

Search for a narrow resonance decaying to two photons with the ATLAS detector using 21 fb^{-1} of proton-proton collision data

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- Calorimeter studies for LHC Run 2
 - Liquid Argon Calorimeter noise study and study of LAr samples
- Performance studies in Run 1
 - Photon energy scale intercalibration in ϕ
- Physics Analysis
 - Signal modelling of $H \rightarrow \gamma\gamma$ Monte Carlo samples from 80 GeV to 1 TeV



Search for a narrow resonance decaying to diphotons in ATLAS

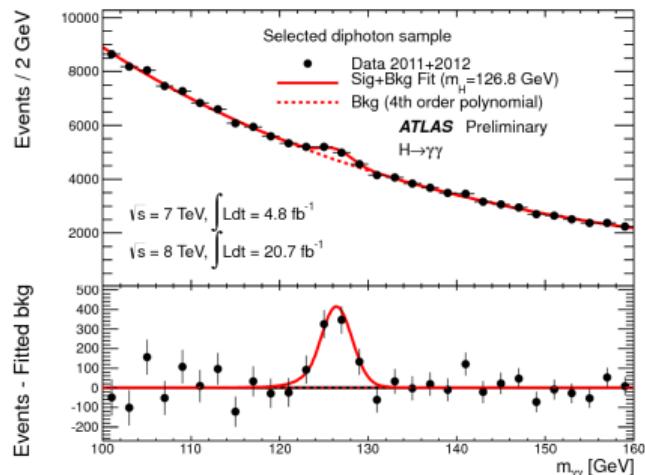
Outline

- Motivation - keywords: narrow, fiducial, model independent
- Event selection
- Fiducial volume definition
- **Signal modelling**
- Background modelling
- Systematic uncertainties
- Results

Motivation

Where we stand now in $H \rightarrow \gamma\gamma$ in ATLAS

- $m_H = 126.8 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$ GeV
- precision of mass measurement $\approx 0.6\%$ dominated by photon energy scale uncertainties
- signal strength (wrt SM prediction) $\mu = \frac{N_{\text{observed}}}{N_{\text{SM}}} = 1.57 \pm 0.22(\text{stat})^{+0.24}_{-0.18}(\text{syst})$
- **only looking at the $m_{\gamma\gamma}$ region between 100 - 160 GeV**



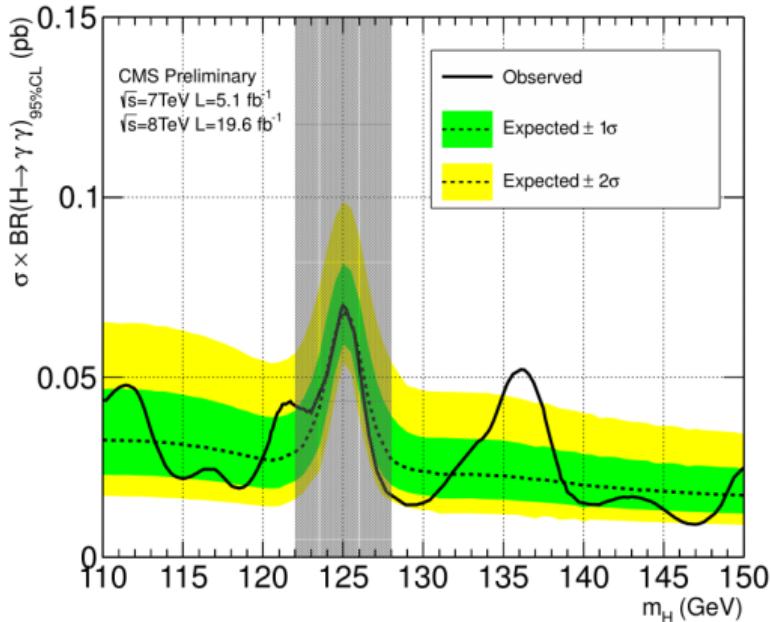
Search for other ' $H \rightarrow \gamma\gamma$ ' states in ATLAS

Goals of the analysis:

- extend the mass region to $70 \text{ GeV} < m_X < 600 \text{ GeV}$
- search for additional Higgs-like states (apart from 126 GeV)
 - Higgs singlet (G. Pruna, T. Robens. arXiv:1303.1150), extra Higgs singlet coupling only to Higgs, interesting at low mass
 - 2HDM model: $h, H, A, H^+ H^-$, additional doublet \rightarrow one more scalar
- set a limit on the fiducial cross section of a narrow resonance decaying to diphotons in this mass region
 - narrow = in experimental terms - up to the detector resolution
 - fiducial = defining a region with the best sensitivity
 - provide a model independent measurement
 - analysis similar to SM Higgs search in diphotons
 - analysis split to low mass and high mass part (70-110 GeV, 110-600 GeV)
 - $H(126)$ signal included as background

Other searches for additional 'H' states decaying to $\gamma\gamma$ so far

- CMS limit on additional states in the mass window of 110 - 150 GeV
- ATLAS: extend the mass region and measure fiducial cross-section



Event selection

Event selection

Default selection - same as $H \rightarrow \gamma\gamma$ analysis

- 2012 data – $\sqrt{s} = 8$ TeV p–p collisions
- diphoton trigger – $E_{\gamma T}^{leading} > 35$ GeV, $E_{\gamma T}^{sub-leading} > 25$ GeV, loose shower shape criteria
- standard data quality requirements: no errors in calorimeter, data suitable for physics measurements
- total integrated luminosity used: 20.7 ± 0.7 fb^{-1}

Relative E_T cuts

- to provide better sensitivity for masses above 126 GeV (maximizing the ratio of the significance with relative cuts wrt default cuts, plus leakage undercorrection)
- $E_{\gamma T}^{leading} / m_{\gamma\gamma} > 0.4$, $E_{\gamma T}^{sub-leading} / m_{\gamma\gamma} > 0.3$

Tight cuts - on shower shape variables
Isolation cuts

- to get a constant calorimeter isolation efficiency with E_T
- $I_{calo}^{corr} = I_{calo}$ (6 GeV cut) for $E_T \leq 80$ GeV
- $I_{calo}^{corr} = I_{calo} - 0.7\%(E_T - 80 \text{ GeV})$ for $E_T > 80$ GeV

Eta region: $|\eta| < 2.37$

To ensure model independence - the signal reconstruction efficiency needs to be constant
→ using relative E_T and isolation cuts + defining fiducial volume

Fiducial volume definition

Fiducial volume definition

- for fiducial cross-section → correct the number of fitted signal events in data for the detector effects: reconstruction, identification and selection efficiencies

$$\sigma.BR = \frac{N_{events}}{\epsilon L} \quad \epsilon = A.C_H \quad A - \text{truth acceptance}$$

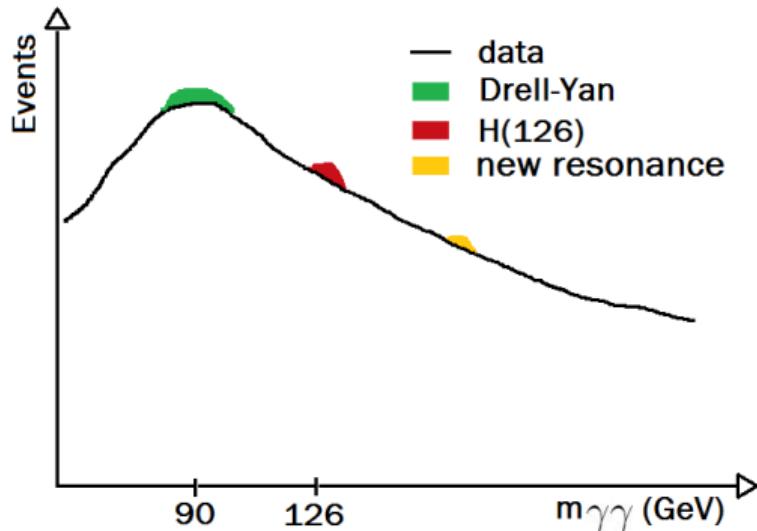
$$\sigma_{fid}.BR = \frac{N_{events}}{C_H L} \quad C_H = \frac{N_{selection}}{N_{acceptance}} - \text{correction factor, to assure model independence}$$

Acceptance cuts applied at truth level:

- $E_{\gamma T}^{leading}/m_{\gamma\gamma} > 0.4, E_{\gamma T}^{sub-leading}/m_{\gamma\gamma} > 0.3$ (relative = mass dependent cuts)
- truth isolation cut (in MC):** P_T sum of all stable particles found within a cone of $\Delta R < 0.4$ must be lower than 12 GeV (corresponds to the calorimeter isolation energy cut of 6 GeV)

What are we dealing with?

- Signal modelling
- Background modelling
- a lot of uncertainties



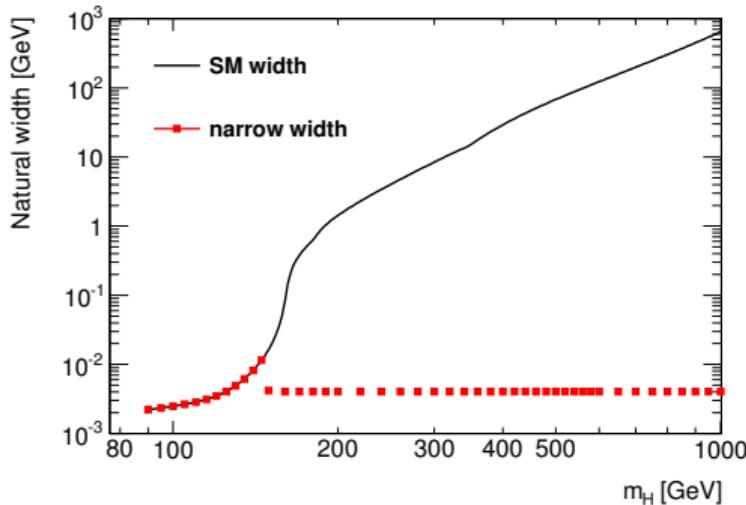
Signal modelling

80 GeV - 1 TeV

Signal modelling

Signal modelling of m_X :

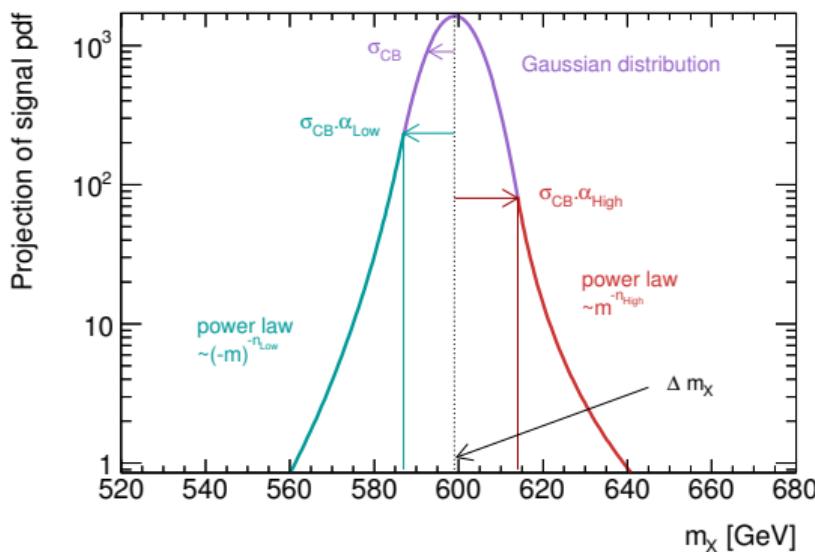
- MC samples (PowHeg and Pythia) in a wide diphoton invariant mass region (up to 1 TeV - possibility to increase mass range after taking more data in 2015)
- simulated with a narrow width approximation
 - $m_X > 150$ GeV
 $\Gamma_X = 4$ MeV
 - $m_X \leq 150$ GeV $\Gamma_X = \Gamma_{SMH}$



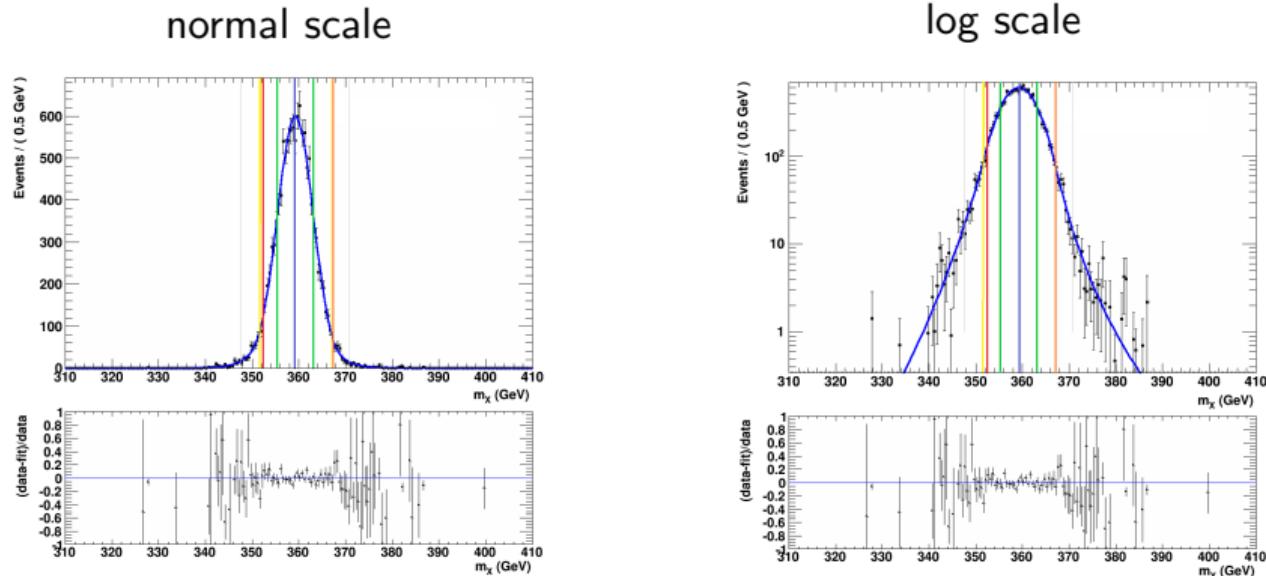
Signal fit function

Double sided Crystal ball

- Gaussian core in the center of the peak (energy resolution of the detector)
- power law tails - asymmetric low and high mass tails (calibration, material mismodelling)

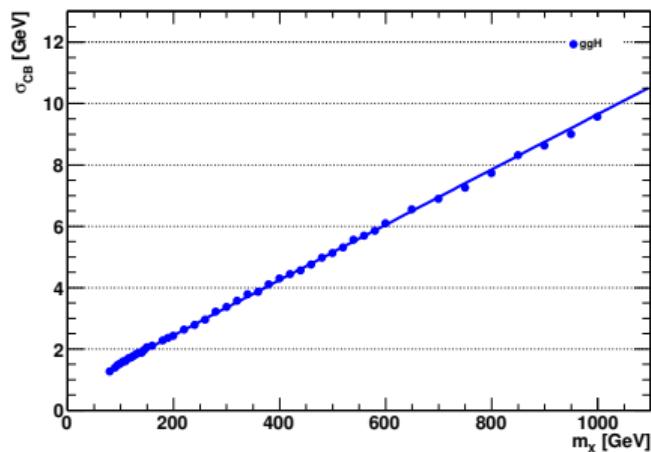
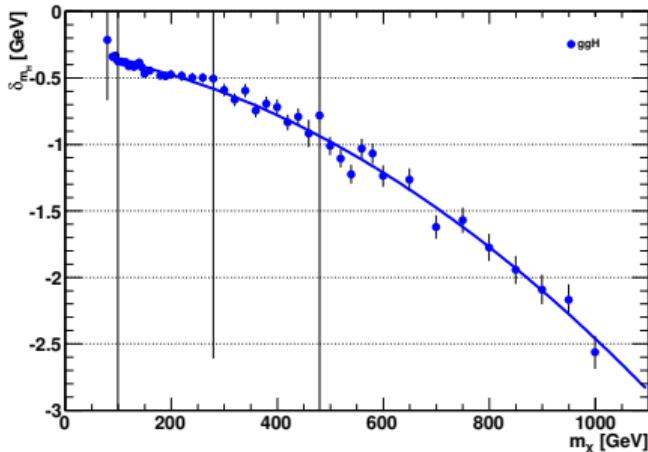


Example of a fit - ggF at 360 GeV



μ_{CB} , $\pm 1\sigma_{CB}$, $\pm 2\sigma_{CB}$, $\pm 3\sigma_{CB}$, $\sigma_{CB}.\alpha_{Low}$, $\sigma_{CB}.\alpha_{High}$
→ obtain 6 parameters from all mass points
→ plot them as a function of m_χ

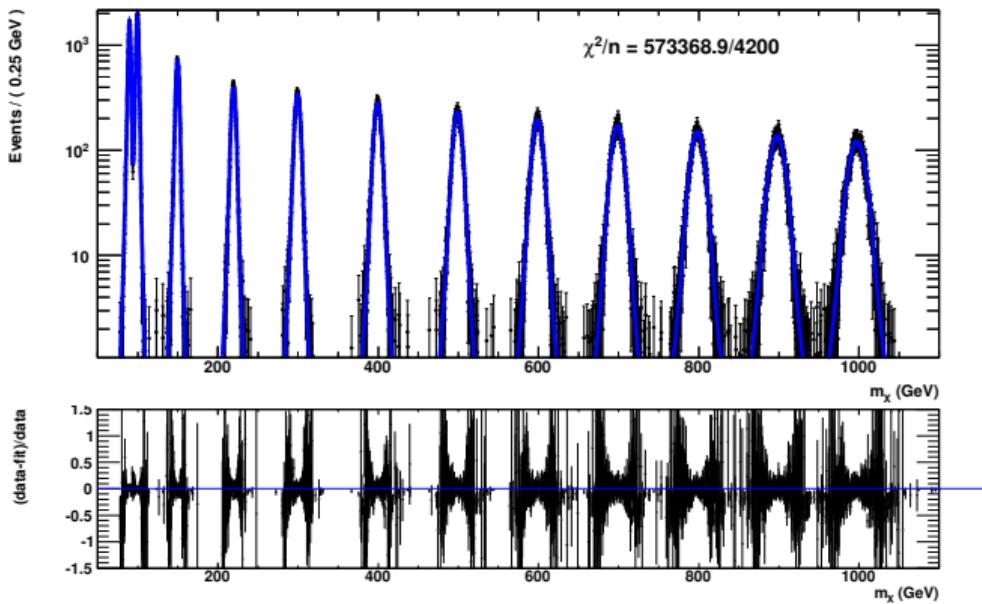
$\delta m_X = \mu_{CB} - m_X$ and σ_{CB} – width of the Gaussian core



→ σ_{CB} dominated by the detector effect

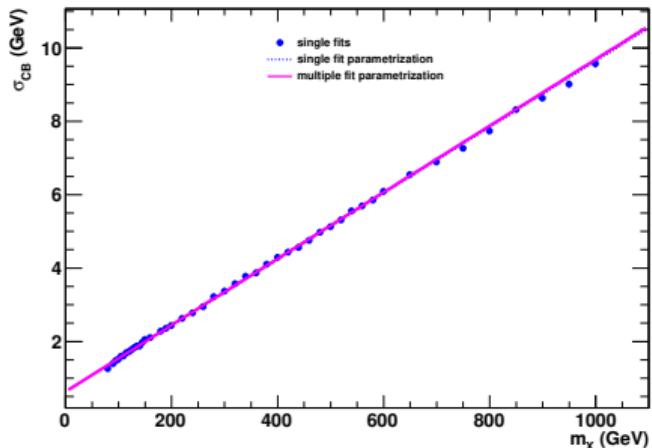
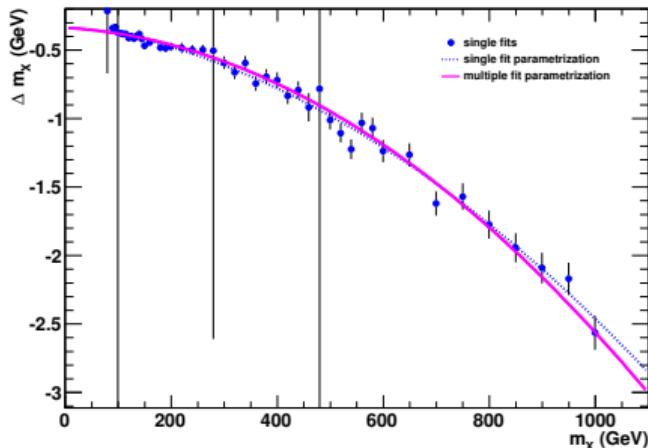
- determine the appropriate function describing the parameter evolution with mass - a parametrization
- use the parametrization as input for a multiple mass point fit

Multiple mass point fit, ggF, select samples



→ simultaneous fit of multiple mass points

Comparison of single and multiple mass point fit results



→ excellent agreement

→ input into the limit calculation

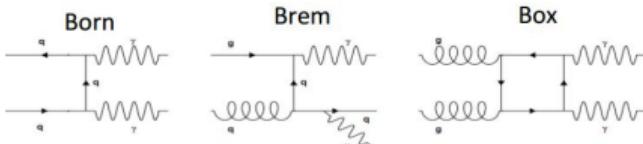
Background modelling

Background modelling

Main backgrounds:

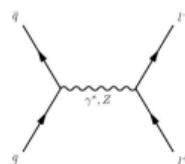
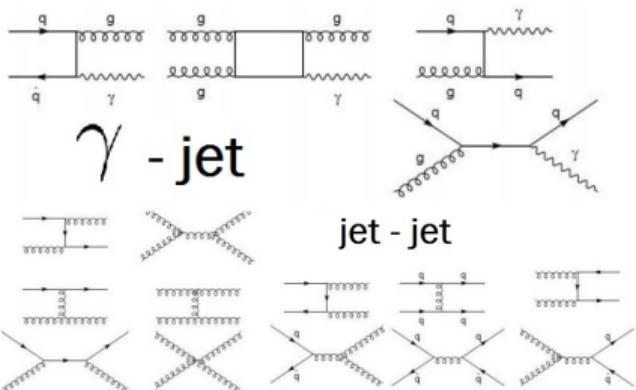
- **irreducible**

- Standard Model diphoton production
- H(126) included with $\mu = 1$ (SM-like)



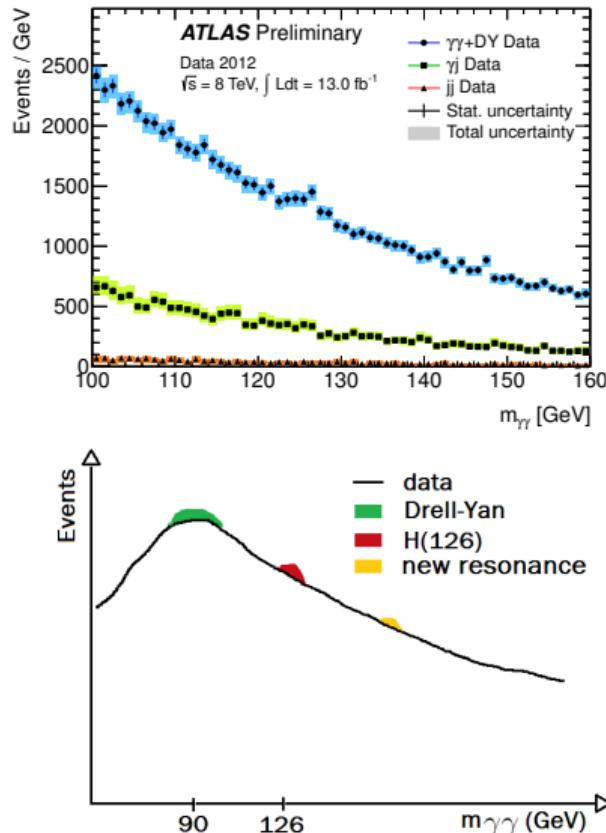
- **reducible**

- γ -jet, jet-jet pair events (one or two jets misidentified as photons)
- resonant (Z) and non-resonant (Drell-Yan) e^-e^+ production with electrons misidentified as photons



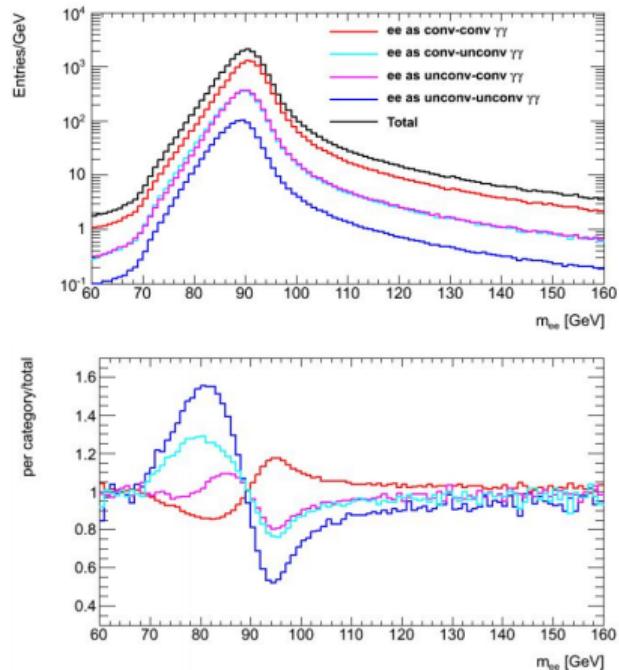
Background modelling

- **GOAL: finding the proper function to describe data** in much larger mass range than before: 70-600 GeV
- blind analysis - model on Monte Carlo background samples - Sherpa, Diphox
- challenges:
 - Drell-Yan peak (around Z mass)
 - Higgs peak (126 GeV)
 - turn-on at low mass (around Z mass - trigger choice)
 - Drell-Yan on top of turn-on
 - spurious signal



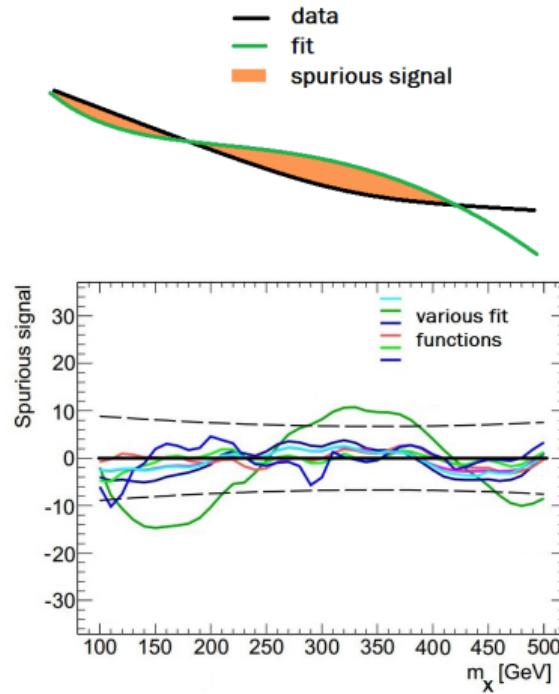
Background modelling - Drell-Yan template

- to obtain a template - need to properly understand fake rates to correctly estimate the position and amplitude of the Drell-Yan peak
- fake rates - electrons reconstructed as photons and vice versa
- use $Z \rightarrow e^+e^-$ MC events to estimate fake rates
- to get the best description - introducing conversion categories at low mass, splitting the analysis to **low mass (70-110 GeV) and high mass part (110-600 GeV)**
- obtain 3 templates (converted-converted, unconverted-unconverted, converted-unconverted + unconverted-converted)
- use the templates in the final background fit



Background modelling - spurious signal uncertainty computation

- spurious signal - number of events fitted as signal in a signal plus background fit while only using background events (high statistics MC)
- in ATLAS: must be below 20% of background uncertainty



Systematic uncertainties

Systematic uncertainties

Signal yield:

- luminosity, trigger, photon identification, isolation efficiency, photon energy scale

Signal modelling:

- **pile-up** - difference between candidates from low/high pile-up conditions
- **uncertainty coming from the different production processes**
(besides ggH, there is VBFH, VH, $t\bar{t}H$)
- **photon energy resolution**
$$\frac{\sigma(E)}{E} \cong \frac{A}{\sqrt{E}} + C$$
, A = sampling term,
C = constant term
(noise term is negligible in this study)

C_H factors:

- production processes
- pile-up
- multiple parton interaction

Background modelling:

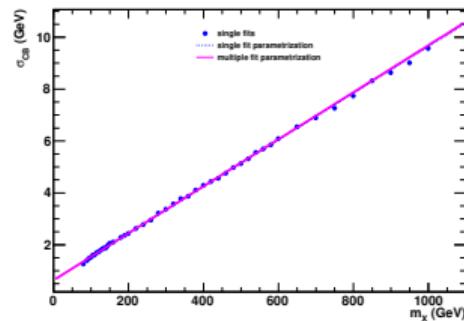
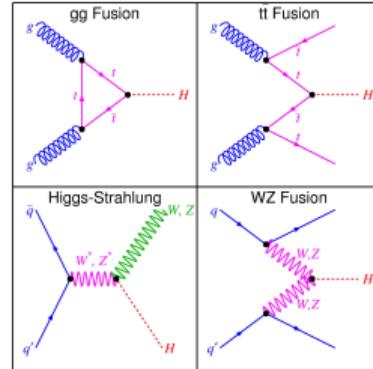
- spurious signal
- Higgs background theory (ggF, VBFH, $t\bar{t}H$, WH, ZH)
- branching ratio
- Drell-Yan background modelling:
normalization, energy scale, resolution, shape

Systematic uncertainties - signal modelling

- **pile-up:** studied the effect of low and high pile-up - multiple mass point fit of events coming from low ($\mu < 18$) and high ($\mu \geq 18$) pile-up events
→ then computed the event yield difference between the two obtained parametrizations → **NEGLIGIBLE**
- **production process difference:** determined a **below 1%** systematic uncertainty on the event yield due to production process
- **photon energy resolution:**

$$\frac{\sigma(E)}{E} \approx \frac{A}{\sqrt{E}} + \frac{B}{E} + C$$

- $A \approx 9.5\%$ sampling term
- $B \approx 250$ MeV noise term
- $C \approx 1\%$ constant term
- $\approx 20\%$ at 126 GeV



Results

Statistical model

Maximum likelihood method:

- performing an unbinned likelihood fit on the whole $m_{\gamma\gamma}$ range - split to two parts
- high mass part :new resonance X, Higgs at 126 GeV, background

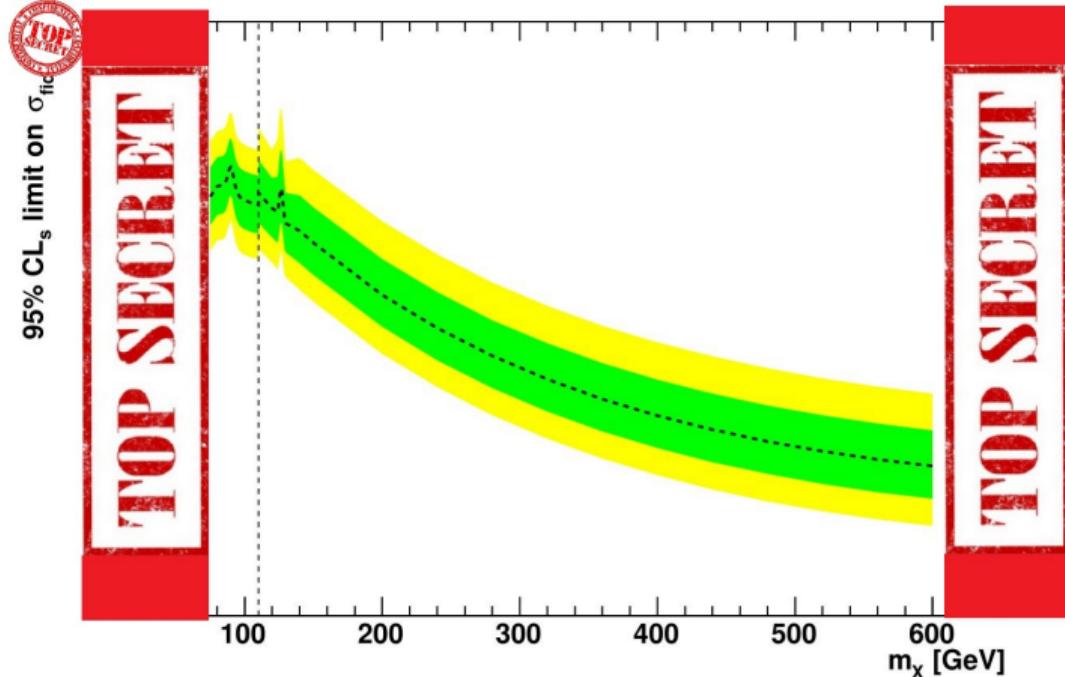
$$\begin{aligned}\mathcal{L}(m_{\gamma\gamma}; \sigma_{fid}, m_X, \mu, m_H, N_{bkg}, \xi, \vec{\theta}) &= N_X(\sigma_{fid}, m_X, \vec{\theta}_{N_X}, \theta_{ss}) f_X(m_{\gamma\gamma}, m_X, \vec{x}_X(m_X), \theta_\sigma) \\ &+ N_H(\mu, \vec{\theta}_{N_H}) f_H(m_{\gamma\gamma}, m_H, \vec{x}_H(m_H), \vec{\theta}_H) \\ &+ N_{bkg} f_{bkg}(m_{\gamma\gamma}, \xi(m_H))\end{aligned}$$

- parameter of interest: σ_{fid}
- nuisance parameters: PDF parameters, background, efficiencies

Likelihood including the extended and constraint terms:

$$\begin{aligned}\mathcal{L}(\sigma_{fid}, m_X, \mu, m_H, N_{bkg}, \xi, \vec{\theta}) &= \\ e^{-(N_X + N_H + N_{bkg})} &\left[\prod_{i=1}^n \mathcal{L}(m_{\gamma\gamma}; \sigma_{fid}, m_X, \mu, m_H, N_{bkg}, \xi, \vec{\theta}) \right] \left[\prod_{k=1}^{\dim \vec{\theta}} \exp \left(-\frac{1}{2} (\theta_i - \theta_i^{aux})^2 \right) \right]\end{aligned}$$

The expected limit on fiducial cross section



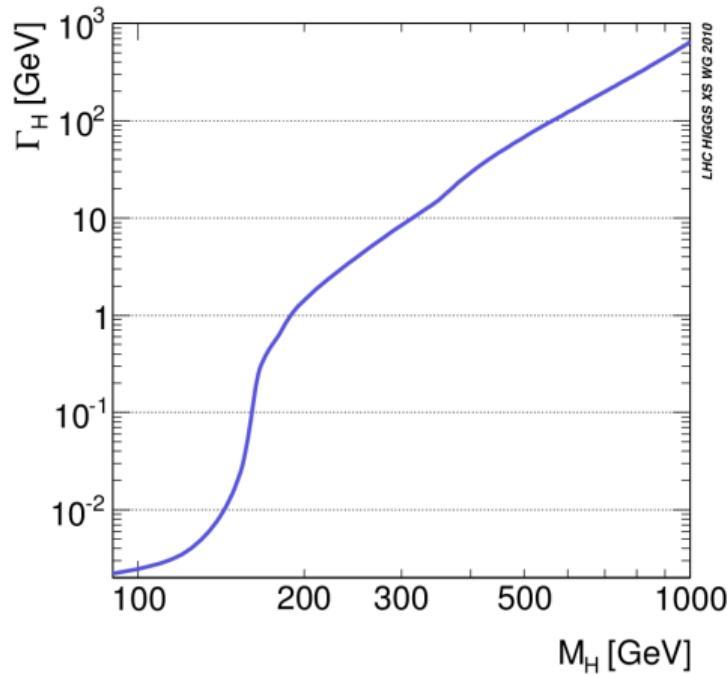
- stay tuned for the final result - paper coming soon

Conclusion

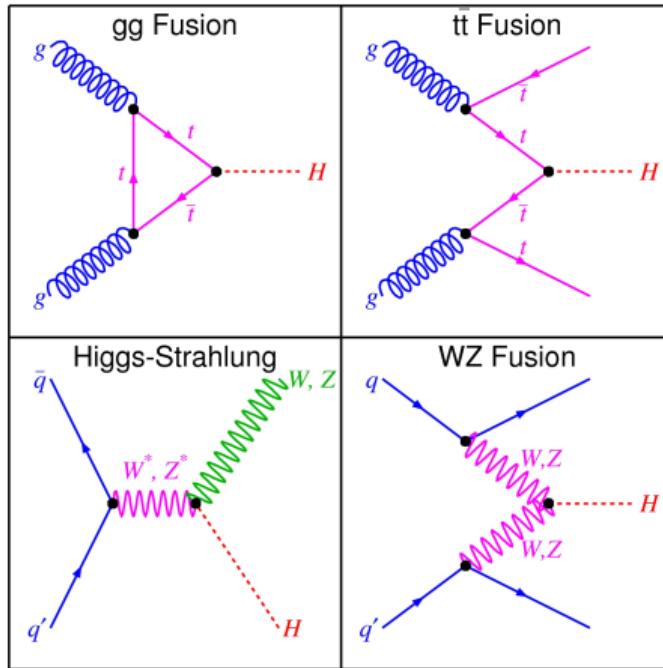
- important to search for new diphoton resonances
- setting a limit on the fiducial cross section may help exclude some models or at least parts of their parameter space
- personally:
 - provided the signal parametrization for this analysis
 - computed major systematic uncertainties
- analysis in finishing stages, approval process soon, publication expected in early 2014

BACKUP

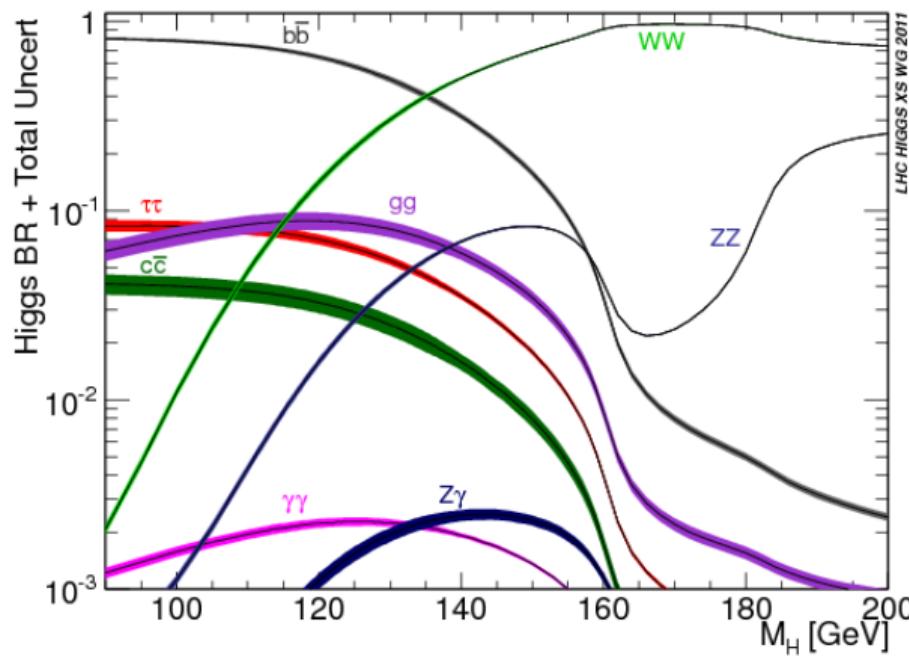
SM Higgs width



SM Higgs production processes



SM Higgs production branching ratio at LHC



Photon energy resolution

Energy resolution

- invariant mass

$$m_{\gamma\gamma} = \sqrt{E_1 E_2 (1 - \cos \theta_{12})}$$

- error of the energy of individual photons

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

the only important term at high energies

$$a \approx 9.5\%$$

$$b \approx 250 \text{ MeV}$$

$$c \approx 1\%$$

- at high mass, only the constant term is important

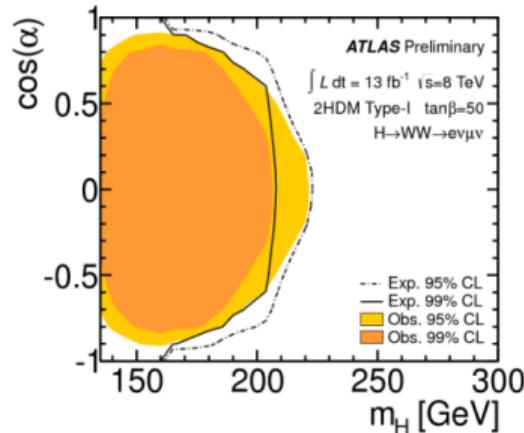
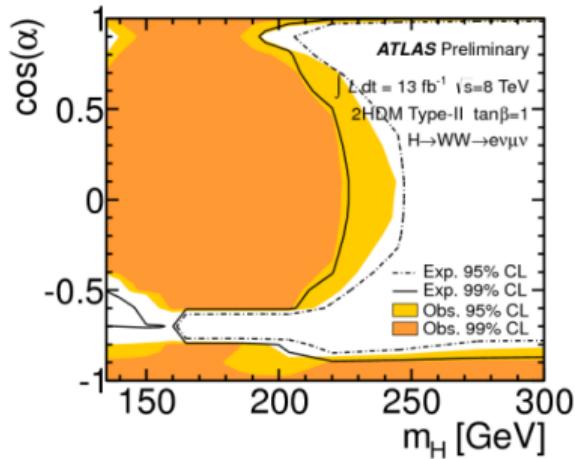
- error of the energy of a diphoton system

$$\frac{\sigma_{m_{\gamma\gamma}}}{m_{\gamma\gamma}} = \frac{1}{2} \sqrt{\left(\frac{\sigma_{E_1}}{E_1}\right)^2 \oplus \left(\frac{\sigma_{E_1}}{E_1}\right)^2 \oplus \left(\frac{\sigma_{\theta_{12}}}{\tan\left(\frac{\theta_{12}}{2}\right)}\right)^2}$$

BSM models - 2HDM

Some results for $H \rightarrow WW$ (

<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2013-027>)



BSM models - 2HDM $A \rightarrow \gamma\gamma$

B, Grinstein, P. Uttayarat, arXiv:1304.0028

No coupling to gauge bosons $\rightarrow \gamma\gamma$ competitive below $t\bar{t}$ and HZ threshold

