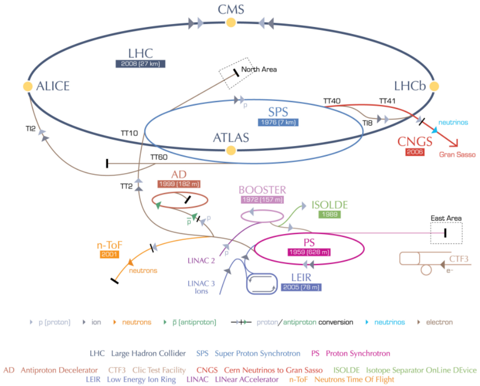
Search for new resonances in the 100 to 195 GeV diphoton invariant mass range using 140 fb^{-1} of pp collisions collected at $\sqrt{s}$=13 TeV with the ATLAS detector

Pietro Daniele

UNIVERSITÀ
DEGLI STUDI
DI MILANO

LHC

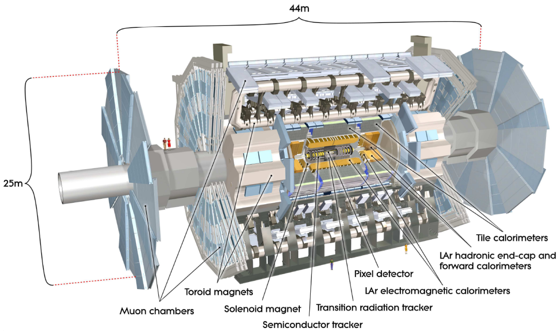
- The *Large Hadron Collider* (LHC) is a protons and heavy ions collider installed in the 27 km long LEP tunnel
- Run2 *pp* collisions $\sqrt{s} = 13$ TeV
- Four leading experiments installed in the four *pp* interaction points:
  - **ATLAS**
  - CMS
  - LHCb
  - ALICE



ATLAS

The ATLAS experiment:

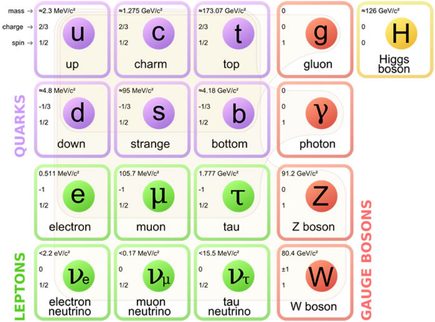
- a multi purpose detector
- forward-backward symmetric detector with a $\sim 4\pi$ angular coverage
- composed of several layers:
  - Inner Detector (ID)
  - Calorimetric system
  - Muon Spectrometer
- Magnetic field:
  - a solenoid
  - a barrel toroid and two end-cap toroids
- Trigger system
  - 40 MHz $\rightarrow$ 1 kHz



Standard Model (SM)

The Standard Model of particle physics is a quantum field theory:

- based on $SU(2)_L \otimes U(1)_Y \otimes SU(3)_C$ gauge symmetry
- explains the basic building blocks of matter interactions
- classifies all the subatomic known particles
- predicted new particles:
  - gluon
  - top (t) and charm (c) quarks
  - W and Z bosons $\leftarrow$ *massless*



W and Z bosons discovered in 1983 $\begin{cases} m_W = 80\ GeV \\ m_Z = 91\ GeV \end{cases}$

$\Rightarrow$ the introduction of W, Z mass terms in the SM Lagrangian would break the local gauge invariance of the theory

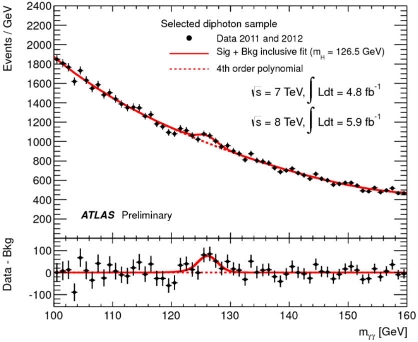
$\Rightarrow$ *Spontaneous Symmetry Breaking*

$\Rightarrow$ **Higgs Boson**

Higgs boson discovery

Higgs boson:

- a massive scalar boson
- spin-0
- no electric and colour charge
- couples only to massive particles
- discovered by the ATLAS and CMS experiments in July 2012:
  - $m_H = 125.09 \pm 0.24$ GeV (Run1)
  - the $H \rightarrow \gamma\gamma$ channel was used in the ATLAS experiment
    - Non resonant background
    - final state kinematic fully reconstructed
    - Excellent invariant mass resolution (1-2 GeV)



Non resonant background → 70% / 30%:

- Irr $\rightarrow$ QCD di-photon production (70%)
- Red $\rightarrow$ (γ,jet), (jet,jet) with jet misidentification (*fake rate*) (30%)

SM limitations

SM is not the final theory of nature:

- no dark matter candidate
- no explanation for the matter-antimatter asymmetry

→ **BSM physics**

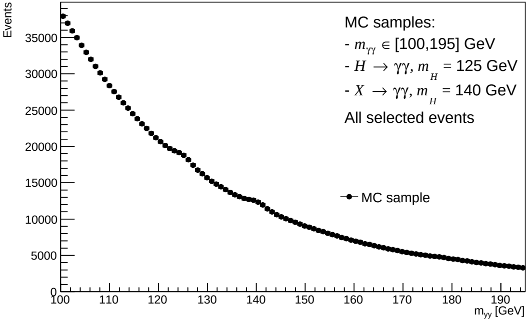
Higgs field:

- a complex doublet under $SU(2)_L$ symmetry group
- could be extended $\Rightarrow$ larger scalar sectors:
  - BSM resolution
  - Higgs sector
  - additional structures $\Rightarrow$ **NEW BOSONS**
  - new theory
    - 2HDM $\leftarrow$ *bottom-up* approach
    - SUSY $\leftarrow$ *top-down* approach

New spin-0 resonances analysis

BSM physics $\Rightarrow$ New spin-0 resonances search

- **Channel**: $H \to \gamma\gamma$
- **Aim**: find an excess of events over the expected background
- **Signal**:
  - $X \to \gamma\gamma$
  - a function of the resonance mass m_X
  - small SM assumptions
- **Background**
  - Non resonant background
  - SM Higgs boson background
- **Results**
  - combined maximum likelihood fit



Signal model SM independence

New physics search:
⇒ An analysis as much independent as possible from assumptions based on Standard Model

- the SM Higgs production modes are: *ggF*, *VBF*, *WH*, *ZH*...
- only *ggF* is considered for the signal model creation
- other production modes included as a signal yield systematic uncertainty $\sigma^{prod\ \ modes}$

Advantages

- small assumptions on the production modes for the new resonances
- include and parameterise the ignorance of the relative importance of different production modes for additional scalar Higgs bosons searches.

Disadvantages

- $\sigma^{prod\ \ modes}$ increases in the more granular categorisation
  ⇒ the analysis performances decrease
- No Higgs discovery Run1 categorisation

Events Selection

$H \to \gamma\gamma$ channel: **Event selected**

- $m_{\gamma\gamma}$ ϵ $[100, 195]$ GeV
- two photons:
  - identified
  - isolation
  - $p_T^{\gamma_i}/m_{\gamma\gamma}$

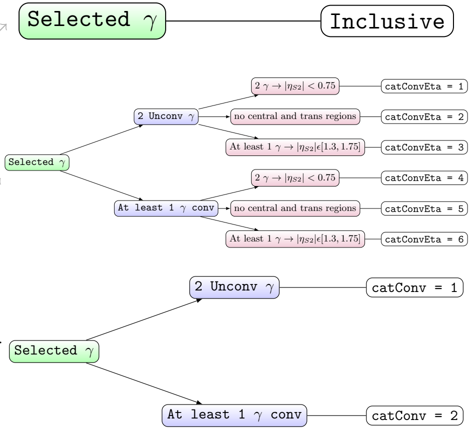
Parameter	Name	Reconstruction Level	Truth Level
$\|\eta^{\gamma_i}\|$	η cut	< 2.37	< 2.37
$p_T^{\gamma_1}/m_{\gamma\gamma}$	Scalar relative p_T cut	> 0.3	> 0.3
$p_T^{\gamma_2}/m_{\gamma\gamma}$	Scalar relative p_T cut	> 0.25	> 0.25
$E_T^{cone20\ \gamma_i}/p_T^{\gamma_i}$	Isolation cut	< 0.065	< 0.065
$p_T^{cone20\ \gamma_i}/p_T^{\gamma_i}$	Isolation cut	< 0.05	

$\Downarrow$

1. Categorisation
2. Signal model
3. Non-resonant background model
4. SM Higgs boson background model
5. Systematic uncertainties
6. Expected results

Categorisation

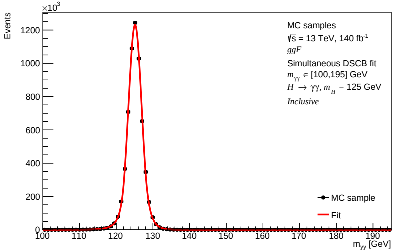
- The events are classified into mutually exclusive categories
- Designed to enhance the analysis sensitivity
  - maximise the signal and bkg ratio $\frac{S}{B}$
  - minimise the systematic uncertainties
- three categorisation tested and compared:
  - Inclusive, catConvEta, catConv
  - γ conversion status
  - η position cuts
    - central region $|\eta| < 0.75$
    - trans region $\eta \epsilon [1.3, 1.75]$
    - no central and trans regions

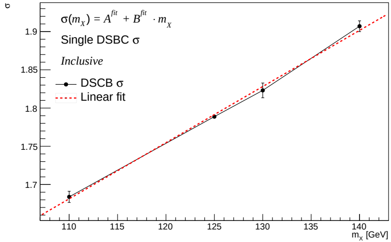


Signal model

For each category:

- **Function form**: *Double-Sided Crystal Ball* (DSCB):
  - a gaussian core + power-law tails
  - 6 parameters $(\mu, \sigma, a_{1,2}, p_{1,2})$
- **Samples**: *ggF* MC samples with four different resonance mass m_X (110, 125, 130 and 140 GeV)
- **Fit**: a simultaneous DSCB fit:
  - $[100, 195]$ GeV $m_{\gamma\gamma}$ range
  - DSCB parameters $\propto m_X$: $par(m_X) = A^{par} + B^{par} \cdot m_X$
  - A and B params fixed after fit





Signal yield(m_X)

In each category i, the signal yield is expressed as:

$$N^i(m_X) = \sigma_{ggF}(m_X) \cdot Br_{\gamma\gamma}(m_X) \cdot \mathscr{L}_{Run2} \cdot A_X(m_X) \cdot C_X^i(m_X)$$

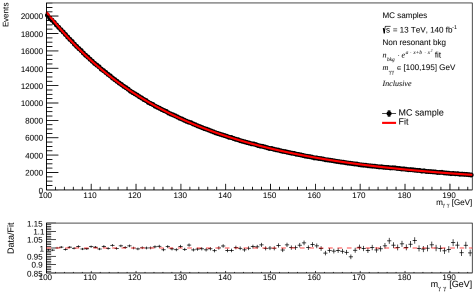
Fiducial volume:

- the regions of the detector volume sensitive to the distinctive process signatures
- *Fiducial* events:
  - criteria applied before the reconstruction → *Truth level*
  - fiducial criteria mimic the selection criteria

Non-resonant background

For each category:

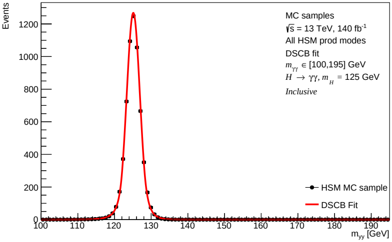
- modelled using MC samples
- **Functional form**:
  $f^i_{bkg}(m_{\gamma\gamma}, N^i_{bkg}, a^i, b^i) = N^i_{bkg} \cdot \exp^{(a^i \cdot m_{\gamma\gamma} + b^i \cdot m^2_{\gamma\gamma})}$
  - N^i_{bkg}, a_i, bi are free parameters
- **Sample**: di-photon MC samples
- **Fit**: *exp(poly2)* fit:
  - fit $\rightarrow$ [100,195] GeV $m_{\gamma\gamma}$ range
- the functional form, chosen using MC samples, will applied to data



HSM background

For each category:

- **Function form**: *Double-Sided Crystal Ball* (DSCB):
  - a gaussian core + power-law tails
  - 6 parameters $(\mu, \sigma, a_{1,2}, p_{1,2})$
- **Samples**: all SM Higgs 125 GeV production modes MC sample
- **Fit**: a single DSCB fit:
  - DSCB parameters fixed after the fit
  - $[100, 195]$ GeV $m_{\gamma\gamma}$ range
  - yield set from SM predictions



Systematic Uncertainties

Systematic uncertainties

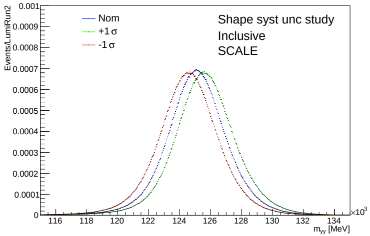
- arise from experimental sources
- specific for each category
- are included into the likelihood model of the measurement as nuisance parameters
- divided into two different groups:

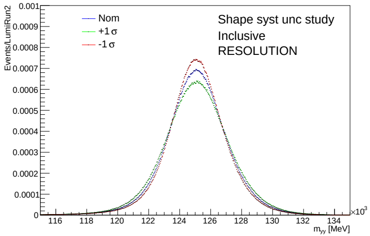
1. shape systematic uncertainties
2. yield systematic uncertainties

Shape systematic uncertainties

Shape systematic uncertainties → the modelling of $m_{\gamma\gamma}$ distribution:

- photon energy scale uncertainties:
  - affect the peak position (μ^{DSCB})
  - impact of less than 0.5%
- photon energy resolution uncertainties
  - affect the Gaussian width (σ^{DSCB})
  - impact of less than 12%
- LHC Higgs mass uncertainty
  - affect the peak position (μ^{DSCB})
  - impact of 0.2%
  - only on HSM model



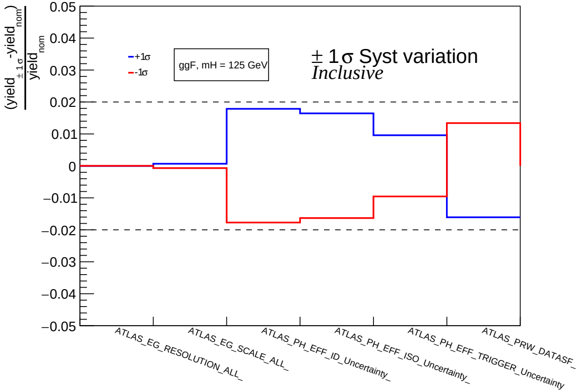


Yield systematic uncertainties

Yield systematic uncertainties $\rightarrow$ the expected signal and HSM yields

- the γ energy scale and resolution uncertainties on the selection efficiency
- the γ identification and isolation efficiencies
- the efficiency of the diphoton trigger
- the modelling of pile-up in the simulation

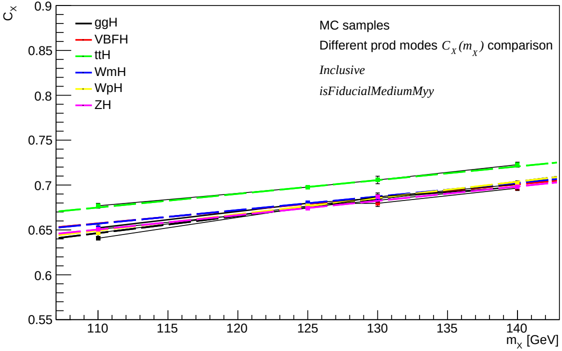
$\Rightarrow$ an impact of less than 2%



Yield systematic uncertainties

Yield systematic uncertainties $\rightarrow$ the expected signal and HSM yields
The production mode dependence $\sigma^{prod\ modes}$

- on signal model
- For each category C_X^{prod} parametrised as functions of m_X
- $\sigma^{prod\ modes}$
  - is maximum of linear fits difference
  - by varying prod modes and resonance mass



Combined maximum likelihood fit

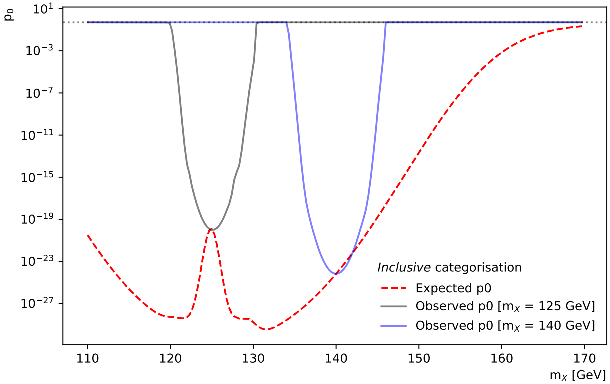
Selected events, different categorisations, models and systematic uncertainties are used as building blocks for a combined maximum likelihood fit:

- a method of estimating the parameters which maximise an assumed probability distribution ($\mathcal{L}$ likelihood), given data.
- the systematic uncertainties and the non-resonant bkg model parameter are inserted in the fit as Nuisance Parameters (**NPs**)
- μ is the **POI** of the fit which is performed simultaneously over every category of a specific categorisation for different m_X values
- the maximum likelihood fit estimates:
  - the POI $\mu \leftarrow$ free
  - NPs
    - Systematic Uncertainties $\leftarrow$ constrained
    - Non-res bkg parameters $\leftarrow$ free

Expected results

$\Longrightarrow$ a combined maximum likelihood fit in all the categories is performed

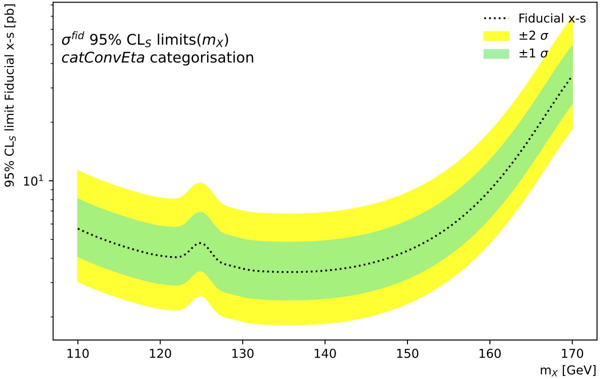
- investigating the presence of a signal by computing the compatibility of the MC template with the background only hypothesis p_0



Expected results

$\Longrightarrow$ a combined maximum likelihood fit in all the categories is performed

- assessing limits, in a fiducial region, on the x-s in case no excess of signal is observed.



Categories | Sig model | Bkg model | HSM model | Syst uncs | **Exp results**

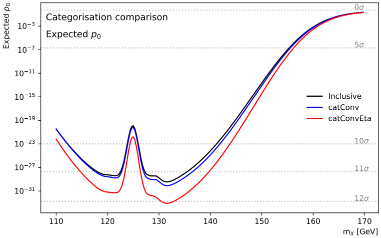
Expected results

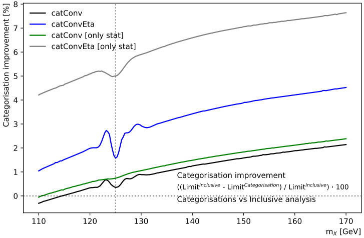
Without systematic uncertainties improvement compared to `Inclusive` category

- discovery potential
  - `catConvEta` → ∼6.3%
  - `catConv` → ∼1.2%
- limits setting
  - `catConvEta` → ∼7.6%
  - `catConv` → ∼2.4%

With systematic uncertainties improvement compared to `Inclusive` category

- limits setting
  - `catConvEta`
    - always positive improvement
    - maximum value 4.2% at m_X=170 GeV
  - `catConv`
    - not always positive improvement ⇒ should be discarded





Conclusions

- The potential of search for new resonances in [100,195] GeV $m_{\gamma\gamma}$ range has been investigated
- The best categorisation obtained from the trade-off between performances and SM independence is `catConvEta`:
  - a signal significance ranging from few σ to $\sim 12\sigma$ can be achieved in the search for new spin-0 resonance, assuming the SM mass dependence of the cross-section
  - the excluded fiducial cross-section for a signal ranges from $\sim$3.4 pb to $\sim$34.6 pb depending on the new resonance mass.
- The analysis is still blind so no results based on data have been shown
- The results presented in this thesis represent the first step towards the unblinding.

Backup

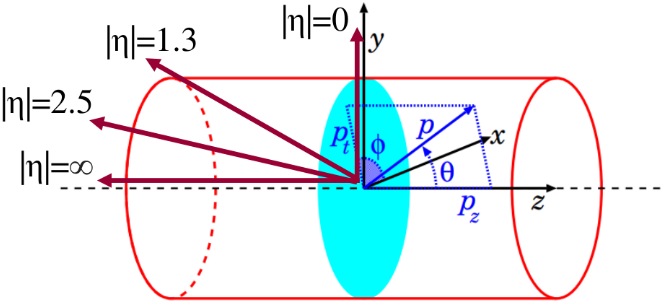
Spontaneous Symmetry Breaking

With the *Higgs mechanism* and the *Spontaneous Symmetry Breaking* is possible to introduce a gauge invariant mass term of the W, Z gauge boson

ATLAS coordinate system

ATLAS coordinate system

- origin at the nominal interaction point
- z-axis along the beam axis, (x-y) transverse plane
- azimuthal angle ϕ
- polar angle θ
- pseudorapidity $\eta = \text{-ln}\left(\tan\left(\frac{\theta}{2}\right)\right)$



2HDM

Two Higgs Doublet Model (2HDM)

- there are two Higgs fields, ϕ_1 and ϕ_2, both of which are complex doublets.
- the Higgs potential

$$V = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - [m_{12}^2 \phi_1^\dagger \phi_2 + h.c.] + \lambda_1 (\phi_1^\dagger \phi_1)^2 + \lambda_2 (\phi_2^\dagger \phi_2)^2$$
$$+ \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + [\lambda_5 (\phi_1^\dagger \phi_2)^2 + h.c.]$$

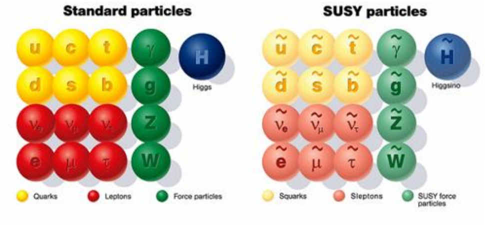
- Five physical states: two CP-even Higgs bosons h (HSM boson) and H (scalars), a CP-odd Higgs boson A(pseudoscalar), and two charged Higgs bosons $H^\pm$
- The most general 2HDM contains 14 free parameters.

aggiungi i due doppietti

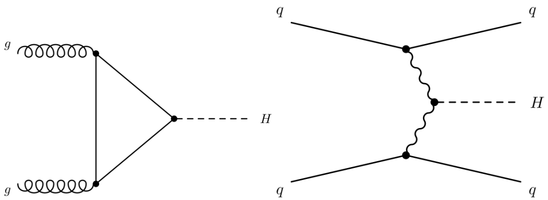
SUSY

Super Symmetry (SUSY)

- is an extension of the Standard Model that aims to fill some of the gap
- predicts a partner particle for each particle in the Standard Model
    - $\text{fermion}^{SM} \rightarrow \text{boson}^{SUSY}$
    - $\text{boson}^{SM} \rightarrow \text{fermion}^{SUSY}$
- Motivation
    1. SUSY allows unification of forces
    2. SUSY cancels the SM divergences
    3. Lightest SUSY particle is a candidate for DM
    4. SUSY provides a theoretical route to implement gravity in SM



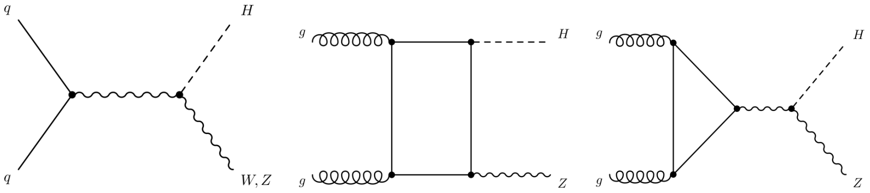
SM Higgs production modes



(a) (b)

Figure: Examples of leading-order Feynman diagrams for Higgs boson production via the (a) *ggF* and (b) *VBF* production processes.

SM Higgs production modes



(a) (b) (c)

Figure: Examples of leading-order Feynman diagrams for Higgs boson production via the (a) $qq \rightarrow VH$ and (b,c) $gg \rightarrow ZH$ production processes.

SM Higgs production modes

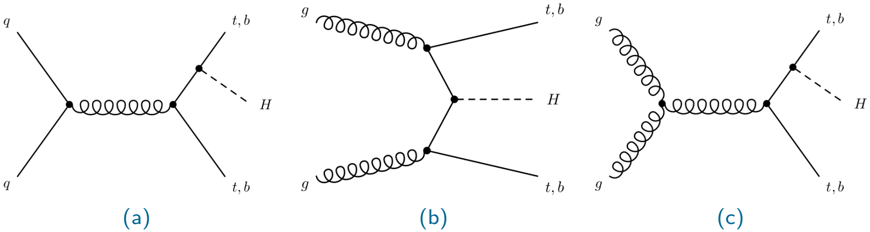


Figure: Examples of leading-order Feynman diagrams for Higgs boson production via the $qq/gg \to ttH$ and $qq/gg \to bbH$ processes.

SM Higgs production modes

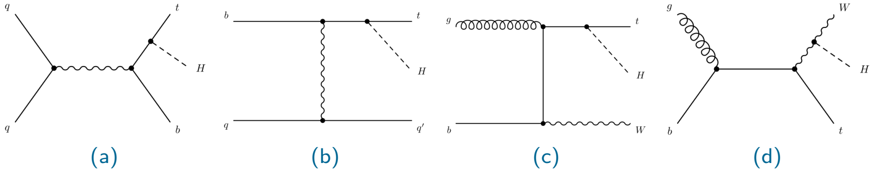


Figure: Examples of leading-order Feynman diagrams for Higgs boson production in association with a single top quark via the (a,b) tHq and (c,d) tHW production processes.

SM Higgs production modes x-s

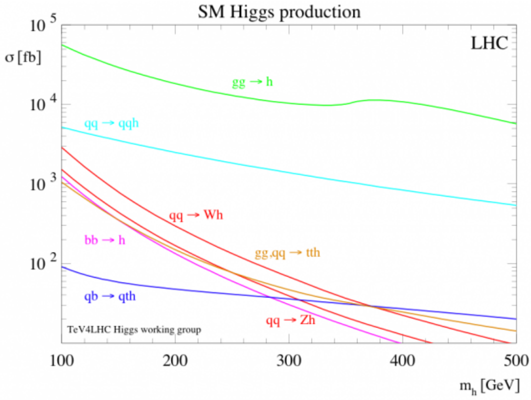


Figure: The production cross section of the Higgs boson as a function of the Higgs mass at the LHC.

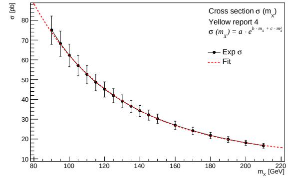
Run1 Categorisation

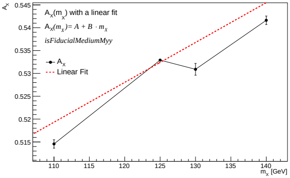
DSCB parameters

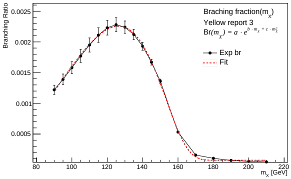
Signal yield(m_X)

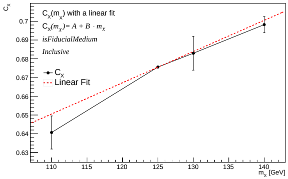
In each category i, the signal yield is expressed as:

$$N^i(m_X) = \sigma_{ggF}(m_X) \cdot A_X(m_X) \cdot Br_{\gamma\gamma}(m_X) \cdot \mathscr{L}_{Run2} \cdot C_X^i(m_X)$$









Categories Sig model Bkg model HSM model Syst uncs Exp results

Spurious signal

Shape systematic uncertainties

Yield systematic uncertainties

p0 plot

Limits plot