ATLAS measurements of the Higgs boson decay to a pair of τ leptons

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Standard Model (I)

- Particle interactions: electromagnetic, weak and strong
- Mass constituents – fermions: quarks and leptons
- Force carriers – bosons: photon, gluon, W and Z bosons

The structure of the Standard Model (I)

Fundamental principle: Local gauge invariance

Quantum Electrodynamics (QED) – U(1)

- Free Dirac equation: $i\gamma^{\mu}\partial_{\mu}\psi - m\psi = 0$
- Lagrangian formalism: $L = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi$
- Local gauge transformation: $\psi(x) \rightarrow e^{i\omega(x)}\psi(x)$
- term $\partial_{\mu}\omega(x)$ breaks invariance of L
  $\partial_{\mu}\psi(x) \rightarrow e^{i\omega(x)}\partial_{\mu}\psi(x) + ie^{i\omega(x)}\psi(x)\partial_{\mu}\omega(x)$
- Invariance of L under local gauge transformations can be accomplished by itroducing a gauge field A_{μ}, which transforms as $A_{\mu}(x) \rightarrow A_{\mu}(x) + \frac{1}{e}\partial_{\mu}\omega(x)$
- Can be formally achieved by the construction of a "modified" derivative
  $\partial_{\mu} \rightarrow D_{\mu} = \partial_{\mu} - ieA_{\mu}$ (covariant derivative)

The structure of the Standard Model (II)

- Lagrangian of QED:
  $L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi + e\bar{\psi}\gamma^{\mu}\psi A_{\mu} \rightarrow$
  $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m\bar{\psi}\psi - \bar{\psi}\gamma^{\mu}\psi\partial_{\mu}\omega + e\bar{\psi}\gamma^{\mu}\psi A_{\mu} + \bar{\psi}\gamma^{\mu}\psi\partial_{\mu}\omega$
  where $F_{\mu\nu}$ is the usual field strength tensor: $F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$

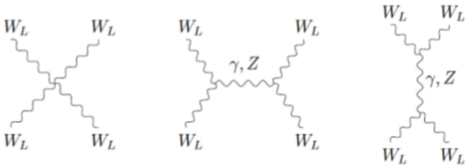
Note:

- Interacting term necessary for gauge invariance
- A mass term ($\frac{1}{2}m^2A_{\mu}A^{\mu}$) for the gauge field A_{μ} would violate gauge invariance

Problems at that stage

Similarly, weak and electromagnetic interactions are described by theory with the symmetry group $SU(2) \times U(1)$

- Such theory results into massless gauge bosons, but we know that W and Z posses some mass
- Divergences in the theory (scattering of W bosons)

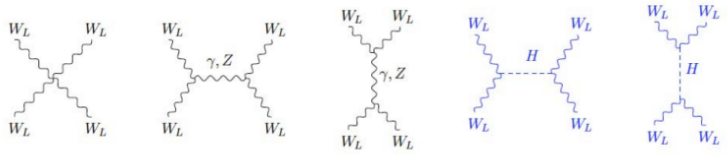


$-iM(W^+W^- \to W^+W^-) \sim \frac{s}{M_W^2}$ for $s \to \infty$

Higgs mechanism (I)

Solution to both problems:

- Create mass via spontaneous breaking of electroweak symmetry
- Introduce a scalar particle that regulates the WW scattering amplitude
    - Higgs boson guarantees unitarity (if its mass is $<\sim 1$ TeV)



$$-iM(W^+W^- \to W^+W^-) \sim m_H^2 \qquad \text{for } s \to \infty$$

Higgs mechanism (II)

- Introduce a new complex doublet field $\Phi = \binom{\phi^+}{\phi^0}$ and add its kinetic term and potential into Lagrangian
  $L = L_{EW} + (D_\mu \Phi^\dagger)(D^\mu \Phi) - V(\Phi)$
  $D_\mu = \partial_\mu - ig_1 Y B_\mu - ig_2 A^i_\mu \frac{\sigma^i}{2}$
  $V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$
- B_μ and A^i_μ are linear combination of photon, $W^\pm$ and Z bosons fields
- Min. energy (vacuum) for const. field $\Phi^\dagger \Phi = \frac{\mu^2}{2\lambda} = \frac{v^2}{2}$
- After gauge transform one scalar field survives (Higgs field), which effectively generates mass terms via the interaction with other particles

Higgs mechanism (III)

- Finally, we get Lagrangian with mass terms for $W^{\pm}$ and Z and a new particle with spin 0 – Higgs boson
- The same Higgs doublet which generates $W^{\pm}$ and Z masses is sufficient to give masses to the fermions (leptons and quarks)
- The strength of the Higgs interaction is proportional to the particle's mass

  $g_{WWH} = g m_W$
  $g_{ZZH} = \frac{g}{2\cos\theta_W} m_Z$
  $g_{ffH} = -\frac{g}{2}\frac{m_f}{m_W}$
- The theory predicts all Higgs boson properties except of its mass

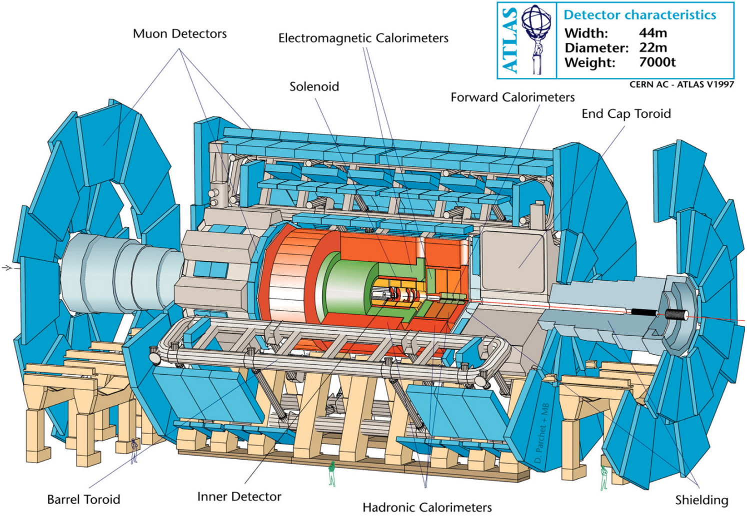
Standard Model (II)

- 1967: The theory of electroweak interaction was formulated
- 1973: Neutral currents – neutrino scattering, Gargamelle
- 1983: W and Z bosons were discovered at SPS (CERN)
- 2012: Higgs boson was discovered at LHC (CERN)
- But, is it really SM Higgs boson?
  - Measurements of coupling constants HWW, HZZ, $H\tau\tau$, ...
  - Spin and parity measurements
  - BSM? $H \to \tau e$ or $H \to \tau\mu$ – Prague involved

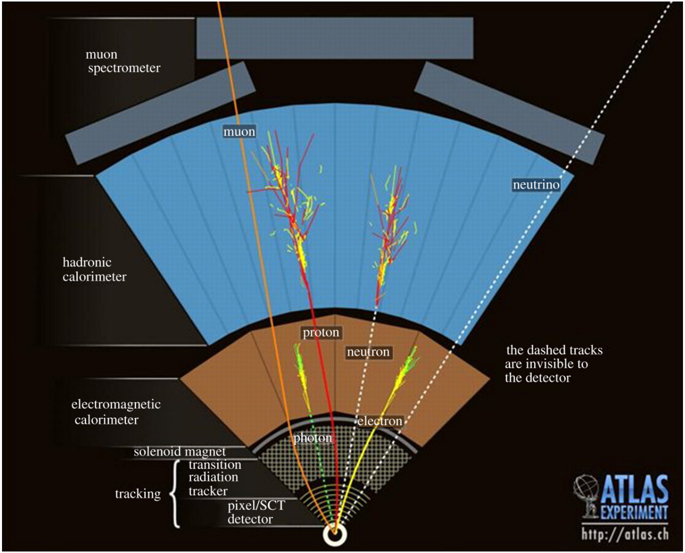
LHC – Large Hadron Collider

- Laboratory CERN, Geneva
- Proton-proton collider
- Circumference 27 km
- Run-1
    - 2010-2012
    - Int. luminosity $25fb^{-1}$
    - Energy 7, 8 TeV
- Run-2
    - 2015 -
    - Int. luminosity $38fb^{-1}$
    - Energy 13 TeV

Experiment ATLAS (I)

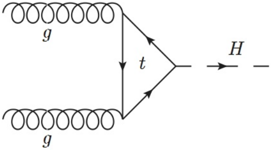


Experiment ATLAS (II)

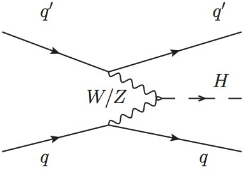


Higgs production at LHC

- Processes: ggH – dominant, VBF (10x less frequent), VH, ttH



a)



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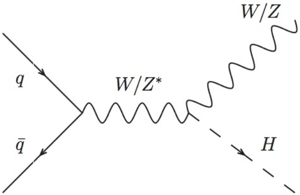
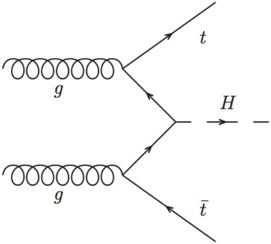


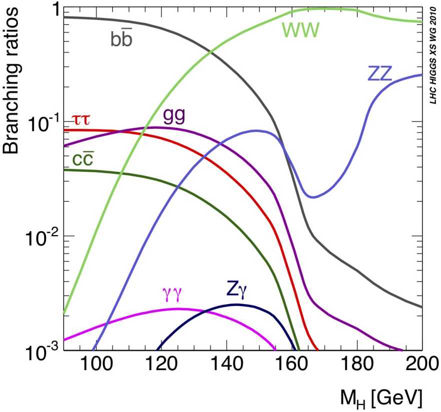
c)

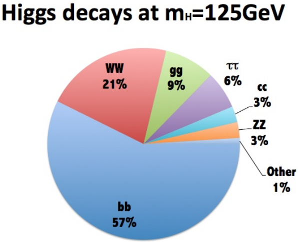


d)

Higgs boson decays

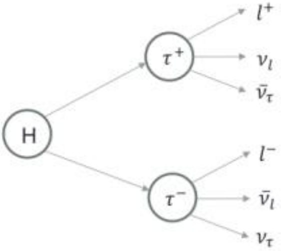
- $H \to b\bar{b}$ dominant, but very difficult to measure
- Discovery: $H \to ZZ^*$, $H \to WW^*$, $H \to \gamma\gamma$
- Important to measure Higgs coupling to fermions: $H \to \tau\tau$
  - 5σ significance when combining ATLAS and CMS Run-1 results

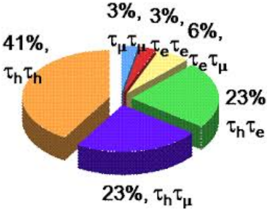




$H \to \tau^+\tau^-$ decay modes

- Di-lepton: $H \to \tau^+\tau^- \to \ell^+\ell^- 4\nu$
- Semi-lepton: $H \to \tau^+\tau^- \to n\pi\ell 3\nu$ $(1-3\pi)$
- Hadronic: $H \to \tau^+\tau^- \to n\pi 2\nu$ $(2-6\pi)$





$H \to \tau^+\tau^- \to \ell^+\ell^- 4\nu$

- Signal selection and cutflow – Tomas' presentation
- Dominant background processes $H \to \tau^+\tau^- \to \ell^+\ell^- 4\nu$:
  - $Z \to \tau^+\tau^- \to \ell^+\ell^- 4\nu$
  - $Z \to \ell^+\ell^-$
  - $t \to bW\ (\to \ell\nu)$
- Mass reconstruction
  - 4 neutrinos in the final state
    - not possible to fully reconstruct invariant mass
  - Collinear approximation
    - neutrinos parallel to tau leptons
    - mass calculated using MET
  - MMC (missing mass calculator)
    - consider probability angular distribution of the decay products
    - search for the most probable decay configuration for given lepton momenta and MET

Statistical analysis of the Higgs boson decay (I)

- Poisson distribution applied to a histogram with i bins

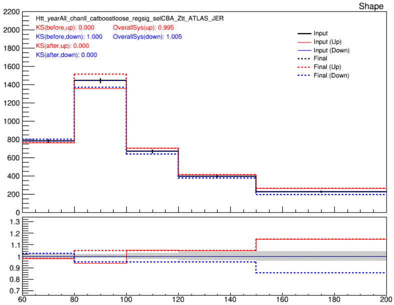
$$P(n_i|\nu_i(\boldsymbol{\theta})) = \frac{\nu_i(\boldsymbol{\theta})^{n_i}}{n_i!} e^{-\nu_i(\boldsymbol{\theta})}$$

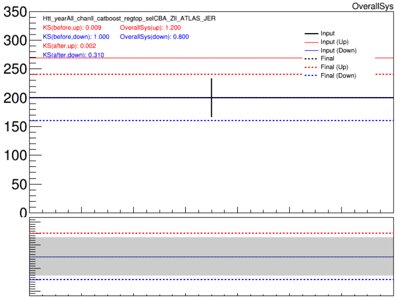
  - Probability to observe n_i events when $\nu_i = \mu s_i + b_i$ are expected
  - s_i and b_i are the SM expected values for signal and background bin content (may be function of $\boldsymbol{\theta}$)
  - Nuisance parameters $\boldsymbol{\theta}$ are related to statistical and systematic uncertainties and to the normalisation of background contributions measured in control data samples
- PoI is signal strength $\mu = \frac{\sigma}{\sigma_{SM}}$
- Over 100 nuisance parameters, their values $\boldsymbol{\theta}$ and stat. deviations $\boldsymbol{\sigma}$ measured by *combined performance group* → Gauss term:

$$L = \sum_i P(n_i|\mu s_i(\boldsymbol{\theta}) + b_i(\boldsymbol{\theta}))G(\boldsymbol{\theta}, \boldsymbol{\sigma}))$$

Statistical analysis of the Higgs boson decay (II)

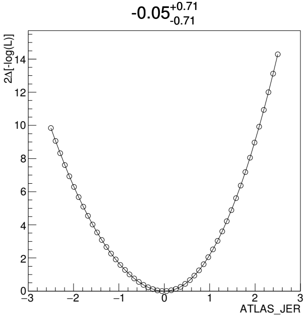
- Impact of different sources of systematic uncertainties is expressed in terms of relative changes of the expected event yields
- Uncertainty is obtained by varying a given experimental or theoretical quantity by ±1 standard deviation around the nominal value



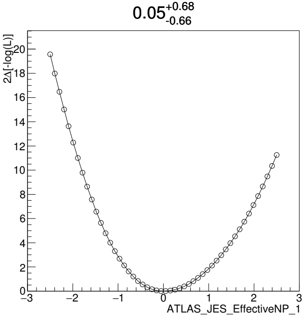


Statistical analysis of the Higgs boson decay (III)

- Profile likelihood ratio: $\lambda(\mu) = \frac{L(\mu,\hat{\hat{\theta}}(\mu))}{L(\hat{\mu},\hat{\theta}(\mu))}$
  - Conditional max likelihood estimator $L(\mu, \hat{\hat{\theta}}(\mu))$ provides max likelihood estimate of the NP $\boldsymbol{\theta}$ for a given value of μ
  - Unconditional max likelihood estimator $L(\hat{\mu}, \hat{\theta}(\mu))$ corresponds to the best fit result
- Negative log-likelihood: $-2ln\lambda(\mu)$



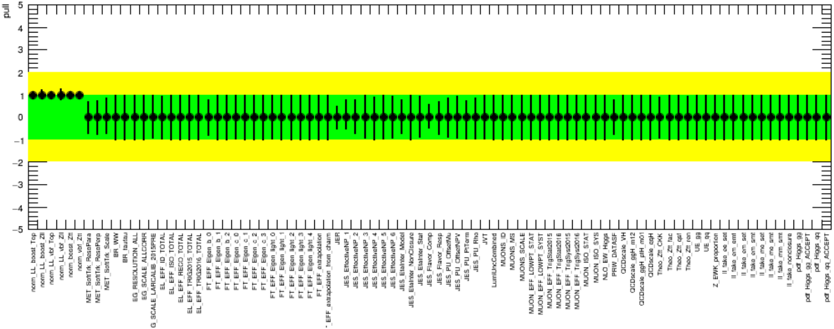
$-0.05^{+0.71}_{-0.71}$



$0.05^{+0.68}_{-0.66}$

Statistical analysis of the Higgs boson decay (IV)

- Variety of checks are performing to identify unwanted nuisance parameter's behaviour, such as strong correlations, NP pulled far from their nominal values in the fit, NP which exhibit double-minima or non-parabolic behaviour in negative log-likelihood distribution



Conclusions

- Higgs boson decay to a pair of τ leptons is proven above 5σ significance when combining ATLAS and CMS Run-1 results
- The goal in Run-2 is to improve precision, with so far acquired data in 2015+2016 ATLAS should be able to reach 5σ. Hope to be ready for summer conferences
- Apart from Higgs boson decays predicted by SM, searches for other decay modes as well as for eventual other Higgs bosons (e.g. MSSM Higgs) continue