1 What kind of properties are required for an event to be identified as H $\rightarrow$ ZZ*$\rightarrow$llll in A?

General: The H $\rightarrow$ ZZ*$\rightarrow$llll channel is a very clean channel because the final state particles are electrons or muons. Since the electron is stable and the muons energy is high enough to leave the detector before decaying or being stopped, the four final state particles can directly be observed. This does not require a the use of sophisticated jet reconstruction techniques as in hadronic decays of the Z boson (except background identification). Because of the good momentum resolution for leptons in ATLAS and CMS, this is channel offers a good sensitivity to the higgs mass.

Event selection Search for two pairs of isolated leptons, each with same flavour and opposite charge. Trigger requirements(if two numbers are given, they apply to $\sqrt{\mathrm{s}} = 7\mathrm{TeV}$ or $\sqrt{\mathrm{s}} = 8\mathrm{TeV}$ respectively):

- Single lepton trigger: Minimum $\mathrm{E_T}$ at 18GeV and 24GeV for muons and 20GeV and 24GeV for electrons.
- Dilepton trigger: 12GeV for electrons and 10GeV and 13GeV for muons

Identifying particle candidates:

- Muon candidates: matching reconstructed tracks in the particle identification (ID) system (inner tracking detector of ATLAS especially the transition radiation tracker) and the muon system (MS)
- electron candidates: reconstructed track in the ID system matched to a cluster in the electromagnetic calorimeter. The clusters have to match the shape criteria of electromagnetic showers (explained in the "particle detectors" part of the lecture).

Each electron candidate has to have a $\mathrm{p_T}$ (momentum transverse to the beam axis) of 7GeV, each muon has to have a $\mathrm{p_T}$ of 6GeV. The candidates have to be measured at a pseudorapidity of $\eta < 2.5$ ($\sim$ 8 degree to the beam axis). At least one of the single leptons has to satisfy the single lepton trigger *or* one lepton pair has to satisfy the dilepton trigger.
Additional requirements: The leptons have to satisfy certain isolation criteria implemented as minimum distances in the $\eta - \phi$-plane. Additional thresholds are applied to the $\mathrm{p_T}$ of the individual particles, as well as to the reconstructed invariant mass of the lepton pairs.
Reminder:Invariant mass The invariant mass of a bound state is the total mass of the state in its rest frame, it is independent of the particles momentum in an arbitrary lorentz transformed frame of reference. It is the rest mass of a particle. The invariant mass of a two particle system is defined as

$$M_{inv} = \sqrt{(E_1 + E_2)^2 - ||p_1 + p_2||^2} \tag{1}$$

The invariant mass requirement is used to restrict the reconstructed lepton pairs to the mass range where the Z boson lies. By setting additional requirements on distance of the reconstructed vertex to the interaction point in longitudinal and transverse beam direction the background contamination is further reduced.

2 Why is the reconstructed invariant mass of the Z bosons not at 91GeV for both of the bosons?

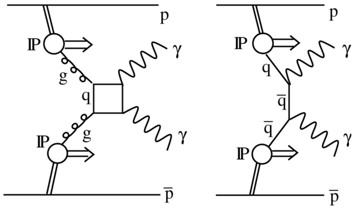
Assuming the Higgs boson is produced at rest in a particle collision where the momentum sum of the initial particles vanishes. The rest mass of the Higgs boson ($\sim$ 125 GeV) is not enough to create two Z bosons ($\sim$ 182GeV). However, the decay is possible because one of the Z bosons is off the *mass shell*. In contrast to on shell particles that have to satisfy the energy-momentum relation

$$E^2 = m^2 + |\vec{p}|^2, \tag{2}$$

an off shell particle can have a mass, different from the mass of its on shell version. In terms of Feynman diagrams, virtual particles can be off shell, but they are not produced as final states.

3 What are possible background processed to H→ $\gamma\gamma$?

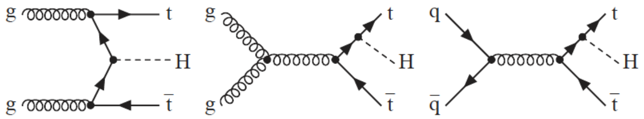
- Standard model $\gamma\gamma$ production, e.g.



- Drell Yan $q\bar{q} \rightarrow Z^*/\gamma^* \rightarrow e^+e^-$
- Misidentified jets in dijet production

4 How can the $t\bar{t}H$ process be produced at LHC?

The coupling of the Higgs field to the quark fields in the standard model is described by Yukawa coupling. In general, this coupling describes the interaction between a scalar and a dirac field. The $t\bar{t}H$ process is a valuable probe to measure the top Yukawa coupling, which is subject to a wide range of BSM searches e.g. for additional charged or CP-violating Higgs bosons (Higgs compositeness), as those will modify the SM Yukawa coupling. Additionally, the large Yukawa coupling of the top quark can be used to investigate the "running" of the constant to understand the generation of the heavy quark masses (infrared fixed point). At hadron colliders, the $t\bar{t}H$ process can be produced as shown below.



5 Why is the ttH process hard to identify at hadron colliders?

- Complicated final state in itself, small cross section at LHC energy ($\sim$ 0.5pb , gluon fusion has $\sim$43pb)
- Only one known decay: $t \to bW^+$ is most of the time a three jet event because the W boson decays preferably to $q\bar{q} \to$ huge background.
- Clear Higgs decay channels with good mass resolution have small branching fraction (e.g. $H \to ZZ^* \to llll$ is at $1.2 \cdot 10^{-4}$)