Higgs at the LHC

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1. Important Higgs production processes at LHC
2. Higgs boson decay modes
3. Higgs Partial Decay Widths
4. Is the Higgs Standard Model-like or not?
5. Conclusions

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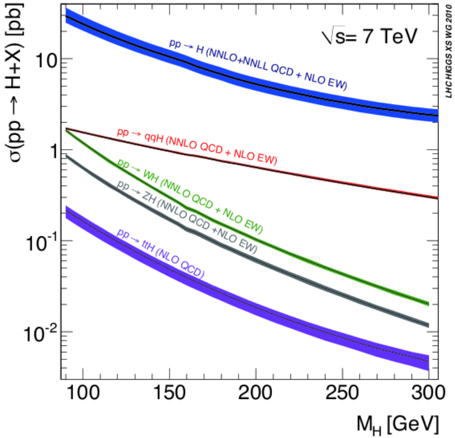
Important Higgs production processes at LHC



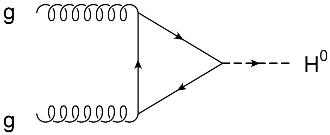
SM-Higgs boson production cross sections at LHC.

- gluon fusion:
  $gg \longrightarrow H$
- weak boson fusion (WBF):
  $q\bar{q} \longrightarrow q\bar{q}H$
- weak boson associated production:
  $q\bar{q} \longrightarrow WH$

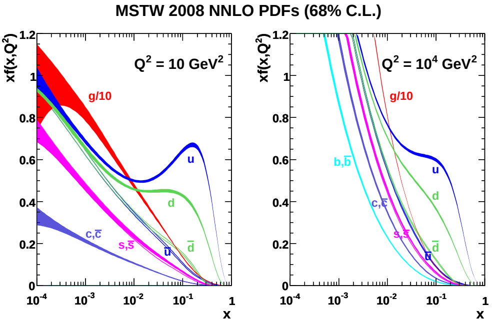
  weak boson associated production:
  $q\bar{q} \longrightarrow ZH$
- top quark associated production:
  $pp \longrightarrow t\bar{t}H$

Important Higgs production processes at LHC

Gluon-gluon fusion $gg \longrightarrow H$



- 1-loop process.
- $\lambda_t = \dfrac{m_t}{v}$
- Dominant process known at NNLO.
- 0.5 M events produced.

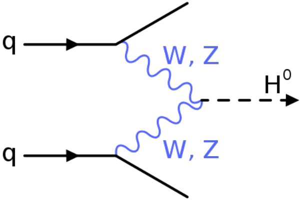


Distribution of x times the unpolarized pdf's.

Large gluon PDF at lower parton momentum fraction x

Important Higgs production processes at LHC

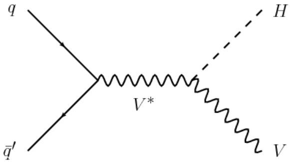
Weak boson fusion $q\bar{q} \longrightarrow Hq\bar{q}$



- Distinctive signature with two outgoing jets mainly in the forward direction.
- The hadronic activity is heavily suppressed in the central region.
- 40 k events produced.

Important Higgs production processes at LHC

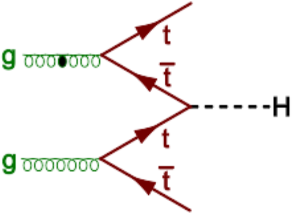
Higgs-strahlung or Vector boson associated production: $\bar{q}q \longrightarrow HW, Z$



- Not useful for Higgs search at LHC, but used at Tevatron and LEP ($e^- e^+$).
- Very distinctive feature with a Z or W decaying leptonically.
- 20 k events produced.

Important Higgs production processes at LHC

$t\bar{t}$ fusion $pp \longrightarrow t\bar{t}H$



- Very rare process with a characteristic signature but too crowded.
- 3 k events produced.

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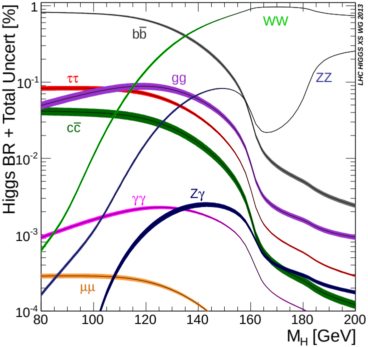
Higgs boson decay modes

Important issues for the discovery of the Higgs

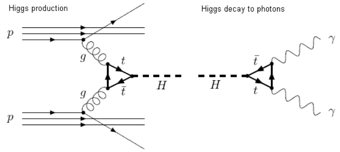


SM Higgs boson decay branching ratios.

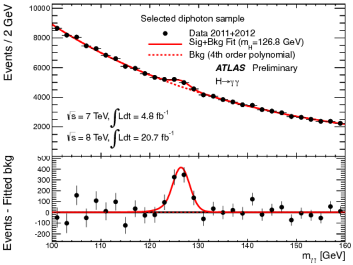
- branching ratio
- signature
- background
- mass resolution

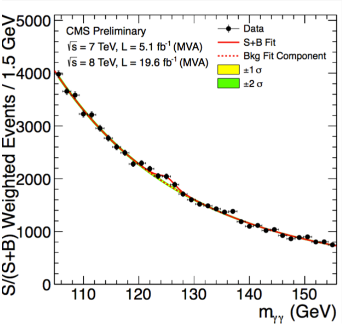
Higgs boson decay modes

Two-photon channel: $H \longrightarrow \gamma\gamma$



- small branching ratio
- clear signature: two back-to-back isolated high-p_T photons.
- main backgrounds: irreducible $\gamma\gamma$ continuum, γ-jets and jets-jets events.
- key observable: di-photon mass $m_{\gamma\gamma}$
- sensitive to BSM heavy particles.





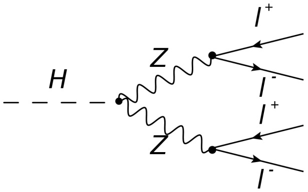
Invariant mass distribution of diphoton candidates.

$$m_H^{ATLAS} = 126.8 \pm 0.2\ (\text{stat}) \pm 0.7\ (\text{syst})\ \text{GeV}$$

$$m_H^{CMS} = 125.4 \pm 0.5\ (\text{stat}) \pm 0.6\ (\text{syst})\ \text{GeV}$$

Higgs boson decay modes

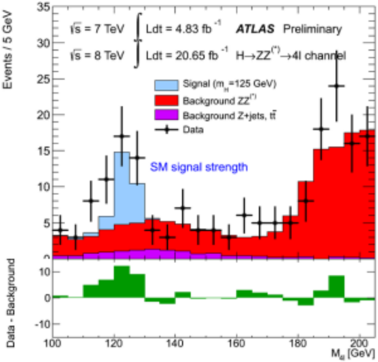
Four-lepton channel: $H \longrightarrow ZZ^* \longrightarrow \ell^+\ell^-\ell^+\ell^-$

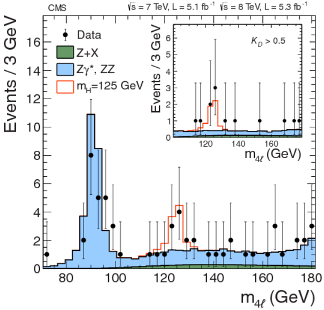


- very clear signature: 2 pairs of same flavour, opposite charged leptons.
- particularly clean from the background.
- background is mostly due to irreducible ZZ continuum.
- key observable: four-lepton invariant mass $m_{4\ell}$

Higgs boson decay modes

Four-lepton channel: $H \longrightarrow ZZ^* \longrightarrow \ell^+\ell^-\ell^+\ell^-$





Four-lepton invariant mass distribution.

$$m_H^{ATLAS} = 124.3^{+0.6}_{-0.5}(\text{stat})^{+0.5}_{-0.3}(\text{syst})\ \text{GeV}$$

$$m_H^{CMS} = 125.8 \pm 0.5\ (\text{stat}) \pm 0.2\ (\text{syst})\ \text{GeV}$$

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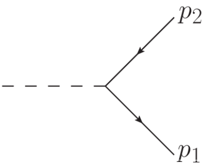
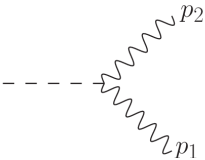
Higgs Decays at Tree Level

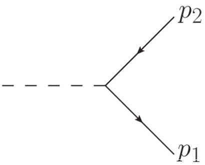
- Tree level decays - direct couplings.
- Direct couplings to massive fields (fermions and gauge bosons):





- Due to kinematics the matrix element is independent of angles.
- We calculate the phase space and matrix elements separately.

The Fermion Amplitude



$$\mathscr{M} = \frac{m_f}{v} \bar{u}_{s_1}(p_1) v_{s_2}(p_2)$$

$$\sum_{spins} |\mathscr{M}|^2 = \left(\frac{m_f}{v}\right)^2 Tr[(\not{p}_1 + m_f)(\not{p}_2 - m_f)]$$

$$= 2\left(\frac{m_f}{v}\right)^2 \left[m_H^2 - 4m_f^2\right]$$

$$\sum_{spins,\ colors} |\mathscr{M}|^2 = 2\sqrt{2} N_f^{(c)} G_f m_f^2 m_H^2 \left[1 - \left(\frac{m_f}{m_H}\right)^2\right]$$

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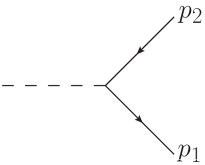

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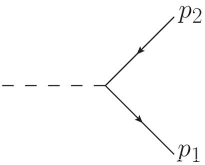

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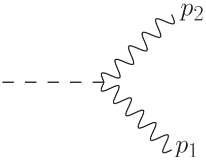
The Gauge Boson Amplitude



$$\mathscr{M} = i2\frac{m_A^2}{v}\varepsilon^{\mu}_{\lambda_1}(p_1)\varepsilon_{\lambda_2\mu}(p_2)$$

$$\sum_{polarisations} |\mathscr{M}|^2 = 4\frac{m_A^4}{v^2}\left[-g^{\mu\nu} + \frac{p_1^{\mu} p_1^{\nu}}{m_A^2}\right]\left[-g_{\mu\nu} + \frac{p_{2\mu} p_{2\nu}}{m_A^2}\right]$$

$$= \frac{m_H^4}{v^2}\left[1 - 4\frac{m_A^2}{m_H^2} + 12\frac{m_A^4}{m_H^4}\right]$$

$$\sum_{\substack{polarisations \\ (with\ \ symmetry)}} |\mathscr{M}|^2 = S_A\sqrt{2}G_f m_H^4\left[1 - 4\frac{m_A^2}{m_H^2} + 12\frac{m_A^4}{m_H^4}\right]$$

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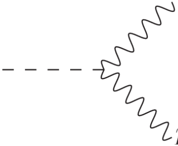

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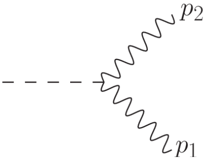

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Higgs Partial Decay Widths

$$\Gamma_i = \frac{1}{2m_H}\int d\phi_2 \sum |\mathcal{M}_i|^2 = \frac{1}{16\pi m_H}\left(1-\frac{4m_i^2}{m_h^2}\right)^{\frac{1}{2}} \sum |\mathcal{M}_i|^2$$

$$\Gamma(H \to f\bar{f}) = \frac{1}{4\sqrt{2}\pi} N_f^{(c)} G_f m_f^2 m_H \left[1-\left(\frac{m_f}{m_H}\right)^2\right]^{\frac{3}{2}}$$

$$\Gamma(H \to W^+W^-) = \frac{G_f m_H^3}{8\sqrt{2}\pi}\left(1-\frac{4m_W^2}{m_H^2}\right)^{\frac{1}{2}}\left[1-4\frac{m_W^2}{m_H^2}+12\frac{m_W^4}{m_H^4}\right]$$

$$\Gamma(H \to ZZ) = \frac{G_f m_H^3}{16\sqrt{2}\pi}\left(1-\frac{4m_Z^2}{m_H^2}\right)^{\frac{1}{2}}\left[1-4\frac{m_Z^2}{m_H^2}+12\frac{m_Z^4}{m_H^4}\right]$$

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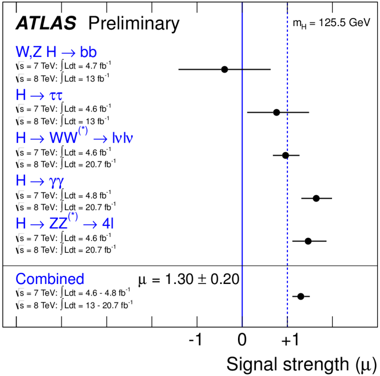
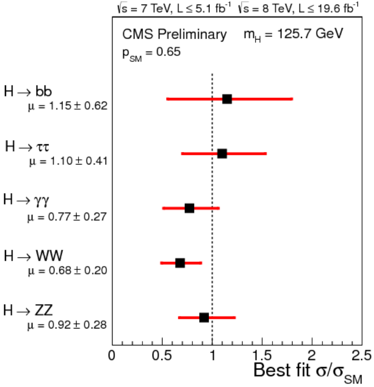
Is the Higgs Standard Model-like or not?

As you know, a new particle has been observed at the LHC. Within the experimental uncertainties, it has characteristics consistent with those expected from the Higgs boson predicted by the SM.





Is the Higgs Standard Model-like or not?

Spin and parity

The SM spin-parity $J^P = 0^+$ is compared with alternative hypotheses using the Higgs boson decays $H \to \gamma\gamma$, $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$, as well as the combination of these channels.

- The measurements are based on the kinematic properties of the three final states.
  - From the production angle $\cos\theta^*$ distribution
  - From the decay angles and the spin correlation when applicable
- The spin-1 hypotheses is strongly disfavoured by the observation of the $H \to \gamma\gamma$ decay.

The data are compatible with the SM $J^P = 0^+$ quantum numbers for the Higgs boson, whereas all alternative hypothesis $J^P = 0^-, 1^+, 1^-, 2^+$ are excluded at CLs above 97.8 %.

Is the Higgs Standard Model-like or not?

Couplings

- The Higgs boson seems to couple to W, Z, t and b very much like the SM Higgs boson. However, these measurements have strong correlations.
- Given a suficiently high integrated luminosity these properties are expected to be accessible to analysis.
- The measurement of Higgs self-couplings, however, may suffer from poor sensitivity at LHC

The HL-LHC could allow for a more precise measurement.

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Conclusions

- Despite their low branching ratio, the diphoton and 4-lepton channels are the ones in which a new boson has been discovered.
- Last results (combined mass):

$$m_H^{ATLAS} = 125.5 \pm 0.2(\text{stat})^{+0.5}_{-0.6}(\text{syst})\,GeV$$

$$m_H^{CMS} = 125.3 \pm 0.4\ (\text{stat}) \pm 0.5\ (\text{syst})\,GeV$$

- This is a milestone in the quest to understand the origin of electroweak symmetry breaking.
- So far, all measurements are consistent with expectations for a SM-like Higgs boson, within experimental uncertainties.
- More precise measurements will be available in the future. So...

STAY TUNED!!

References

- J. Beringer et al. (Particle Data Group). 2013 partial update for the 2014 edition.
- *Observation of a Higgs-like boson in CMS at the LHC.* Pushpalatha C. Bhat. doi:10.1016/j.nuclphysbps.2012.11.003
- *Higgs search at ATLAS.* Sofia Maria Consonni. arXiv:1305.3315v1
- And much more...

THANK YOU FOR YOUR ATTENTION!!!

and now...

questions or **cocktail**?