Search for new resonances in γγ channel with the ATLAS detector

Yufeng Wang[1,2]

Supervisors: Yanwen Liu[1], Lydia Roos[2]

[1]University of Science and Technology of China

[2]**L**aboratoire de **P**hysique **N**ucleaire et de **H**autes **E**nergies – Paris

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1. Theoretical context

Extension of Standard Model

Two Higgs-doublet models (2HDM)

TWO HIGGS-DOUBLET MODELS ARE SIMPLE EXTENSION OF THE SM WITH AN ENRICHED SCALAR SECTOR

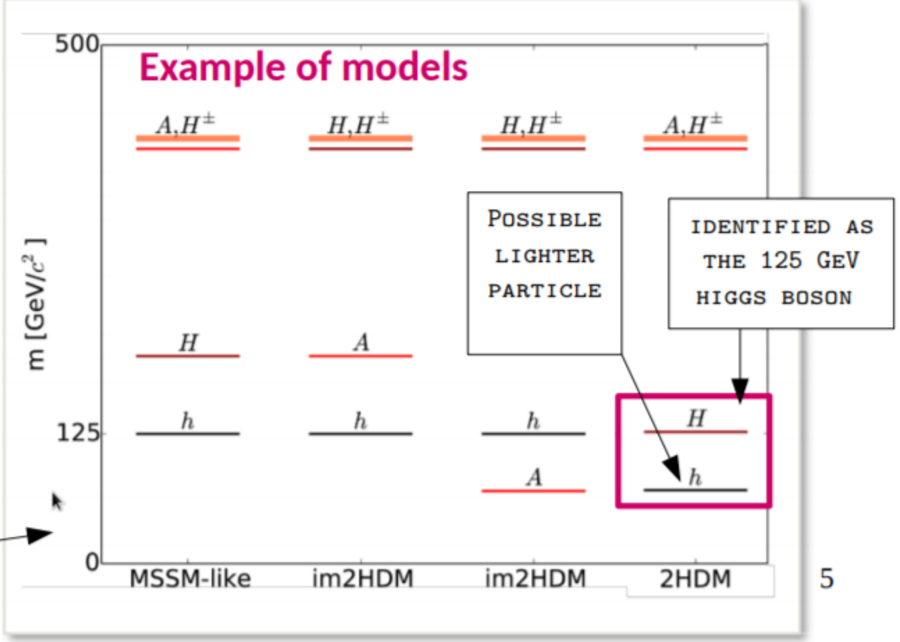
→ Introduction of an **additional scalar field** => 2 doublet scalar fields Φ_1 and Φ_2 in the SM lagrangian (8 degrees of freedom).

→ After symmetry breaking => Prediction of physical 5 states/**Higgs Boson :**

- Two CP-even bosons h and H
- One CP-odd boson A
- Two charged bosons H^+ and H^-

→ **4 ways of couplings** to quark and leptons => 4 **types of models**

→ Different **mass hierarchy**



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→ Taken from Camille's talk

Same motivation, different experiment!

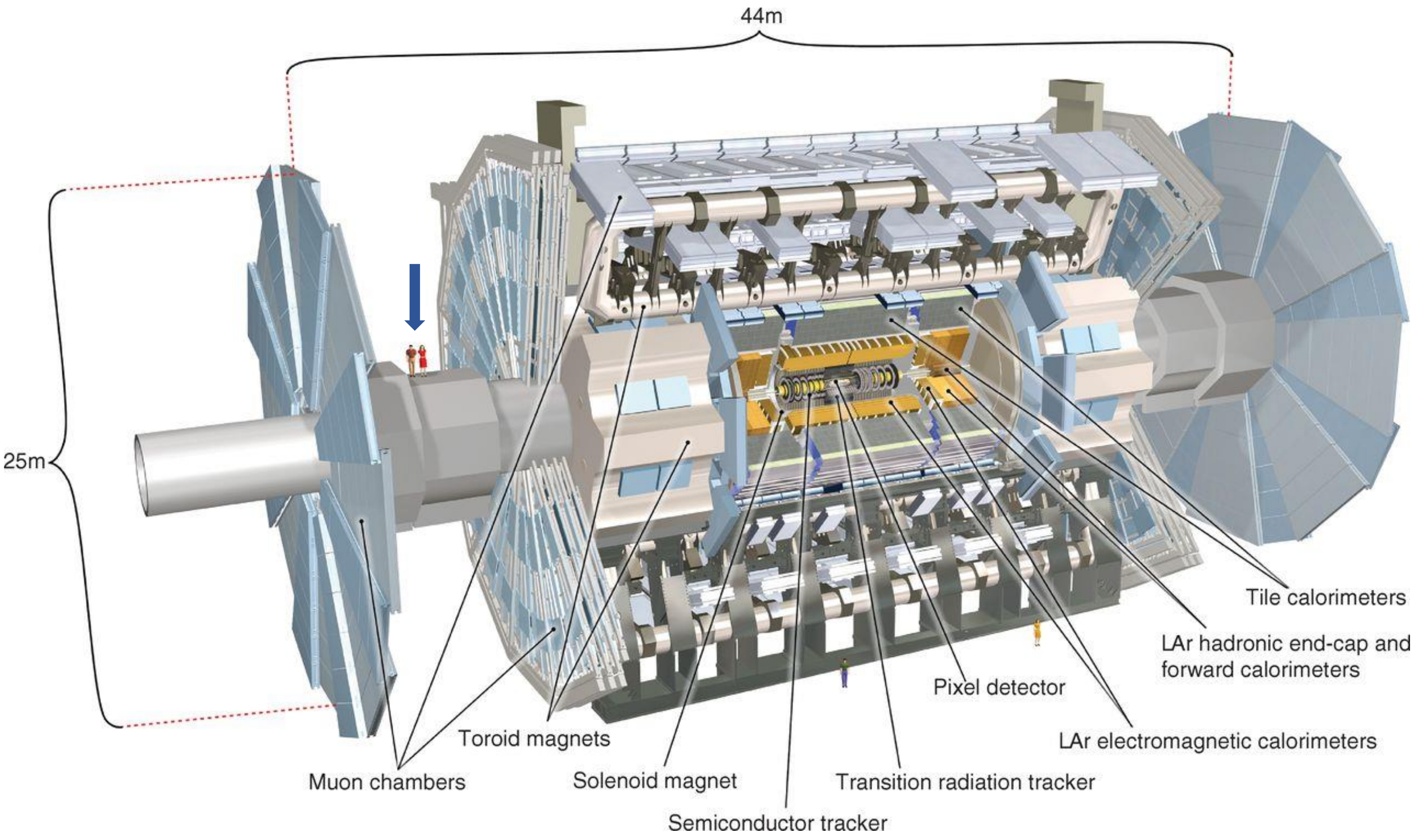
2 neutral CP-even bosons: **H, h** **with $m_H > m_h$**

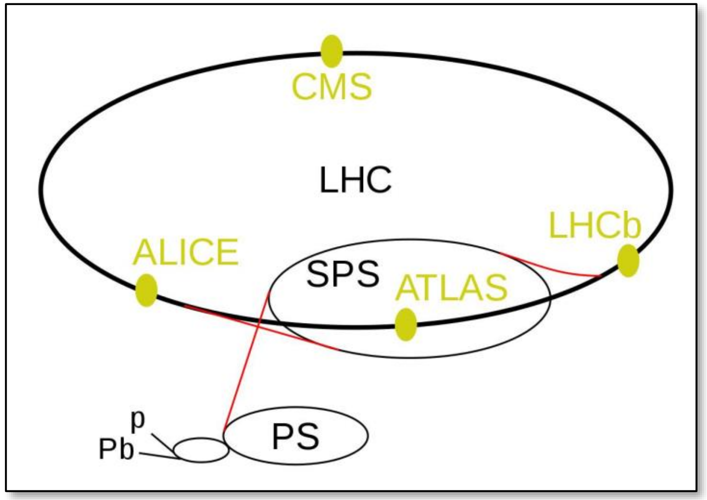
H or h might be the 125 GeV boson discovered 2012…
→ what about the other one?

Theory and phenomenology of two-Higgs-doublet models

2. Experiment

ATLAS Detector

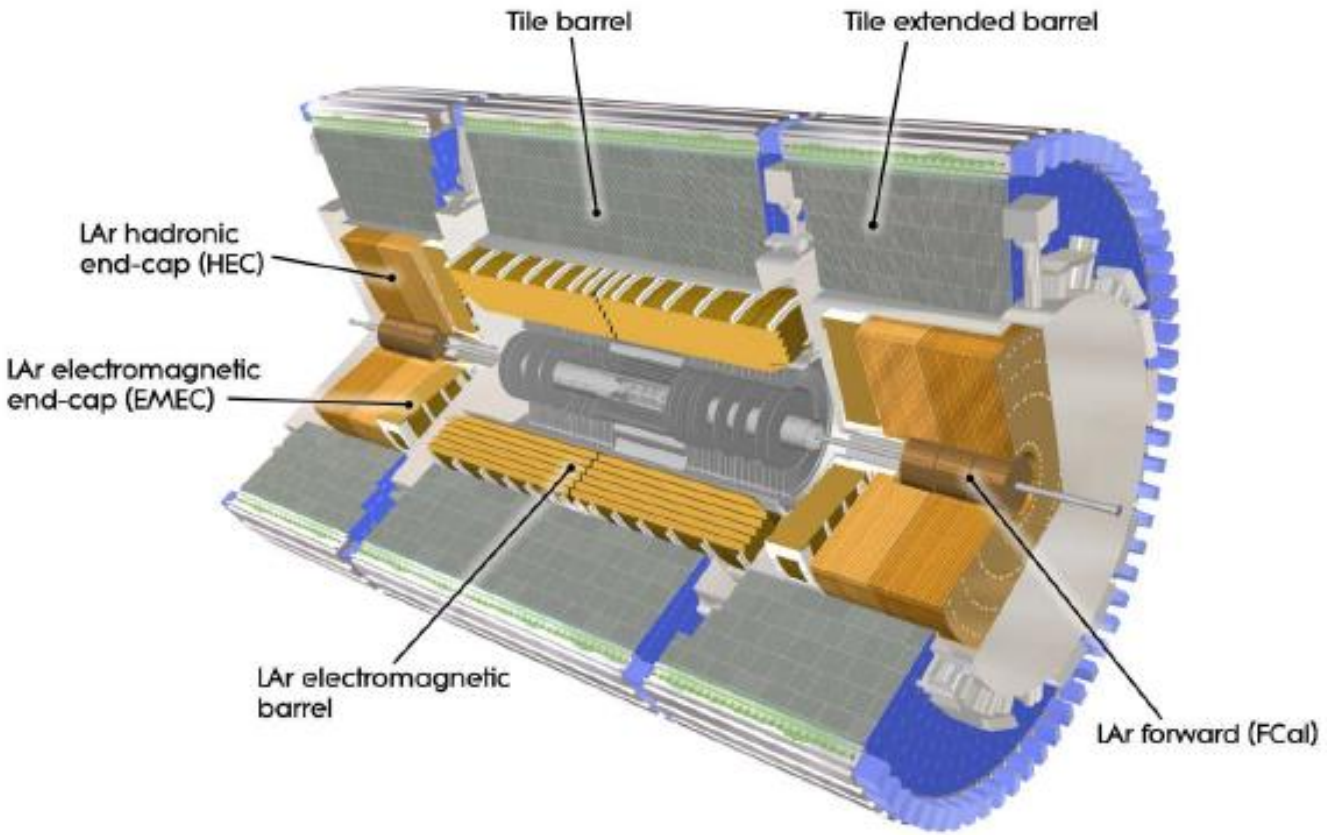


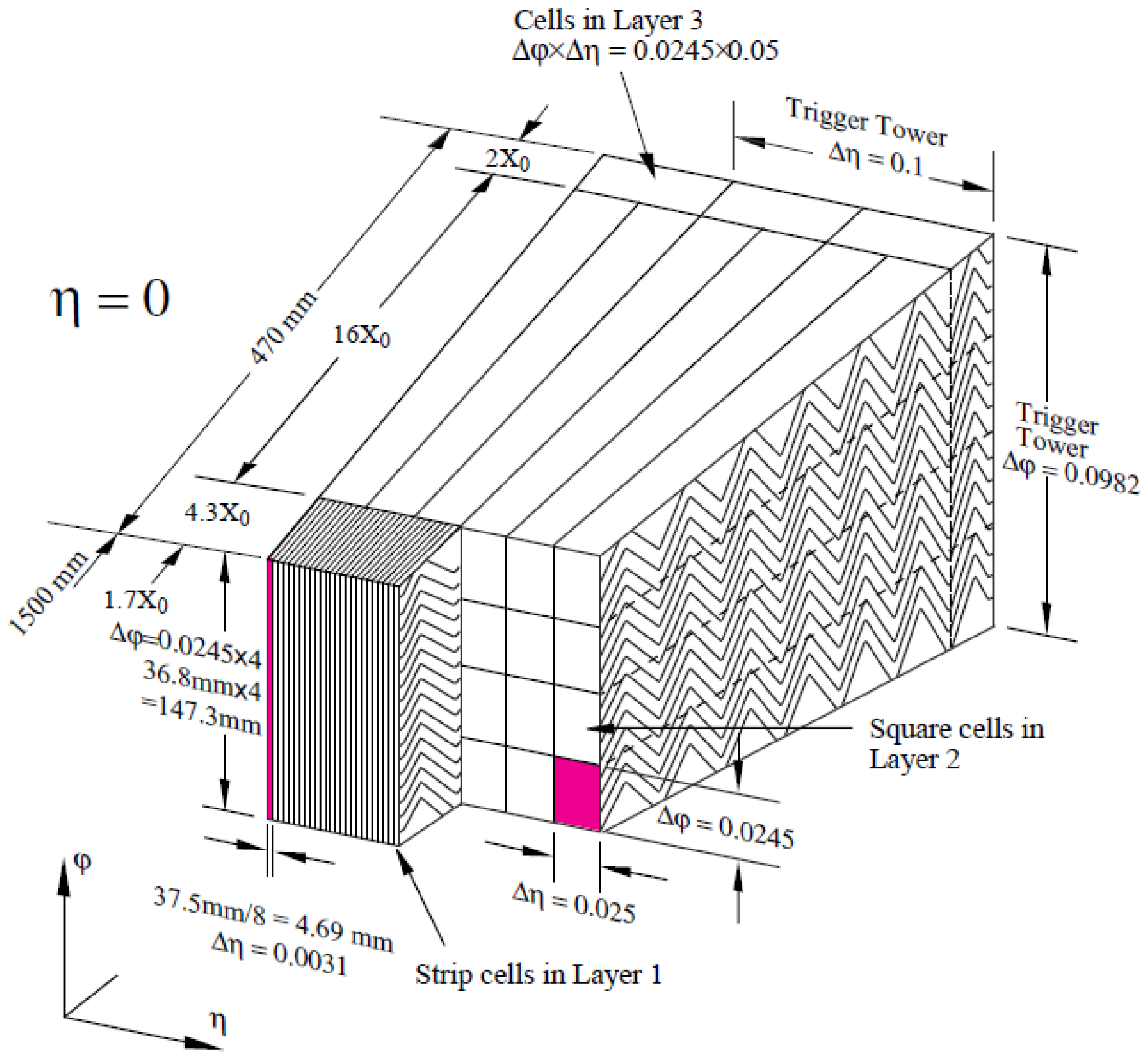


→ EM calorimeter and inner tracking detector are most relevant for reconstruction of photon candidates.

ATLAS experiment at the CERN Large Hadron collider

Electromagnetic calorimeter





3. A photon candidate in ATLAS

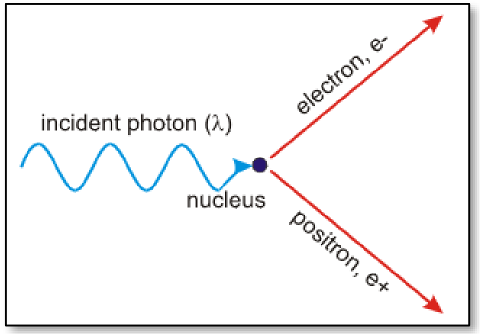
A photon candidate in ATLAS …

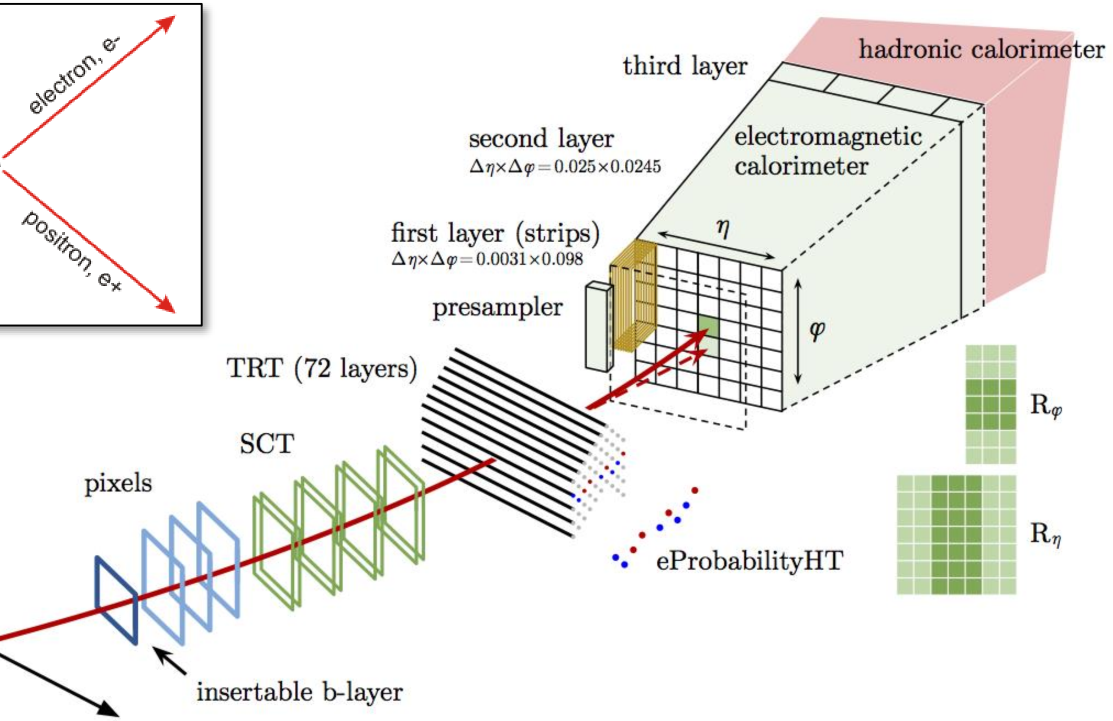
- **Photon reconstruction**
- **Photon energy calibration**
- **Photon identification**
- **Photon isolation**

Photons in ATLAS detector are reconstructed through:

- interactions with the EM calorimeters → energy deposited in a **cluster** of calorimeter cells
- interactions upstream of the calorimeter (possible) → conversions to electron pairs: leaving **tracks** matched to a EM cluster

Photon conversion





- **Electrons:** clusters matched to ID track from a vertex in interaction region
- **Converted photons:** clusters matched to a track from a conversion vertex
- **Unconverted photons:** clusters without matching tracks

A photon candidate in ATLAS …

[Electron and photon energy calibration with the ATLAS detector using 2015-2016 LHC proton-proton collision data]

- **Photon Reconstruction**
- **Photon energy calibration**
- **Photon identification**
- **Photon isolation**

(See Hicham' talk yesterday)

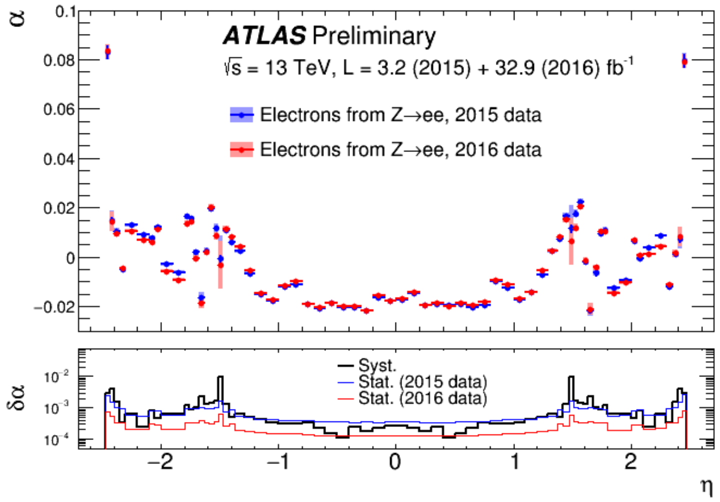
➢ interactions with the EM calorimeters → energy deposited in a **cluster** of calorimeter cells

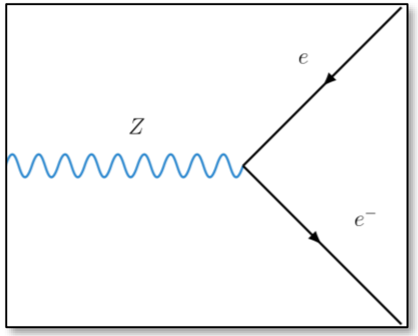
➢ interactions upstream of the calorimeter (possible) → conversions to electron pairs: leaving **tracks** matched to a EM cluster

Photon energy corrected by a dedicated energy calibration:

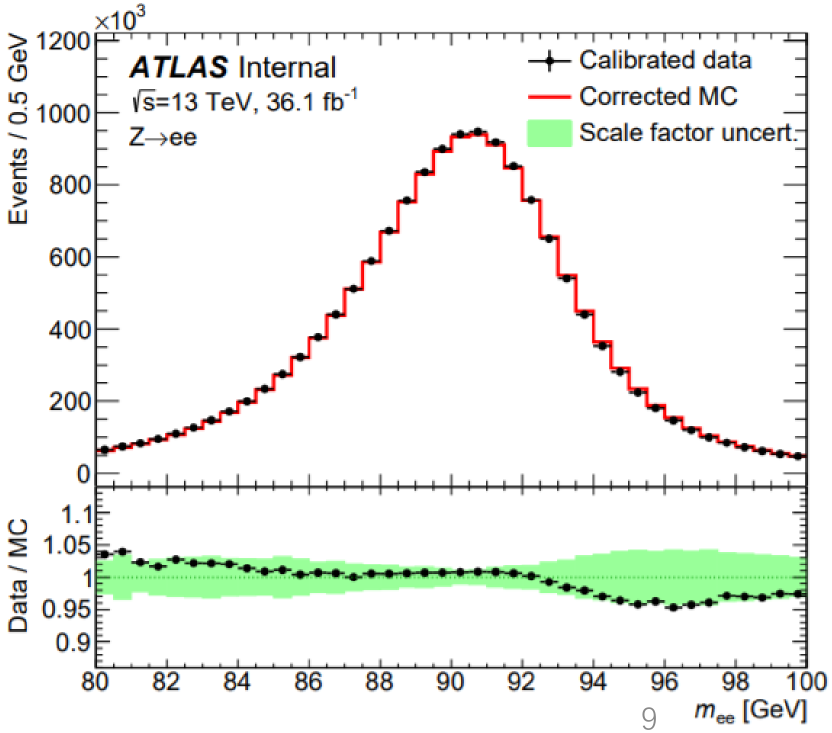
➢ **MC based calibration**
Calibrate the cluster energy to the original electron or photon energy

➢ **absolute energy scale (data-driven)**
Correct for data/MC difference using $Z \rightarrow ee$ samples





- validation with $J/\psi \rightarrow ee$ and $Z \rightarrow ll\gamma$ samples
- Photon specific uncertainties

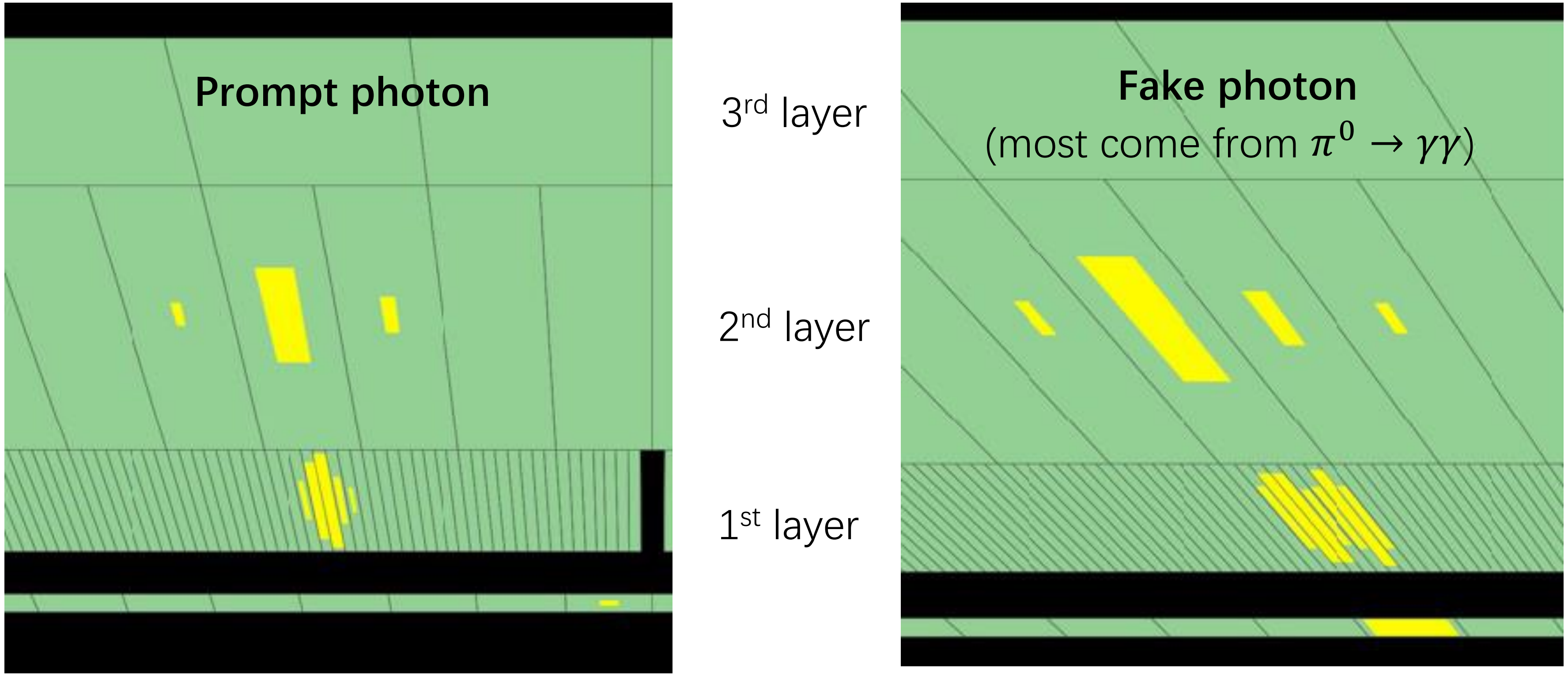


A photon candidate in ATLAS …

- **Photon Reconstruction**
- **Photon energy calibration**
- **Photon identification**
- **Photon isolation**

Reject background candidates after reconstruction using:

- Leakage in the hadronic calorimeter
- Cluster shape in 2^{nd} layer of EM calorimeter
- Cluster shape in 1^{st} layer of EM calorimeter (tighter)



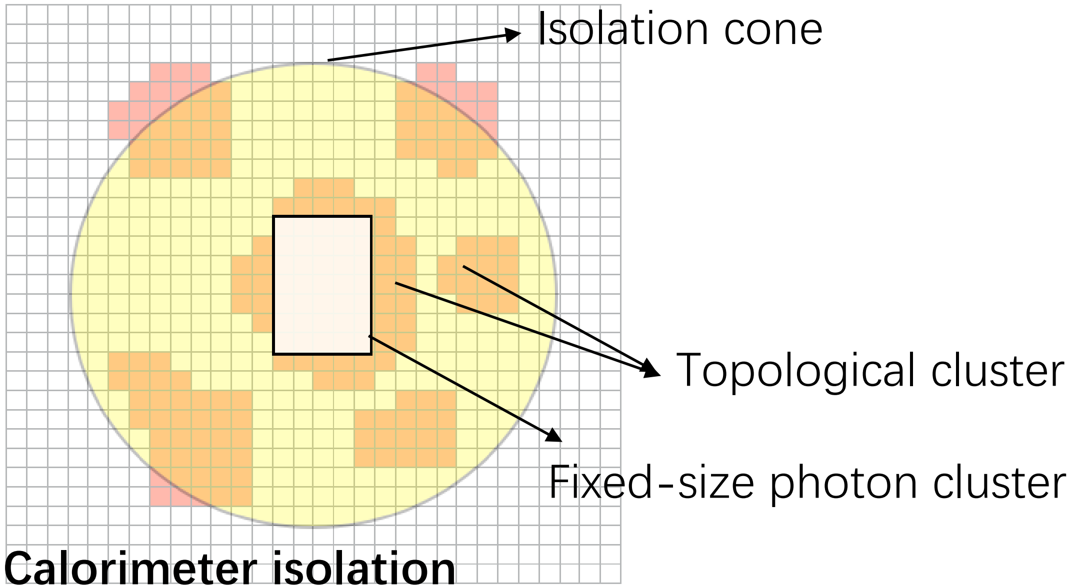
[Photon identification with ATLAS detector]

A photon candidate in ATLAS ...

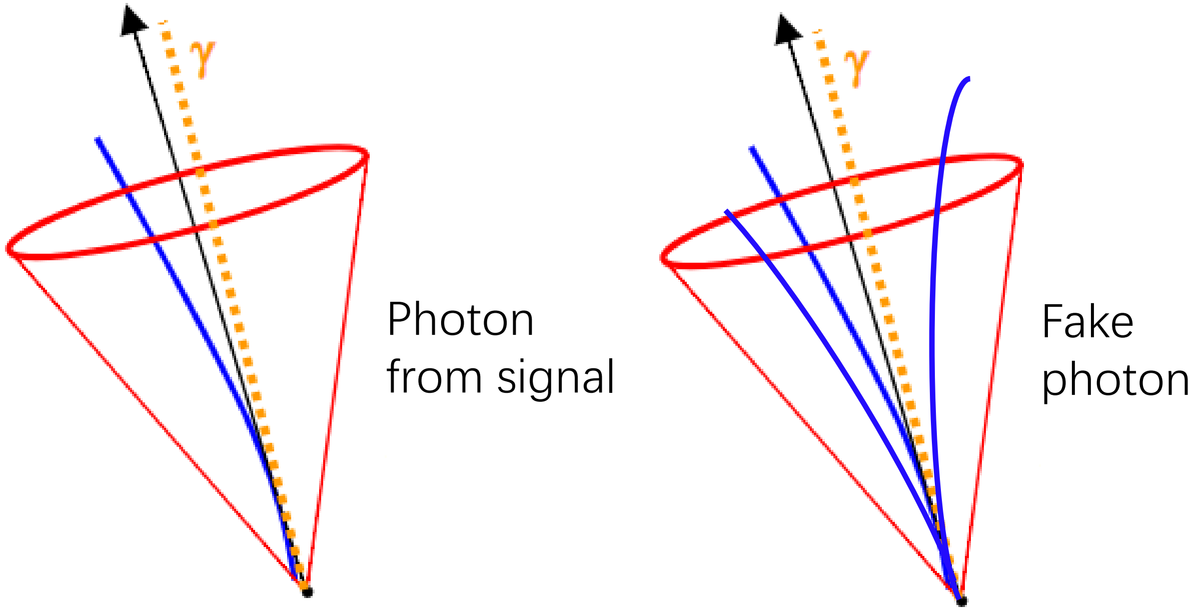
- **Photon Reconstruction**
- **Photon energy calibration**
- **Photon identification**
- **Photon isolation**

Photons from hard process (e.g. from resonance decays) expected to be well isolated from hadronic activity.

- **Track based isolation variable:** scalar sum of transverse momenta of tracks in a cone around γ candidate.
- **Calorimeter-based isolation variable:** sum of the transverse energy of the clusters in a cone around γ candidate (subtracting candidate contribution)



Calorimeter isolation

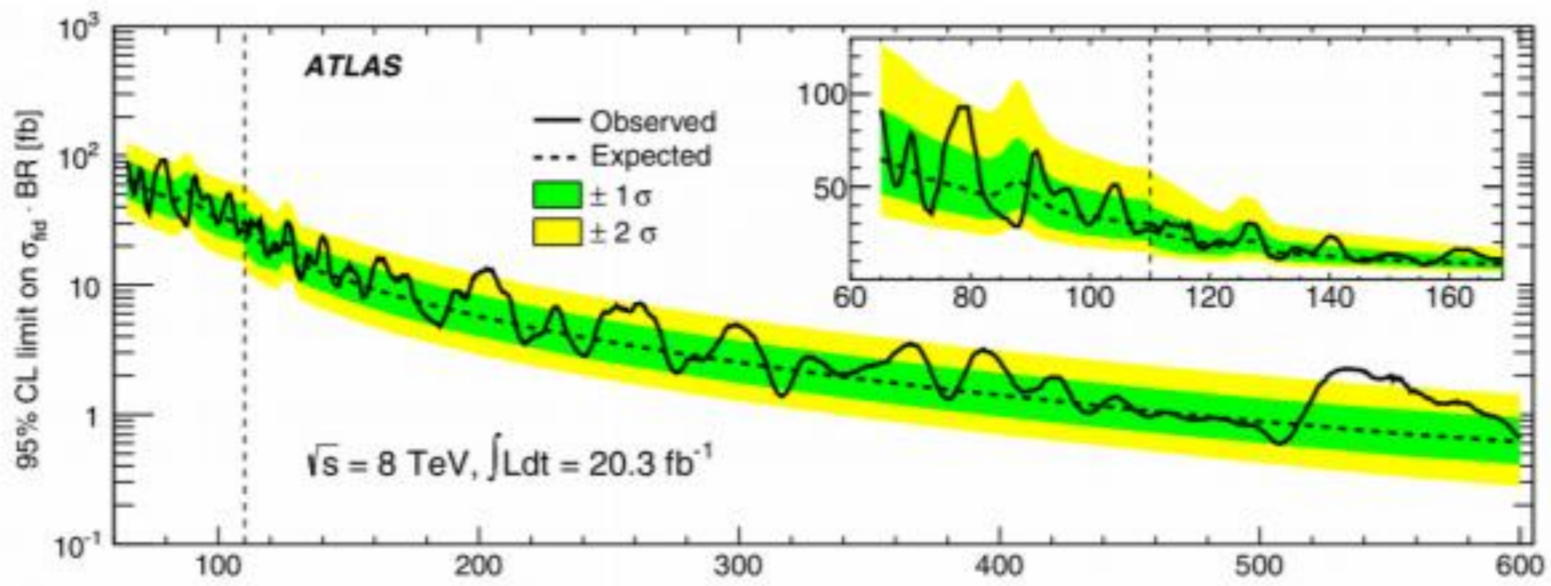


Track isolation

4. Search for new resonance in $\gamma\gamma$ channel

Analysis status

Search for a new resonances in $\gamma\gamma$ channel:



Run 1 result

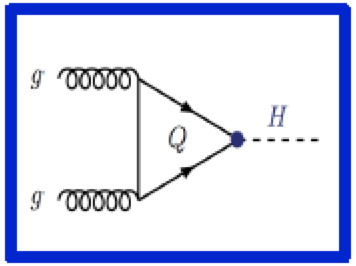
Run 1 (2011-2012):
→ search for narrow resonances in [65;600] GeV

Run 2 (2015-2018):
A low mass [65;110] GeV CONF note (ICHEP 2018) with 2015 – 2017 data

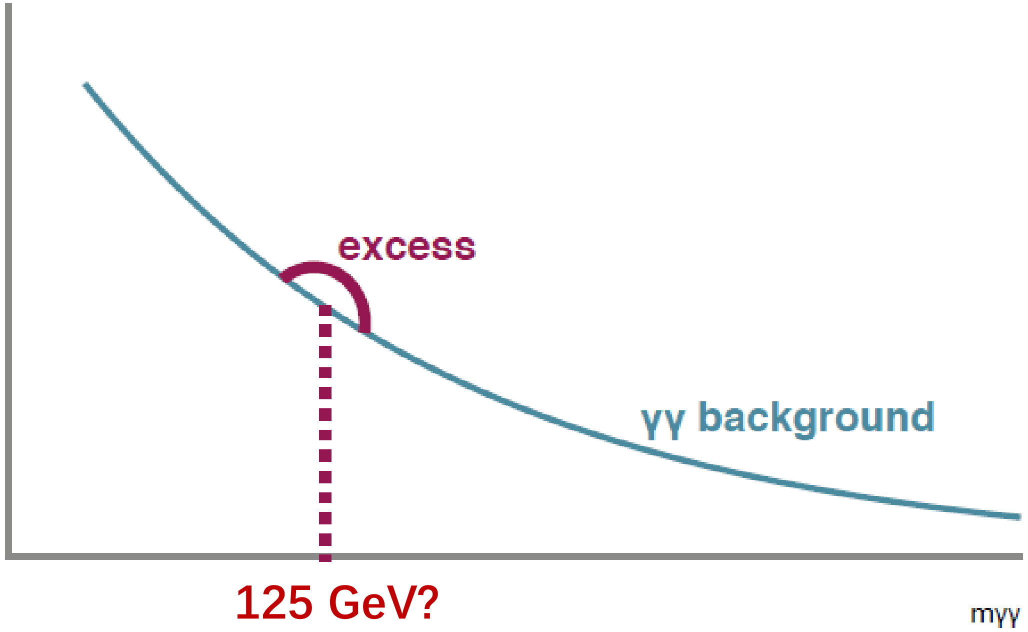
→ **Extend**: Full 2015 – 2018 dataset and Full mass range

We are here!

Analysis overview



Gluon fusion production mode:
- ➢ LHC: gluon-gluon collider
- ➢ Largest cross-section for SM Higgs

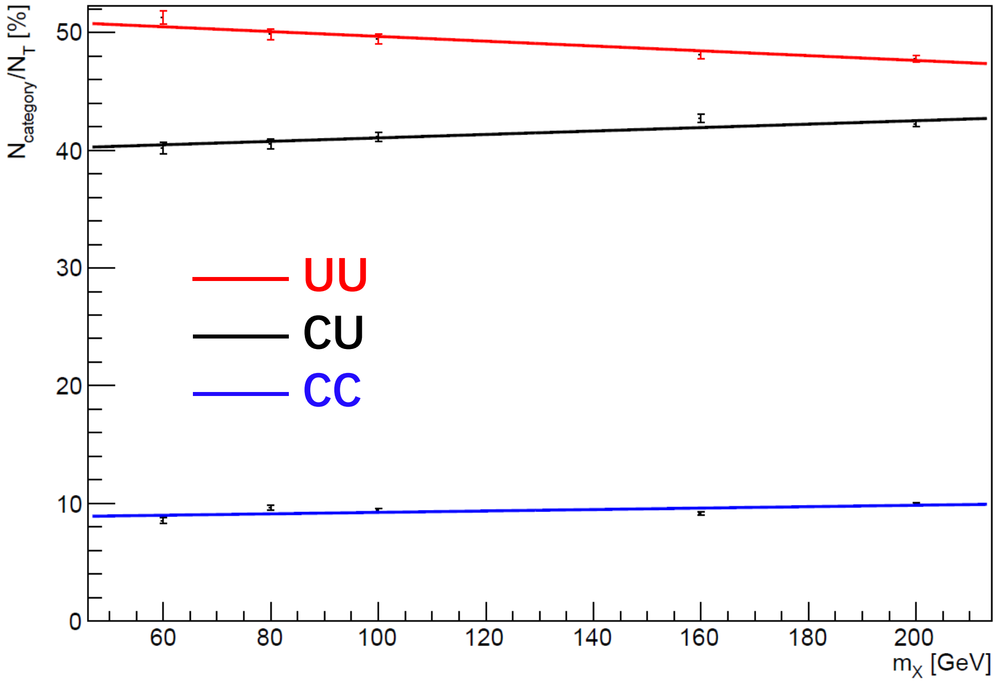


Run 2 **low-mass** search: 65-110 GeV

Event selection:

- Pass di-photon trigger
- $p_T^{\gamma} > 22$ GeV
- photon ID and isolation requirements

Categories:
Three categories according to conversion status:
converted (C) or **unconverted (U)** → UU, CU, CC



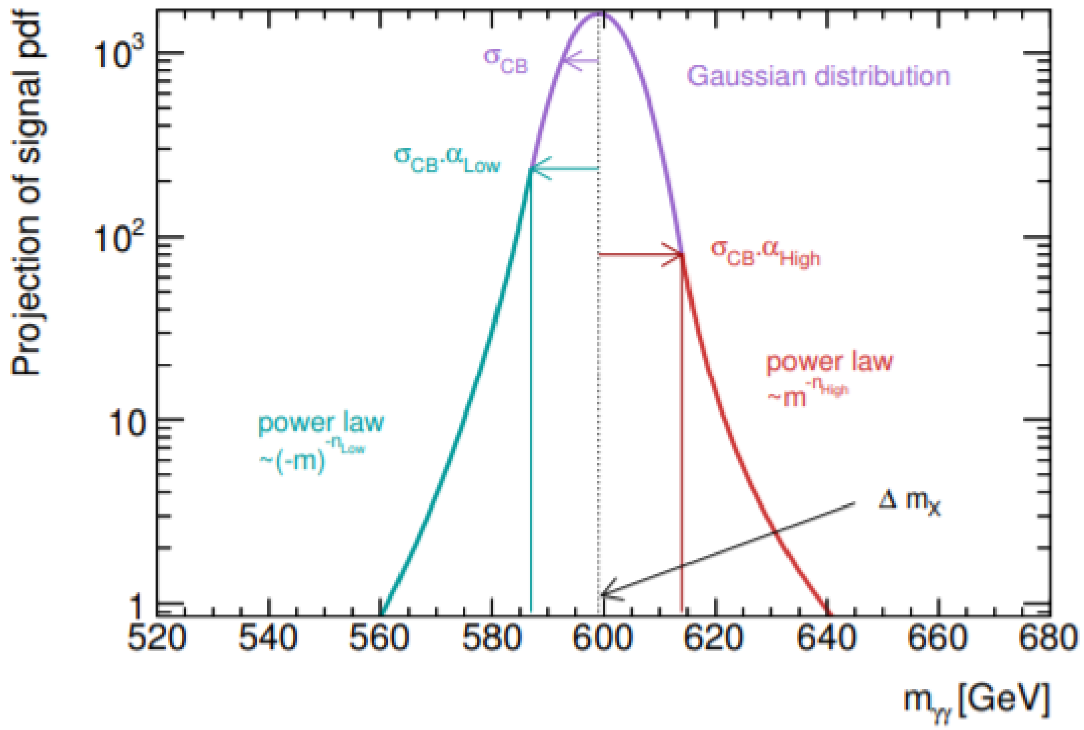
Signal Modeling

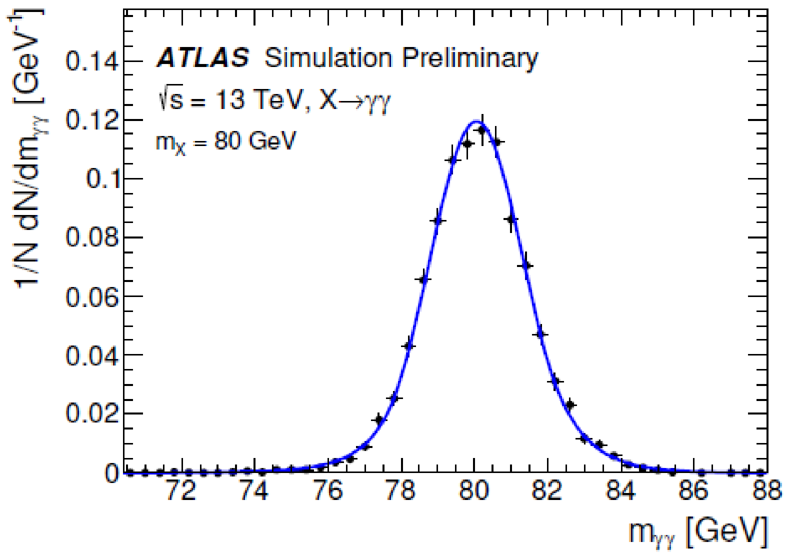
Narrow-width resonance: shape dominated by the detector resolution

Shape of signal: modeled using a **double-sided Crystal Ball (DSCB)** function.

6 parameters describing:
- ➢ A Gaussian core
- ➢ power-law low-end and high-end tails

Parameters extracted from MC.





Background modeling

- **Continuum:**
  - real **γγ** events: irreducible
    (from MC samples)
  - Jet faking photons (**γ+jet, multi-jet**): reducible
    (from data-driven control regions)
- **Resonant:**
  - Drell Yan $Z/\gamma^{*}\to$**ee** events misidentified as γγ
    (from di-electron data sample)
  - SM Higgs (negligible)

→ Build background templates of each components

Background modeling

- **Continuum:**
  - real **γγ** events: irreducible (from MC samples)
  - Jet faking photons (**γ+jet, multi-jet**): reducible (from data-driven control regions)
- **Resonant:**
  - Drell Yan Z/γ*→**ee** events misidentified as γγ (from di-electron data sample)
  - SM Higgs (negligible)

- **Continuum (γγ, γ+jet):**
  - two components added together according to their respective fraction measured in data
  - described by an analytic function
- **Resonant (Drell-Yan):**
  - normalized to the amount of di-electron events faking diphoton events
  - modeled using a DSCB function

2x2D sideband method for background decomposition

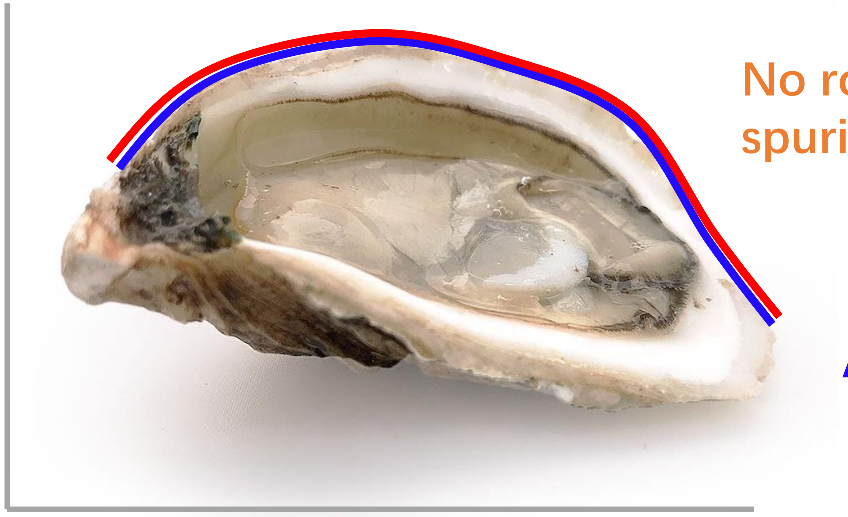
Background modeling

Check the quality of background modelling: we hope there's no **"spurious signal"**

→ **Signal**+**background** fit to a **background-only** template

- **Continuum (γγ, γ+jet):**
  - two components added together according to their respective fraction measured in data
  - described by an analytic function
- **Resonant (Drell-Yan):**
  - normalized to the amount of di-electron events faking diphoton events
  - modeled using a DSCB function

Ideal: A good oyster template! ☺



No room for spurious signal

Analytic Function

Mass of oyster

Reality: a bad oyster template…? ☹

Spurious signal everywhere!

Mass of oyster

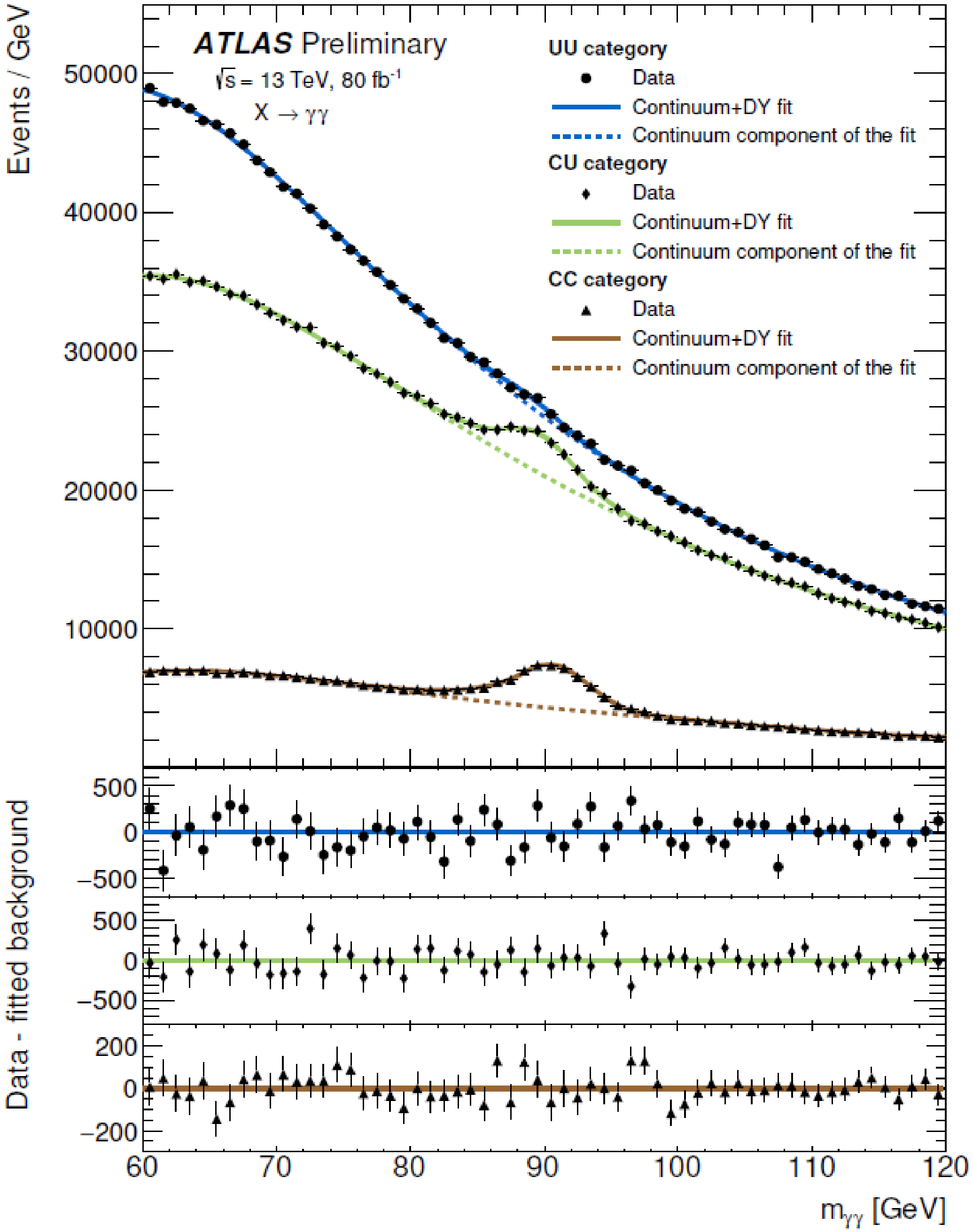
5. Results

Post-fit distributions

Background-only fit:

DY peak is clearly visible. Most prominent in the CC category, as expected.

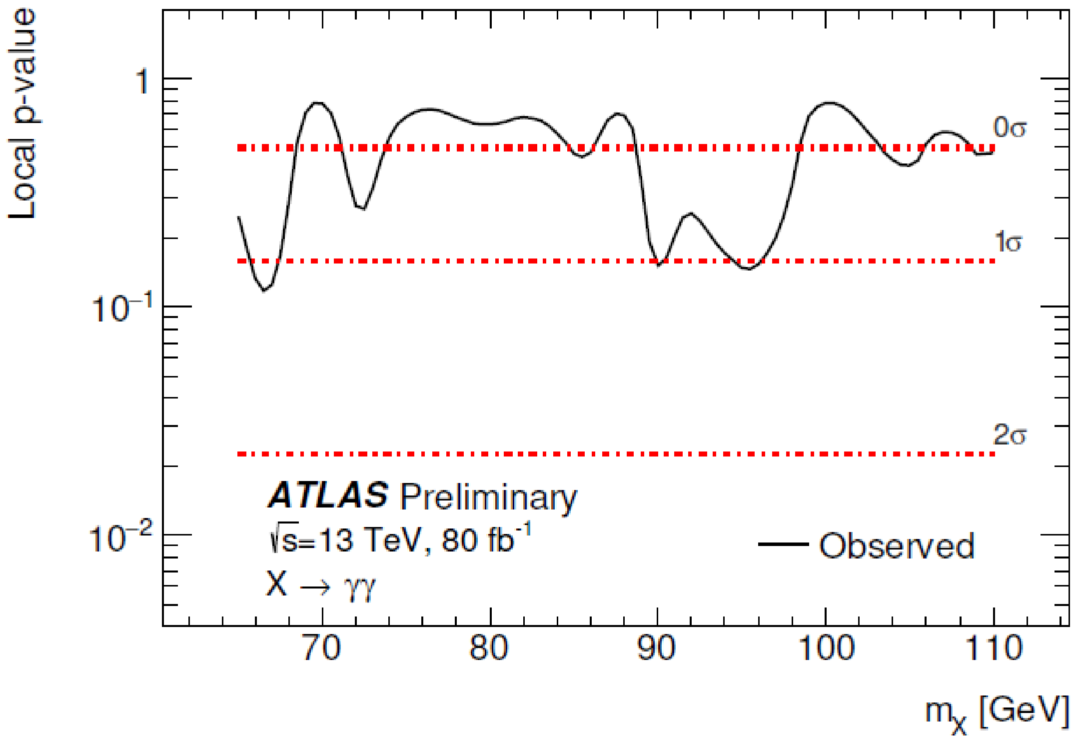
No structure seen in the residuals.

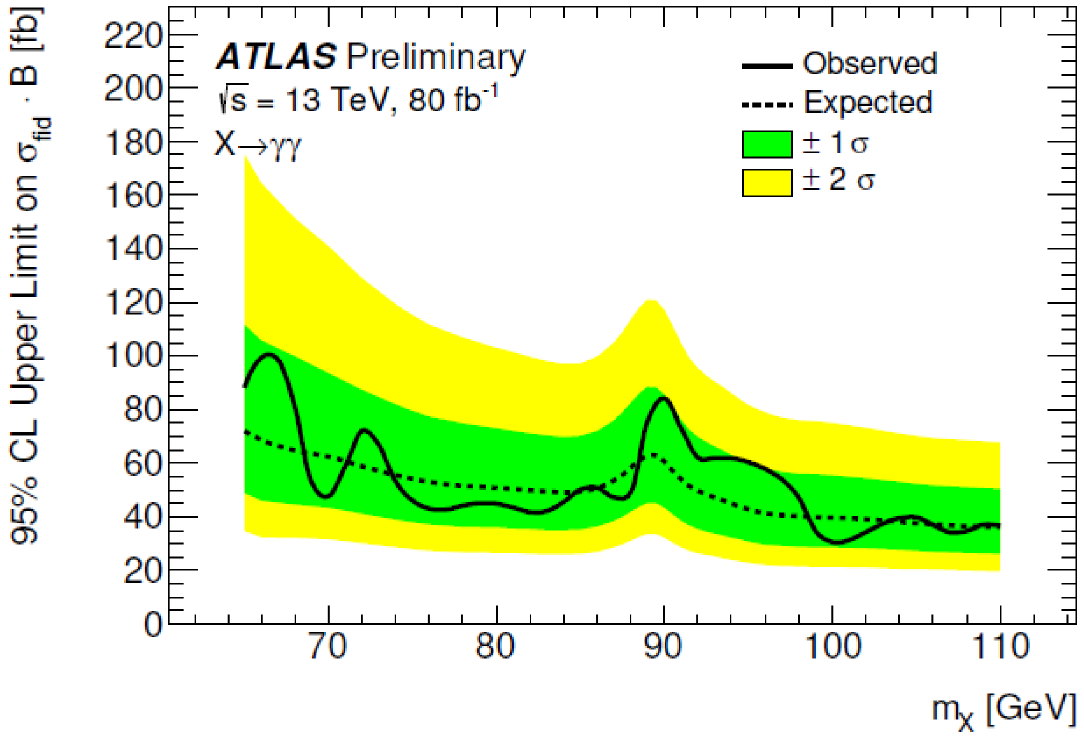


Summary of systematics

Source	Uncertainty [%]	Remarks
Signal yield		
Luminosity	±2	
Trigger eff.	±1.4 – 1.7	m_X-dependent
Photon identification eff.	±1.5 – 2.3	m_X-dependent
Isolation eff.	±4	
Photon energy scale	±0.13 – 0.49	m_X-dependent
Photon energy resolution	±0.053 – 0.28	m_X-dependent
Pile-up	±1.8 – 4.1	m_X-dependent
Production mode	±2.4 – 25	m_X-dependent
Signal modeling		
Photon energy scale	±0.3 – 0.5	m_X- and category–dependent
Photon energy resolution	±2 – 8	m_X- and category-dependent
Migration between categories		
Material	−2.0 / +1.0 / +4.1	category-dependent (UU/CU/CC)
Non-resonant Background		
Spurious Signal	128 / 104 / 79 (604 / 496 / 181 events)	ratio to the expected spurious signal uncertainty (category-dependent)
DY Background modeling		
Peak position	±0.1 – 0.2	category-dependent
Peak width	±2 – 3	category-dependent
Normalization	±9 – 21	category-dependent

Results

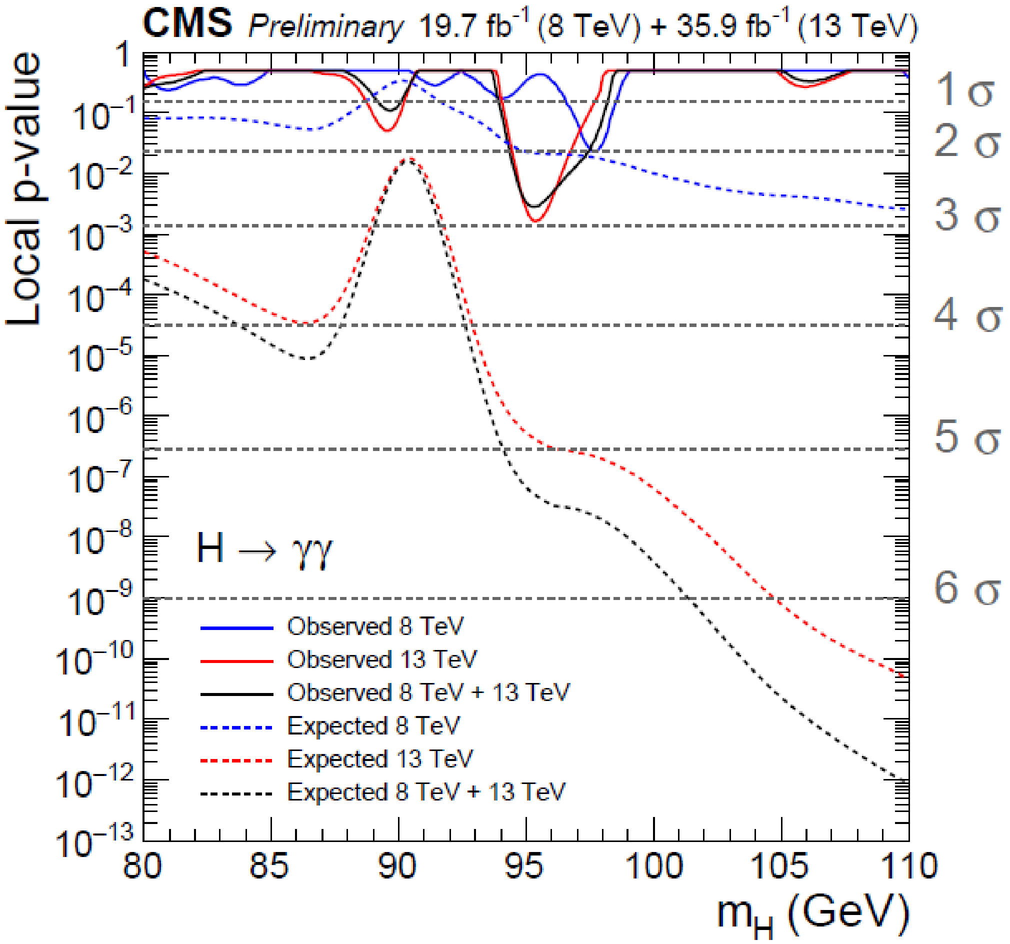


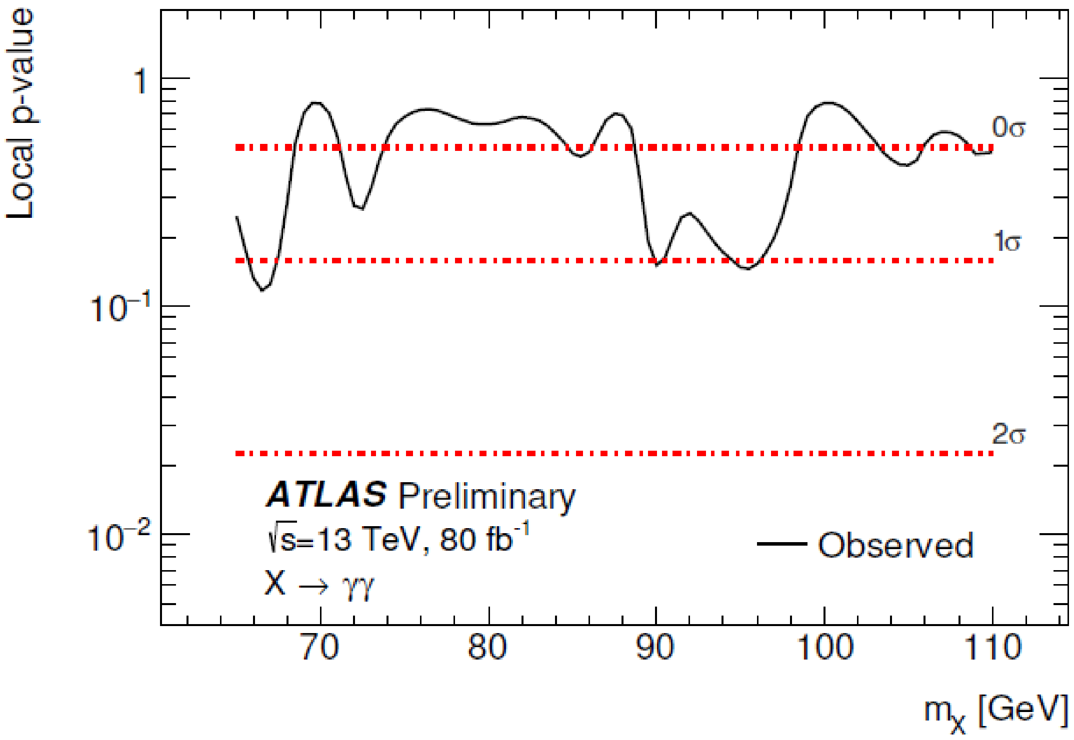


No significant excess with respect to the background-only hypothesis is observed.

An upper limit at the 95% CL is set on $\sigma_{fid} \cdot \mathcal{B}$ from 30 to 101 fb in the range 65 < m < 110 GeV.

CMS results: comparison





~2.9σ local excess at 96 GeV, not seen by ATLAS.

CMS note

Conclusion and further plan

In search for a new resonances below the Higgs mass in $\gamma\gamma$ channel:

- ATLAS sees no significant excesses above 1σ
- Not confirming the CMS excess (but can't exclude it yet)

Started analysis with Full 2015 – 2018 dataset and Full mass range:

- ➢ **Very low mass range:** below 65 GeV?
- ➢ **Low-mass range:** [65-110] GeV
- ➢ **Intermediate mass range:** [110-200] GeV
- ➢ **High-mass range:** above 200 GeV for spin0 and spin2

Optimizations (systematics, templates, etc) ongoing…

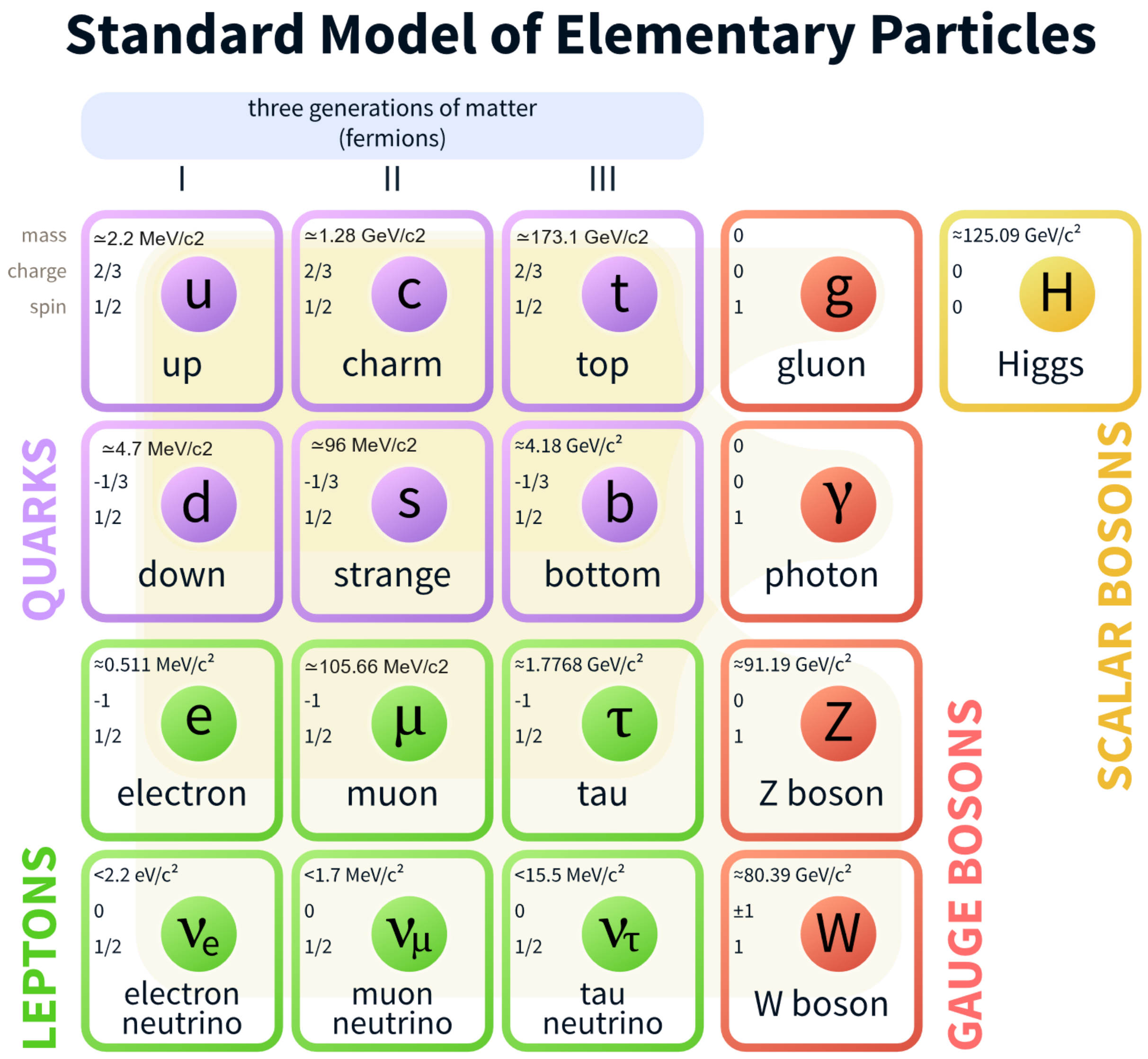
Back up

Standard Model

A theory of fundamental particles and how they interact.

- **Elementary fermions** (half-integer spin): 3 generations of quarks and leptons
- **Gauge bosons** (integer spin): 4 force carriers of fundamental interactions
  - ➢ Gluon (strong interaction)
  - ➢ Photon (electromagnetic interaction)
  - ➢ W and Z boson (weak interaction)
- **Higgs boson**: One last missing piece of SM, discovered in 2012 at the LHC
  - ➢ h(125), scalar boson, spin = 0

→ Currently our best description of elementary particles and their interaction. However, the standard model is incomplete.



[Standard Model](#)

Extension of Standard Model

- **Standard Model:** only one SU(2) doublet

$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix},$$ ϕ are normalized real scalar fields

- **Two-Higgs-doublet model(2HDM):** simple possible extension of SM

$$\Phi_j = \begin{pmatrix} \Phi_j^+ \\ (v_j + \rho_j + i\eta_j)/\sqrt{2} \end{pmatrix},$$ j=1,2

- 2 complex scalar SU(2) doublets → 8 fields:
  - 3 get eaten to give mass to W and Z gauge bosons
  - 5 are **physical scalar (Higgs) fields**
    - 1 neutral CP-odd: **A**
    - 2 neutral CP-even: **H, h with $m_H > m_h$**
    - 2 charged: $H^{\pm}$

H or h might be the H(125) discovered 2012

→ What about the other?

Theory and phenomenology of two-Higgs-doublet models

Lagrangian giving mass terms in 2HDM

- With minimization of the potential, the mass terms are given by:
- $\mathcal{L}_{\Phi^{\pm}\,mass} = [m_{12}^2 - (\lambda_4 + \lambda_5)v_1 v_2](\phi_1^- \quad \phi_2^-)\begin{pmatrix} \frac{v_2}{v_1} & -1 \\ -1 & \frac{v_1}{v_2} \end{pmatrix}\begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}$
- $\mathcal{L}_{\eta\,mass} = \frac{m_{\mathrm{A}}^2}{v_1^2+v_2^2}(\eta_1 \quad \eta_2)\begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix}\begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}$
- $\mathcal{L}_{\rho\,mass} = -(\rho_1 \quad \rho_2)\begin{pmatrix} m_{12}^2\frac{v_2}{v_1} + \lambda_1 v_1^2 & -m_{12}^2 + \lambda_{345} v_1 v_2 \\ -m_{12}^2 + \lambda_{345} v_1 v_2 & m_{12}^2\frac{v_1}{v_2} + \lambda_2 v_2^2 \end{pmatrix}\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$ with $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$

Yukawa couplings

Yukawa Lagrangian: (f couple to Higgs in SM: $\frac{m_f}{v}$)

$$\mathcal{L}_{Yukawa}^{2HDM} = -\sum_{f=u,d,l} \frac{m_f}{v}\left(\xi_h^f \bar{f} f h + \xi_H^f \bar{f} f H - i\xi_A^f \bar{f}\gamma_5 f A\right) - \left\{\frac{\sqrt{2}V_{ud}}{v}\bar{u}\left(m_u \xi_A^u P_L + m_d \xi_A^d P_R\right) d H^+ + \frac{\sqrt{2} m_l \xi_A^l}{v}\bar{\nu}_l l_R H^+ + H.c.\right\}$$

$P_{L/R}$: projection operators for left-/right-handed fermions

The coupling of the neutral Higgs bosons to the W and Z are the same in all models.

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Two-Higgs-doublet models

Most general **potential** for two doublets Φ_1 and Φ_2:

- $V = m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3\Phi_1^\dagger\Phi_1\Phi_2^\dagger\Phi_2 + \lambda_4\Phi_1^\dagger\Phi_2\Phi_2^\dagger\Phi_1 + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + (\Phi_2^\dagger\Phi_1)^2\right]$

All the parameters are real (5 independent coupling **λ** and 3 mass parameters **m**).

- Scalar doublets: $\Phi_j = \begin{pmatrix} \Phi_j^+ \\ (v_j + \rho_j + i\eta_j)/\sqrt{2} \end{pmatrix}$ j=1,2

2 complex scalar SU(2) doublets→8 fields:

- 3 get eaten to give mass to W and Z gauge bosons
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- 1 neutral CP-odd: **A**
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- 2 charged: $\boldsymbol{H^\pm}$

Orthogonal combinations of ρ_j → **physical scalars:**

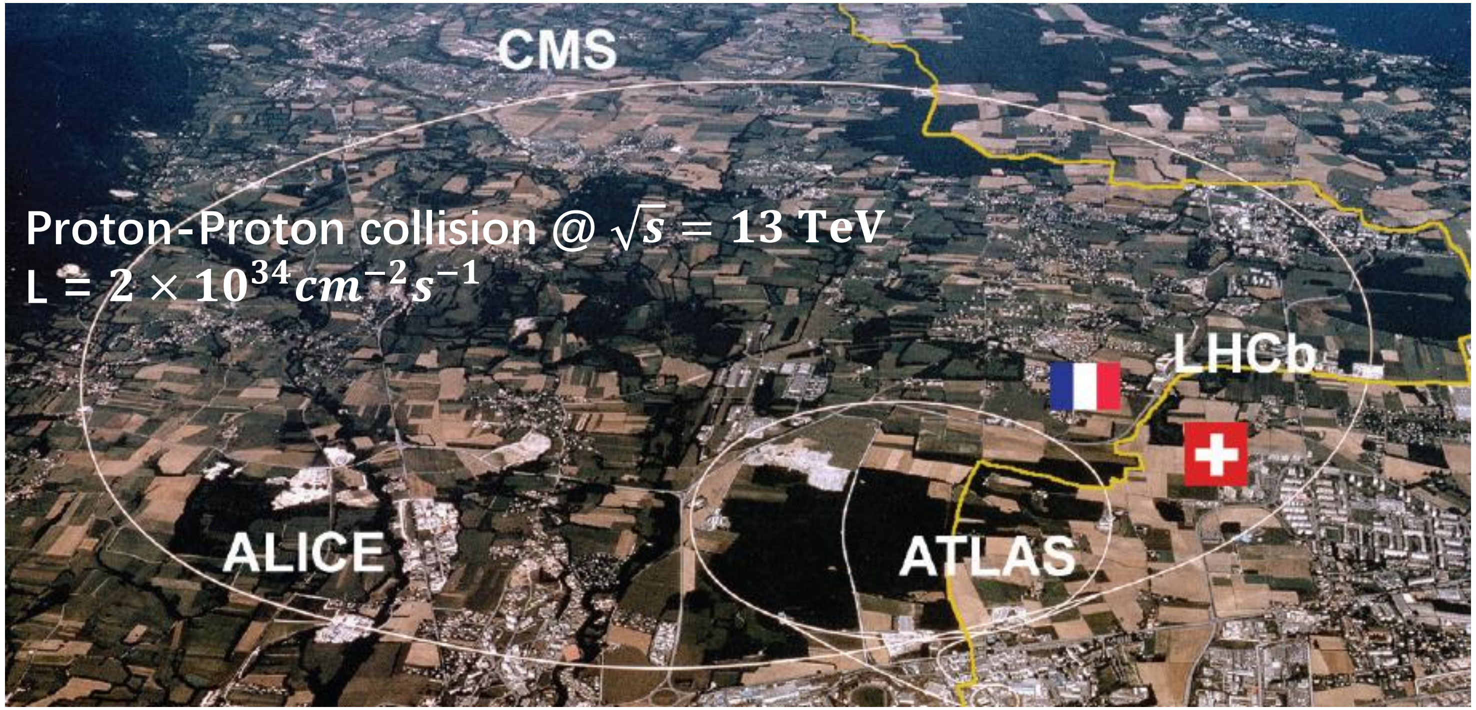
- $h = \rho_1 sin\alpha - \rho_2 cos\alpha$
- $\mathrm{H} = -\rho_1 cos\alpha - \rho_2 sin\alpha$

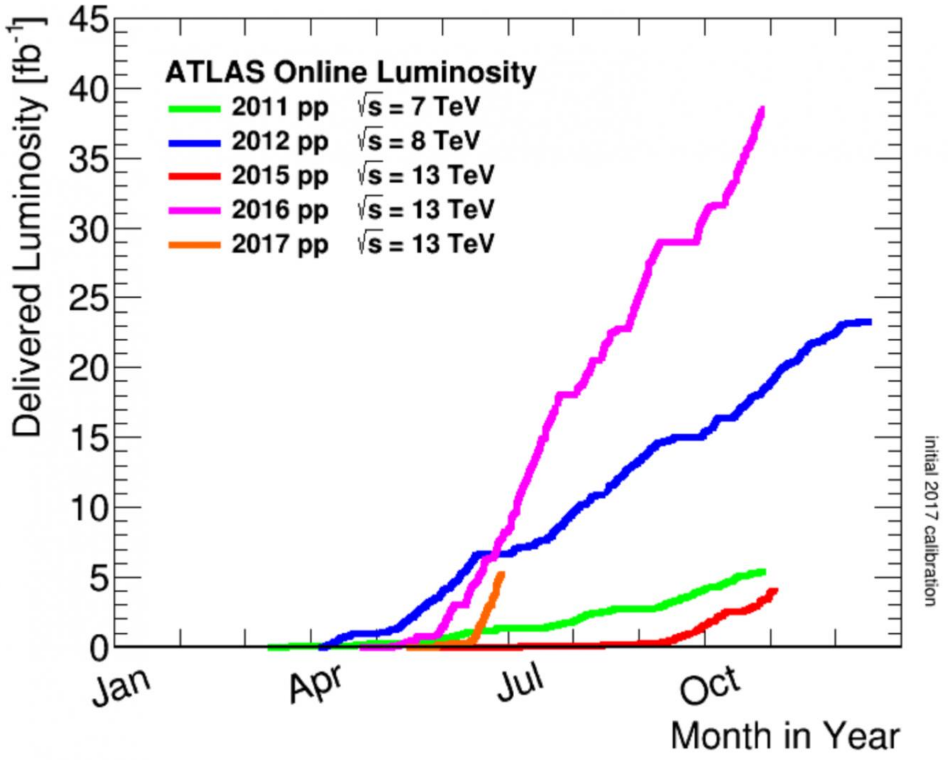
See backup: Lagrangian for mass terms

SM Higgs boson:

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

Experiments at LHC





Seven experiments at the Large Hadron Collider (LHC) use detectors to analyse the myriad of particles produced by collisions in the accelerator.

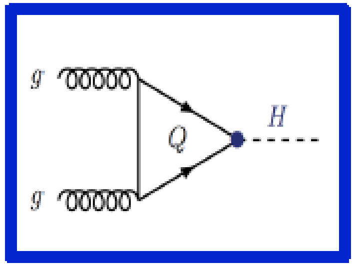
ATLAS, CMS: general-purpose detectors, investigate the largest range of physics possible.
ALICE, LHCb: detectors specialized for focusing on specific phenomena.
TOTEM, LHCf: focus on "forward particles".
MoEDAL: search for a hypothetical particle: the magnetic monopole.

LHC experiments

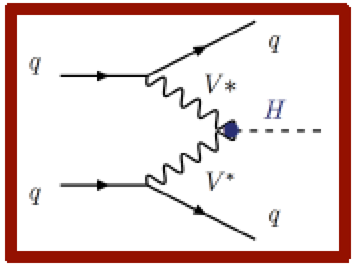
Designed parameters

Detector component	Required resolution	η coverage	
		Measurement	Trigger
Tracking	$\sigma_{p_T}/p_T = 0.05\%\ p_T \oplus 1\%$	± 2.5	
EM calorimetry	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	± 3.2	± 2.5
Hadronic calorimetry (jets)			
barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	± 3.2	± 3.2
forward	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \|\eta\| < 4.9$	$3.1 < \|\eta\| < 4.9$
Muon spectrometer	σ_{p_T}/p_T=10% at p_T = 1 TeV	± 2.7	± 2.4

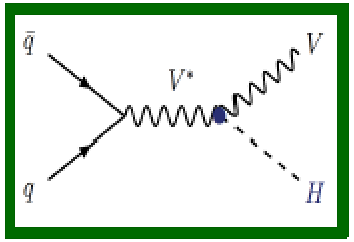
Higgs production



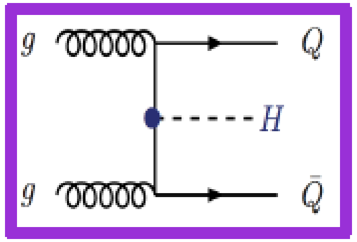
Gluon fusion



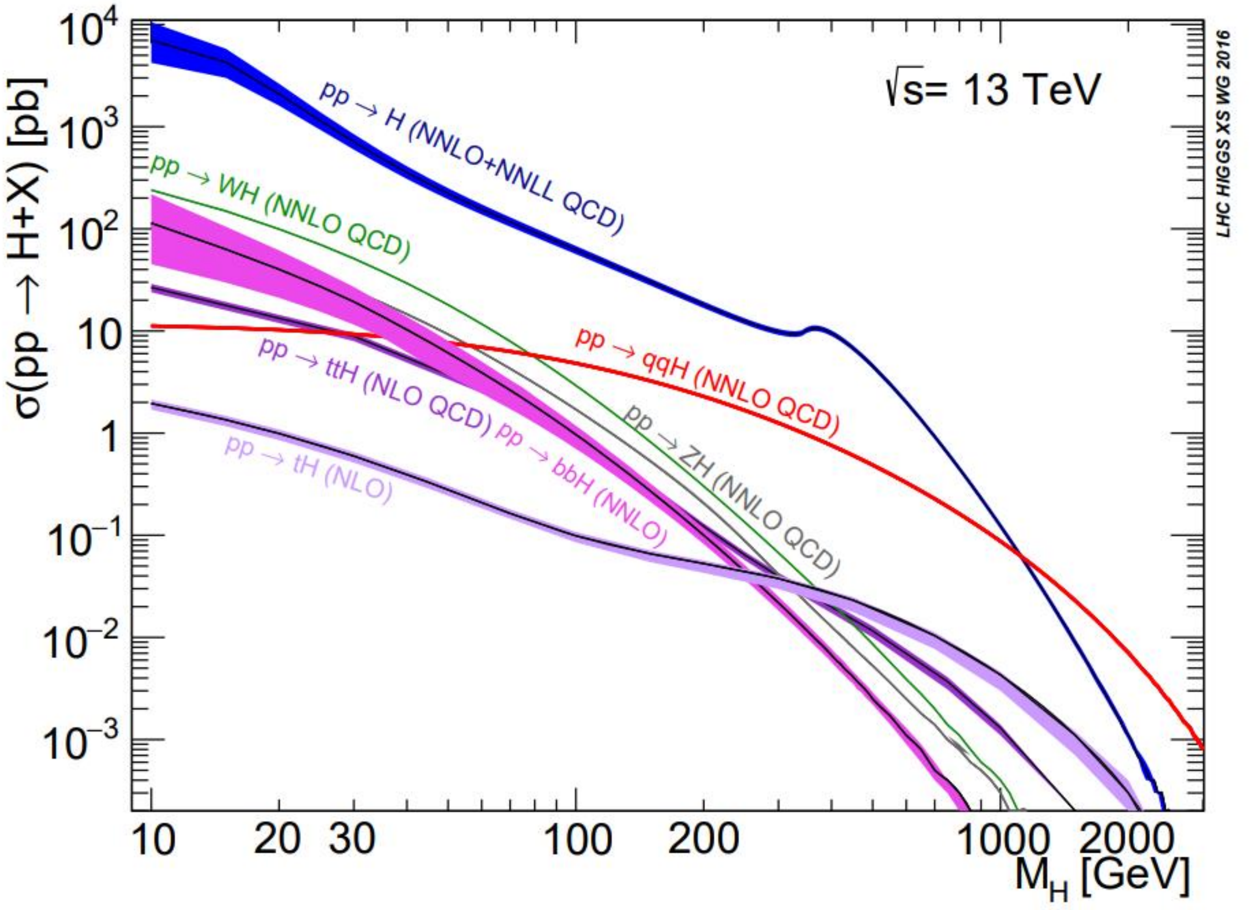
Vector boson fusion (VBF)



Association with W/Z



Association with tt



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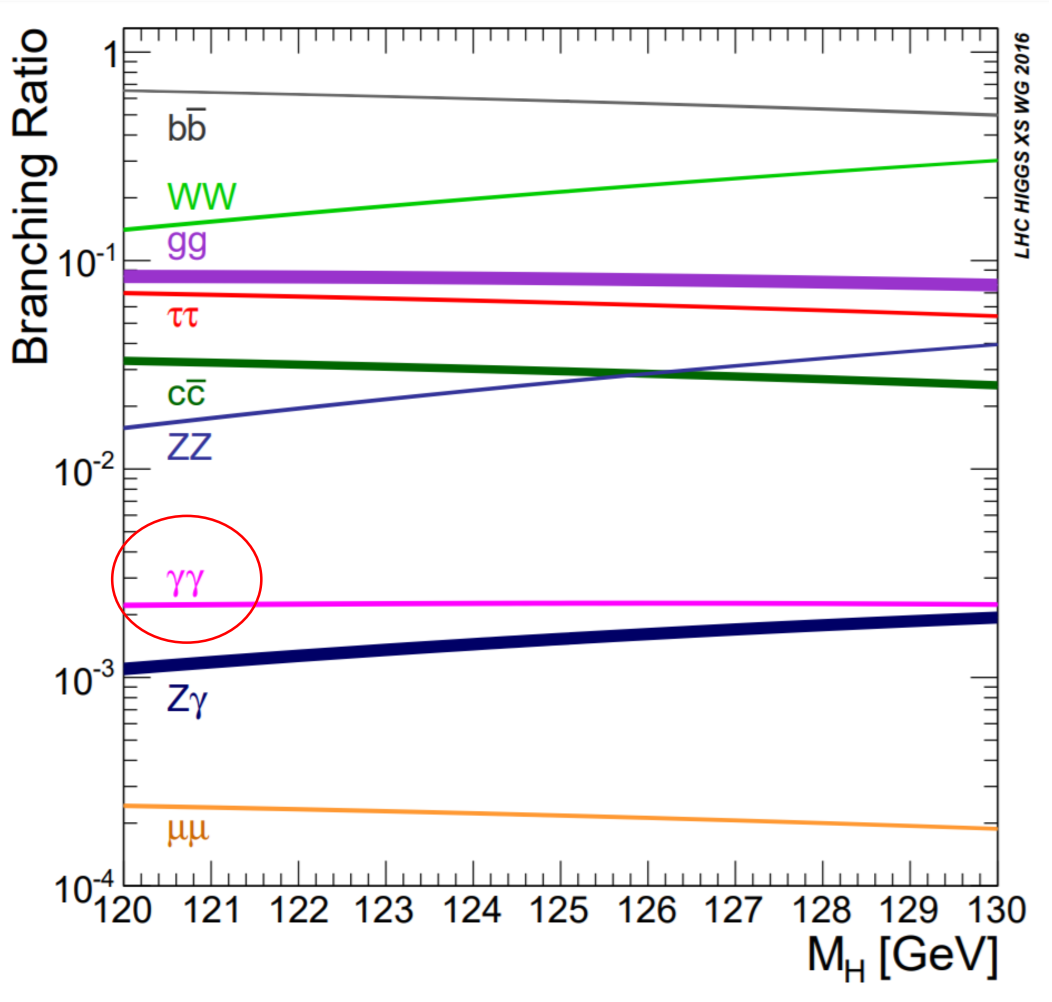
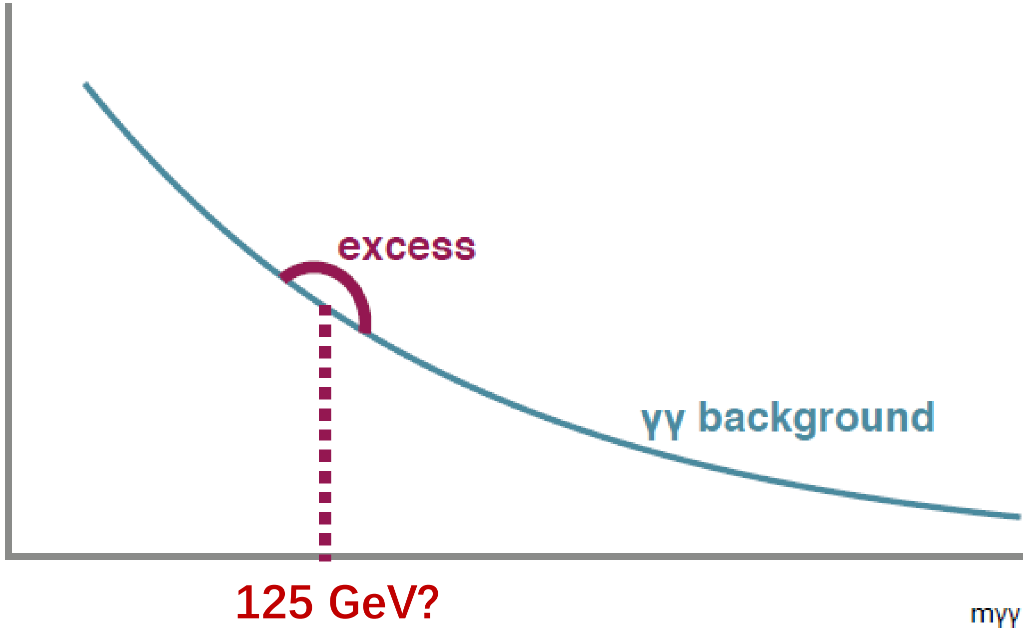
search in $\gamma\gamma$ channel



Branching ratio predicted by 2HDM: similar as SM with a fraction depending on model type

The $\gamma\gamma$ decay channel has the advantage of a clean experimental signature：

- excellent mass resolution
- smoothly falling background (diphoton production by QCD processes)



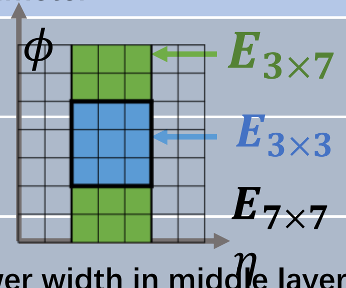
Event selection

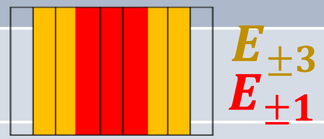
Event selection:

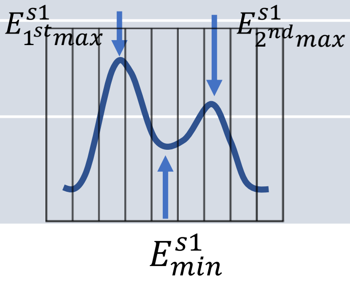
- 2g20_tight trigger for 2015+2016 periods A-D3
- 2g22_tight trigger for 2016 periods D4-after
- 2g20_tight_icalovloose trigger for 2017
- ET{leading,subleading} > 22 GeV
- Tight photon ID
- Photon isolation: FixedCutLoose
- Invariant mass range :
- 60-120 GeV and **Search in 65-110 GeV**

Photon identification

Variable	Definition	Description
Leakage in the hadronic calorimeter	$R_{had} = \frac{E_T^{had}}{E_T}$	Leakage in the hadronic calorimeter
Middle η energy ratio	$R_\eta = \frac{E^{s2}_{3\times7}}{E^{s2}_{7\times7}}$	
Middle ϕ energy ratio	$R_\phi = \frac{E^{s2}_{3\times3}}{E^{s2}_{3\times7}}$	
Middle lateral width	$\omega_{\eta^2} = \sqrt{\frac{\sum E_i\eta_i^2}{\sum E_i} - (\frac{\sum E_i\eta_i}{\sum E_i})^2}$	Shower width in middle layer
Front side energy ratio	$F_{side} = \frac{E(\pm3) - E(\pm1)}{E(\pm1)}$	
Front lateral width (3 strips)	$\omega_{s3} = \sqrt{\frac{\sum E_i(i - i_{\max})^2}{\sum E_i}}$	Shower width in 3 strips around the hottest strip
Front lateral width (total)	$\omega_{s,tot} = \sqrt{\frac{\sum E_i(i - i_{\max})^2}{\sum E_i}}$	Shower width in all strips
Front second maximum difference	$\Delta E = [E^{s1}_{2^{nd}max} - E^{s1}_{min}]$	
Front maxima relative ratio	$E_{ratio} = \frac{E^{s1}_{1^{st}max} - E^{s1}_{2^{nd}max}}{E^{s1}_{1^{st}max} + E^{s1}_{2^{nd}max}}$	

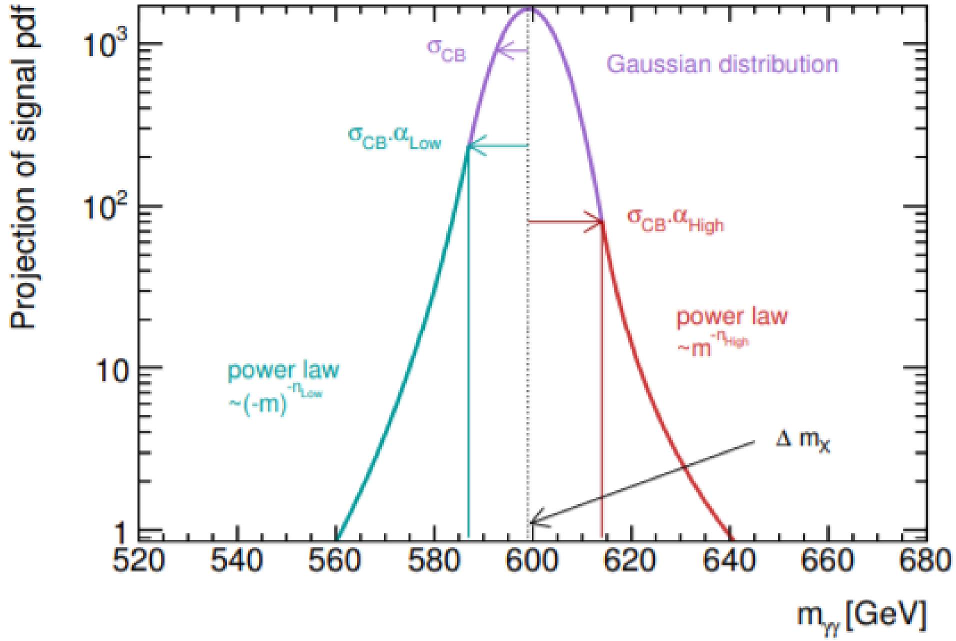






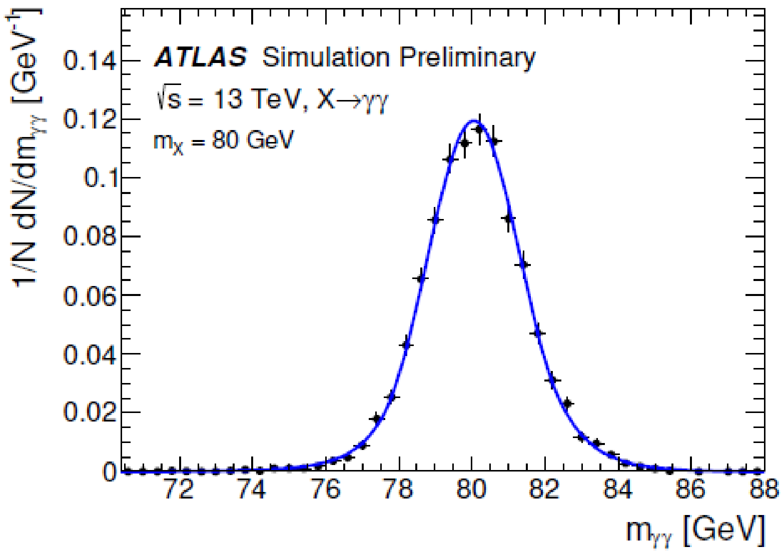
Signal Modeling

Narrow width resonance: shape dominated by the detector re



While there is no assumption on the production mode of the resonance, the shape of signal is modelled using a **double-sided crystal ball (DSCB)** function.

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



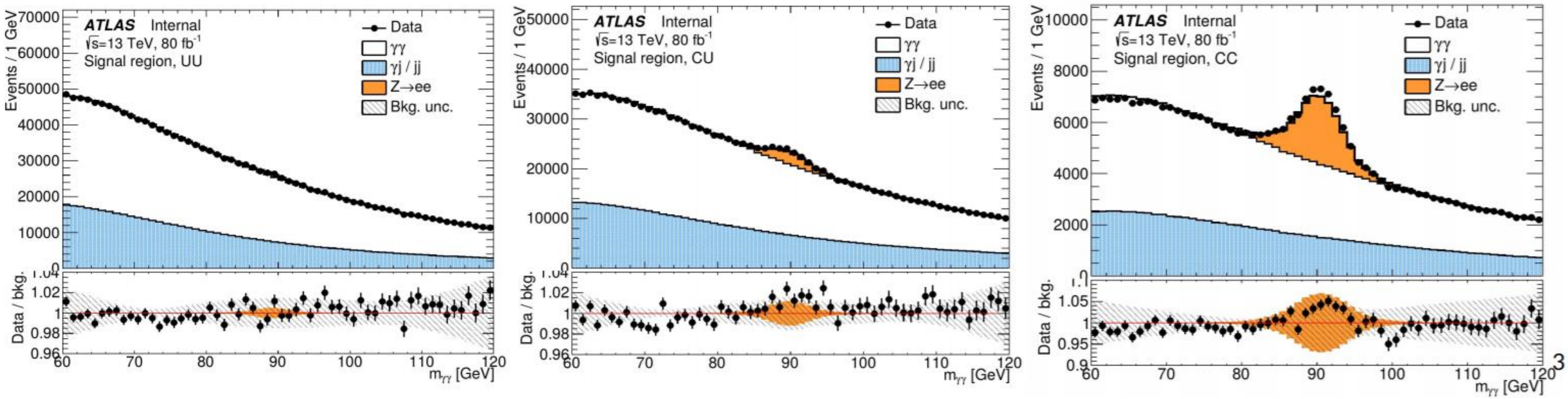
6 parameters of DSCB:

- $\Delta m_X, \alpha_{Low}, \alpha_{High}, \sigma_{CB}$ → mass dependent
- n_{Low}, n_{High} → mass independent (constant)

Each parameter is determined in a fit to the fixed-mass simulated samples, and is parametrized as a function of mass separately for each conversion category.

Pre-fit distributions

Search range: 65~110 GeV (width of signal~1.5GeV)



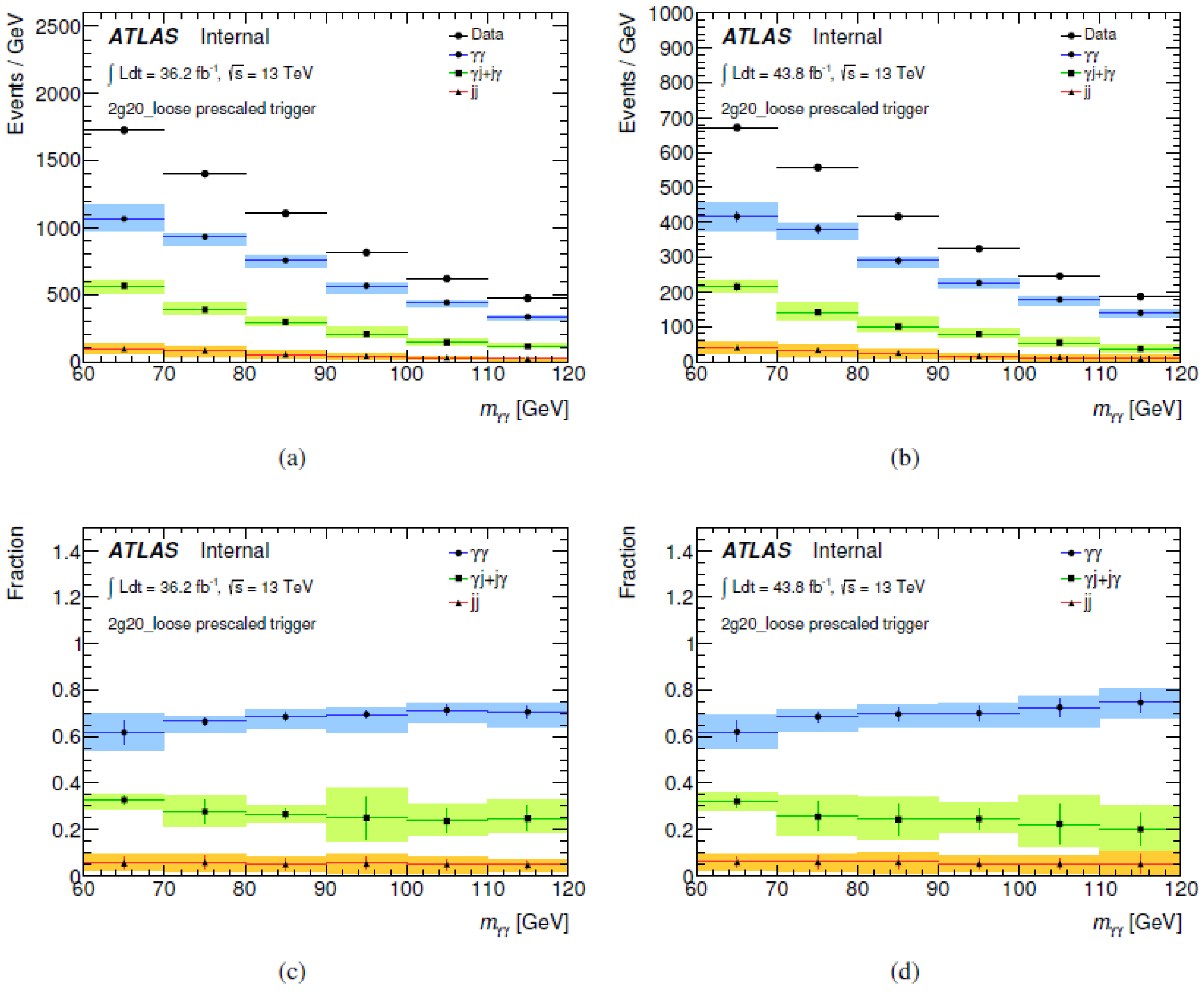
- ➢ Data in good agreement with the background template within uncertainties.
- ➢ Small excess around the DY region, but covered by the systematics.

Continuum backgrounds

- **irreducible (γγ):**
taken from high-statistics MC samples
- **reducible (γ+jet, multi-jet):**
taken from data-driven **control regions**

Step 1: build a **template** (irreducible and reducible) representative of the non-resonant background.

Step 2: add the two parts together according to their **respective fraction** measured in data.

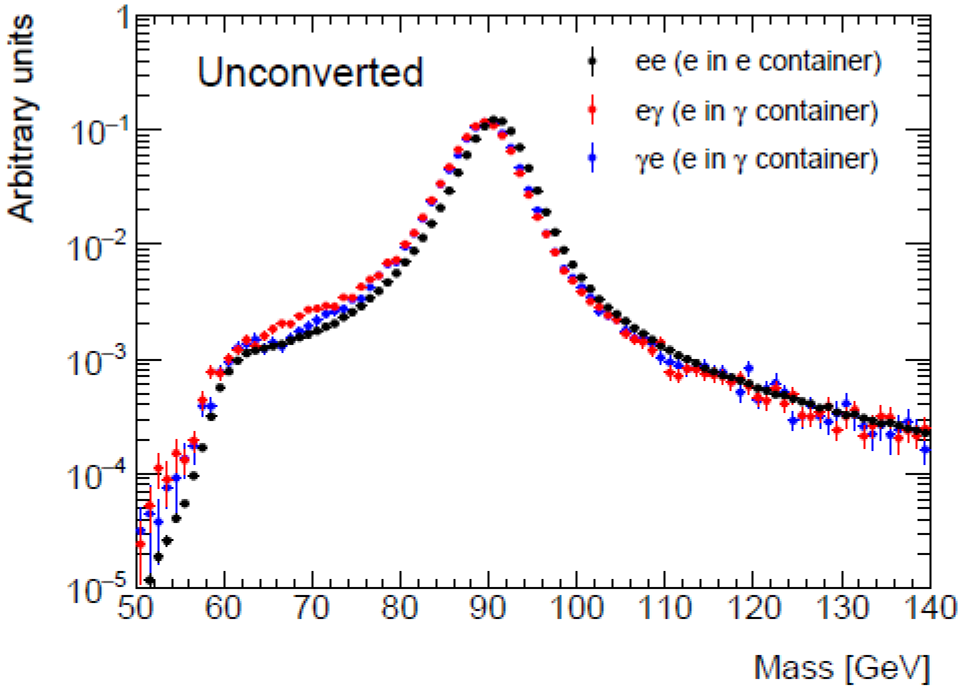


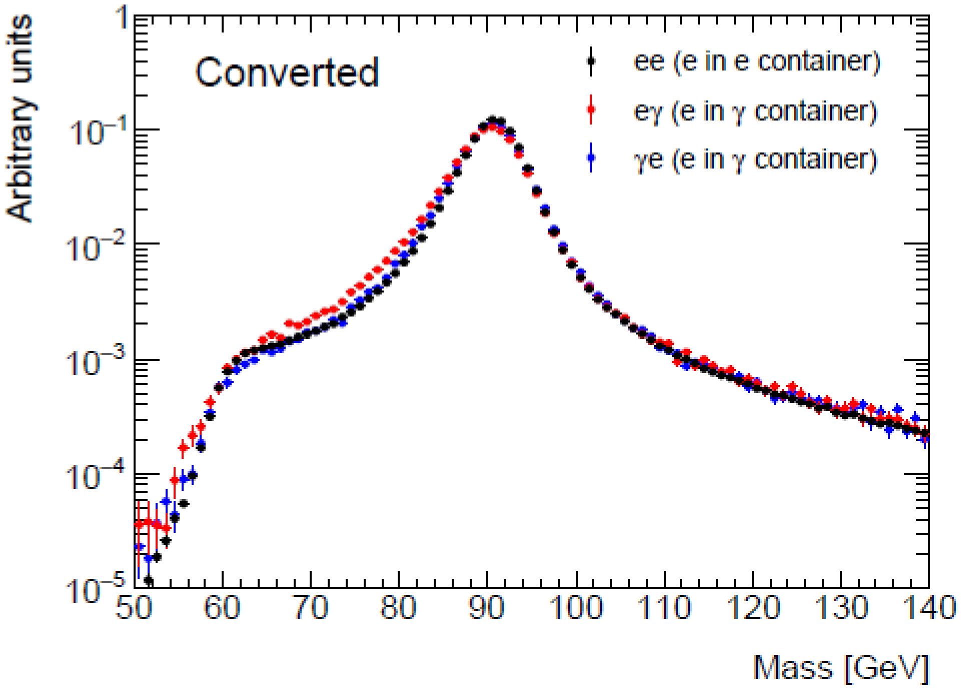
[2x2D sideband method]

Resonant Drell-Yan backgrounds

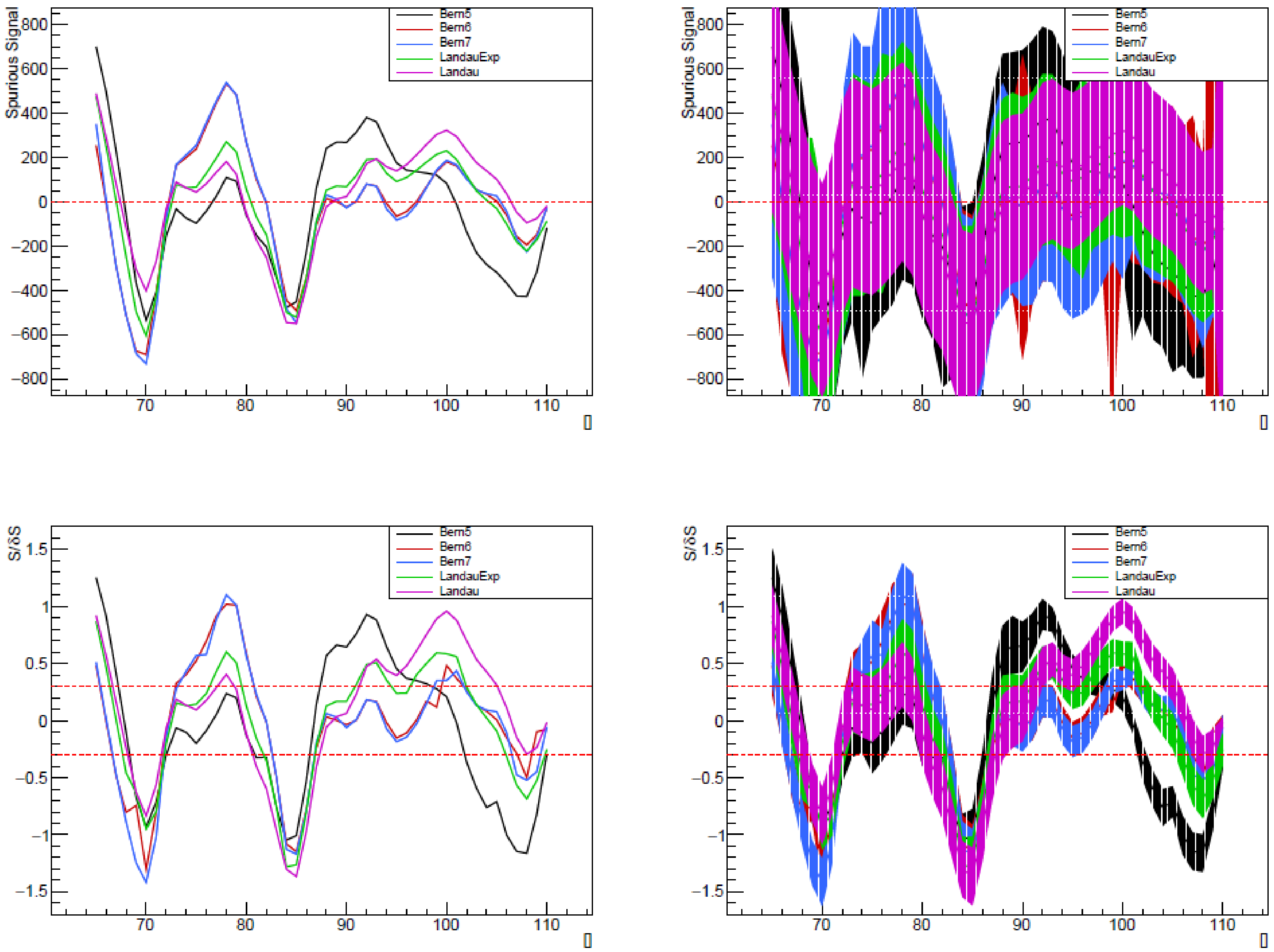
Crucial ingredient for background estimation: **Z→ee misidentified as γγ**

- Using a di-electron data sample to build a Drell-Yan template
- Normalize the Drell-Yan template to the amount of di-electrons events faking diphoton events





Spurious signal test



Statistical model

- The data are described using an extended PDF expressed as:

$$\mathcal{L} = \prod_{c=1}^{n_c} e^{-N_c^{total}} \prod_{i=1}^{n_c^{data}} \mathcal{L}_c(m_{\gamma\gamma}(i,c))$$

$n_c = 3$: number of categories
n_c^{data}: number of data events
n_c^{total}: number of fitted events

- The per-event term is expressed as:

$$\begin{aligned}\mathcal{L}_c(m_{\gamma\gamma};\sigma_{fid},m_X,N_{uu,c},N_{uc,c},N_{cu,c},N_{cc,c},N_{bkg,c},c_c,\theta) &= N_{X.c}(\sigma_{fid},m_X,\theta_{N_X},\theta_{SS})f_X(m_{\gamma\gamma},m_X,x_X(m_X),\theta_\sigma) \\ &+ N_{uu,c}(\theta_{N_{uu,c}})f_{uu,c}(m_{\gamma\gamma},x_{uu,c},\theta_{uu,c}) \\ &+ N_{uc,c}(\theta_{N_{uc,c}})f_{uc,c}(m_{\gamma\gamma},x_{uc,c},\theta_{uc,c}) \\ &+ N_{cu,c}(\theta_{N_{cu,c}})f_{cu,c}(m_{\gamma\gamma},x_{cu,c},\theta_{cu,c}) \\ &+ N_{cc,c}(\theta_{N_{cc,c}})f_{cc,c}(m_{\gamma\gamma},x_{cc,c},\theta_{cc,c}) \\ &+ N_{bkg,c}f_{bkg,c}(m_{\gamma\gamma},c_c)\end{aligned}$$

σ_{fid}: fiducial production cross-section of the new resonance
$N_{xx,c}$: number of DY background events identified as (and contribute to) UU, UC or CC
$N_{bkg,c}$: fitted number of background events
c_c: collectively refers to the background parameters used to describe its shape
θ: collectively designates the nuisance parameters used to describe the systematic uncertainties

The continuum background PDF $f_{bkg,c}$ is described by the function chosen for each category mentioned before.