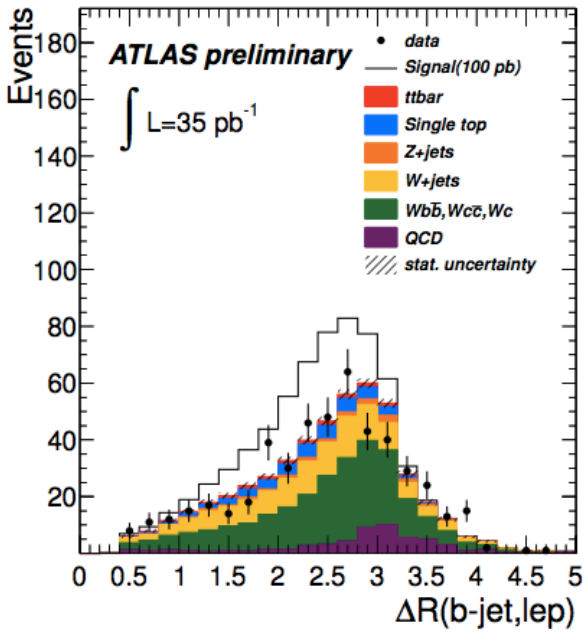


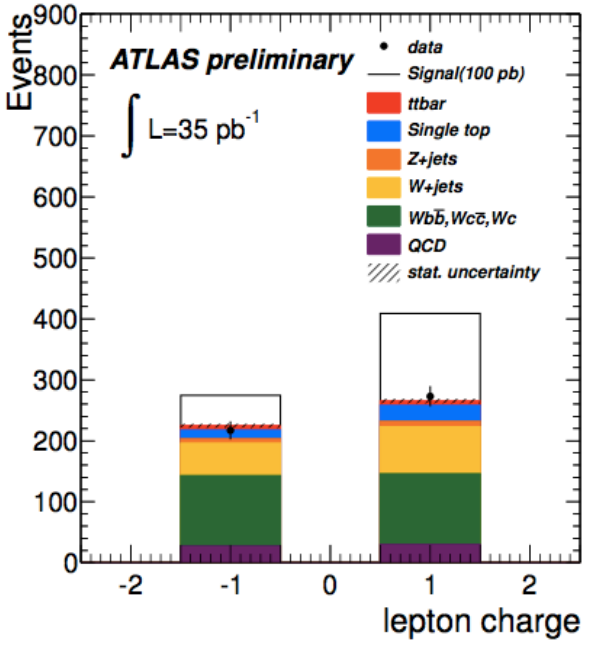
- ATLAS also searches for the t→gq neutral current. This channel is observed through top quark production (gq→t), where:
  - The top quark decays into Wb, the dominant SM mode
  - The W decays leptonically (e or μ and associated neutrino)
- **The event selection requires:**
  - One high P_t lepton
  - One tagged b-jet
  - Electron channel
    - MET > 35 GeV
    - Transverse W mass > 60 GeV (to reduce QCD multijets)
  - Muon channel
    - MET > 20 GeV
    - Transverse W mass > 25 GeV

Top Quark FCNC - gq→t

- A neural network package is used to separate signal and background events.
- This neural network uses 13 variables, and the three most discriminating are pictured below after the full event selection.

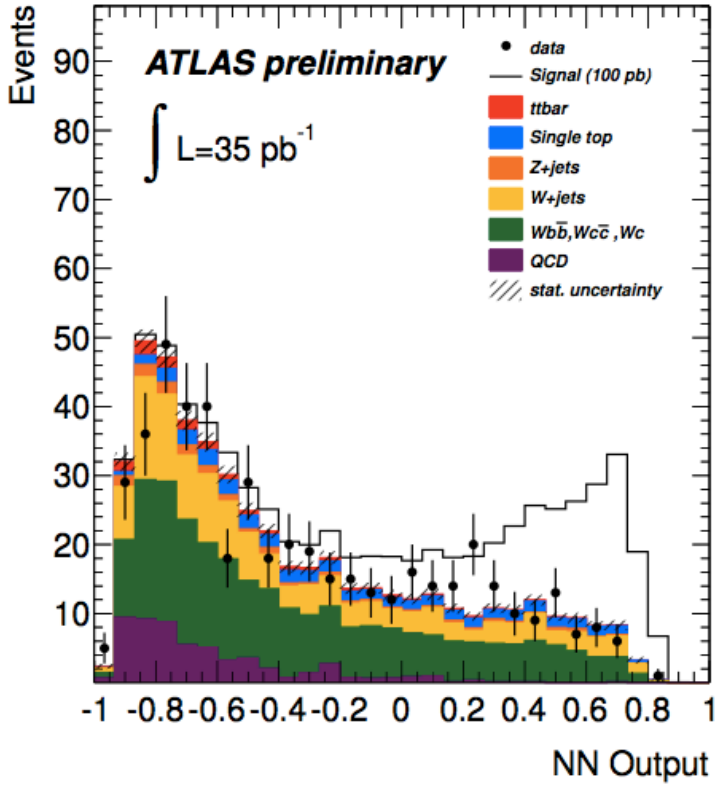






Top Quark FCNC - gq→t

- No evidence for FCNC in single top quarks is observed.
- An upper limit is set on the cross-section using a Bayesian method, with systematics as nuisance parameters.
  - The limit is estimated using 10,000 pseudo-experiments
  - It is defined by the mean of the resulting distribution of the upper limit of each pseudo-experiment.



	expected			observed
	(-1σ)	median	$(+1\sigma)$	
with all systematics	12.0 pb	17.4 pb	25.6 pb	17.3 pb

CMS PAS EXO-11-005

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Top Quark FCNC - T→tZ

- In a slightly different search for top quark FCNC, CMS searches for T→tZ
- ***The decay chain is pp →TT → tZtZ → bbW⁺W⁻ZZ.***

- **Event Selection:**
- Two leptons from a Z-decay
  - Opposite sign, same flavor
  - $60 < M_{ll} < 120$ GeV/c^2
- A third isolated lepton
- At least 2 jets
- Total P_t of leptons and jets, excluding the leading two of each, > 80 GeV/c

- ***T is a top-like quark***
  - It is expected in composite Higgs models, Little Higgs models, and models with extra dimensions.
  - It is a vector-like quark of charge 2/3
  - It could have tree-level FCNC couplings, and may preferentially decay to tZ.

Top Quark FCNC - T→tZ

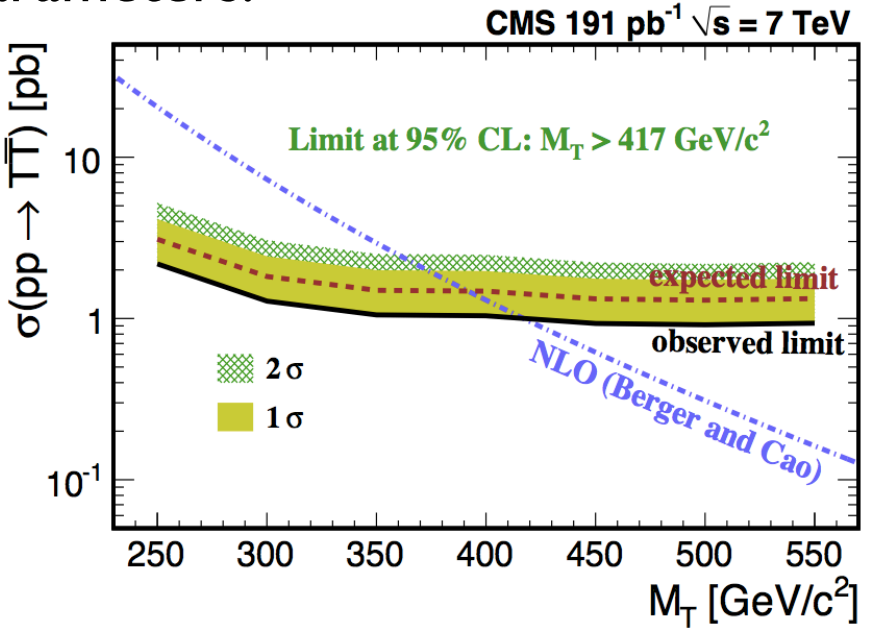
- The background with three real leptons is estimated from simulated events.
- The background with two real leptons is estimated using a data driven method.

Process	Cross-section (pb)	ϵ[%]	Yield
$T\bar{T}$, $M(T) = 250$ GeV/c^2	20.5 (NLO)	14.5 ± 3.0	30.4
$T\bar{T}$, $M(T) = 300$ GeV/c^2	7.29 (NLO)	24.6 ± 5.0	18.4
$T\bar{T}$, $M(T) = 350$ GeV/c^2	2.94 (NLO)	29.9 ± 6.8	8.99
$T\bar{T}$, $M(T) = 400$ GeV/c^2	1.30 (NLO)	30.3 ± 6.9	4.03
$T\bar{T}$, $M(T) = 450$ GeV/c^2	0.617 (NLO)	33.8 ± 7.7	2.13
$T\bar{T}$, $M(T) = 500$ GeV/c^2	0.310 (NLO)	34.4 ± 7.9	1.09
$T\bar{T}$, $M(T) = 550$ GeV/c^2	0.162 (NLO)	33.6 ± 7.9	0.56
$t\bar{t}$ + jets	158 (CMS)	$(2.6 \pm 2.0) \times 10^{-4}$	0.08
Z + jets	2.9×10^3 (CMS)	$(6.3 \pm 5.4) \times 10^{-5}$	0.35
WZ inclusive	18.0 (NLO)	$(3.3 \pm 0.5) \times 10^{-3}$	0.12
ZZ inclusive	5.9 (NLO)	$(5.9 \pm 0.6) \times 10^{-3}$	0.07
$t\bar{t}$ + W + jet	0.144 (LO)	$(1.3 \pm 1.3) \times 10^{-2}$	0.004
$t\bar{t}$ + Z + jet	0.094 (LO)	$(5.4 \pm 1.3) \times 10^{-1}$	0.10
Expected background from simulated samples			0.71
Background with two real leptons (data-driven)			0.45 ± 0.28
Background with three real leptons (simulated)			0.28 ± 0.11
Sum (estimated background)			0.73 ± 0.31
Data (191 pb^{-1})			0

- **Data Driven Method**
- The **efficiency** of identifying leptons with the **regular** object selection vs. a **loosened** selection criteria is measured from data.
- This efficiency is applied to data events with **two regular leptons** and one lepton that passes the loosened selection to estimate the background.

Top Quark FCNC - T→tZ

- The results are consistent with contributions from SM processes.
- The upper limit on the cross section is calculated using a Bayesian method with flat priors and a log-normal model for integration over the nuisance parameters.
- Comparing the upper limit on the cross section with the NLO calculated cross sections with respect to T mass, a limit of $m_T > 417$ GeV/c^2 is obtained.



Conclusions

- ATLAS and CMS have set strong exclusion limits on the branching ratio of $t \rightarrow H^+b$ using the $H^+ \rightarrow \tau \upsilon$ channel
  - 0.03-0.1 for ATLAS (depending on m_{H+})
  - 0.04-0.05 for CMS (depending on m_{H+})
- For the charged Higgs boson have also ruled out a large region of parameter space in the m_{H+}-tan(β) plane of the m_h-max scenario of the MSSM.
- ATLAS has also set limits on BR($t \rightarrow H^+b$) for the channel $H^+ \rightarrow cs$
  - 0.14-0.25 (depending on m_{H+})
- For FCNC, ATLAS has shown BR($t \rightarrow qZ$) < 17%, and set an upper limit of 17. 3 pb on the production cross section of $gq \rightarrow t$.
- CMS has set upper limits on the cross section of the FCNC process $T \rightarrow tZ$, and set a lower bound on $m_T > 417$ GeV/c^2.

- With the current rate of data taking, major discoveries or exclusions from top quark decays may be just around the corner!

Backup

Charged Higgs Search: $H^+ \rightarrow \tau \upsilon$, Background Estimation

- The major SM backgrounds to the analysis have been estimated using almost completely data-driven methods.
- The backgrounds can be broken up into those from:

Correctly identified τ leptons (mostly SM tt, some W+jets, single top, diboson):

Estimated by identifying μ +jets events in collision data and "embedding" simulated τ signatures in place of the μ.

QCD multijet events:

Estimated by using a template fitting method, using a defined "orthogonal selection" as a model of the shape of the multijet distribution.

Electrons misidentified as τ leptons (Z→ee, some tt):

Scale factor, defined by calculated misidentification probability in Z→ee from simulation and data, applied to simulated events.

Jets misidentified as τ leptons (W+jets, some tt):

Misidentification probability measured from Υ+jets events in data and applied to simulated events.

Charged Higgs Search: $H^+ \rightarrow \tau \upsilon$, "Fully Hadronic" Channel, Background Estimation

- The backgrounds to this channel are separated into three categories:

Backgrounds from QCD multijet events:

The event selection, except for the MET cut and b-tag requirement, are applied to data. The fraction of QCD in this data sample is taken as the difference from the expectation from simulation. The amount of QCD after all cuts is taken as:

$$N^{QCD} = \sum_i N_{presel,\,i} \times f^{QCD}_{presel,\,i} \times \epsilon_i^{MET+b}$$

Where 'i' refers to binning with respect to the τ P_t

Backgrounds with τ leptons (mostly SM tt, some W+jets, single top, diboson):

Estimated by identifying μ +jets events in collision data and "embedding" simulated τ signatures in place of the μ.

Backgrounds with fake τ leptons (Z/W+jets some tt):

Estimation taken from simulated events.

Charged Higgs Search: $H^+ \rightarrow \tau \upsilon$, "$\mu + \tau$" Channel, Background Estimation

- The backgrounds to this channel are separated into two categories:

Backgrounds from events with fake τ leptons

Estimated using data driven fake rates. Two misidentification probabilities are calculated, one from a region **rich in QCD multijets**, the other in a region **rich with W+jets**.

The number of fakes before requiring μ and τ have opposite sign charge is:

$$N^{\tau \text{ fakes}} = \frac{\sum_i^N \sum_j^n w^j_{W+jets,\, i} + \sum_i^N \sum_j^n w^j_{QCD,\, i}}{2}$$

where i is the event index and j is the jet index.

The total number of of events is calculated by multiplying $\mathbf{N}^{\tau \text{ fakes}}$ by the efficiency of the μ / τ **opposite sign cut**, taken from simulation.

Backgrounds from events with τ leptons:

Estimation taken from simulated events.