Search for new particles with diphoton final state at LHC at $\sqrt{s}$=13 TeV with the ATLAS experiment

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ATLAS EXPERIMENT

JJC 2015

Enigmass The enigma of mass

lapp

Plan

Introduction

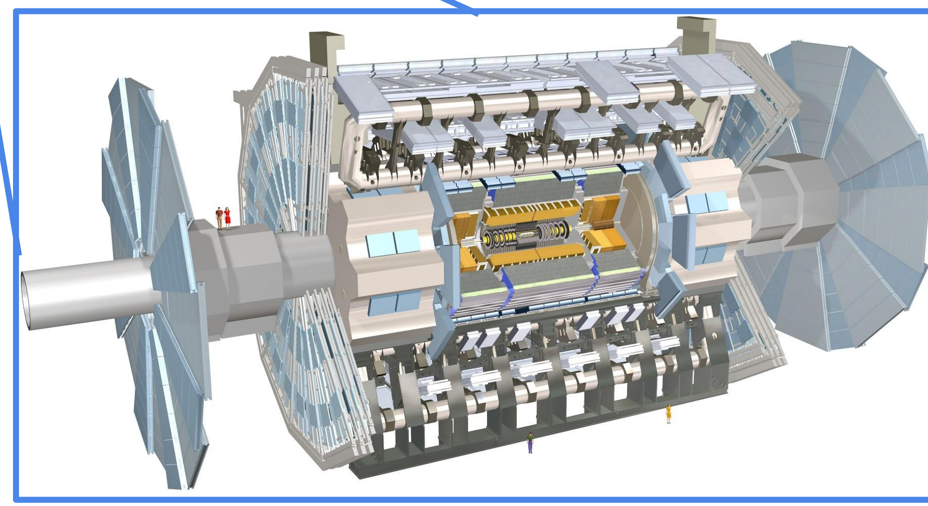
Searching for a resonance ingredients:

- Having a model
  - Theory
  - Production/Decay
- Background parametrization
- Signal parametrization
- Apply ingredients to get:
  - **excess** (discovery)
  - cross-section $\times$ BR limit

Introduction

ATLAS
(A Toroidal LHC ApparatuS)
general-purpose detector:

- search for new physics
- test predictions of the Standard Model (including the Higgs boson)

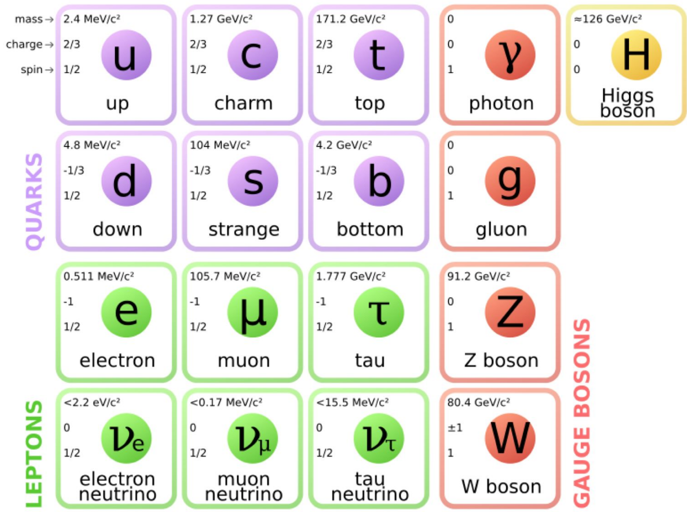


The Nobel Prize in Physics 2013
François Englert, Peter Higgs

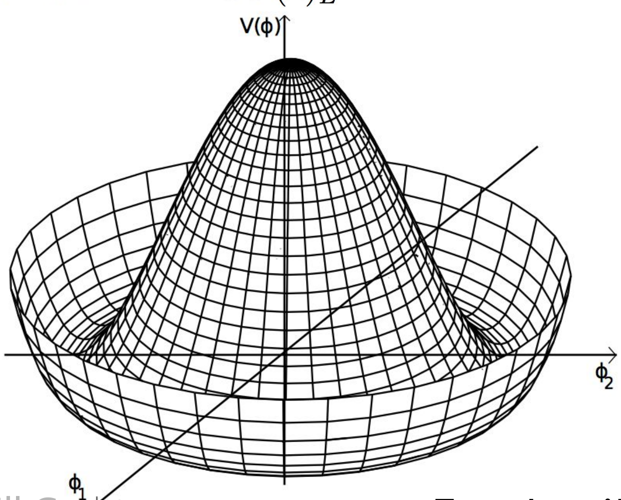
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the **ATLAS** and CMS experiments at CERN's Large Hadron Collider"

Having a model

Standard Model



$\mu^2 < 0$ broken $SU(2)_L$



Symmetries: $U(1)_Y \otimes SU(2)_L \otimes SU(3)_C$

Doublet

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} = \begin{pmatrix}\phi^+ \\ \phi^0\end{pmatrix}$$

Two complex fields ϕ^+ ϕ^0 are parametrized as 4 real fields

Potential:

$$V(\Phi) = \frac{1}{2}\mu^2\Phi^\dagger\Phi + \frac{1}{4}\lambda(\Phi^\dagger\Phi)^2$$

Field in unitary gauge:

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v + H(x)\end{pmatrix}$$

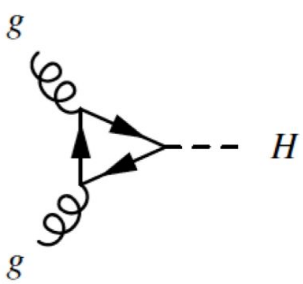
$v/\sqrt{2} = \sqrt{-\mu^2/\lambda}$ stable vacuum

H is a physical scalar field, which quantum excitation is called the Higgs boson

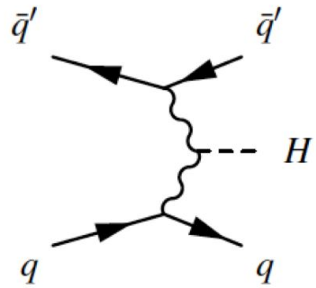
For details look at Nicolas Morange talk at tuesday

Production

The Higgs boson can be produced via the interaction of quarks and gluons from the colliding protons; the four production modes considered:

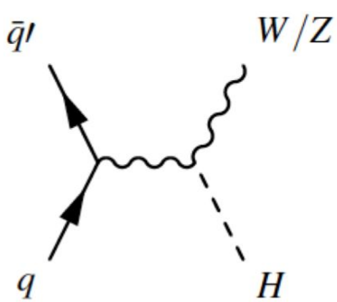


(a) $gg \to H$ (87%)

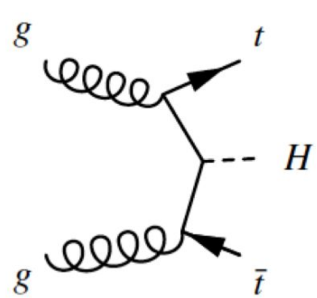


(b) VBF (7%)

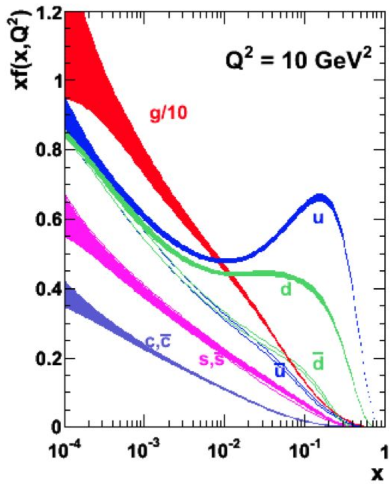
fraction for m_H=125 GeV

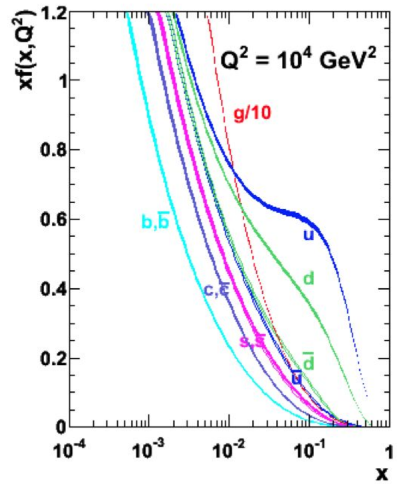


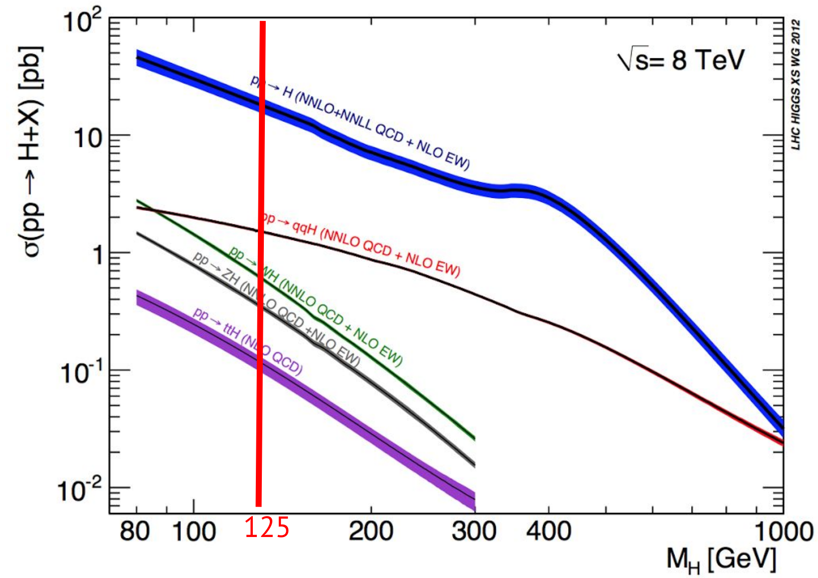
(c) VH (5%)



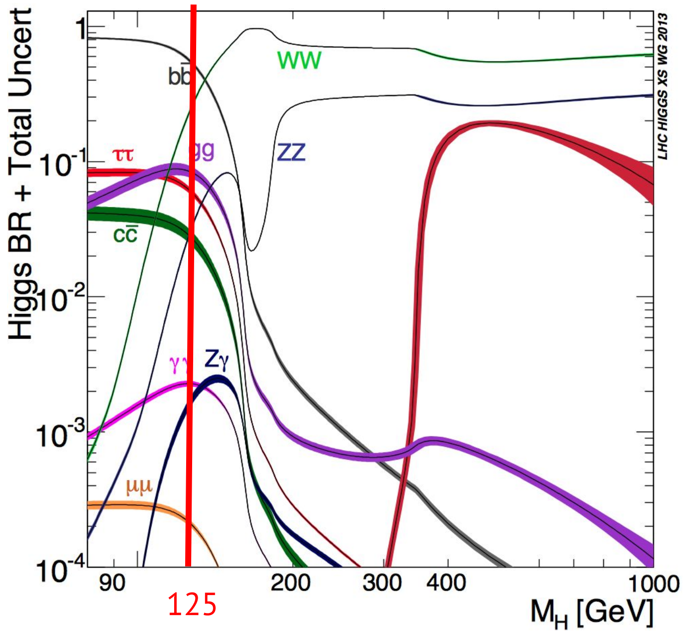
(d) $t\bar{t}H$ (1%)



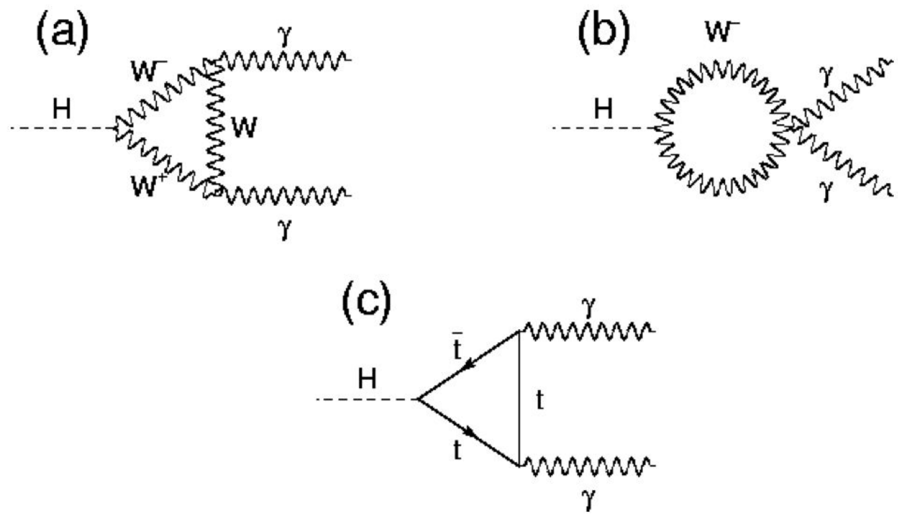




In the Standard Model, the Higgs boson can decay in various ways:

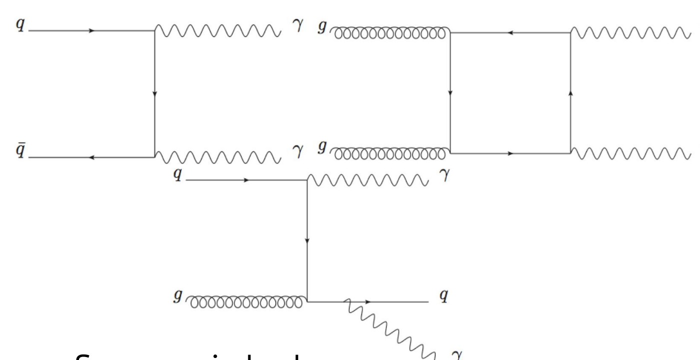


Signal in diphoton channel



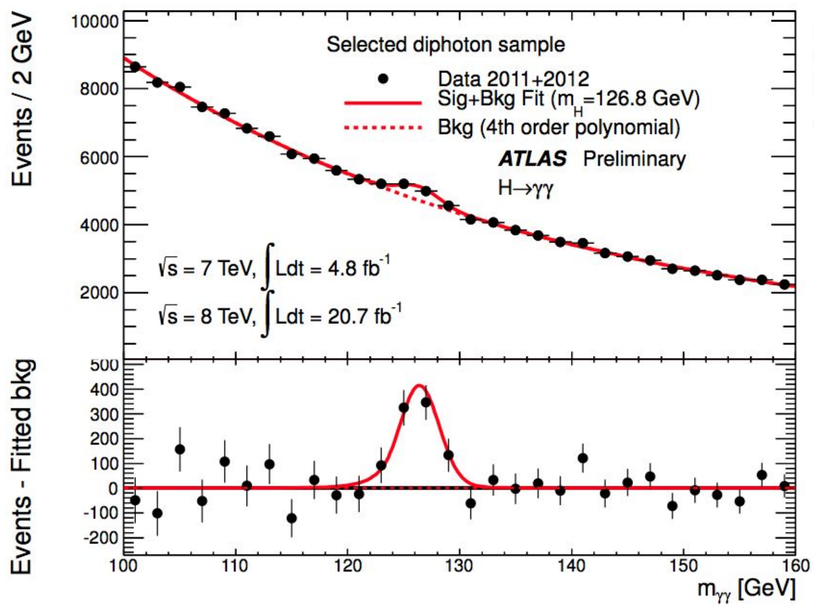
But in real life we have SM background:

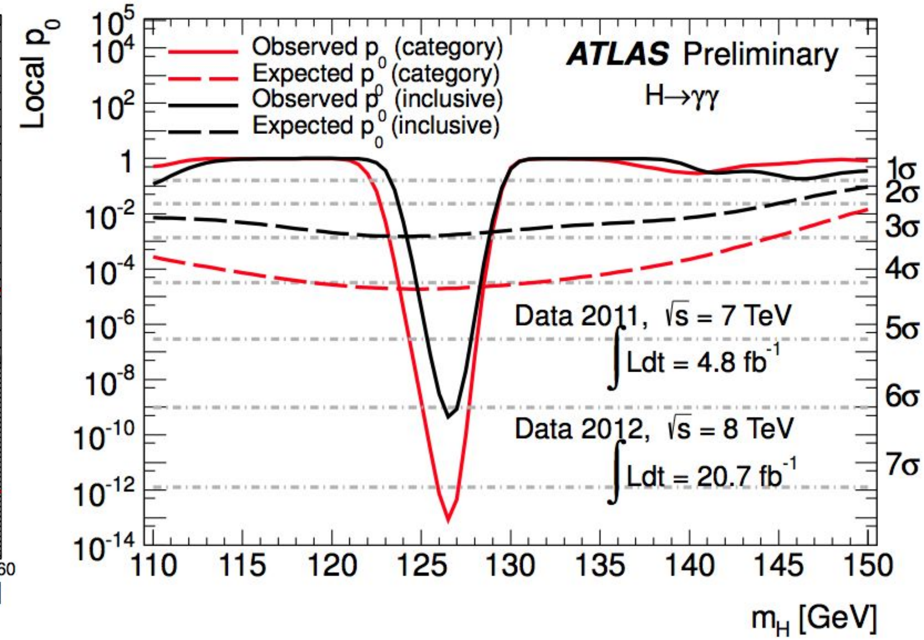
1) non-resonant γγ
2) γj - one jet misidentified as photon
3) jj - two jets misidentified as photons



See more in backup

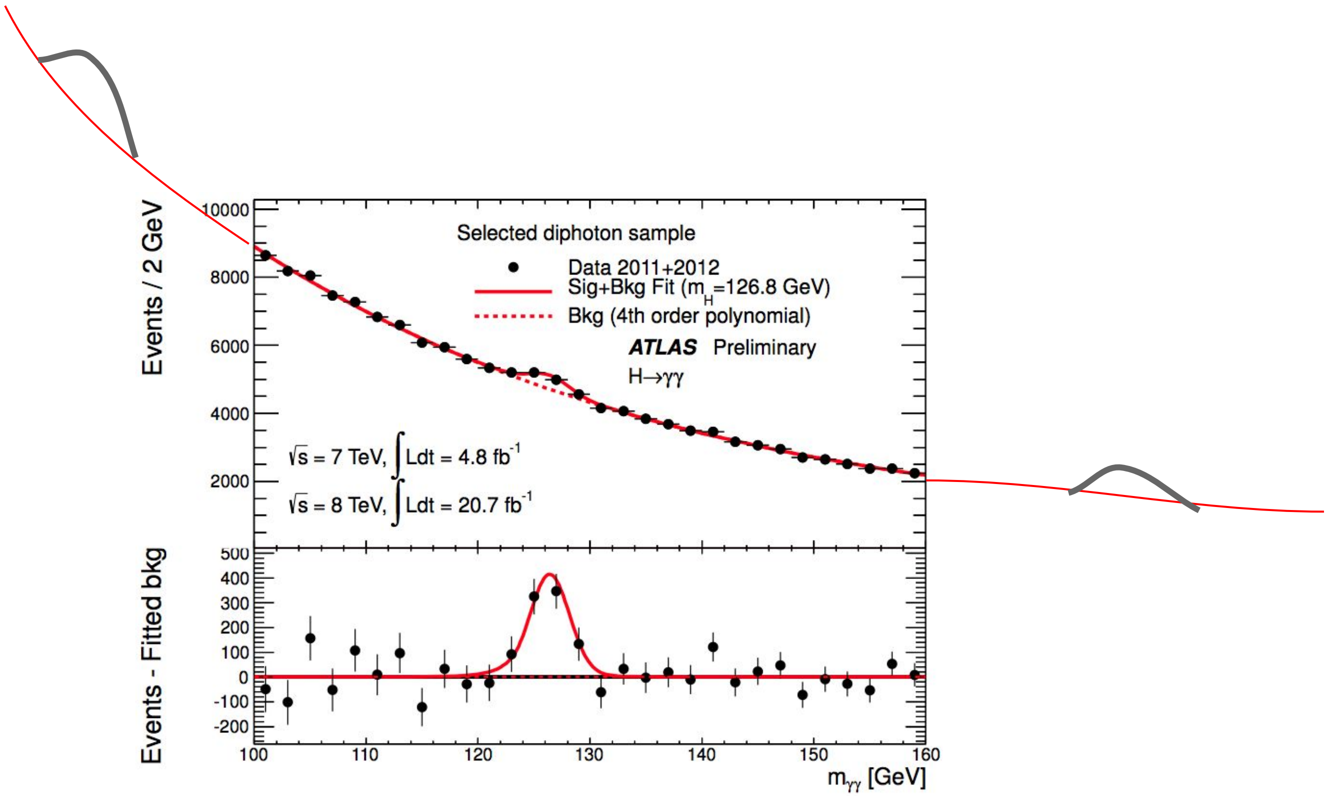
In 2012, THE ATLAS & CMS collaborations presented the observation of a new resonance: **a Higgs Boson of the Standard Model**





p_0 - local significance, probability of background mimic signal
where excess below 3σ treated as statistical fluctuations

What if there are more of them?



Having a model

There are theories, like two-Higgs doublet model (2HDM), which require a second scalar particle.

SM Standard Model	**2HDM** two Higgs Doublets Model
Free parameters: 1	Free parameters: 14
Potential: $V(\Phi) = \frac{1}{2}\mu^2\Phi^\dagger\Phi + \frac{1}{4}\lambda(\Phi^\dagger\Phi)^2$	Potential: $V = m_{11}^2\,\Phi_1^\dagger\Phi_1 + m_{22}^2\,\Phi_2^\dagger\Phi_2 - m_{12}^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \lambda_3\,\Phi_1^\dagger\Phi_1\,\Phi_2^\dagger\Phi_2 + \lambda_4\,\Phi_1^\dagger\Phi_2\,\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \left(\Phi_2^\dagger\Phi_1\right)^2\right],$
Field: $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	Fields: $\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix}, \quad a = 1, 2$
3+1: $W^{\pm}, Z^0$ **+ *H***	3+5: $W^{\pm}, Z^0$ **+ 5*H**

Note!: The models are **guides**; but the search would reveal a resonance even if it is not the one predicted by any model.

Search for a resonance

$$\tan\beta \equiv \frac{v_2}{v_1}$$

The angles α and β are the rotation angles which diagonalizes matrices. They determine the interactions of the various Higgs fields with the vector bosons and with the fermions

$$\Phi_a = \begin{pmatrix} \phi_a^+ \\ (v_a + \rho_a + i\eta_a)/\sqrt{2} \end{pmatrix}, \quad a = 1, 2$$

$$v_1 = v\cos\beta$$

$$v_2 = v\sin\beta$$

The addition of the second Higgs doublet leads to 5 physical states:

- the CP even neutral Higgs bosons *h* and ***H*** *(heavier than h)*

$$h = \rho_1 \sin\alpha - \rho_2 \cos\alpha \qquad H = -\rho_1 \cos\alpha - \rho_2 \sin\alpha$$

$$H^{\mathrm{SM}} = \rho_1 \cos\beta + \rho_2 \sin\beta = h \sin(\alpha - \beta) - H \cos(\alpha - \beta)$$

the "alignment limit" α-β=π/2: $H^{\mathrm{SM}}_{125} = h$

- the CP odd pseudoscalar *A*

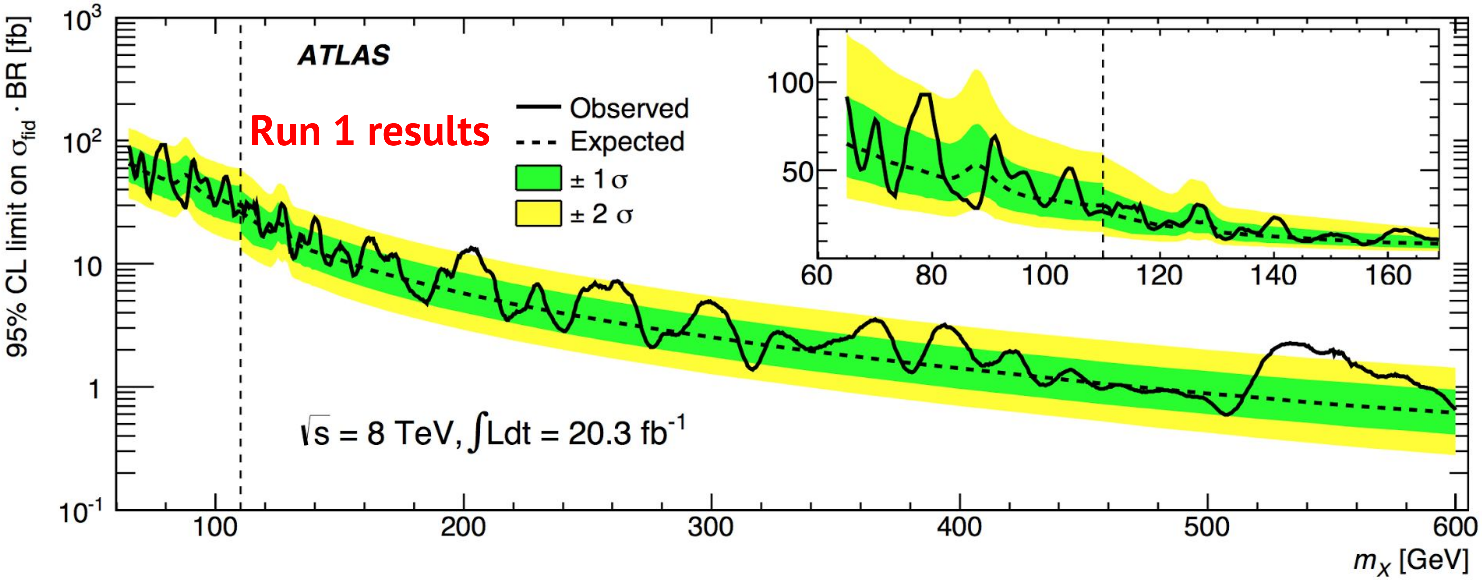
$$A = \eta_1 \sin\beta - \eta_2 \cos\beta$$

- two charged Higgs bosons $H^{\pm}$

Note!: The models are **guides**; but the search would reveal a resonance even if it is not the one predicted by any model.

Search for a resonance

Limits were set for Run 1 - no excess found



Search for a resonance

Cross Section increases in Run 2, and we are **searching again!**

$\sqrt{s}$ (TeV)	$\sigma^{total}_{pp\to H}$ (pb)	$\sigma_{pp\to H\to\gamma\gamma}$ (fb)
7	13.37	30.48
8	22.13	50.46
14	56.98	129.91

During LHC run 1, ATLAS collected: 4.8 fb^{-1} @ 7 TeV

20.7 fb^{-1} @ 8 TeV

In 2015, ATLAS has collected and validated 3.3 fb^{-1} @ 13 TeV

Luminosity proportional to the number of expected events *N* for a process over its cross section σ

$$L = \frac{N^{events}}{\sigma_{pp}}$$

Search for a resonance

In collected data with "diphoton" signature we have combination of photon-photon , photon-jet and jet-jet events.

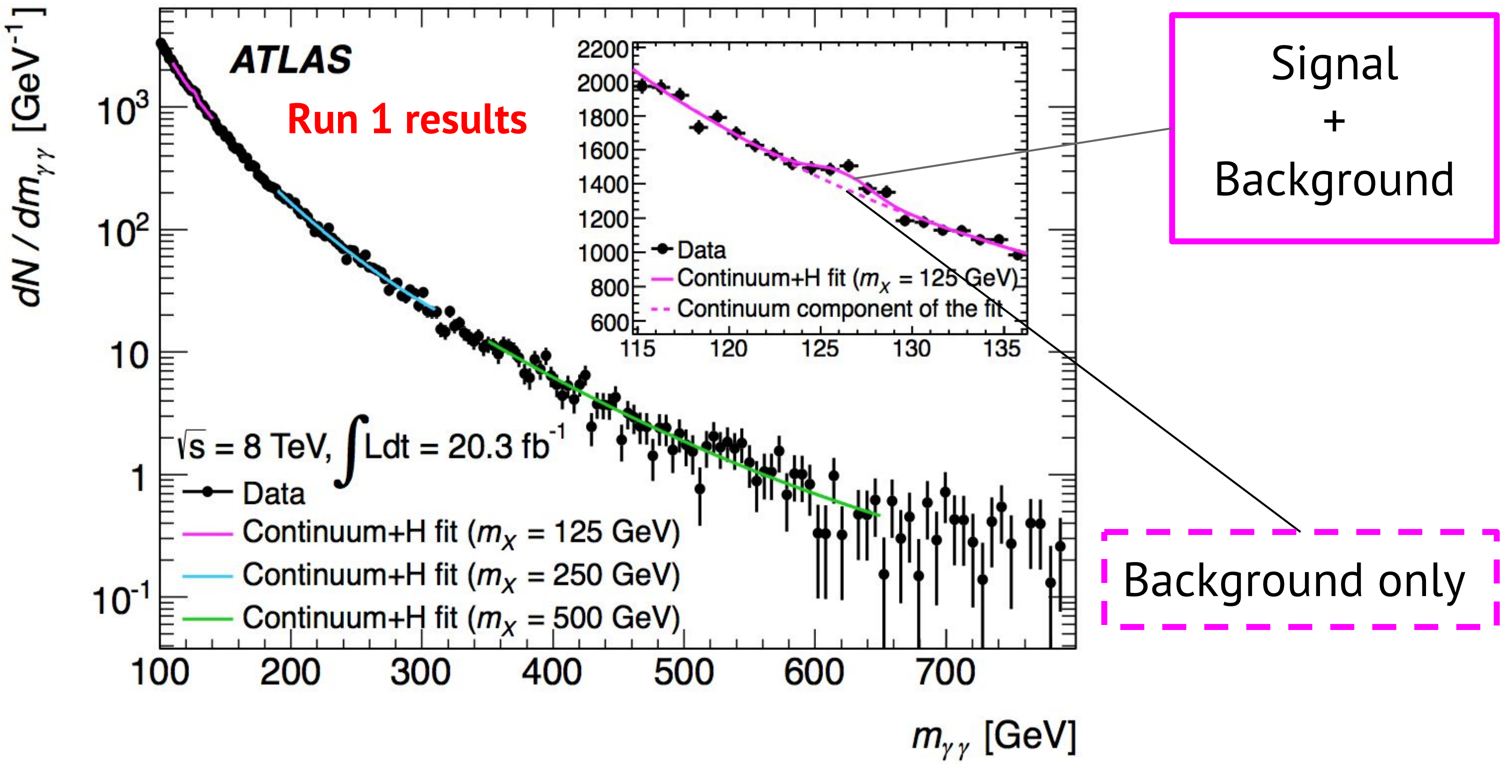
1) Select events with a pair of photons, applying selection criteria to maximize a high photon purity
2) The selected events contains events from direct $\gamma\gamma$, γj, jj production, decays from the Higgs boson (H_{125}) (and possibly a new resonance ?)
3) The background is continuous and its shape can be parametrized
4) The possible signal is parametrized as a Narrow Width Resonance
5) Data are fitted with the sum of the background + a possible signal ("3+4")

The analysis is ongoing right now. As the collaboration has not reviewed the results, I cannot present them. Everything below will be **simulation** or **public results from Run 1**

Background parametrization

The background contribution to the $m_{\gamma\gamma}$ spectrum is modeled by a smooth functional form.

Standard Model Higgs resonance accounted to background during fit



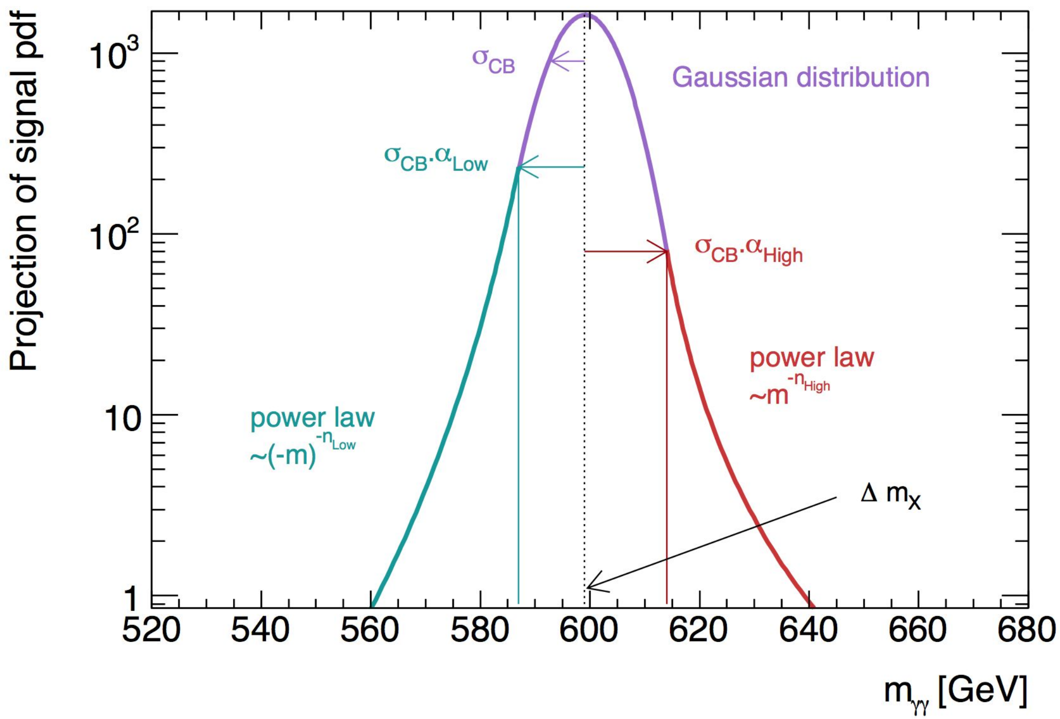
Signal+Background fit presented for Run 1 data.

I'm responsible for **Signal Parametrization** in Run 2 analysis

Signal parametrization

Search for scalar diphoton resonances at √s = 13 TeV
in the mass range from 200 GeV to 3 TeV

Parametrize signals with Double-Sided Crystal Ball (DSCB) function using simulation:

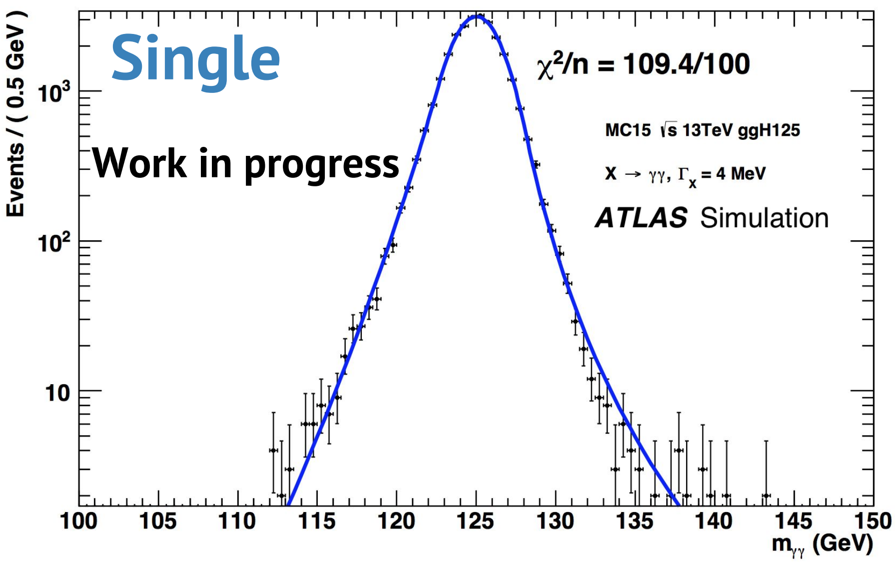


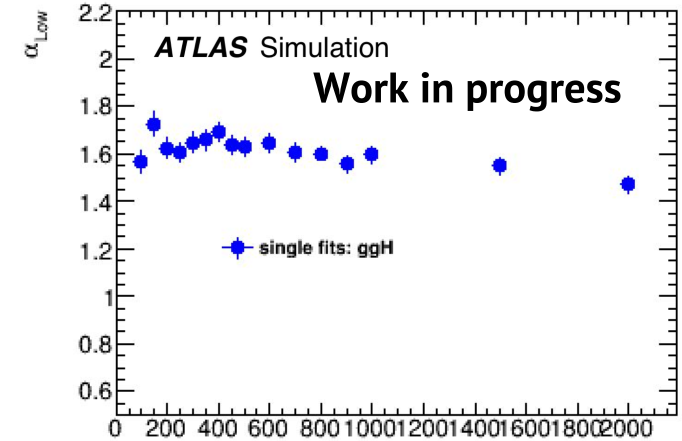
MC signal samples produced for several mass points.

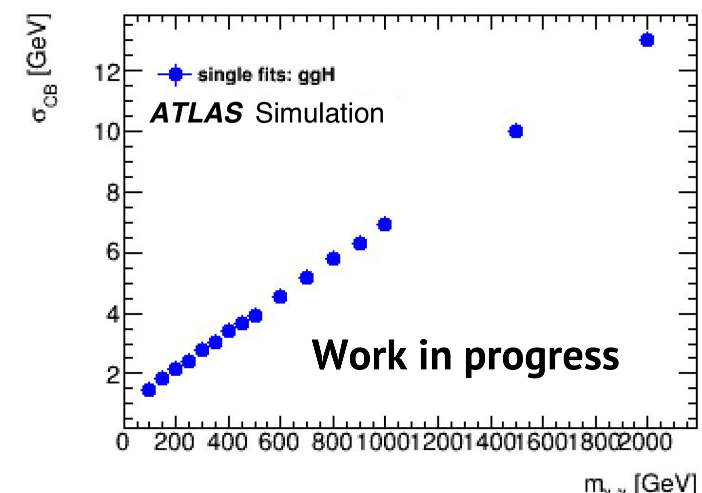
Parametrization derived on those points and provide function to continuously cover all the mass range

Signal parametrization

- An unbinned fit of the $m_{\gamma\gamma}$ distribution of all the events passing the selection cuts (single mass point fit)







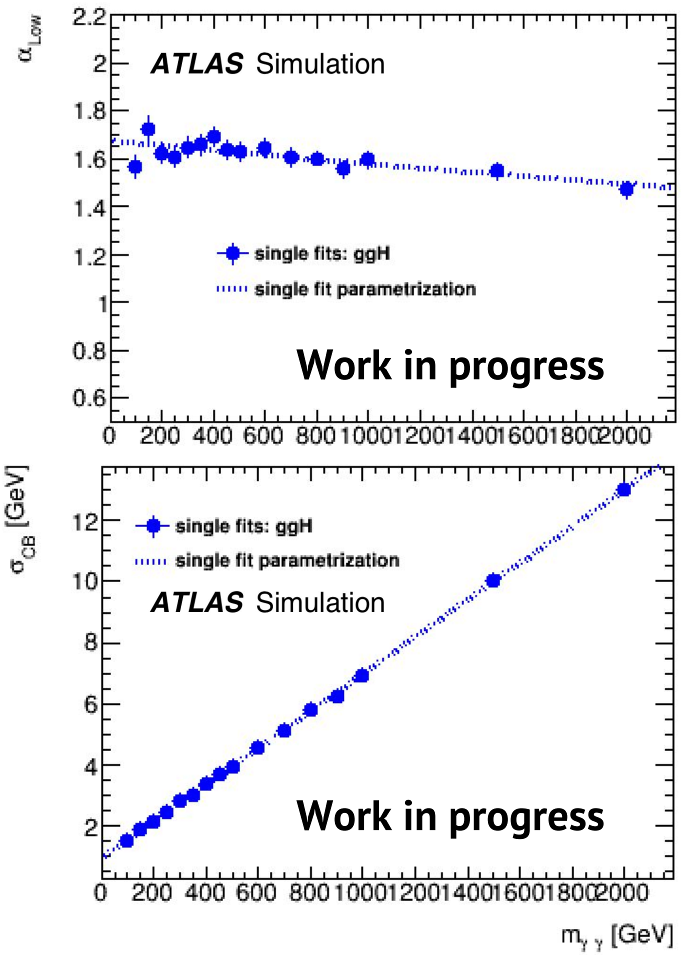
The double-sided Crystal Ball function is defined as

$$N \cdot \begin{cases} e^{-t^2/2} & \text{if } -\alpha_{Low} \geq t \geq \alpha_{High} \\ \dfrac{e^{-0.5\alpha_{Low}^2}}{\left[\frac{\alpha_{Low}}{n_{Low}}\left(\frac{n_{Low}}{\alpha_{Low}} - \alpha_{Low} - t\right)\right]^{n_{Low}}} & \text{if } t < \text{-} t = \Delta m_X/\sigma_{CB},\ \Delta m_X = m_X - \mu_{CB} \\ \dfrac{e^{-0.5\alpha_{High}^2}}{\left[\frac{\alpha_{High}}{n_{High}}\left(\frac{n_{High}}{\alpha_{High}} - \alpha_{High} + t\right)\right]^{n_{High}}} & \text{if } t > \alpha_{High}, \end{cases}$$

where $t=\Delta m_X/\sigma_{CB}$, $\Delta m_X = m_X - \mu_{CB}$, N is a normalisation parameter, μ_{CB} is the peak of the Gaussian distribution, σ_{CB} represents the width of the Gaussian part of the function, α_{Low} (α_{High}) is the point where the Gaussian becomes a power law on the low (high) mass side, n_{Low} (n_{High}) is the exponent of this power law

Signal parametrization

- The evolution of the Double-Sided Crystal Ball (DSCB) parameters as a function of $m_{\gamma\gamma}$ are then fitted to extract parameterizations.



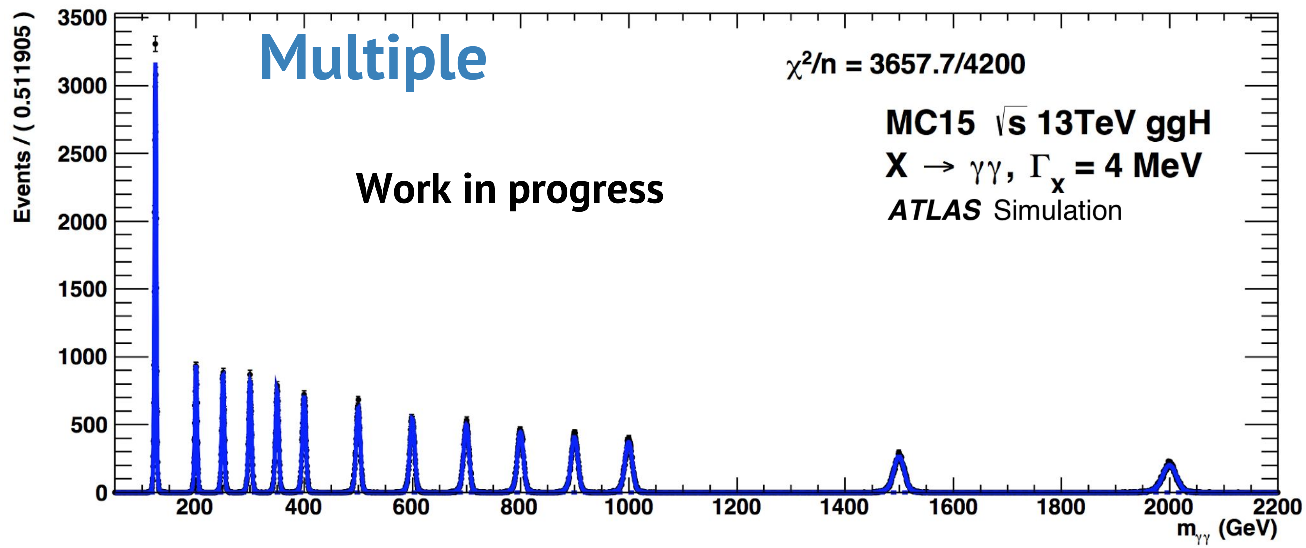
Parametrization DSCB

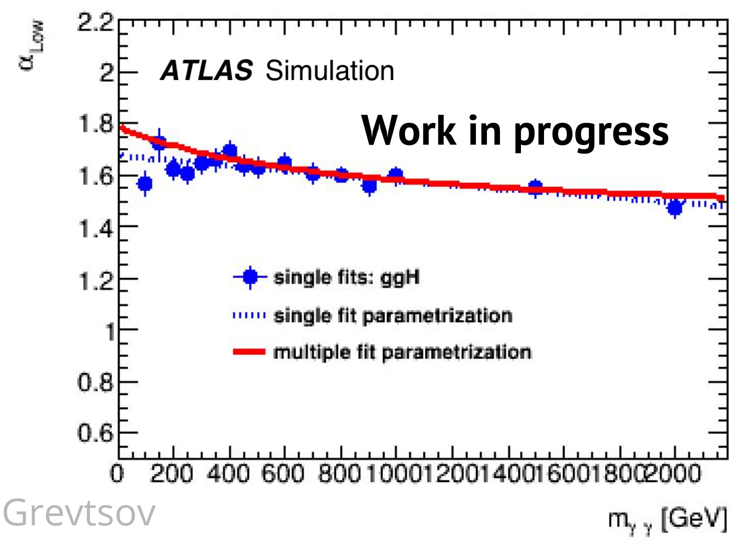
Parameter	Parametrization
Δm_X	$a+bm_{nX}+cm^2_{nX}$
σ_{CB}	$a+bm_{nX}$
α_{Low}	$a+b/(m_{nX}+c)$
n_{Low}	a
α_{High}	$a+b/(m_{nX}+c)$
n_{High}	a

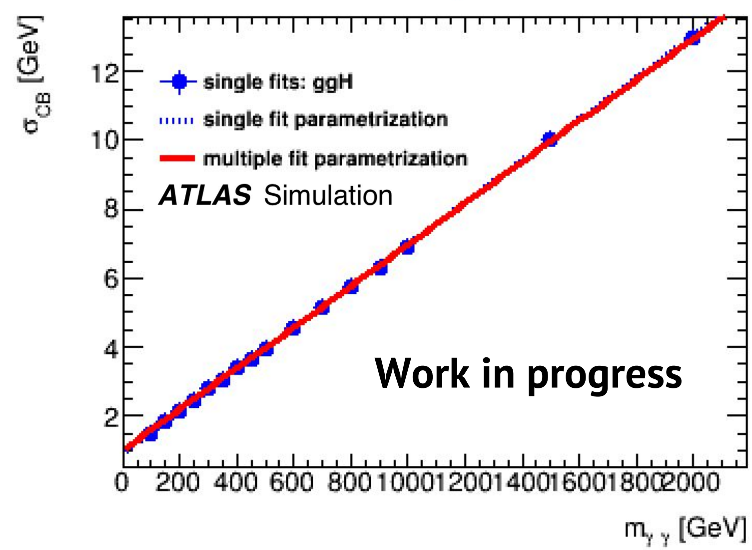
$m_{nX}=(m_X-100)/100$

Signal parametrization

- The parameterization functions of the DSCB parameters are used as input for a binned multiple mass point fit, where all the mass points are fitted simultaneously.

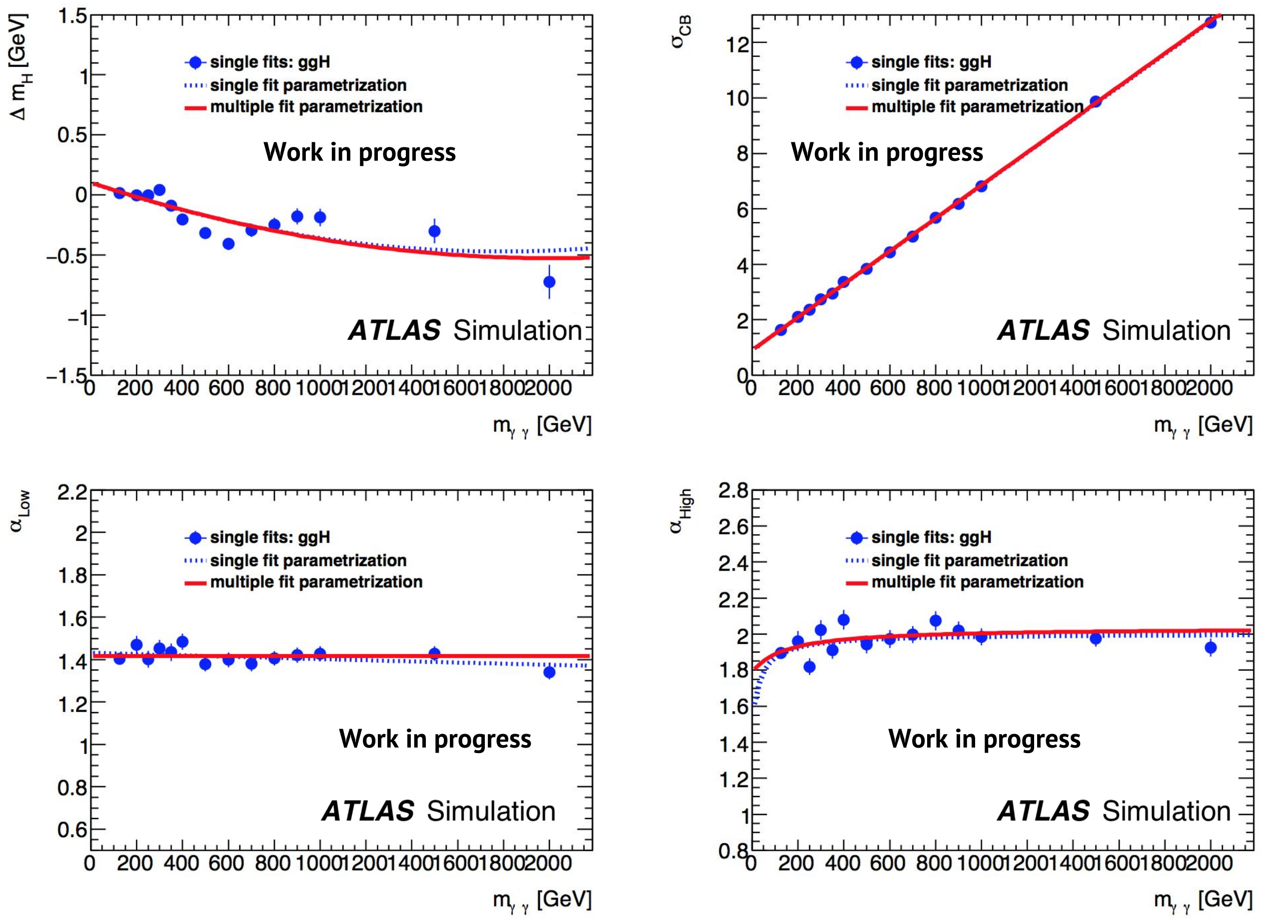






Signal parametrization

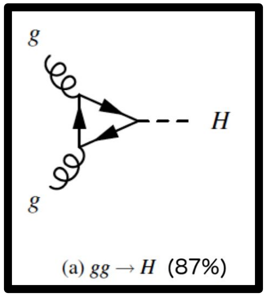
Signal parametrization procedure for Run 2



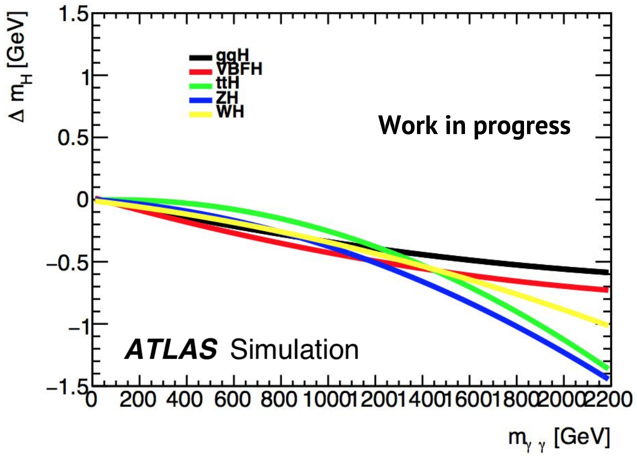
In order to make model independent search, signal parametrization was done for all production modes

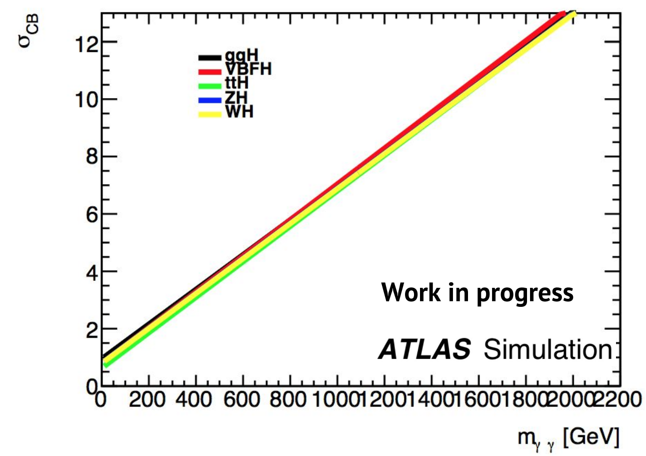
All production modes

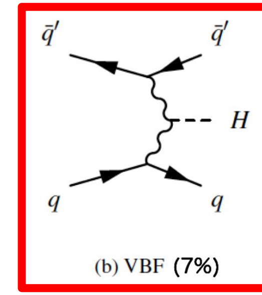
Checks were done to prove stability of procedure independently to production mode



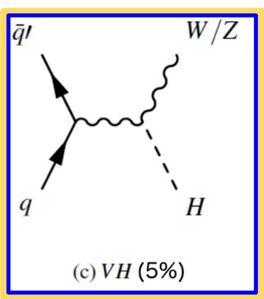
(a) $gg \to H$ (87%)



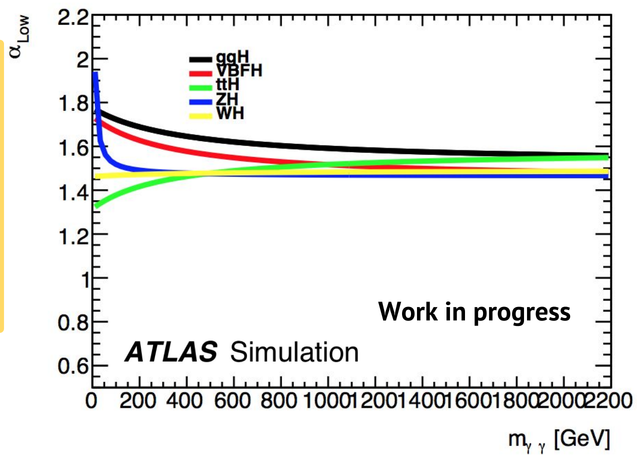


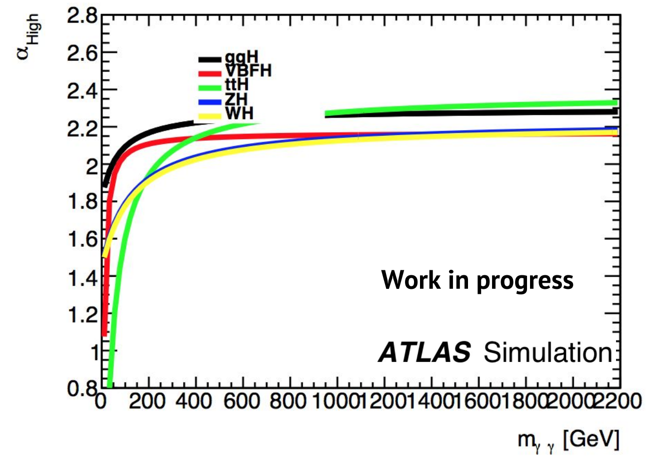


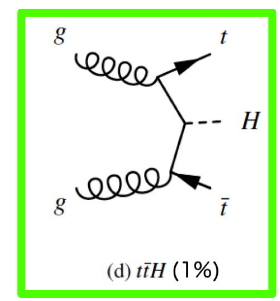
(b) VBF (7%)



(c) VH (5%)



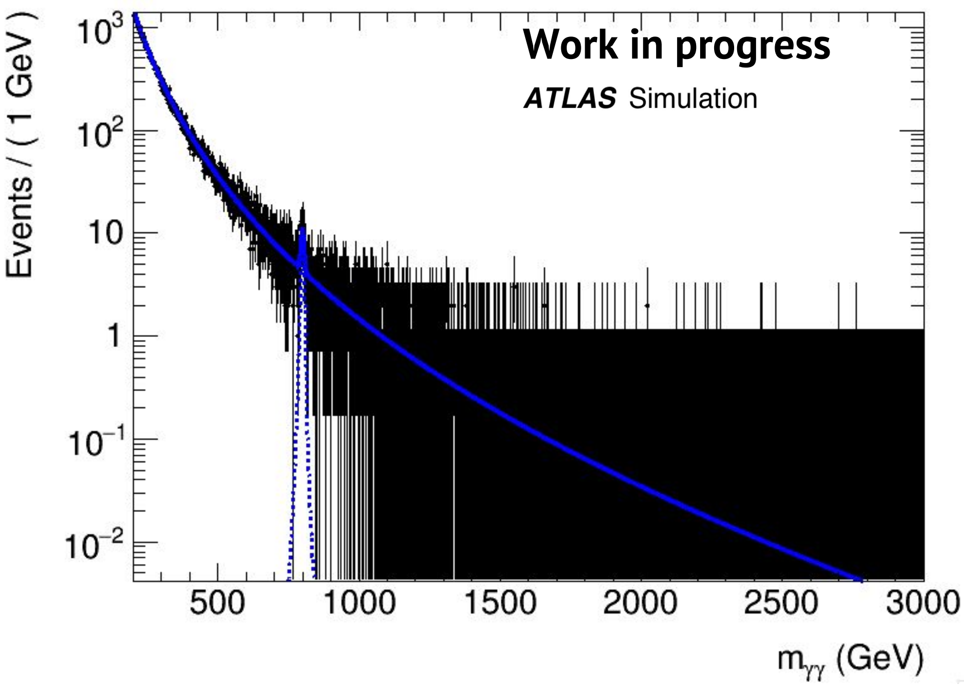


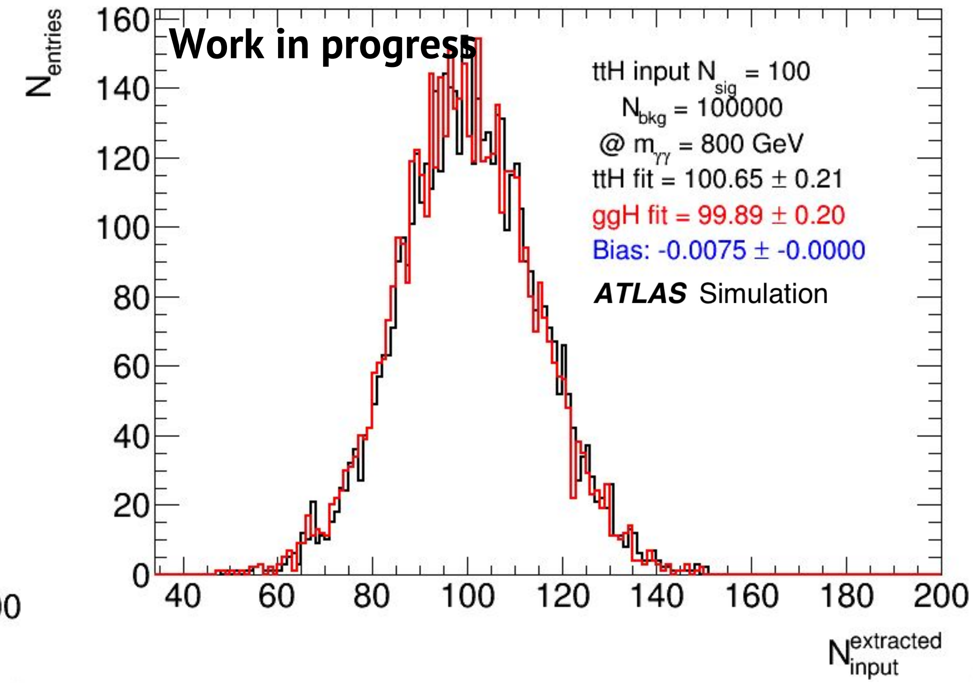


(d) $t\bar{t}H$ (1%)

To estimate impact of difference in signal parametrization for production modes, injection test been done

To estimate bias of choice of production mode, “toy” simulation was done. ttH signal was injected to background, and fitted with ggH assumption.



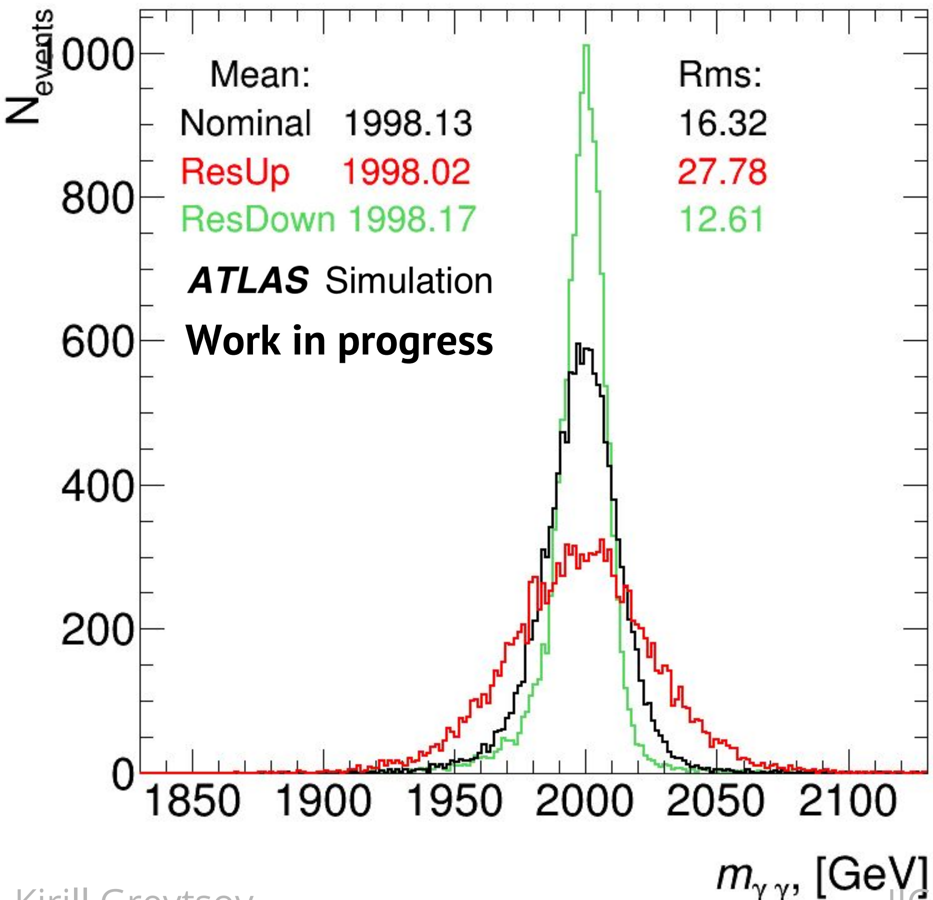


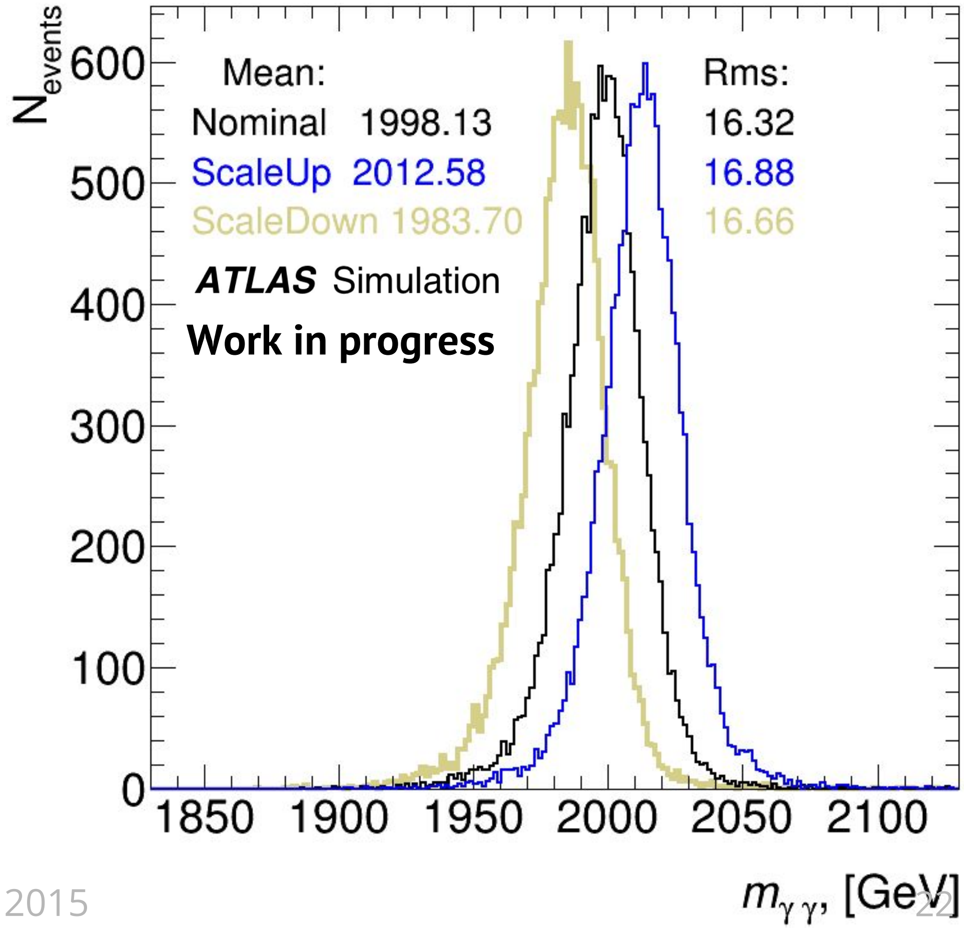
Bias of ~0.75% will be accounted as systematic uncertainty on choice of production mode for the signal parametrization

Variations

Use “simplified” decorrelation modes, vary up and down on size of uncertainty

- Resolution
- Scale

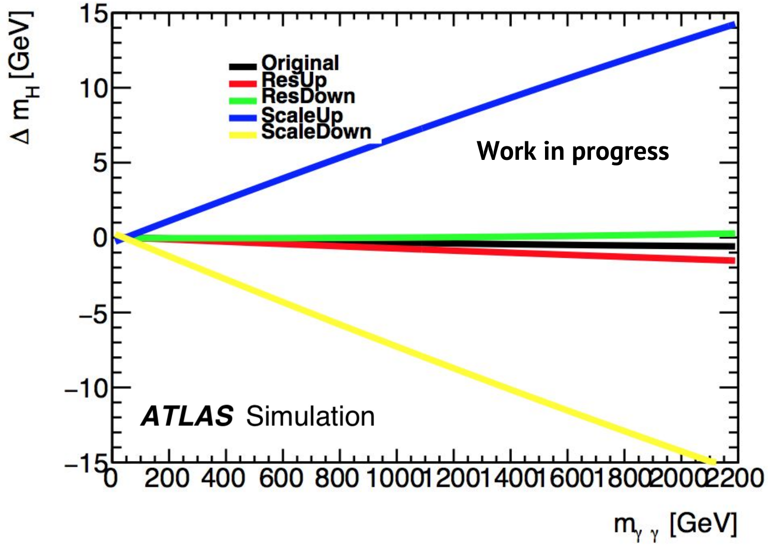




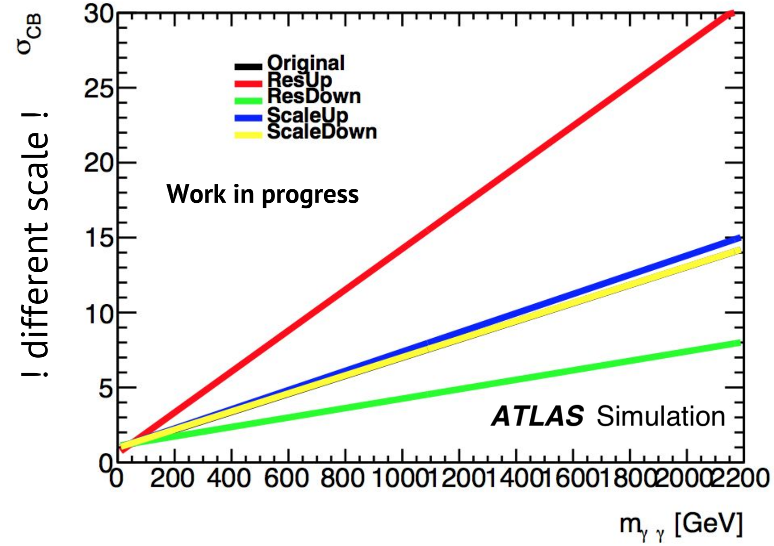
Variations

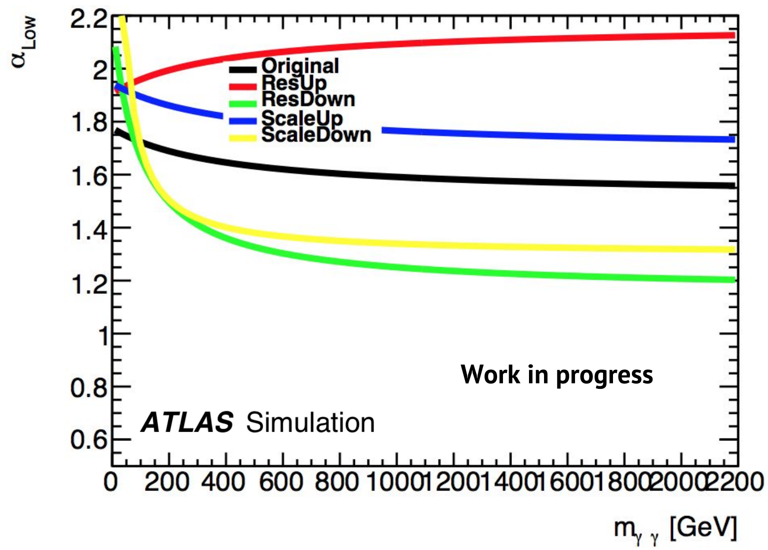
Impact on signal parametrization

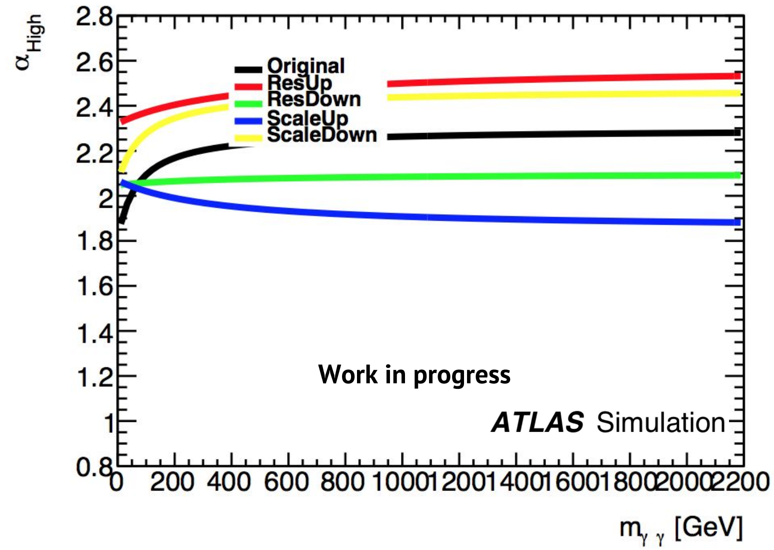
! different scale !



! different scale !

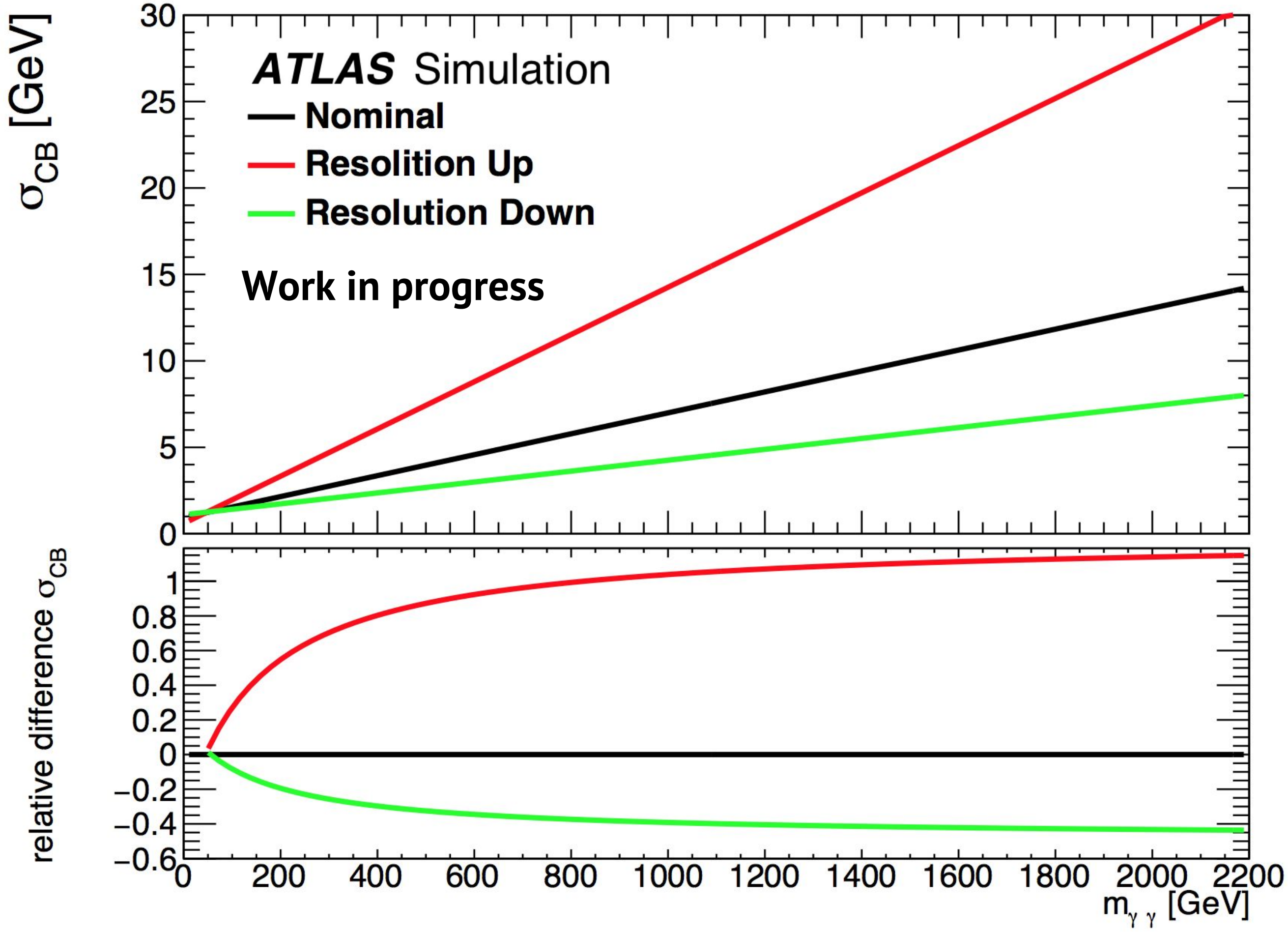






Variations

Dominant contribution from resolution variations will be included in Signal+Background fit as nuisance parameter.



Search for a resonance

All ingredients are ready:

- Look at the data - we have collected 3.3 fb^{-1} for whole 2015
- Present the search (p_0 plot)
- Publish results of the search: excess if any, cross-section $\times$ BR limit
    - I'm co-editor of supporting documentation for this analysis

Current situation

- Work with LAr calorimeter
- Calibration studies
- Photon performance studies
- Part of analysis in $\gamma\gamma$ final state

All these points are logical and are essential in the preparation of my thesis:

"Search for new particles with diphoton final state at LHC at $\sqrt{s}$=13 TeV with the ATLAS experiment and Higgs boson mass measurement."

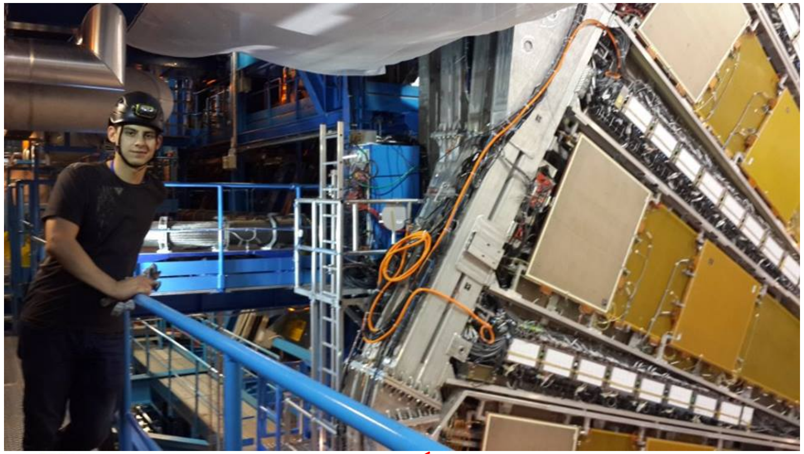
Thank you for your attention

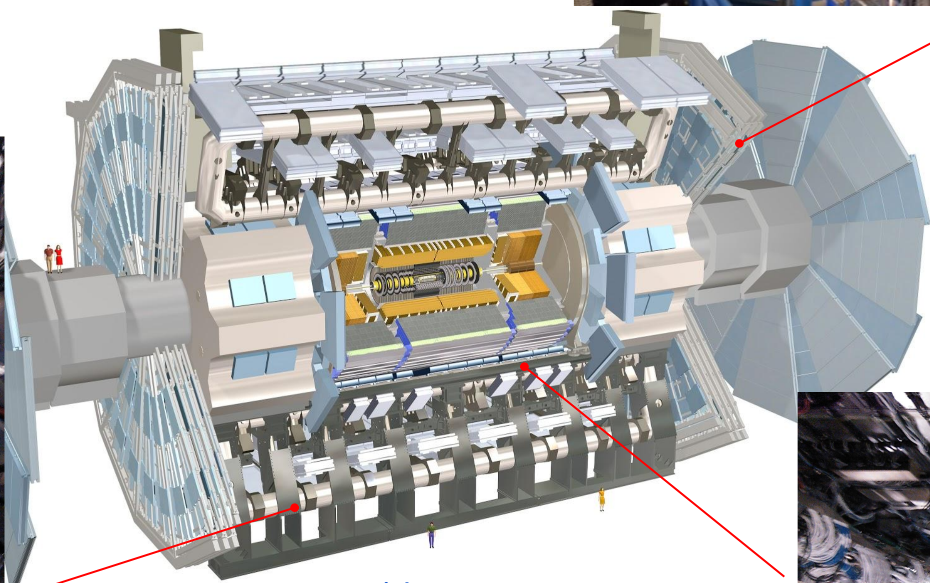
Inspection of the ATLAS cavern

Have a look on ATLAS!

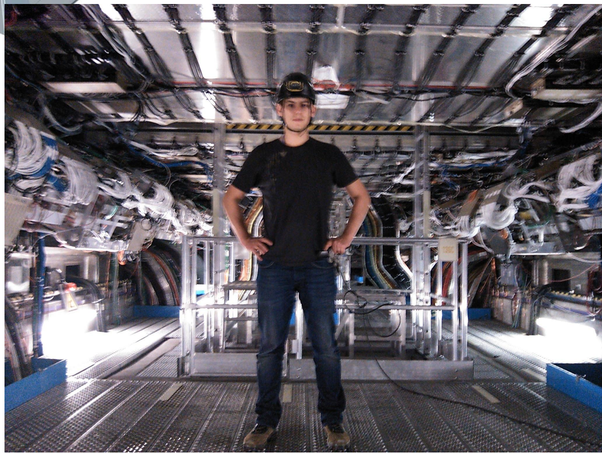
Inspection inside/outside before

ramping up ATLAS toroid magnet





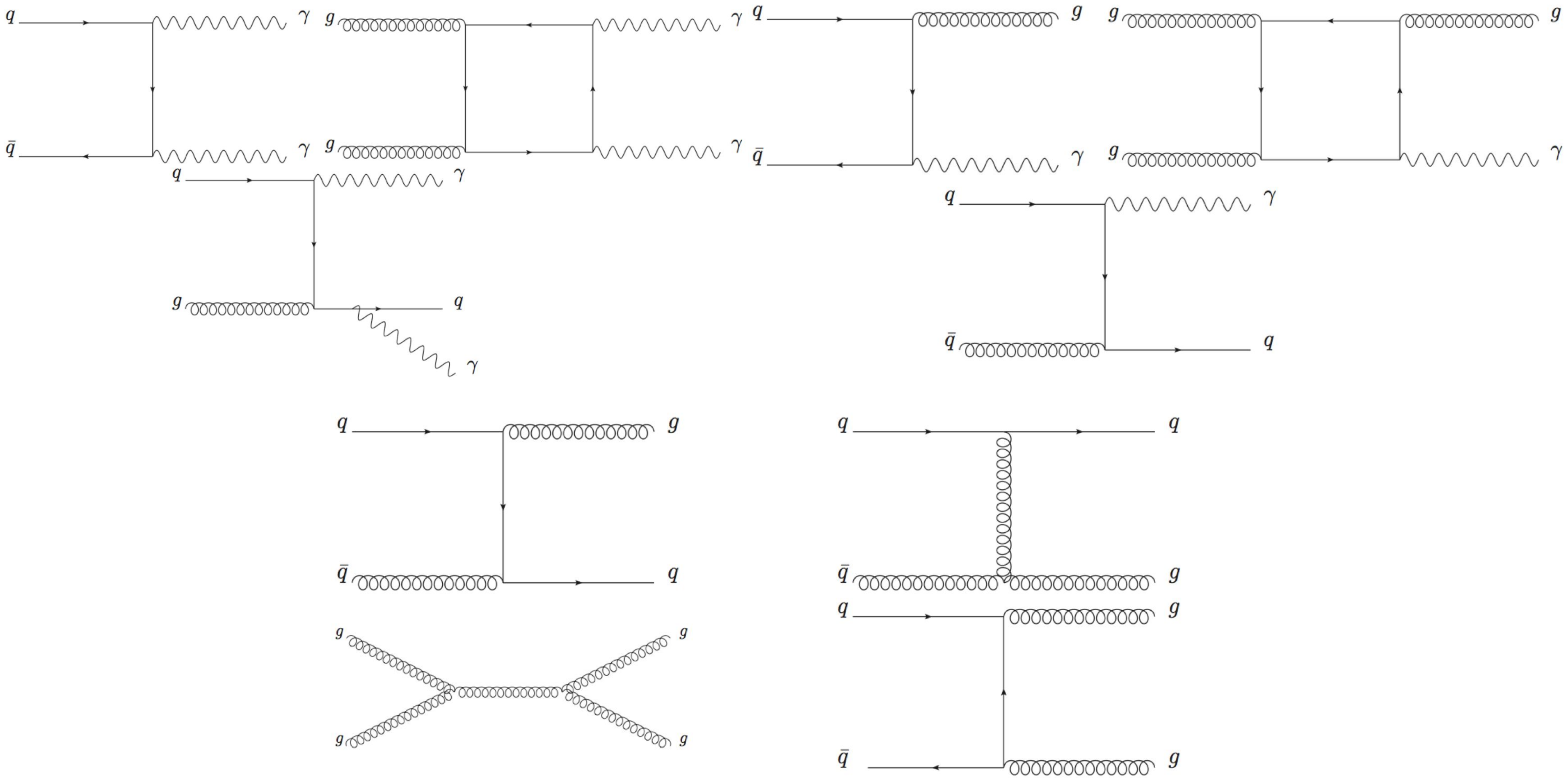
video tour



Backup

Search for a resonance

Decay - Background



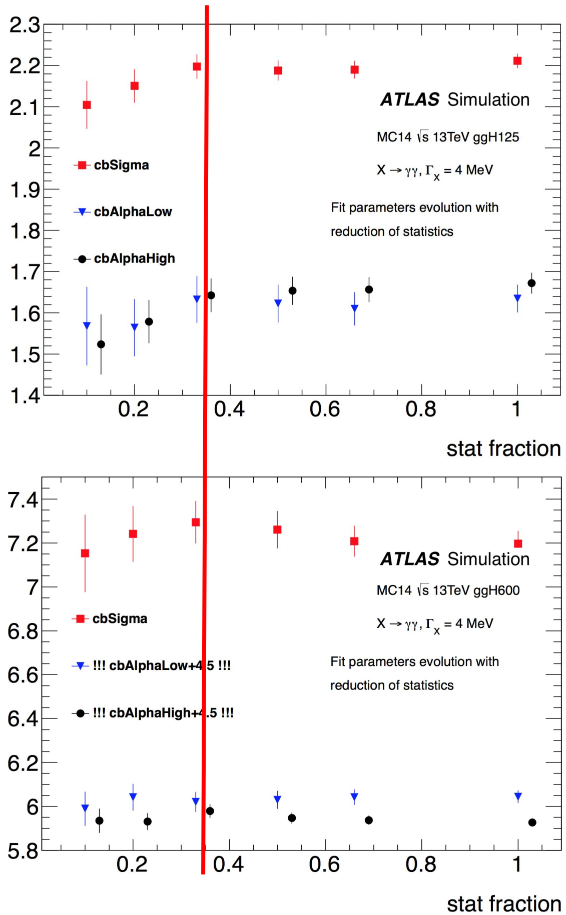
Selections

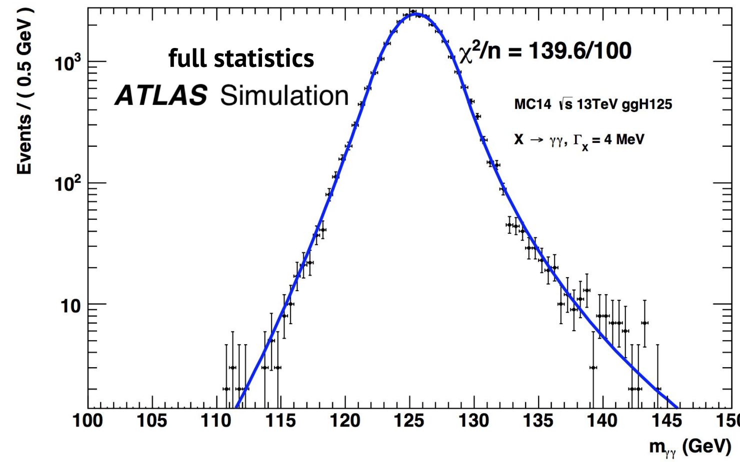
We require:

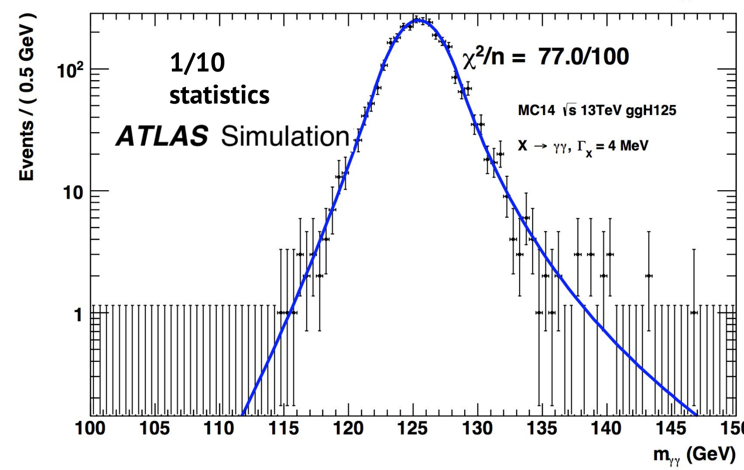
- basic preselections
  - trigger (HLT_g35_loose_g25_loose)
  - in good detector acceptance $|\eta|<2.37$ excluding crack)
  - photon's E_T greater than *15* GeV
- Tight photons (after this step we select pair of photons)
- Isolation (topoetcone40 < $0.022^* E_T + 2.45$ GeV && ptcone20 < $0.05^* p_T$)
- Relative p_T cuts: $E_T^{\gamma_i}/m_{\gamma\gamma} > 0.4/0.3$ (leading/subleading)

Estimation of required MC samples

Due to limitation of total amount of Monte Carlo, we have to reduce size of requested samples. Studies was done to **estimate limit, where signal parametrization is still valid**:

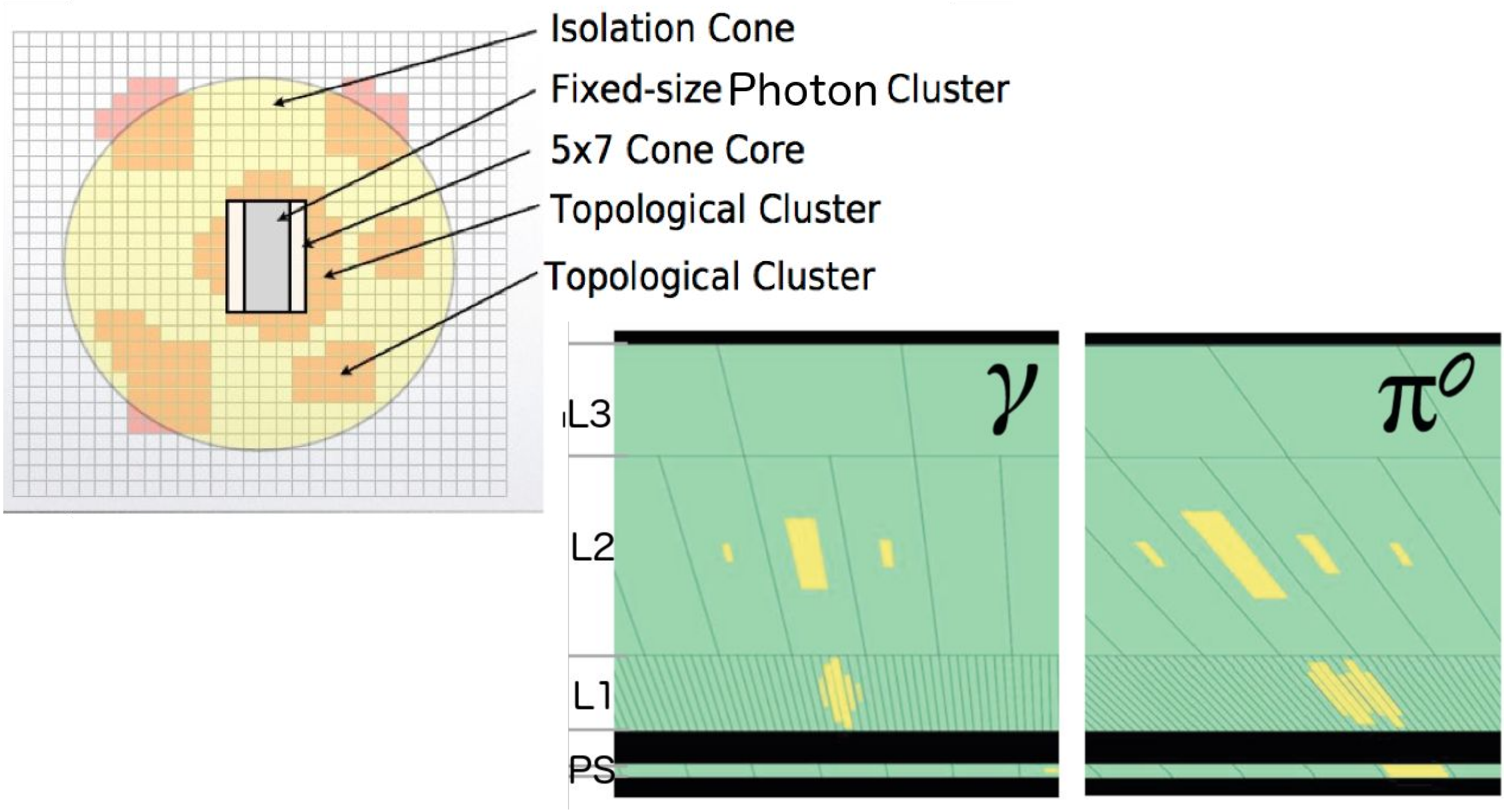






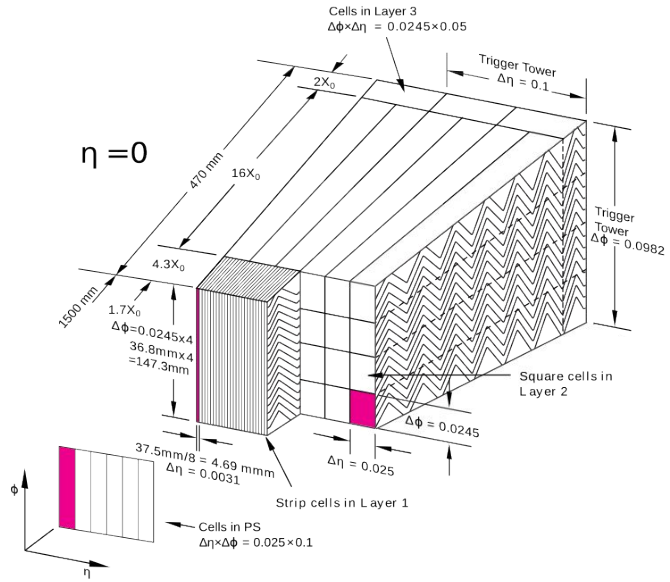
Decision was done to use ⅓ of statistics

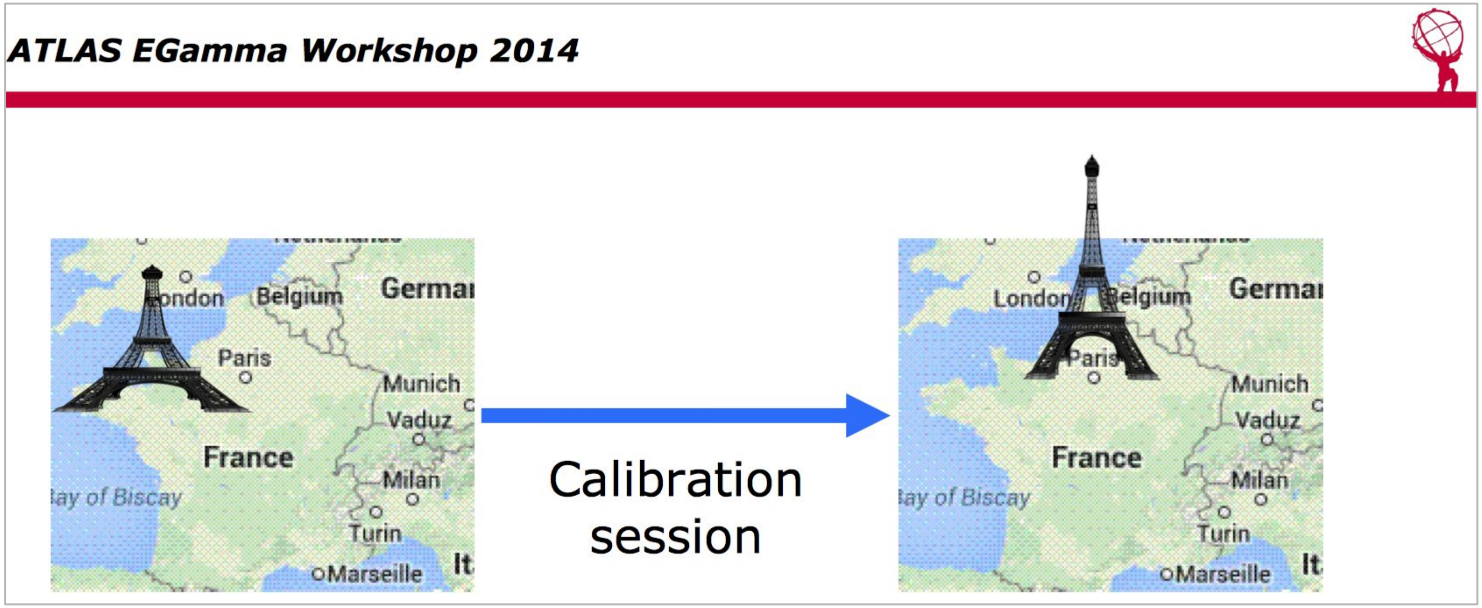
An isolation requirement, based on the transverse energy deposited in the calorimeters in a cone around the photon candidate, is used to further suppress the main background from neutral hadrons decaying into two photons.



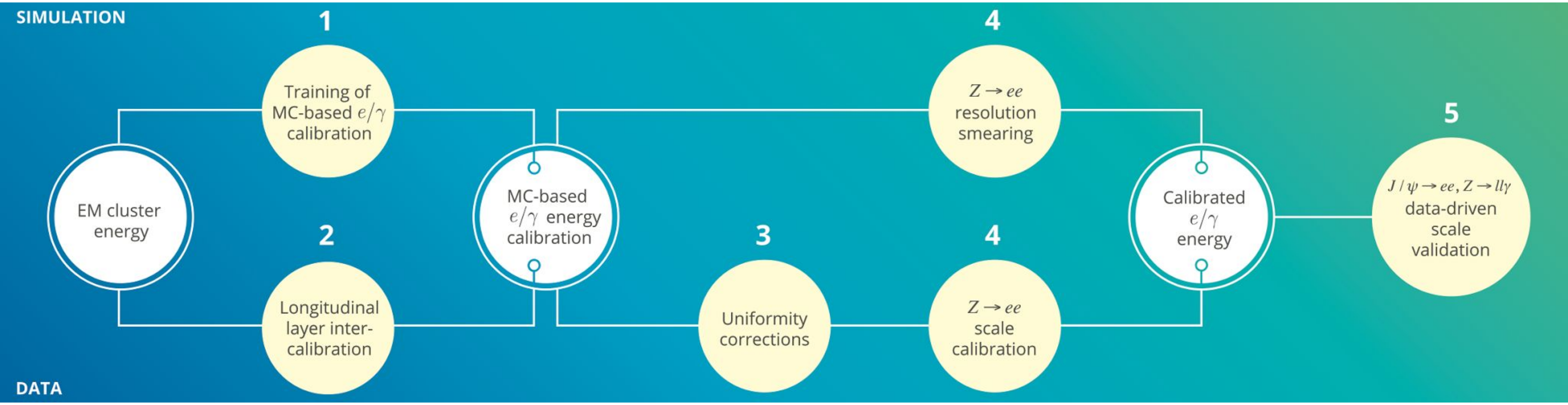
EM (e/γ) particle

- Collect deposited energy in EM calorimeter
- Signal reconstruction
  - particle reconstruction
  - identification
  - **calibration**





Calibration in ATLAS



1 - Optimisation of E_{reco}/E_{truth} using multivariate algorithm (MC-based)

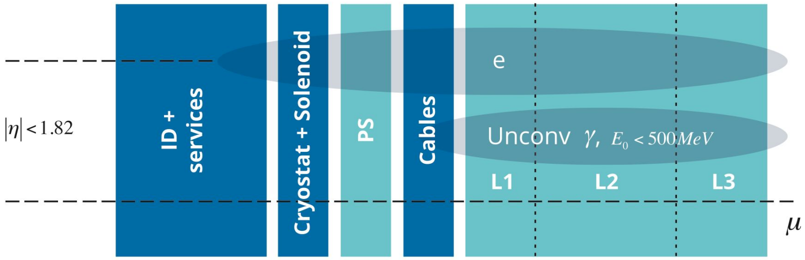
Inputs: $E_{\text{accordion}}, E_0 / E_{\text{accordion}}, X, \eta_{cluster}, \eta^{calo}_{cluster}, \varphi^{calo}_{cluster}$

energy deposited in the cluster

ratio of presampler to cluster energies

shower depth

position parameters



2,3 - specific data handling:

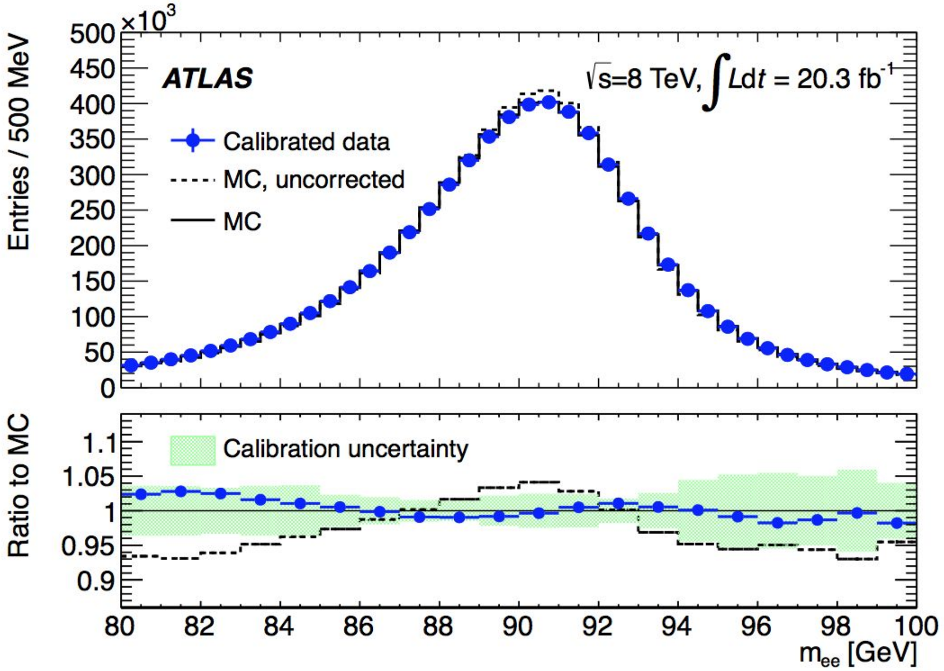
- Intercalibration of the 1st and 2nd calorimeter layers
- uniformity corrections

4 - energy scale and resolution:

difference in response between data and simulation

5 - data-driven validation

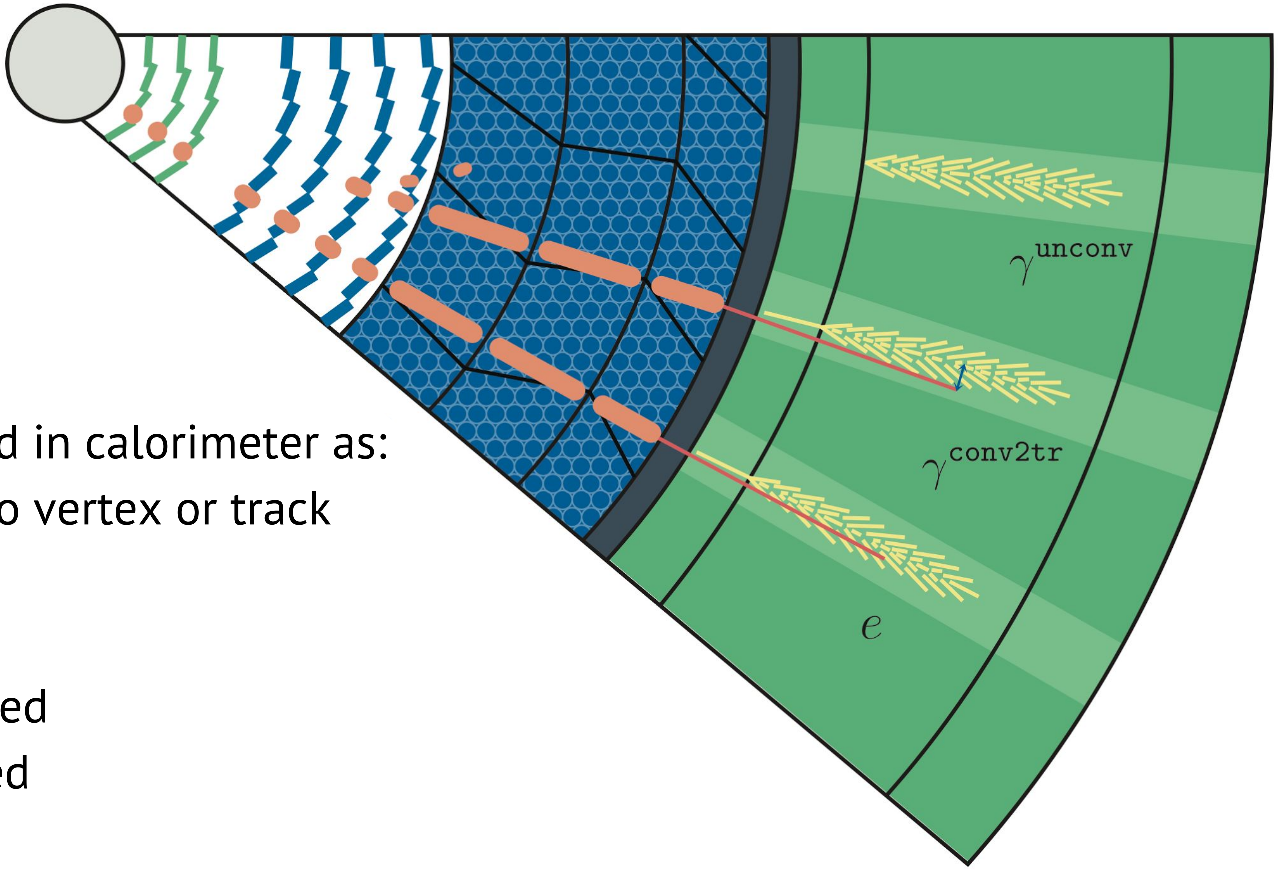
And we do it with incredible precision:



Electron pair invariant mass distribution for *Z→ee* decays in data and improved simulation. Ratio of the data and uncorrected MC distributions to the corrected MC distribution with the calibration uncertainty band.

MC corresponds to Data within ~1-2%, which is inside systematic coverage.

Photon conversion

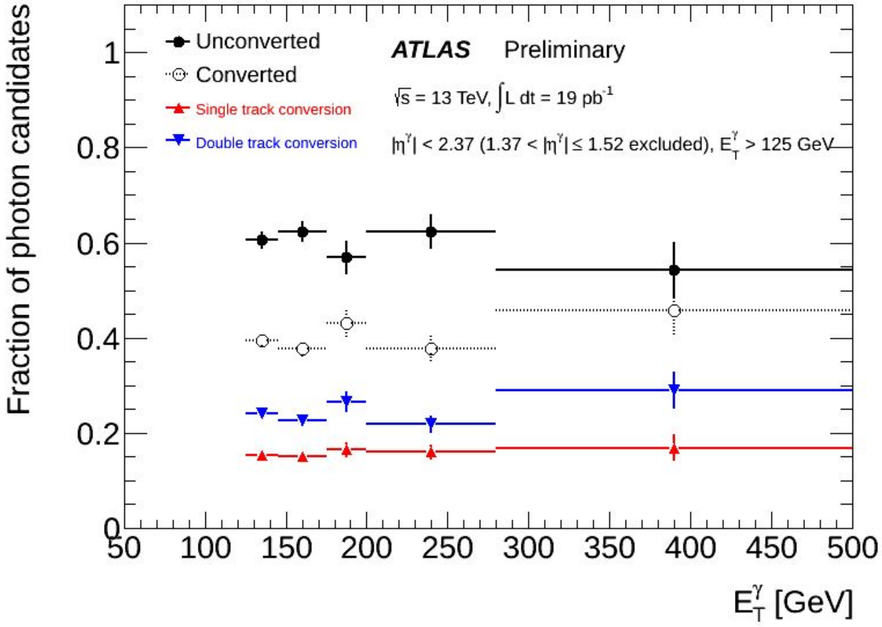


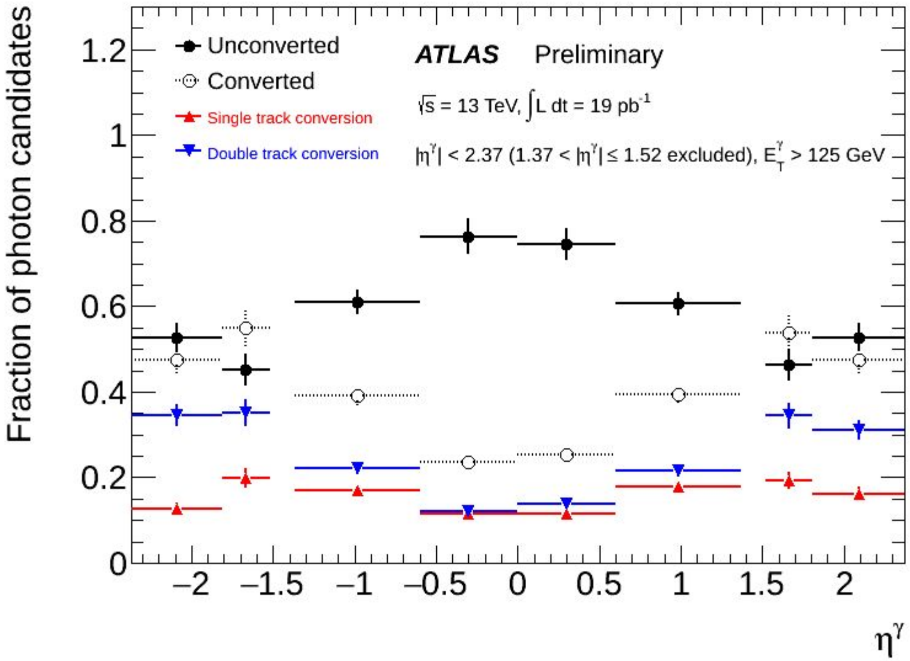
Photons can be reconstructed in calorimeter as:

- unconverted photons (no vertex or track matched to the cluster)
- converted photons
  - double track matched
  - single track matched

Photon conversion

Using first 2015 data, the performance of the ATLAS detector was tested.
I studied the fraction of the three types of photon candidates
Requiring high E_T cut, isolation and η region we selected photon candidates with 95% purity

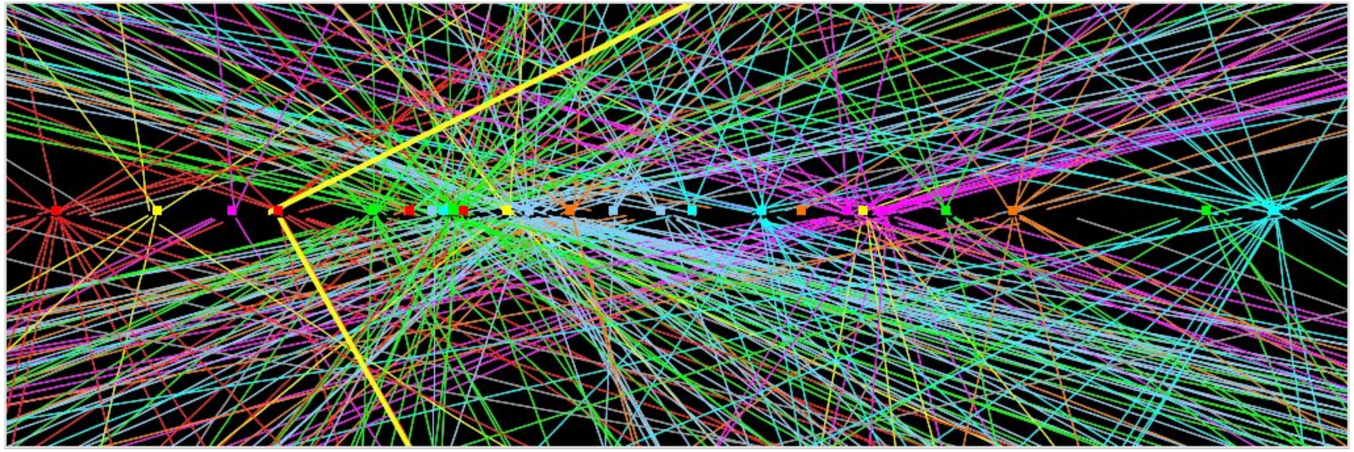




These plots were approved as public by ATLAS for the EPS conference, and shown there in my poster

Pileup

Proton-proton collisions in LHC produce multiple interactions per bunch crossings



	2010-2011	2012-2013	2015
√*s*, TeV	7	8	13
<μ>	9.1	20.7	*~25*

MC simulated before, and to account various number of pileup in data, in MC it is generated in wide range