Search for a new particle X in the X → HH → yybb decay channel with the ATLAS detector

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PhD Seminar

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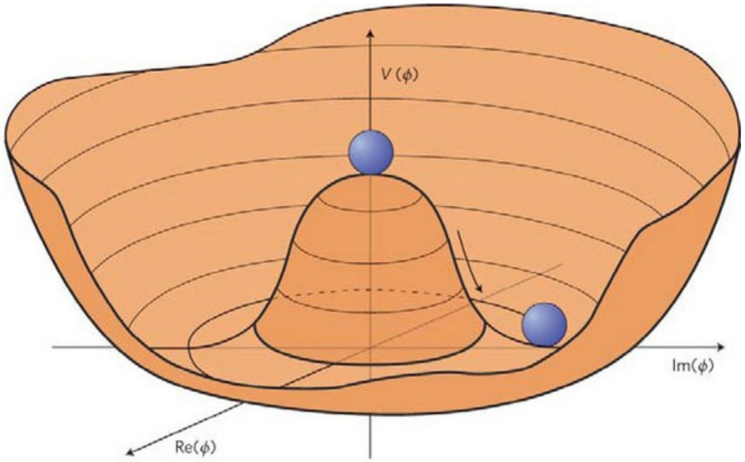
STARK Jan & PETIT Elisabeth

Outline

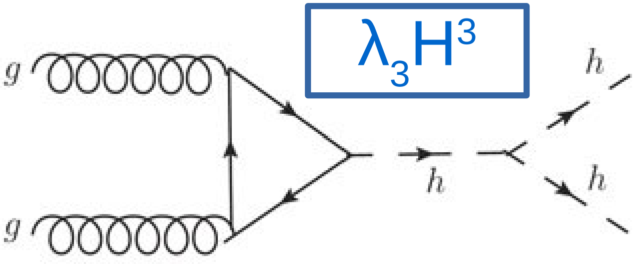
- Theoretical motivation for the new particle
- Description of the analysis
- Previous result
- New proposal for the analysis
- Ongoing result

Measurement of the Higgs potential



- Higgs potential : will define the shape of the Mexican hat

$$\boxed{V(H) = \mu^2 \varphi^+\varphi^- + \lambda (\varphi^+\varphi^-)^2}$$



$\boxed{\lambda_3 H^3}$

- Trilinear coupling :

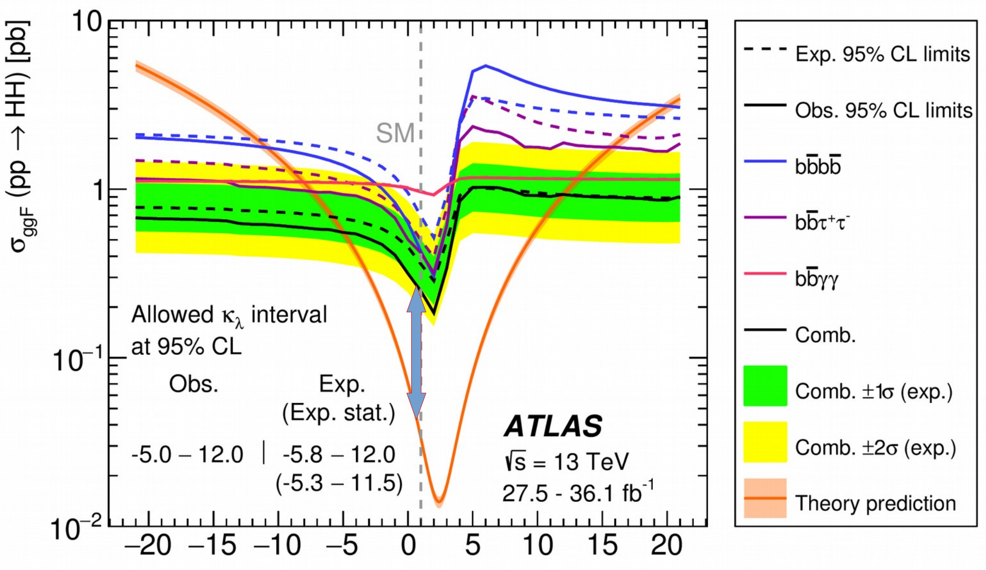
  with $\lambda_3 = M_H^2/2v$ and $M_H^2 = 2\,\lambda^* v^2$
  where v is the vacuum expected value (246 GeV)

- All this leads to $\boxed{\lambda_3 = \lambda^* v}$
  Measuring the trilinear coupling will lead to constrain the Higgs potential

Current knowledge of the trilinear coupling

- The production of Higgs pair with the trilinear coupling is 1000 times lower than the cross section of one Higgs.

- The experimental limit is, for now, 10 times the theoretical value → we need more data, the theoretical value will be reached with the help of the HL-LHC (High-luminosity LHC) and will be one of its main goal

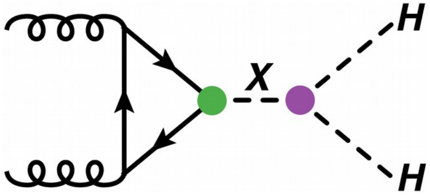


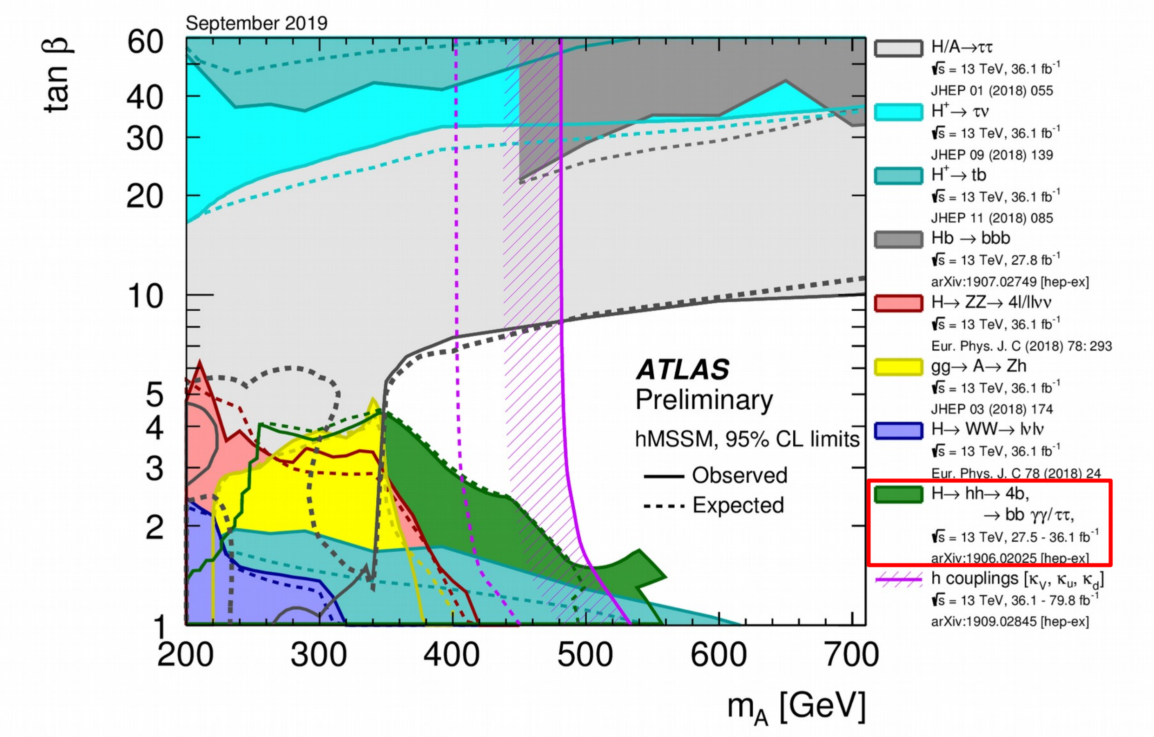
https://arxiv.org/pdf/1906.02025.pdf

- For now we can only put constraint on the value of λ_3, ($-5.0 < \lambda_3/\lambda_3^{SM} < 12.0$) 95% CL with λ_3^{SM} being the value predicted by the Standard Model

Motivation of the X->HH

- Huge program of search for a new spin 0 particle in ATLAS, covering many decay channels



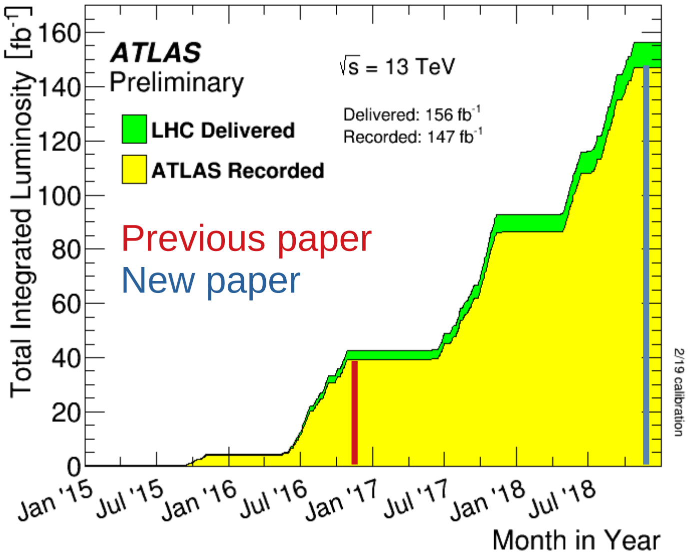


$\tan(\beta) = v_u/v_d$

- Many theories predict the existence of a heavy particle decaying into a pair of Higgs boson. Models with two higgs doublets (MSSM, twin Higgs models and composite Higgs models) could explain such a particle.

Creation and detection

- Proton-proton collision at the LHC
- Last publication was made with a luminosity (N= σ*L) of 36fb^{-1}. We will use all the 140fb^{-1} available now for the new paper.
- We will use the data collected by the ATLAS detector



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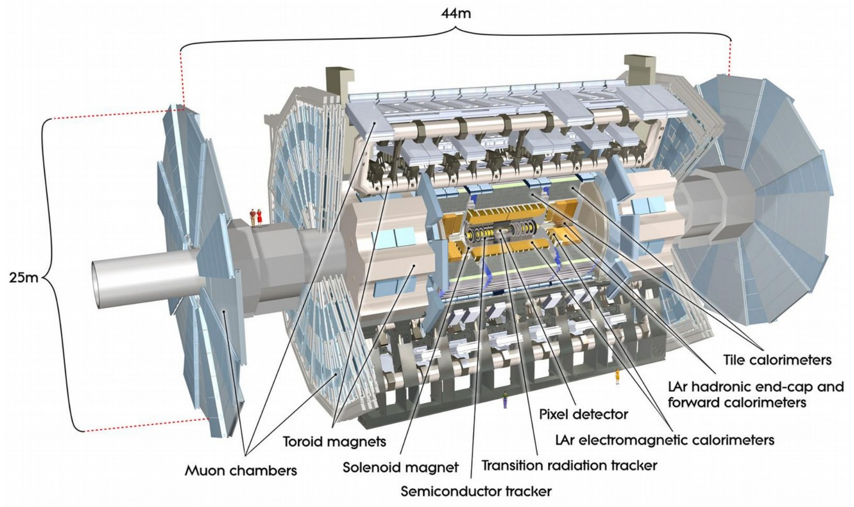
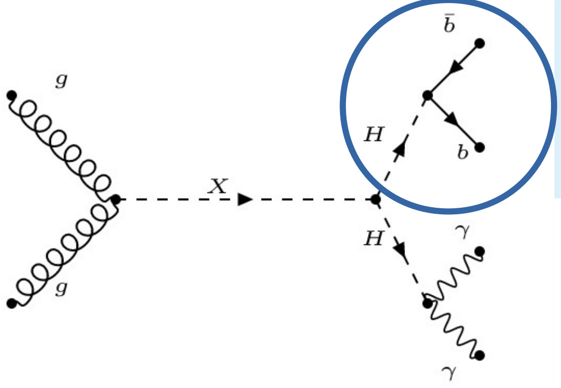
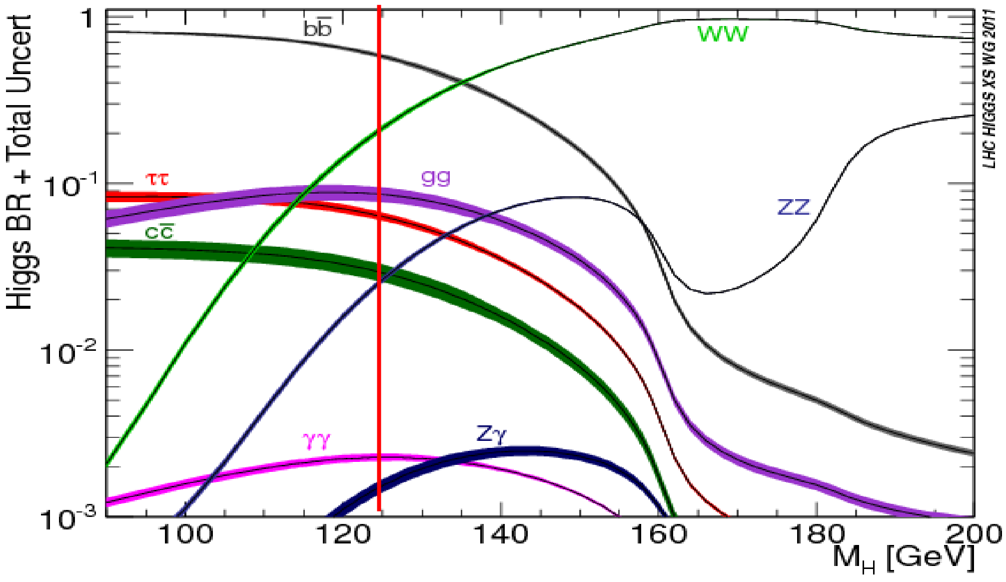


Decay channel X->HH->yybb



Decay of one Higgs boson into a b-quark pair : best branching ratio

BR [%]



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Channels used for the search of HH production

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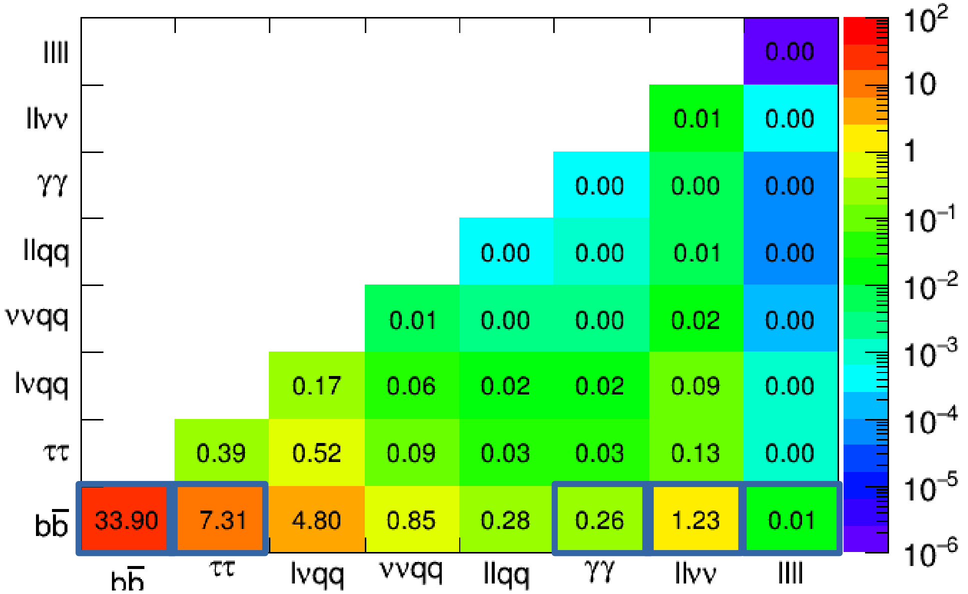
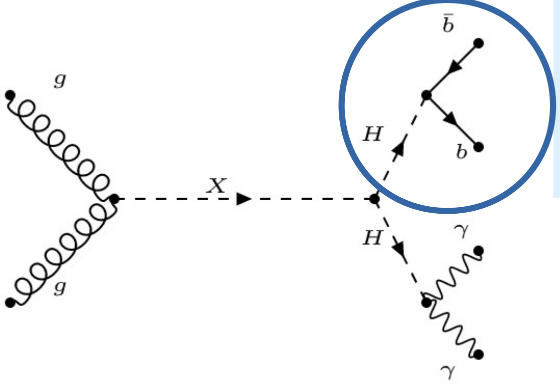


llll								0.00
llνν							0.01	0.00
γγ						0.00	0.00	0.00
llqq					0.00	0.00	0.01	0.00
ννqq				0.01	0.00	0.00	0.02	0.00
lνqq			0.17	0.06	0.02	0.02	0.09	0.00
ττ		0.39	0.52	0.09	0.03	0.03	0.13	0.00
$b\bar{b}$	33.90	7.31	4.80	0.85	0.28	0.26	1.23	0.01
	$b\bar{b}$	ττ	lνqq	ννqq	llqq	γγ	llνν	llll

Decay channel X->HH->yybb



Decay of one Higgs boson into a b-quark pair : best branching ratio

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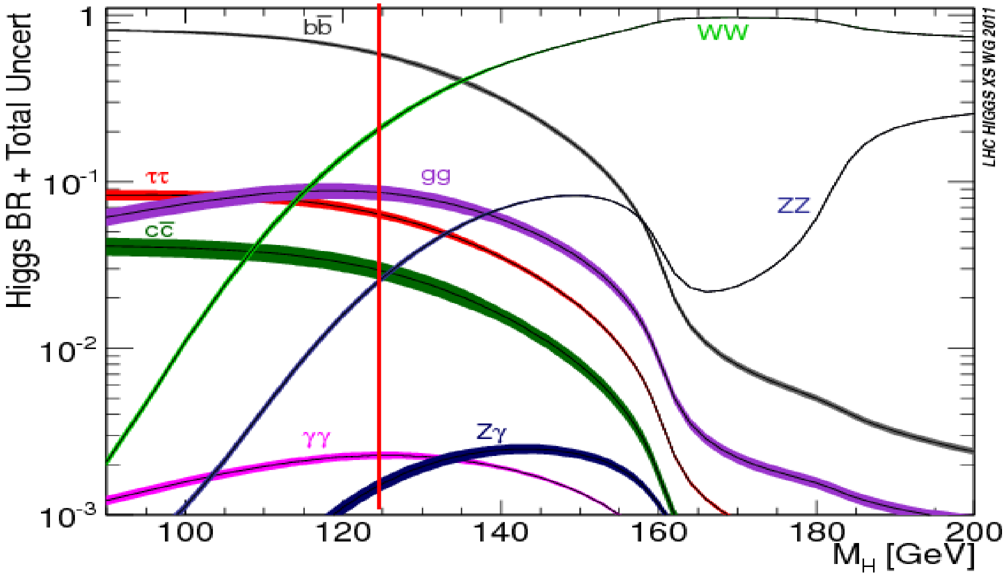

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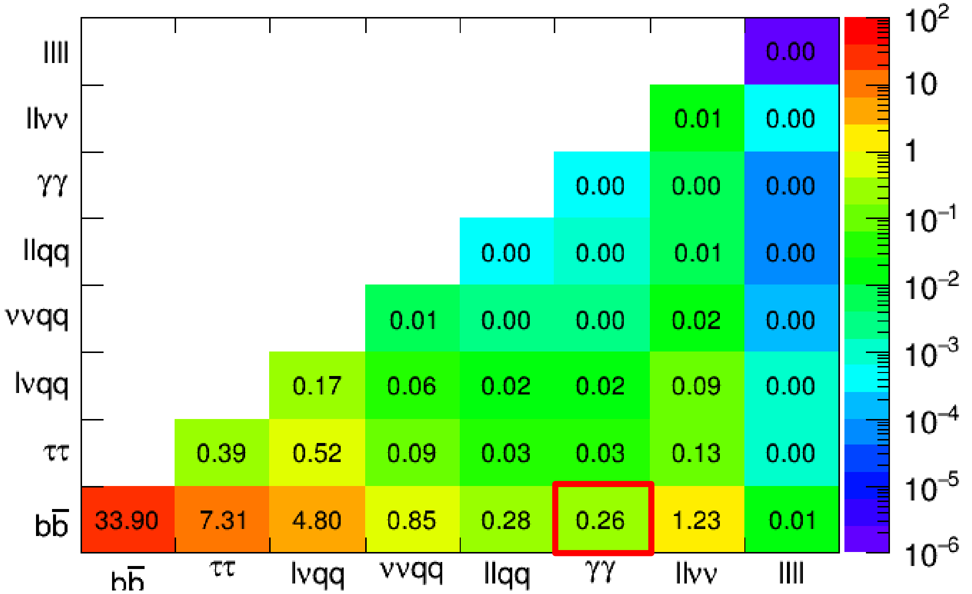

	$b\bar{b}$	ττ	lνqq	ννqq	llqq	γγ	llνν	llll
llll								0.00
llνν							0.01	0.00
γγ						0.00	0.00	0.00
llqq					0.00	0.00	0.01	0.00
ννqq				0.01	0.00	0.00	0.02	0.00
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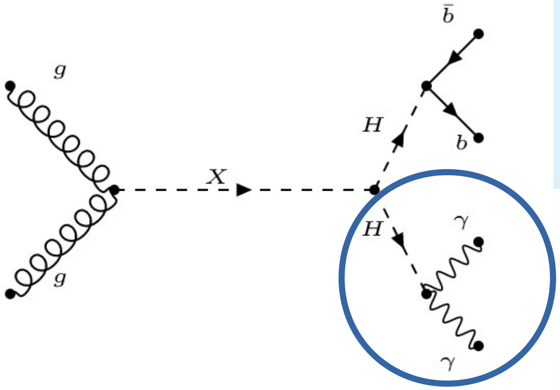
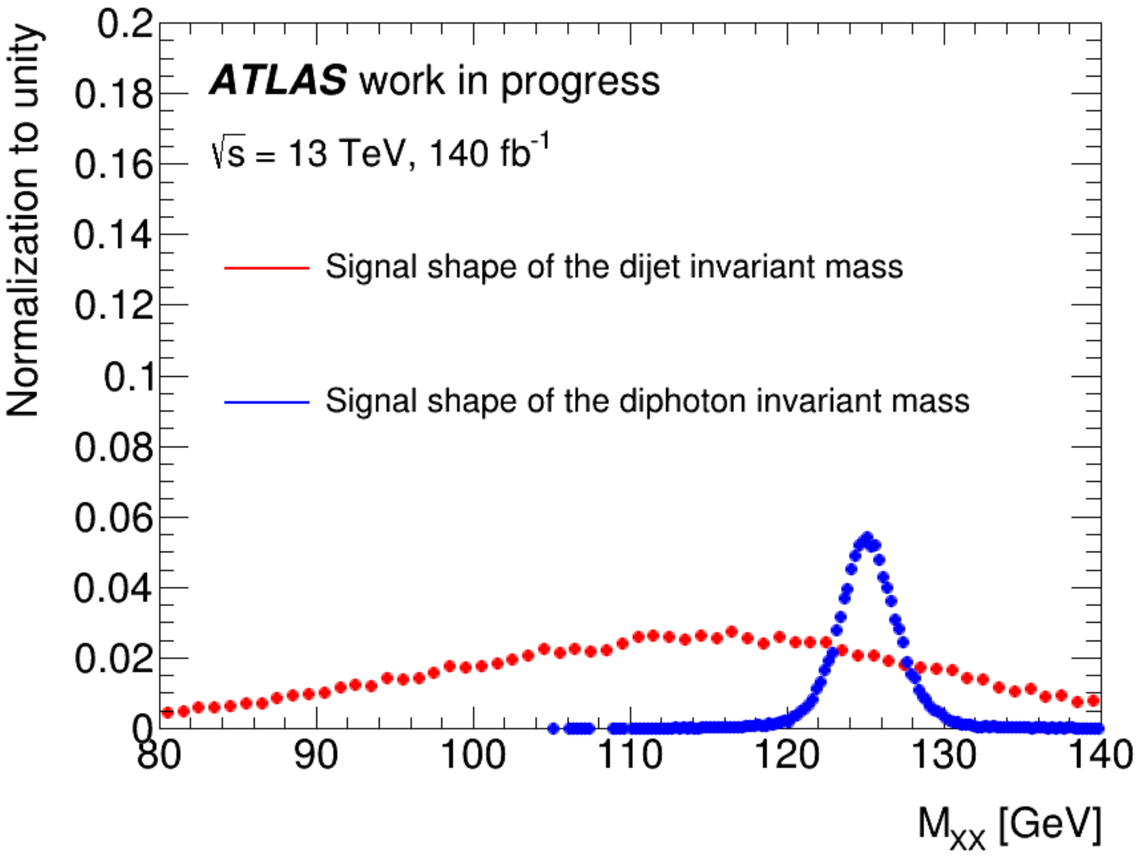
ττ		0.39	0.52	0.09	0.03	0.03	0.13	0.00
$b\bar{b}$	33.90	7.31	4.80	0.85	0.28	0.26	1.23	0.01

Around 15 people working in this channel

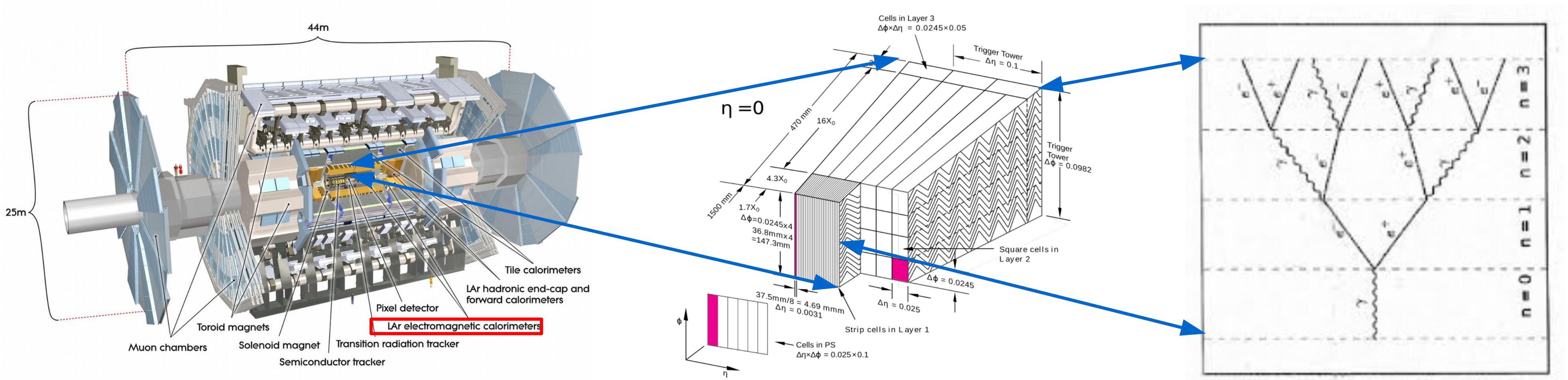
Decay channel X->HH->yybb



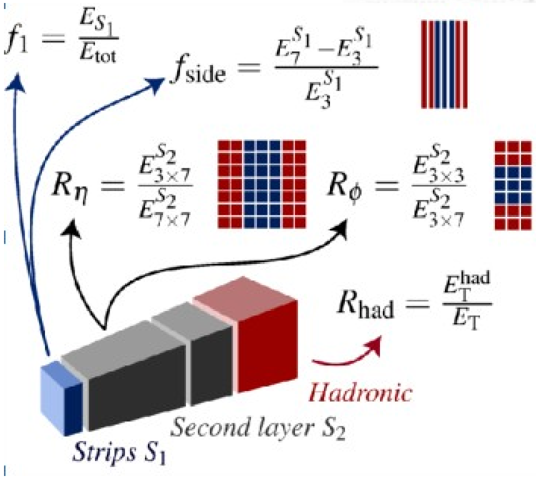


Decay of the other Higgs boson into a photon pair : best resolution and reconstruction efficiency

How to identify photons in ATLAS ?



- Photon create shower when entering the calorimeter.
  Use of shower-shapes (variables that are computed with the energy inside the Electromagnetic calorimeter cells).

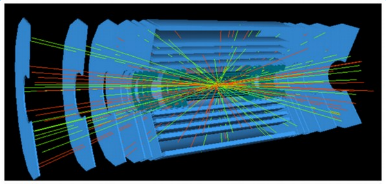


- A selection is made for each variable, it will allow us to discriminate the photon from background photon coming from jet (mainly $\pi^0 \rightarrow \gamma\gamma$)

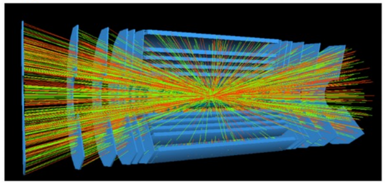
Effect of the pile-up on the photon

- Decrease of the efficiency with the pile-up (average number of particle interactions per bunch-crossing) even worse for the HL-LHC

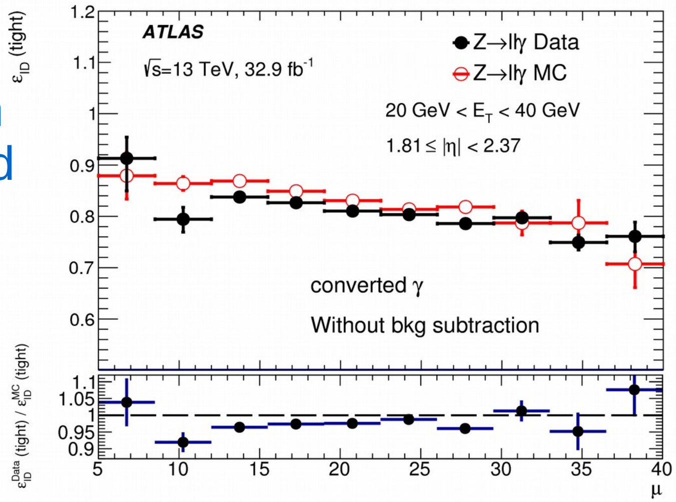
Nowadays pile-up

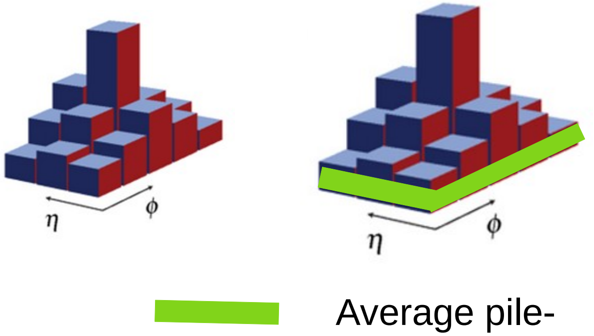


Expected pile-up for HL-LHC



- Relaxing the selection of the selection of the shower-shapes have been tried but it shows limit as the projection gives only a ~50% identification efficiency at the HL-LHC



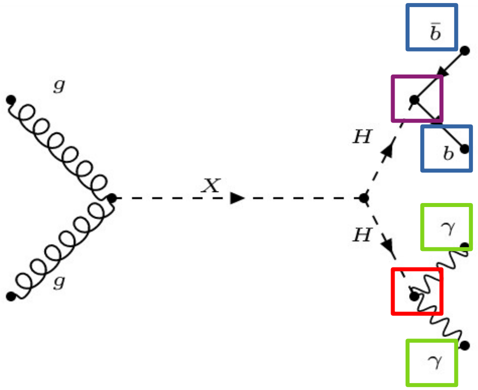


🟩 Average pile-up on the event

- I tried a more low-level correction, a Cell by cell subtraction of the average pile-up per event.
- This correction is used to correct jets from the effects of the pile-up but I showed that the effect is too subtle to be efficient for the photons
- Work will be continued by another student (search for new shower shapes)

Selecting the signal

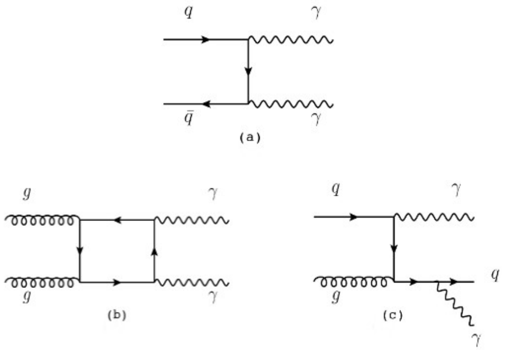
- The identification of the b-jets and the photons remove the reducible background, we are left with the irreducible one.



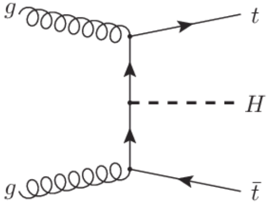
Selections for reductible background :
- asking for two identified photons
- asking fot two identified b-jets

Selection for irreductible background :
- kinematic selection on the photons
- kinematic selection on the diphoton invariant mass
- kinematic selection on the jets
- kinematic selection on the dijets invariant mass

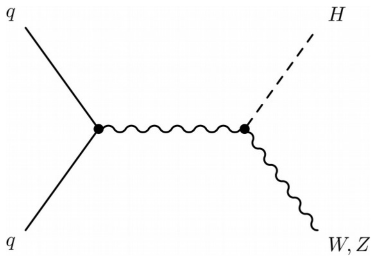
Continuum diphoton



Single Higgs ttH



Single Higgs W,Z H

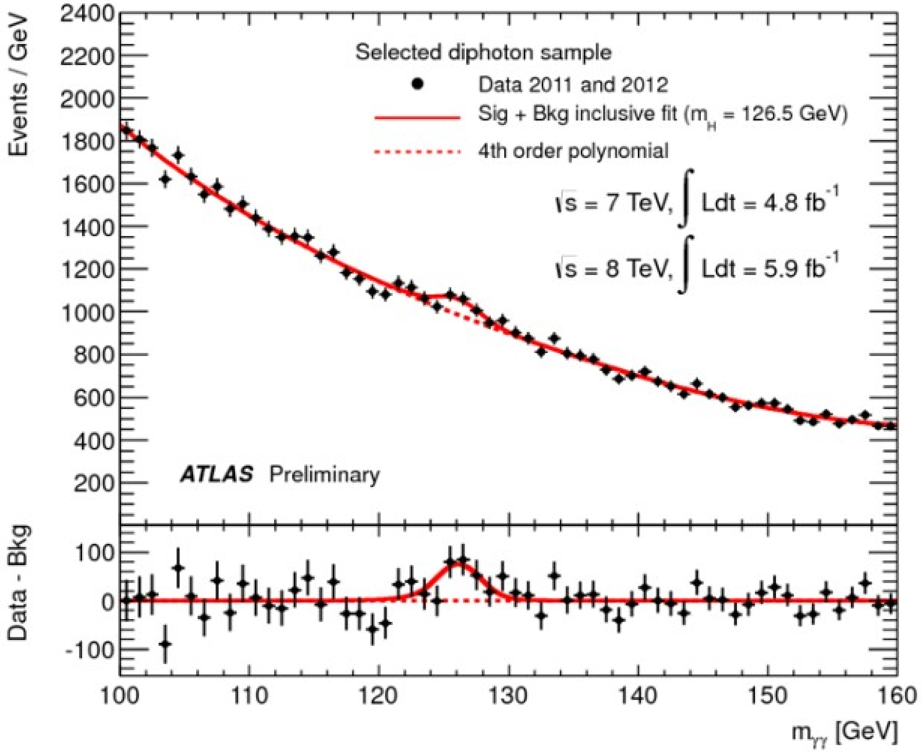


- The signal is hidden behind this background, we need to apply more selection cuts in order to increase the ratio signal/background.

For the Signal at 300 GeV	Number Single Higgs	Number continuum diphoton	Number signal	Ratio S/B
Before the selection	7205.07	229734	5.38	2.27e-05
After the selection	0.98	31.88	3.51	0.11

How to do a search à la H->yy ?

- We search for in bump in the data compared to the background only hypothesis
- For that we search for the best background+signal hypothesis that fit the diphoton invariant mass the Data

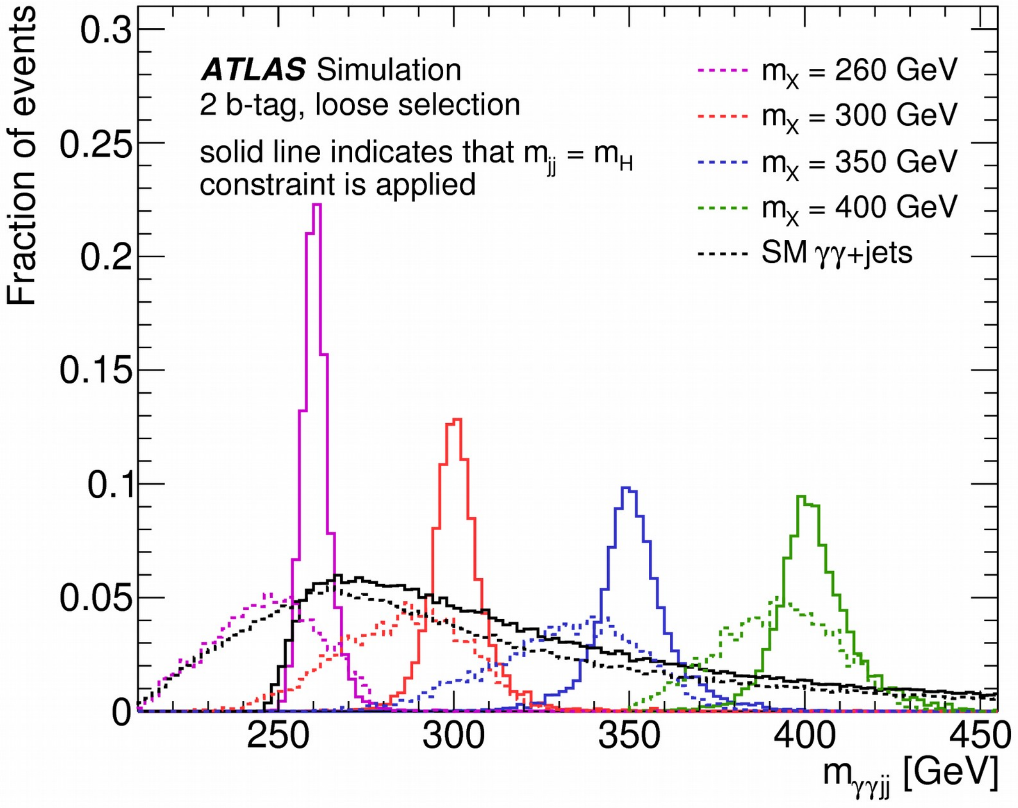


https://arxiv.org/pdf/1207.7214.pdf

Example of the Higgs Boson discovery by ATLAS
Dash line :
Fit of the data with the background only hypothesis
Full line :
Fit of the data with the background+signal hypothesis

Fit of the background and signal

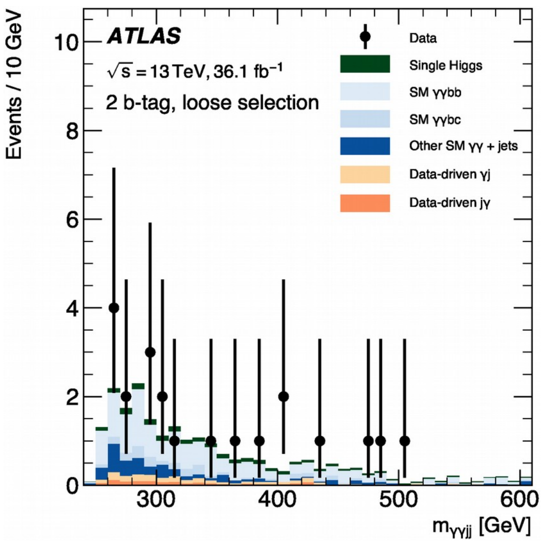
- Once the selections are applied we fit the di-Higgs invariant mass for background and the signal

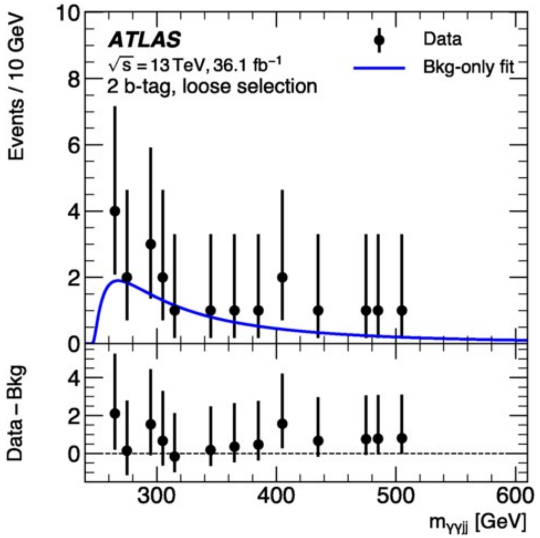


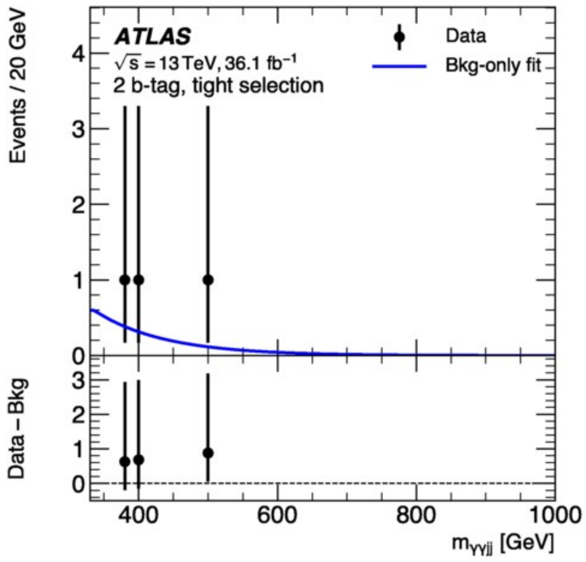
https://arxiv.org/pdf/1807.04873.pdf

Previous result

- Result of the 2016 analysis :
  No huge differences between the data and the background only hypothesis (No bump). Our fits are limited by the low number of events in the tail.







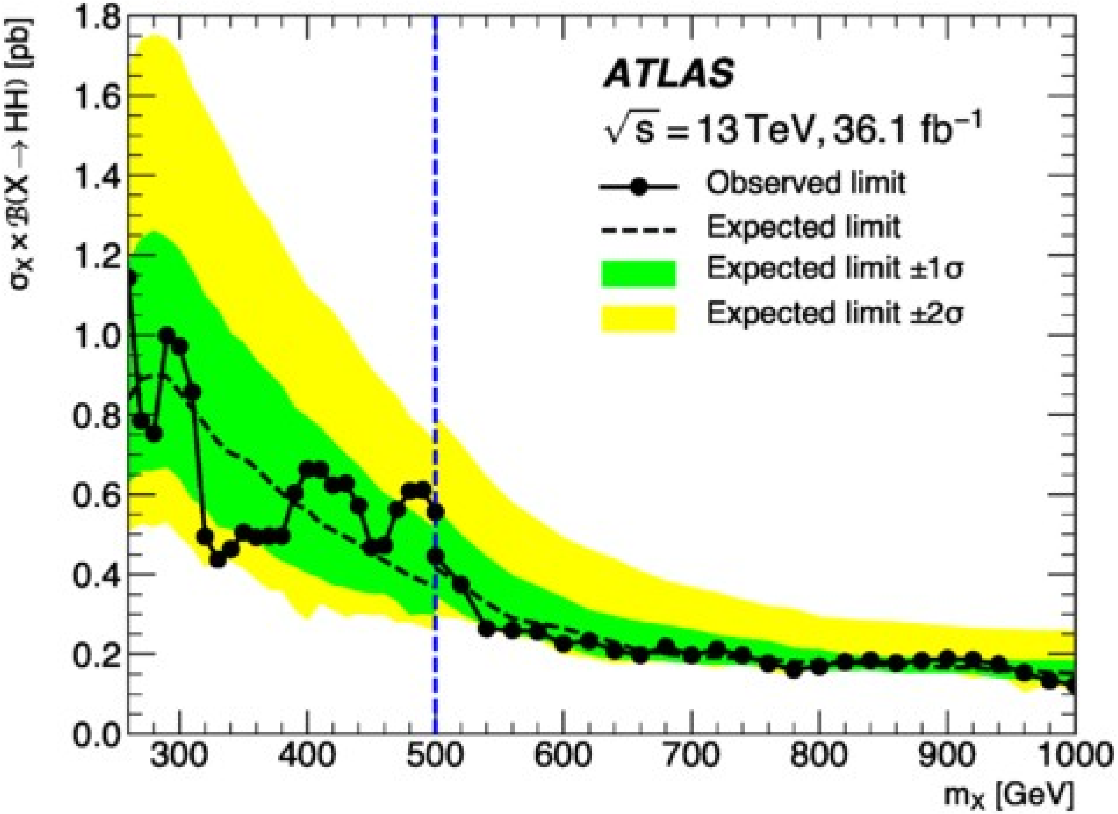
https://arxiv.org/pdf/1807.04873.pdf

- We then reinterpret our result as limit on the cross section

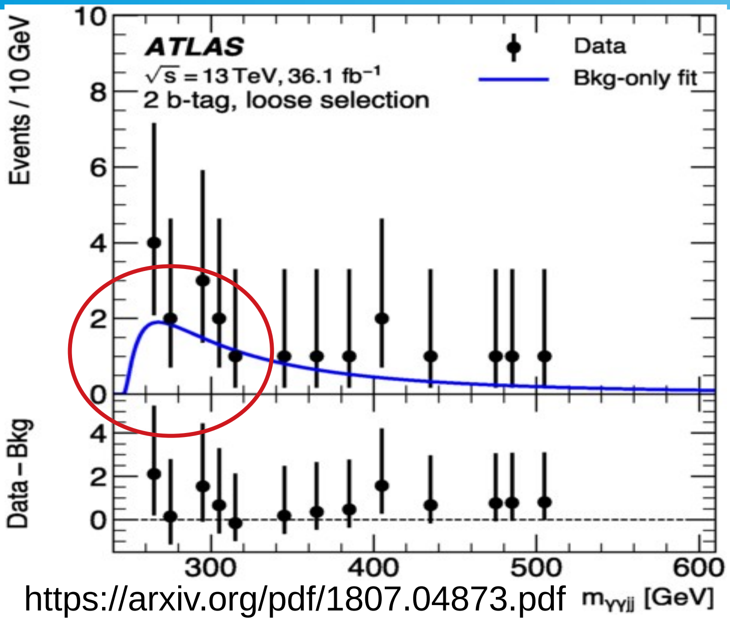
Limit on the cross section

- Limit at 95% confidence level of the cross section of the X → HH decay.

Everything that is over this line is excluded at 95%

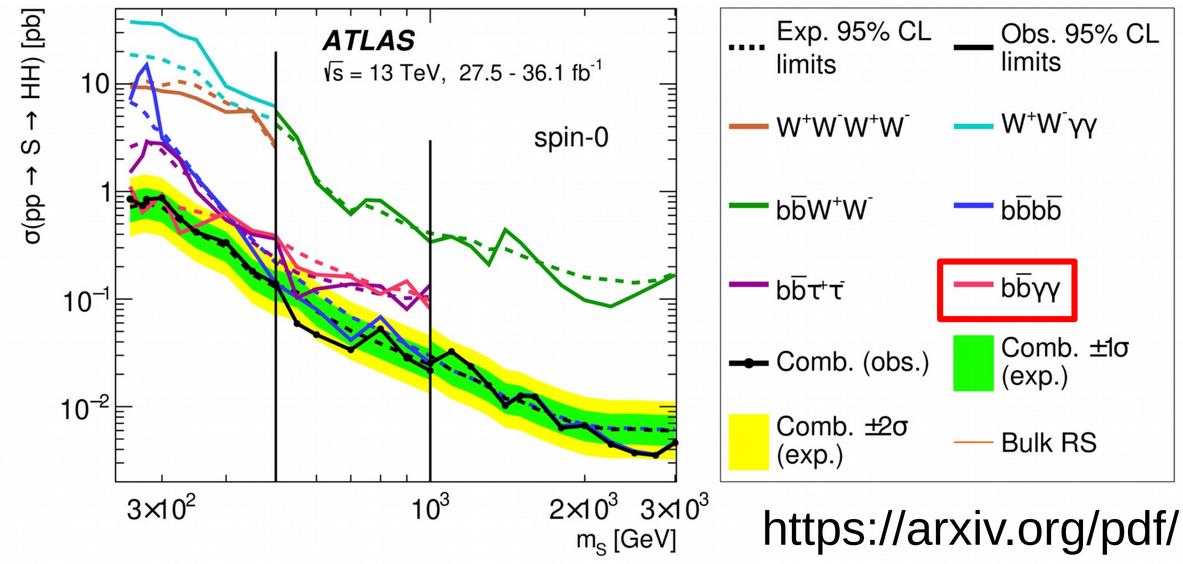


Limitation of this technique



https://arxiv.org/pdf/1807.04873.pdf

- Presence of a kinematic “turn-on” makes it hard to fit specifically at low mass
- But it’s at low mass that the yybb is the most important



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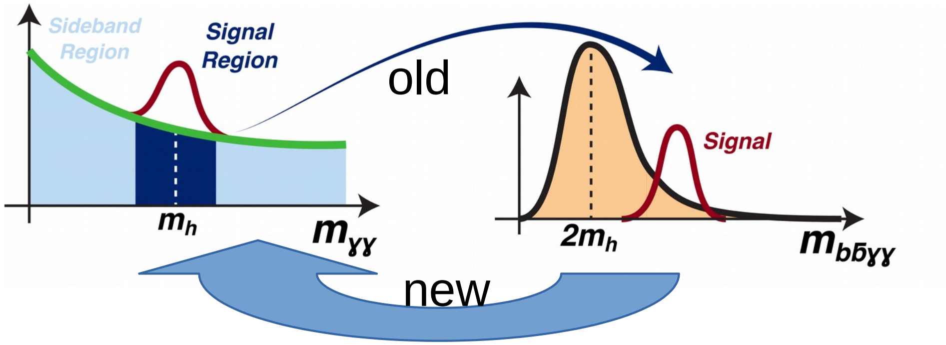
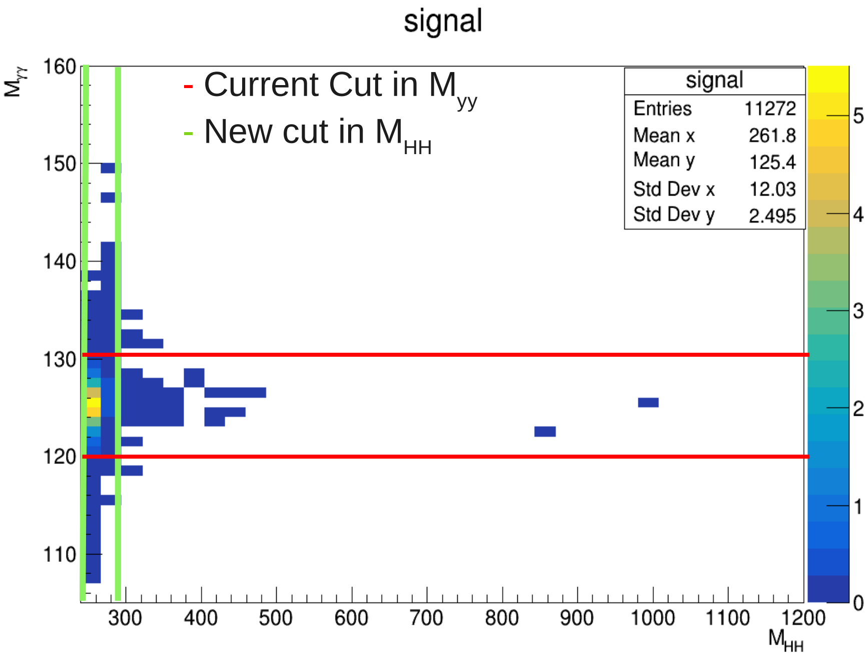
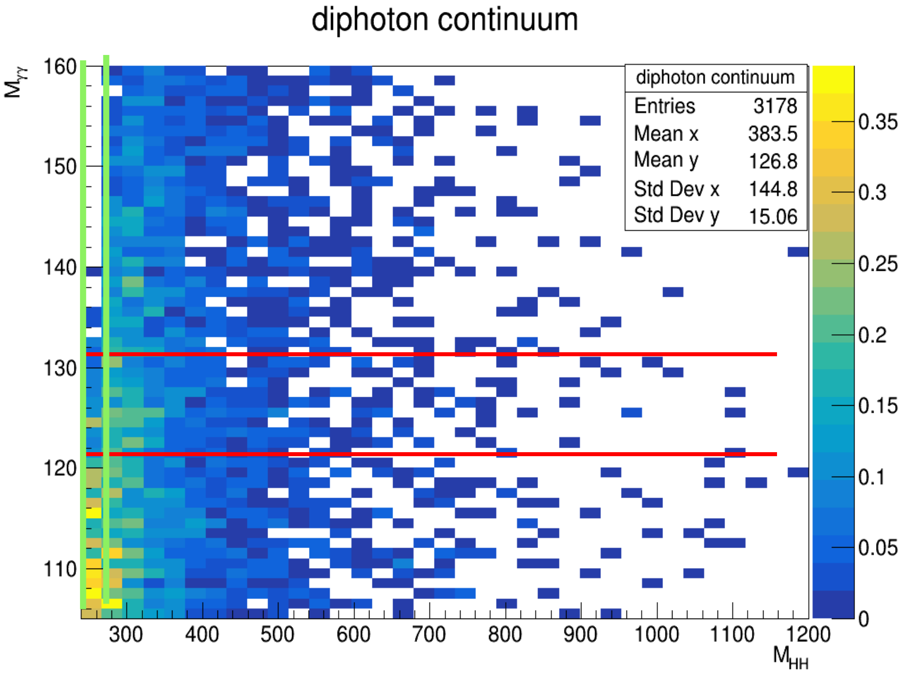
New methodology : first proposal



- More data helps to develop a more advance technique
- First change : from a fit on M_{HH} with a cut on M_{yy} to a fit on M_{yy} with a cut on M_{HH}

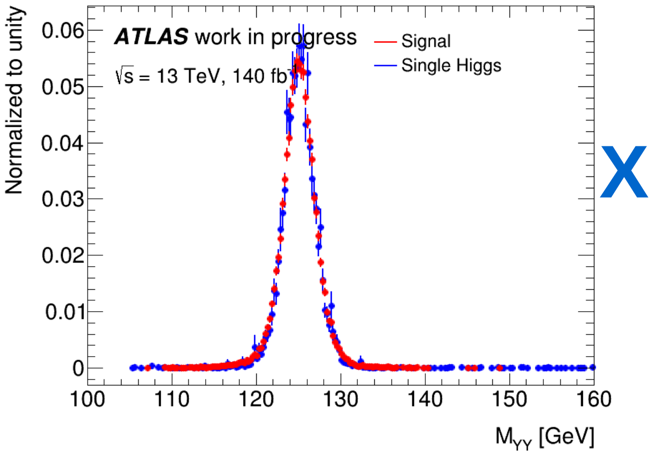


Technique used by CMS

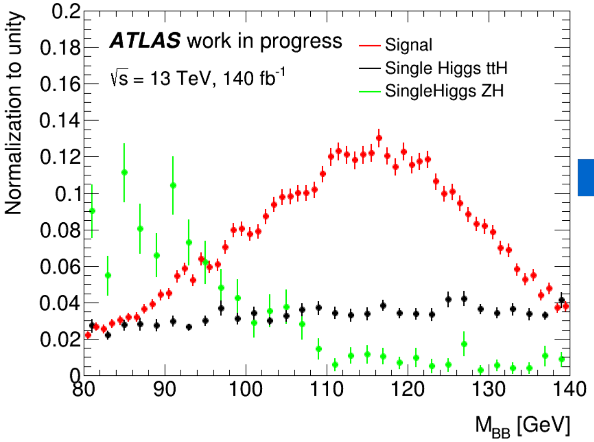


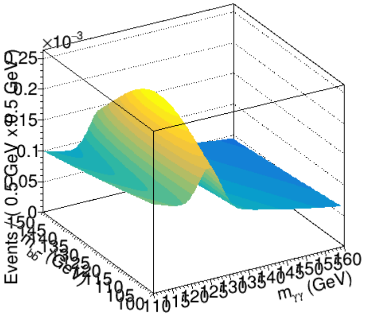
Second proposal : using a 2D fit

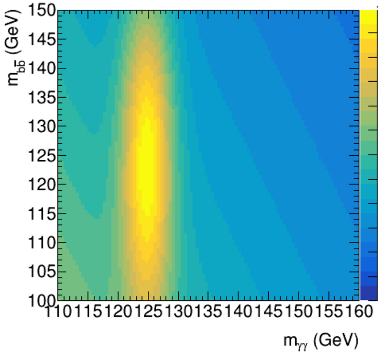
- Second change : from a 1D fit on M_{yy} to a 2D fit on $M_{yy}*M_{bb}$



X

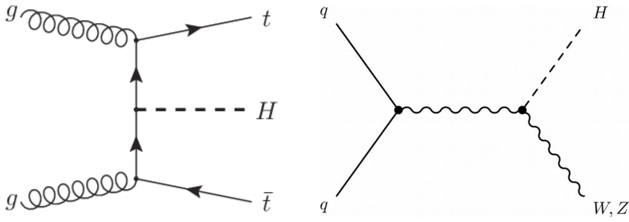






- Improvement could be made using the fact that the shape of the SingleHiggs background peak differ as function of the decay channel

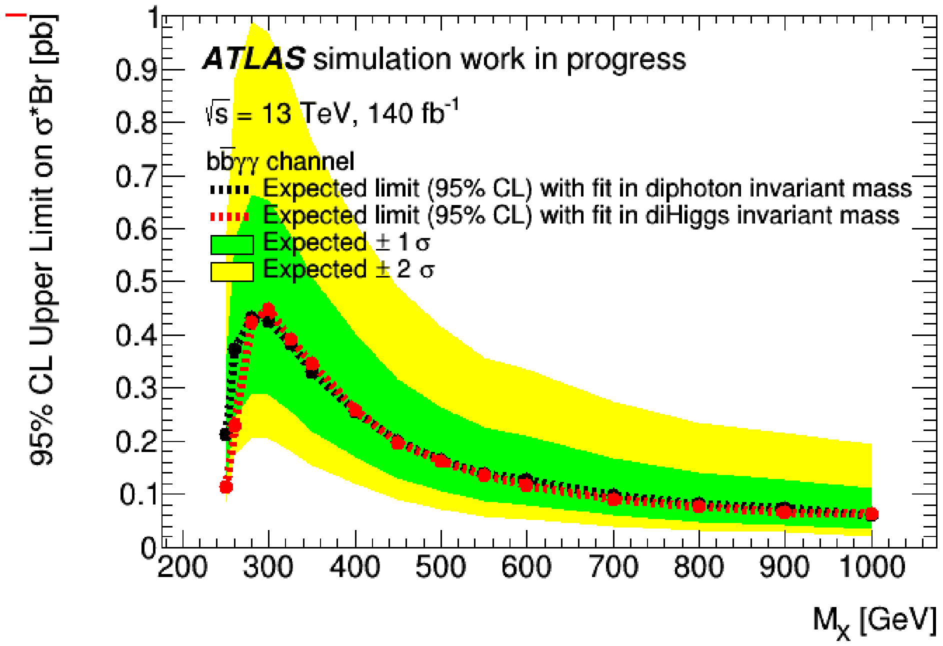
- The 2D method could also be used for the SM measurement



My ongoing result (1)

- Starting from the chosen selection I developed my own tools to fit the signal and background, and use the official statistical tools in order to compute the limits

- Those limits I compute are used as the figure of merit of the two improvements I proposed, and for other changes proposed by the team



YY : using the 1D fit on M_{yy}

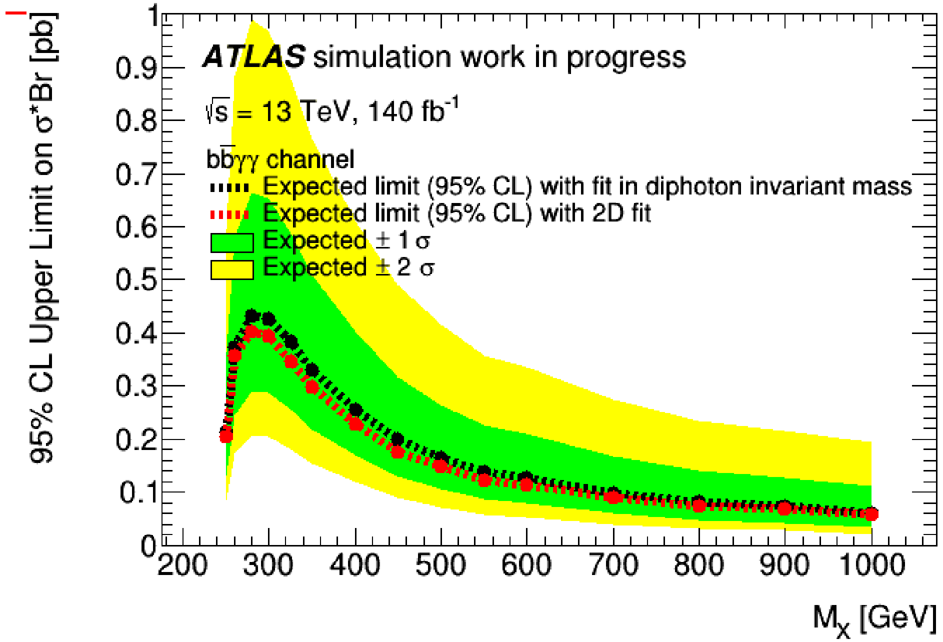
HH : using the 1D fit on M_{HH} (method of the previous paper)

For limit result : the lower the better
Result with statistical error only

- Fitting M_{yy} give equivalent to fitting M_{HH} without having to fit the kinematic turn-on.

My ongoing result (2)

- It is the first time such 2D fit is done in the group, I had to adapt the official tools in order to get the result for the 2D fits



YY : using the 1D fit on M_{yy}

2D : using the 2D fit on $M_{yy}*M_{bb}$

For limit result : the lower the better
Result with statistical error only

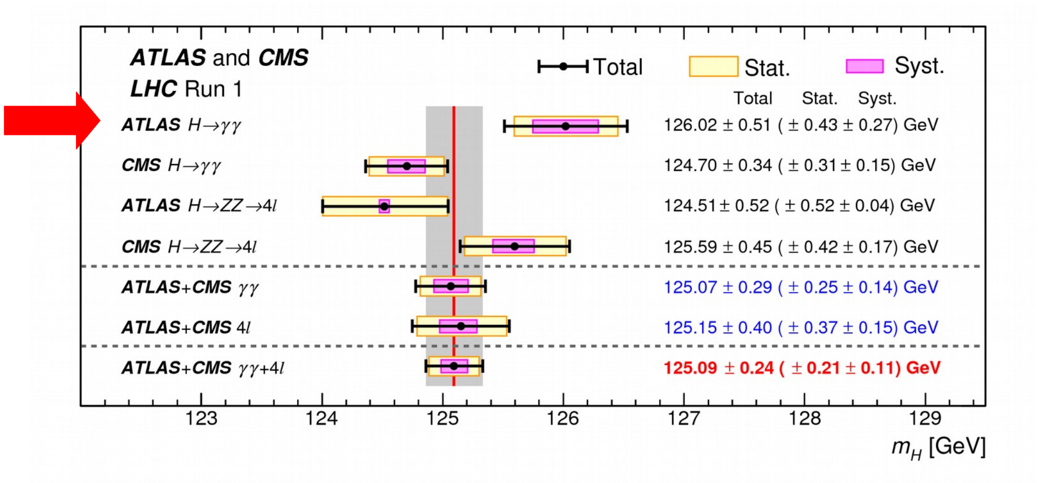
- There is an improvement using the 2D fit comparing to the YY fit.
- We are dominated by the statistical error but there is work in progress to estimate the systematics

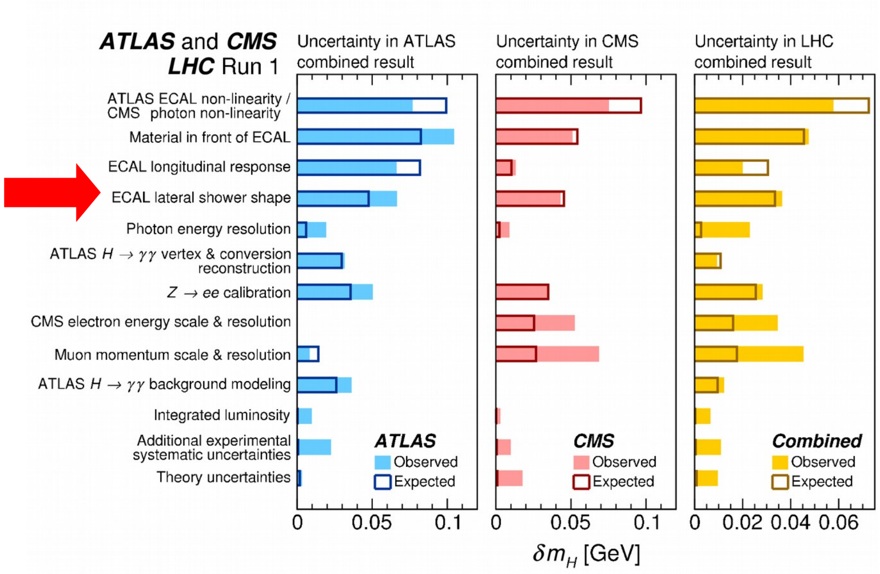
Conclusion

- Familiarization with the tools used by ATLAS and EM calorimeter thanks to the work on photons
- Already some improvement have been shown using new methodology in the X→HH→bbyy
- There are still some work to be done to compute the uncertainties and in order to fix the choice of the fit function

Outlook

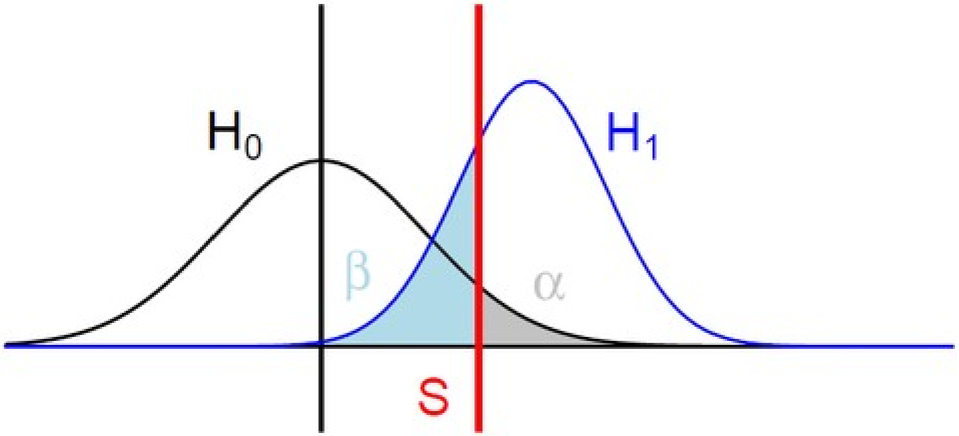
- The result that we aim to publish in the end of 2020 will be the reference until the end of the run-3 in 2024
- I work, in parallel, on the photon calibration aiming to improve the sensitivity of the precision measurement of the Higgs mass (It would be complementary to my search work)

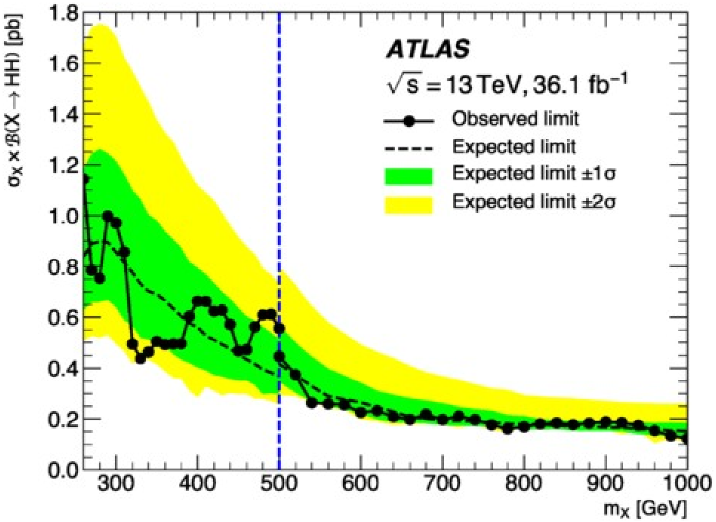




CLs Method

- H0: backround only hypothesis
- H1: background+signal hypothesis
- S : value measured
- α: accepting H1 whereas H0 is true (highlightling at 3 σ and 5 σ)
- β: accepting H0 whereas H1 is true (treshold : β <0.05 this value will fix the value for our limit)

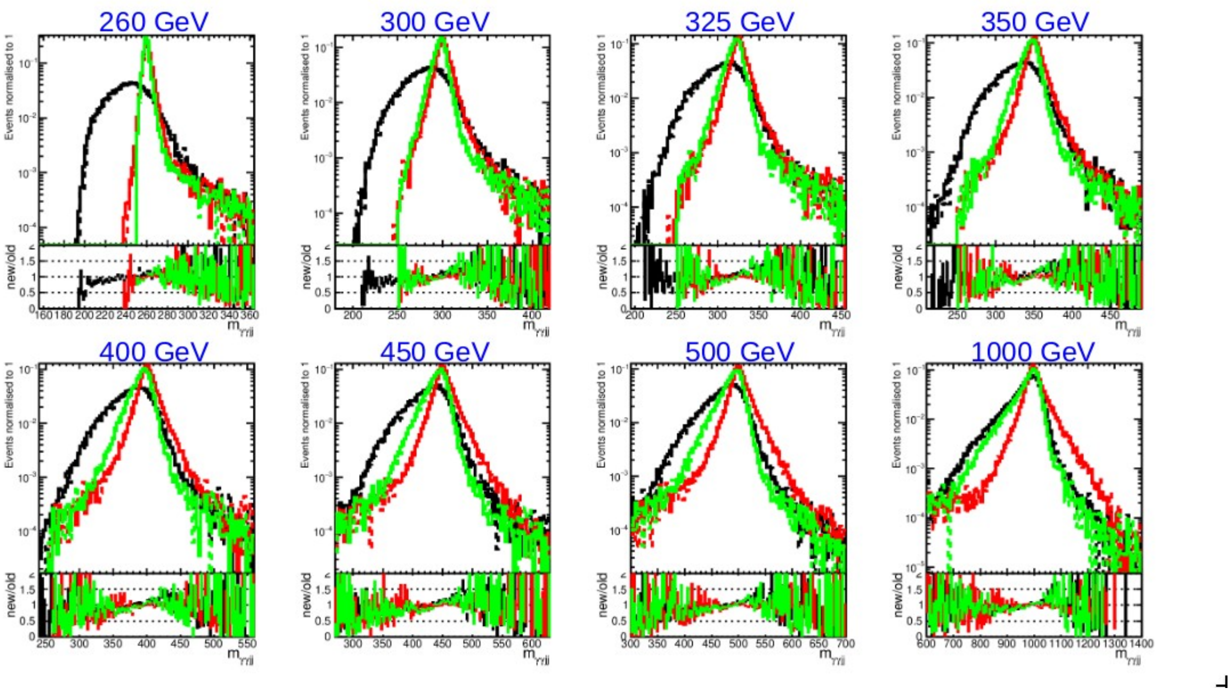




https://arxiv.org/pdf/1807.04873.pdf

Redefinition if the diHiggs invariant mass

- We want to use correction on the diHiggs invariant mass to reduce the spread of the signal



Old = bb.M + yy.M

Cnstrnd = $bb_{cnstrnd}$.M + yy.M (the one used for now)
with $bb_{cnstrnd}$ = bb/bb.M *125

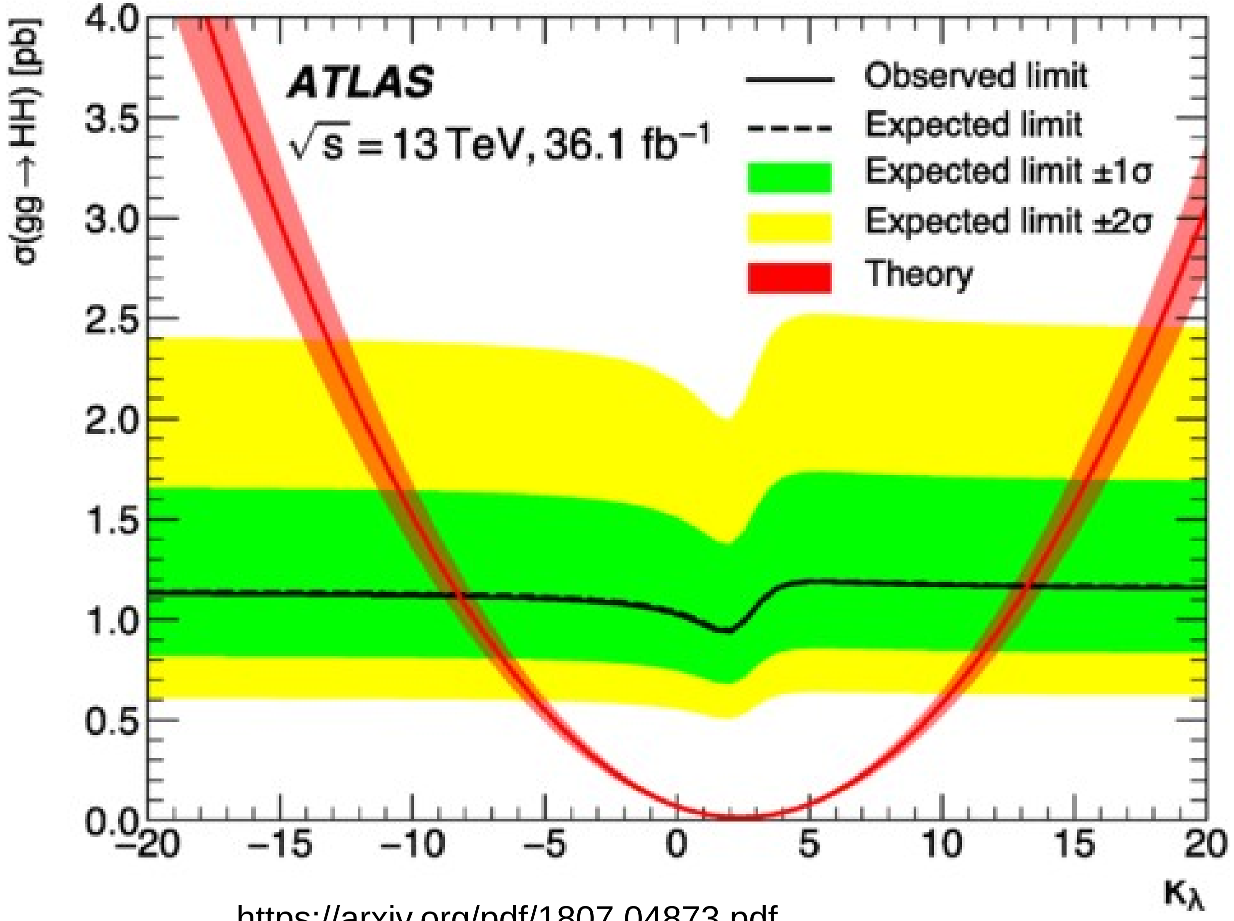
Tilde = yybb.M – yy.M – bb.M +250

Backup : b-tagging and photon identification

- There are some parameter used to characterize each type of particle then we use an MVA to discriminate the type of the particle.
- We can choose the MVA cut depending on how clean we want our signal to be.
  (tighter discriminant → cleaner signal)

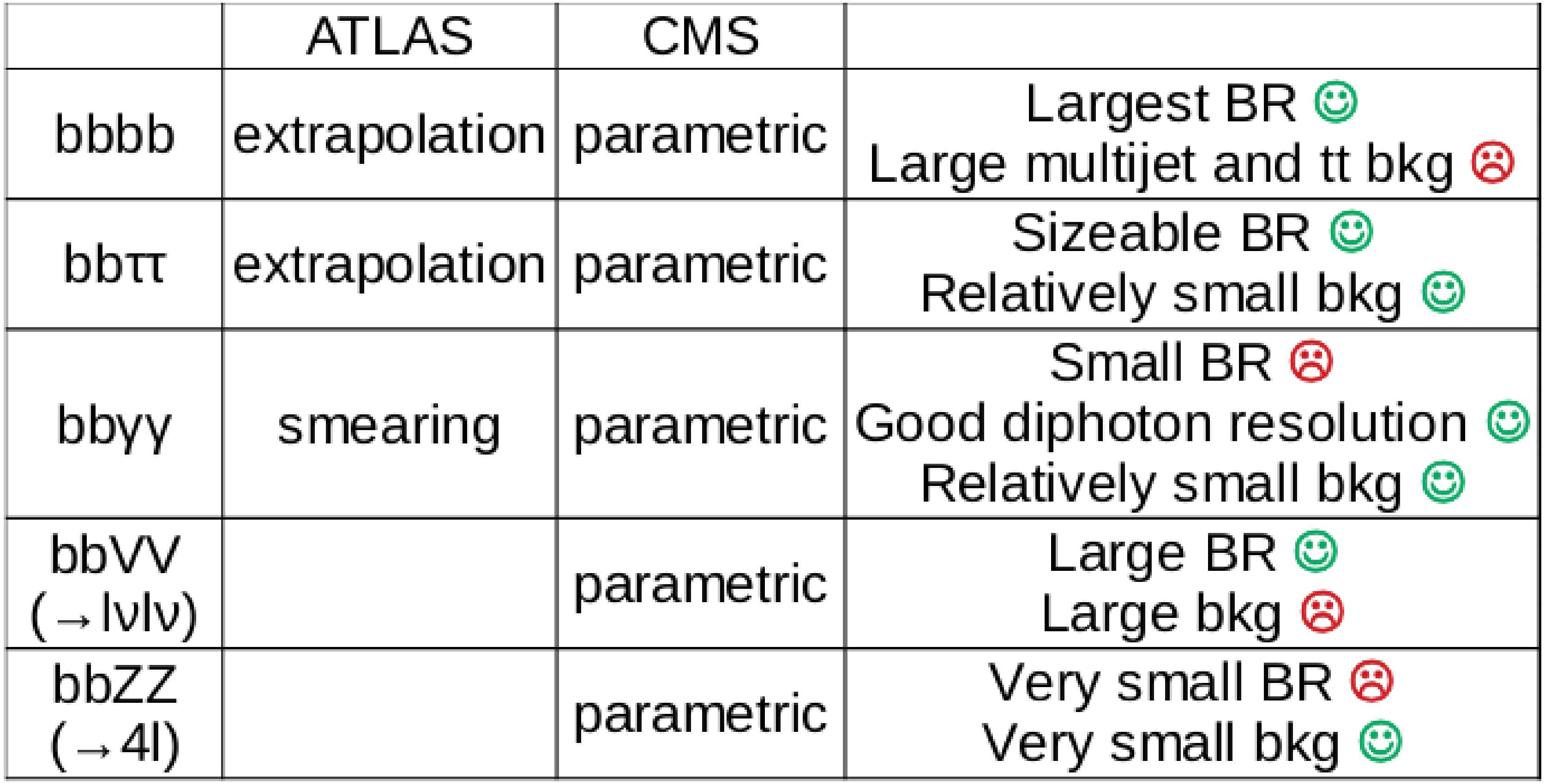
Backup non-resonant result

- $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$



https://arxiv.org/pdf/1807.04873.pdf

Advantage and drawback of each channels



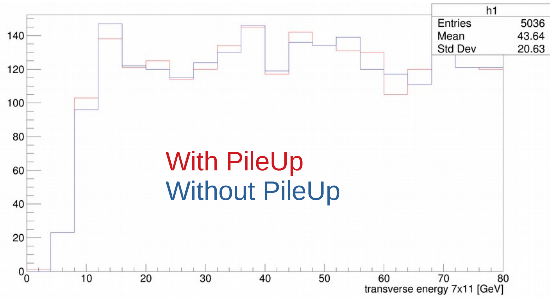
	ATLAS	CMS	
bbbb	extrapolation	parametric	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	extrapolation	parametric	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	smearing	parametric	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→lνlν)		parametric	Large BR ☺ Large bkg ☹
bbZZ (→4l)		parametric	Very small BR ☹ Very small bkg ☺

Backup on the photon identification

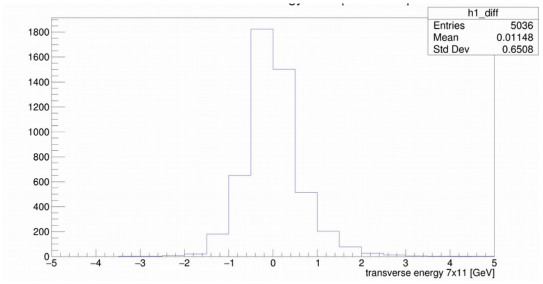
$$E_{new} = E_{old} - \rho_{median} \times \cosh(\gamma_{\eta}) \times \text{coefficient}$$

- Using two types of MC files (one with backup and one without) to look at the cell energy differences as a function of the pile-up in order to find the coefficient

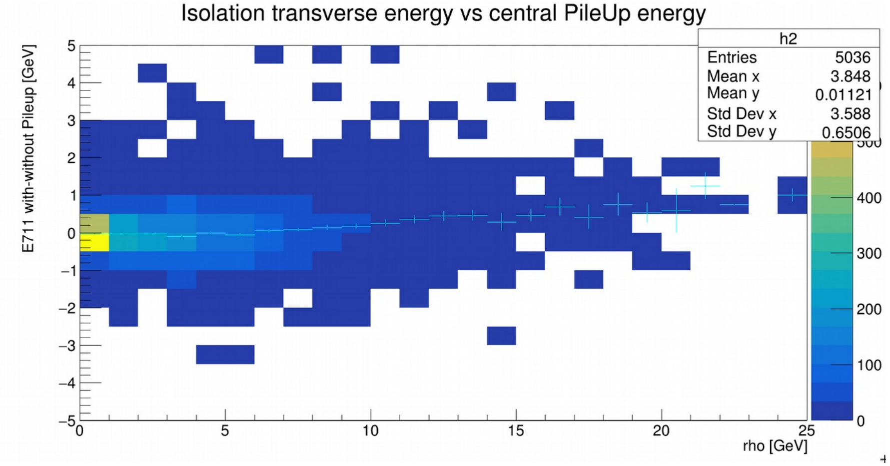
Comparison PileUp with NoPileUp



Difference PileUp with NoPileUp event by event



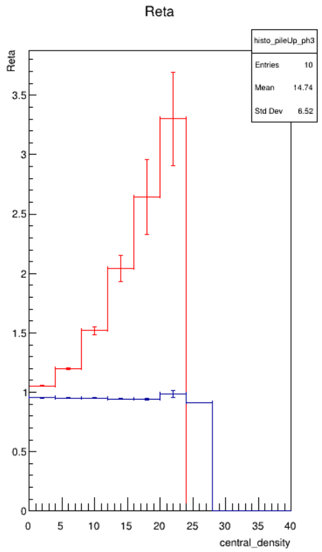
E711 (with-without PileUp) energy vs Rho



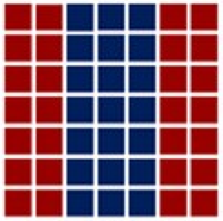
Problem : No strong correlation and no clear effect due to high fluctuation around the mean

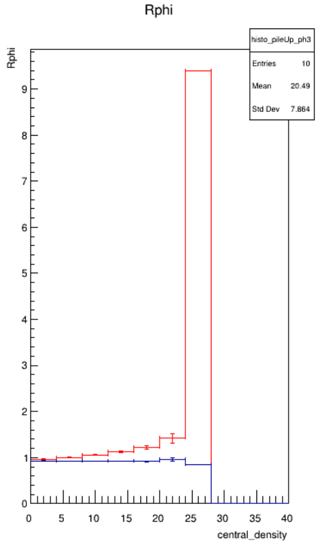
Effect of correction on Rphi and Reta

I showed that such correction is too strong and gives some weird results such as negative energies.

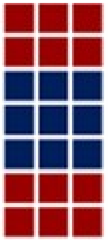


$$R_\eta = \frac{E^{S_2}_{3\times7}}{E^{S_2}_{7\times7}}$$



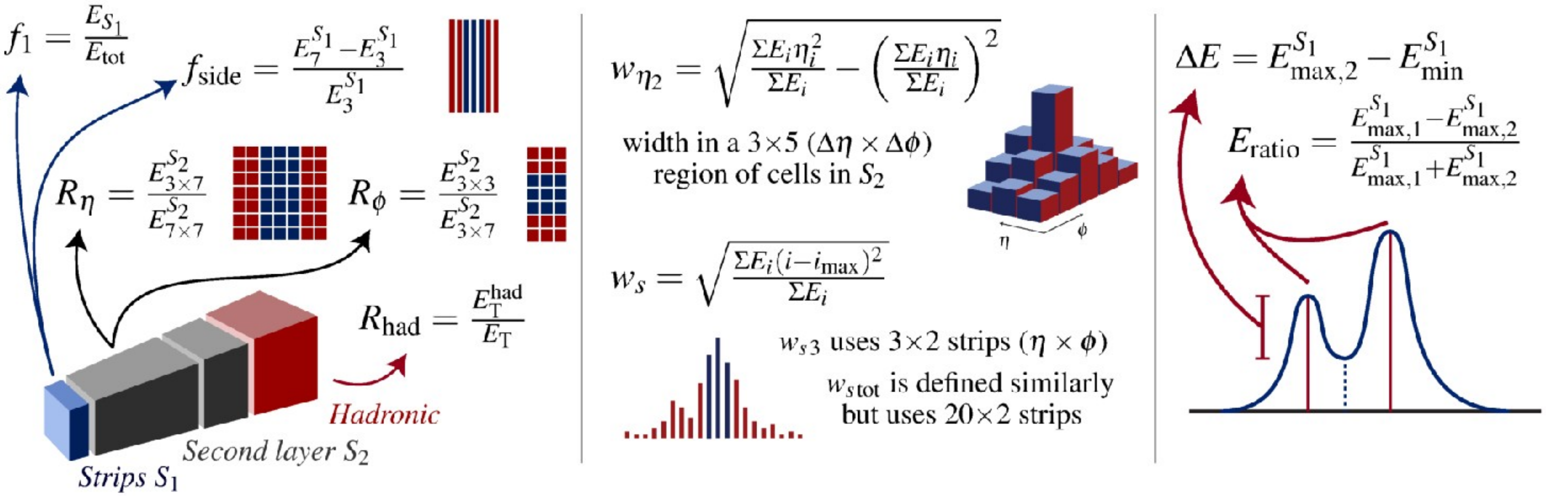


$$R_\phi = \frac{E^{S_2}_{3\times3}}{E^{S_2}_{3\times7}}$$

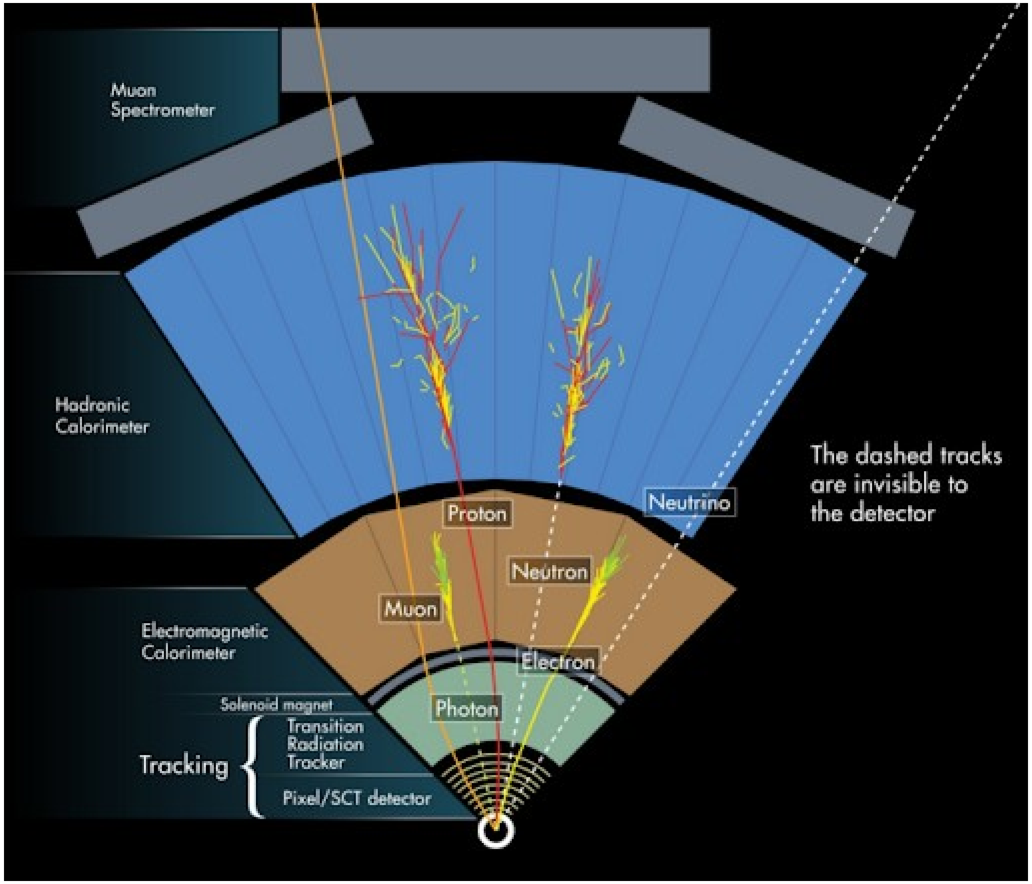


I found two effects that can explain such change:
- The energy correction will lower more the denominator than the numerator as it contains more cells.
- Some cells on the edge had negative energy after the correction

Shower shapes



Particle path inside the detector



Possible new physics

Model	Higgs Spectrum	Possible Higgs pair final states from resonant production
RxSM SM+real singlet	\`dark phase': H_SM, DM \`broken phase´: H_SM, S	DM DM H_SM H_SM, SS
CxSM SM+complex singlet	\`dark phase´: H_SM,S,DM \`broken phase´: H_SM,H1, H2	H_SM H_SM, SS, DM DM H_SM H_SM, H1 H1, H2H2, H1 H2, H_SM H1
2HDM 2 Higgs doublets	CP-conserving: H_SM,H,A	H_SM H_SM, HH
MSSM 2 Higgs doublets, SUSY!	CP-conserving: H_SM,H,A	H_SM H_SM no HH (due to constraints)
C2HDM 3 Higgses mix	CP-violating: H_SM,H1, H2	H_SM H_SM, H1 H1, H2 H2 H1 H2, H_SM H1
N2HDM 2 doublets, 1 real singlet	H_SM,H1,H2,A	H_SM H_SM, H1 H1, H2 H2 H_SM H1, H1 H2
NMSSM SUSY! 2 doublets + 1complex singlet	H_SM,H1,H2,A1,A2	H_SM H_SM, H1 H1, H_SM H1, H_SM A1 A1 H1 (no H1 H2, A1 H2 due to conststraints)