Charged Higgs boson searches in $H^{\pm} \to \tau\nu$ channel in the ATLAS experiment at the LHC

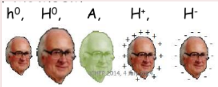
anna bożena kowalewska

Cracow School of Theoretical Physics

Institute of Nuclear Physics
Polish Academy of Sciences

Motivation

- the study of the Higgs sector including searches for other fundamental spin-0 particles, which existence is postulated in many theories of BSM physics.
- in the great majority of cases, for example in the two Higgs doublet class of models (2HDM), such additional scalar particles are weakly interacting.



- it follows, due to the gauge symmetry conservation, that in such cases an electromagnetically charged state has to exist ⇒ charged Higgs boson.

Discovery of charged Higgs ⇒ definite signal of new physics!

Outline

1. The ATLAS experiment - "*Mapping the Secrets of the Universe*"
2. Charged Higgs production and signals in $H^{\pm} \to \tau\nu$ channel
3. Prospects for the determination of $\tan\beta$
4. Effects of the τ polarization
5. If large "extra dimensions" exist ... ?
6. ATLAS Run1 results

PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: *December 23, 2014*
REVISED: *February 6, 2015*
ACCEPTED: *February 17, 2015*
PUBLISHED: *March 17, 2015*

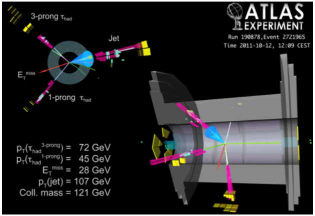
JHEP03(2015)088

Search for charged Higgs bosons decaying via $H^{\pm} \to \tau^{\pm}\nu$ in fully hadronic final states using pp collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS

- one of the four main scientific experiments conducted at the LHC
- 2011-2012 ALTAS collected data of total integrated luminosity $\sim 30\ \text{fb}^{-1}$ for $p-p$ collisions with energies of 7 and 8 TeV in the center of mass frame
- finding the proof of existence of the neutral Higgs boson and first determination of its properties
- confirming the validity of the Standard Model up to unreachable earlier energies
- $\Rightarrow$these results lead to very stringent constraints on BSM physics, in particular practically excluding existence of new, yet undiscovered strongly interacting particles in the vicinity of the electroweak scale

Display of H -> tautau event

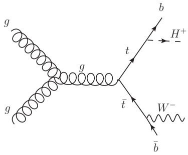


- Priority *for Run2* $\Rightarrow$ study of *the Higgs sector* including searches for yet undiscovered fundamental spin-0 particles.

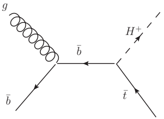
Theory

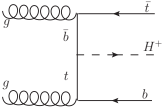
Charged Higgs production

- In $p-p$ collision $H^{\pm}$ boson could be produced in two types of processes:
  1. *the $t\bar{t}$ production followed by the top quark decay* (channel open only for $m_{H^{\pm}} < m_t$)



  2. *top t quark associated production.*

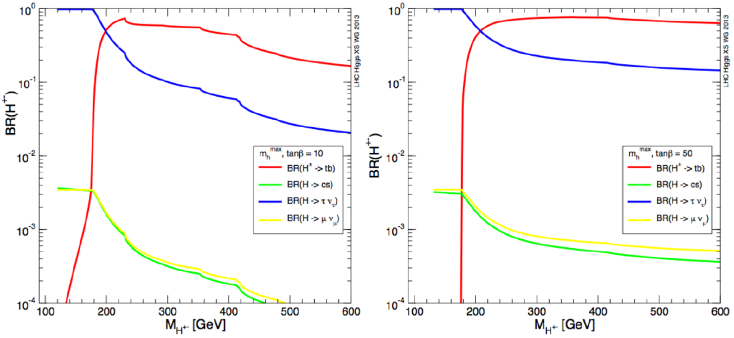




⇒ **where *top* quark has the strongest coupling to the charged Higgs boson in MSSM like scenarios.**

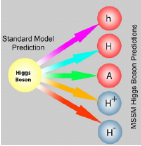
Main signals of $H^{\pm}$

- **In the ATLAS experiment one of the two main signals of $H^{\pm}$ is a decay to $\tau^{\pm}\nu_{\tau}(\bar{\nu}_{\tau})$,**
- **where the $m_{H^{\pm}} < m_t$, this decay channel is practically the only one possible.**



- **In the heavy Higgs scenario ($m_{H^{\pm}} > m_t$), also in $H^{+} \rightarrow t\bar{b}$**

Prospects for the determination of $\tan\beta$



- **In the 2HDM models, the two complex Higgs doublets correspond to eight scalar states. Symmetry breaking leads to five Higgs bosons, three neutral (two CP-even h, H and one CP-odd A) and a charged pair $H^{\pm}$.**

At tree level, *the Higgs sector of the MSSM* is specified (generally) by two parameters: m_A ⇒ *mass of the CP-odd Higgs* A and $\tan\beta$ ⇒ *the ratio of the vacuum expectation values of the two Higgs doublets*.

where

$$\tan\beta = \frac{v_2}{v_1} \quad and \quad \frac{v}{\sqrt{2}} = \sqrt{v_1^2 + v_2^2}$$

v: vacuum expectation value of the SM and v_1, v_2: vacuum expectation values of the 2HDM. **and in the MSSM, $m_{H^{\pm}}$ at tree level is related to m_A as:** $m^2_{H^{\pm}} = m^2_W + m^2_A$, where W mass is equal: $m^2_W = \frac{g^2 v^2}{4}$.

We can determine $\tan\beta$ by measuring the signal rate in the $\tau\nu$ channel:

$$\Gamma(H^- \to \tau^- \nu_\tau) \simeq \frac{m_H^{\pm}}{8\pi v^2}\left[m_\tau^2 \tan^2\beta \times \left(1 - \frac{m_\tau^2}{m^2_{H^{\pm}}}\right)\right] \times \left(1 - \frac{m_\tau^2}{m^2_{H^{\pm}}}\right).$$

Effects of the τ polarization,

τ leptons are the only leptons whose spin information is preserved in the decay product kinematics recorded in ATLAS.

- P_τ: **measure of the asymmetry of the cross-section for left-handed and right-handed τ production**

$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \Longrightarrow$$

Process	$W \to \tau_h \nu_\tau$	$Z \to \tau\tau$	$H \to \tau\tau$	$H^- \to \tau\nu$
P_τ	-1	≈ -0.15	0	+1

- **can be used as a discriminating variable in searches for new particles that decay to τ leptons,**
- **in the $W \to \tau\nu$, the *SM* predicts $P_\tau = -1$** (reflecting the parity violating structure of the charged weak current). **Parity conserving interaction, $H \to \tau\tau$ yield to $P_\tau = 0$, where *MSSM charged scalar Higgs* decaying via $H^+ \to \tau^+\nu$ is expected to produce $P_\tau = 1$,**
- **if found $H^+ \to \tau^+\nu$, P_τ could provide insight into the nature of the new particle's couplings.**

Tau Polarization Observable in Data $\Rightarrow$ *"charged asymmetry"* Υ

- Υ **is calculated as follows:** $$\frac{E_T^{\pi^-} - E_T^{\pi^0}}{p_T} \approx 2\frac{p_T^{trk}}{p_T} - 1 = \Upsilon$$

  It measures the energy sharing of the $\pi^{\pm}$ and π^0 in the τ decay relative to the visible momentum of τ.

Distributions sensitive to the polarization state of τ $\Rightarrow$ one-prong hadronic decays:

$$\tau^{\pm} \rightarrow \rho^{\pm}(\rightarrow \pi^{\pm}\pi^0)\nu_\tau \ (25.2\%) \quad \tau^{\pm} \rightarrow a_1^{\pm}(\rightarrow \pi^{\pm}\pi^0\pi^0)\nu_\tau \ (9.0\%)$$

- **In $\tau \rightarrow \rho\nu$ decays, to conserve angular momentum, *transversely polarized* ρ is favored in left-handed τ decays leading to a symmetric energy sharing between $\pi^{\pm}$ and π^0**
- ***longitudinally polarized* ρ would be preferred in hypothetical *non-SM* decays to right-handed τ leptons leading to an asymmetric energy sharing.**

- Experimentally, the energy associated with $\pi^{\pm}$ is given by p_T of the single track associated with the τ_{vis} candidate. The energy ascribed to π^0 is calculated as the difference between the τ_{vis} lepton p_T measured in the calorimeter and the track p_T of the τ candidate.

If large "extra dimensions" exist ... ?

- In 2-Higgs Doublet Model of type II, 2HDM-II (MSSM)

$H^- \to \tau_R^- \bar{\nu}$, H^- to τ_L^- suppressed

- In Large Extra Dimensions $H^- \to \tau_L^- \psi$ can be enhanced by large number of Kaluza-Klein states. Thus:

$$H^- \to \tau_R^- \bar{\nu} + \tau_L^- \psi$$

Bulk neutrino

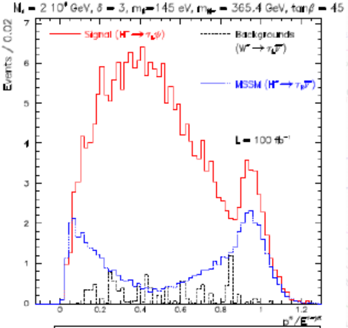
- Measurement of the polarisation asymmetry can be used (A~func (model parameters))

$$A = \frac{\Gamma(H^- \to \tau_L^- \psi) - \Gamma(H^- \to \tau_R^- \bar{\nu})}{\Gamma(H^- \to \tau_L^- \psi) + \Gamma(H^- \to \tau_R^- \bar{\nu})}$$

-Observation of signal in m_T distribution is not sufficient to distinguish between 2HDM and L.E.D.

-The reconstruction of p_π/E_{jet} should determine the scenario: 2HDM or L.E.D.

- Further measurement of the asymmetry may provide a distinctive signature for L.E.D.



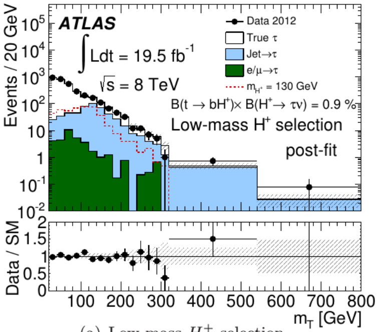
fraction of E carried by the charged track in 1P decays

Anna Kaczmarska **Tau 06, Pisa, September 2006**

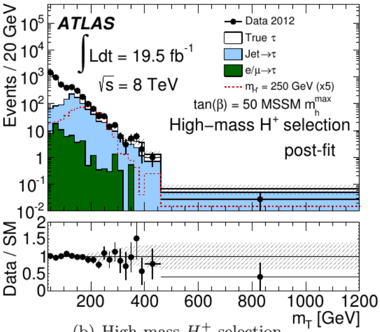
results

Final distributions of *transverse mass* ⇒ final discriminating variable

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



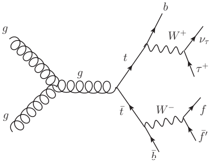
(a) Low-mass H^+ selection



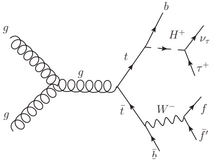
(b) High-mass H^+ selection

Data-driven technique of background estimation ⇒ *embedding method*

- **It is hard to distinguish the signatures of the $H^{\pm} \to \tau^{\pm}\nu$ process from the ones of SM $W^{\pm} \to \tau^{\pm}\nu$: *the dominant part of the irreducible background for the charged Higgs boson searches in the channel $t\bar{t} \to bH(\tau\nu)\bar{b}W$.***



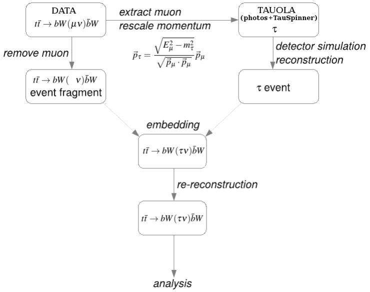
$t\bar{t}$ background

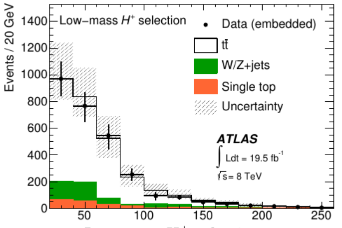


$H^{\pm}$ signal

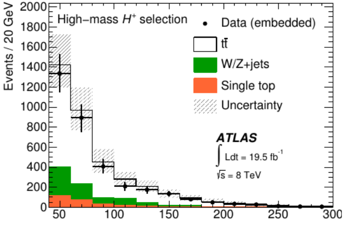
- **$t\bar{t}$ background dominant ⇒ precisely determine its contribution,**
- **⇒ MC simulations: significant systematic uncertainties related to the insufficient theoretical understanding of the details of the proton-proton collision,**
- **⇒ *embedding method*: advantage that nearly everything in a given event, *including the contribution from the so-called pile-up, underlying event and missing transverse momentum determination*, is obtained directly from the measurement.**

- $\Rightarrow$ ***embedding method relies on constructing hybrid background samples with τ basing upon measured and selected data from $W^{\pm} \to \mu^{\pm}\nu$. The latter are replaced, on the level of reconstructed tracks and calorimeter cells with τ simulated by MC methods. Hence, one relies on the simulations only for the well understood electroweak decays of W, τ decays and the detector response.***





Low-mass H^+ selection



High-mass H^+ selection

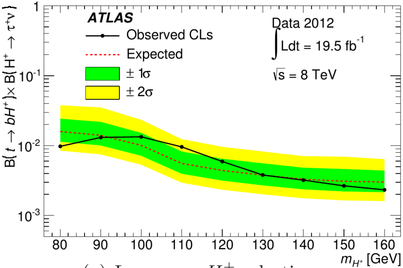
- ***comparison of the backgrounds obtained through embedding (black points) with simulation (histogram) for m_T,***
- ***statistical and systematical errors of the embedding method are given by the black error bars, while of the simulation by gray hashed area.***

Limits - model independent

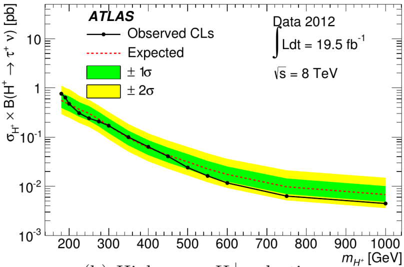
- **The work cited above also give the most up to date model independent limits for the existence of the charged Higgs bosons.**
- **In the context of the MSSM, $H^{\pm}$ was excluded for nearly all values of $\tan\beta > 1$ for $80 < m_{H^{\pm}} < 160$GeV while in the case of large $\tan\beta$ values also in the mass region $200 < m_{H^{\pm}} < 250$GeV.**
- **These searches will be continued and updated in the Run-2 and will provide the most sensitive model independent checks of theories with more than one Higgs doublet.**

- **For all of these results, $B(H^{+} \to \tau^{+}\nu) = 100\%$ was assumed.**

Limits - model independent



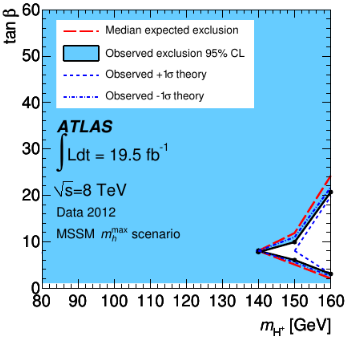
(a) Low-mass H^+ selection



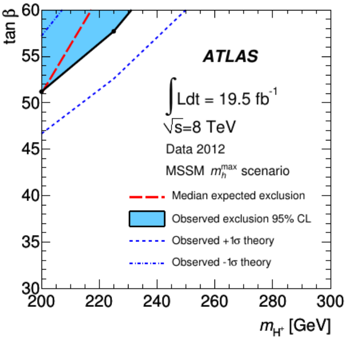
(b) High-mass H^+ selection

Observed and expected 95% CL exclusion limits on the production and decay of (a) low-mass and (b) high-mass charged Higgs bosons. For (a) search the limit is computed for $B(t \to bH^+) \times B(H^+ \to \tau^+\nu)$ for charged Higgs boson production from top-quark decays as a function of m_{H^+}. For (b), the limit is computed for $\sigma(pp \to \bar{t}H^+ + X) \times B(H^+ \to \tau^+\nu)$, and is to be understood as applying to the total production cross section times branching ratio of H^+ and H^- combined.

Limits - interpretations in models



(a) $m_h^{\max}$ scenario, low-mass H^+ selection

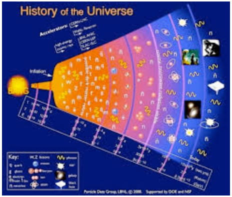


(b) $m_h^{\max}$ scenario, high-mass H^+ selection

The 95% CL exclusion limits on $\tan\beta$ as a function of m_{H^+}. Results are shown in the context of different benchmark scenarios of the MSSM for the regions in which reliable theoretical predictions exist. Results are shown for low-mass (a) and high-mass (b) H^+ search in the m_h^{max} scenario.

conclusion

A discovery of a charged Higgs boson would be an undeniable proof for existence of the physics beyond the Standard Model. It would also show us a way we should follow in the quest of more deep understanding of the fundamental rules governing our Universe.

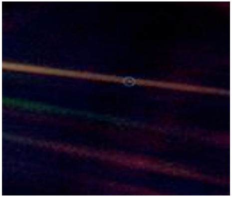


The evolution of the Universe depends on its

→

matter composition and fundamental interactions

Pale Blue Dot: The Earth from a distance of about 6. 4 bln km



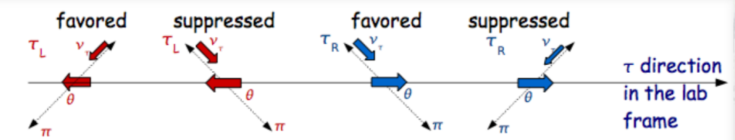
"It has been said that astronomy is a humbling and character-building experience. There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world. To me, it underscores our responsibility to deal more kindly with one another, and to preserve and cherish the pale blue dot, the only home we have ever known."

Carl Sagan " Pale Blue Dot: A Vision of the Human Future in Space"

Thank you for your attention

Effects of the τ polarization

- Spin effects express themselves differently depending on the particular decay channel, **where Decay Distribution W** $\sim (1 - P_\tau \cos(\theta))$
- Simplest case: $\tau \to \pi\nu_\tau$, where kinematics is driven by left handed neutrino



Tau polarization - as an observable :)

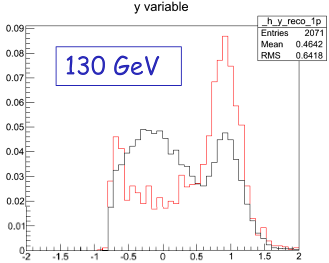
- **Looking at variable Y which is good for τ decays to ρ:** $\tau \to \rho^- \nu_\tau \to \pi^- \pi^0 \nu_\tau$

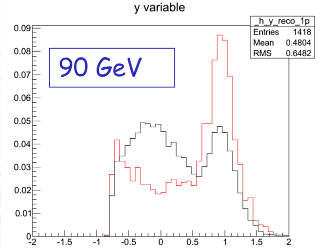
$$\cos\psi = \frac{m_v}{\sqrt{m_v^2 - 4m_\pi^2}} \frac{E_{\pi^-} - E_{\pi^0}}{|\mathbf{p}_{\pi^-} + \mathbf{p}_{\pi^0}|}, \Rightarrow \frac{E_T^{\pi^-} - E_T^{\pi^0}}{p_T} \approx 2\frac{p_T^{trk}}{p_T} - 1 = \Upsilon.$$

- **The difference of $\pi^\pm$ and π^0 energies is determined by the spin of ρ which originates from the spin of τ.**

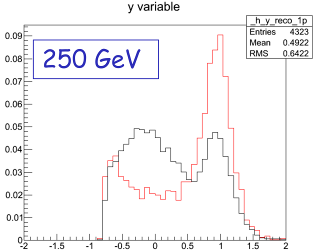
Polarisation - mass impact

All 1P decays





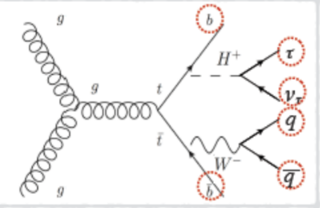
ATLAS
work in progress



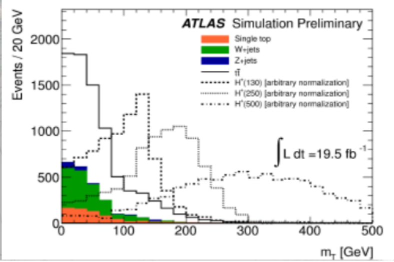
Y variable not dependent on mass of charged Higgs

Analysis overview

- Only hadronic decays of τ considered
  - BR(τ_{had})~ 0.65
- Only hadronic decays of W considered
- Challenges:
  - complex final state
  - fraction of τ energy carried away by ν. Only visible part of τ decay accessible

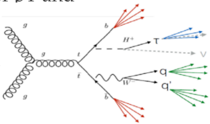


- Background events due to
  - top quark pair production
  - single top quark production
  - W+jets / Z+jets / di-boson
  - multi-jet production
- Final discriminating variable m_T
  - transverse mass of W bosons for background events with true τ jets, H⁺ bosons for signal events



Event Selection

- Trigger : $\tau_{\text{had-vis}}$ +E_T^{miss} trigger with 27/29 GeV cut of pT and 40/50 GeV on E_T^{miss}
- At least 4(3) jets for low(high) mass signal selection
- at least one of these jets is b-tagged
- at least one $\tau_{\text{had-vis}}$ with pT> 40 GeV matched to a trigger object
- no electrons or muons, or a second $\tau_{\text{had-vis}}$ with pT > 20 GeV
- E_T^{miss} > 65 (80) GeV for the low(high) mass H^+
- $\frac{E_T^{miss}}{0.5\sqrt{\sum p_T^{PVtrk}}} > 13(12) GeV^{1/2}$ for low(high) H^+
- m_T > 20 (40) GeV cut for low(high) H^+



- Triggers are only available in data, so emulation is used in simulation.

- ***Note that another way in which such theories can be tested is via flavour physics processes, e.g. by doing fits to the leptonic nad semileptonic decays, channel where bottom quark decays to a strange quark and a photon ($b \to s\gamma$), B mesons mixings and Z boson decays to bottom and anti-bottom quark pair ($Z \to b\bar{b}$).***
- ***Typically such limits are even stronger, but they are also model dependent, e.g. from the analysis in*** **"The Two Higgs Doublet of Type II facing flavour physics data" (http://arxiv.org/abs/0907.5135[arXiv:0907.5135 [hep-ph]])** ***the limit reads $m_{H^\pm} > 316$ GeV, for all values of $\tan\beta$, but can only be applied to non-supersymmetric versions of Type-II 2HDMs.***
- ***A complete list of current limits for the charged Higgs bosons can be found in*** **"Review of Particle Physics"** (http://iopscience.iop.org/1674-1137/38/9/090001/).