Search for new particles decaying to a pair of Higgs bosons with the ATLAS experiment

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Overview

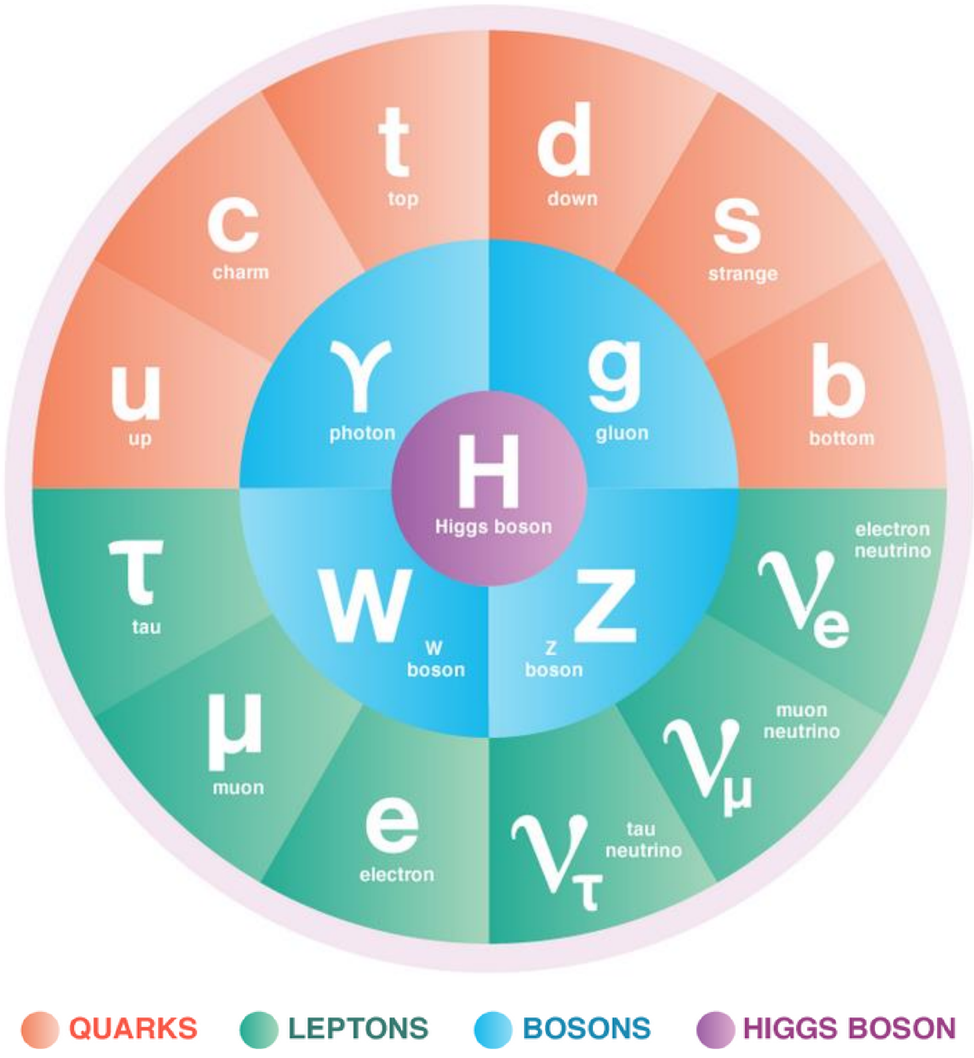
- Introduction
- Why are we studying the Higgs pair production ?
- Production process and decay mode HH
- Selection
- Modeling
- Final Fit
- Conclusions and next steps

The Standard Model (SM)

- Currently the **most experimentally validated** theory, it **fails** to explain some observations, suggesting that a **more fundamental theory exists**

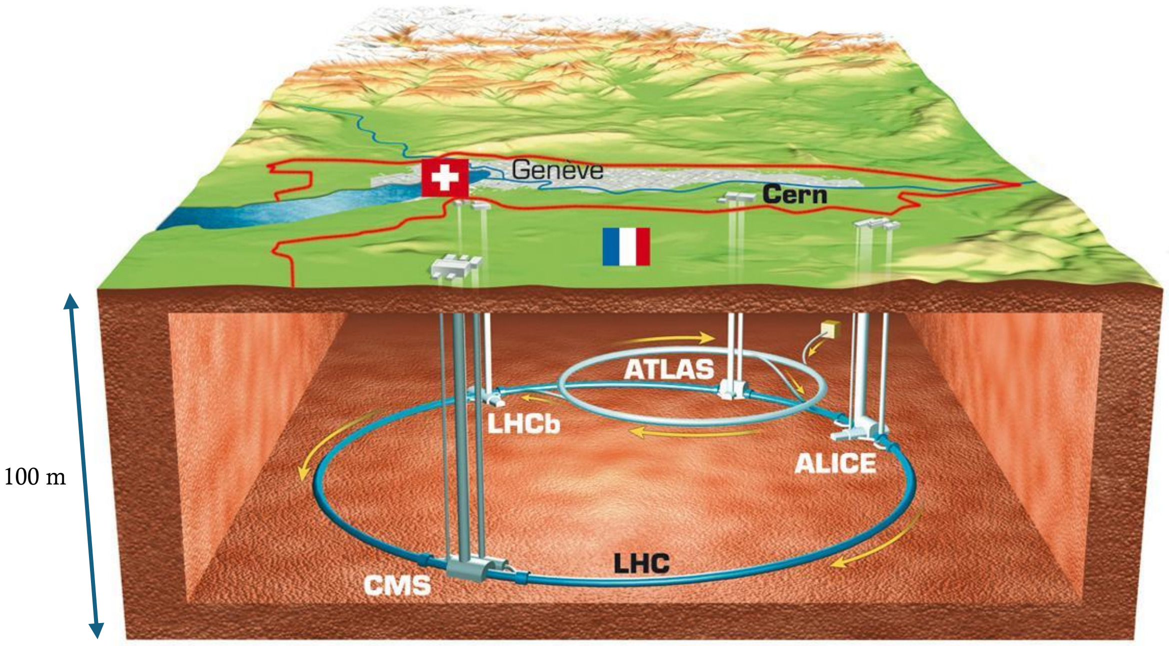
- 12 **fermions** (6 quarks 6 leptons) : elementary constituents of matter
- 4 gauge **bosons**: mediators of fundamental interactions($g, \gamma, Z^0, W^{\pm}$)

- **Higgs boson** (2012):
  Brout-Englert-Higgs mechanism (1964) that **gives mass** to elementary particles

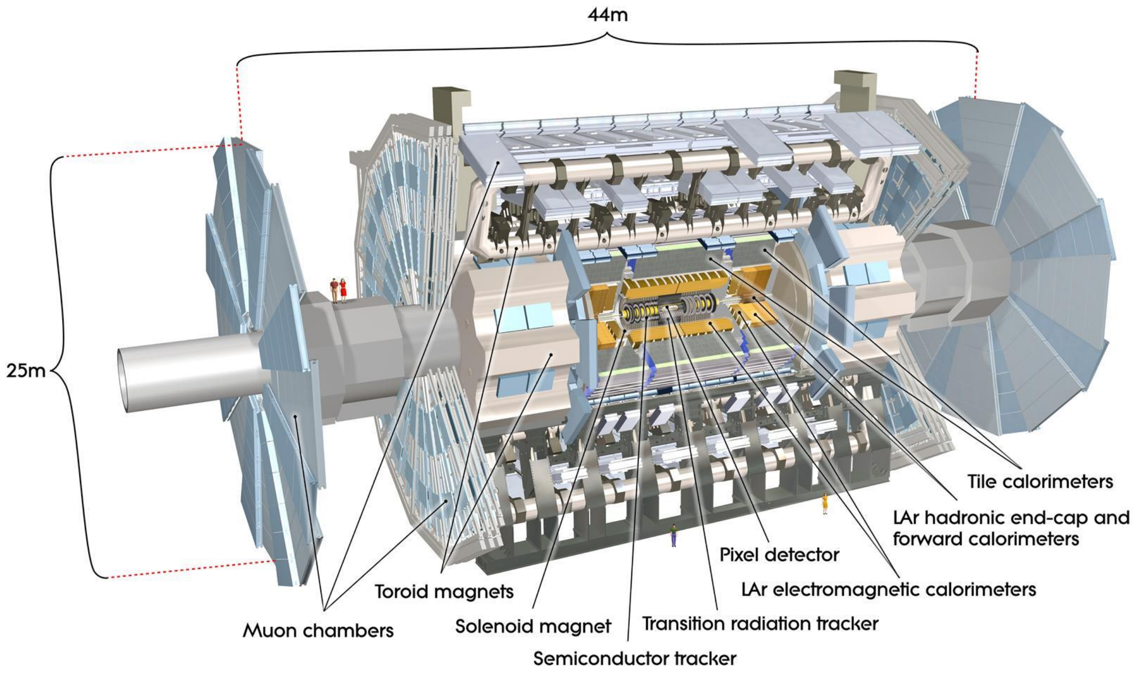


The Experimental Framework

The **LHC** (Large Hadron Collider) at **CERN**
World's largest **accelerator**
Proton-proton **collider**



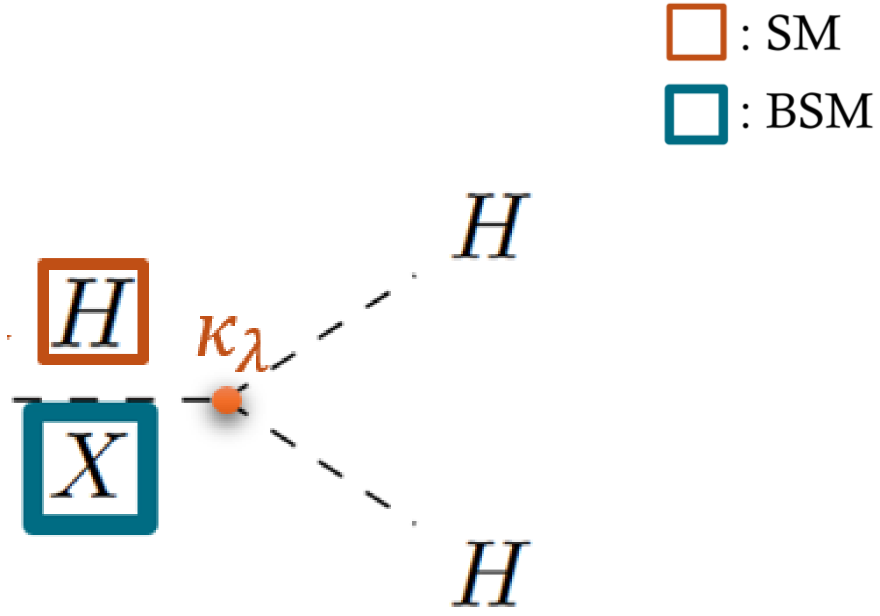
27 km in circumference



The **detector** (almost 4π coverage) of the **ATLAS** experiment
Trackers and Calorimeters:
designed to measure **trajectory** and **energy** of emitted particles

Why are we studying the Higgs pair production ?

Search for new particles decaying to a pair of Higgs bosons with the ATLAS experiment



Resonant Production mode: X is a scalar particle

- **Higgs mechanism** gives **mass** to particles so we can **probe** the potential **existence** of a **new massive X scalar boson** through its interaction with the Higgs boson

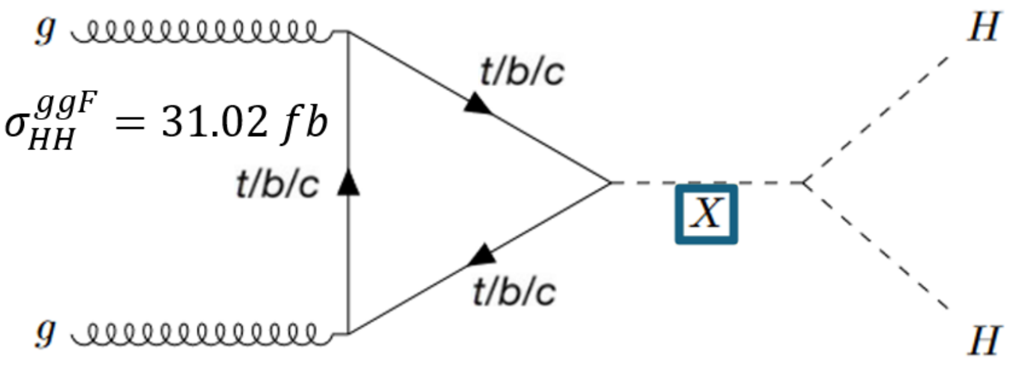
- Possibility to discover a new particle or **set limits on** the **production** of a **new scalar boson** through this analysis and to **characterize the Higgs boson self-coupling** (κ_λ)

Internship supervised by Louis D'Eramo

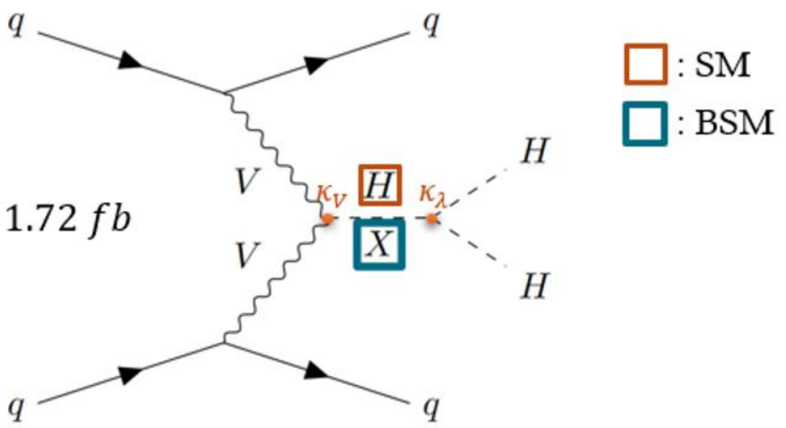
Production and Decay HH

- **Gluon-Gluon Fusion (ggF)** : 90% of HH production

$\sigma_{HH}^{ggF} = 31.02\, fb$



$\sigma_{HH}^{VBF} = 1.72\, fb$



- **Vector Boson Fusion** (VBF) **HH** (V = W or Z)

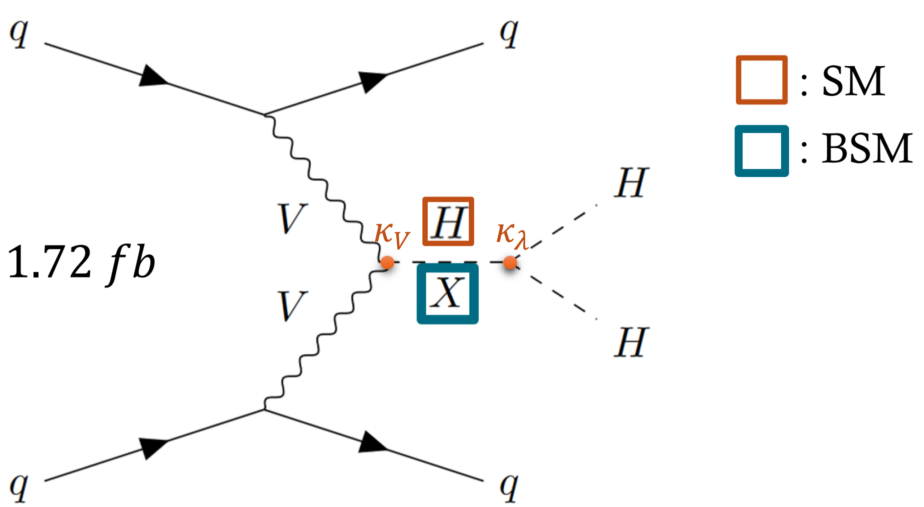
Most **studied channels** :

- HH → $b\bar{b}b\bar{b}$
- HH → $b\bar{b}\tau^+\tau^-$
- HH → $b\bar{b}\gamma\gamma$

$BR(HH \rightarrow XXYY)$ (gluons, c, muon not shown)

	bb	WW	ττ	ZZ	γγ
bb	34 %				
WW	25 %	4.6 %			
ττ	7.3 %	2.7 %	0.39 %		
ZZ	3.1 %	1.1 %	0.33 %	0.069 %	
γγ	0.26 %	0.10 %	0.028 %	0.012 %	0.0005 %

Production and Decay HH



$\sigma_{HH}^{VBF} = 1.72\ fb$

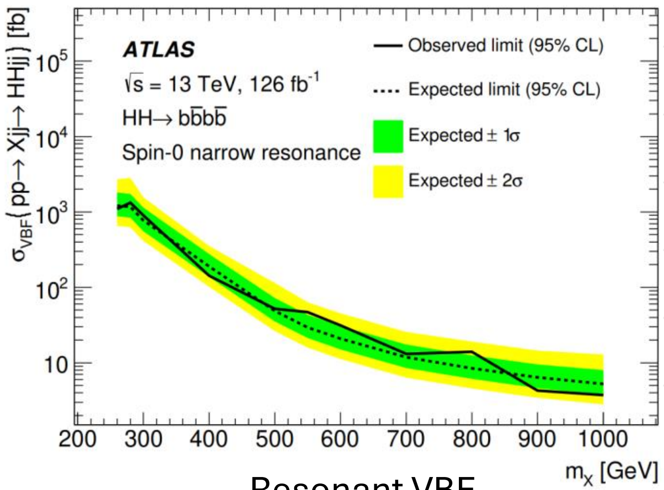
Vector Boson Fusion (VBF) **HH** (V = W or Z)
Resonant : X is a spin-0 particle

- Cross-section for the **single Higgs Boson VBF** production which is a rare process is around $\boldsymbol{\sigma_H^{VBF} = 3.78}$ **pb (2000 times the di-Higgs one)**

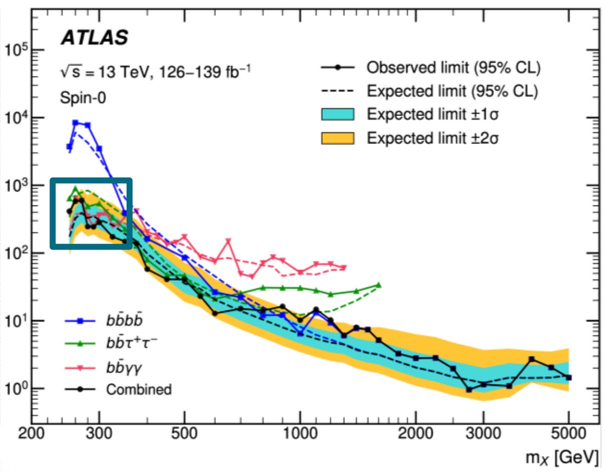
- Detection only of **signatures** (final states) because the **lifetime of the Higgs** is too low ($10^{-22}\ s$)

HH → $b\bar{b}\gamma\gamma$

- **H →** $\boldsymbol{b\bar{b}}$ **:** High Branching Ratio (57%)
- **H →** $\boldsymbol{\gamma\gamma}$ **:** photons allows to trigger **events at a lower energy** and to obtain a **good resolution** for $m_{\gamma\gamma}$ and m_X thanks to the electromagnetic calorimeter (Lar)



Resonant VBF



Resonant ggF

arXiv:2001.05178v5
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/HDBS-2023-17/fig_01b.png

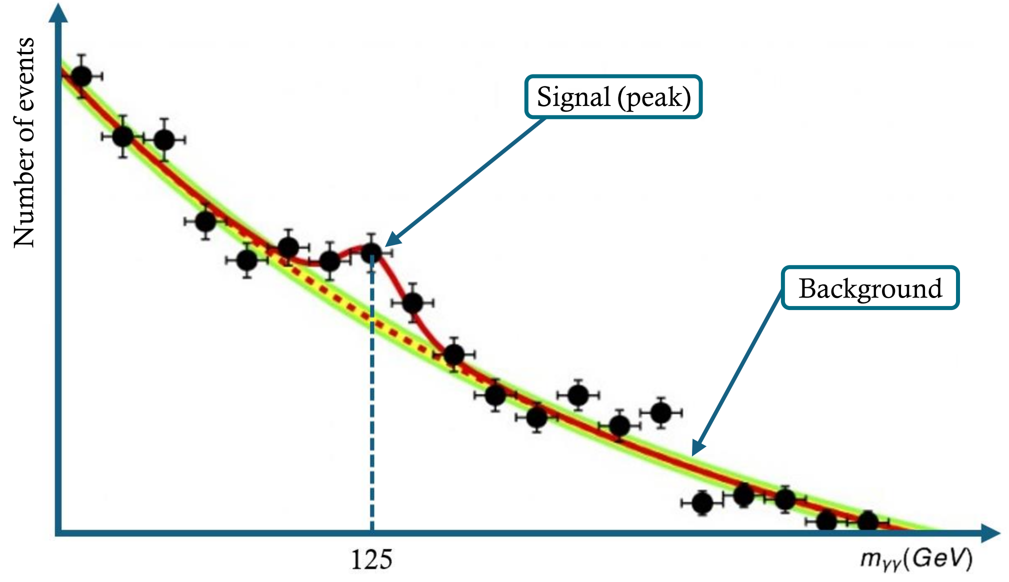
Objective : Final Fit

$$f_{final}(x) = f_{signal}(x) + f_{bckg}(x)$$

where $f_{signal}(x)$ denotes the **fitted** function for **the signal** (smallest χ^2), while $f_{bckg}(x)$ represents all the background, modeled by a function for the **continuous background**, and includes **single H** and **double Higgs** production, both described by the **same function** as the one of the **signal**.

- Perform the **FIT** adding the **fitted pdf** of the **signal** and the one of the **background** (smallest spurious signal) to know if the **BDT** used in **SM HH** production is **adapted** to the **VBF Resonant** HH data.

- **Establish an upper limit** (exclusion zone for new models) on the cross-section $\boldsymbol{\sigma_{VBF}(X \to HH)}$.



Selection

Pre-selection

- Exactly 2 b-jets
- < 6 central jets
- Exactly 2 high-quality photons
- No lepton ($t \rightarrow bW \rightarrow b\ell^{-}\bar{\nu}_{\ell}$)

- Identification of 2 high-quality photons
  - ➢ with transverse momentum $p_T^{\gamma} > 35$ GeV and $|\eta^{\gamma}| < 2.5$ (η, the pseudo-rapidity, is an angle that describe the direction of a particle in the detector with respect to the beam pipe)
  - ➢ isolated to reduce background contamination (the energy within a certain area around the photon's energy deposit must remain below a defined threshold)

- The invariant mass of the two selected photons must be in the range $105 < m_{\gamma\gamma} < 160$ GeV

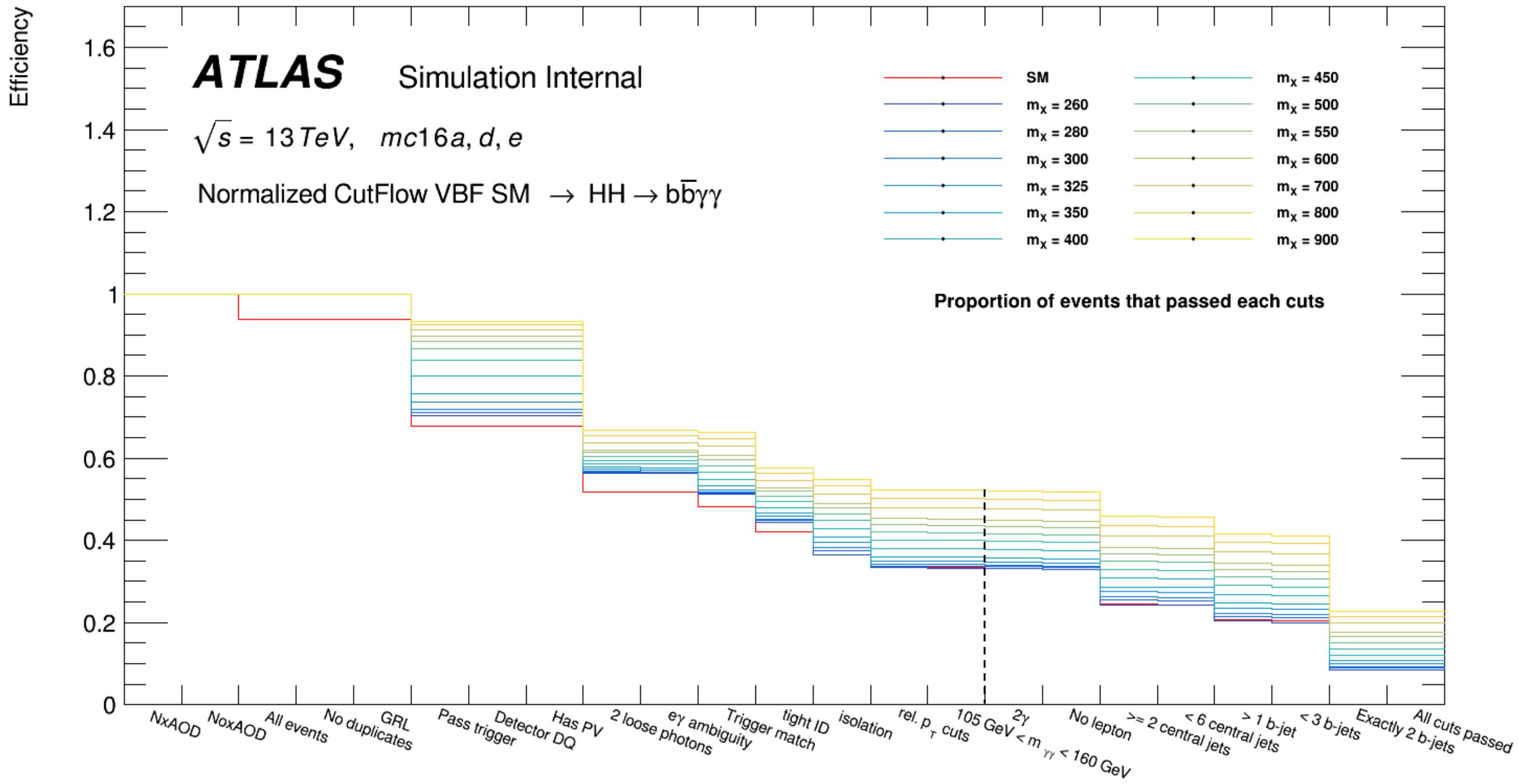
- B-jet selection: Each b-tagged jet must have a transverse momentum $p_T > 30$ GeV and $|\eta| < 2.5$

Selection CutFlow : Signal all m_X

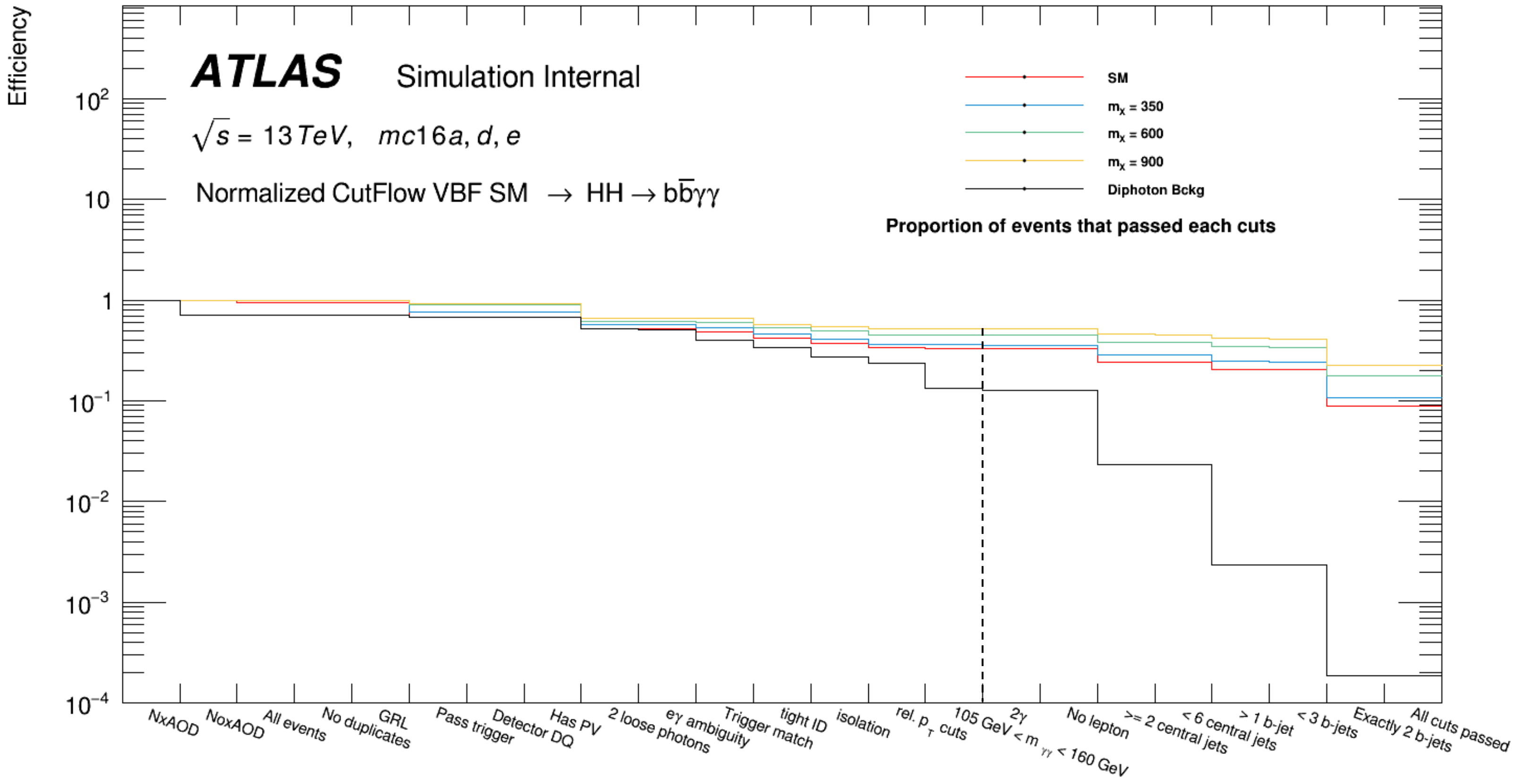
- Reconstruct the **CutFlow** applying **cuts after cuts** in order to **select signal-like events** which correspond to the final state $b\bar{b}\,\gamma\gamma$.

- CutFlow **renormalised** divided into two parts, the **H→γγ cuts** (selecting good data taking conditions and 2 good photons) and the **HH** → $b\bar{b}\gamma\gamma$ (b-jet selection) ones.

- Development of an automatic algorithm that scan all the **cuts efficiency** (number of events after a cut / number of events before this cut) and select the ones that **remove the most data** to **plots them** in function of m_X (backup).



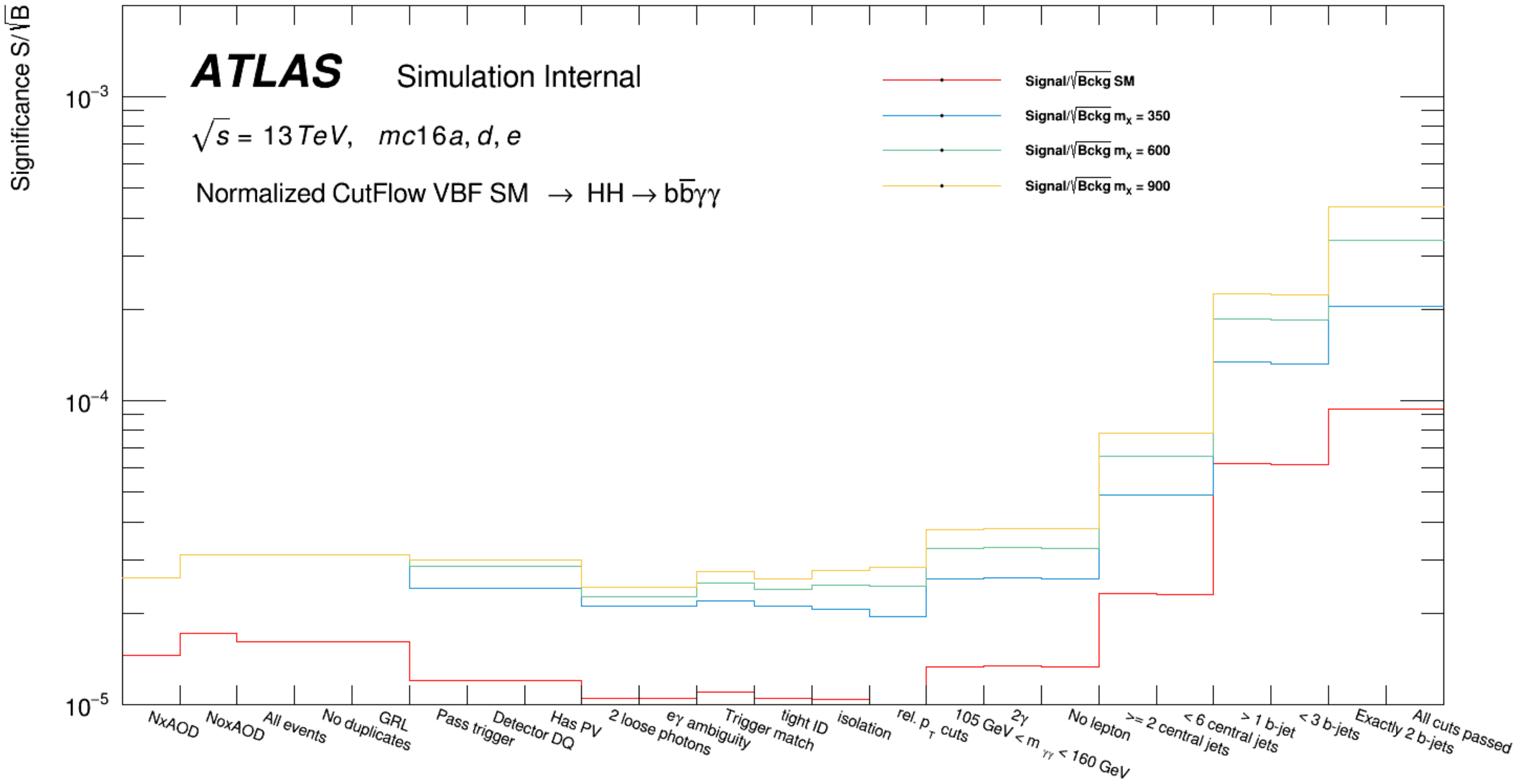
Selection : Signal and Background



- Until now, we have only talked about the study of the signal so let's see **how the background reacts** to this **selection**.
- For that I decide to work with only the **SM** and **3 samples m_X** and the **diphoton background**.

- As we were expecting the cuts are removing the background much more than the signal and $m_X \nearrow \Longrightarrow$ **Efficiency** ↗ (more **boosted objects so better identification**).
- Plot the **Significance** which is the Signal over the square root of the background ($\frac{S}{\sqrt{B}}$). Significance increasing cuts after cuts and $m_X \nearrow \Longrightarrow$ **Significance** ↗.

Selection : Significance



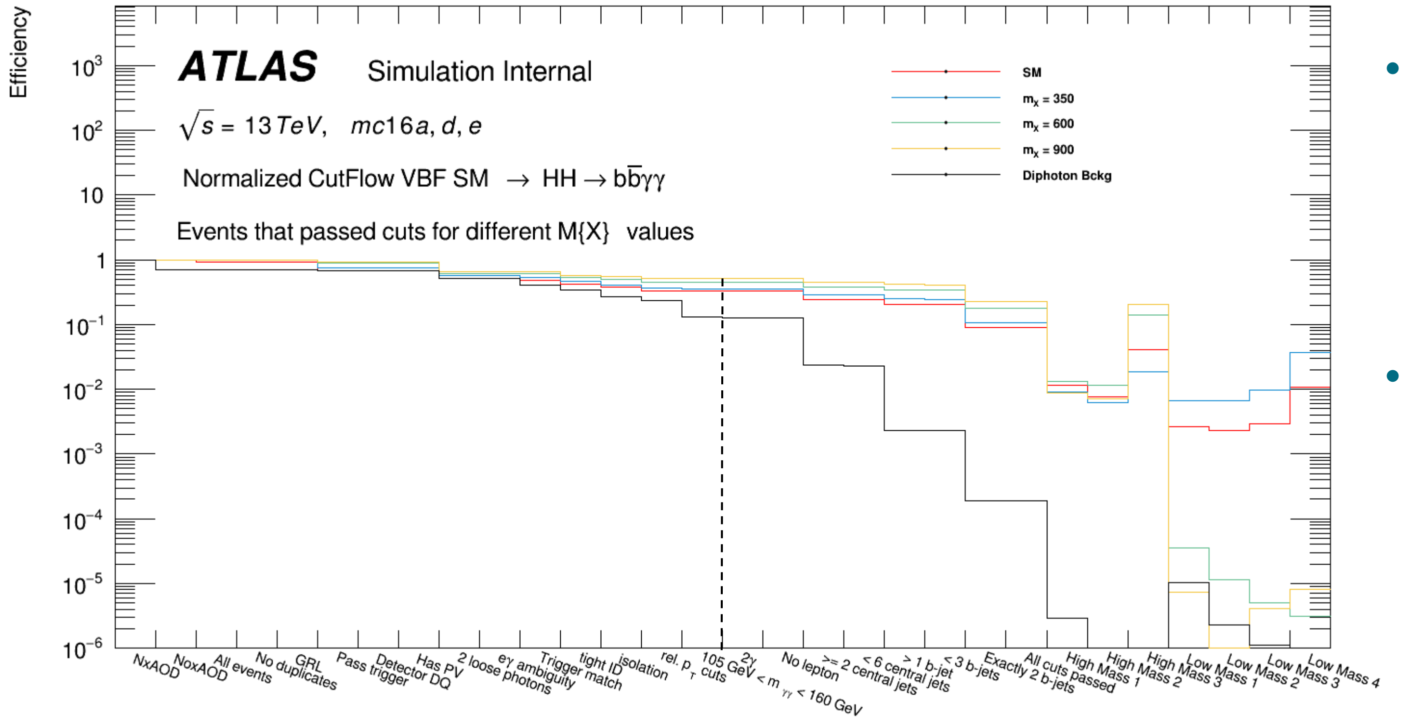
$b\bar{b}\gamma\gamma$ Selection : Mass categories

$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125) - (m_{\gamma\gamma} - 125)\ (Gev)$$

To reduce the width of the $m_{b\bar{b}\gamma\gamma}$ peak

High mass if $m^*_{b\bar{b}\gamma\gamma} > 350$ Gev (sensitive to SM signal $\kappa_\lambda = 1$)

Low mass if $m^*_{b\bar{b}\gamma\gamma} \leq 350$ Gev (sensitive to BSM signal $\kappa_\lambda = 10$) (backup)



- The analysis follows the **selection methodology** from a previously published study on **non-resonant HH →** $\boldsymbol{b\bar{b}\gamma\gamma}$ (JHEP 01 2024 066)

- **Worked with a BDT** (Boosted Decision Tree) algorithm and the **mass categories** created thanks to BDT score ∈ [**0** , **1**[(**signal purity** indicator).

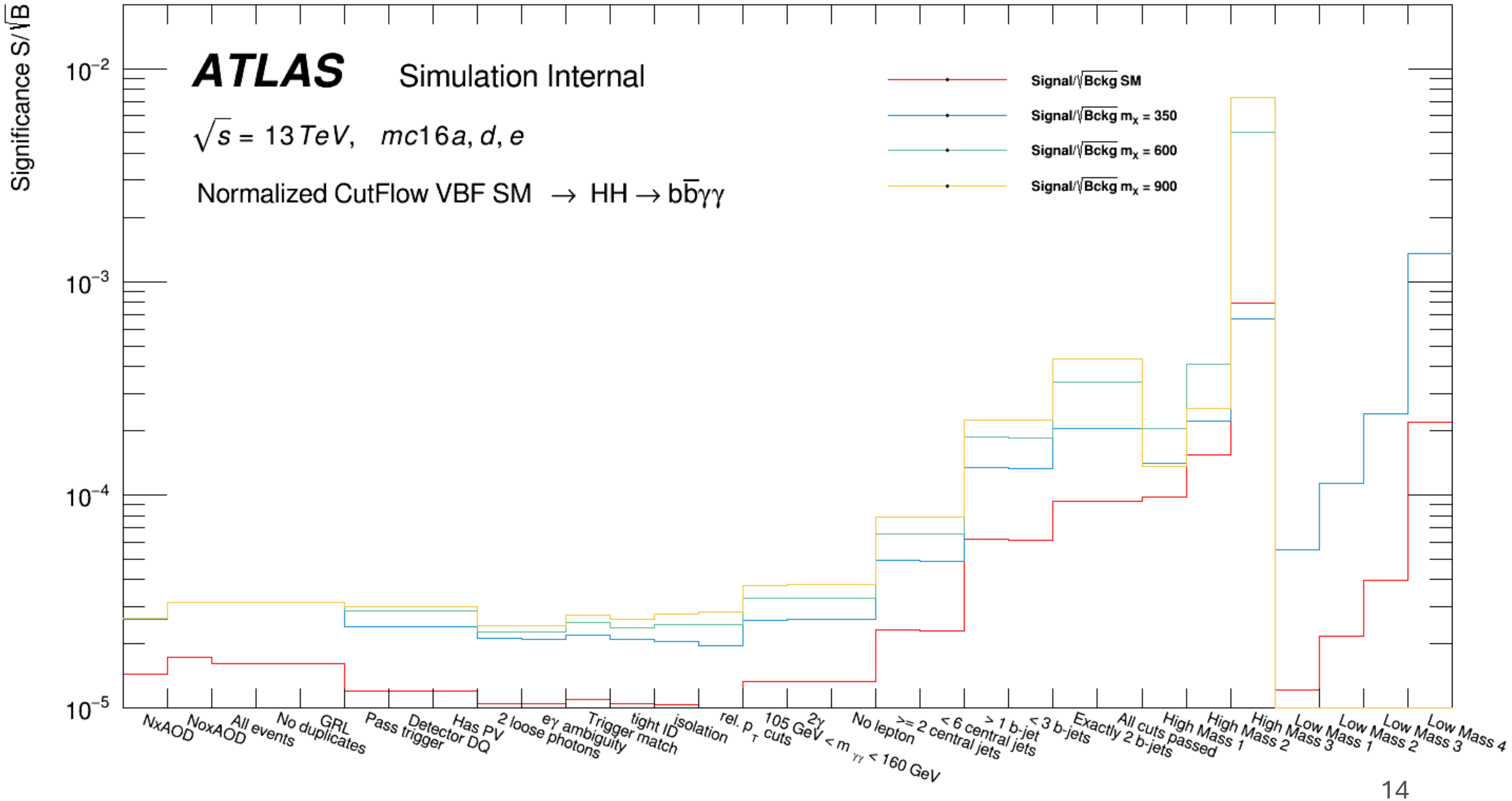
- **3 High Mass** categories and **4 Low Mass** ones defined to **optimize** the **significance** considering the various possible κ_λ values and designed to **improve** the **selection** of events

Selection : Mass categories' Significance

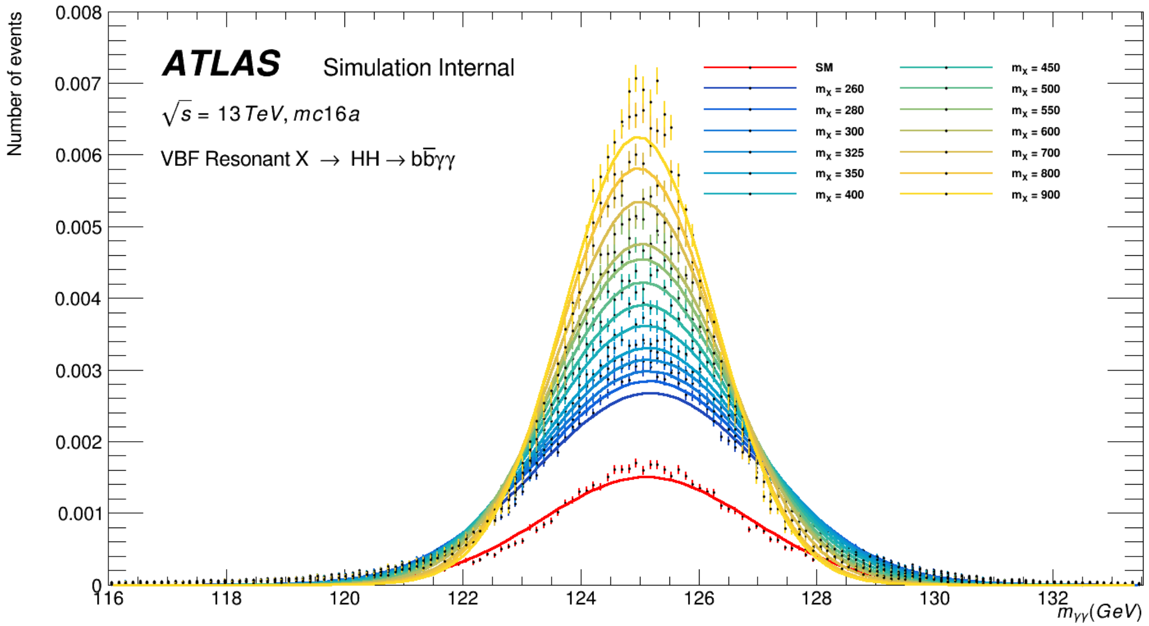
m_X	S_{tot} Total Significance
125 (SM)	8.44×10^{-4}
260	0.00143
280	0.00165
300	0.00183
350	0.00157
400	0.00262
450	0.00338
500	0.00402
550	0.00459
600	0.00508
700	0.00595
800	0.00665
900	0.00729

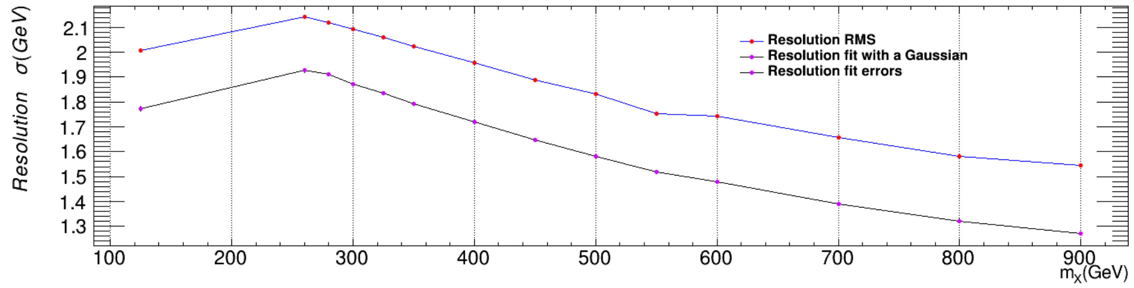
$$S_{tot} = \sqrt{\sum_{i \in mass\ categories} S_i^2}$$

$\boldsymbol{\sigma_{th}^{HH} = 1\ fb}$: arbitrarily set



Modeling Resonant signal



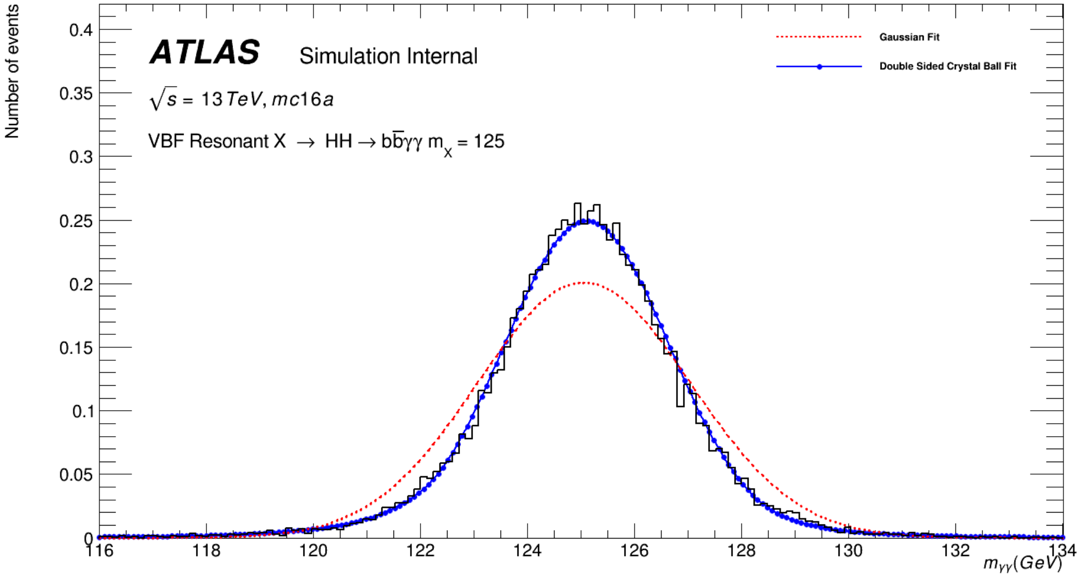


- On the upper plot we can see that when $\boldsymbol{m_X} \nearrow \Longrightarrow$ $\boldsymbol{Number\ of\ events} \nearrow$ (more **boosted objects so better identification**)

- Code to plot the $\boldsymbol{m_{\gamma\gamma}}$ branch applying **pre-selection** and **weights** for different Monte-Carlo generated root files with $\boldsymbol{m_X} \in [\mathbf{260}\,,\mathbf{900}]\ GeV$

- Graphs of **resolution $\boldsymbol{\sigma}$** of **gaussian which fit the data** but this function is **not optimal** as we can see for the peak and the tails → Double Sided **Crystal Ball function** and applied to both a **$\boldsymbol{\chi^2}$ test** to compare them

Goodness of fit



- **Fit the data** with a **DoubleSidedCrystalBall** (DSCB) function instead of fit it with a **gaussian** to compare their **goodness of fit** (ChiSquare/ndof)

- As we can see in this table the **goodness of fit of the DSCB** function is quite **better than the gaussian** one, thanks to the **adaptable tails** of the DSCB function

(backup)

m_X	Gaussian $\chi^2/ndof$	DSCB $\chi^2/ndof$
125 (SM)	55,7	7,22
260	76,3	4,41
280	94,7	4,94
300	84,9	5,14
325	102,5	4,95
350	105,7	5,18
400	95,2	5,02
450	101,6	6,05
500	113,2	5,88
550	104,3	7,23
600	110	6,82
700	133,7	7,61
800	113,9	8,04
900	127,9	7,99

Background Modeling

Different types of background

- **Continuum diphoton** production with jets ($\gamma\gamma$ + jets)
  - $\boldsymbol{t\bar{t}\gamma\gamma}$ production, where top quark pairs are produced alongside two photons
- **Single and pair Higgs boson** production through : ggF, VBF, ttH, bbH

Fit functions of the **continuous background**

- **Decreasing Exponential** Function

$$\boldsymbol{f_{bckg}(x) = Ae^{-Bx}}$$

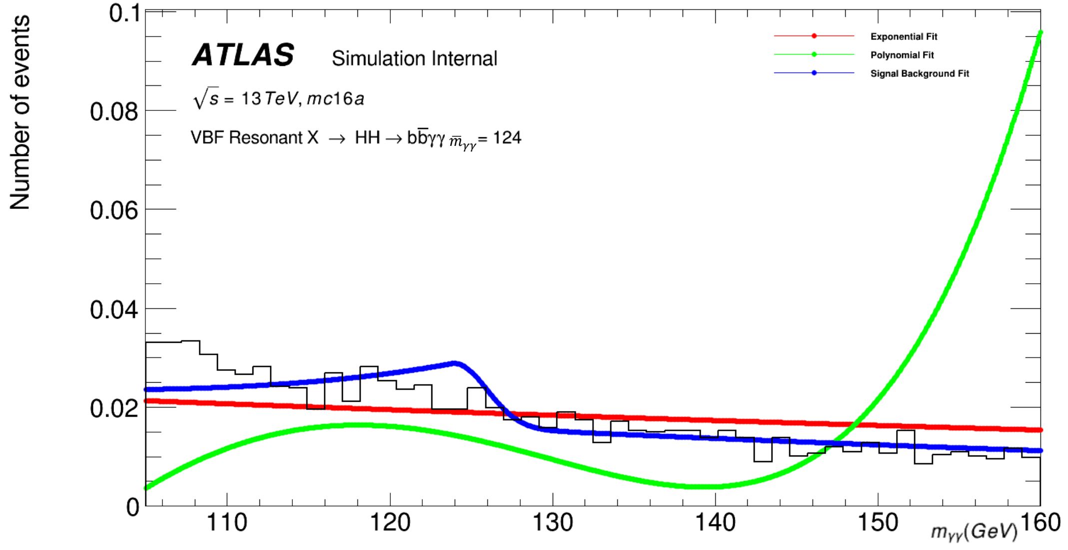
where A and B determined by fitting the background data in regions outside of the signal window ∈ [120 , 130] Gev (**blinding** the signal region)

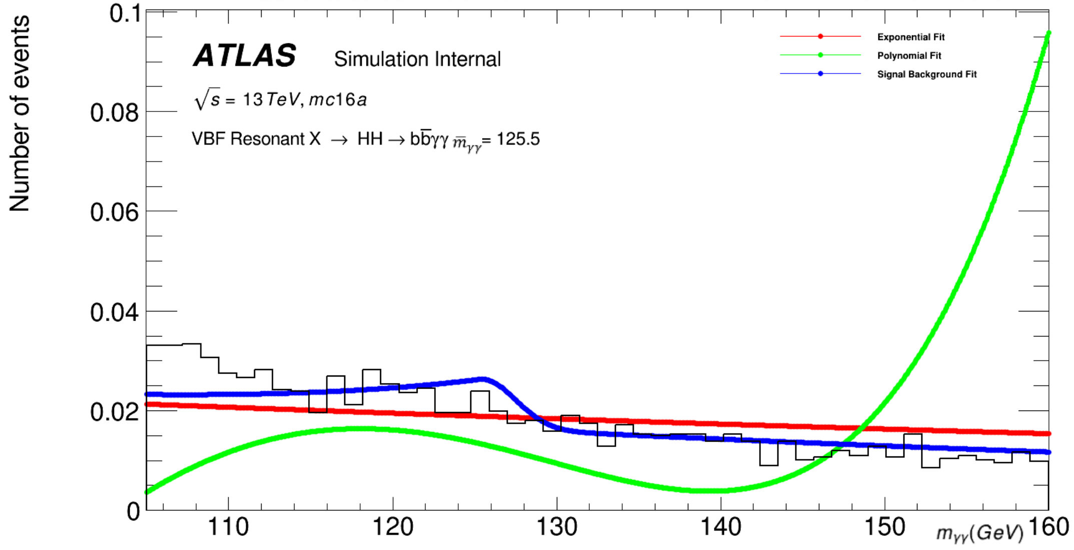
- **Polynomial** Function

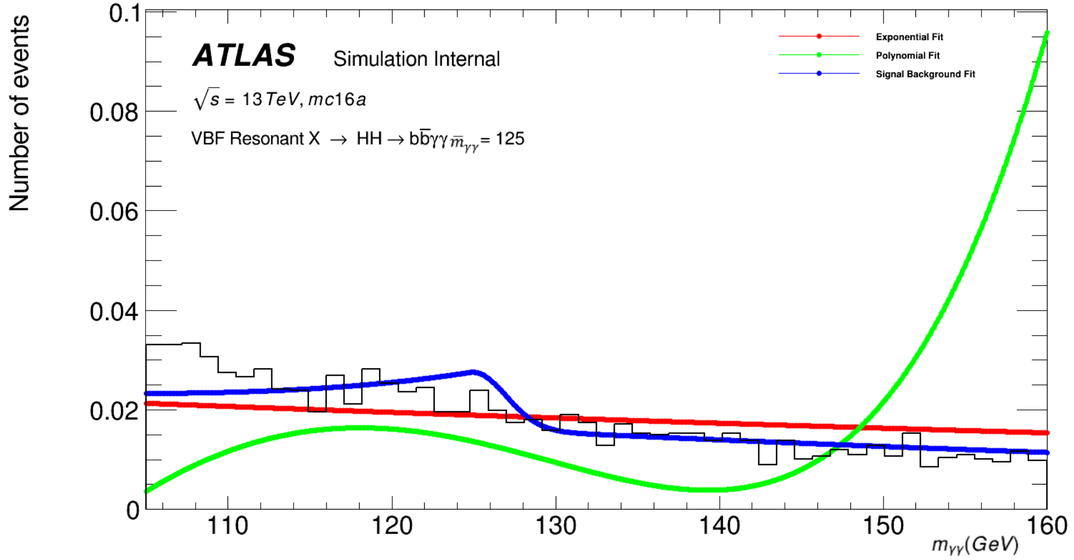
$$\boldsymbol{f_{bckg}(x) = a_0 + a_1 x + a_2 x^2 + \cdots + a_n x^n}$$

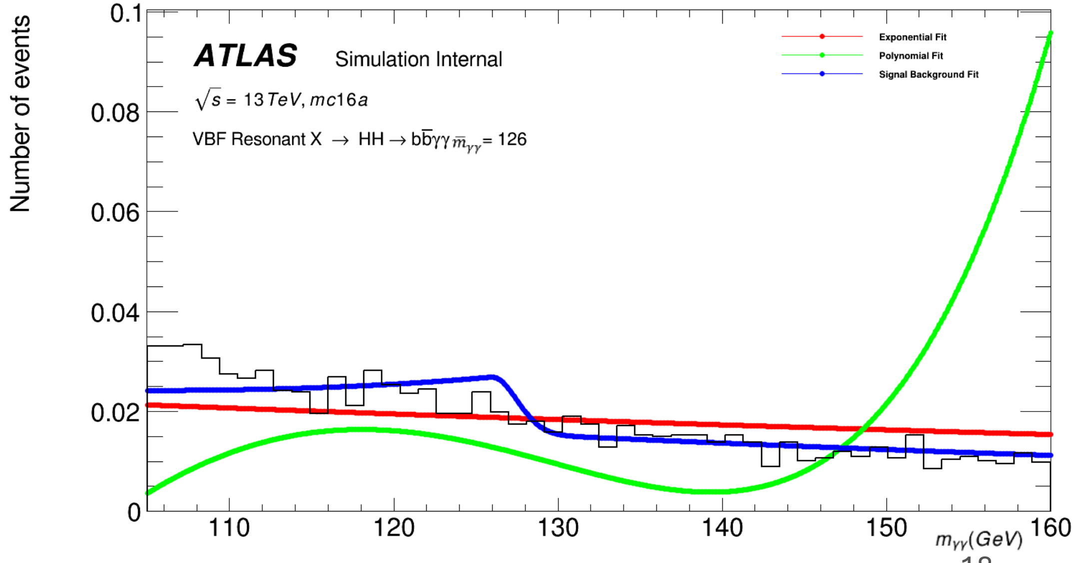
where the coefficients $a_0,\ a_1,\ a_2,\ .\ .\ .\ ,\ a_n$ determined through the fitting process. The choice of polynomial degree n is balanced to ensure sufficient **flexibility without overfitting**

Signal + Bckg over Bckg

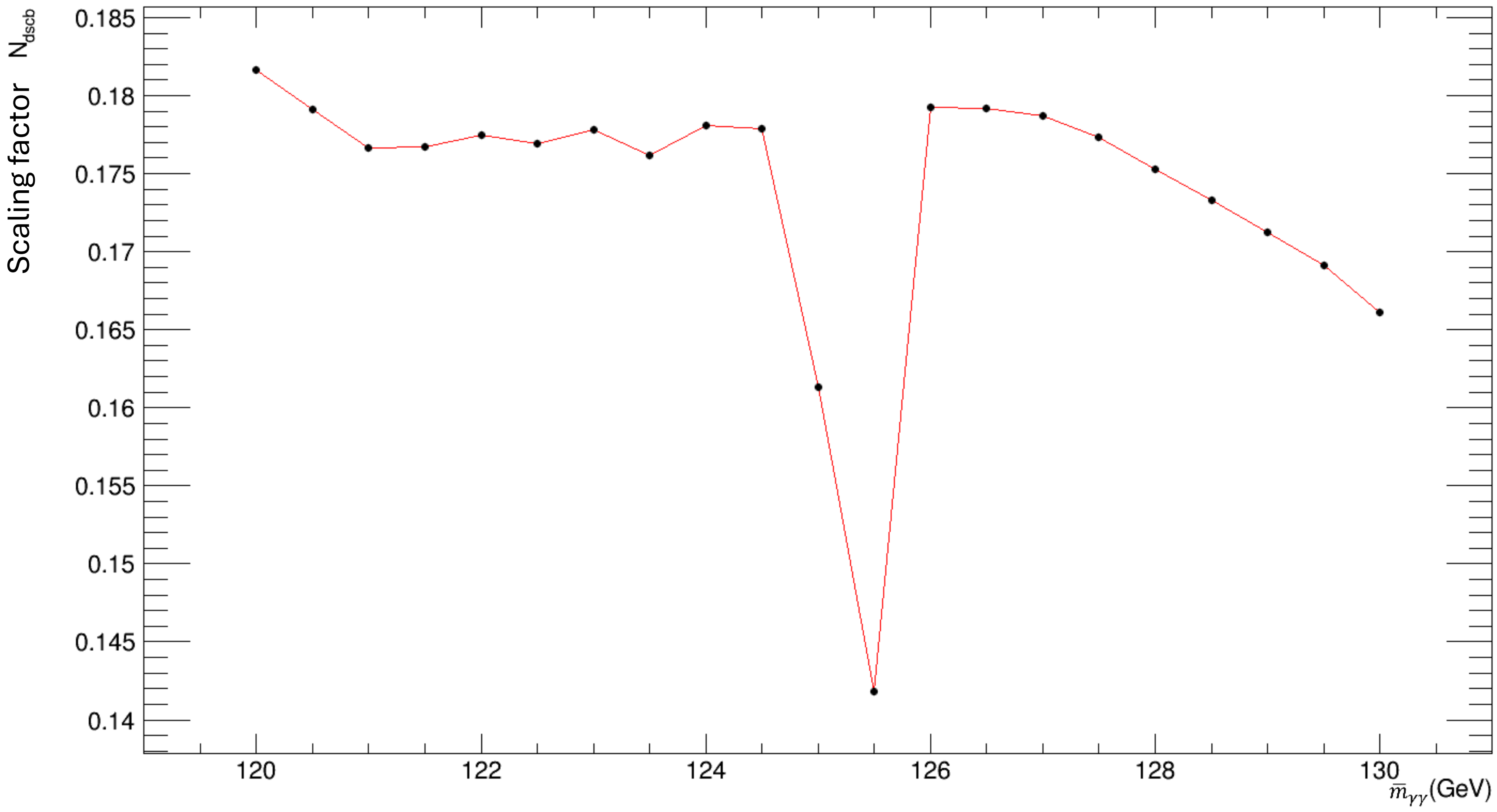








Spurious Signal

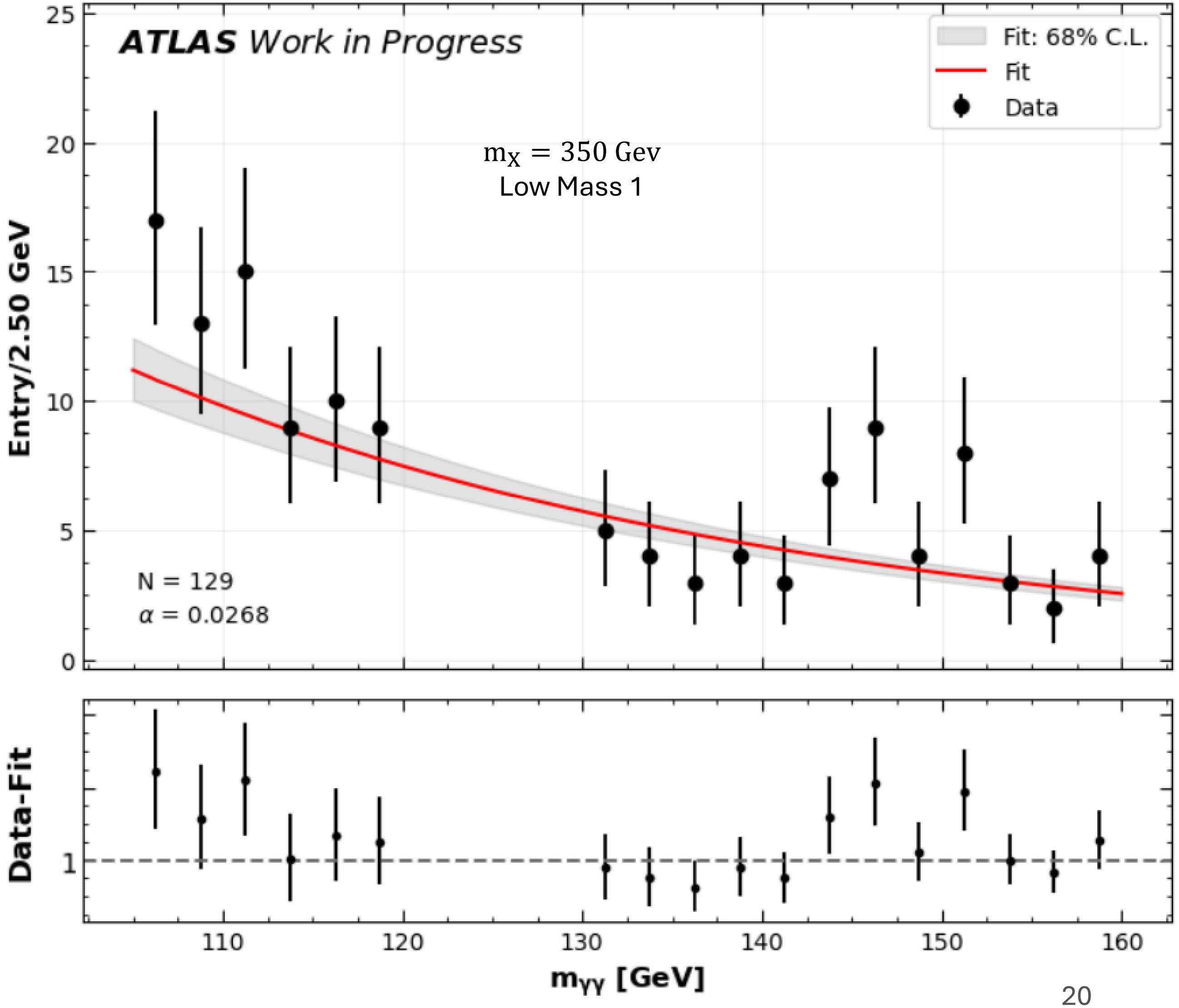


- $\bar{\boldsymbol{m}}_{\boldsymbol{\gamma\gamma}} \in [120{,}130]\ Gev$ as a **free parameter**
- **Spurious signal** (N_{dscb}) : **Maximum** of **'fakesignal'** find out when fitting signal +background function **onto the background only** sample.
- Nuisance parameter so we want to **find** the **function** fitting the background with the **lower spurious signal**

Data continuum background fit

- Finally using the **decreasing exponential** function to fit the continuous background component (often preferred for **smoothly falling distributions**)

- As an **example**, we have on the right the **background fit of the data** for $m_X =$ 350 Gev and for the Low Mass 1.



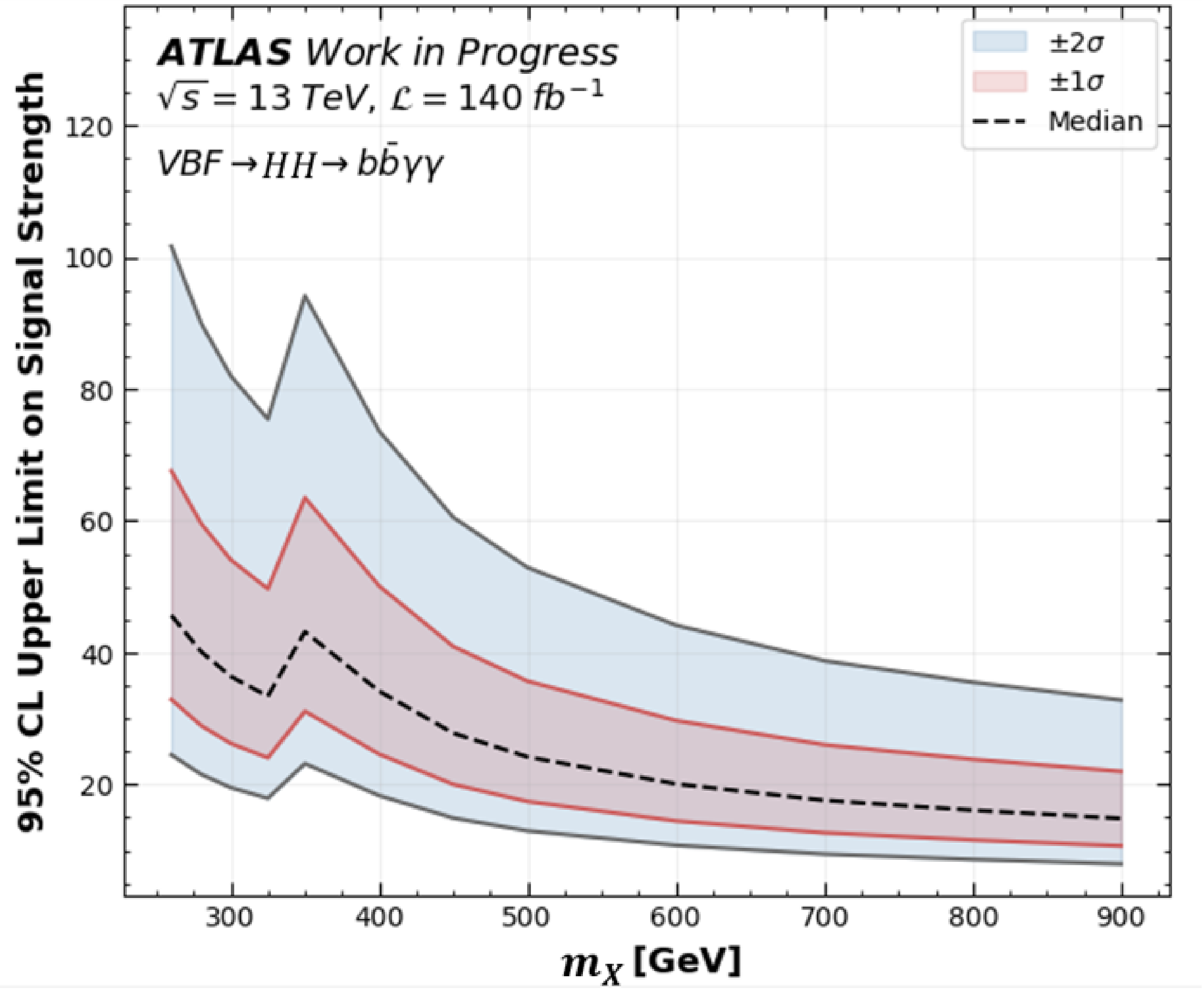
Final Fit : signal strength

- Performed a **blinded** Asimov (data equal to expected value) **fit** using only **sideband data** to **avoid bias** from potential real signals.

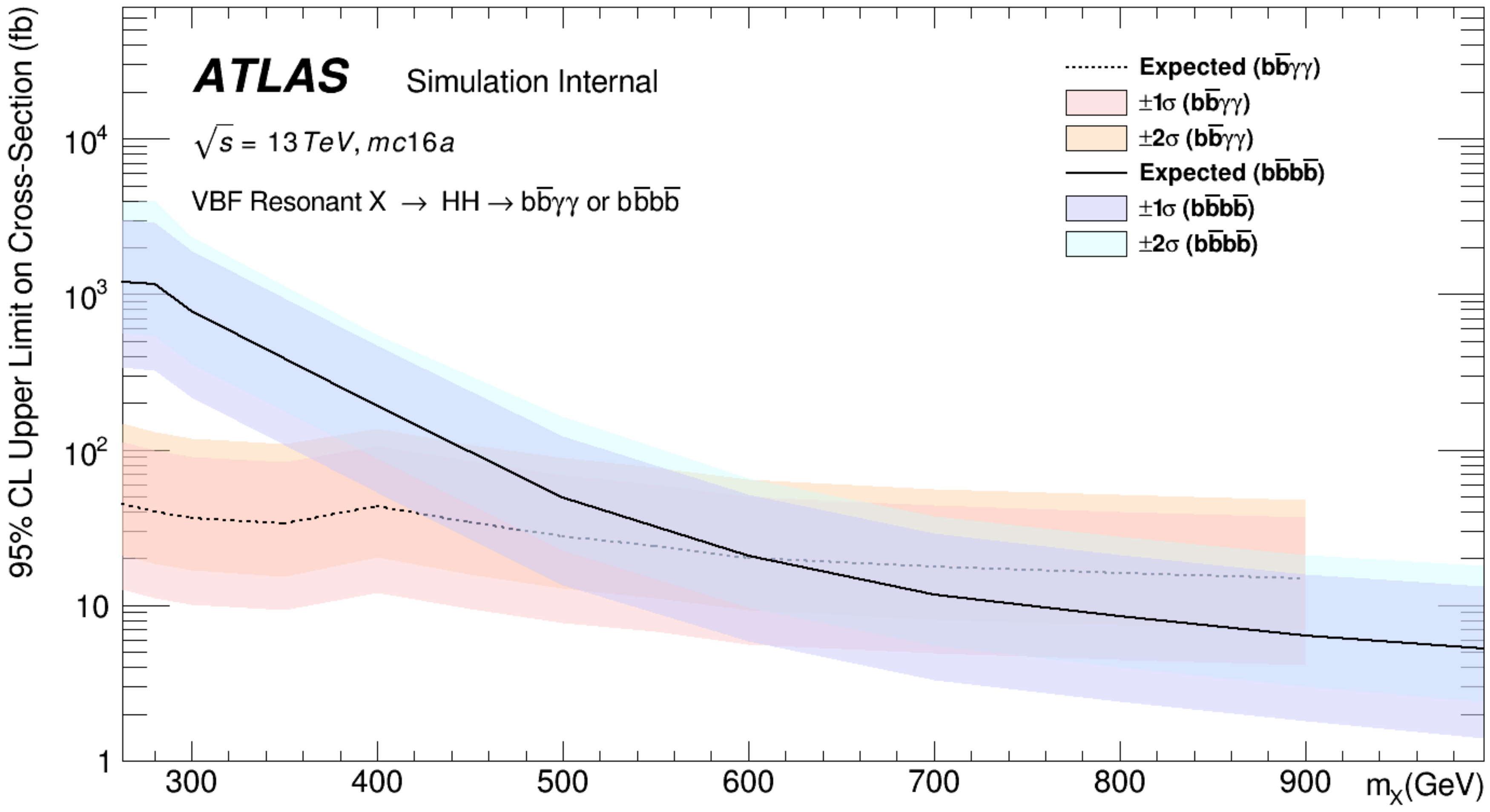
- Compute at the end the **signal strength** :

$$\mu_{HH} = \frac{\sigma_{obs}^{HH}\,(upper\ limit)}{\sigma_{th}^{HH}}$$

- Peak (350 GeV) could be explained from the **choice** of discrimination variable ($\boldsymbol{m^{*}_{b\bar{b}\gamma\gamma}}$) and the **transition between Low and High Mass categories**, redistributing signal events across more categories and **reducing** total **significance** for $\boldsymbol{m_X}$ ~ 350 Gev



Upper limit : Cross-section



- **Upper limit cross-section** for **resonant HH** model **improved for m_X below 600 GeV** thanks to this study focused on $b\bar{b}\gamma\gamma$ final state

- **Combining $b\bar{b}\gamma\gamma$** and **$b\bar{b}b\bar{b}$** channels enhances the upper limit and is **crucial** for **constraining** the **resonant HH VBF** process

Conclusions

- This internship represent the **first Resonant HH VBF** into $\boldsymbol{b\bar{b}\gamma\gamma}$ **analysis**

- Used Double-Sided Crystal Ball (DSCB) for signal, exponential for background with the study of the **spurious signal** and the $\boldsymbol{\chi^2}$ **function** to **optimize the fits**

- Applied and study **Selection** and **Categorization** in order to optimize the **Significance**

- **Improved upper limit on cross-section** (for masses $\boldsymbol{m_X} < 600$ GeV) of **VBF Resonant HH** process thanks to the $\boldsymbol{b\bar{b}\gamma\gamma}$ final state

Next steps

Current and following steps for the PhD :

Selection

- **Adapt** the **BDT's structure** and the **definition of the mass categories** to the resonant signal to **improve cuts' efficiency** and significance
- **Explore neural networks** for enhanced mass categorization and better signal-background separation

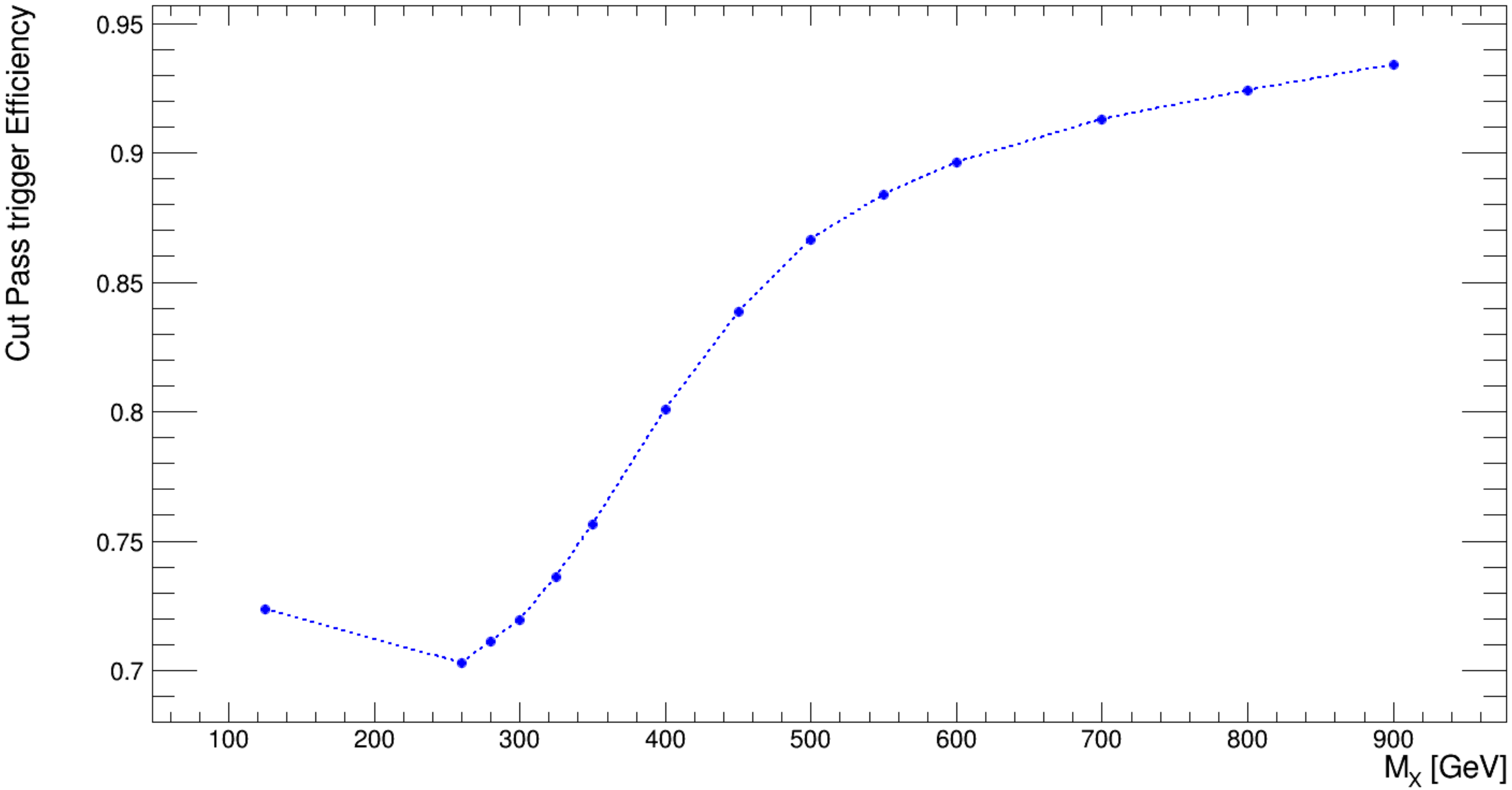
Modeling

- Future analyses should **incorporate systematic uncertainties** to provide more comprehensive and realistic results. While these had **minimal impact** in the **non-resonant analysis** due to **limited data**, they will become **crucial for improving fit accuracy as datasets grow**

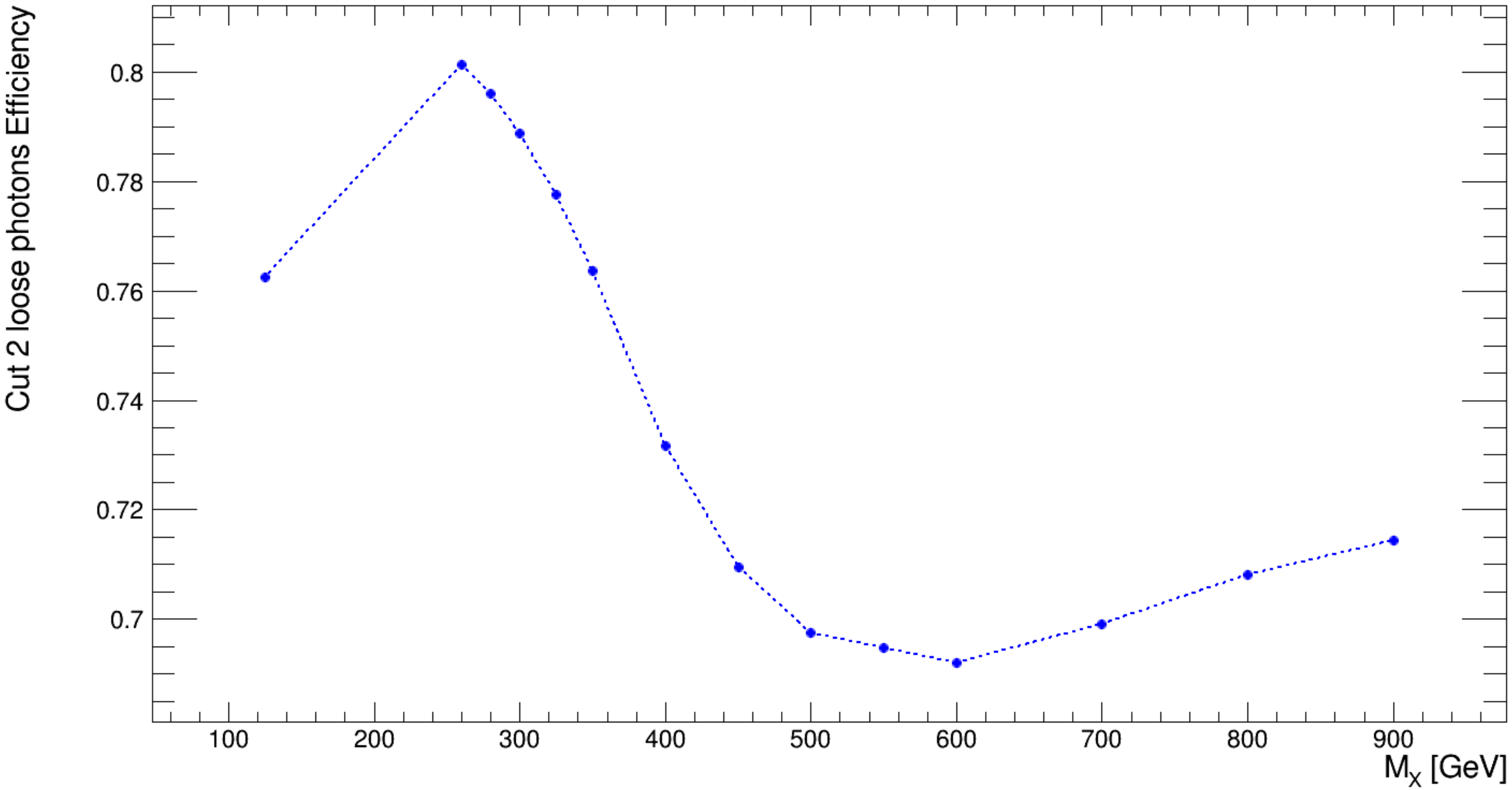
Thank you for your attention

Backup slides

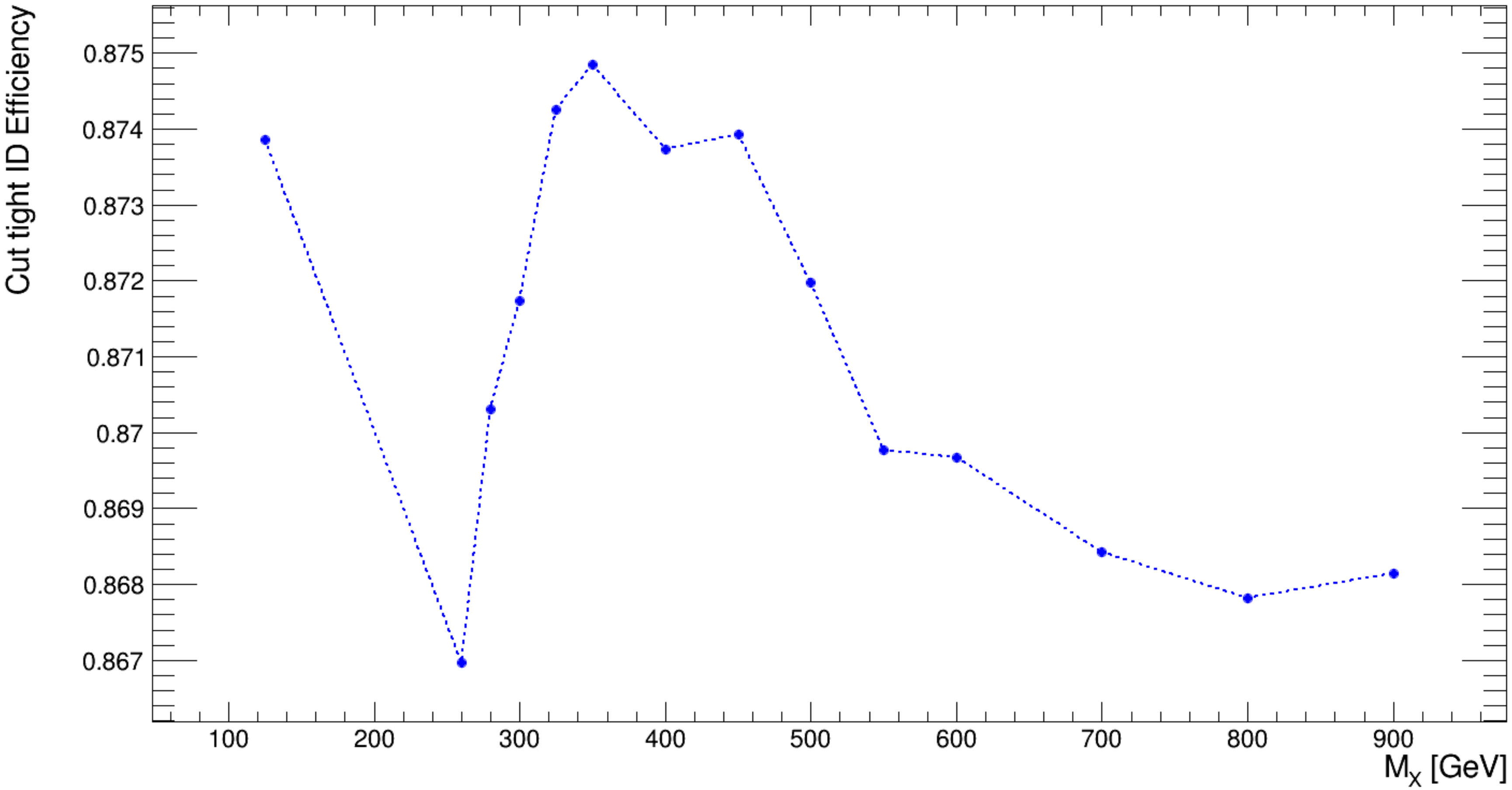
CutFlow : Cuts efficiency



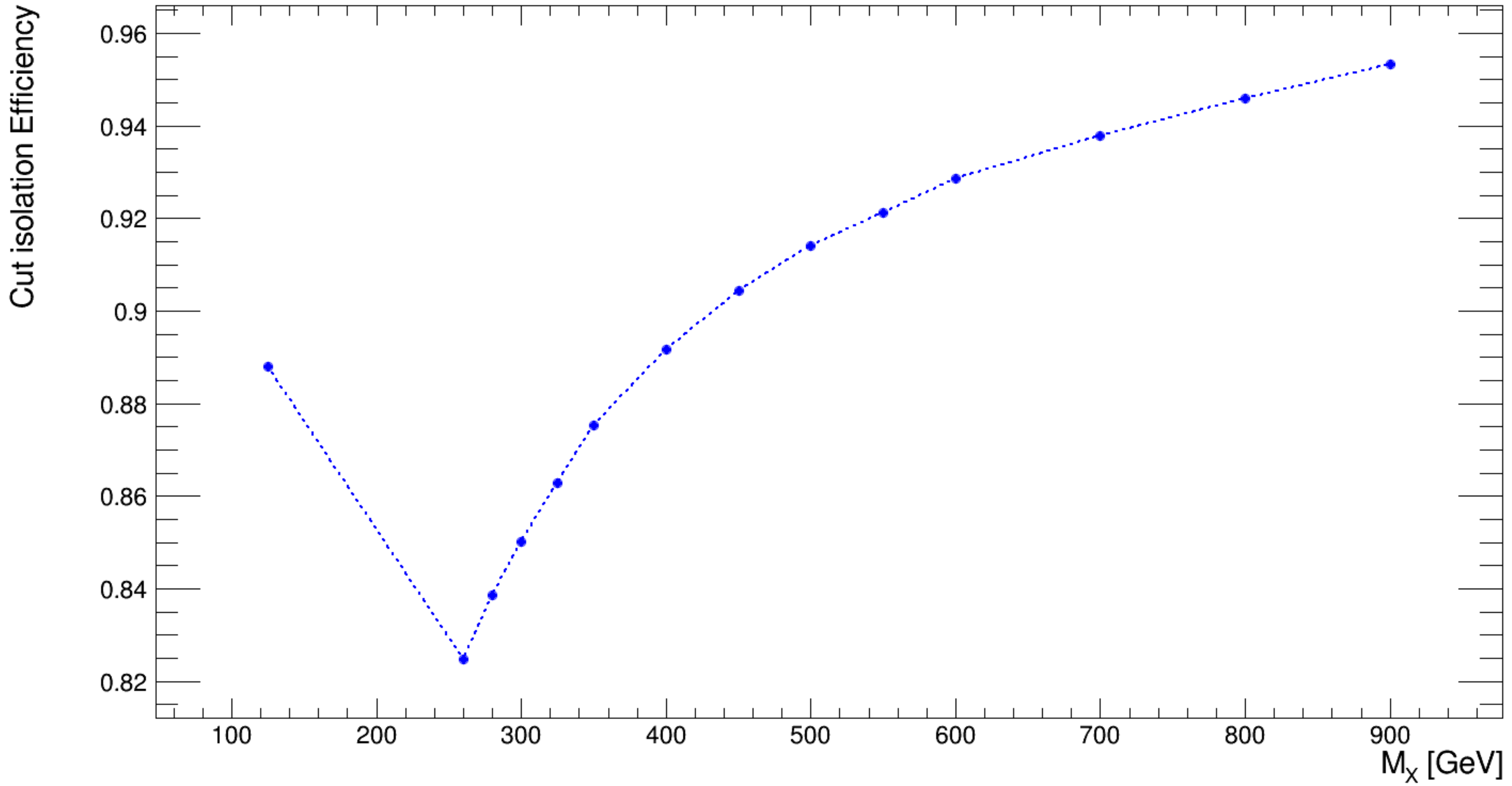
CutFlow : Cuts efficiency



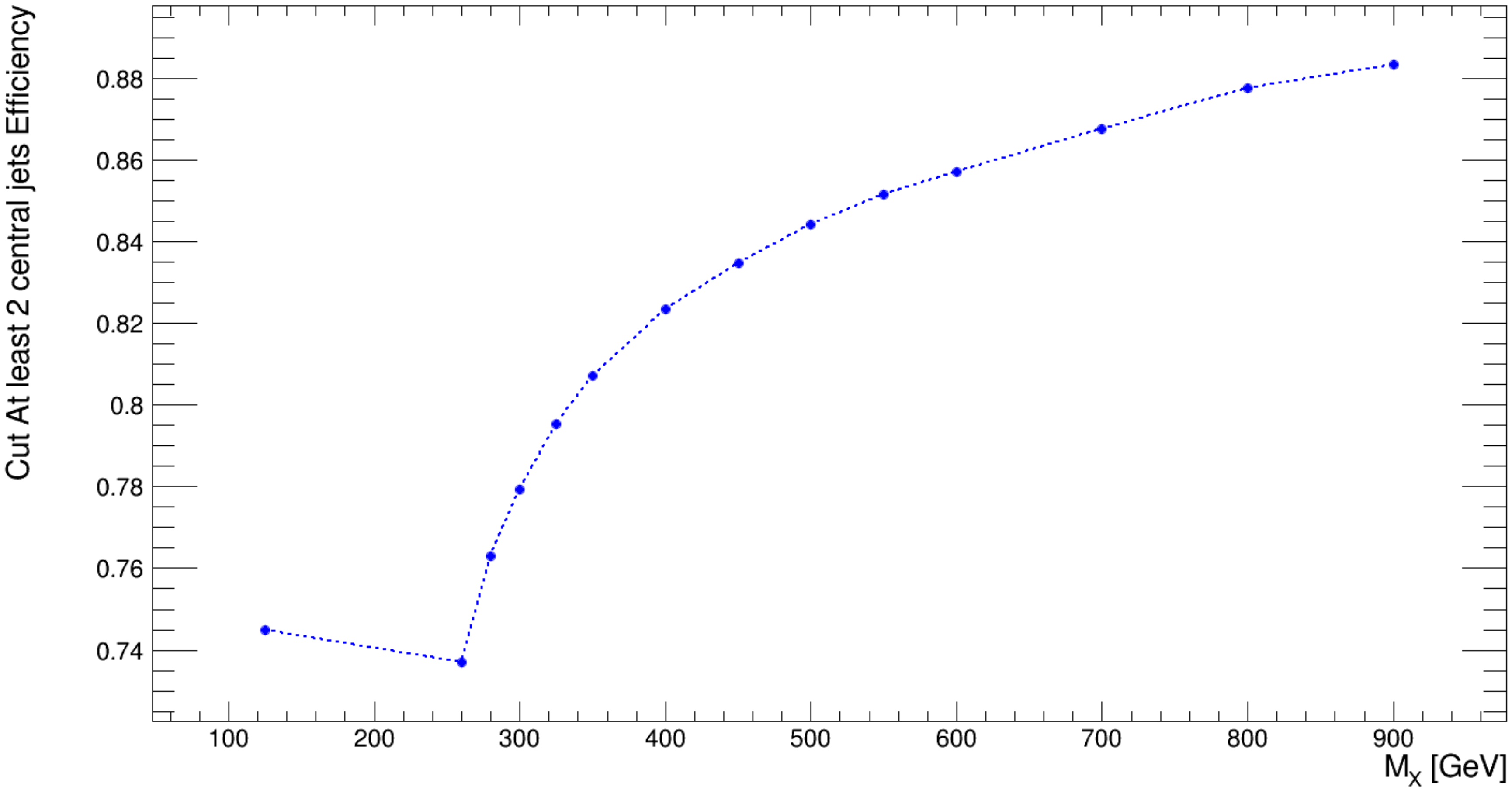
CutFlow : Cuts efficiency



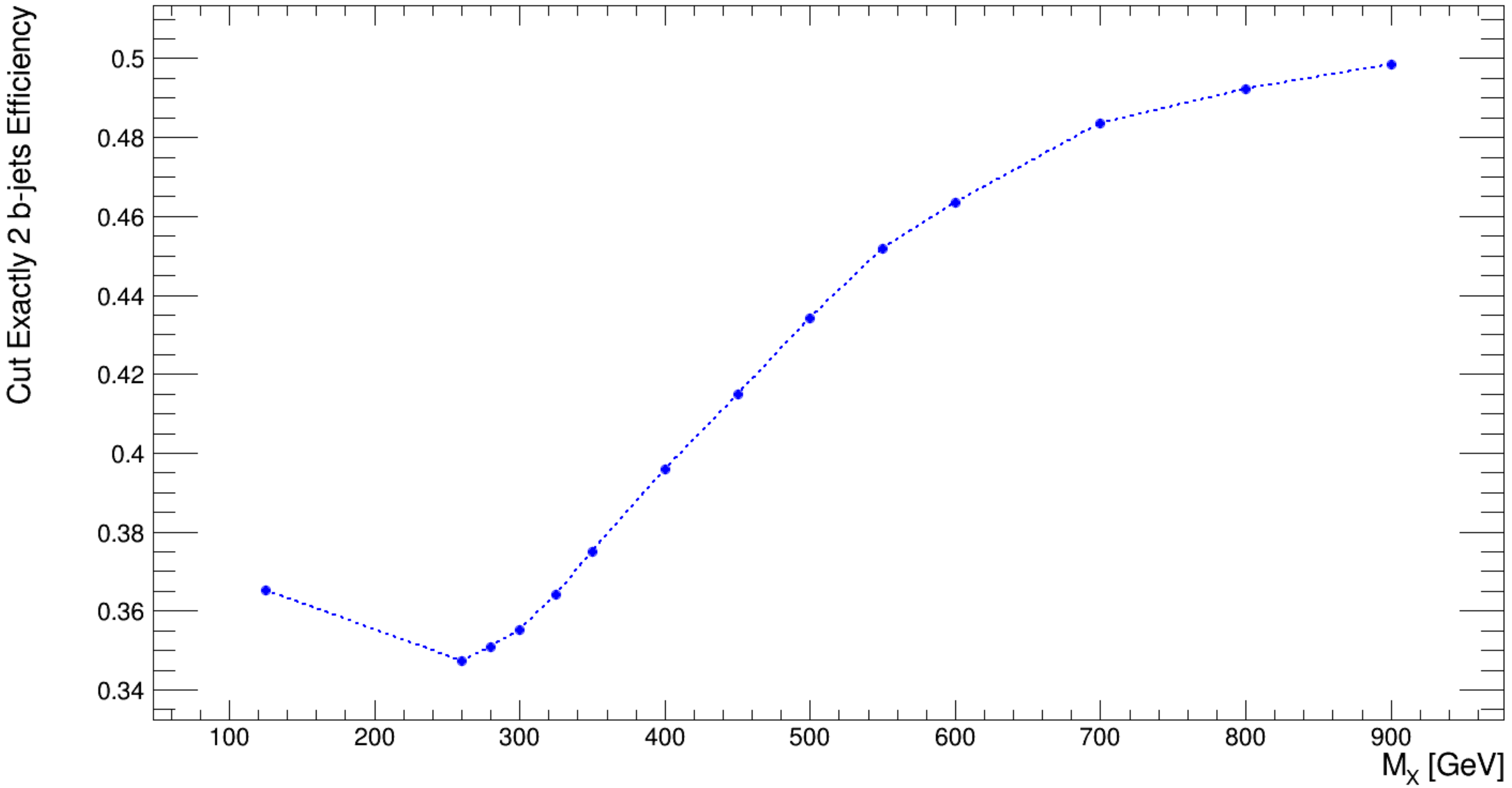
CutFlow : Cuts efficiency



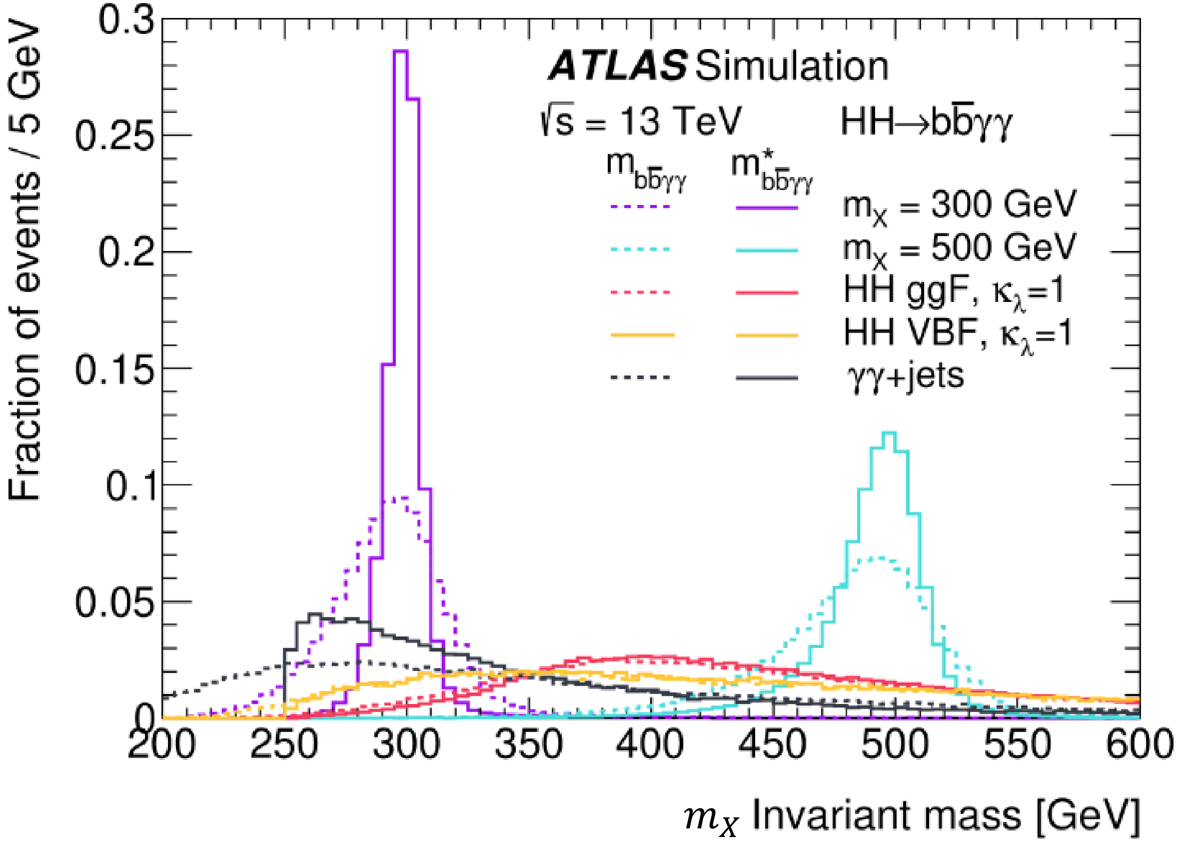
CutFlow : Cuts efficiency

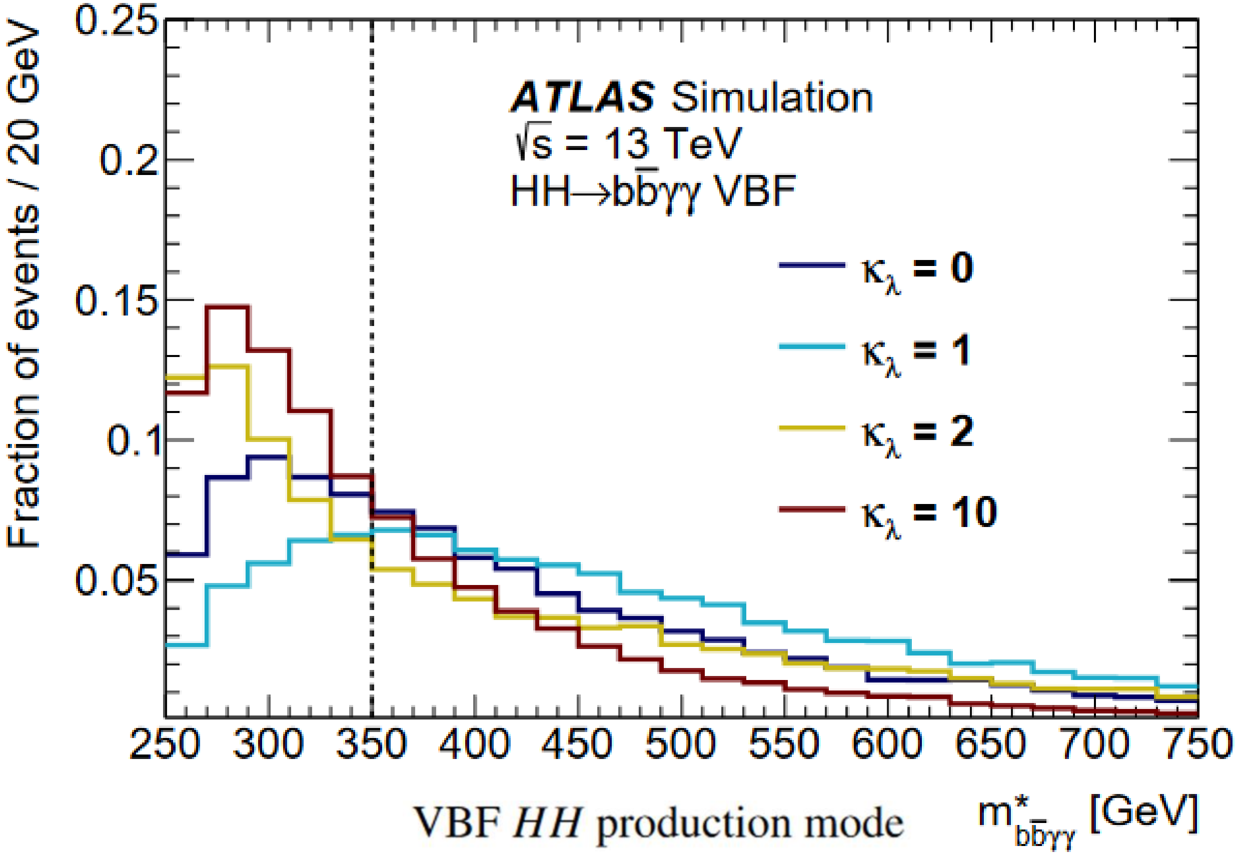


CutFlow : Cuts efficiency



CutFlow : BDT mass categories

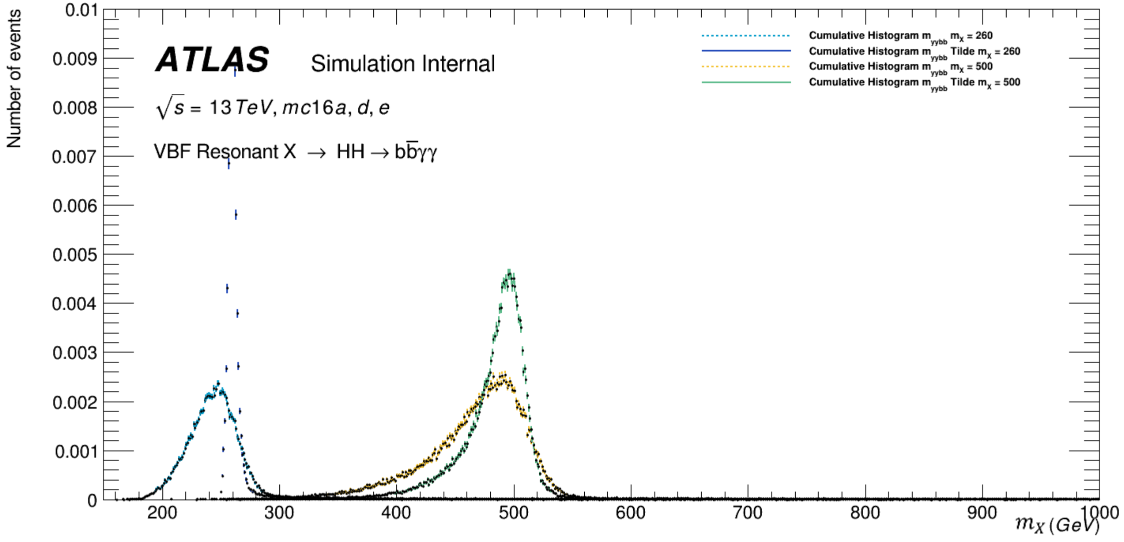


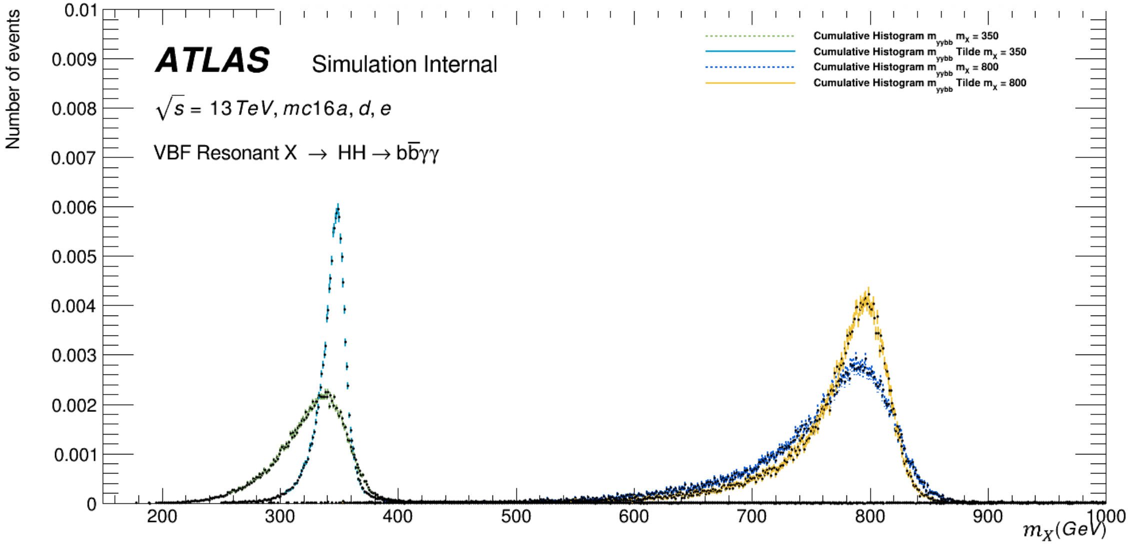


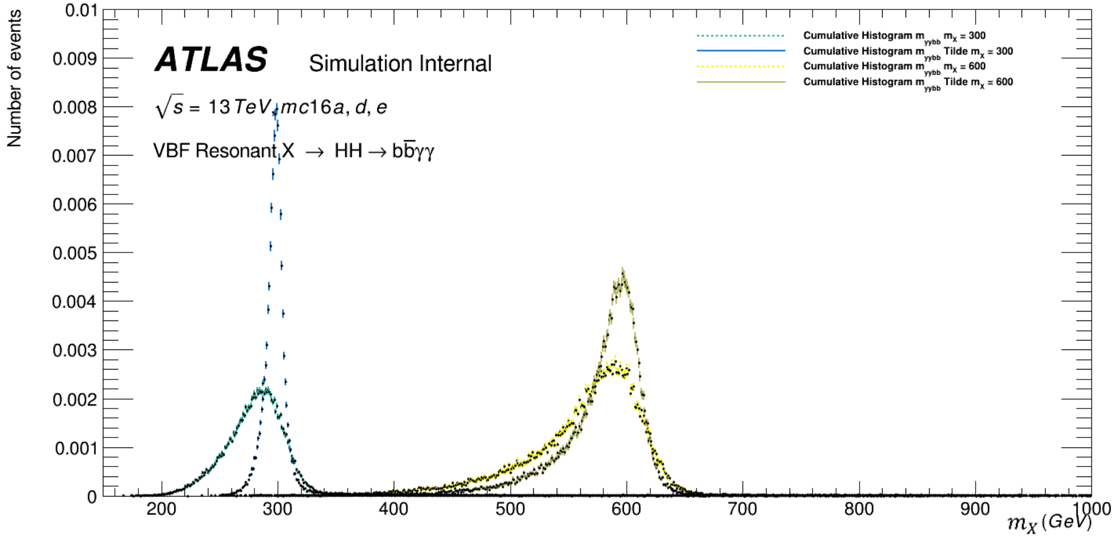
VBF HH production mode

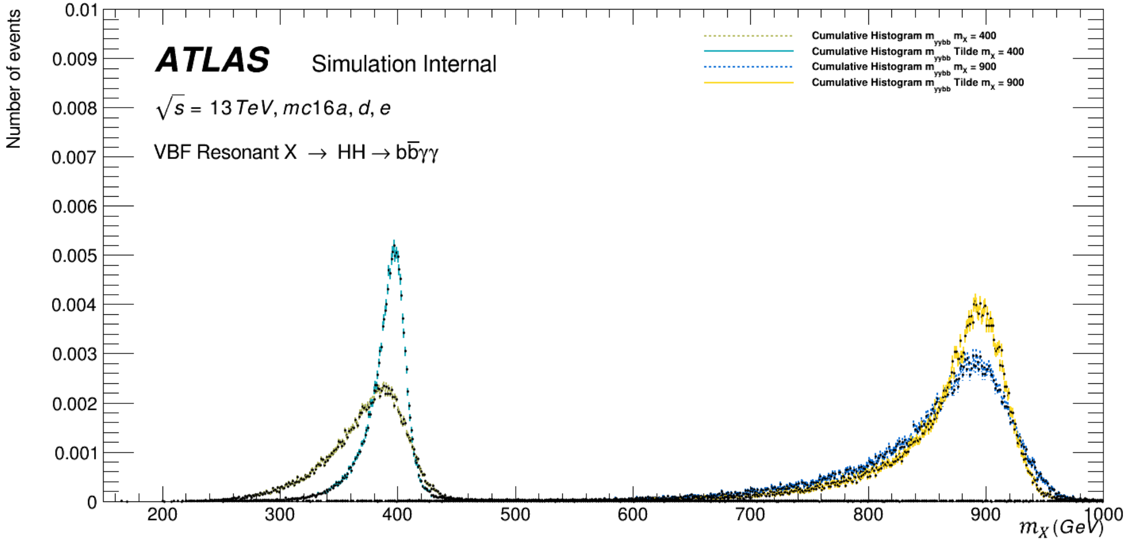
arXiv:2112.11876 [hep-ex]

Selection : $m^*_{b\bar{b}\gamma\gamma}$ vs $m_{b\bar{b}\gamma\gamma}$

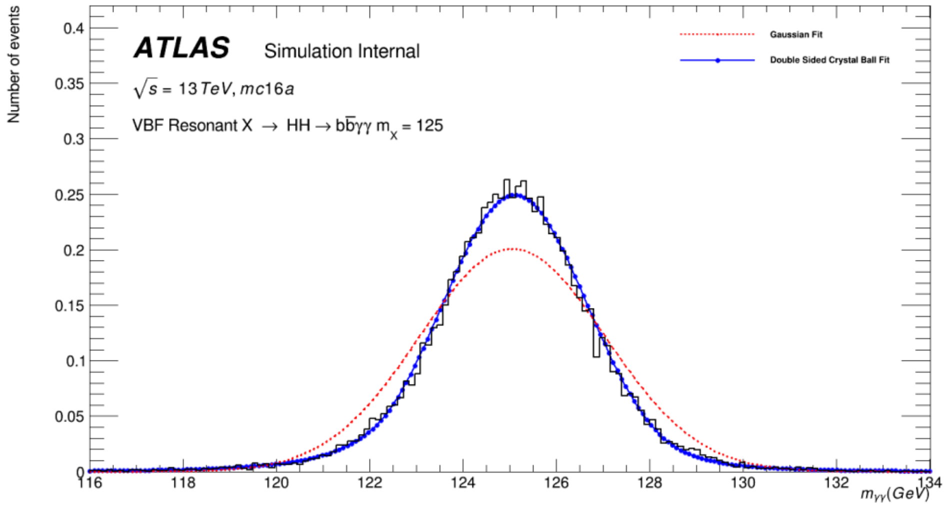


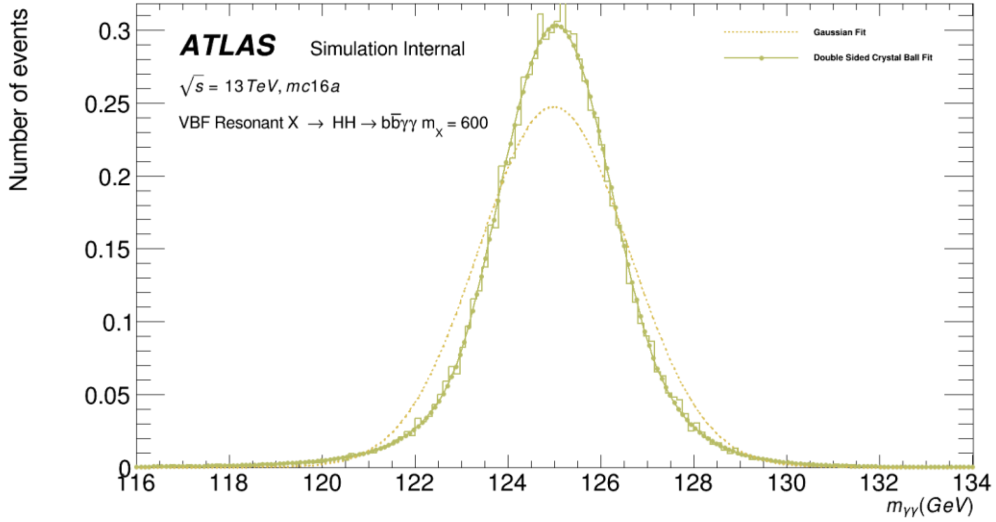


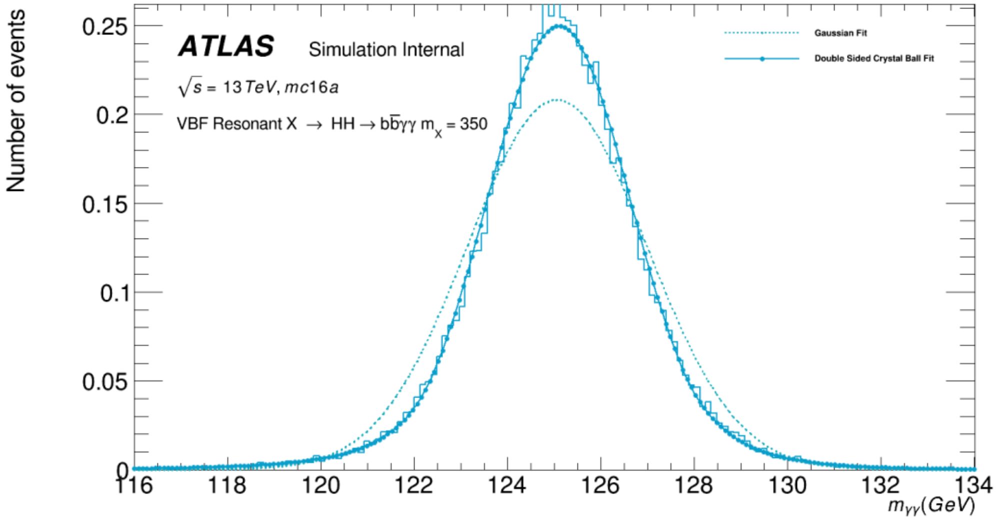


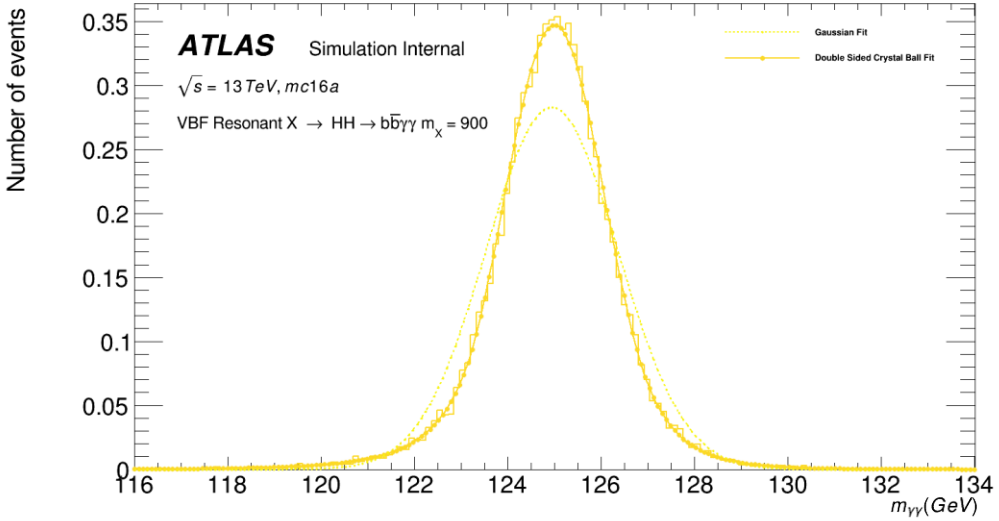


DSCB Fit vs Gaussian Fit









Formulas

Gaussian function :

$$f(x) = \frac{1}{\sigma\sqrt{2\,\pi}}\,\mathrm{e}^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Exponential function :

$$f(x;\lambda) = \begin{cases} \lambda e^{-\lambda x} & x \geq 0, \\ 0 & x < 0. \end{cases}$$

Double Sided Crystal Ball function :

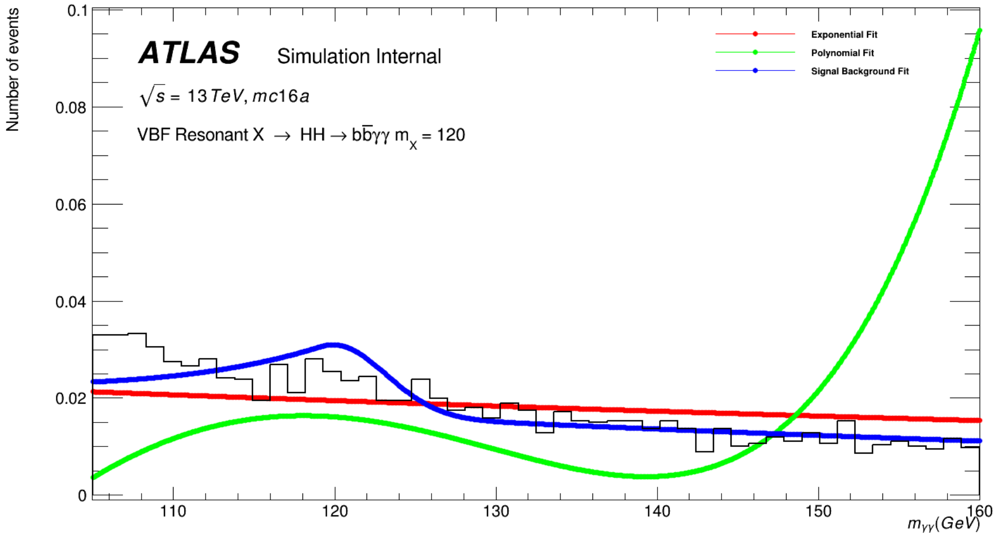
$$f(m; m_0, \sigma, \alpha_L, n_L, \alpha_R, n_R) = \begin{cases} A_L \cdot (B_L - \frac{m-m_0}{\sigma_L})^{-n_L}, & \text{for } \frac{m-m_0}{\sigma_L} < -\alpha_L \\ \exp\left(-\frac{1}{2}\cdot\left[\frac{m-m_0}{\sigma_L}\right]^2\right), & \text{for } \frac{m-m_0}{\sigma_L} \leq 0 \\ \exp\left(-\frac{1}{2}\cdot\left[\frac{m-m_0}{\sigma_R}\right]^2\right), & \text{for } \frac{m-m_0}{\sigma_R} \leq \alpha_R \\ A_R \cdot (B_R + \frac{m-m_0}{\sigma_R})^{-n_R}, & \text{otherwise,} \end{cases}$$

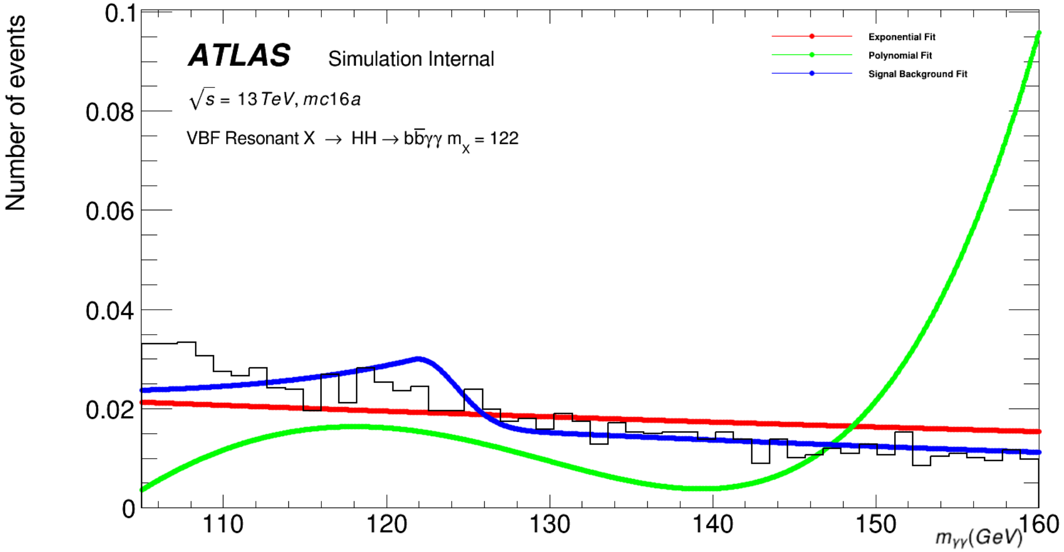
where

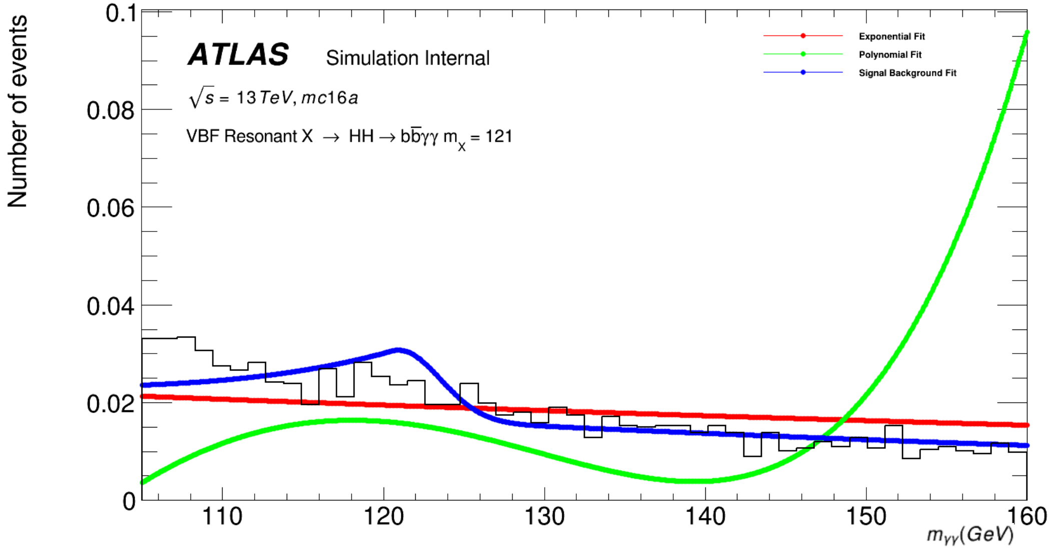
$$A_i = \left(\frac{n_i}{|\alpha_i|}\right)^{n_i} \cdot \exp\left(-\frac{|\alpha_i|^2}{2}\right)$$

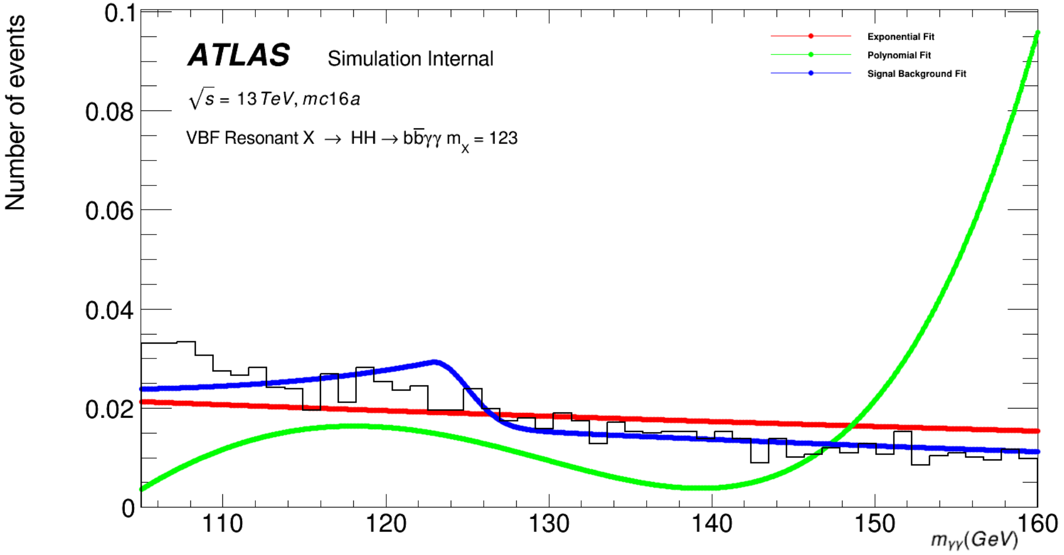
$$B_i = \frac{n_i}{|\alpha_i|} - |\alpha_i|$$

Signal and Bckg over Bckg

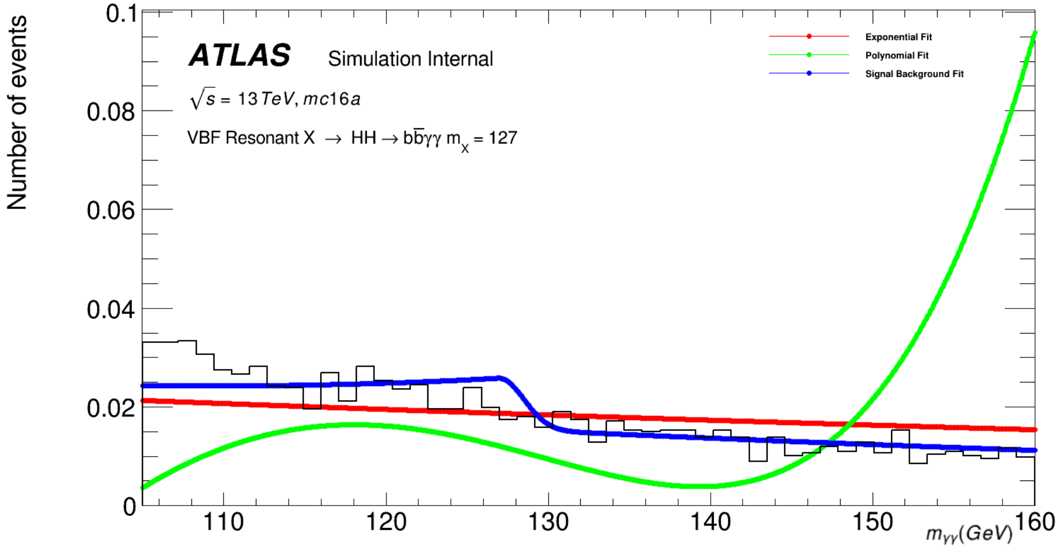


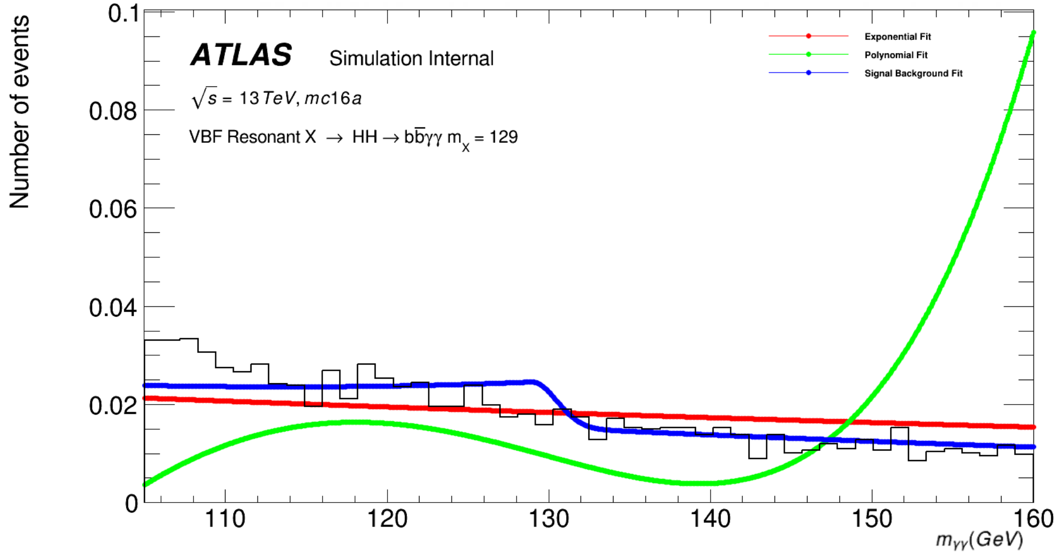


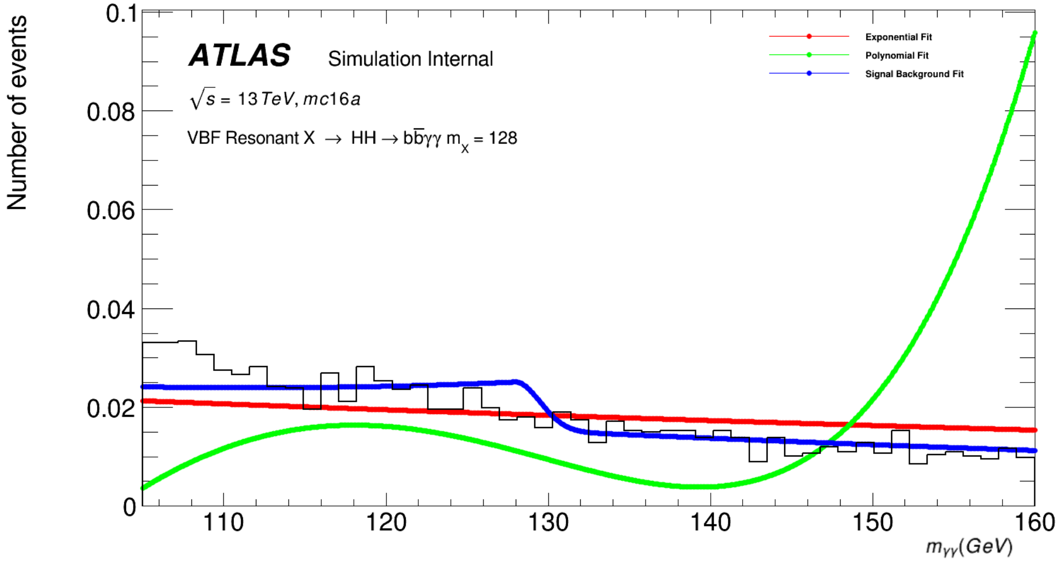


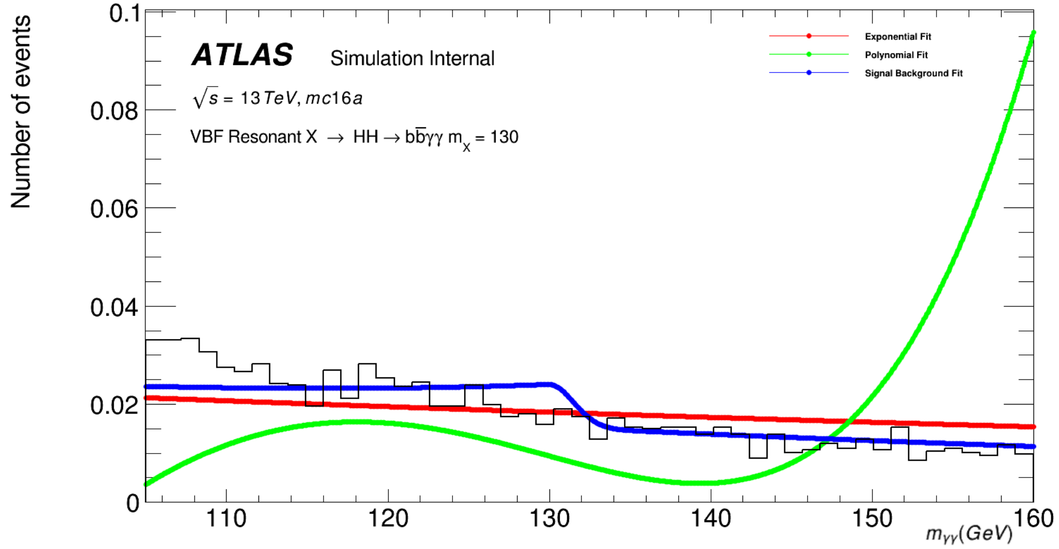


Signal and Bckg over Bckg









Efficiency

m_X	Cuts passed	High Mass 1	High Mass 2	High Mass 3	Low Mass 1	Low Mass 2	Low Mass 3	Low Mass 4
125 (SM)	0.08867	0.01151	0.00775	0.04049	0.00269	0.00230	0.00291	0.01076
260	0.08384	7.47×10^{-5}	1.60×10^{-5}	1.86×10^{-5}	0.01373	0.01097	0.01256	0.03752
280	0.08872	$1{,}31 \times 10^{-4}$	5.19×10^{-5}	3.28×10^{-5}	0.01202	0.01087	0.01355	0.04345
300	0.09271	$2{,}36 \times 10^{-4}$	6.60×10^{-5}	5.23×10^{-5}	0.01100	0.01028	0.01402	0.04873
350	0.10674	0.00916	0.00617	0.01884	0.00677	0.00659	0.00971	0.03715
400	0.09920	0.01846	0.01449	0.07197	6.59×10^{-4}	3.26×10^{-4}	3.41×10^{-4}	4.50×10^{-4}
450	0.13597	0.01593	0.01309	0.09423	1.88×10^{-4}	6.24×10^{-5}	5.07×10^{-5}	4.80×10^{-5}
500	0.15060	0.01486	0.01218	0.11257	1.27×10^{-4}	2.50×10^{-5}	1.97×10^{-5}	1.52×10^{-5}
550	0.16489	0.01420	0.01155	0.12877	7.73×10^{-5}	1.58×10^{-5}	1.36×10^{-5}	1.72×10^{-5}
600	0.17644	0.01327	0.01141	0.14253	3.53×10^{-5}	1.16×10^{-5}	4.96×10^{-6}	3.08×10^{-6}
700	0.19796	0.01209	0.01030	0.16749	2.39×10^{-5}	0	2.39×10^{-6}	5.67×10^{-6}
800	0.21402	0.01071	0.00904	0.18737	2.04×10^{-5}	0	0	0
900	0.22720	0.00886	0.00705	0.20541	7.28×10^{-6}	0	4.05×10^{-6}	8.07×10^{-6}
Background	1.87×10^{-4}	2.90×10^{-6}	5.25×10^{-7}	5.48×10^{-7}	1.03×10^{-5}	2.33×10^{-6}	1.12×10^{-6}	5.10×10^{-6}

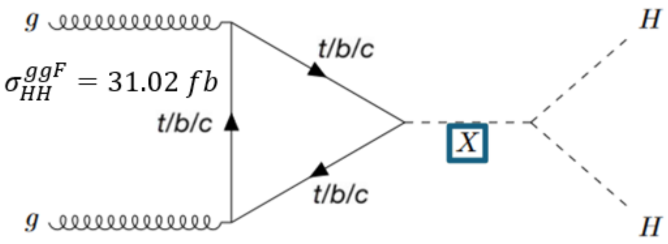
Significance

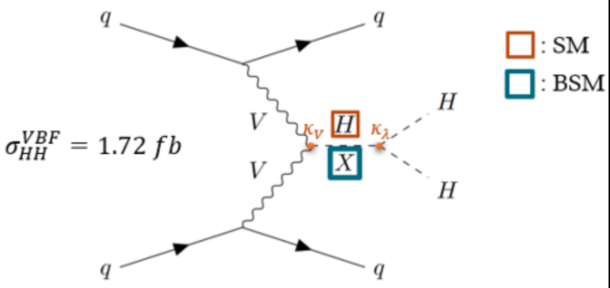
m_X	Cuts passed	High Mass 1	High Mass 2	High Mass 3	Low Mass 1	Low Mass 2	Low Mass 3	Low Mass 4
125 (SM)	9.39×10^{-5}	9.79×10^{-5}	1.55×10^{-4}	7.93×10^{-4}	1.21×10^{-5}	2.18×10^{-5}	3.98×10^{-5}	2.19×10^{-4}
260	1.61×10^{-4}	1.15×10^{-6}	5.81×10^{-7}	6.62×10^{-7}	1.12×10^{-4}	1.89×10^{-4}	3.11×10^{-4}	0.00138
280	1.70×10^{-4}	2.01×10^{-6}	1.88×10^{-6}	1.16×10^{-6}	9.81×10^{-5}	1.87×10^{-4}	3.35×10^{-4}	0.00160
300	1.78×10^{-4}	3.63×10^{-6}	2.39×10^{-6}	1.86×10^{-6}	8.98×10^{-5}	1.77×10^{-4}	3.47×10^{-4}	0.00179
350	2.05×10^{-4}	1.41×10^{-4}	2.23×10^{-4}	6.68×10^{-4}	5.52×10^{-5}	1.13×10^{-4}	2.40×10^{-4}	0.00137
400	2.32×10^{-4}	2.84×10^{-4}	5.25×10^{-4}	0.00255	5.38×10^{-6}	5.60×10^{-6}	8.45×10^{-6}	1.65×10^{-5}
450	2.61×10^{-4}	2.46×10^{-4}	4.74×10^{-4}	0.00334	1.54×10^{-6}	1.07×10^{-6}	1.26×10^{-6}	1.76×10^{-6}
500	2.88×10^{-4}	2.29×10^{-4}	4.41×10^{-4}	0.00399	1.04×10^{-6}	4.31×10^{-7}	4.88×10^{-7}	5.58×10^{-7}
550	3.16×10^{-4}	2.19×10^{-4}	4.18×10^{-4}	0.00456	6.31×10^{-7}	2.71×10^{-7}	3.38×10^{-7}	6.35×10^{-7}
600	3.38×10^{-4}	2.04×10^{-4}	4.13×10^{-4}	0.00505	2.88×10^{-7}	2.00×10^{-7}	1.23×10^{-7}	1.13×10^{-7}
700	3.80×10^{-4}	1.86×10^{-4}	3.73×10^{-4}	0.00594	1.95×10^{-7}	0	5.92×10^{-8}	2.08×10^{-7}
800	4.10×10^{-4}	1.65×10^{-4}	3.27×10^{-4}	0.00664	1.67×10^{-7}	0	0	0
900	4.36×10^{-4}	1.37×10^{-4}	2.55×10^{-4}	0.00728	5.94×10^{-8}	0	1.00×10^{-7}	2.97×10^{-7}

Opportunities

2015	2018	2022	2025	2040
Internship Work: RUN 2	Maintenance	PhD work: RUN 3	PhD Work: HL-LHC and Upgrades	

Fusion Gluon-Gluon (ggF) :
90% de la production HH



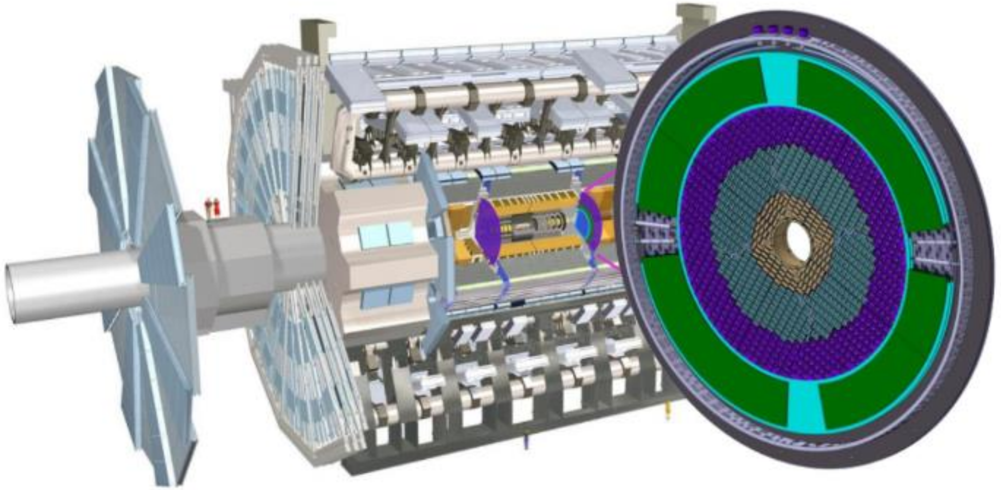


Fusion de Bosons Vecteurs HH (V = W or Z)

First study of VBF Resonant signals HH → $b\bar{b}\gamma\gamma$ **:**
Complementarity and combinations of results HH → $b\bar{b}b\bar{b}$

VBF quarks forward, to **differentiate** them from **b quarks** from H → $b\bar{b}$: HGTD

Instrumentation on the **High Granularity Time Detector (HGTD)** :



Particle **identification** and **differentiation** using **detection time** with a temporal resolution ≤ **50 ps**