Searches for a Charged Higgs Boson in ATLAS and Development of Novel Technology for Future Particle Detector Systems

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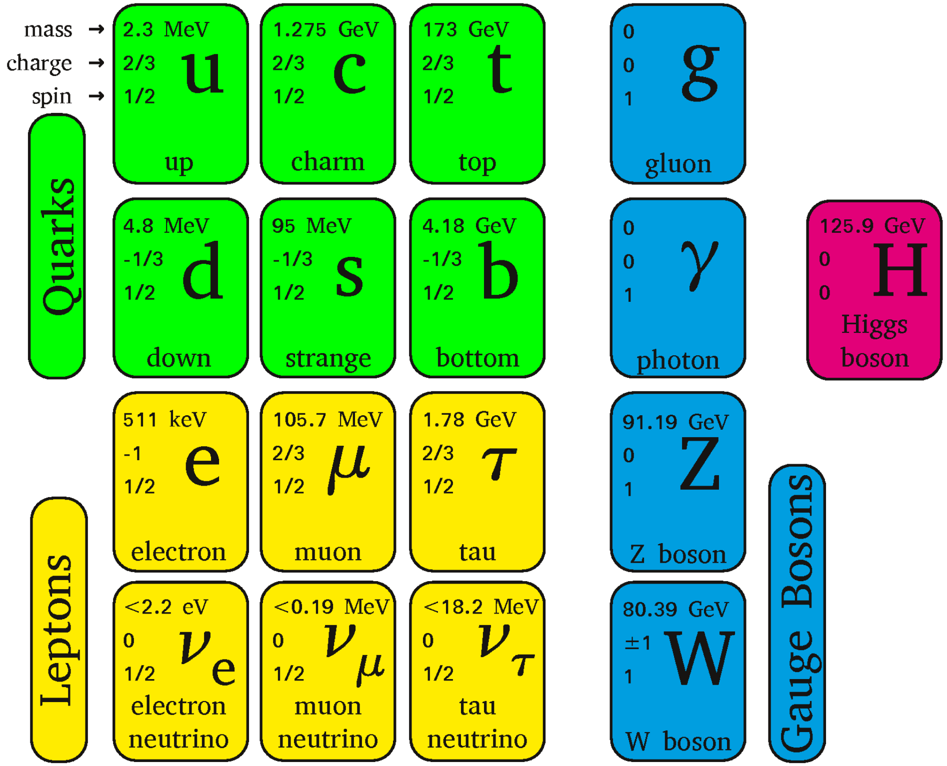
PhD defence presentation

Introduction - Outline

- Theoretical Background
- The ATLAS Experiment
- Research described in this thesis
  - Search for charged Higgs bosons
  - Development of novel detector technology

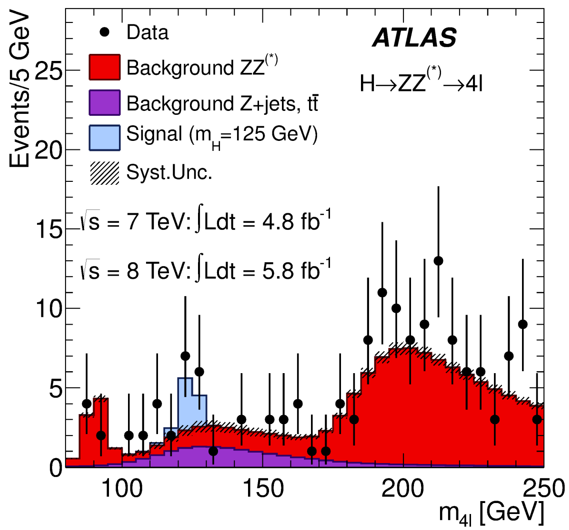
Introduction – The Standard Model

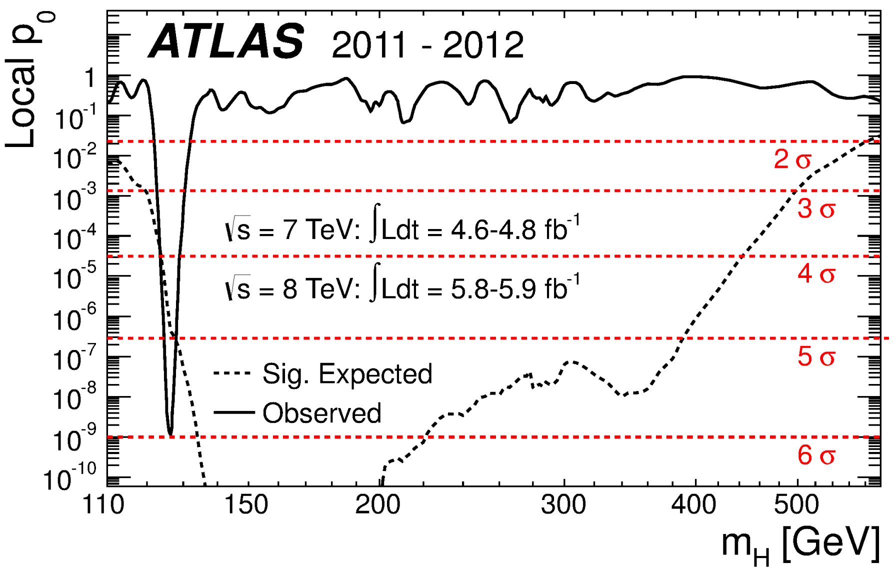


- Describes fundamental constituents
- Interactions:
  - Electromagnetic force
  - Strong force
  - Weak force

The Higgs boson in the SM

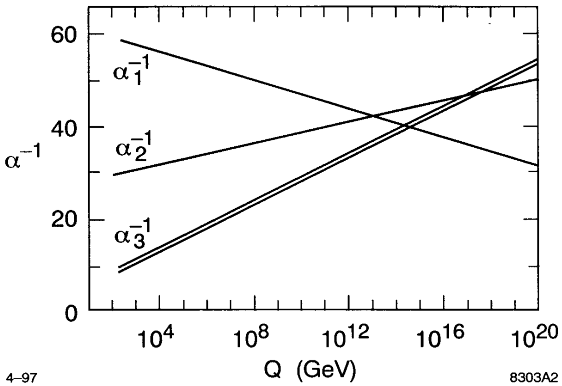
- The Higgs field couples to the particles of the Standard Model (SM) and gives them mass.
- The Higgs field gives rise to a spin-0 Higgs boson.
  - This last missing piece was discovered in 2012 by ATLAS and CMS.



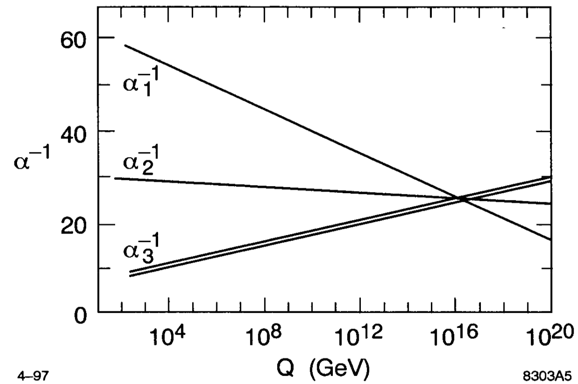


Why is the SM not enough?

- Examples of phenomena not explained by SM:
  - Dark matter and Dark energy
  - Matter anti-matter asymmetry
  - Grand Unification Theory
- Supersymmetry can help to solve some of these problems
  - Unification of the forces at high energy



SM



SUSY

  - At least double the particle spectrum
    - Dark matter candidate
  - At least two scalar Higgs doublets are needed
    - This gives 5 Higgs bosons: H^+, H^-, H^0, h^0, A^0

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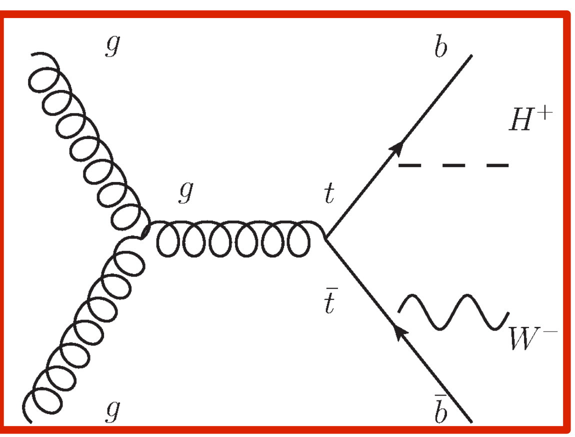
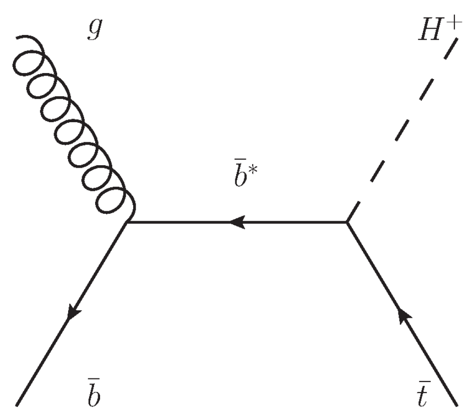
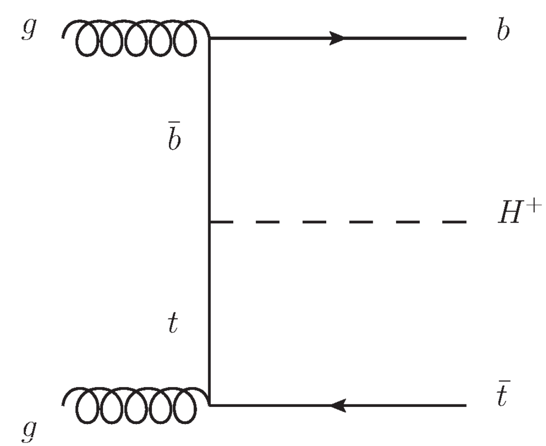
The charged Higgs boson

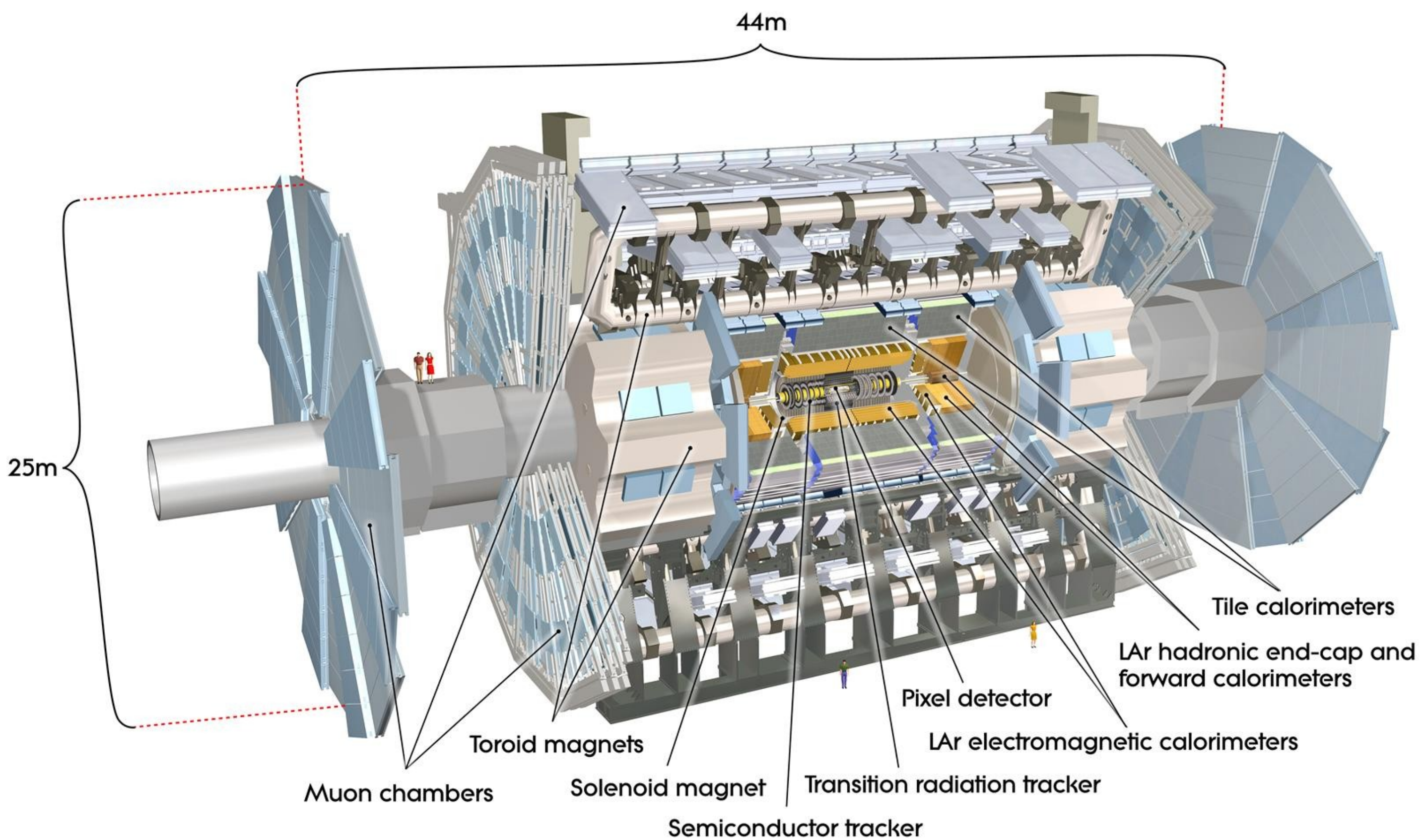
- Finding a charged Higgs boson would be a clear indication for BSM physics.
- Charged Higgs boson production
  - Charged Higgs bosons lighter than the top quark are dominantly produced via gluon-gluon fusion initiated top-pair production.
    - The top quark decays into a charged Higgs boson
    - The charged Higgs boson decays into a tau lepton and a neutrino
  - Charged Higgs boson heavier than the top quark mass:
    - Direct production via gluon-b fusion and gluon-gluon fusion







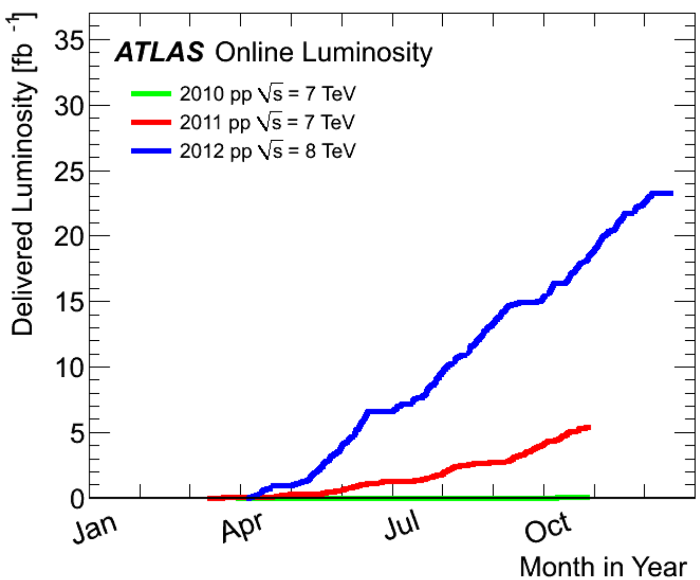
The ATLAS experiment

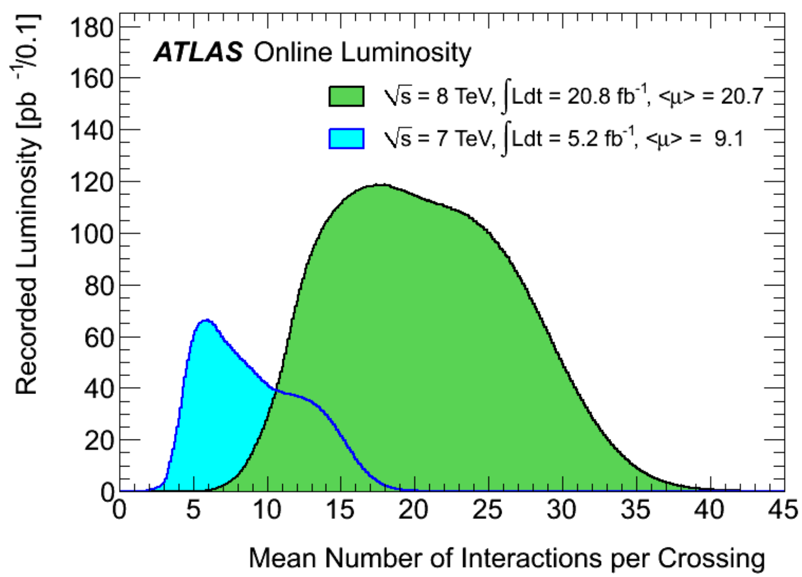


- Large collaboration (>3000 scientists)
- >15 years of research and development
- Designed to search for the Higgs bosons, BSM physics …
- All sub-detectors are used for physics analysis in this thesis.
- New technology is developed with application to improve the tracking detector system.

Data taking

- Increasing luminosity
  - Increasing number of interactions per crossing.
  - Triggers had isolation requirements in 2012.





Papers included in my thesis

- **Papers on charged Higgs boson physics:**
  - Search for charged Higgs bosons decaying via $H^+ \rightarrow \tau\upsilon$ in top quark pair events using pp collision data at √s = 7 TeV with the ATLAS detector, JHEP 1206 (2012) 039
  - Search for charged Higgs bosons through the violation of lepton universality in ttbar events using pp collision data at √s = 7 TeV with the ATLAS experiment, JHEP 03 (2013) 076
  - Estimation of non-prompt and fake lepton backgrounds in final states with top quarks produced in proton-proton collisions at √s = 8 TeV with the ATLAS detector, ATLAS-CONF-2014-058

- **Papers on development of novel technology for future particle detector systems:**
  - Wireless data transfer with mm-waves for future tracking detectors, 2014 JINST 9 C11008
  - Radial transfer of tracking data with wireless links, PoS(TIPP2014)095

Paper III – Estimation of fake leptons

- Methods for the estimation of non-prompt and fake leptons are presented:
  - Matrix Method
    - Method based on measurement of lepton identification efficiencies with relaxed identification criteria using data.
  - Fitting Method (jet-lepton model, anti-muon model)
    - Construction of templates for non-prompt and fake leptons.
- Full 2012 data set is used @ 8 TeV.
- These methods were used in many ATLAS analysis in top-quark related physics, but never studied in detail as in this paper.
  - ~330 pages of supporting document!

Paper III – Fake Leptons

- What are fake leptons?
  - Electron:
    - Semileptonic decay of b- and c-quarks
    - Decay in flight of $\pi^{\pm}$ or *K* mesons
    - Photon conversion
    - Jets with large electromagnetic energy π^{0}, or early showering.
  - Muon:
    - Semileptonic decay of b- and c-quarks.
    - Charged hadrons decaying in the tracking volume or hadronic showers.
    - Punch-through particles from high energy hadron showers.
- Why data driven methods?
  - Misidentification probability is small.

    → large amounts of events would need to be simulated
  - Modelling of lepton isolation in simulation is very difficult.
- Fake leptons are also called misidentified leptons.

Paper III – Matrix Method

- The Matrix Method exploits the difference in lepton identification between real, prompt, and fake or non-prompt electrons and muons.
- Number of loose leptons: $N^l = N^l_r + N^l_f$
- Number of tight leptons: $N^t = \varepsilon_r N^l_r + \varepsilon_f N^l_f$

$$\begin{pmatrix} N^l \\ N^t \end{pmatrix} = \begin{pmatrix} 1 & 1 \\ \varepsilon_r & \varepsilon_f \end{pmatrix} \begin{pmatrix} N^l_r \\ N^l_f \end{pmatrix}$$

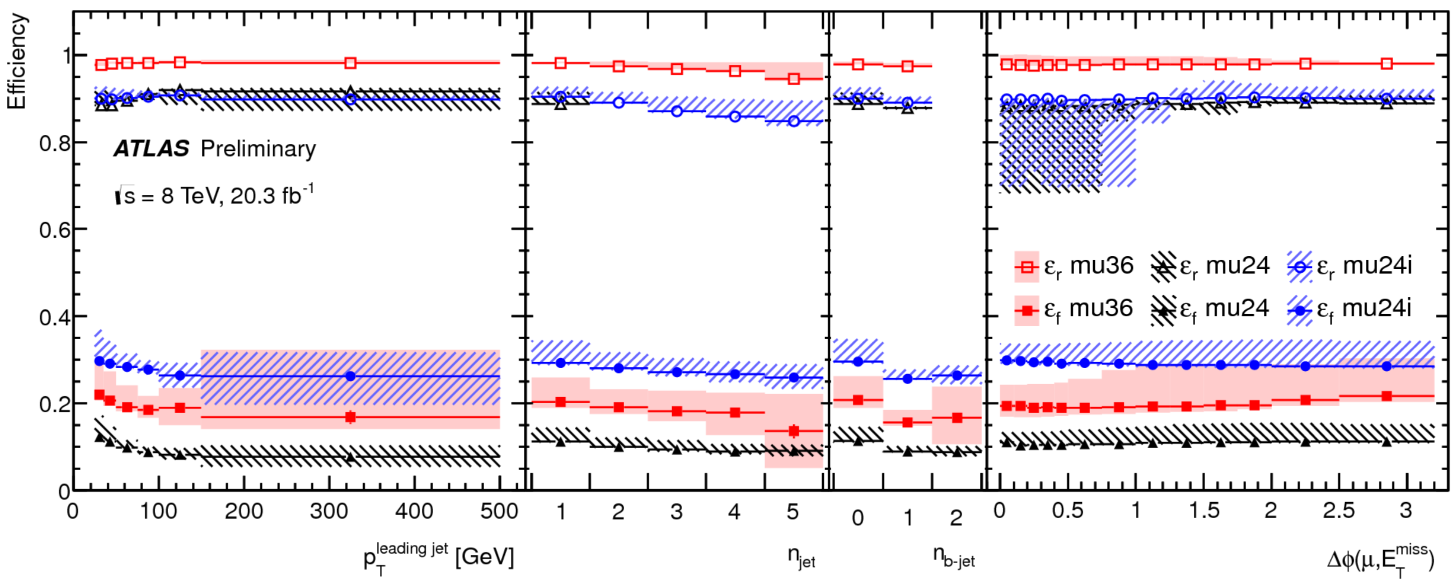
- ε_r: fraction of real leptons in the loose selection (relaxed isolation requirements) passing also the tight selection.
- ε_f: fraction of fake leptons in the loose selection passing also the tight selection.
- Tight selection is a subset of the loose selection.
- The number of fake leptons in the tight selection an be determined by:

$$N^t_f = \frac{\varepsilon_f}{\varepsilon_r - \varepsilon_f} \left(\varepsilon_r N^l - N^t \right)$$

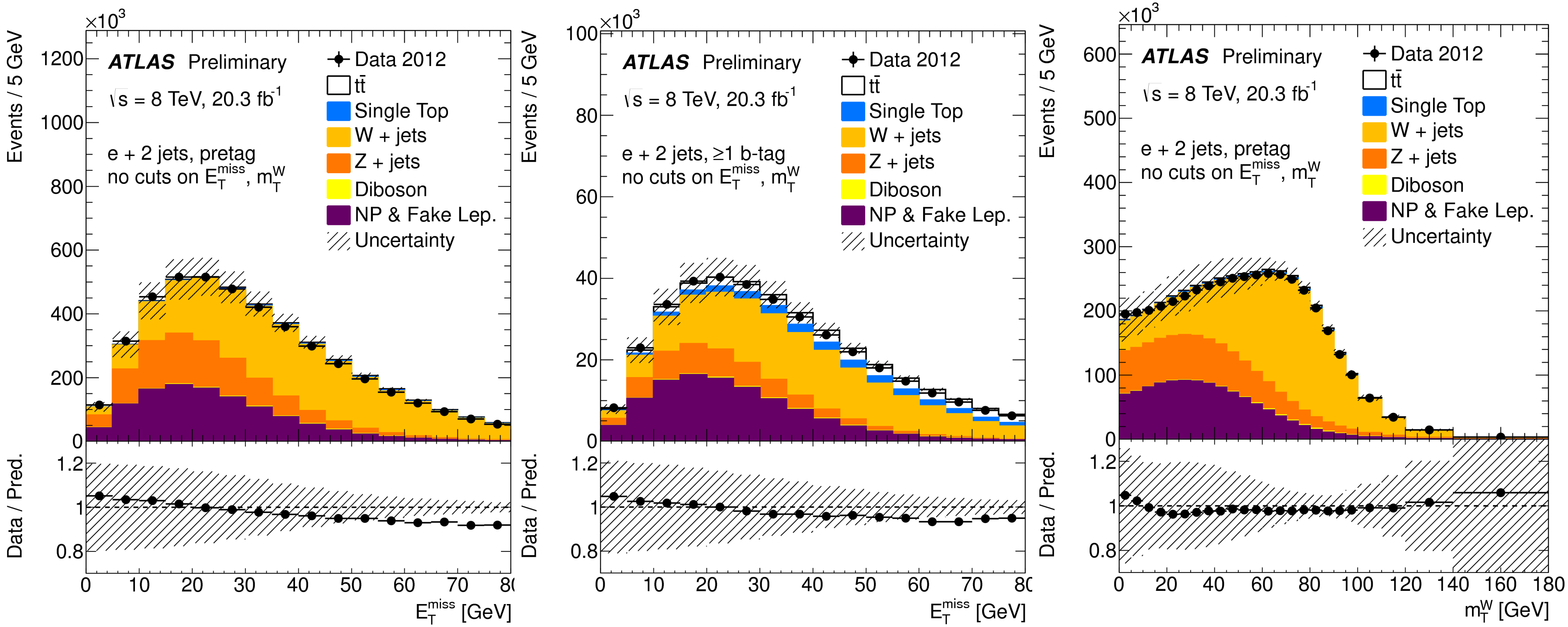
- The hard part is to determine the efficiencies ε_r and ε_f as function of different kinematic variables.

Paper III – Matrix Method

- Estimation of the real efficiency ε_r
  - Use a tag and probe method $Z \rightarrow ee$, $Z \rightarrow \mu\mu$
- Estimation of the fake efficiency ε_f
  - Electron: CR with $m_T^W < 20\,GeV \;\&\&\; m_T^W + E_T^{miss} < 60\,GeV$
  - Muon: muon impact parameter $|d_0^{sig}| > 5$
    - $|d_0^{sig}| = d_0 / \sqrt{err(d_0)}$
    - Transverse coordinate of a track at the point of closest approach to the primary vertex.
- Efficiencies are parametrized as function of different variables

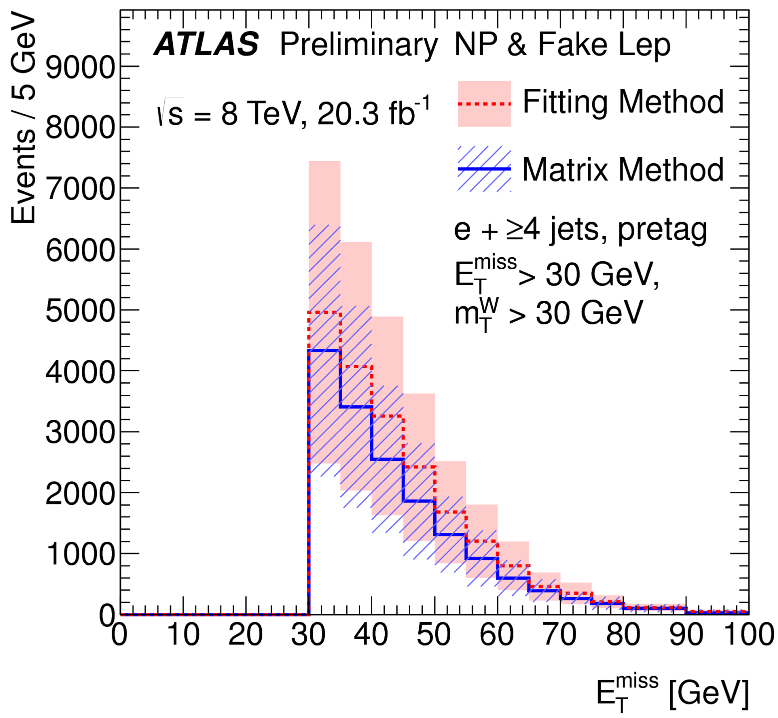


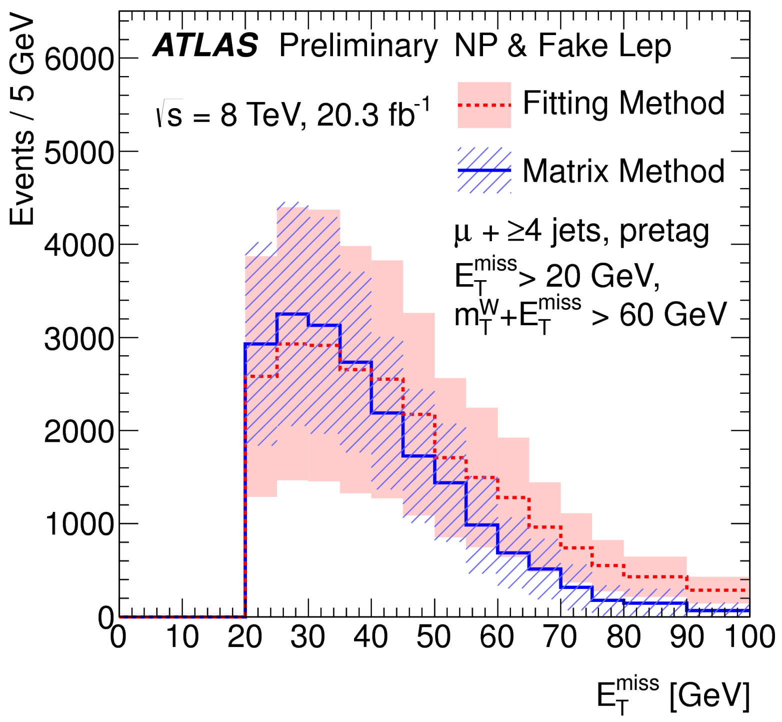
Paper III – Matrix Method



- The fake estimate is monitored throughout the whole cut flow.
- Good agreement between simulation + fake estimate and data.

Compare Matrix vs. Fitting Method

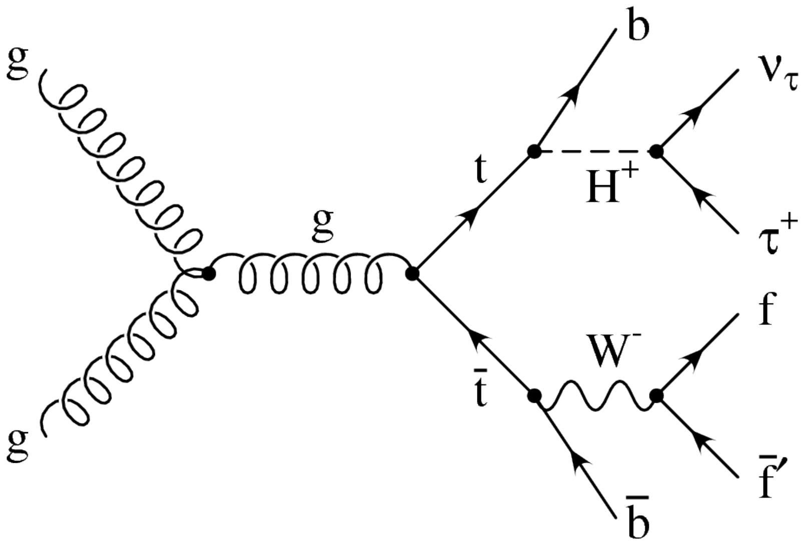




- Matrix Method and Fitting Method are in agreement within systematics.
  - Sys. MM: 10% - 50 %
  - Sys. FM: 50%

Paper I

- The full 2011 dataset with 4.6 fb^{-1} @ 7 TeV was analysed.
- Three different analysis channels were analysed in this paper:
  - Lepton + jets channel:
    - Jets from hadronically decaying W boson.
    - Lepton (el, mu) from $H^+ \rightarrow \tau\upsilon$ where the τ decays leptonically.
  - Tau + lepton channel:
    - Lepton (el, mu) from leptonically decaying W boson.
    - Hadronic tau from $H^+ \rightarrow \tau\upsilon$
  - Tau + jets channel:
    - Jets from hadronically decaying W boson.
    - Hadronic tau from $H^+ \rightarrow \tau\upsilon$



Paper I - Lepton + jets channel

- Selection:
  - One trigger matched lepton, veto on second lepton or tau.
  - >=4 jets, == 2 b-jets, Missing E_T.
- Hadronic decaying top side is found by minimising:

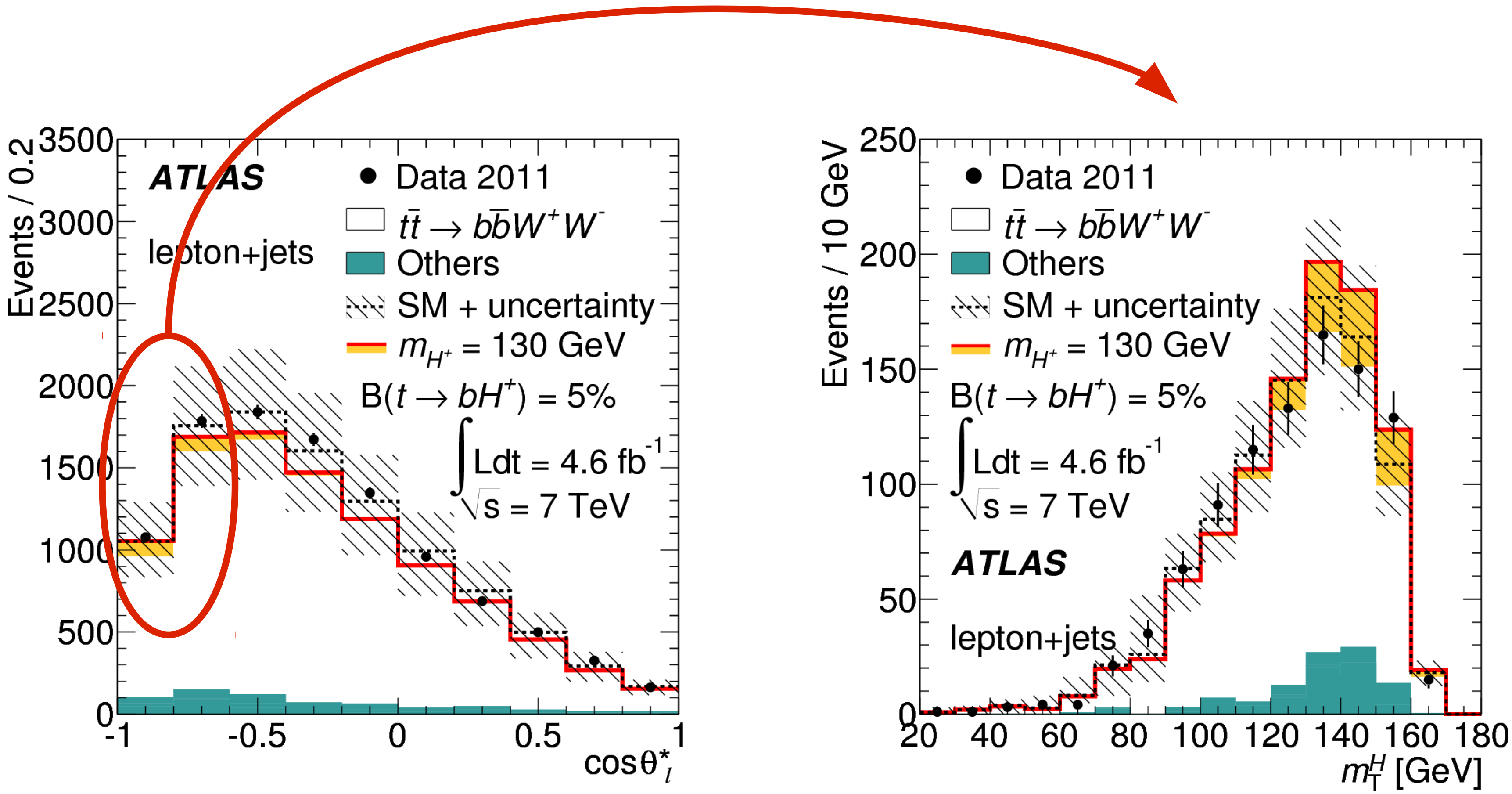
$$\chi^2 = \frac{\left(m_{jjb} - m_{top}\right)^2}{\sigma_{top}^2} + \frac{\left(m_{jj} - m_W\right)^2}{\sigma_W^2}$$

- Discriminating variable is used to separate background and signal:

$$\cos\theta_l^* = \frac{4\,\boldsymbol{p}^b \cdot \boldsymbol{p}^l}{m_{top}^2 - m_W^2} - 1$$

- Background estimation:
  - Misidentified lepton background estimated from data with the Matrix Method.
  - Other backgrounds are taken from simulation.

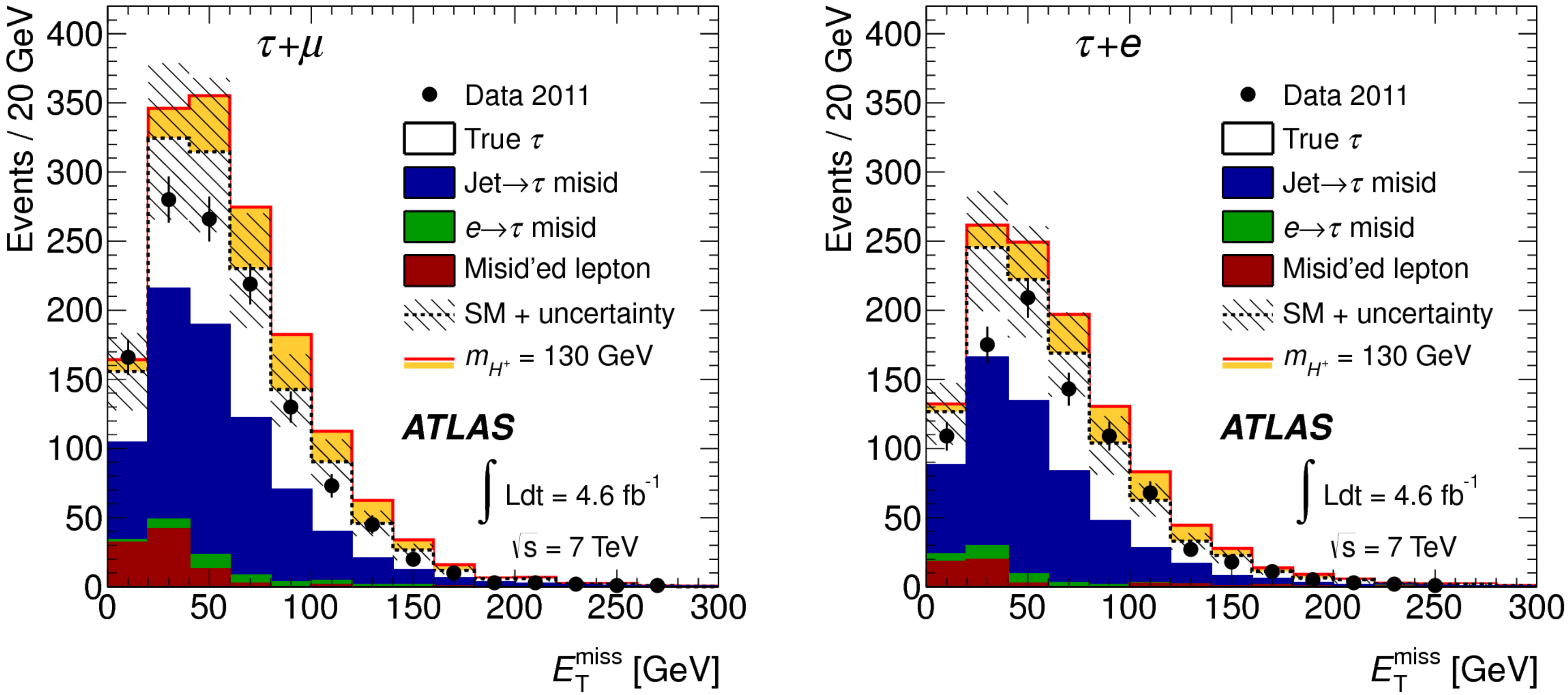
Paper I - Lepton + jets channel



Paper I - Tau + lepton channel

- Selection:
  - One trigger matched lepton, veto on second lepton
  - One tau with opposite charge to the lepton
  - >=2 jets, >= 1 b-jets,
  - Requirement on Σp_T
- Missing E_T is used as discriminating variable
- Estimation of backgrounds:
  - Misidentified lepton background estimated from data with the Matrix Method.
  - Electrons misidentified as taus: reweighting simulation by data driven scale factors.
  - Jets misidentified as taus: reweighting simulation by data driven scale factors.
  - Background with true taus is taken from MC.

Paper I - Tau + lepton channel



- $Br(t \rightarrow bH^+)=5\%$

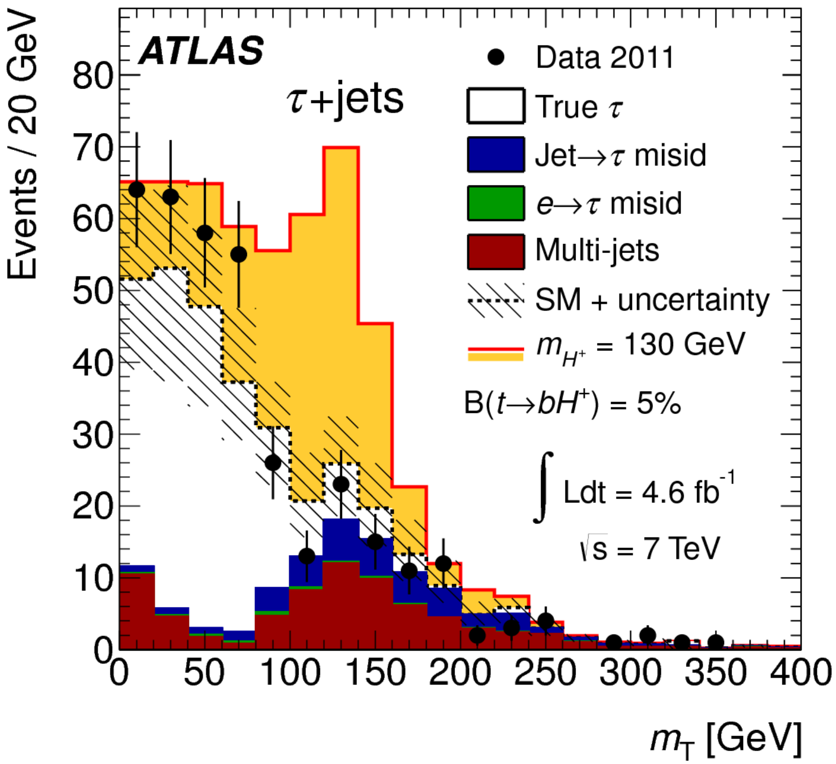
Paper I - Tau + jets channel

- Selection:
  - τ + missing E_T trigger
  - >=4 jets, >=1 bjet,
  - == one trigger matched τ, veto events with el and mu
  - Missing E_T requirement
- Discriminating variable is m_T

$$m_T = \sqrt{p_T^{\tau} E_T^{miss} \left(1 - \cos \varphi_{\tau, miss}\right)}$$

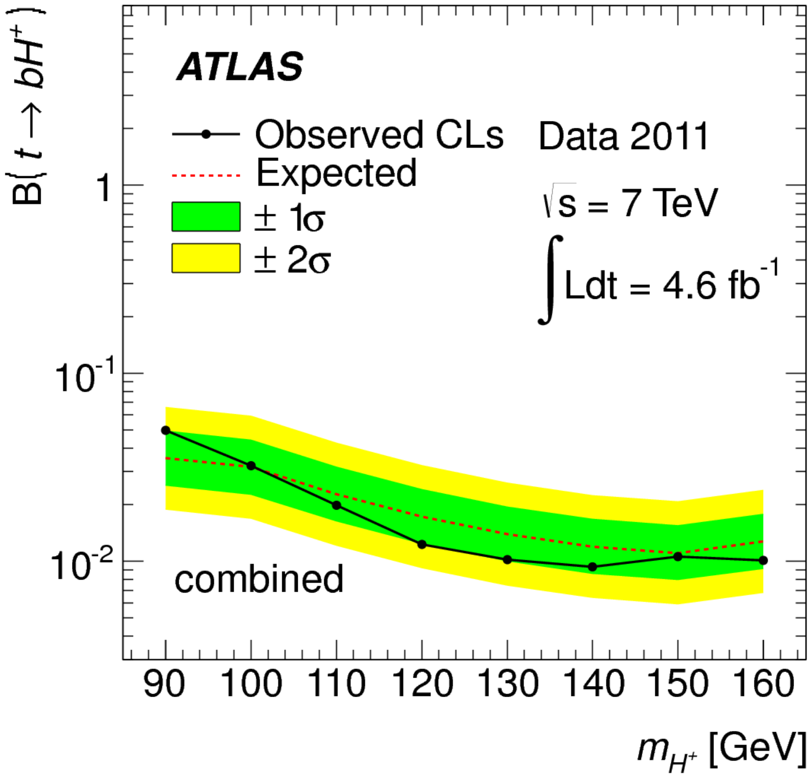
- Estimation of backgrounds:
  - Multijet background estimated from data with template method.
  - Electrons misidentified as taus: reweighting simulation by data driven scale factors.
  - Jets misidentified as taus: reweighting simulation by data driven scale factors.
  - Background with true taus, estimated by data driven embedding method.

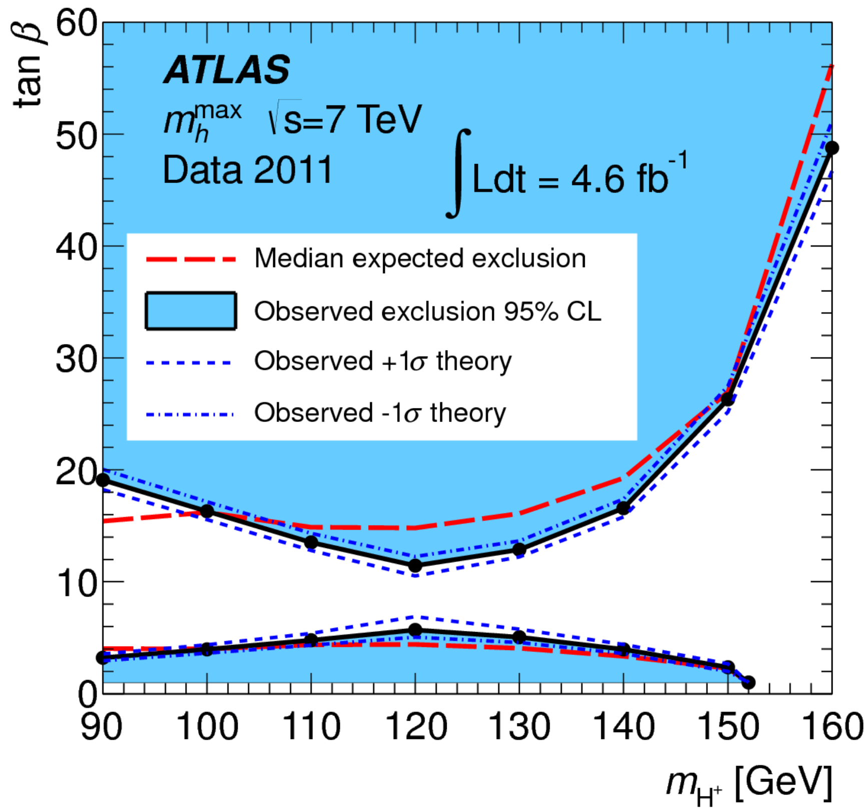
Paper I - Tau + jets channel



- It can be seen that this channel is most sensitive and has the highest discriminating power.

Combined Limits



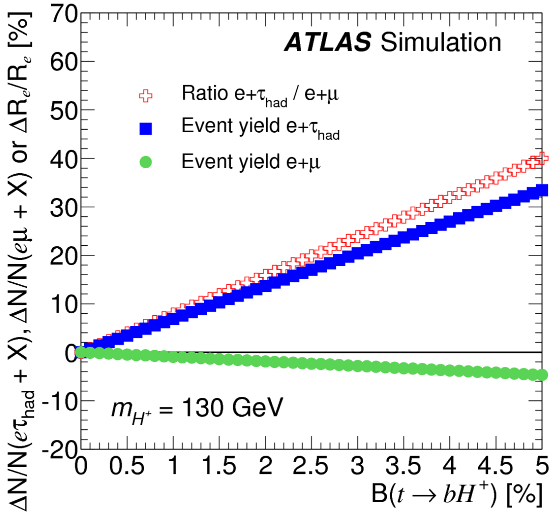


- Limits on the BR(t → bH+) in the range 5% - 1%.
- Limits on the m_H^{max} scenario.
  - Benchmark scenario in the MSSM (Minimal SuperSymmetric Model)
- tan(β) is the ratio of the vacuum expectation values.

Paper II – Ratio Method

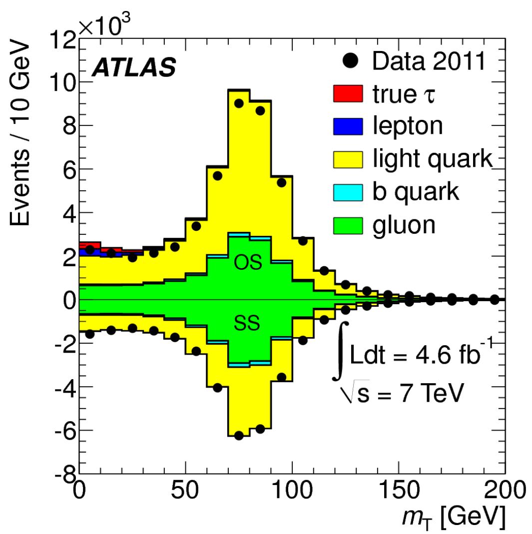
- The full 2011 dataset with 4.6 fb^{-1} @ 7 TeV was re-analysed in the tau+lepton channel.
- Event yield ratios between $e+\tau_{had}$ and $e+\mu$, as well as $\mu+\tau_{had}$ and $\mu+e$ are compared with simulation.
  - The big advantage is that most systematic uncertainties cancel.

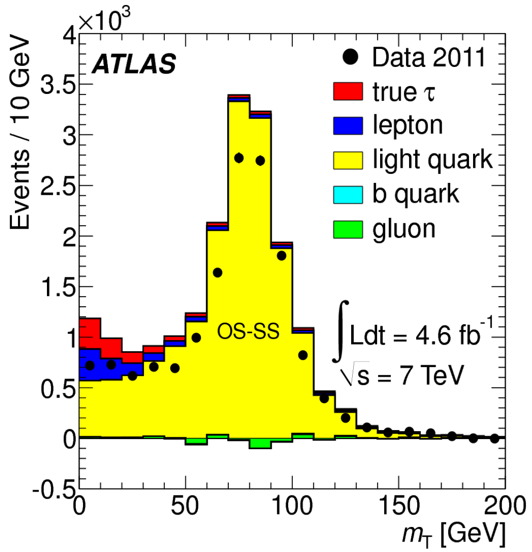
$$R_l = \frac{B\left(t\bar{t} \rightarrow b\bar{b} + l\,\tau_{had} + N\nu\right)}{B\left(t\bar{t} \rightarrow b\bar{b} + l\,l' + N\nu\right)}$$



Paper II – Ratio Method

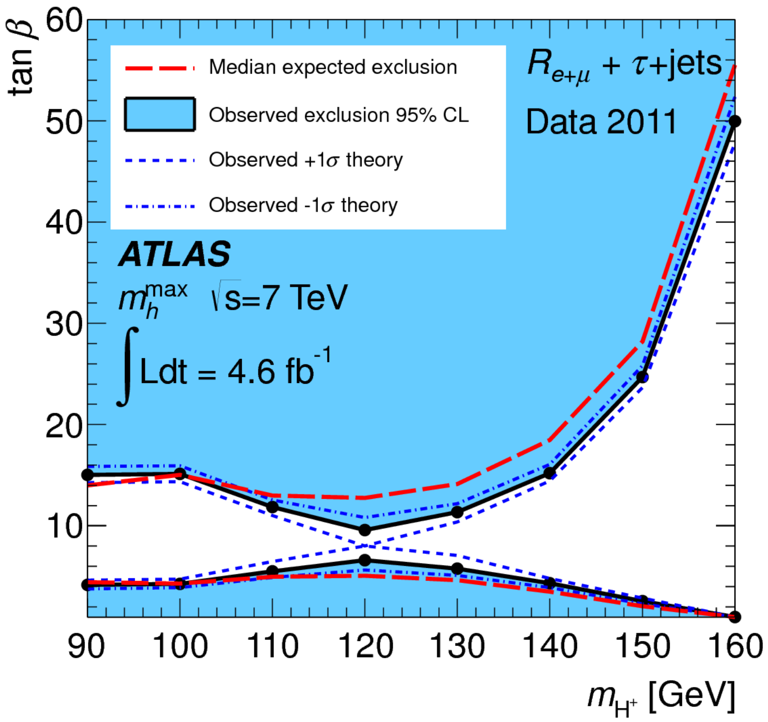
- Background estimation
  - Misidentified electrons and muons: data driven Matrix Method
  - Backgrounds due to misidentified τ jets:
    - OS-SS to remove heavy-flavour quark and gluon fakes.
    - Re-weight simulation by scale factors to account for measured tau track multiplicities.
    - Re-weight simulation to account for measured (OS-SS) light-quark jet$\rightarrow\tau_{had}$ misidentification probabilities.

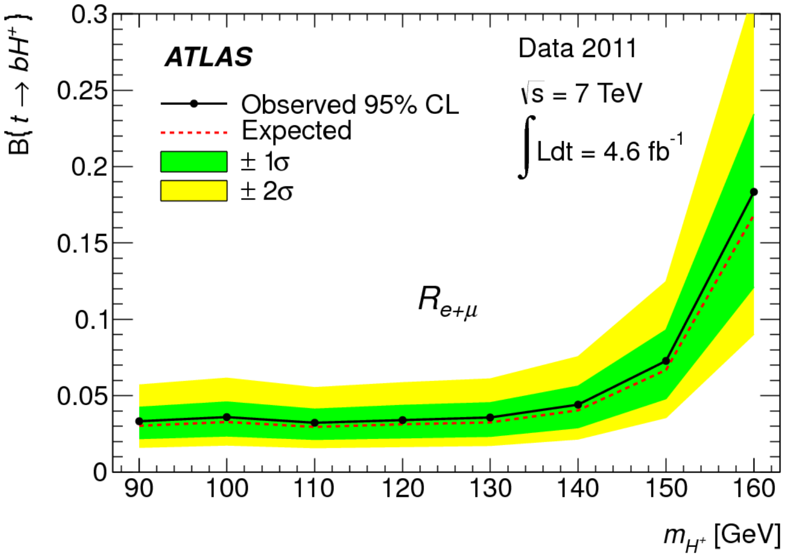


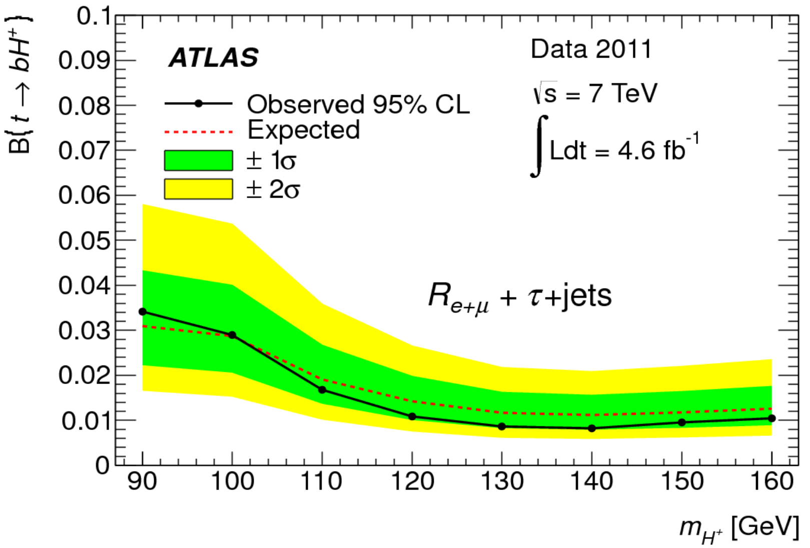


Paper II – Ratio Method

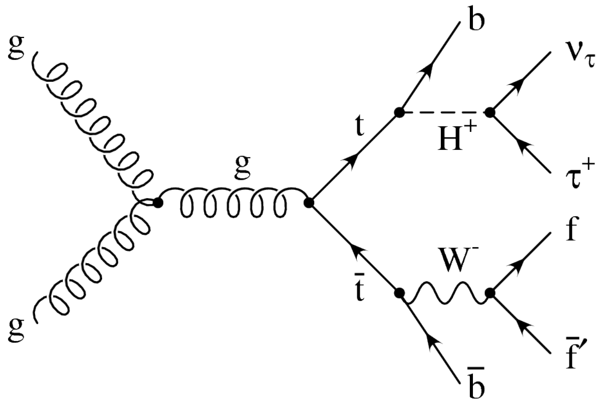
- Improved limits compared to the previous paper 3.4 % - 0.8% in the mass range 90-160 GeV.



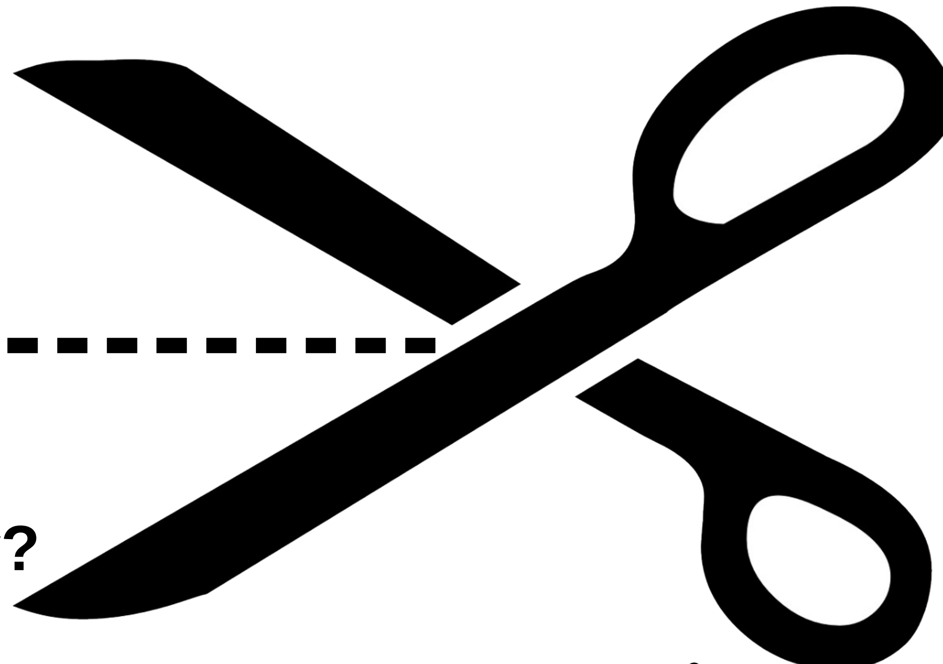




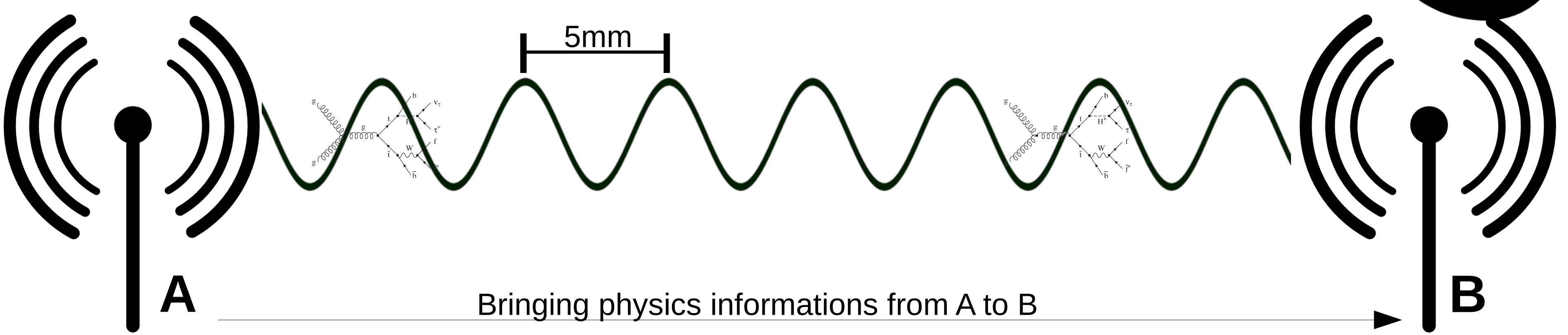
Change of Topic



Charged Higgs Physics



What do we need, to continue doing physics with higher energies and higher luminosity?

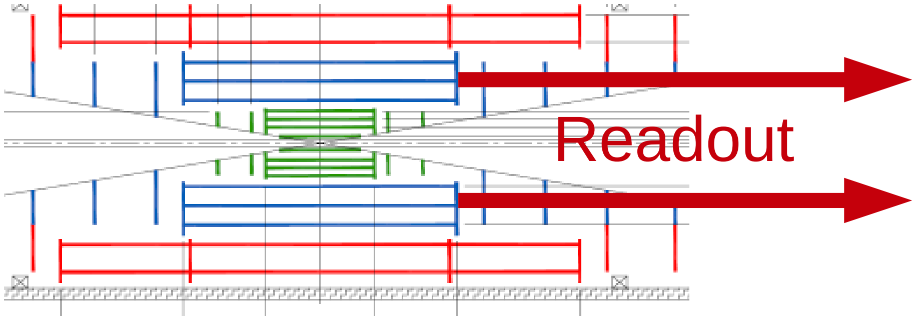


Motivation

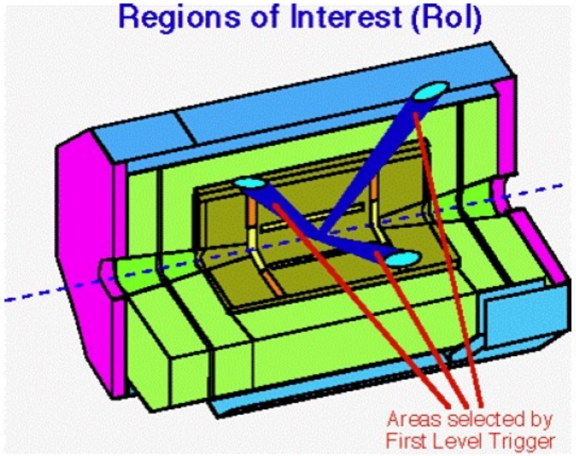
- HL-LHC will deliver 250 fb^{-1} per year.
  - Compared to a total 300 fb^{-1} until 2022 with LHC.
  - ~140 number of interactions per bunch crossing (compared to ~30 in 2012) → large particle fluxes.
  - Higher granularity is needed.
  - Low p_T thresholds (~20 GeV) are needed for physics analysis.
    - At the same time low trigger rates are required in order to read out the detector.
    - A track trigger could help to solve this problem.
    - A lot of communication inside the detector is needed.
      → Increase of material
- Future detector systems would like to read out the whole detector during high interaction rates, with only little or no pre-selection.

Wireless technology can help

- The current readout is not optimal for communication inside the detector.



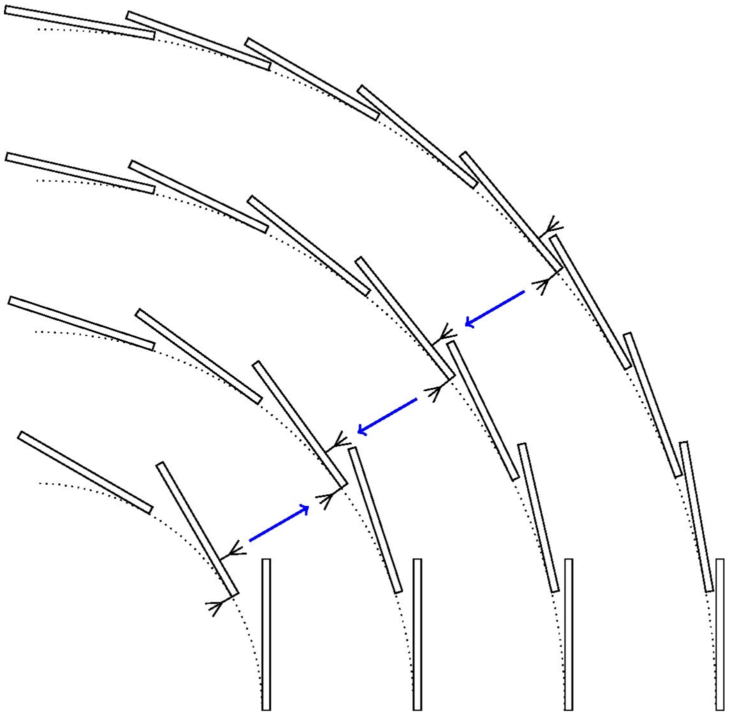
Axial detector readout resulting in long paths, long latency etc.

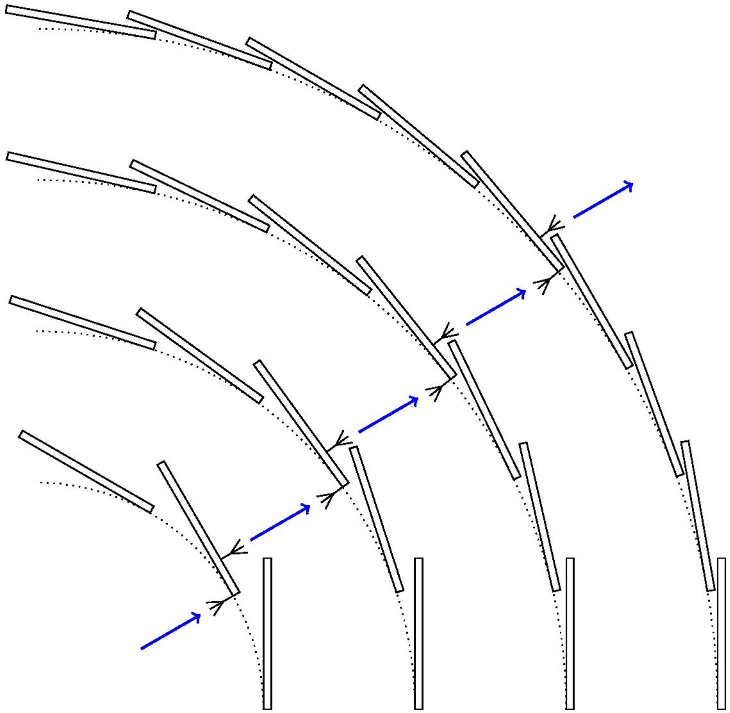


Physics events are triggered in RoI that are conical regions radial from the interaction point in Φ and η.

- **How can wireless technology help to solve the problem?**
  - Radial data transfer gets possible.
    - No cables and connectors needed for data transfer.
  - Up to 7 GHz unlicensed frequency spectrum @ 60 GHz.
  - Small and low mass components (mm-waves).
  - Low power and cost.

Scenarios

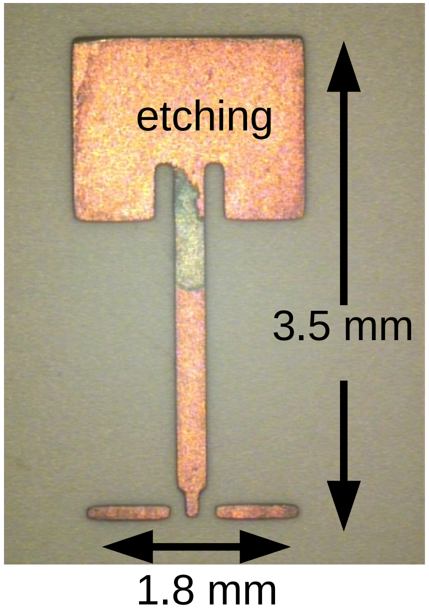




- Inter layer communication
- Radial data readout

Paper IV - Antenna design

- We have started to design and produce patch antennas.
  - Single and antenna arrays.
  - Can be produced on PCB material.
    - Etching and milling.
    - Rogers, DuPont PCB material
  - Very small structure sizes.



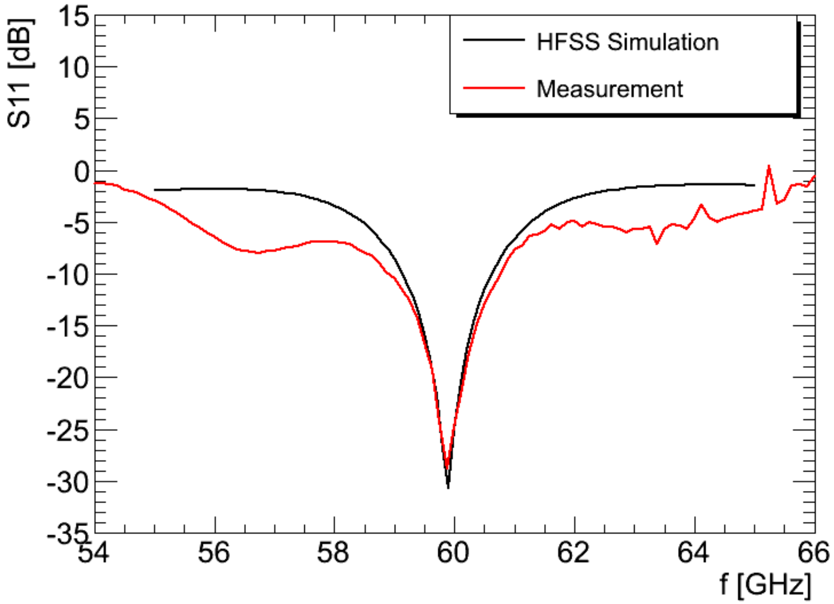
S-parameters

- **S-parameters**:
  - Describe the input-output relationship between ports in an electrical system.
  - Ex.:, 2 ports (Port 1 and Port 2), then S12 represents the power transferred from Port 2 to Port 1.
  - Having a transmitter with an antenna connected:
    - S11 is the reflected power Port 1 is trying to deliver to antenna 1.
    - 0dB all power is reflected
    - - 30dB and below almost no power is reflected

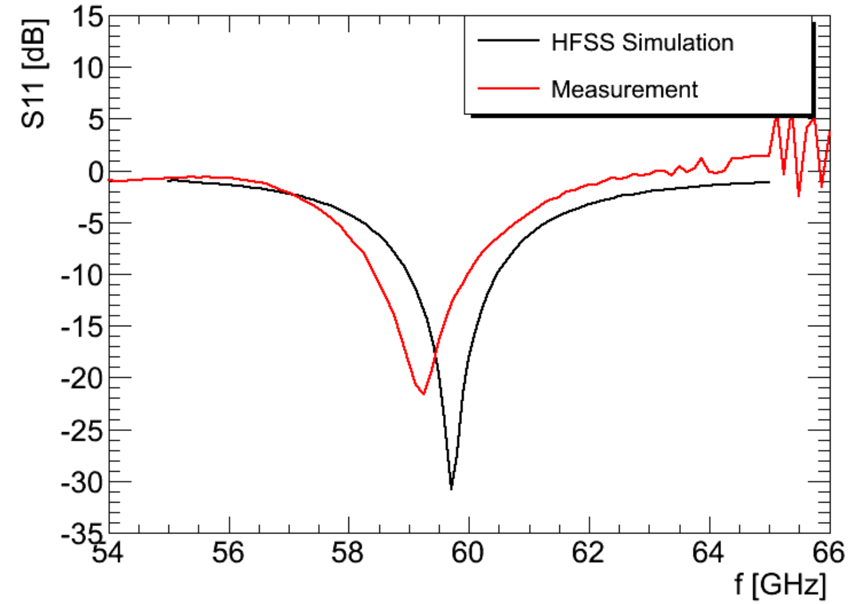
      → good matching
  - Frequency depending variable.

Paper IV - Results

- Compare simulation with a manufactured antenna.
  - This gives feedback how good simulation matches reality.
  - Etched antennas were used (PCB etching process).
    - 4 Patch antenna array: very good agreement with simulation.
    - 1 Patch antenna: a shift of ~500MHz.
      - This is good result and shows that antenna production is feasible.

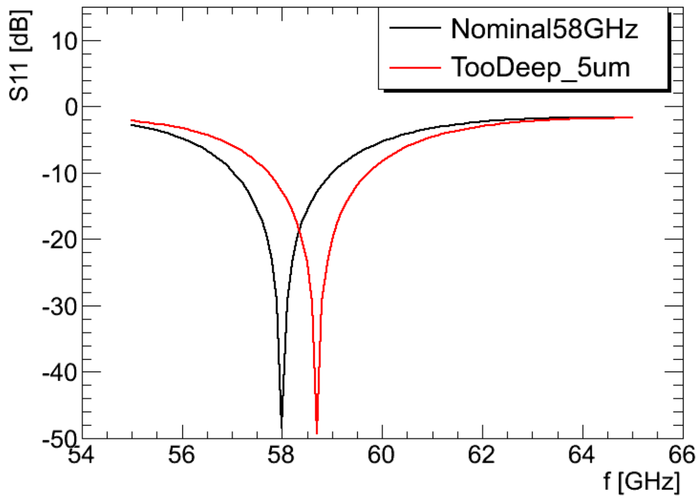


4 Patch array design

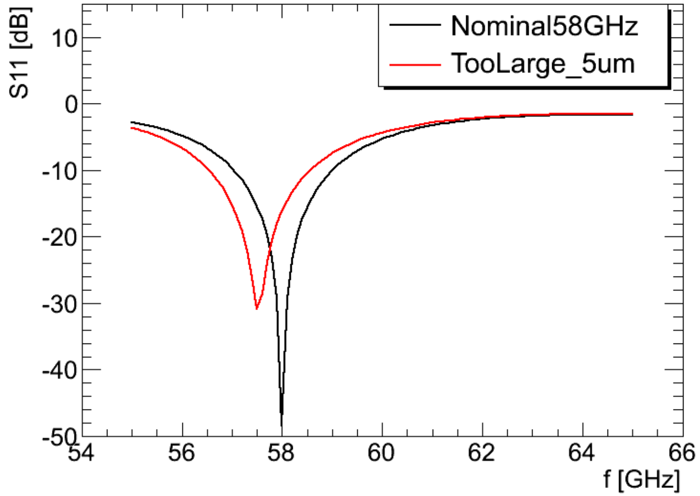


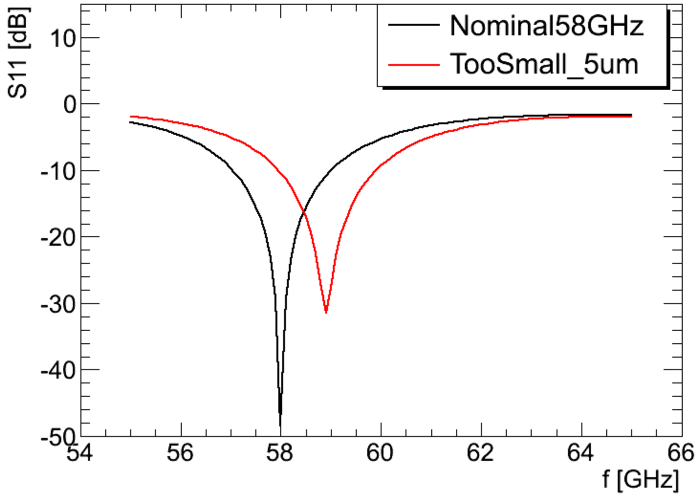
single patch design

Paper IV - fabrication precision



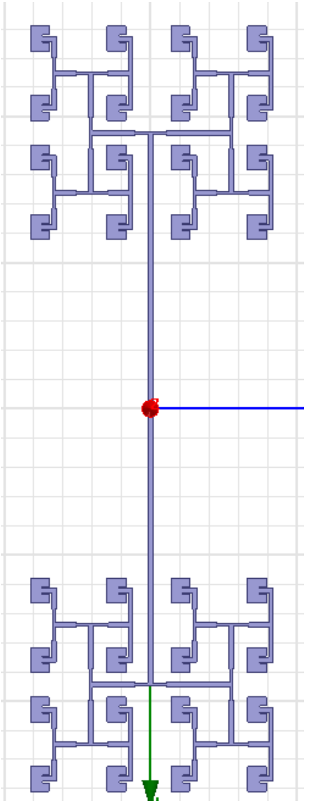
- The effect of fabrication tolerances were studied:
  - Mill too deep through the cooper (remove substrate)
    - → frequency shift to higher f
  - Antenna outer edges 5 µm too large
    - → frequency shift to lower f
  - Antenna outer edges 5 µm too small
    - → frequency shift to high f
- → Tolerances as small as 5µm can cause shift of ~1GHz!

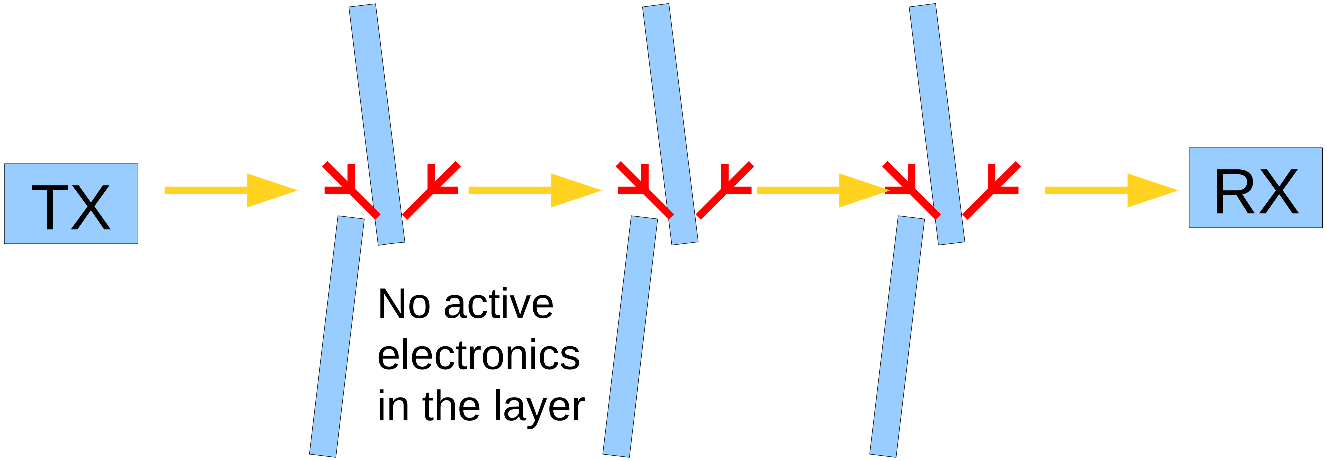




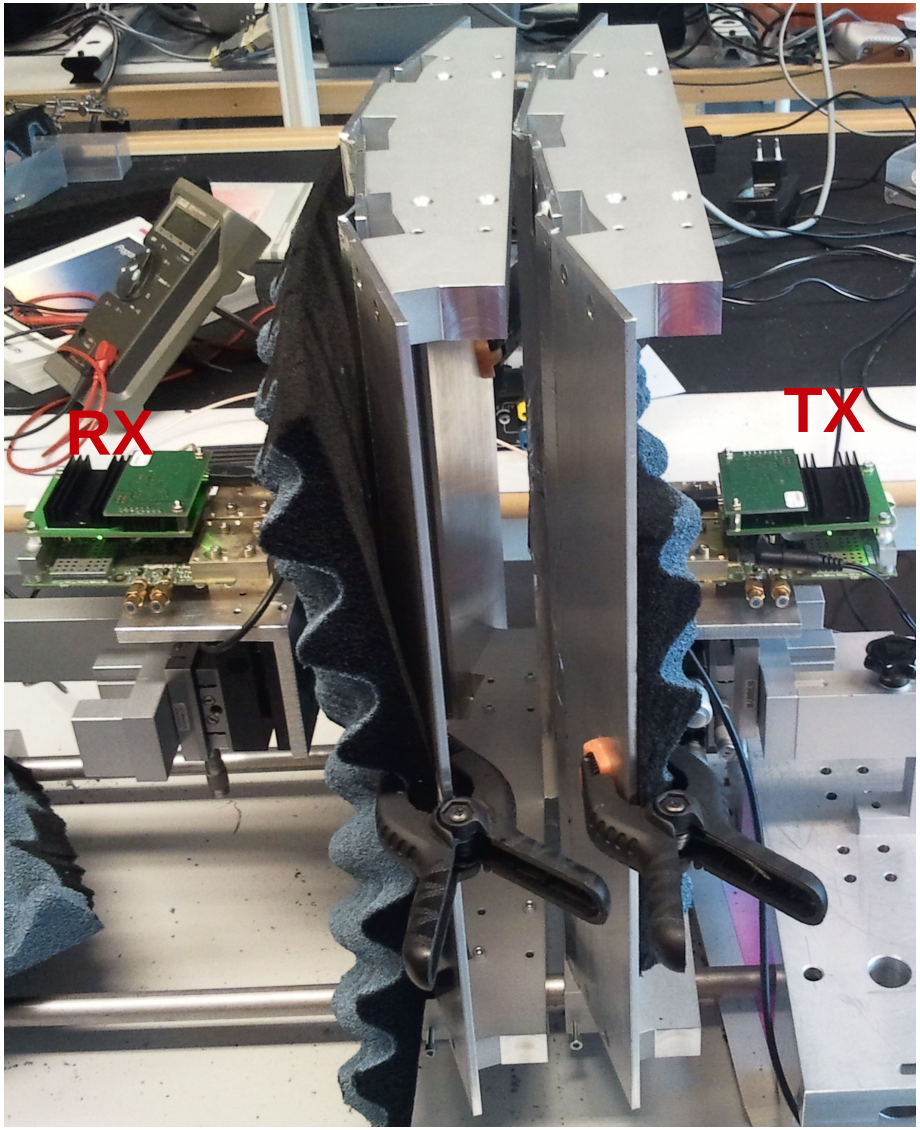
Paper V - Passive data transfer

- The amount of electronics could be reduced significantly if one could radiate through detector layers.
  - No active hardware would be needed as a repeater.
  - The links are spread out uniformly around the detector and do not have to be routed to the extremely dense gap.
- Simple approach:
  - One receiver antenna on one side and a transmitter antenna on the other side.
  - Antennas are connected by a micro strip, no active electronics.

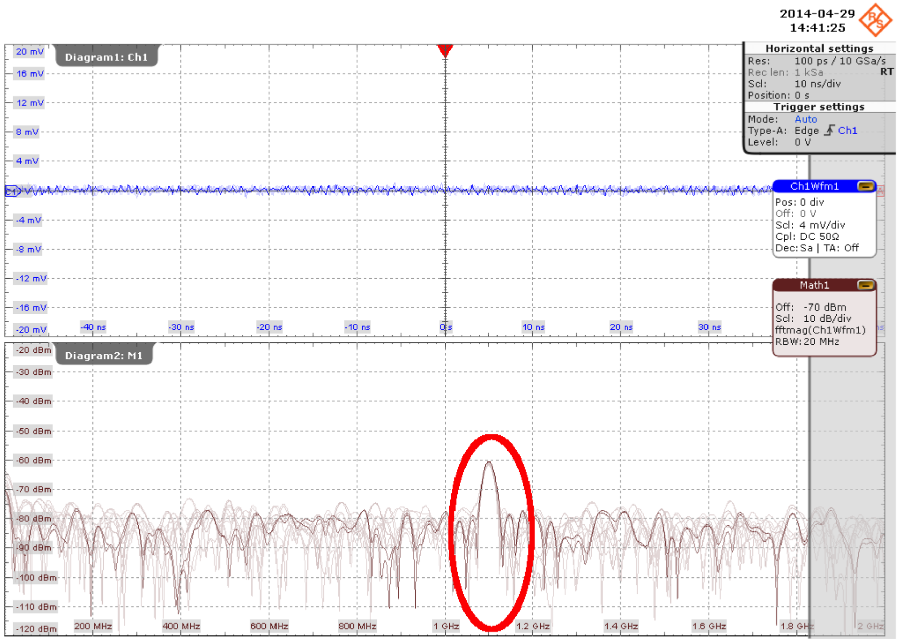




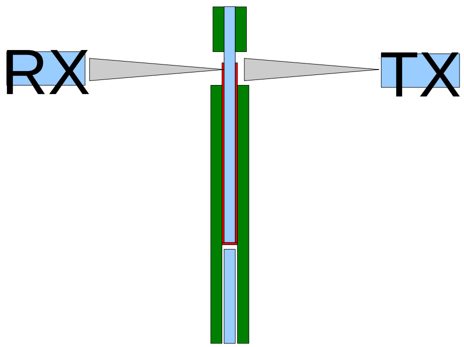
Paper V – Through Layer

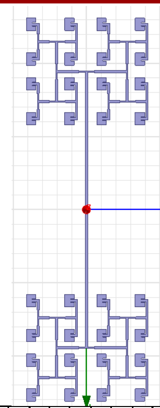


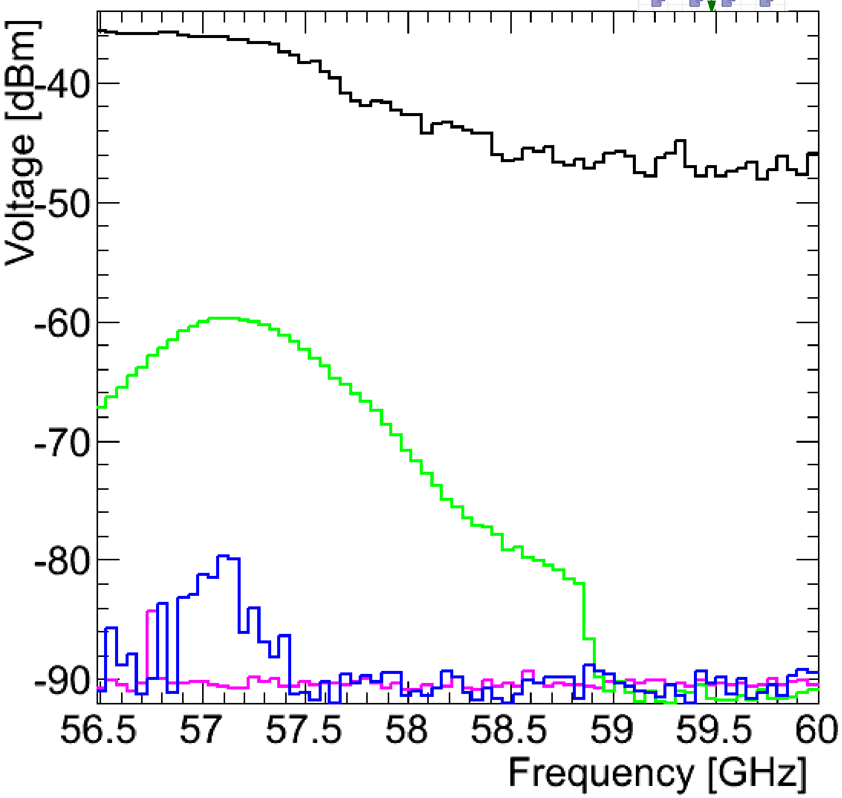
- Aluminium mock-up with small gap to bring though the antenna.
  - Gap is closed by metal tape.
- **We are coming trough two layers with just the passive antennas.**



Paper V - Power loss in the layers

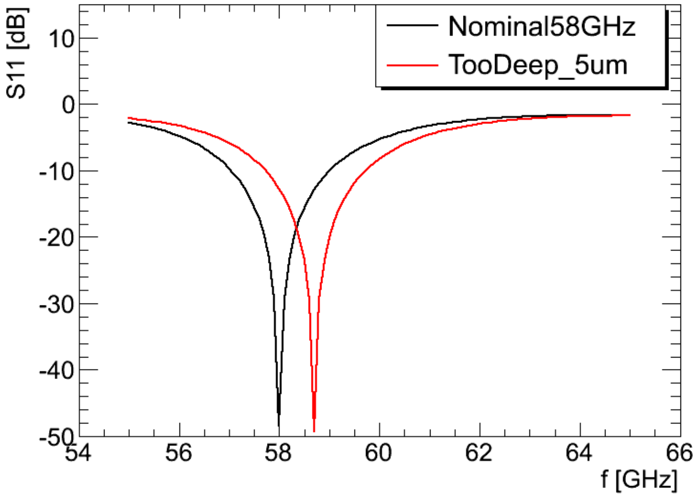




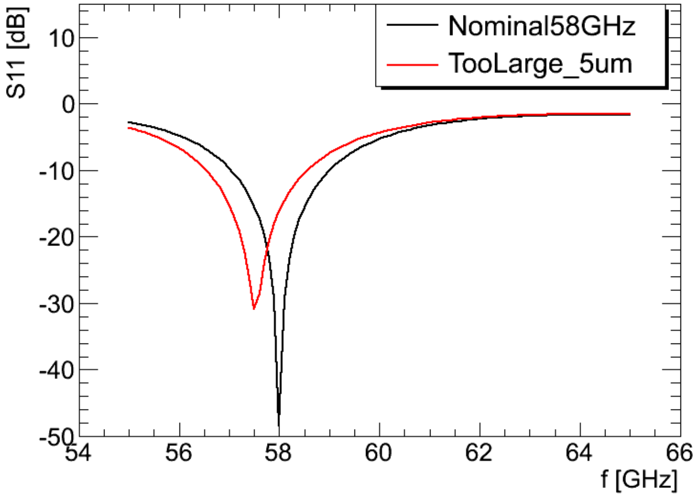


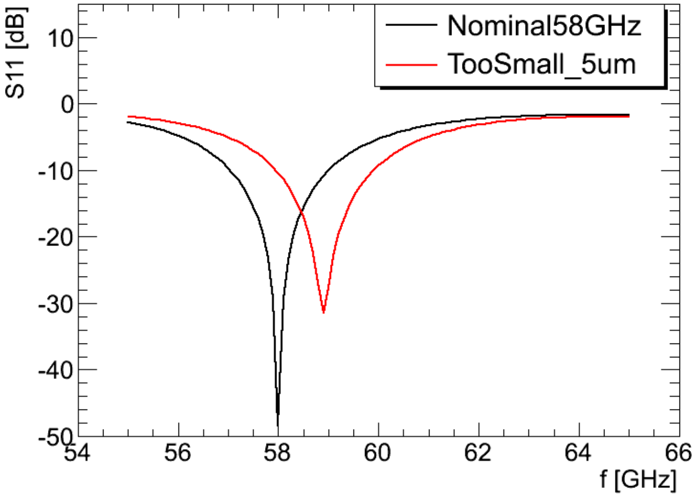
- Frequency dependence of the antenna can be observed.
- 16 Patch – 16 Patch antenna were used.
- **Power estimate:**
  - Horn to Horn 12 cm distance: ~ -40 dBm @ 57.2GHz
  - Single antenna : ~ -60dBm
  - Two antennas : ~ -80dBm
  - Background
  - We have ~20dB insertion loss per detector layer.
  - The test was performed with 0.001 W output power.
    - +10 dB gain on RX side

Paper IV - fabrication precision



- The effect of fabrication tolerances were studied:
  - Mill too deep through the cooper (remove substrate)
    - → frequency shift to higher f
  - Antenna outer edges 5 µm too large
    - → frequency shift to lower f
  - Antenna outer edges 5 µm too small
    - → frequency shift to high f
- → Tolerances as small as 5µm can cause shift of ~1GHz!





Conclusion

- Charged Higgs boson:
  - This thesis presents all charged Higgs boson searches with leptons involved, published by ATLAS (Paper I – II).
  - A detailed evaluation of the Matrix Method with the full 2012 data set was presented (Paper III).
    - Important for the estimation of fake lepton backgrounds in charged Higgs boson searches.
- Novel technology for future detectors:
  - The design and different production method of single- and array patch antennas were studied and demonstrated (Paper IV).
  - A passive repeater structure was fabricated and demonstrated to work (Paper V).

Backup

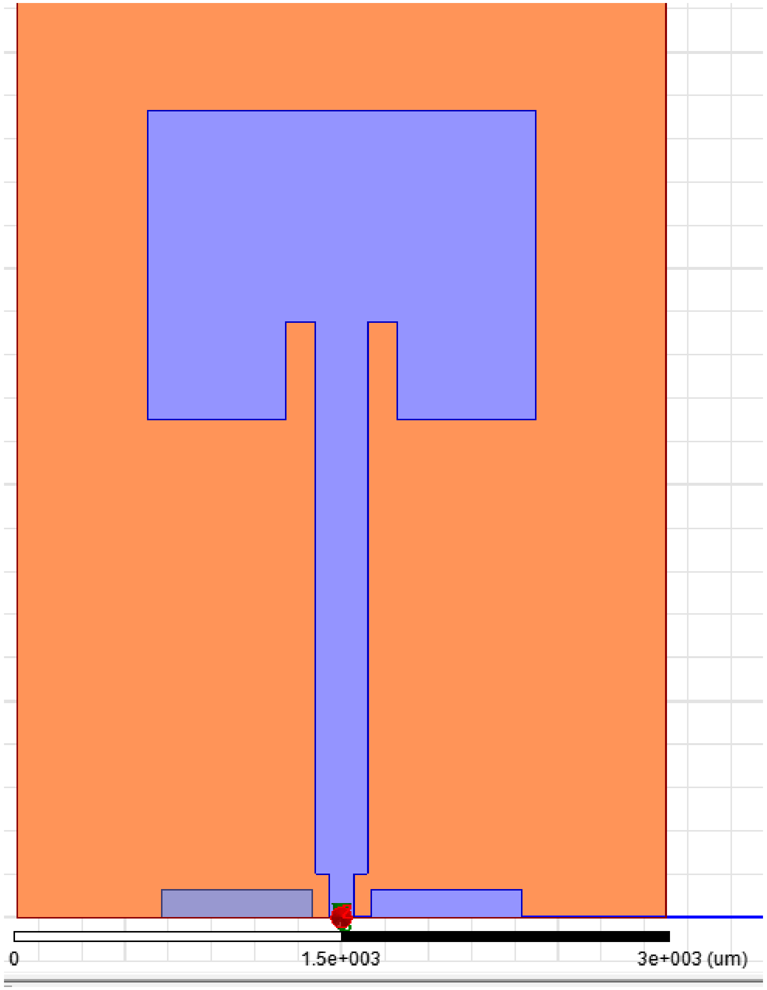
- Backup

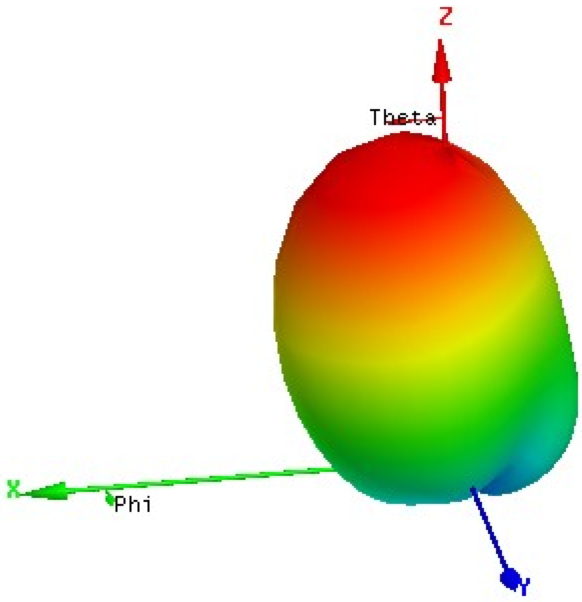
The Fitting Method

- Based on the construction of templates of non-prompt and fake leptons
  - Jet-lepton model
    - Model build from simulated di-jet events
    - Require one jet to be electron like
  - Anti-muon model
    - Data driven template, enriched in non-prompt muons
    - Inverted muon requirements
  - Same cuts are applied on these models as in base selection
  - The template is fitted to the observed data in order to get the normalization
    - Missing E_T and m_T as variables

Antenna design - simulation

- Single patch



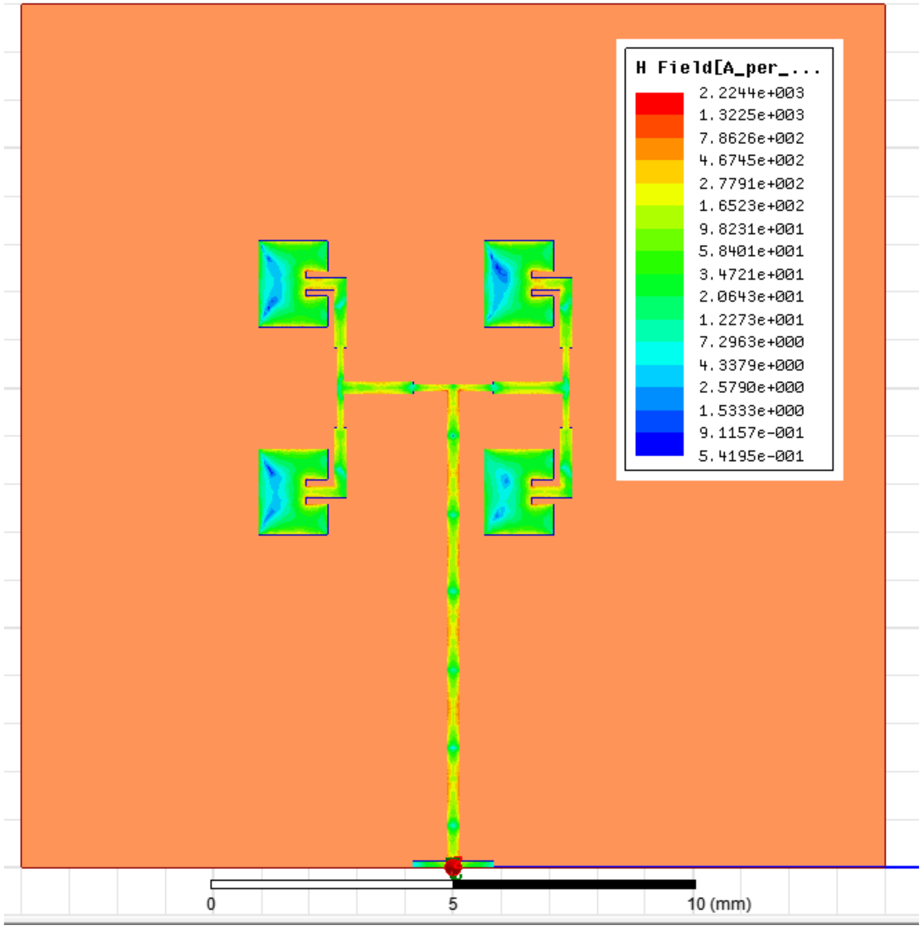


S-parameters

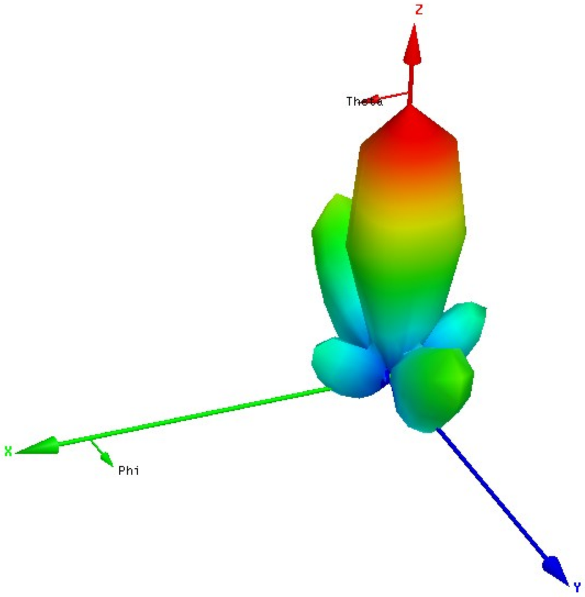
- **S-parameters**:
  - Describe the input-output relationship between ports in an electrical system.
  - Ex.:, 2 ports (Port 1 and Port 2), then S12 represents the power transferred from Port 2 to Port 1.
  - Having a transmitter with an antenna connected:
    - S11 is the reflected power Port 1 is trying to deliver to antenna 1.
    - 0dB all power is reflected
    - - 30dB and below almost no power is reflected

      → good matching
  - Frequency depending variable.

Antenna design - simulation



- Designs for multi patch antennas.
  - 4 Patch design.
  - Higher gain and focus.



Passive data transfer through layers