

# Search for Higgs pair production at the LHC Collider (CERN): The first measurement of the Higgs potential and search for new physics

Ph.D. thesis defence - 15 September 2021

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Supervised by  
Stéphane JEZEQUEL



# Content

## Theoretical framework

- The Standard Model of particle physics
- Higgs boson self-coupling
- Higgs boson pair production

## Experimental setup

- The Large Hadron Collider
- The ATLAS detector

## Measurement of Higgs self-coupling

- Analysis strategy
- Higgs self-coupling constrain

## Interpretation using Effective Field Theory (work in progress)

- Di-Higgs and Effective Field Theory
- EFT coefficients constraints

## Prospects at Run-3 and HL-LHC

- Prospects at the end of Run-3
- Prospects at HL-LHC

## Photon identification using Convolutional Neural Network

- Photon identification with Neural Network
- Photon identification efficiency

## Conclusion

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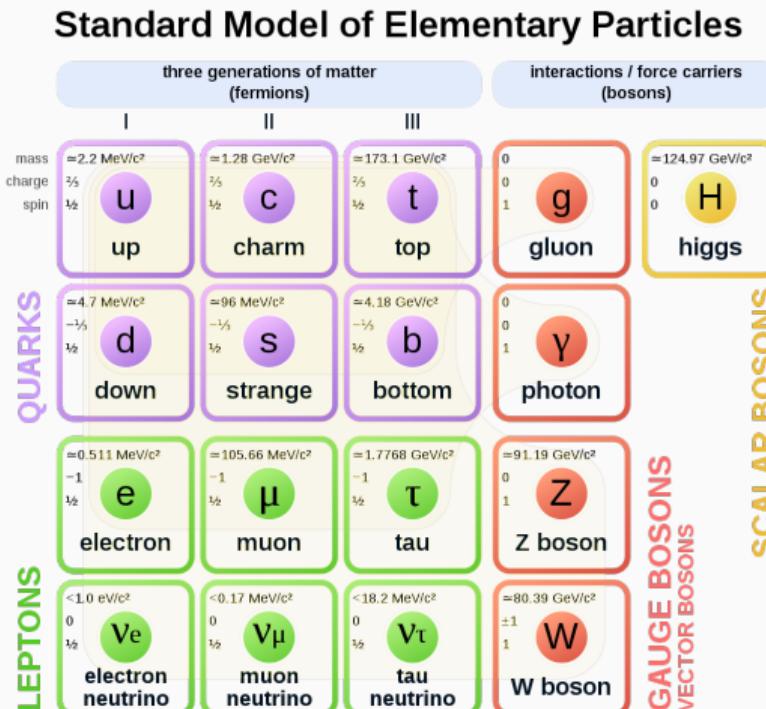
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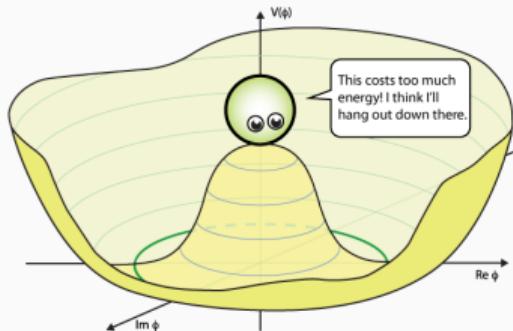
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# The Standard Model (SM) of particle physics

- Quantum field theory, based on the principal gauge invariance  $SU(3) \times SU(2) \times U(1)$
  - Unify **Strong** and **Electro-weak** interactions
  - **Fermions:** matter particles
    - Quarks
    - Leptons
  - **Gauge bosons:** mediators of interactions
  - **Higgs boson:** responsible for mass generation through EWSB mechanism



# Electroweak Symmetry Breaking and Higgs boson



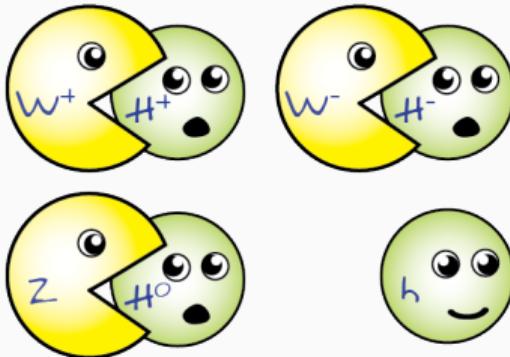
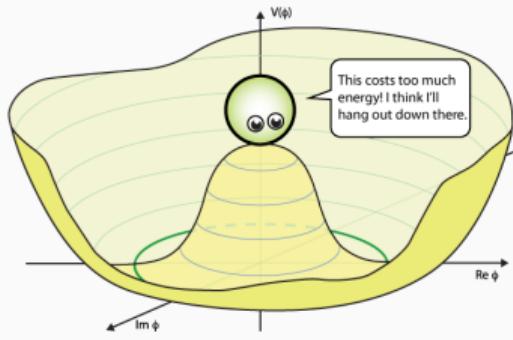
Gauge boson mass terms break gauge symmetry of SM

- Brout-Englert-Higgs (1964) include complex scalar field

$$V(\phi^\dagger \phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$
$$\mu^2 < 0 \rightarrow \text{Mexican hat}$$

- Choice of the vacuum state  $\nu$  spontaneously breaks the symmetry
  - Gauge bosons become massive
  - **Higgs boson:**  $m_H = -2\mu^2$
  - Fermion masses: generated through Yukawa couplings
- Observed in 2012 at LHC,  $m_H \sim 125$  GeV

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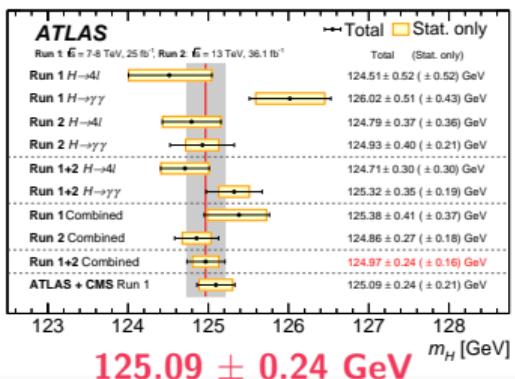
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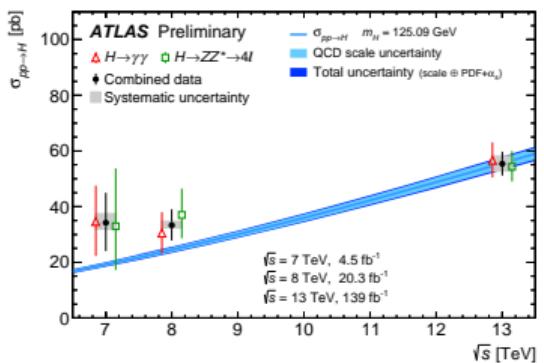


# Measurements of Higgs parameters

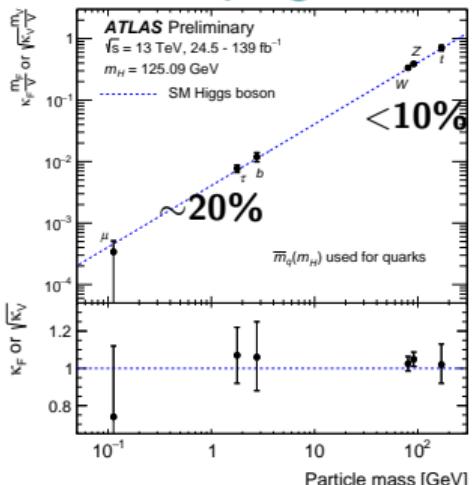
mass



cross-section



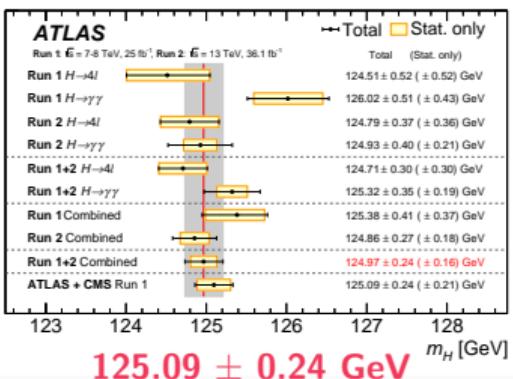
coupling



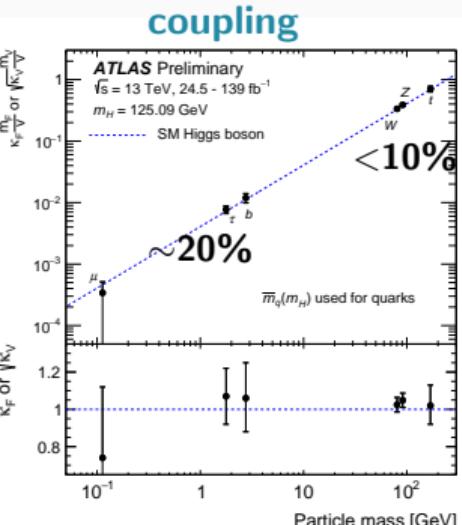
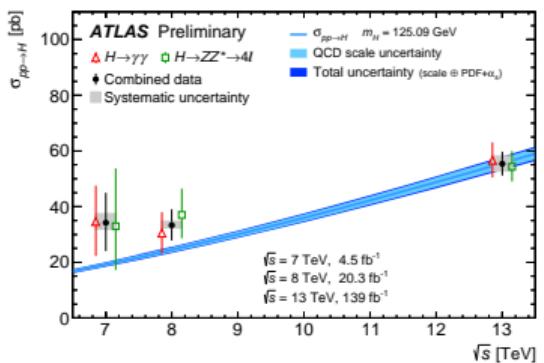
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# Higgs boson self-coupling

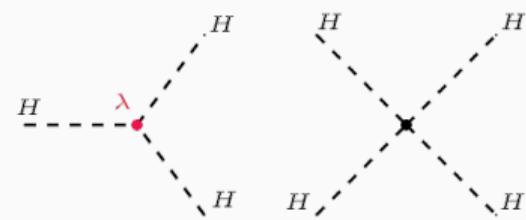
- **Self-coupling:** Higgs boson trilinear coupling
- Controls the shape of the Higgs potential
  - It is important to measure both  $m_H$  and  $\lambda$
- Beyond SM (BSM) physics would impact this coupling, impact quantified as

$$\kappa_\lambda = \frac{\lambda}{\lambda^{SM}}$$

- Measured directly with Higgs boson pair (HH) production

$$V \supset \frac{m_H^2}{2} H^2 + \cancel{\lambda} v H^3 + \frac{\lambda}{v} H^4$$

$$\lambda^{SM} = \frac{m_H^2}{2v^2} \sim 0.13$$



not accessible  
at LHC

# Higgs boson self-coupling

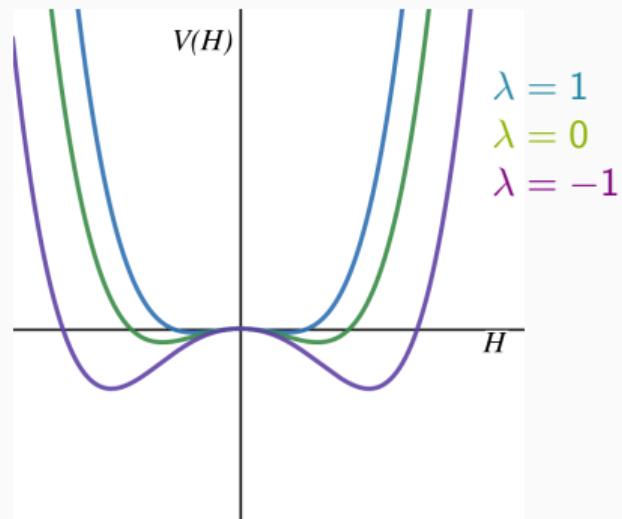
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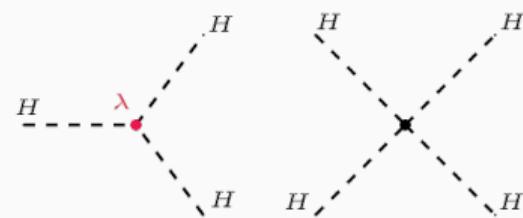
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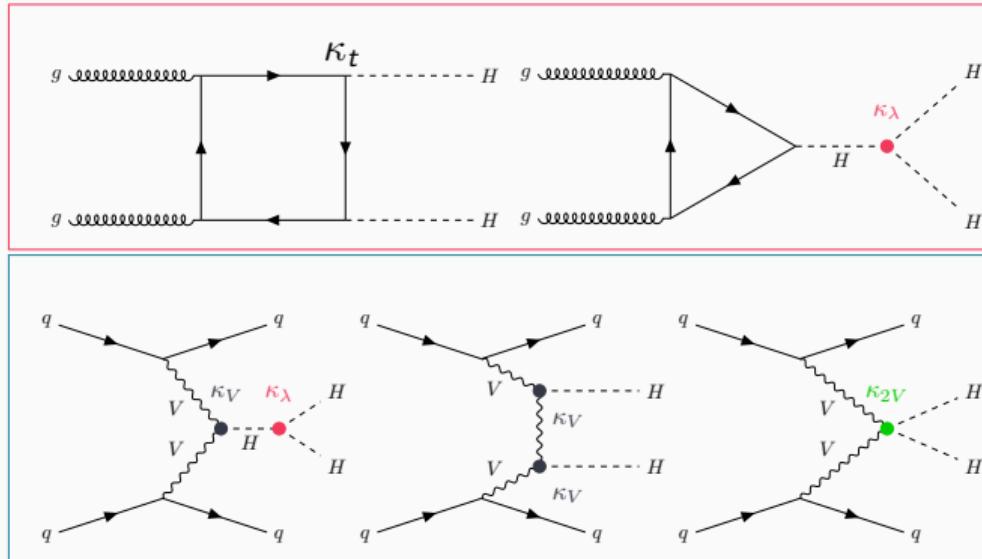


- Measured directly with **Higgs boson pair (HH) production**

# Higgs boson pair production at the LHC

- Produced mainly via **non-resonant gluon-gluon Fusion (ggF)** and **Vector Boson Fusion (VBF)**

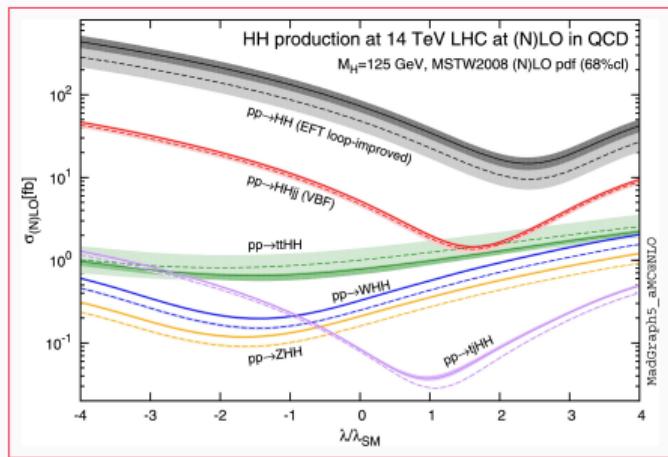
Destructive interference



- At 13 TeV,  $m_H = 125.09$  GeV and  $\kappa_\lambda = 1$ 
  - $\sigma_{HH}^{ggF} = 31.02$  fb, 3 order of magnitude smaller than  $\sigma_H$
  - $\sigma_{HH}^{VBF} = 1.72$  fb, one order of magnitude more smaller than ggF

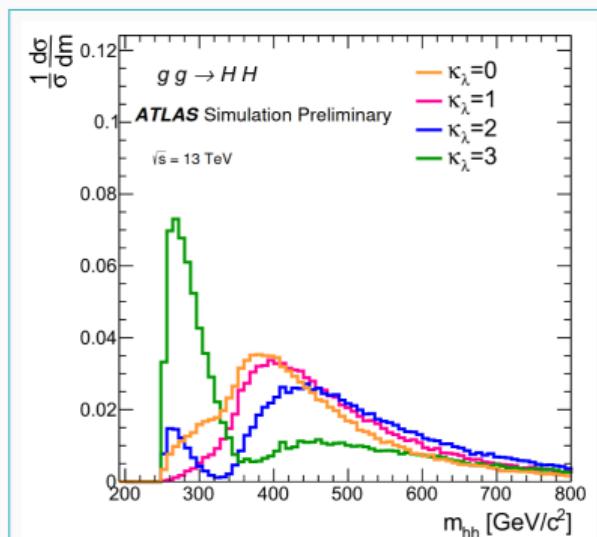
# Di-Higgs boson as a probe of BSM physics

- Low cross-section, BSM anomaly may enhance it
- BSM physics could manifest as deviations
  - **Total** production rate
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- Measurement of  $\kappa_\lambda \rightarrow \kappa_\lambda \neq 1$ , presence of **new physics**



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# Di-Higgs boson decay modes

	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	33%				
WW	25%	4.6%			
$\tau\tau$	7.4%	2.5%	0.39%		
ZZ	3.1%	1.2%	0.34%	0.076%	
$\gamma\gamma$	0.26%*	0.10%	0.029%	0.013%	0.0005%

- Focusing on  $H \rightarrow b\bar{b}$   $H \rightarrow \gamma\gamma$
- Despite low decay rate, competitive channel
  - High  $H \rightarrow b\bar{b}$  branching ratio
  - Excellent  $m_{\gamma\gamma}$  mass resolution → Good signal extraction

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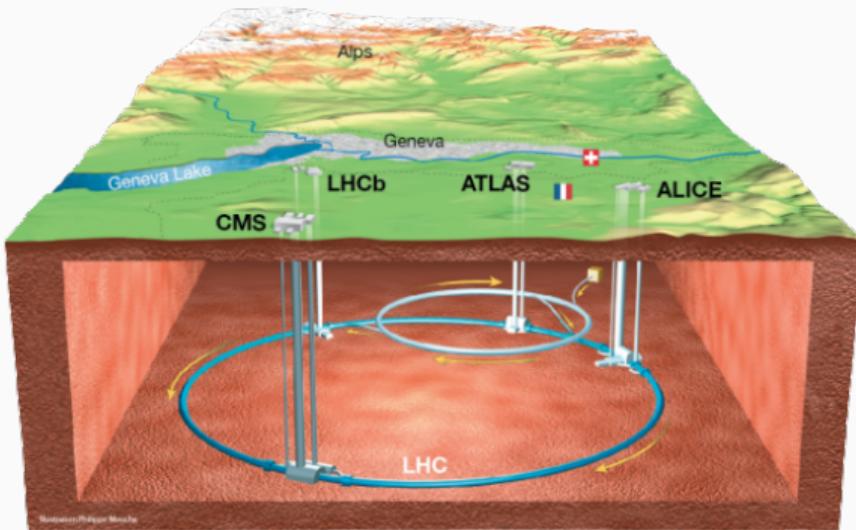
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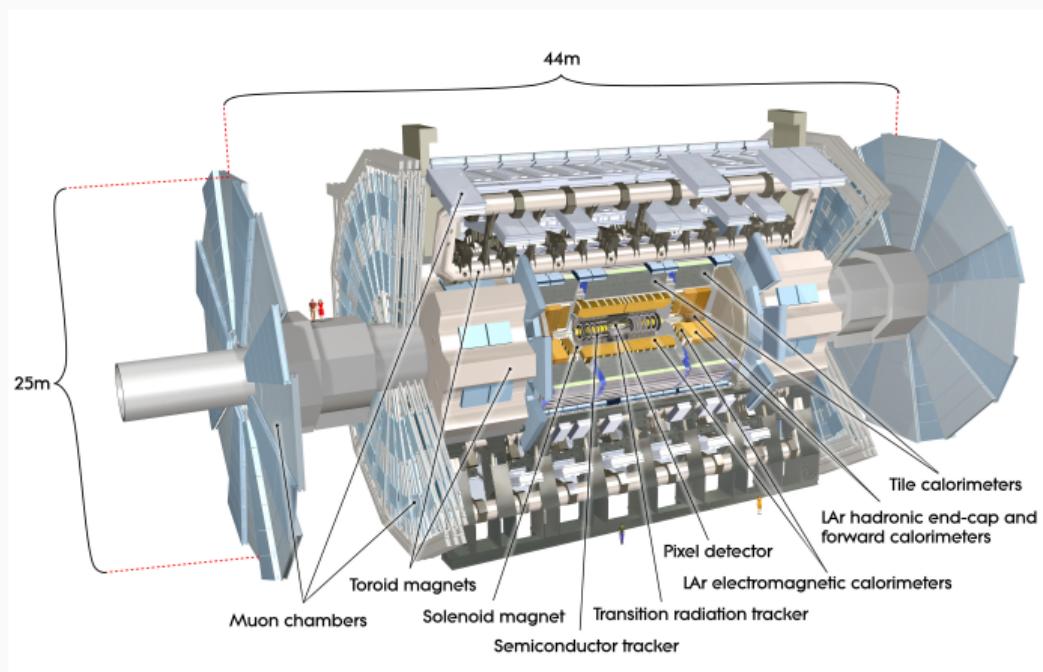
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# The Large Hadron Collider (LHC)

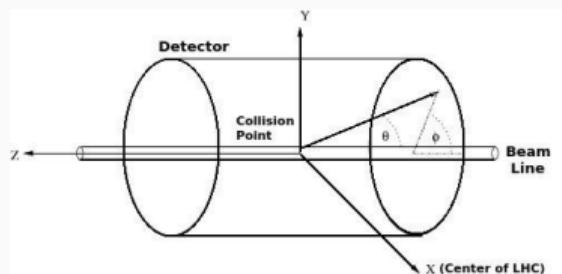
- *pp collisions*, up-to  $\sqrt{s} = 13 \text{ TeV}$
- Four large experiments



# The ATLAS detector



- Different sub-detectors
- Cylindrical coordinate system

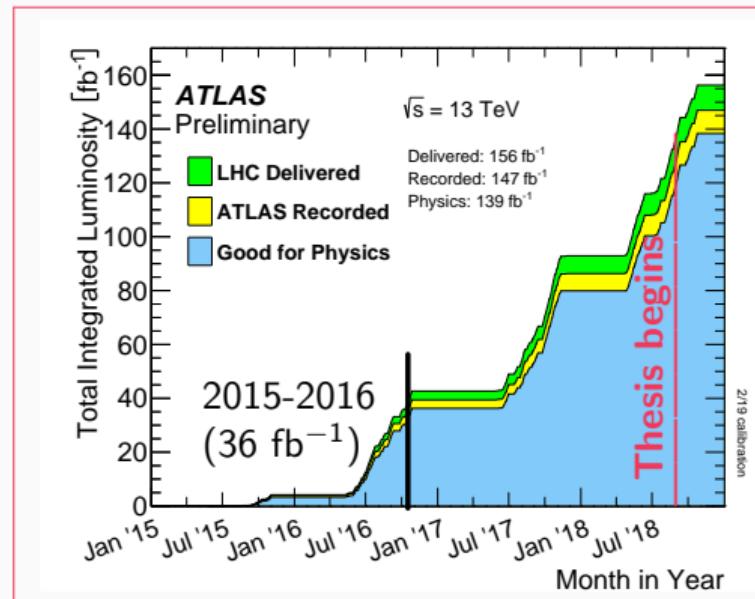


$$(p_T, \phi, \eta)$$

$$\eta = -\ln[\tan \frac{\theta}{2}]$$

# Run-2 data taking

- Run-2 period: 2015-2018
- Integrated luminosity used for presented analysis:  $139 \text{ fb}^{-1}$



# Where are we with $\text{HH} \rightarrow b\bar{b}\gamma\gamma$ ?

- Previous analysis: **2015-2016 data ( $36 \text{ fb}^{-1}$ )** JHEP 11 (2018) 040
  - $\frac{\sigma_{ggF}}{\sigma_{SM}}(\text{HH})$  limit: **22** (Exp. **28**) at 95% CL
  - $\kappa_\lambda$  constrain: **[-8.2, 13.2]** (Exp. **[-8.3, 13.2]**)
- My thesis: **Full run-2 data ( $139 \text{ fb}^{-1}$ )**
  - Improve the analysis sensitivity with different tools

	HH	$\text{HH} \rightarrow b\bar{b}\gamma\gamma$	$\sim 10\%$ eff.
Events	4.3k	11	$\mathcal{O}(1)$

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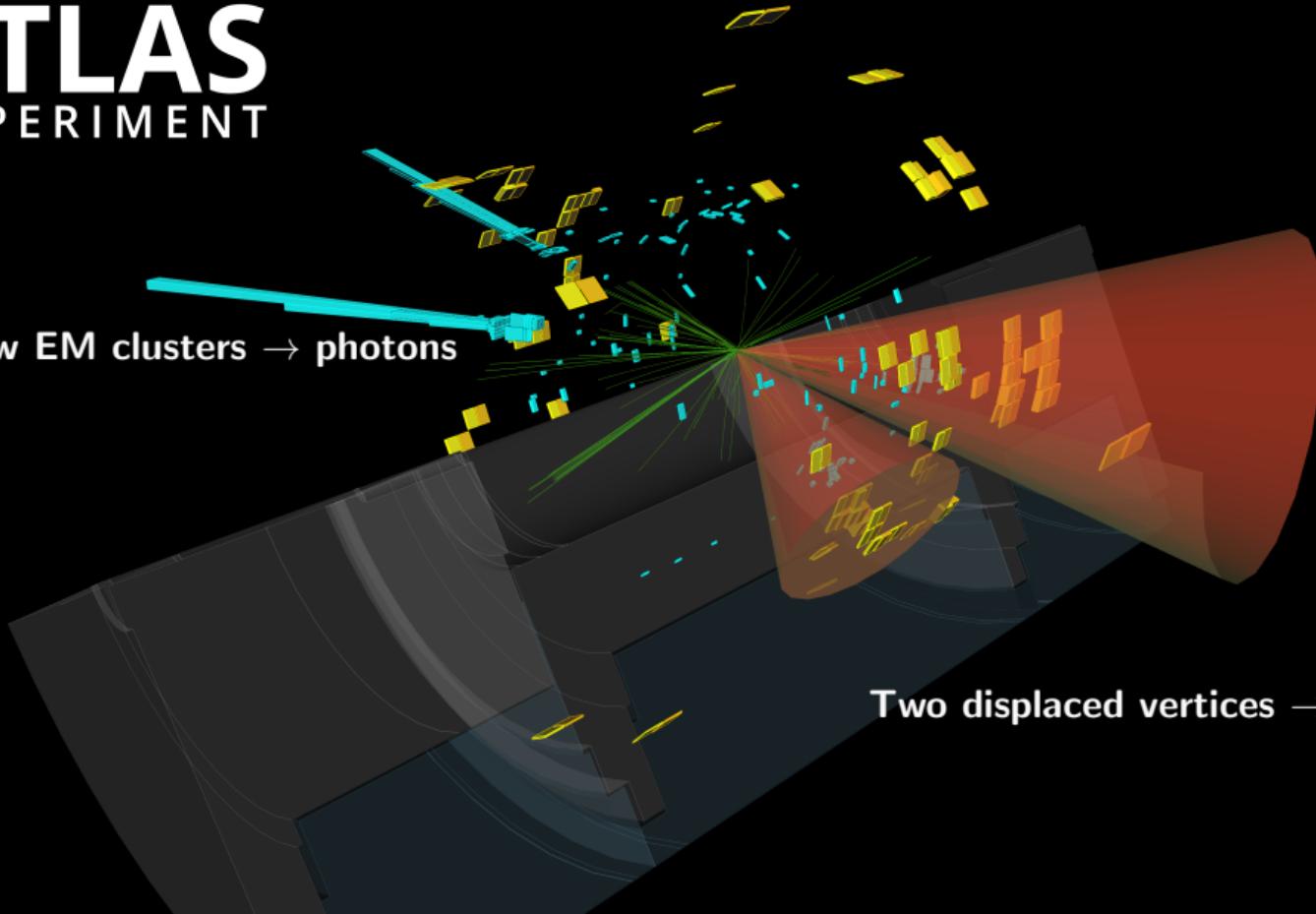
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Two narrow EM clusters → photons



Two displaced vertices →  $b$ -jets

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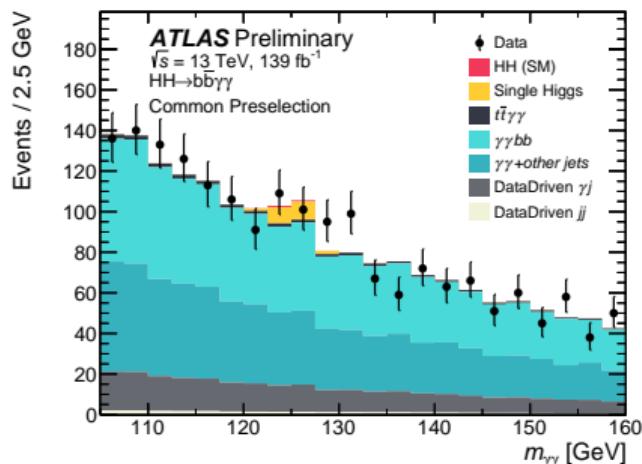
Two displaced vertices →  $b$ -jets

## Backgrounds

- Peaking in  $m_{\gamma\gamma}$ : **single**  $H \rightarrow \gamma\gamma$  ( $t\bar{t}H$ ,  $ZH$ )
- Not peaking: **continuum**  $\gamma\gamma + \text{jets}$

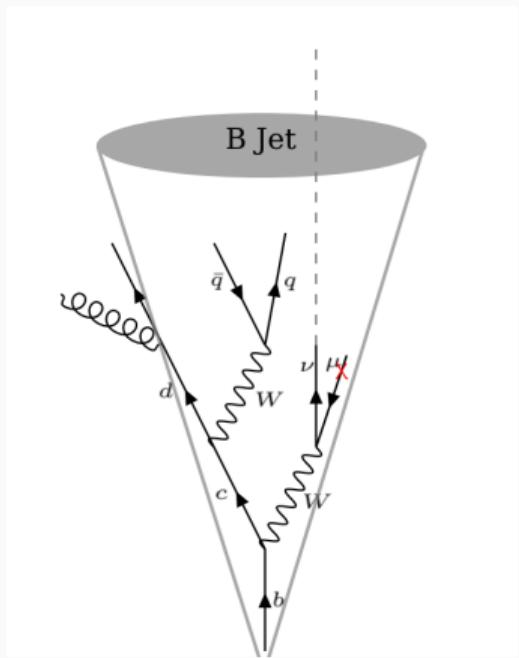
# Events selection

- **Di-photon trigger** (83% efficiency for HH signal)
  - $E_T^\gamma > 35$  (25) GeV for leading (sub-leading)
- **$\geq 2$  Tight and isolated photons ( $H \rightarrow \gamma\gamma$ )**
  - $|\eta| < 2.37$  &  $\frac{p_T^\gamma}{m_{\gamma\gamma}} > 35\%$  (25%) for leading (sub-leading)
  - $m_{\gamma\gamma}$  built with the two leading photons
- **Exactly 2  $b$ -jet ( $H \rightarrow b\bar{b}$ )**
  - $p_T > 25$  GeV &  $|\eta| < 2.5$
  - $b$ -tagging at 77% efficiency
- $< 6$  jets, reject hadronic  $t\bar{t}H$
- Zero leptons, reject semi-leptonic  $t\bar{t}H$



# *b*-jet energy calibration

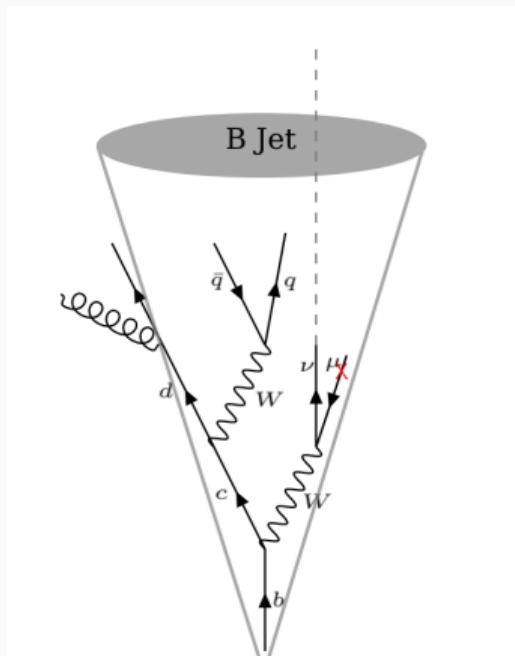
my own work



- $m_{b\bar{b}}$  highly discriminating for  $H \rightarrow b\bar{b}$
- $\sigma_{m_{b\bar{b}}} \sim 16 \text{ GeV}$ ,  $\sigma_{m_{\gamma\gamma}} \sim 2 \text{ GeV}$
- Jets energy calibration not enough for *b*-jets, due to
  - **Semi-leptonic** decay
  - **Large *b*-quark mass**
- Specific *b*-jet energy calibration method
  - **$\mu$ -in-jet correction**: presence of muon
  - **$p_T$  Reco correction**: missing neutrino & out-of-cone radiation

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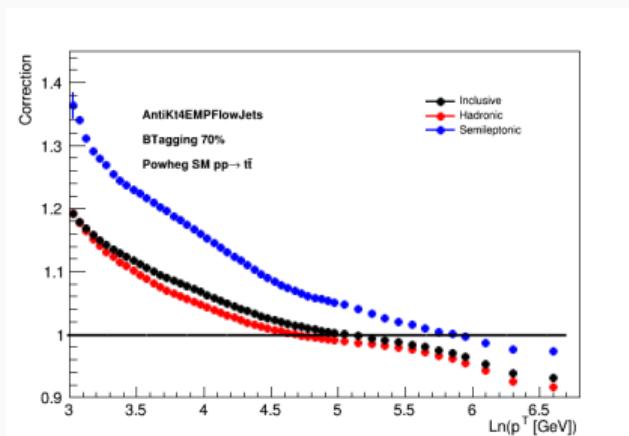
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# $b$ -jet energy calibration

- $\mu$ -in-jet correction
  - Adding back muons
  - Variable  $\Delta R(b\text{-jet}, \text{muon})$
  - Semi-leptonic or hadronic
- $p_T$  Reco correction
  - $p_T$ -dependent scale factor
  - Computed on  $t\bar{t}$  sample



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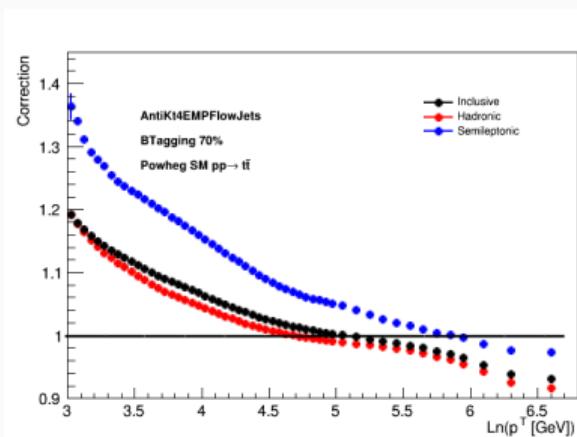
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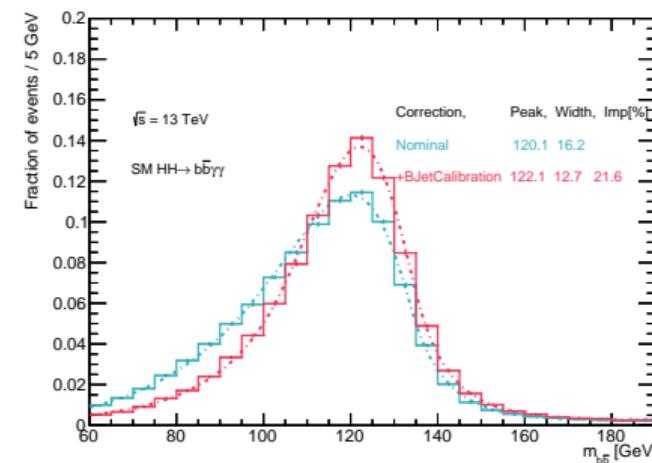
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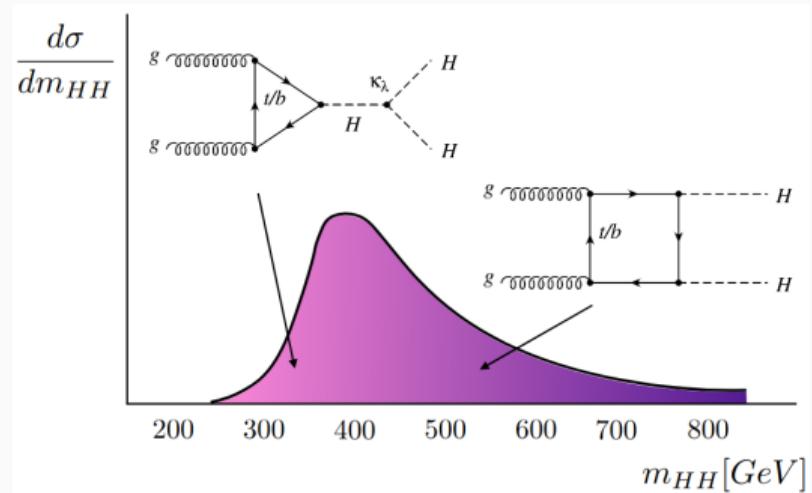
- Applied to  $\text{HH} \rightarrow b\bar{b}\gamma\gamma$   $b$ -jets



- $\sim 22\%$  imp. on  $m_{b\bar{b}}$  resolution
- $7\% \pm 2\%$  imp. on expected significance
- **Baseline  $b$ -jet correction for full Run-2 HH search**

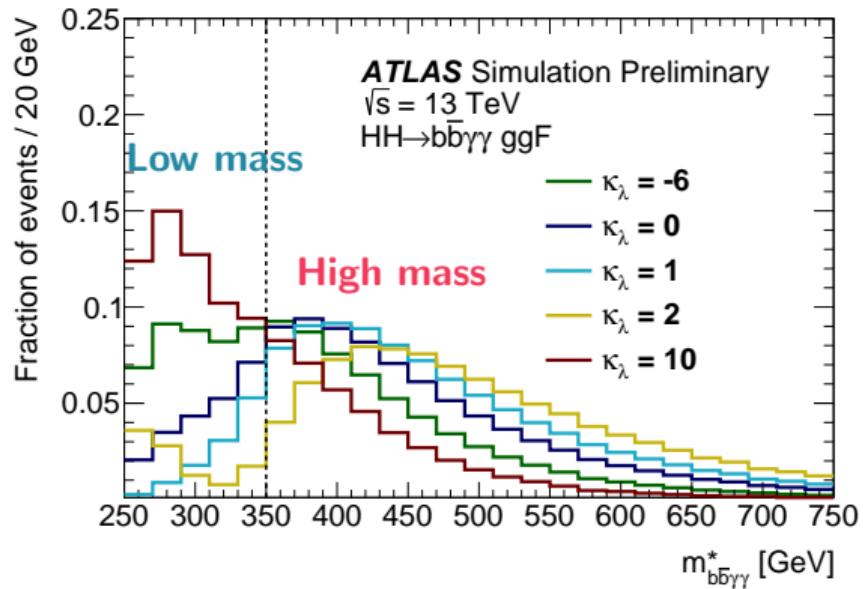
# Categorization strategy

- Sensitivity to
  - SM HH signal
  - $\kappa_\lambda$  deviations
- Two mass regions on  $m_{b\bar{b}\gamma\gamma}^*$ 
  - High mass  $m_{b\bar{b}\gamma\gamma}^* > 350 \text{ GeV}$
  - Low mass  $m_{b\bar{b}\gamma\gamma}^* < 350 \text{ GeV}$
- Signal-background separation: MVA



# Categorization strategy

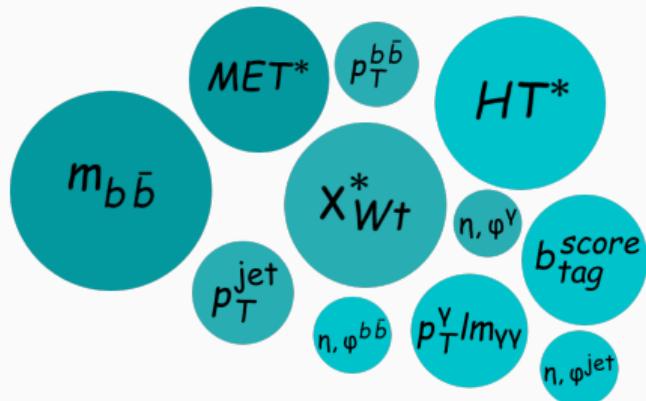
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$$m_{b\bar{b}\gamma\gamma}^* = m_{b\bar{b}\gamma\gamma} - m_{b\bar{b}} - m_{\gamma\gamma} + 250 \text{ GeV}$$

# MVA categorization

- Two MVA are trained to discriminate signal from the backgrounds
  - **High mass:** SM HH ( $\kappa_\lambda = 1$ )
  - **Low mass:** BSM HH ( $\kappa_\lambda = 10$ )
- Same inputs: objects and event kinematic
- MVA techniques
  - **Boosted Decision Trees:** signal vs ( $t\bar{t}H + ZH +$  continuum  $\gamma\gamma +$  jets)
  - **Deep Neural Network:** signal vs  $t\bar{t}H$  vs  $ZH$  vs continuum  $\gamma\gamma +$  jets



\* not used in DNN

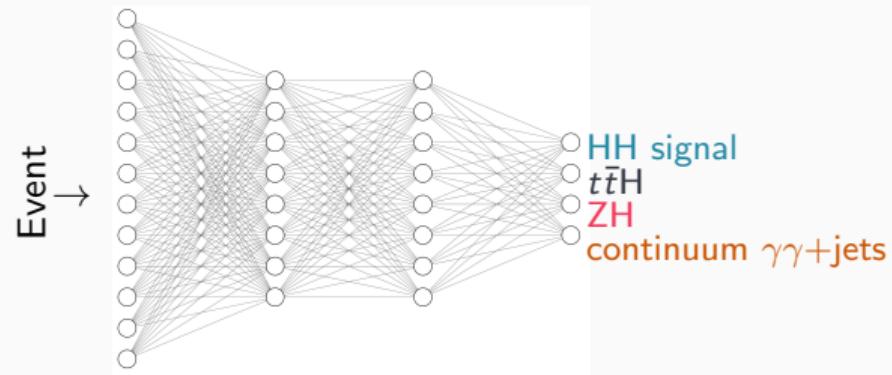
# Deep Neural Network selection

my own work

- $d_{HH}$  discriminate from 4 probabilities:

$$d_{HH} = \log\left(\frac{\sigma_{HH} \cdot p_{HH}}{\sum^3 \sigma_{bkg} \cdot p_{bkg}}\right)$$

- 4 categories maximize combined expected significance
  - tight and loose DNN for each mass region
- Similar performance to the BDT
- Baseline: BDT
- DNN reserved and documented for next analysis round



MVA	SM HH	HH $\kappa_\lambda = 10$
BDT	$0.49\sigma$	$3.59\sigma$
DNN	$0.54\sigma$	$3.47\sigma$

$$\text{significance} = \sqrt{2[(s + b) \times \log(1 + s/b) - s]}$$

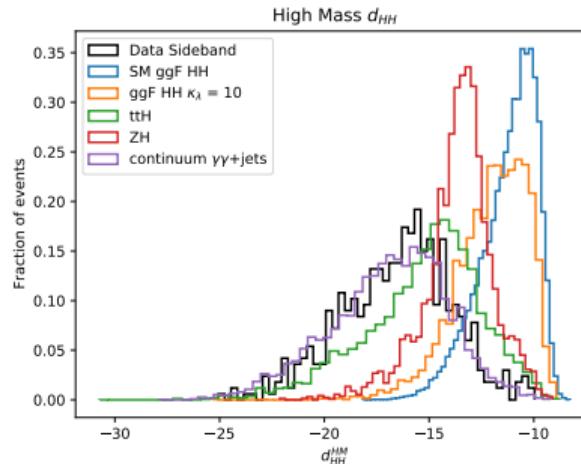
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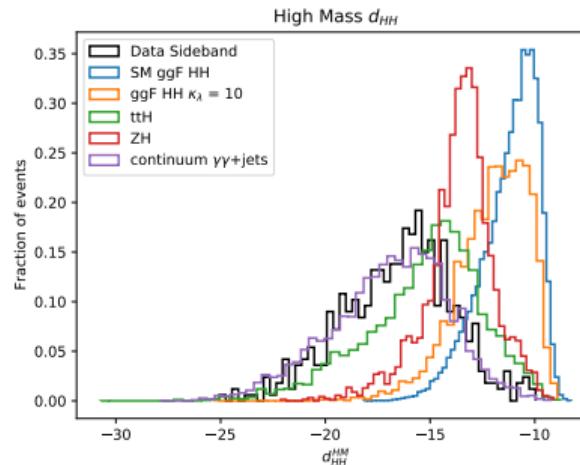
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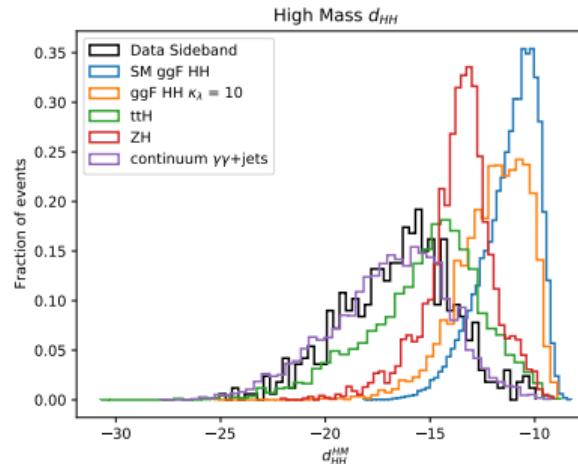
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- $d_{HH}$  discriminate from 4 probabilities:
$$d_{HH} = \log\left(\frac{\sigma_{HH} \cdot p_{HH}}{\sum^3 \sigma_{bkg} \cdot p_{bkg}}\right)$$
- **4 categories** maximize combined expected significance
  - **tight** and **loose** DNN for each mass region
- **Similar performance to the BDT**
- Baseline: **BDT**
- **DNN reserved and documented for next analysis round**

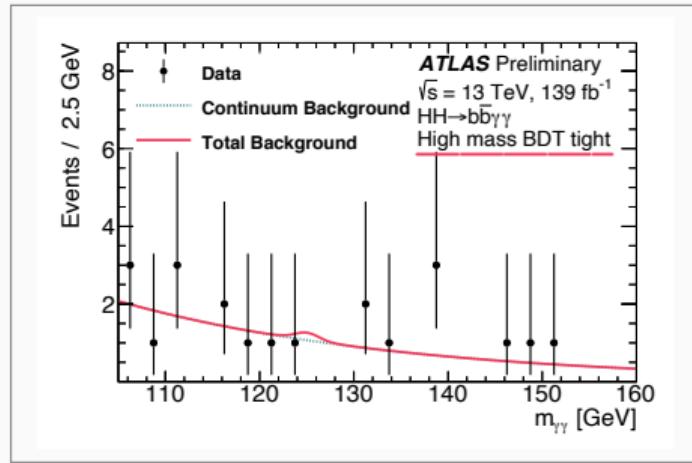


MVA	SM HH	HH $\kappa_\lambda = 10$
BDT	$0.49\sigma$	$3.59\sigma$
DNN	$0.54\sigma$	$3.47\sigma$

$$\text{significance} = \sqrt{2[(s + b) \times \log(1 + s/b) - s]}$$

# Signal extraction and results

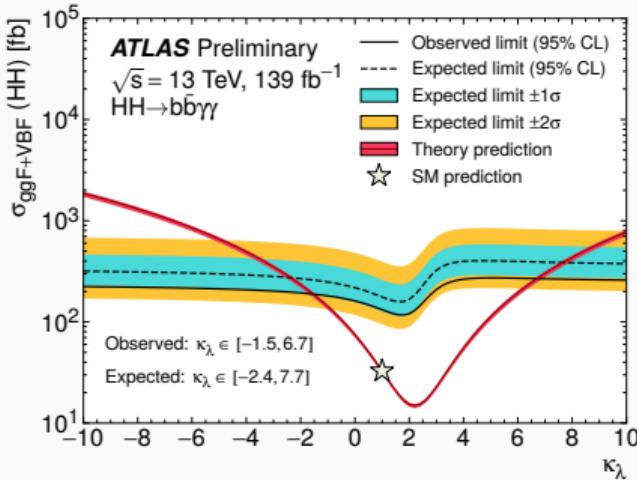
- Simultaneous fit of  $m_{\gamma\gamma}$  in the 4 analysis categories
  - HH signal (ggF + VBF) + Single Higgs
    - ▶ from Monte Carlo using Double-sided Crystal-Ball
  - Continuum  $\gamma\gamma$  + jets
    - ▶ fully data driven
- No significant signal is observed
- 95% CL upper limits on  $\sigma_{ggF+VBF}$  of diHiggs as a function of  $\kappa_\lambda$



most sensitive category

# Limits and $\kappa_\lambda$ constrain

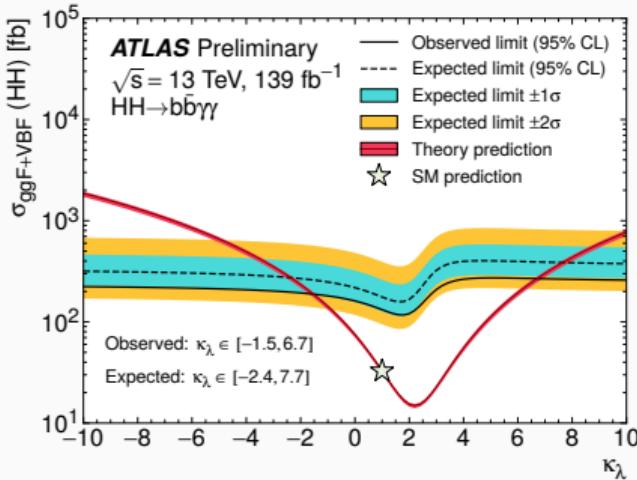
ATLAS-CONF-2021-016



- $\frac{\sigma_{HH}}{\sigma_{SM}^{SM}}$  limit: **4.1** (Exp. **5.5**) at 95% CL
- $\kappa_\lambda$  constrain: **[-1.5, 6.7]** (Exp. **[-2.4, 7.7]**)
- Statistically limited
  - Systematic effect  $\sim 4\%$
  - Background modelling & photon energy scale

# Limits and $\kappa_\lambda$ constrain

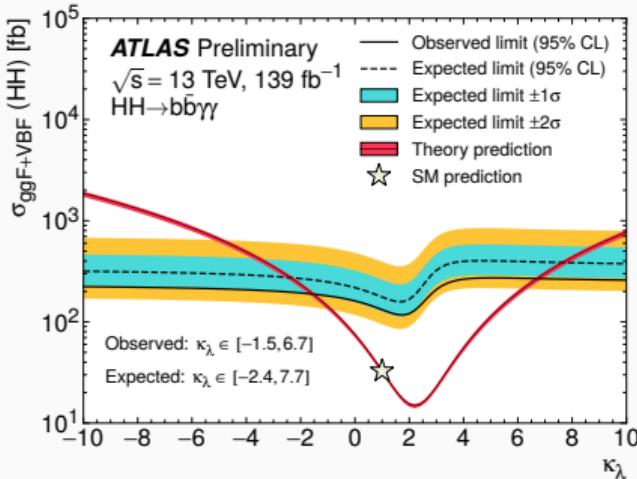
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- Statistically limited
  - Systematic effect  $\sim 4\%$
  - Background modelling & photon energy scale
- **The world's best  $\kappa_\lambda$  limit**
- **5 $\times$  improvement** w.r.t  $36 \text{ fb}^{-1}$ 
  - Increased luminosity: 2 $\times$
  - **Analysis improvement:** almost 3 $\times$ 
    - ▶  $m_{HH}$  categorization and MVA strategy (80%)
    - ▶  $b$ -jet energy calibration (7%)
    - ▶ ...

# Limits and $\kappa_\lambda$ constrain

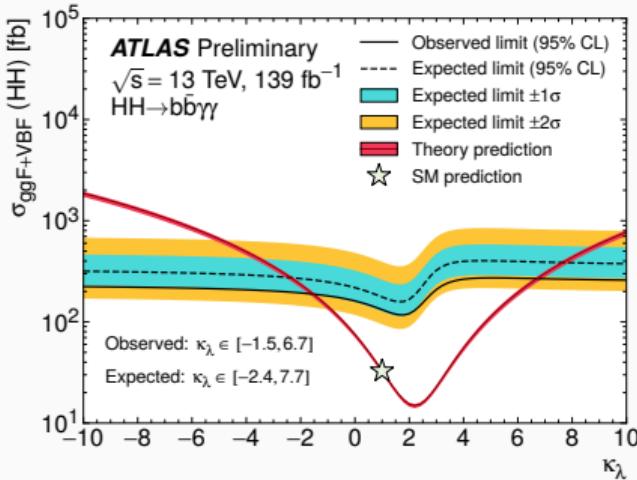
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    - ▶ ...

# Limits and $\kappa_\lambda$ constrain

ATLAS-CONF-2021-016



- $\frac{\sigma_{HH}}{\sigma_{SM}^{SM}}$  limit: **4.1** (Exp. **5.5**) at 95% CL
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# CMS $HH \rightarrow b\bar{b}\gamma\gamma$ results

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- Different analysis strategies

- 14 categories
  - ▶ MVAs output and  $m_{b\bar{b}\gamma\gamma}^*$
  - ▶ 2 dedicated VBF categories
- 2D fit  $m_{\gamma\gamma} \times m_{b\bar{b}}$

	Expected	Observed
CMS $\frac{\sigma_{HH}}{\sigma_{SM}} \text{ limit}$	<b>5.2</b>	7.7
CMS $\kappa_\lambda$ interval	<b>[-2.5, 8.2]</b>	[-3.3, 8.5]
ATLAS $\frac{\sigma_{HH}}{\sigma_{SM}} \text{ limit}$	<b>5.5</b>	4.1
ATLAS $\kappa_\lambda$ interval	<b>[-2.4, 7.7]</b>	[-1.5, 6.7]

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## Interpretation using Effective Field Theory (work in progress)

- Di-Higgs and Effective Field Theory
- EFT coefficients constraints

## Prospects at Run-3 and HL-LHC

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# Effective Field Theory (EFT)

- Search for new physics at large energy scale ( $\Lambda$ ) in a **model independent** way
- At large scale ( $\Lambda \gg v$ ), BSM decouples from SM

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}^5 + \mathcal{L}^6 + \mathcal{L}^7 + \dots, \quad \mathcal{L}^d = \sum_{i=1}^{n_d} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d \quad \text{for } d > 4$$

- **Cross-section** (and **decay width**) can be split

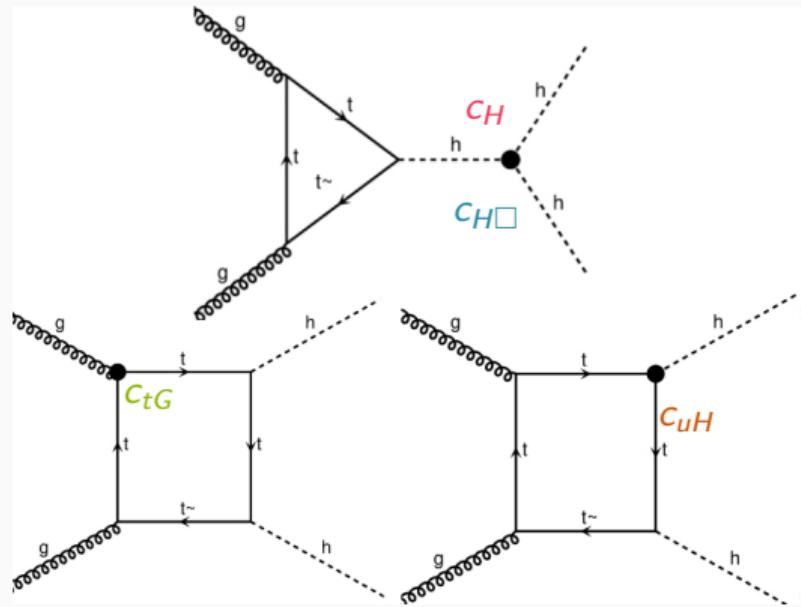
$$\sigma = \sigma_{SM} + \sigma_{int} + \sigma_{BSM}$$

$$\frac{\sigma}{\sigma_{SM}} = 1 + \sum_i a_i \cdot c_i + \sum_{i,j} b_{ij} \cdot c_i \cdot c_j$$

- **Standard Model Effective Field Theory (SMEFT)** in **Warsaw** basis with **d = 6** and  $\Lambda = 1 \text{ TeV}$

# Di-Higgs and EFT

- 5 operators are relevant for di-Higgs
  - $c_H$  and  $c_{H\square}$  modify the Higgs self-coupling  $\kappa_\lambda$
  - $c_{uH}$  and  $c_{tG}$  modify the top quark interaction to the Higgs and gluons.
  - $c_{HG}$ , modify the Higgs coupling to gluons (**not considered**).



# Di-Higgs and EFT

- 5 operators are relevant for di-Higgs

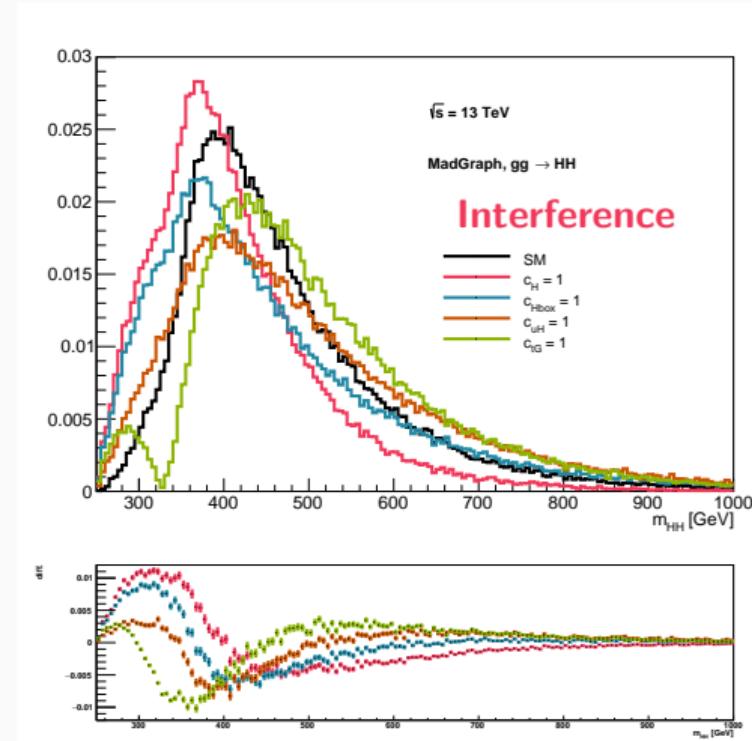
- $c_H$  and  $c_{H\square}$  modify the Higgs self-coupling  $\kappa_\lambda$

$$\kappa_\lambda = 1 - 2 \frac{v^4}{m_H^2} \cdot c_H + 3 \left( c_{H\square} - \frac{c_{HD}}{4} \right)$$

- $c_{uH}$  and  $c_{tG}$  modify the top quark interaction to the Higgs and gluons.

$$\kappa_t = 1 + \left( c_{H\square} - \frac{c_{HD}}{4} \right) - \frac{v^3}{\sqrt{2} m_t} \cdot c_{uH}$$

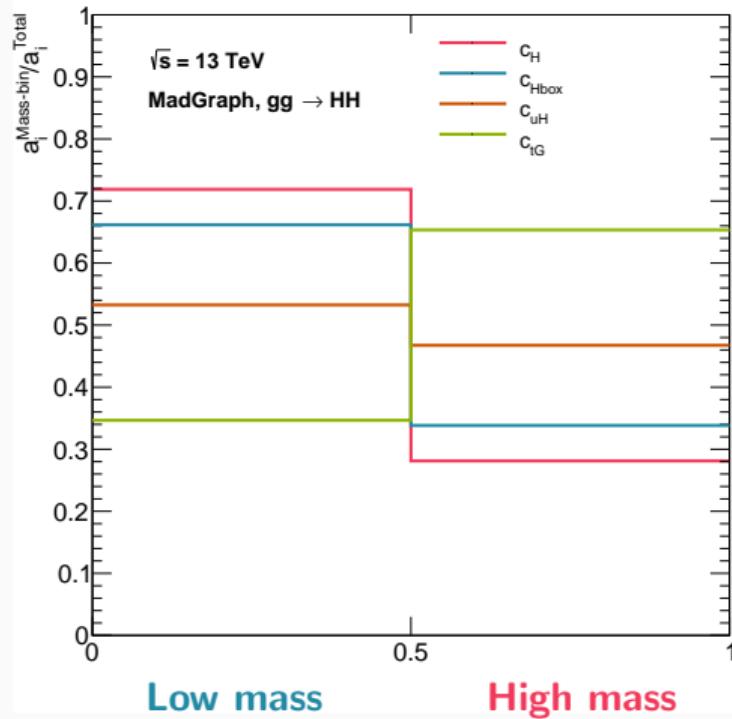
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# Cross-section parameterization in $\text{HH} \rightarrow b\bar{b}\gamma\gamma$

my own work

- $b\bar{b}\gamma\gamma$  measurements in two phase space regions
  - **High mass** ( $m_{\text{HH}} > 350$  GeV)
  - **Low mass** ( $m_{\text{HH}} < 350$  GeV)
- ggF HH cross-section parameterized as function of the Wilson coefficients



# Results

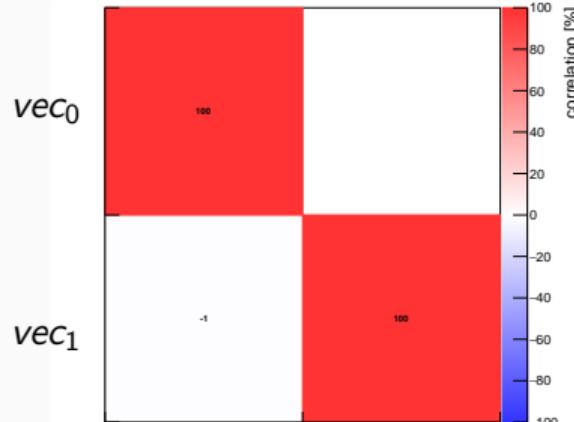
- Not sensitive to all coefficients (**two mass regions**)
  - Need **sensitivity estimate** to find relevant ones
    - Look at the eigenvectors of the inverse covariance matrix of Wilson coefficients

	Eigenvalue	Eigenvector
$\text{vec}_0$	0.0523	$-0.582 \cdot c_H + 0.363 \cdot c_{H\square} - 0.456 \cdot c_{uH} + 0.567 \cdot c_{tG}$
$\text{vec}_1$	0.0001	$-0.696 \cdot c_H + 0.182 \cdot c_{H\square} + 0.206 \cdot c_{uH} - 0.663 \cdot c_{tG}$
$\text{vec}_3$	-0.0000	$-1.025 \cdot c_H - 1.947 \cdot c_{H\square} + 0.702 \cdot c_{uH} + 0.759 \cdot c_{tG}$
$\text{vec}_4$	-0.0000	$-0.235 \cdot c_H - 0.006 \cdot c_{H\square} + 0.977 \cdot c_{uH} + 0.549 \cdot c_{tG}$

- Measurement of most sensitive eigenvectors

	expected error
$\text{vec}_0$	+3.9
$\text{vec}_1$	5.1 +80.8 -102.1

- Additional measurement regions, combination with other measurements (Higgs, Top) needed
- Work in progress**



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# Prospects at the end of Run-3

- **Run-2+Run-3:**  $\mathcal{L}_{int} \sim 300 \text{ fb}^{-1}$ ,  $\sqrt{s} = 13.6 \text{ TeV}$ 
  - Detector upgrades: **no significant impact on**  
 $\text{HH} \rightarrow b\bar{b}\gamma\gamma$
- $\frac{\sigma_{HH}}{\sigma_{SM}^{SM}}$  limit: **3.3 (1.6 $\times$  imp. w.r.t 139 fb $^{-1}$ )**

Scenario	$1\sigma$ CI	$2\sigma$ CI
Run-2	[ <b>-1.3, 6.4</b> ]	[ <b>-2.9, 8</b> ]
Run-2+Run-3	<b>[-0.7, 5.6]</b>	<b>[-1.9, 7]</b>

Potential improvements:

- DNN categorization:  **$\sim 10\%$**
- $m_{b\bar{b}}$  imp. with kinematic fit: **2-5%**
- Photon identification: **7%** (next part)

# Prospects at the end of Run-3

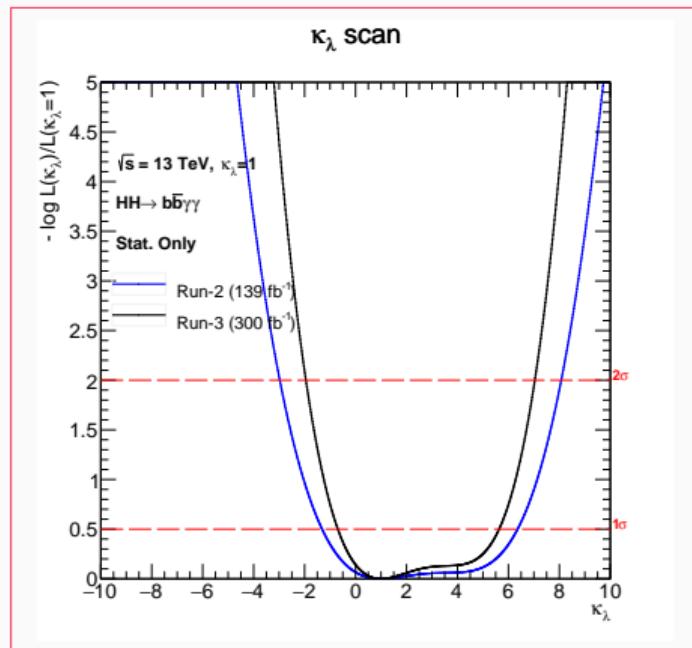
my own work

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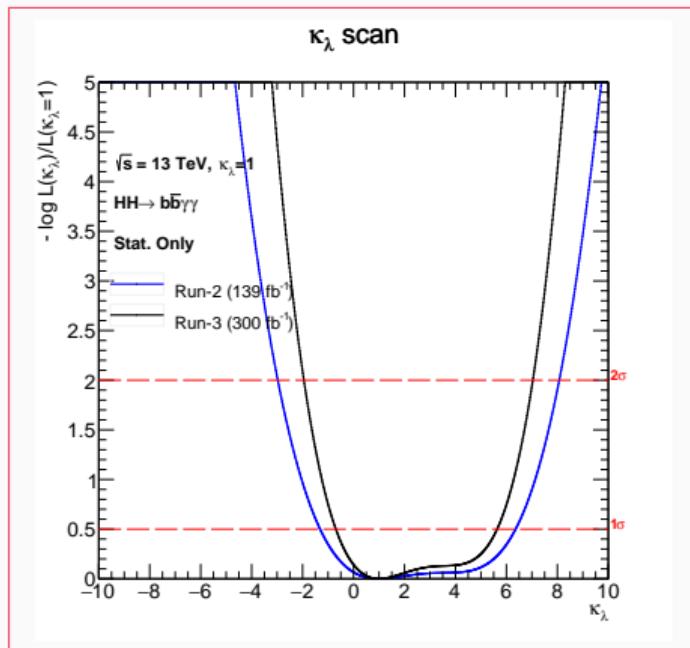
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Potential improvements:

- **DNN categorization:** ~10%
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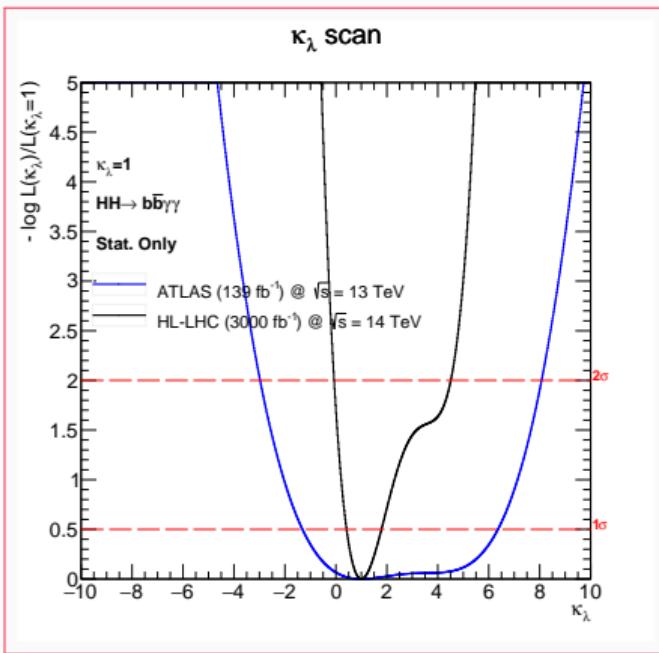


- **HL-LHC:  $\sim 3000 \text{ fb}^{-1}$  at 14 TeV**
  - Detector upgrades: mitigate higher pileup effects
  - European strategy: extrapolation from  $36 \text{ fb}^{-1}$

Scenario	$1\sigma$ CI	$2\sigma$ CI
European strategy	$[-0.1, 2.4]$	$[-1.1, 8.1]$
My Extra. to HL-LHC	$[0.4, 1.8]$	$[-0.1, 4.4]$

# Prospects at HL-LHC

my own work

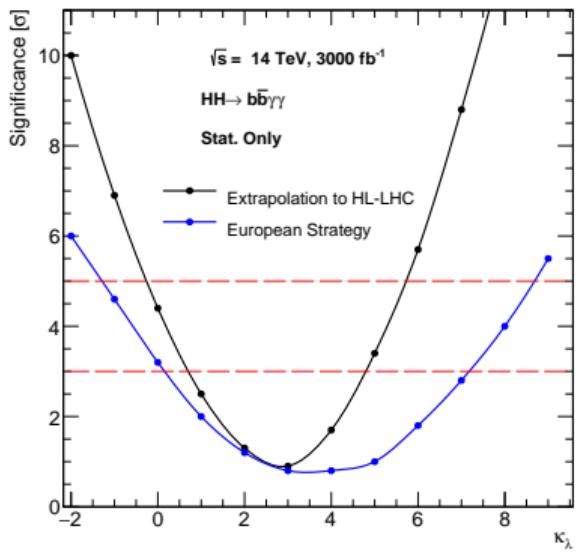


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# Prospects at HL-LHC

my own work



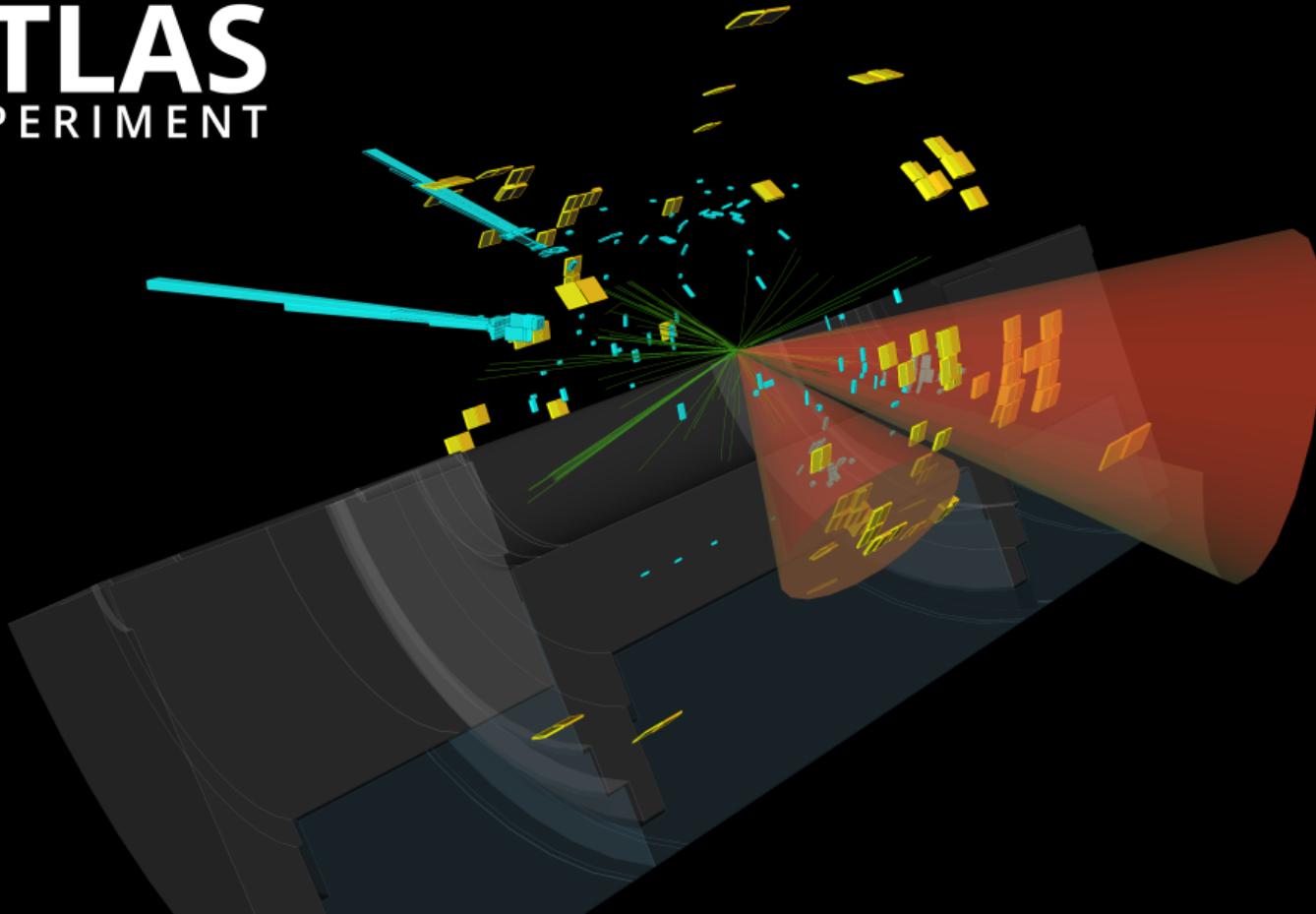
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Scenario	Significance [ $\sigma$ ]
European strategy	2.1
My Extra. to HL-LHC	2.5

Similar performances for SM  
Large gain at high  $\kappa_\lambda$



**ATLAS**  
EXPERIMENT



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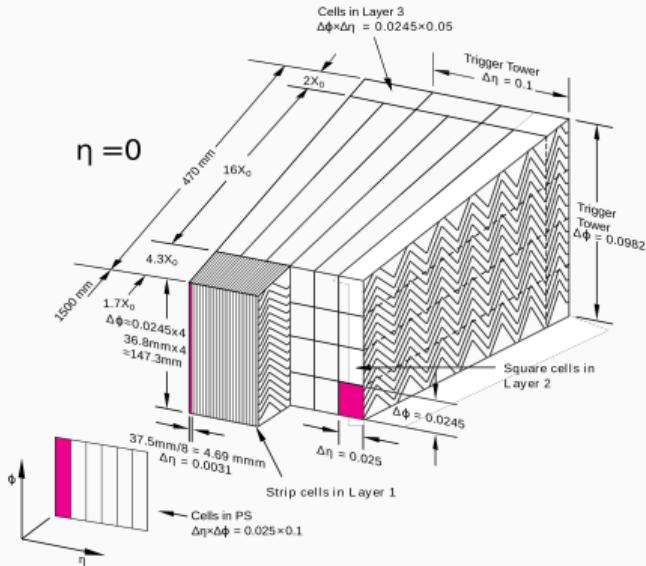
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# EM calorimeter and $\gamma$ object

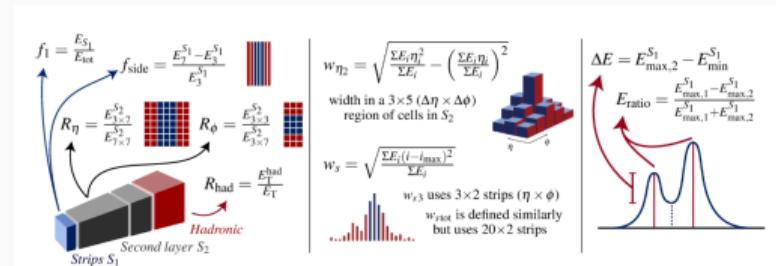
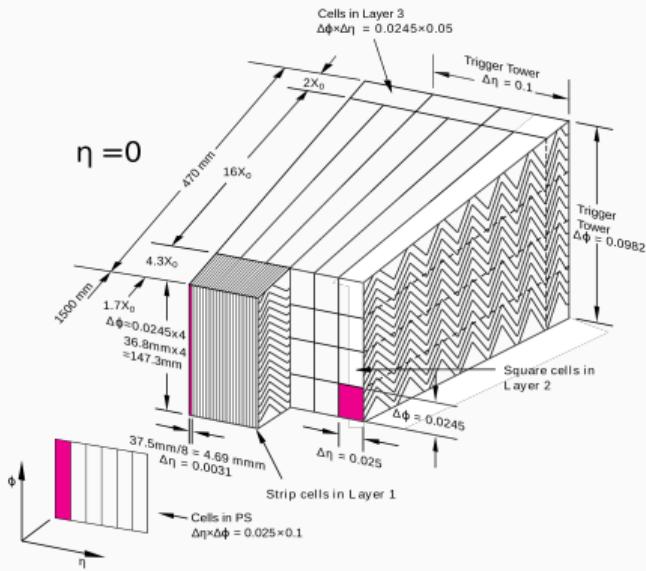
- 3 layers with different **cell size** (+ Presampler)
- $N_\eta \times N_\phi$  **cluster** contains most  $\gamma$  energy
- **Shower shapes** (SS) quantities ( $\sim 11$ ) evaluated from  $7 \times 11$  cluster
  - Lateral & longitudinal EM shower
  - Discriminate between **prompt photons** and background photons (QCD jets)



- Current identification relies on SS: **cut-based algorithm**
- **Propose improvement using Neural Network**

# EM calorimeter and $\gamma$ object

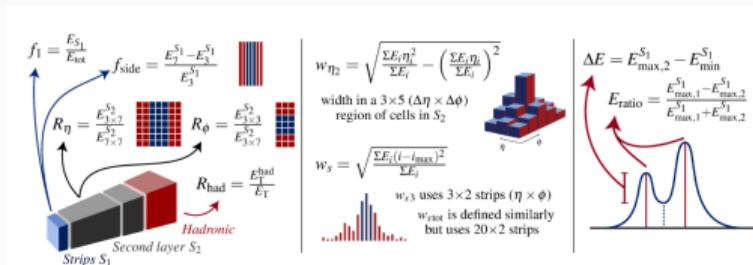
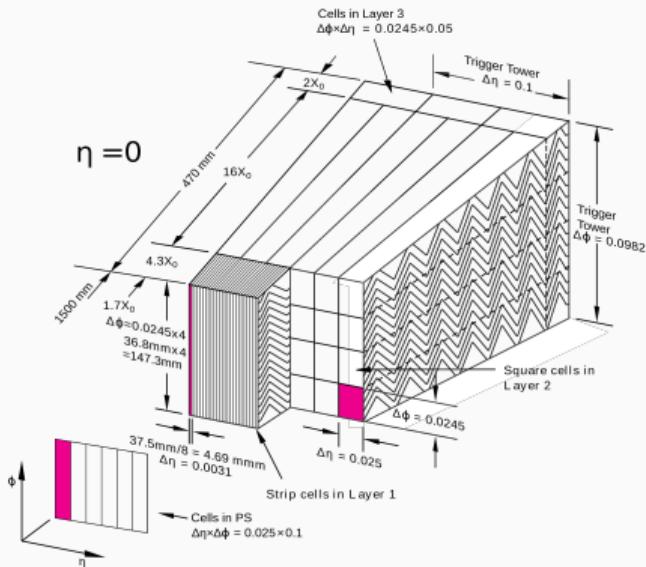
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# Photon identification with Neural Network

- Global shower shapes (High level)

**Cut-based → DNN**

- Limited performance (small features space)

- Solution: breakdown to cell level (Low level)

- Scale up features space dimensionality
    - ▶ Generate more variables
    - ▶ Correlation between cells

- Convolutional Neural Network (CNN)

- Photon cluster represented as an image

- Photon identification (ID) using images from the 3 layers

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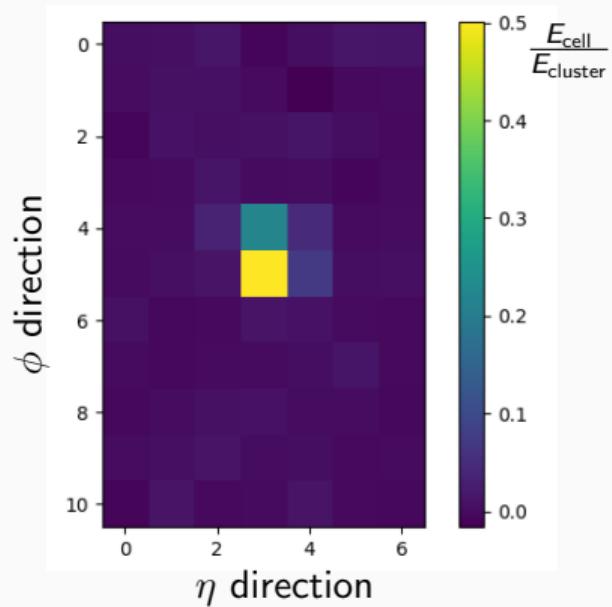
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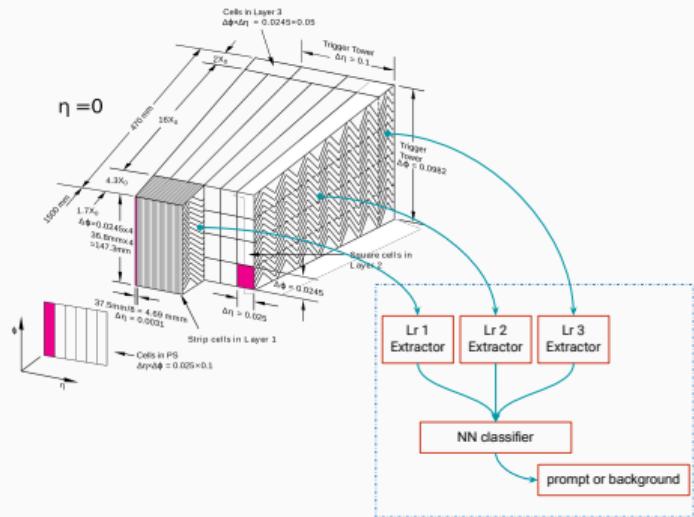
7×11 cluster from 2<sup>nd</sup> layer



# Convolutional Neural Network strategy and training

my own work

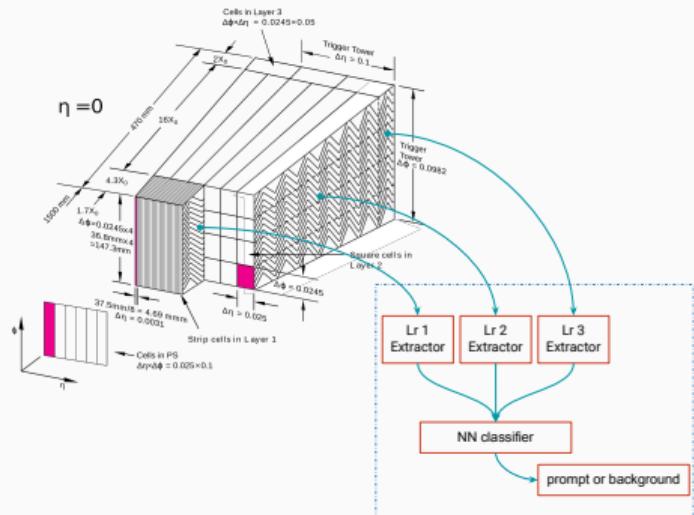
- **Prompt photons:** inclusive  $\gamma + \text{jets}$  events
- **Background photons:** QCD di-jet events
- Images from  $7 \times 11$  windows
  - Energy independent algorithm
  - Image pixel = cell energy fraction
- Inclusive training ( $E_T, |\eta| < 2.4$ , conversion type)
- Trained on Monte Carlo
- CNN **over-performs** the cut-based algorithm



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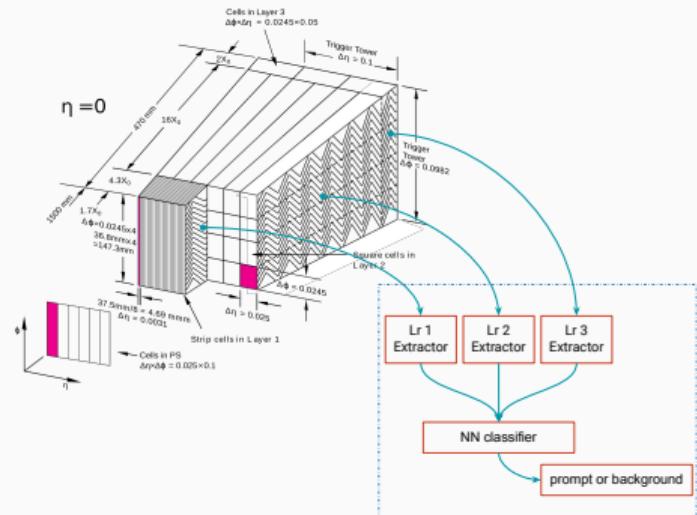
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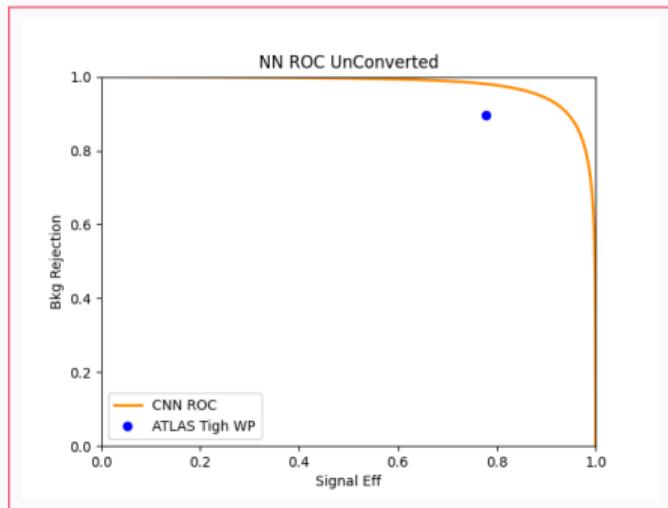
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# Photon identification efficiency

- Identification efficiency with **Radiative Z method**
  - $Z \rightarrow l\gamma$  ( $l=e,\mu$ ), **as a signal**
  - $Z \rightarrow l + \text{jet}$  ( $l=e,\mu$ ), **as a background**
  - **2017 data** ( $43.6 \text{ fb}^{-1}$ )
- Efficiency as

$$\epsilon_{ID} = \frac{N^{\text{after ID}} \times P^{\text{after ID}}}{N^{\text{before ID}} \times P^{\text{before ID}}}$$

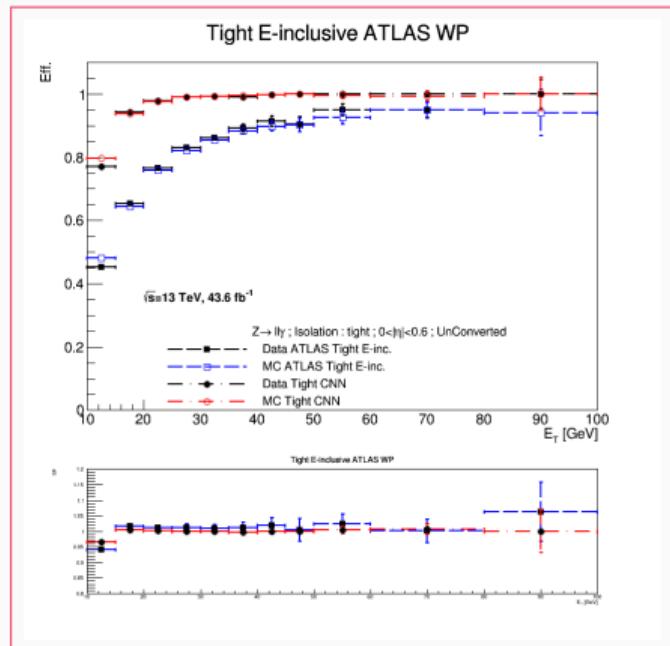
- Purity estimated with **template fit of  $m_{l\gamma}$**
- **Over-performs** the cut-based algorithm
  - Out-of-sample validation: **different event topology**
  - **Good data-MC agreement**

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- Efficiency as

$$\epsilon_{ID} = \frac{N^{\text{after ID}} \times P^{\text{after ID}}}{N^{\text{before ID}} \times P^{\text{before ID}}}$$

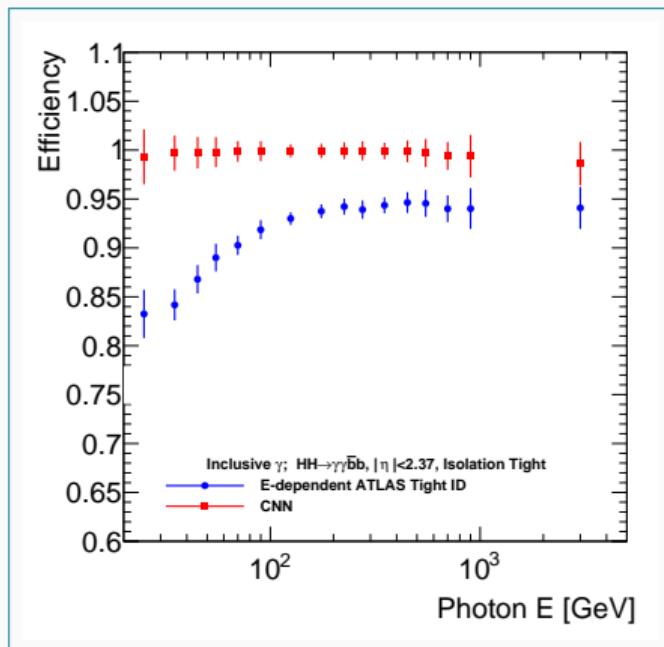
- Purity estimated with **template fit of  $m_{l\bar{l}\gamma}$**
- Over-performs** the cut-based algorithm
  - Out-of-sample validation: **different event topology**
  - Good data-MC agreement**

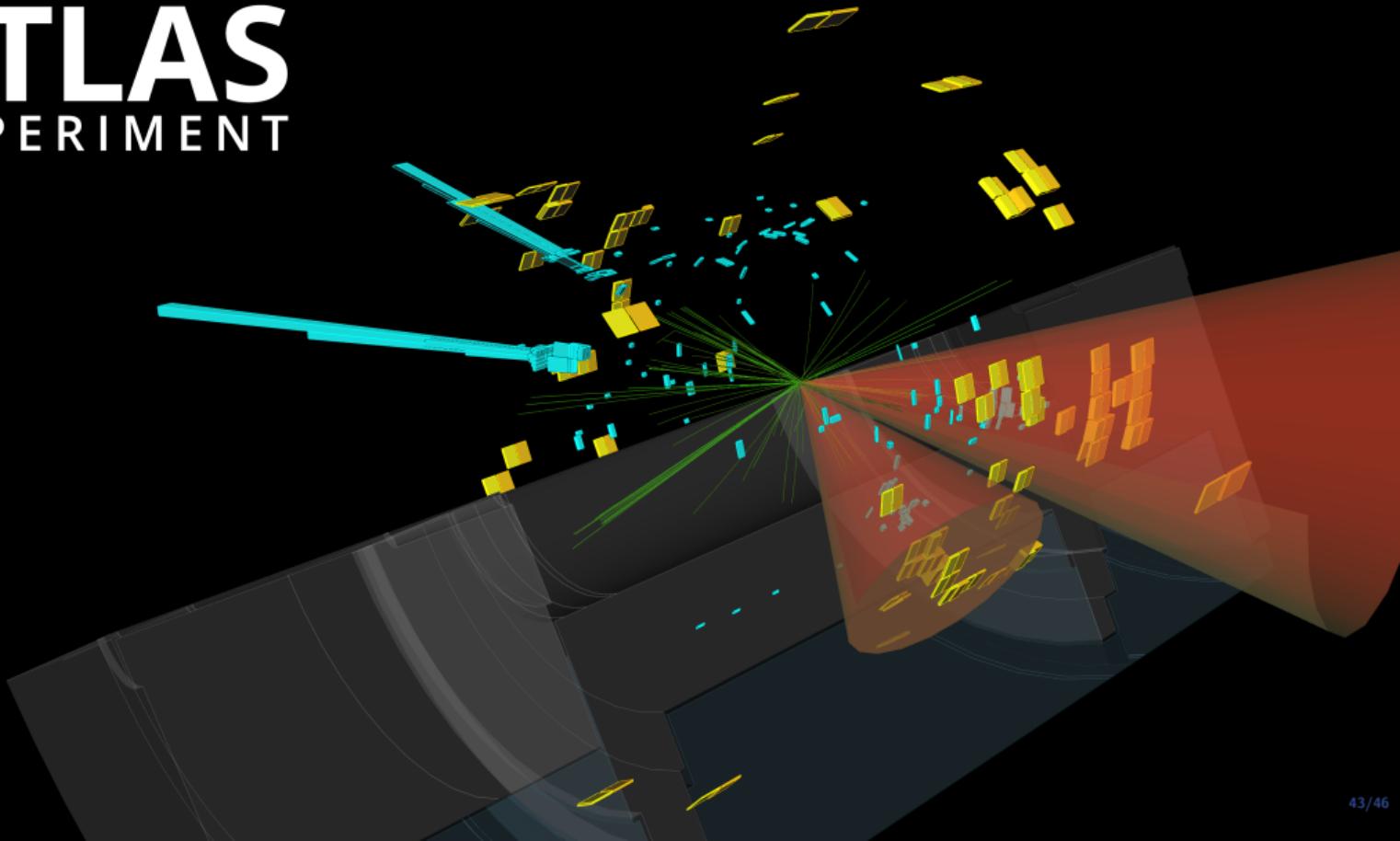


# Impact on $\text{HH} \rightarrow b\bar{b}\gamma\gamma$ analysis

my own work

- CNN applied to photons from  $\text{HH} \rightarrow b\bar{b}\gamma\gamma$  signal
  - Efficiency close to 100%
  - 15% improvement in signal acceptance
- CNN applied to photons from continuum  $\gamma\gamma + \text{jets}$ 
  - high  $\gamma\gamma$  purity
  - 15% increase in statistics
  - Reduce background modelling systematics
- $\sim 7.3\%$  improvement in analysis significance





# Conclusion

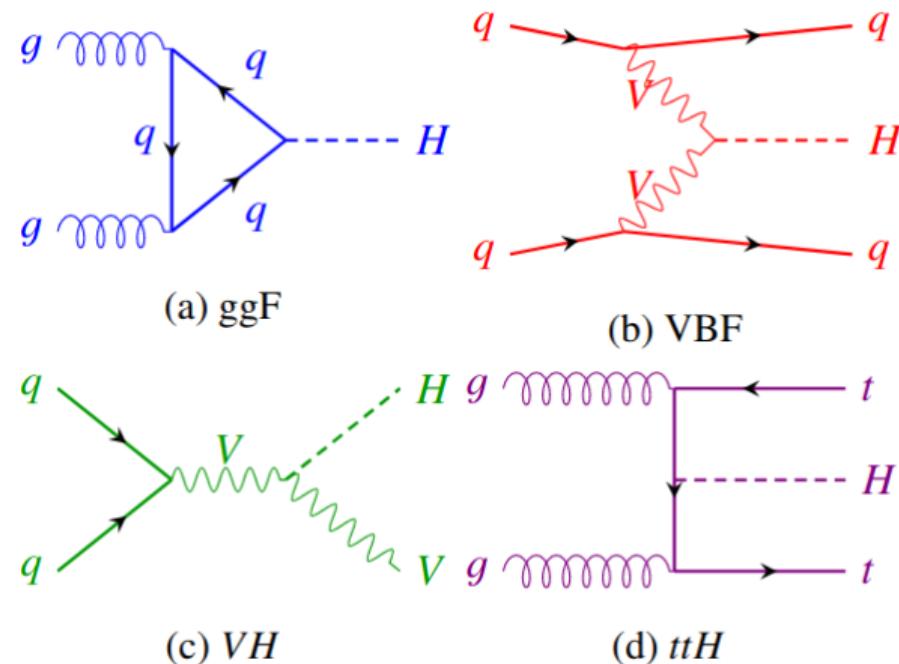
- **Search for non-resonant HH production and measurement of Higgs self-coupling**
  - $\text{HH} \rightarrow b\bar{b}\gamma\gamma$  **golden channel** → **The world's best  $\kappa_\lambda$  limit**
  - **Re-interpretation** within EFT context
  - **Extrapolation** to Run-3 and to HL-LHC
- **New Photon identification using Convolutional Neural Network**
  - **Significance improvement** in different events topologies
  - **Relevant** for  $\text{HH} \rightarrow b\bar{b}\gamma\gamma$  in future
- **Work not presented**
  - **Kinematic Fit** for  $\text{HH} \rightarrow b\bar{b}\gamma\gamma$
  - **Shower shape mis-modelling** correction
- **Parallel work**
  - **96 hours of lab work** at the Savoie Mont Blanc University

# **Thank you for your attention**

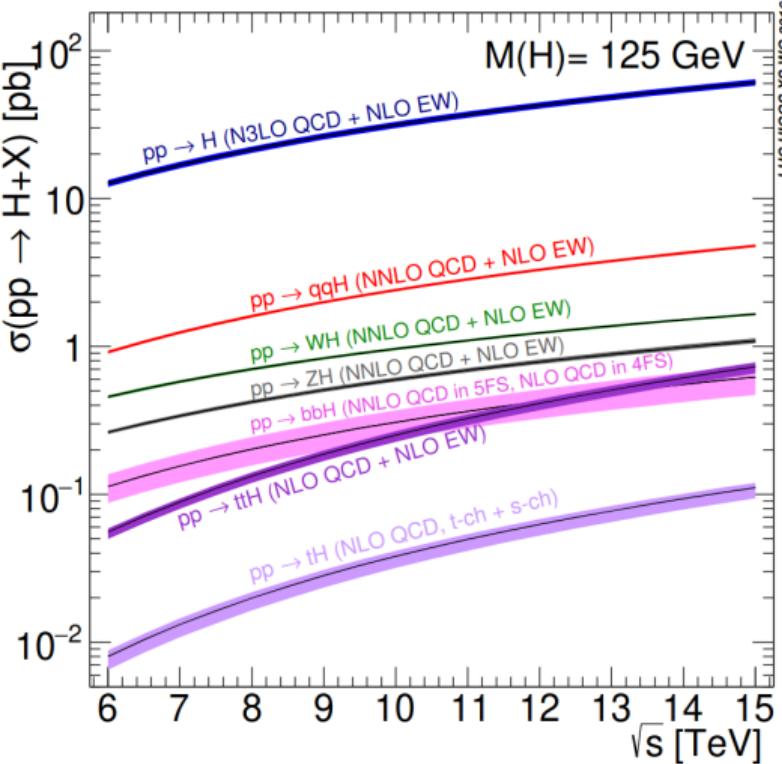
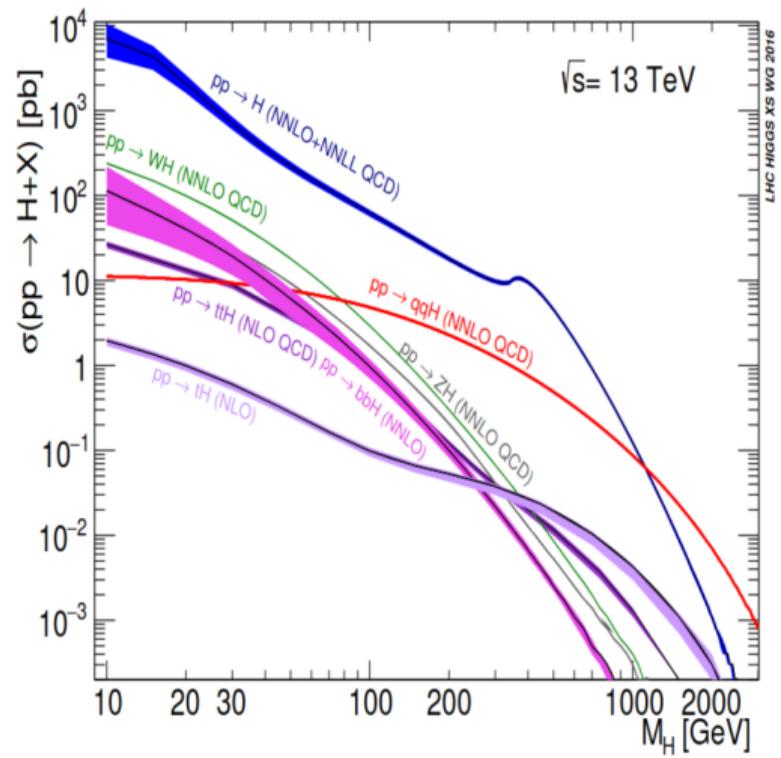
**Big thanks to all the people with whom I had the chance to  
work during my PhD**

# **BACKUP**

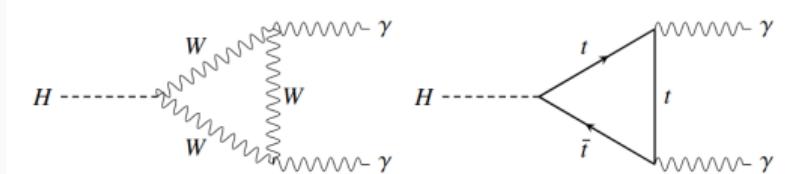
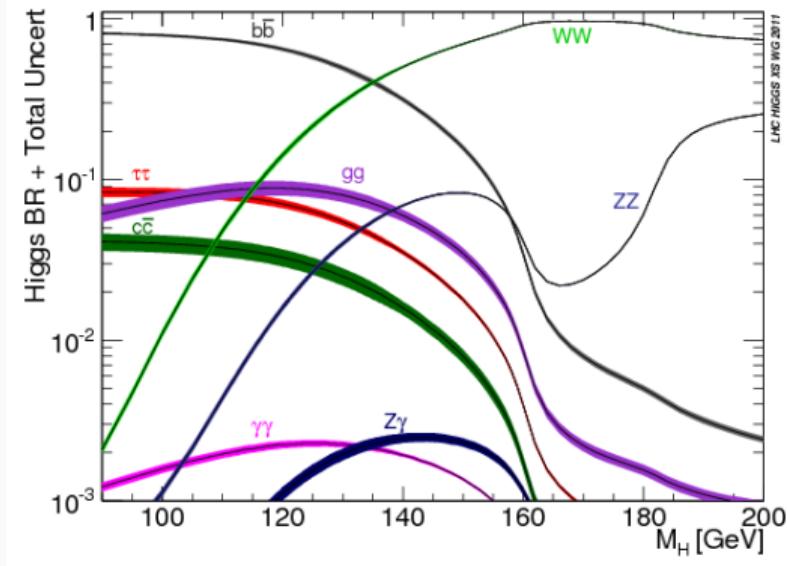
# Higgs production modes



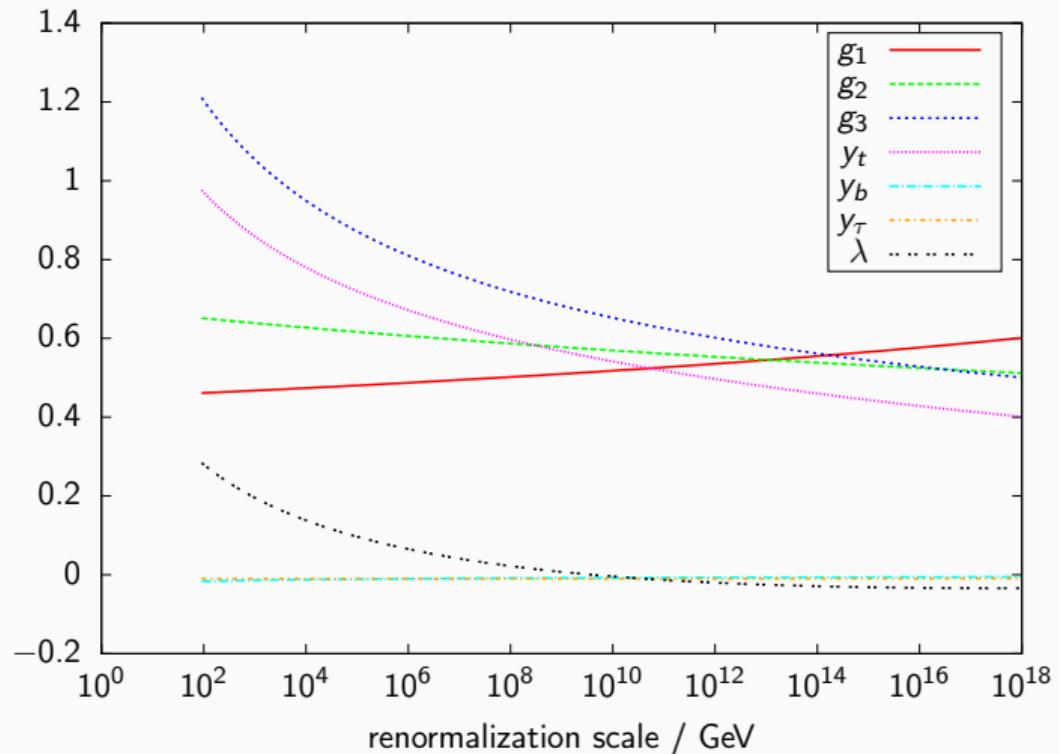
# Higgs cross-section



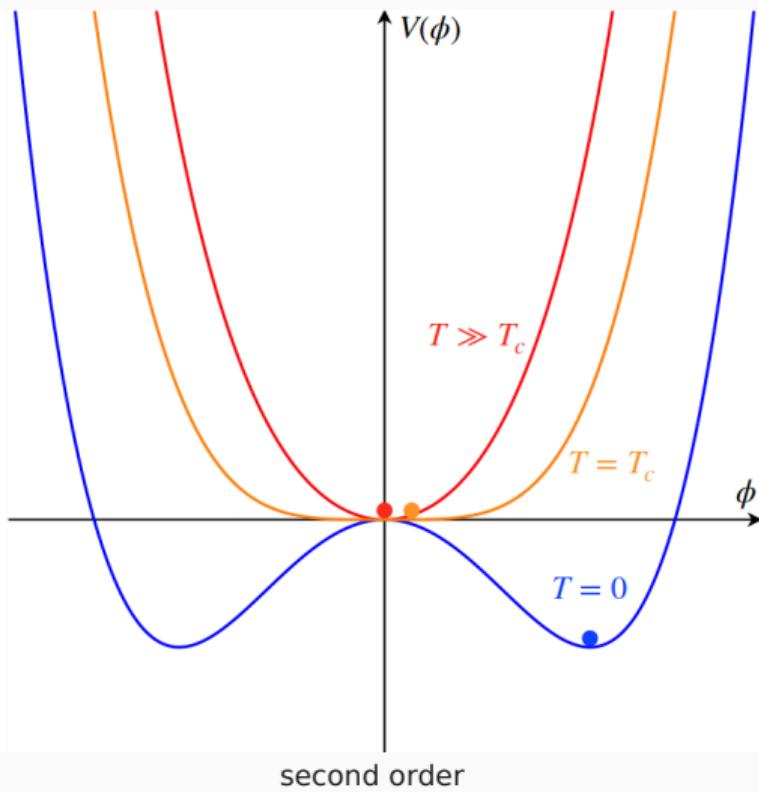
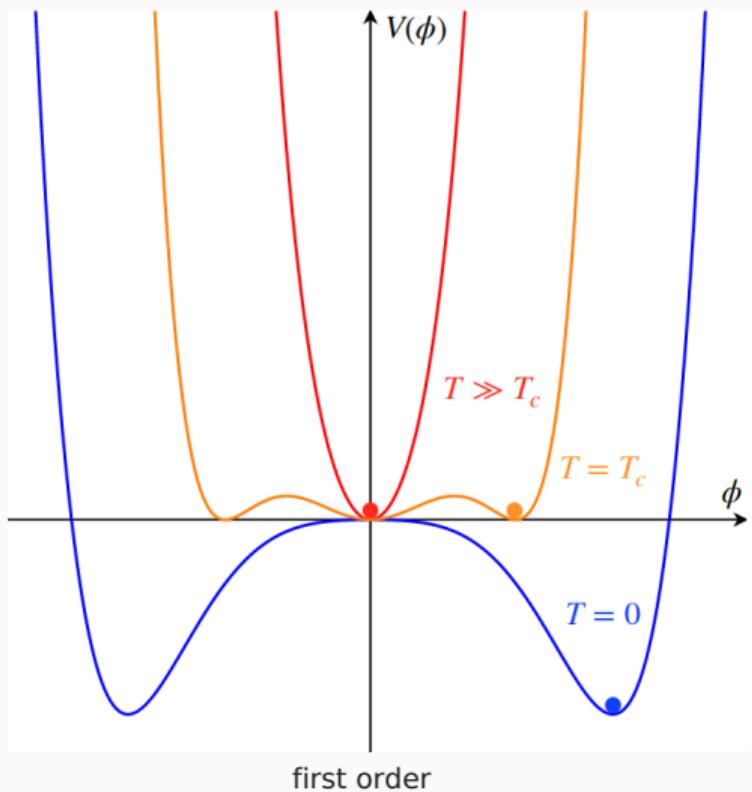
# Higgs decay modes



# Higgs self-coupling



# Di-Higgs pheomonology



# Di-Higgs cross-section

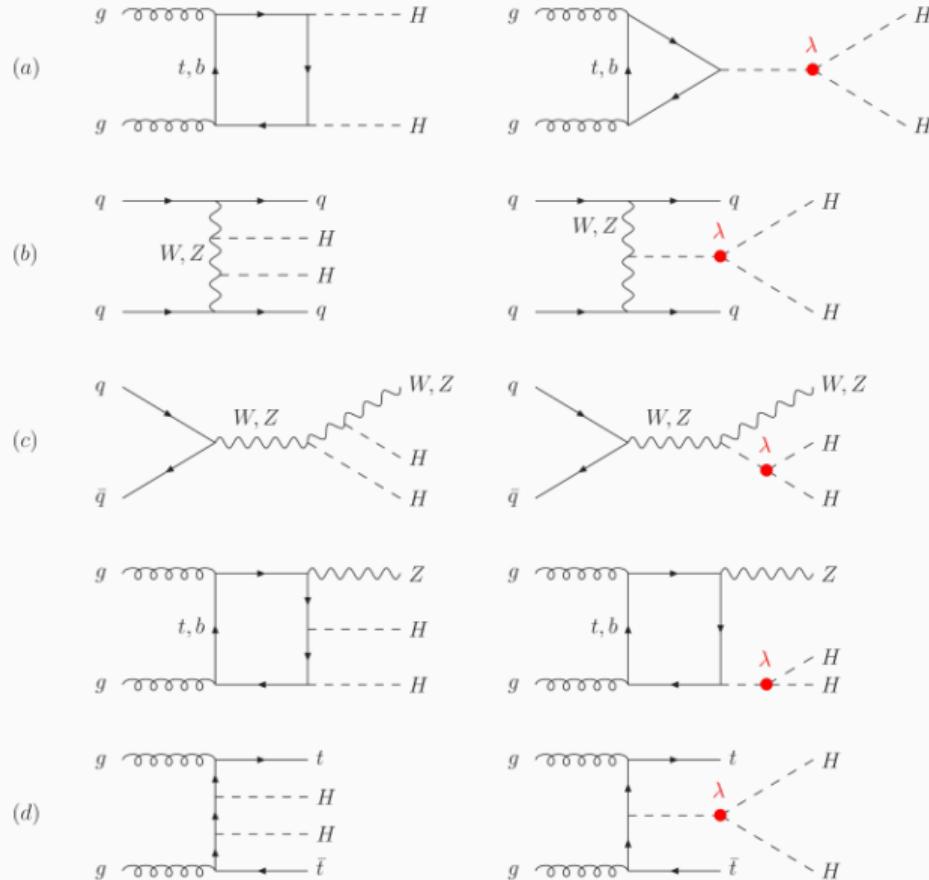
$$A(\lambda_t, \lambda_{HHH}) \equiv \lambda_t^2 \cdot \square + \lambda_t \cdot \lambda_{HHH} \triangle$$

$$\sigma \approx k_t^4 \left[ |\square|^2 + \frac{k_\lambda}{k_t} (\square \triangle + \triangle \square) + \left( \frac{k_\lambda}{k_t} \right)^2 |\triangle|^2 \right]$$

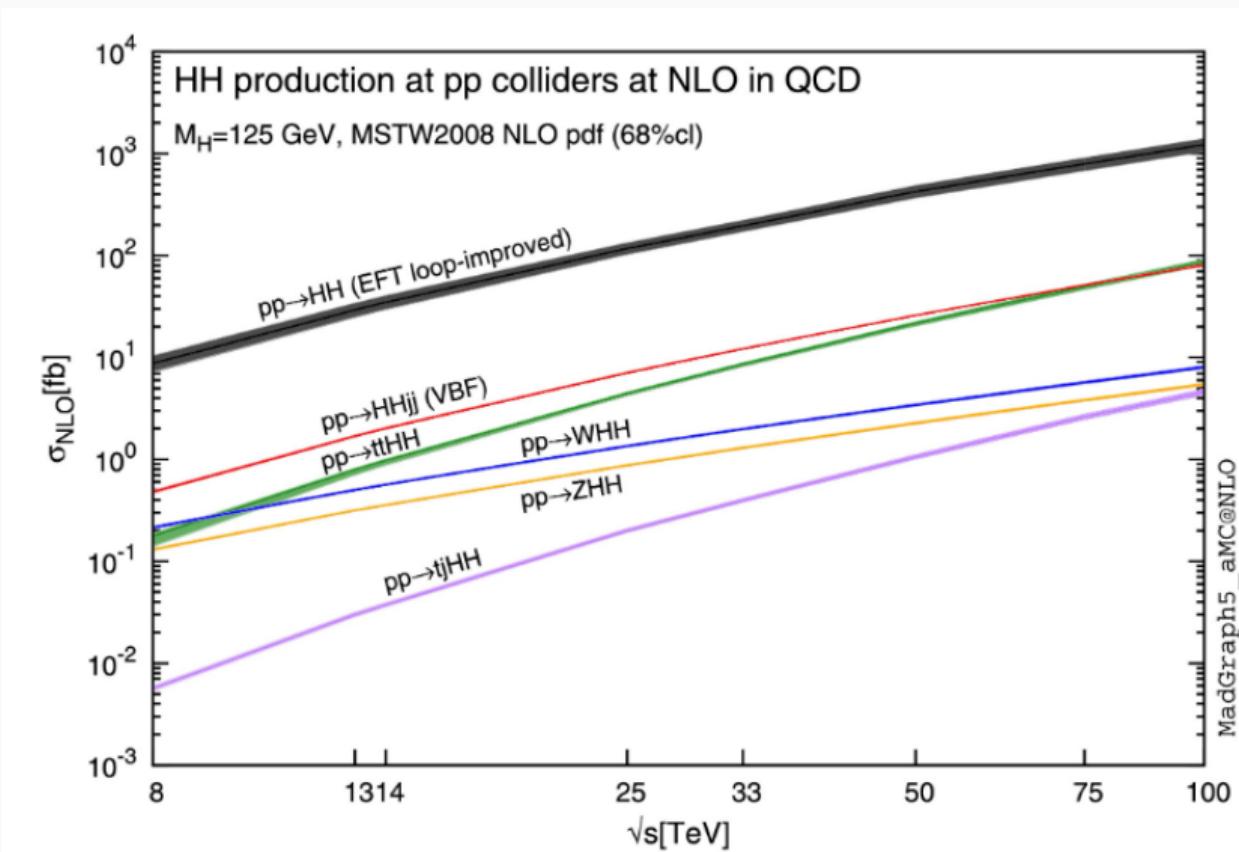
- minimum cross-section at  $\kappa_\lambda = 2.4\kappa_t$
- minimum  $m_{HH}$  at  $m_{HH} = 2m_t$  for  $\kappa_\lambda = 2$
- $\sigma_{\text{ggF HH}}^{\text{NNLO}} = 31.05^{+2.2\%}_{-5.0\%} \text{ fb}$
- $\sigma_{\text{VBF HH}}^{\text{NNLO}} = 1.723^{+0.03\%}_{-0.04\%} \text{ fb}$

per $t$	1 H per 1s	3 HH per 1h	1 HH( $bb\gamma\gamma$ ) per 5d
per $pp$	$2.5 \cdot 10^{-9} \text{ H}$	$2 \cdot 10^{-11} \text{ HH}$	$6.25 \cdot 10^{-16} \text{ 2H}$

# Di-Higgs production modes

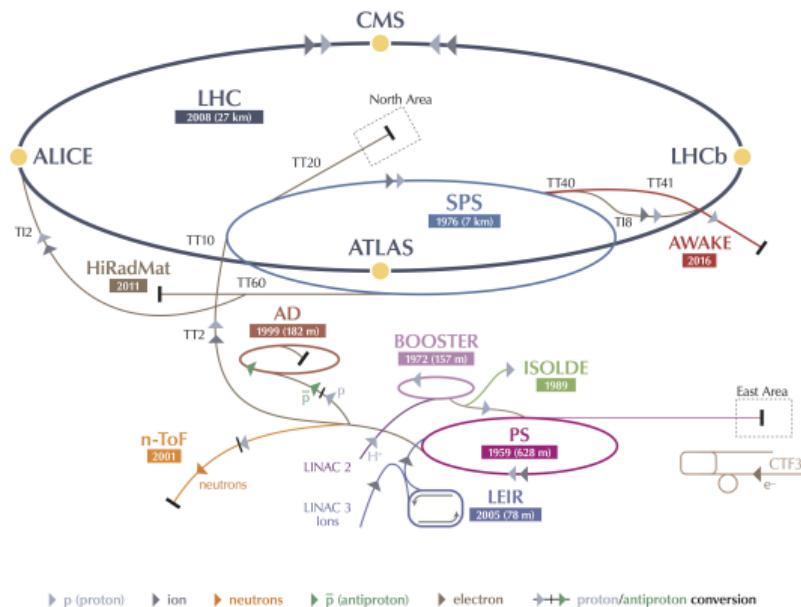


# Di-Higgs cross-section as function of $\sqrt{s}$



# LHC accelerator chain

## CERN's Accelerator Complex



LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility AWAKE Advanced WAKEfield Experiment ISOLDE Isotope Separator OnLine DEvice

LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight HiRadMat High-Radiation to Materials

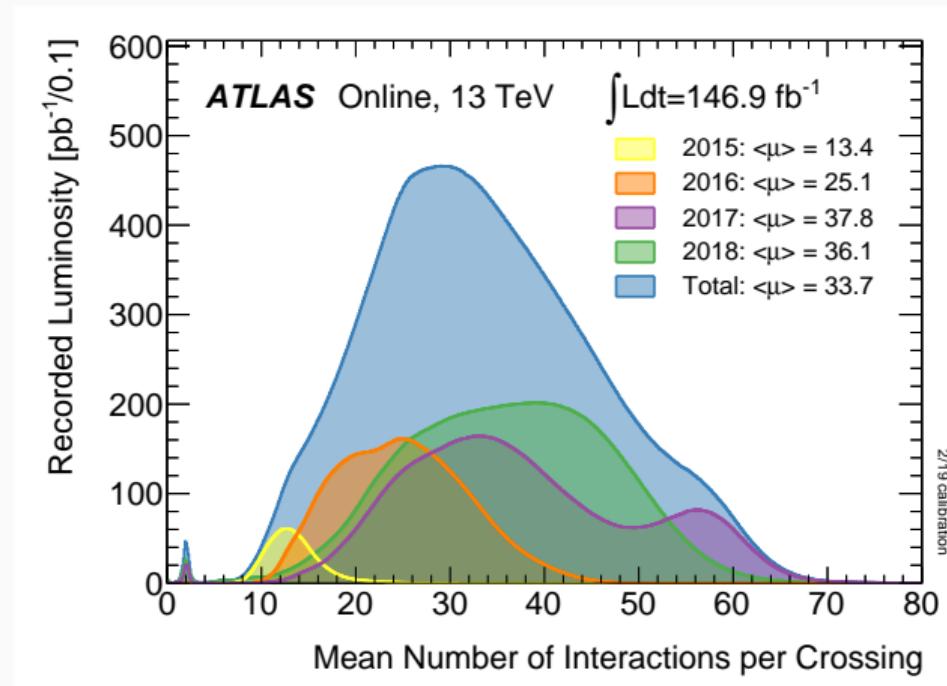
© CERN 2015



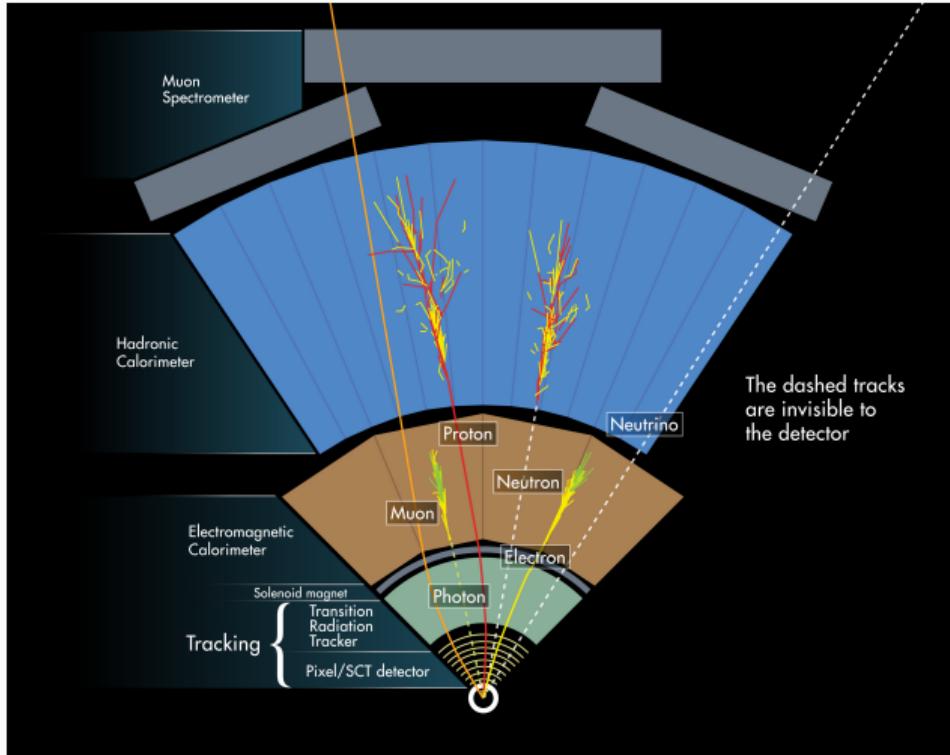
# LHC planning



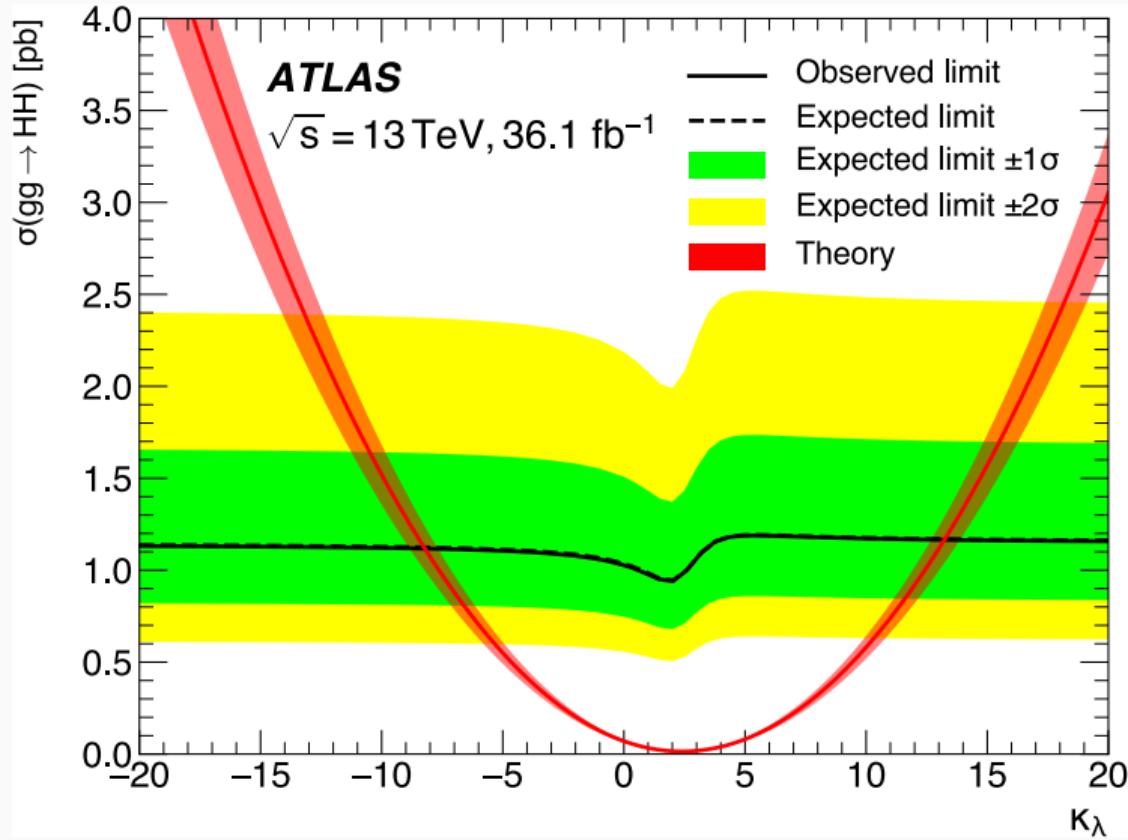
# Pile-Up



# Object reconstruction



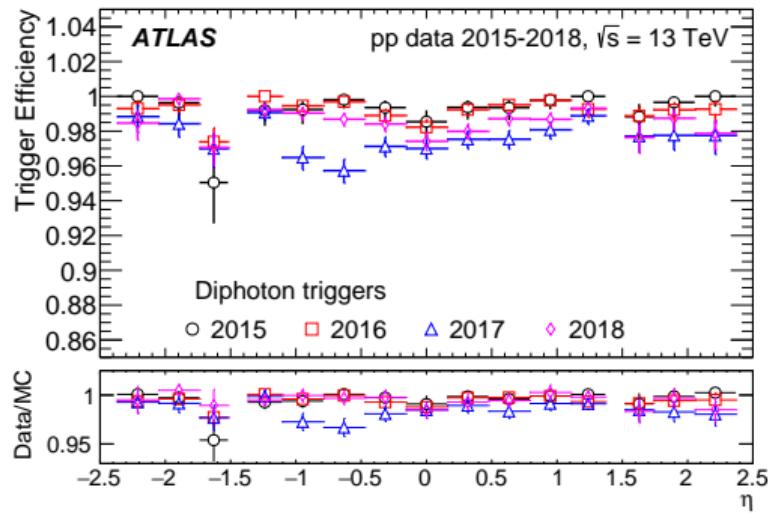
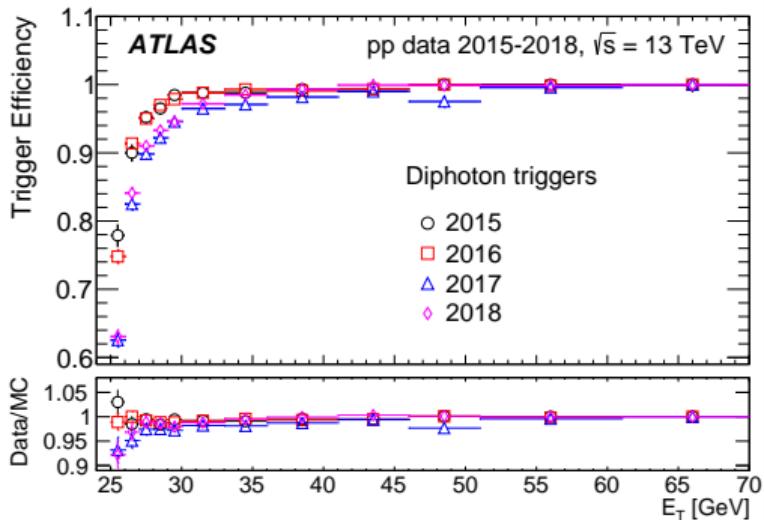
$\text{HH} \rightarrow b\bar{b}\gamma\gamma$  36  $\text{fb}^{-1}$



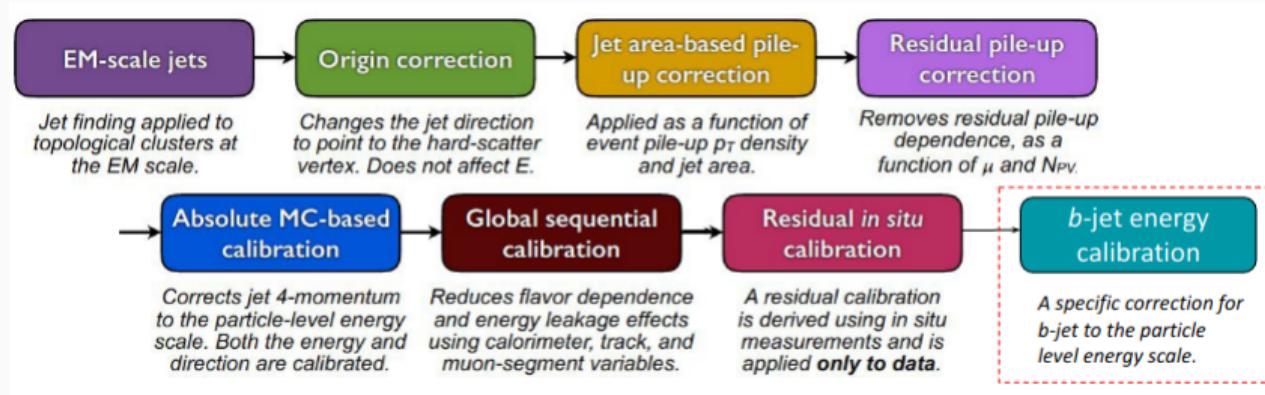
# Simulation

Process	Generator	PDF set	Showering	Tune
ggF	NNLOPS	PDFLHC	PYTHIA 8.2	AZNLO
VBF	POWHEG Box v2	PDFLHC	PYTHIA 8.2	AZNLO
WH	POWHEG Box v2	PDFLHC	PYTHIA 8.2	AZNLO
$qq \rightarrow ZH$	POWHEG Box v2	PDFLHC	PYTHIA 8.2	AZNLO
$gg \rightarrow ZH$	POWHEG Box v2	PDFLHC	PYTHIA 8.2	AZNLO
$t\bar{t}H$	POWHEG Box v2	NNPDF3.0nlo	PYTHIA 8.2	A14
$bbH$	POWHEG Box v2	NNPDF3.0nlo	PYTHIA 8.2	A14
$tHqj$	MADGRAPH5_AMC@NLO	NNPDF3.0nlo	PYTHIA 8.2	A14
$tHW$	MADGRAPH5_AMC@NLO	NNPDF3.0nlo	PYTHIA 8.2	A14
$\gamma\gamma + \text{jets}$	SHERPA v2.2.4	NNPDF3.0nnlo	SHERPA v2.2.4	–
$t\bar{t}\gamma\gamma$	MADGRAPH5_AMC@NLO	NNPDF2.3lo	PYTHIA 8.2	–

# Di-photon trigger efficiency

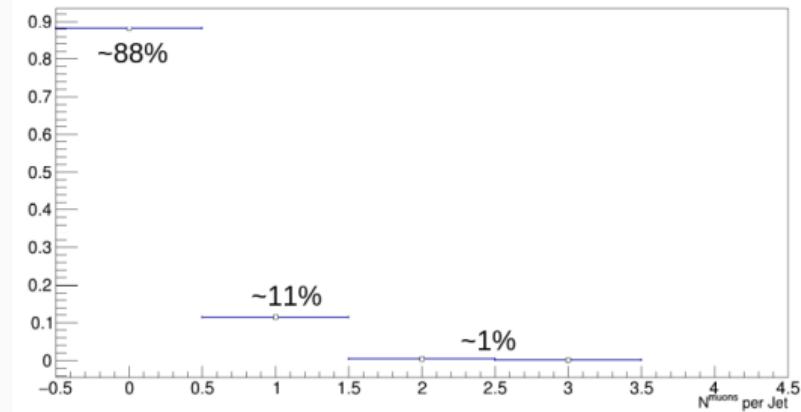


# *b*-jet calibration chain



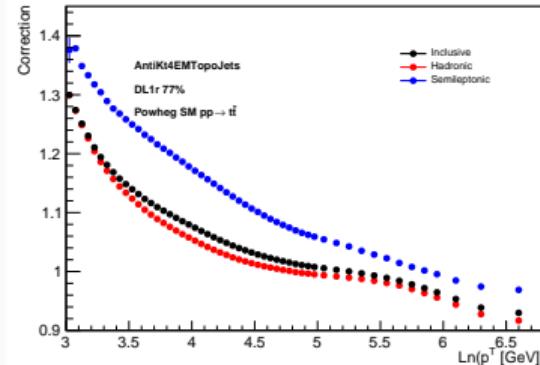
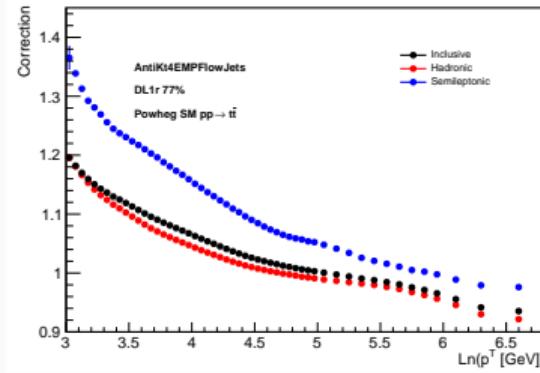
# $\mu$ -in-jet correction selection

Criteria	Selection
$p_T$	$> 4 \text{ GeV}$
ID	Medium
$\Delta R$	$< \min(0.4, 0.004 + 10/p_T)$

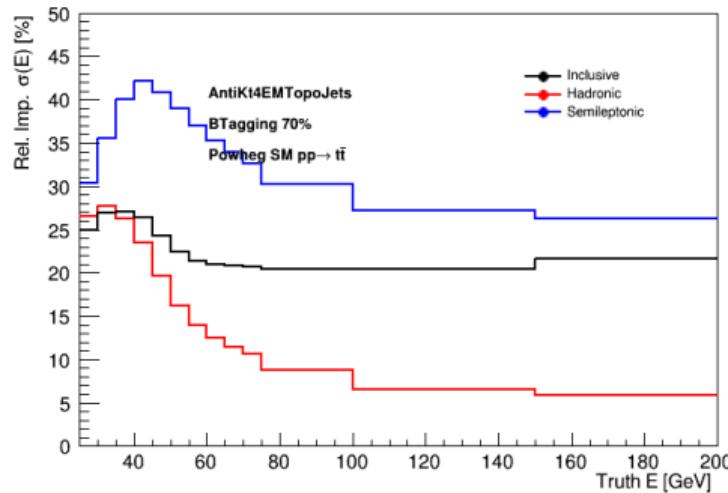
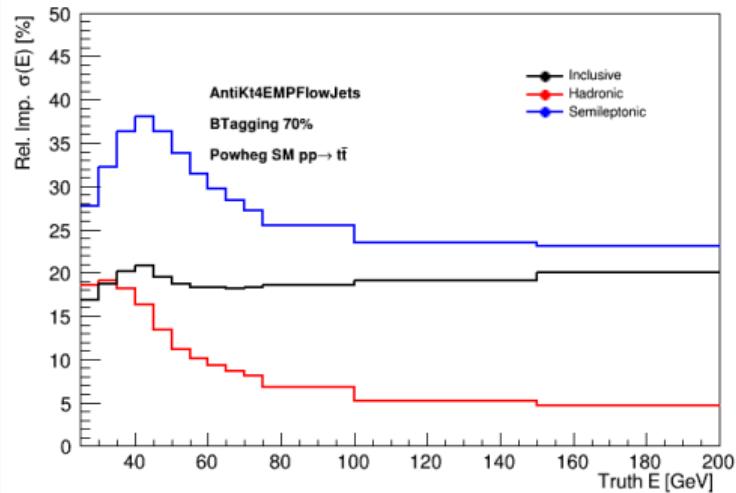


# $p_T$ Reco correction

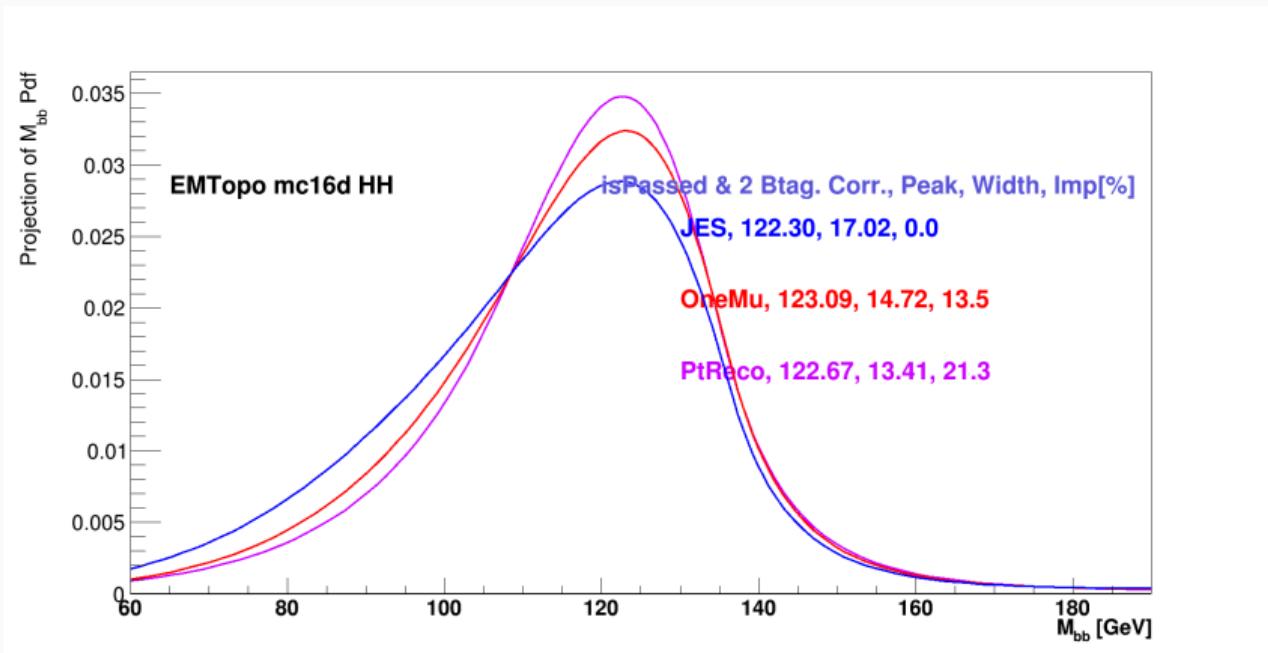
- Target  $\rightarrow$  *TruthWZ* jets, contains reconstructed jets with all stable hadrons and non-isolated muons and neutrinos.  
 $\Delta R(jet^{truth}, jet^{reco})$
- Correction = mean of the  $\frac{p_T^{truth}}{p_T^{reco}}$  distribution



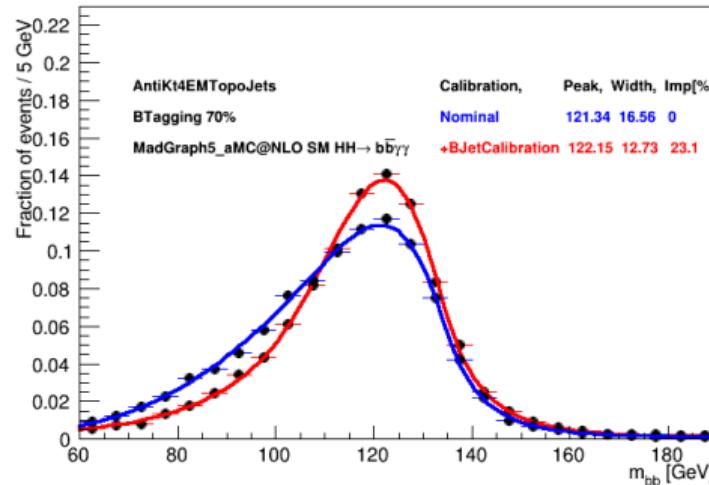
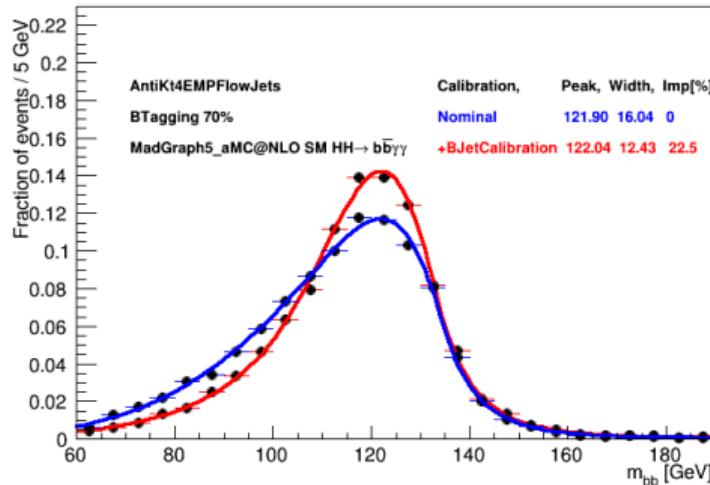
# $p_T$ Reco gain



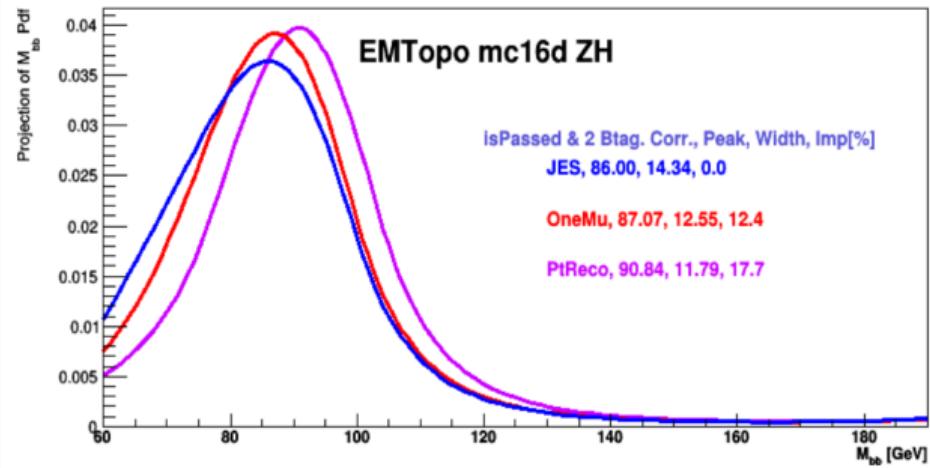
## $m_{bb}$ correction in each step



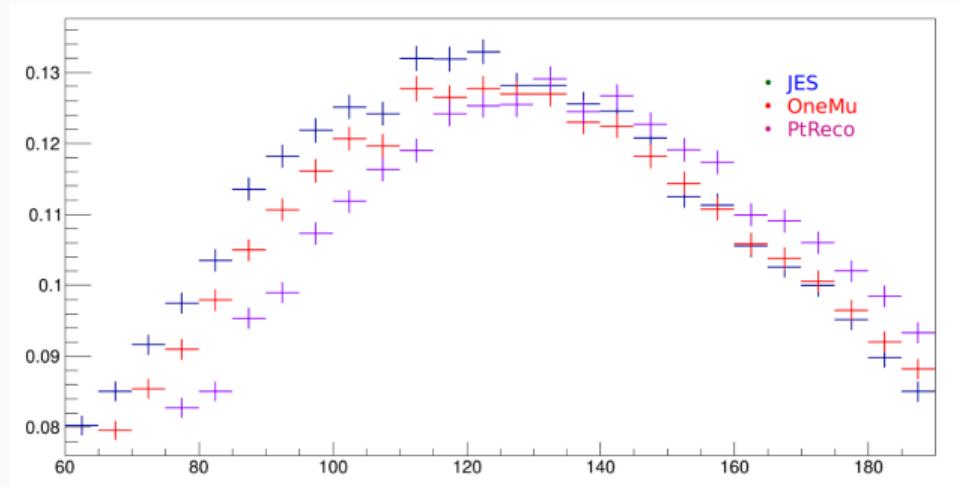
# topological vs particle flow $m_{bb}$



# Impact on ZH background

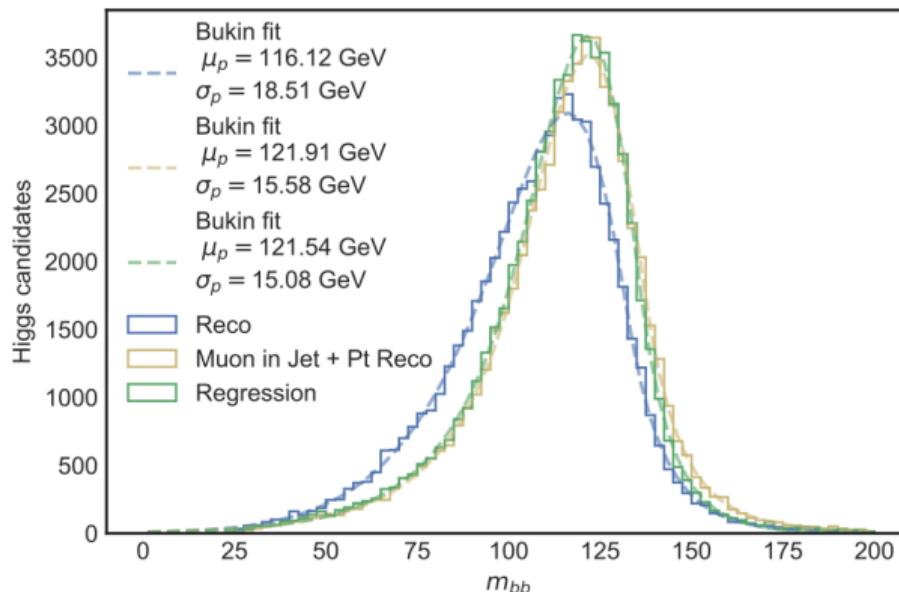


# Impact on $t\bar{t}H$ background



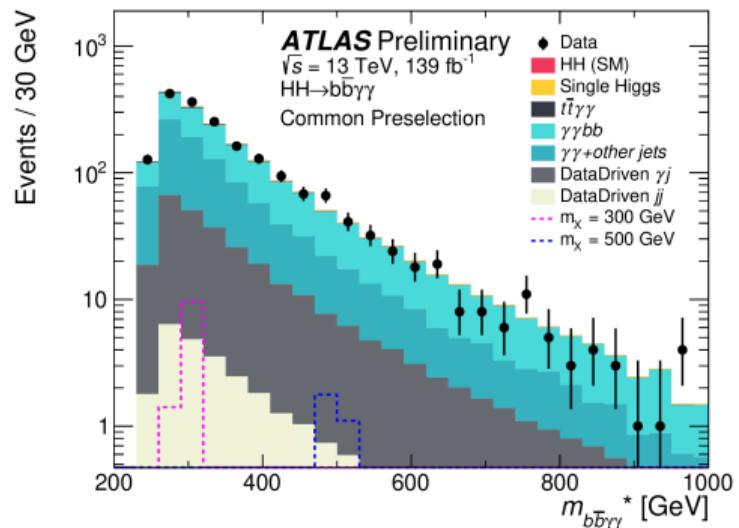
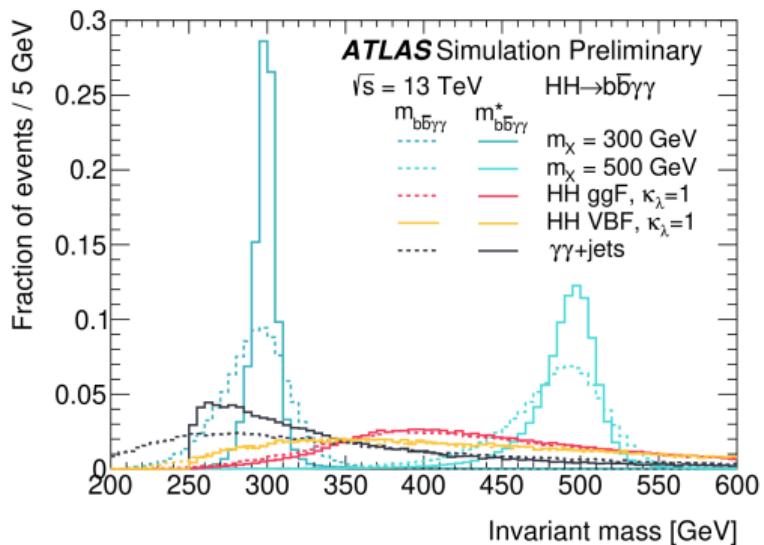
# Neural Network vs $\mu$ -in-jet+ $p_T$ Reco

- $\mu$ -in-jet+ $p_T$  Reco compared to simple NN version.
- NN trained on  $t\bar{t}$  sample
- Comparison performed on  $\text{HH} \rightarrow b\bar{b}b\bar{b}$

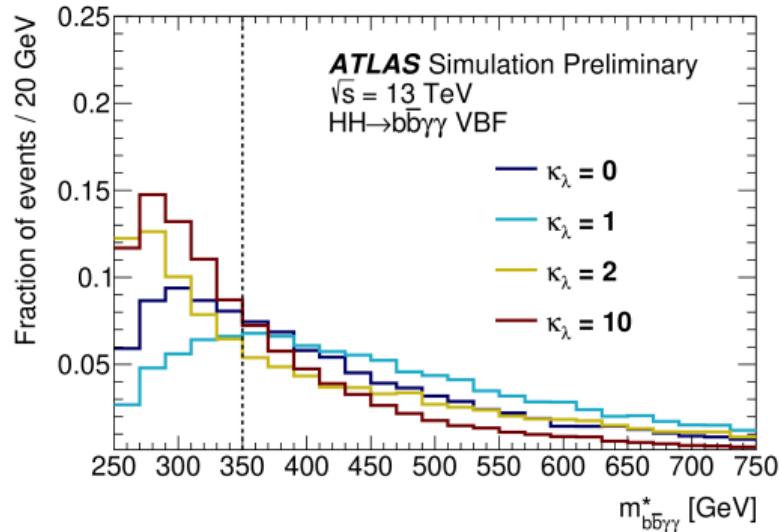
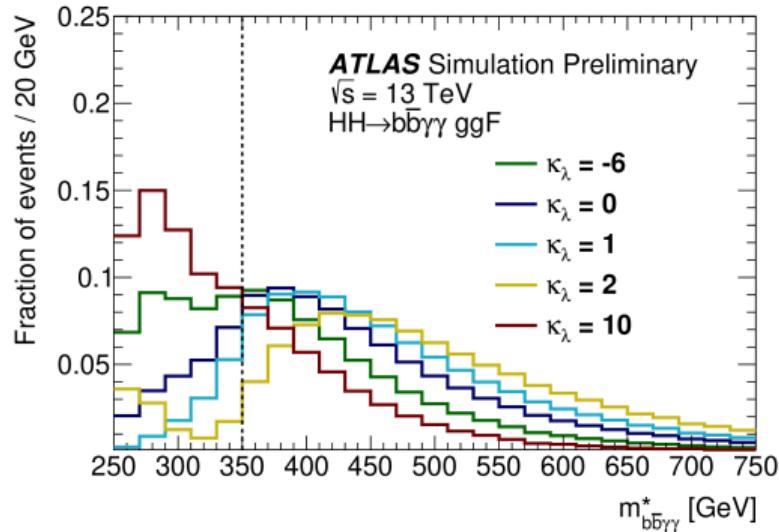


# Motivation for $m_{b\bar{b}\gamma\gamma}^*$

- Improve resolution mainly for resonance analysis



# $m_{b\bar{b}\gamma\gamma}^*$ distribution

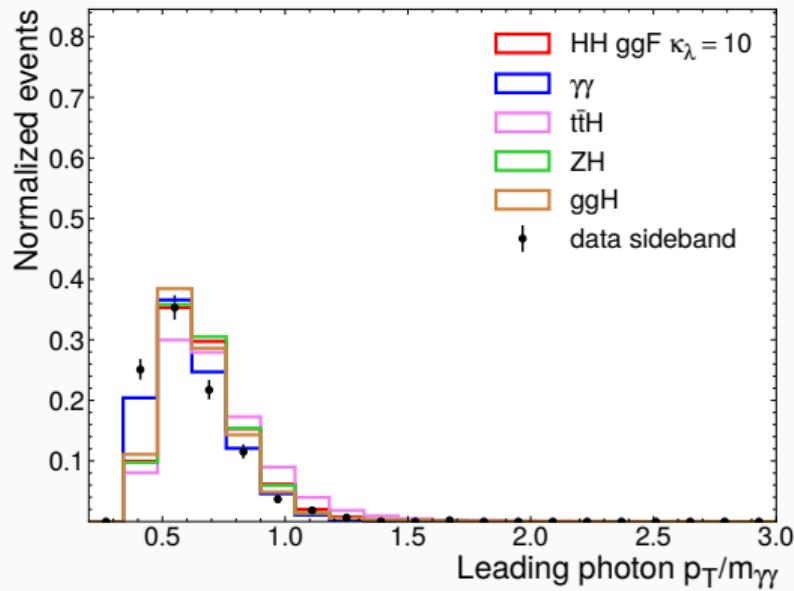
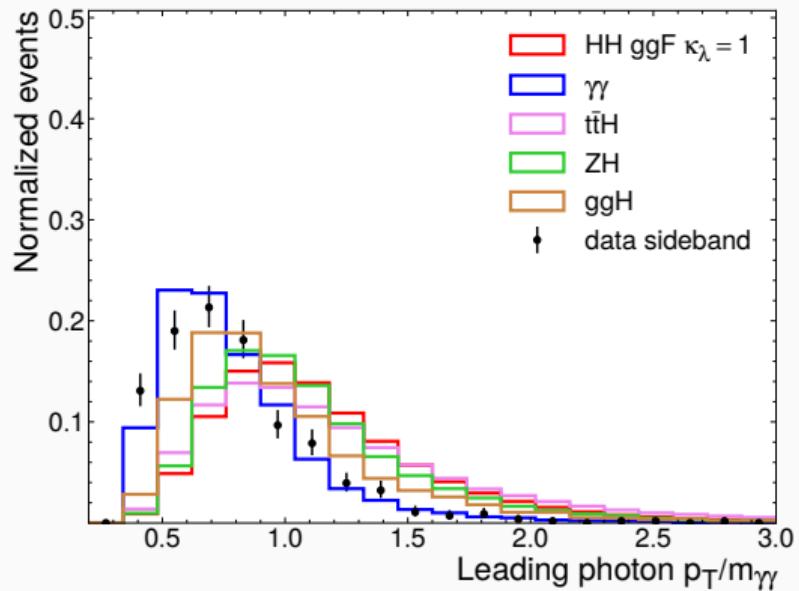


# MVA inputs

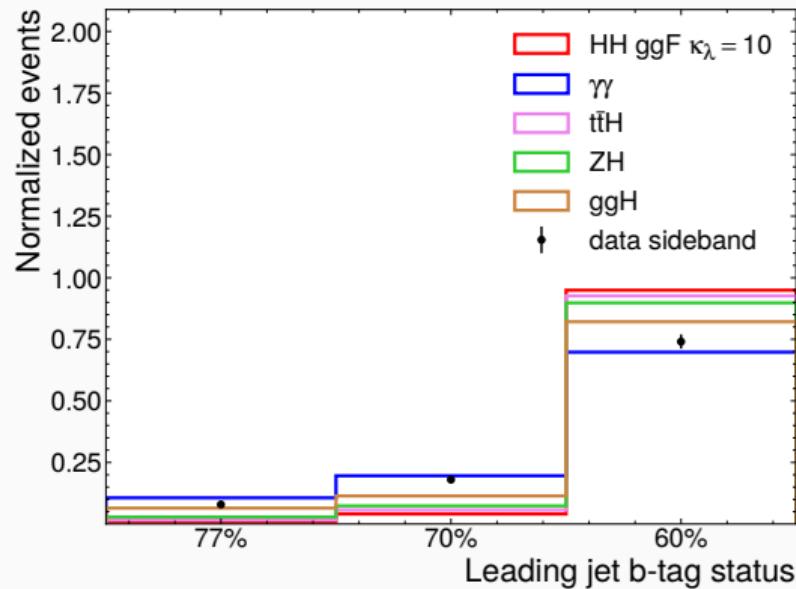
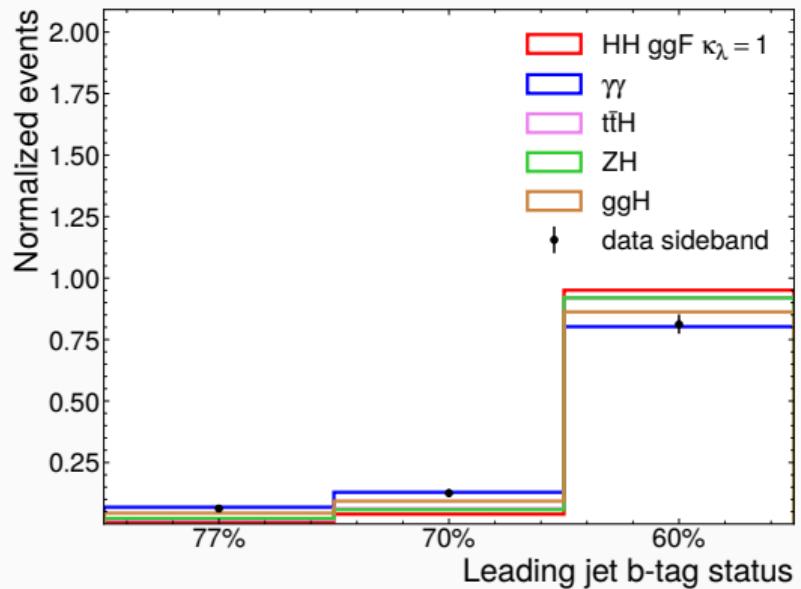
Variable	Definition
Photon-related kinematic variables	
$p_{\text{T}}/m_{\gamma\gamma}$	Transverse momentum of the two photons scaled by their invariant mass $m_{\gamma\gamma}$
$\eta$ and $\phi$	Pseudo-rapidity and azimuthal angle of the leading and sub-leading photon
Jet-related kinematic variables	
$b$ -tag status	Highest fixed $b$ -tag working point that the jet passes
$p_{\text{T}}, \eta$ and $\phi$	Transverse momentum, pseudo-rapidity and azimuthal angle of the two jets with the highest $b$ -tagging score
$p_{\text{T}}^{b\bar{b}}, \eta_{b\bar{b}}$ and $\phi_{b\bar{b}}$	Transverse momentum, pseudo-rapidity and azimuthal angle of $b$ -tagged jets system
$m_{b\bar{b}}$	Invariant mass built with the two jets with the highest $b$ -tagging score
$H_{\text{T}}$	Scalar sum of the $p_{\text{T}}$ of the jets in the event
Single topness	For the definition, see Eq. (??)
Missing transverse momentum-related variables	
$E_{\text{T}}^{\text{miss}}$ and $\phi^{\text{miss}}$	Missing transverse momentum and its azimuthal angle

$$\chi_{Wt} = \min \sqrt{\left( \frac{m_{j_1 j_2} - m_W}{m_W} \right)^2 + \left( \frac{m_{j_1 j_2 j_3} - m_t}{m_t} \right)^2}$$

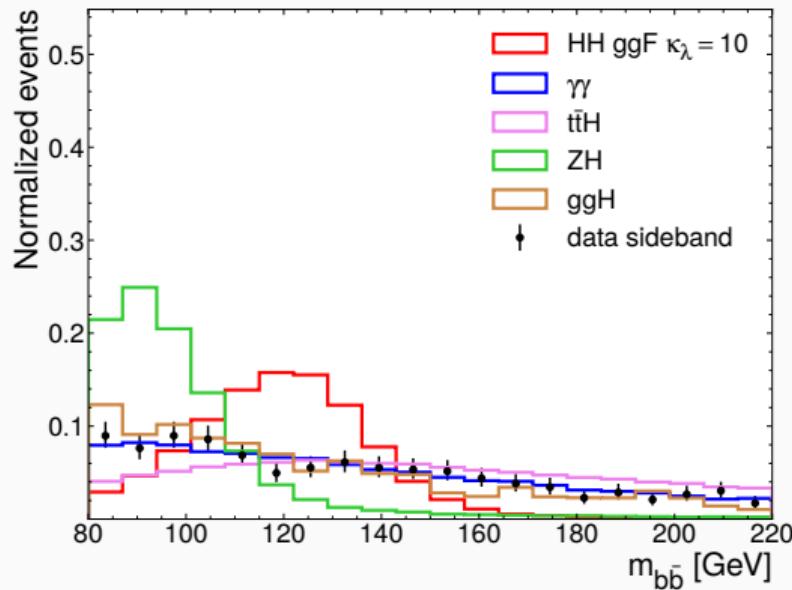
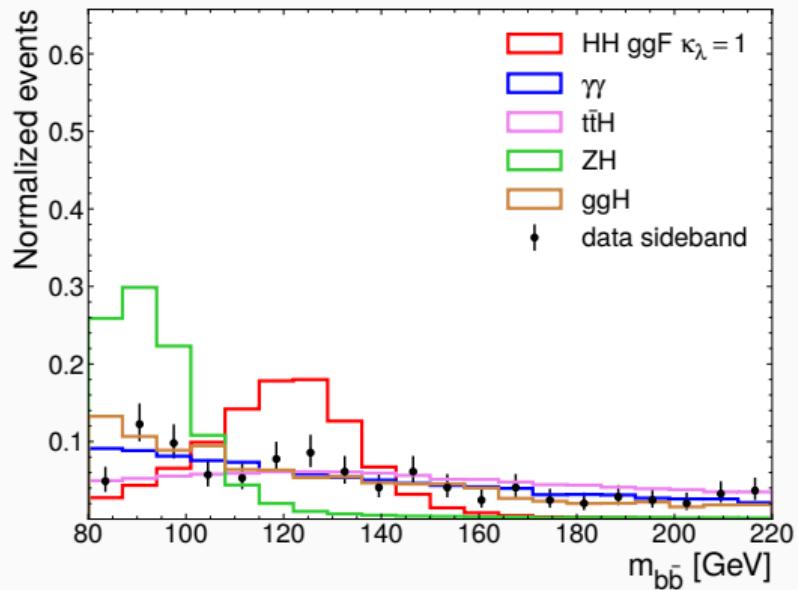
# Variables distributions



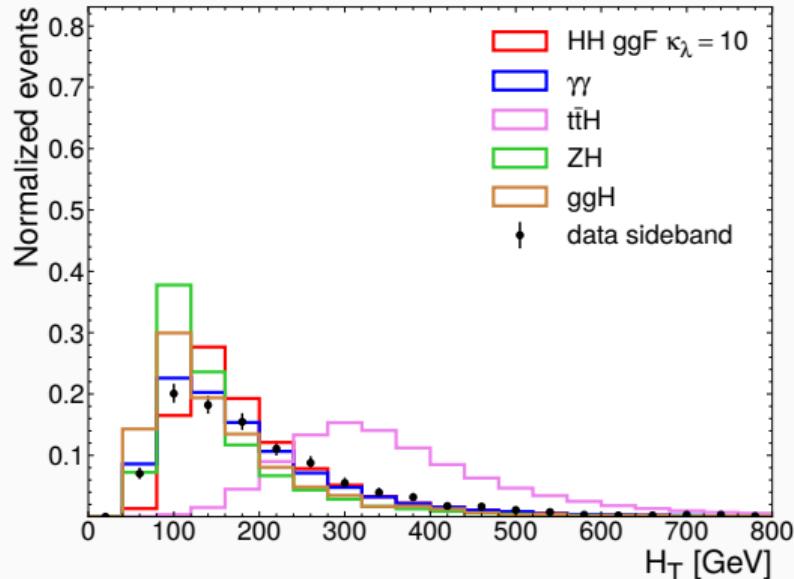
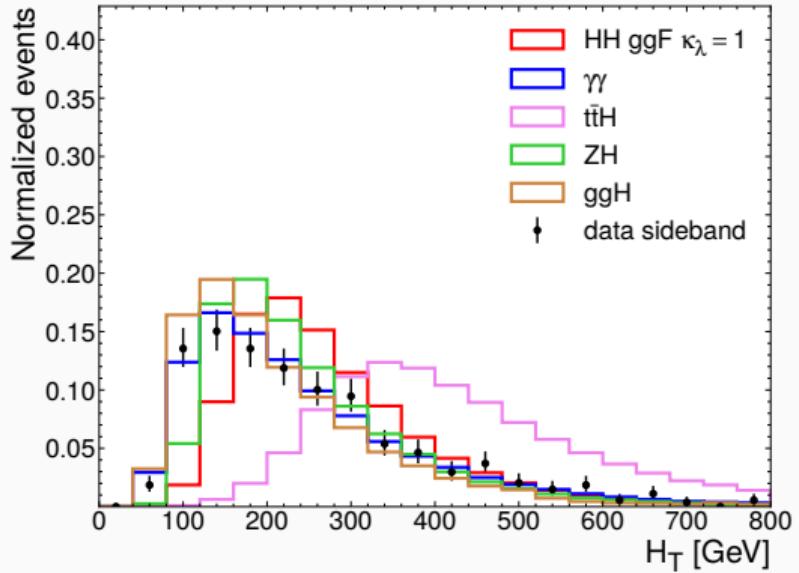
# Variables distributions



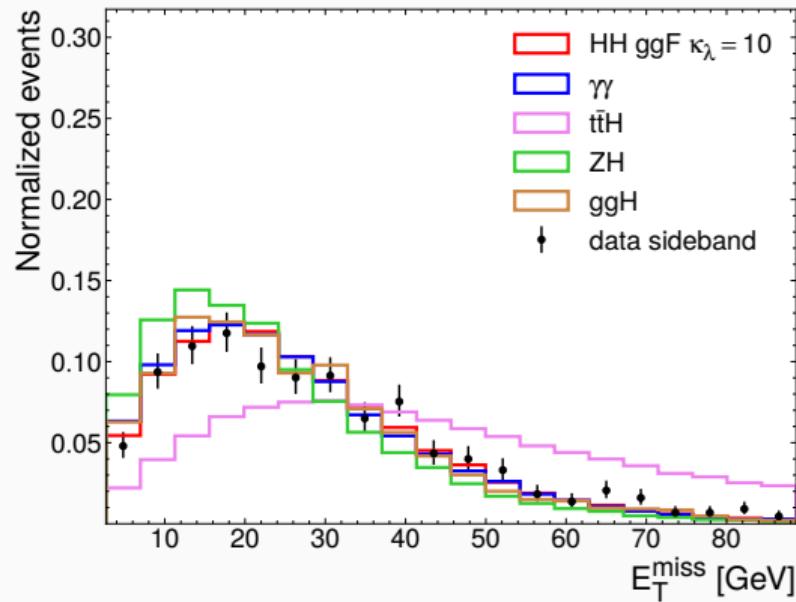
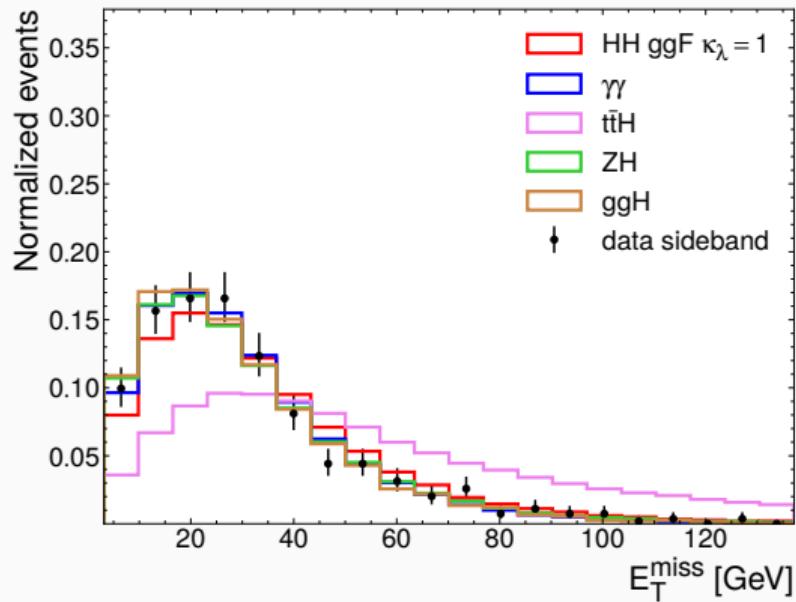
# Variables distributions



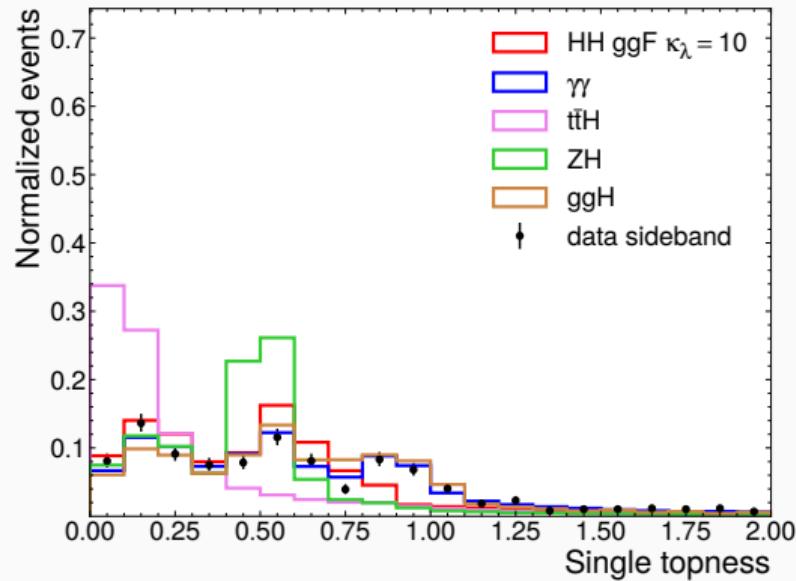
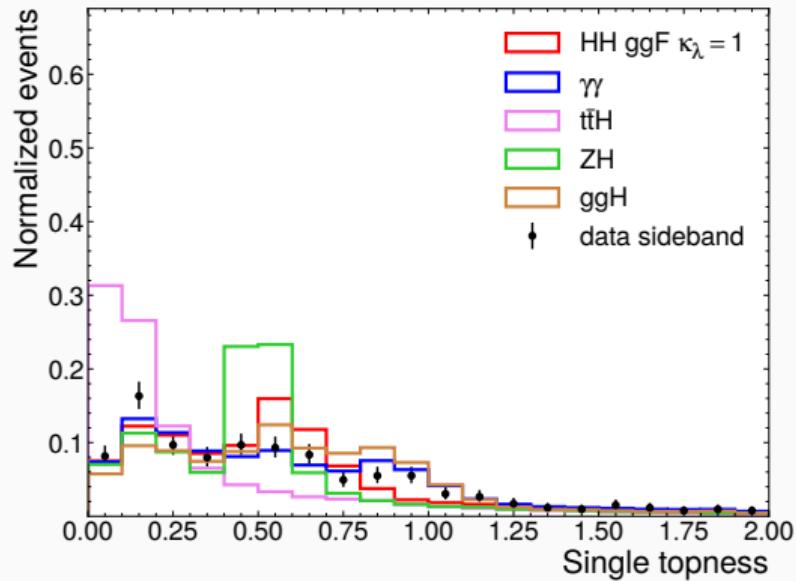
# Variables distributions



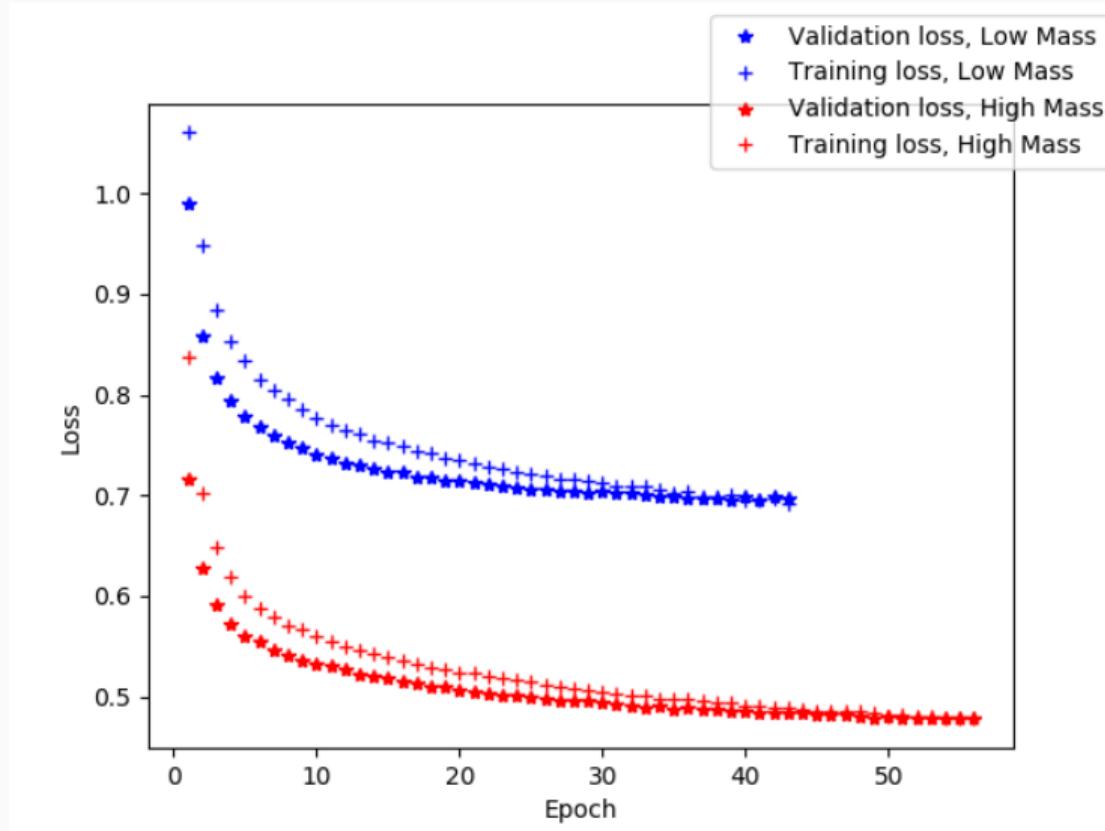
# Variables distributions



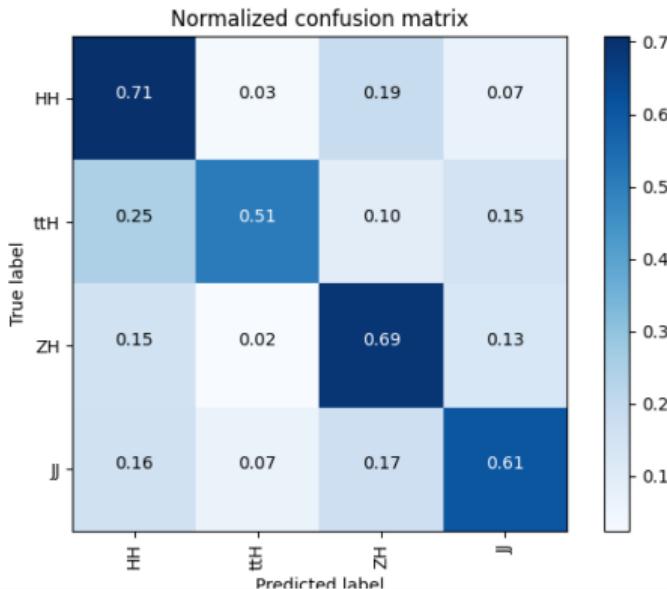
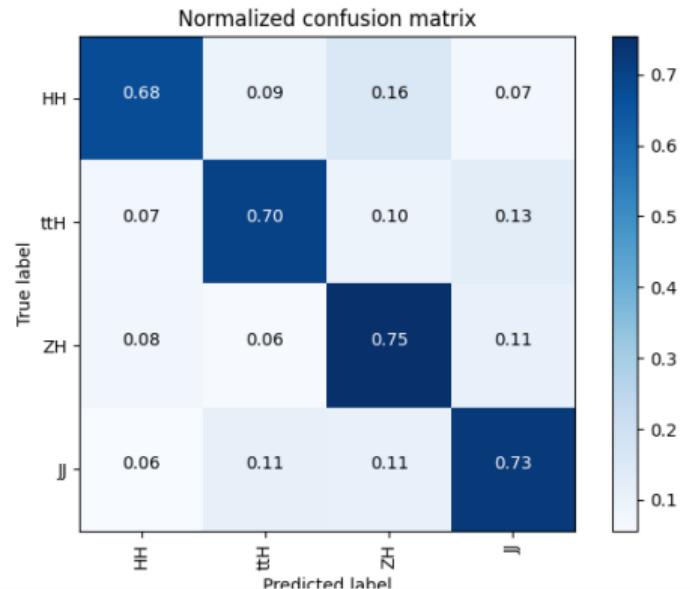
# Variables distributions



# DNN loss function

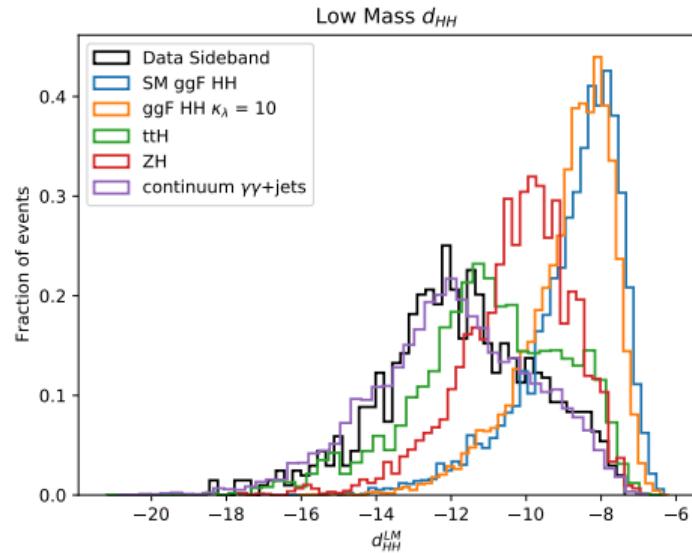
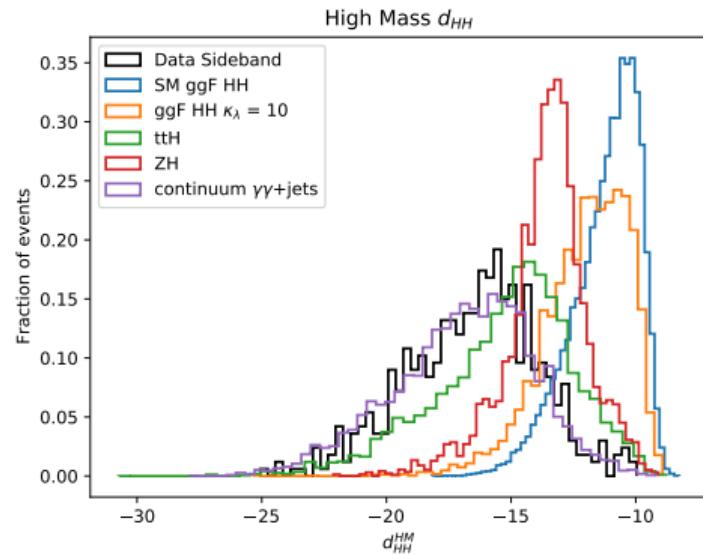


# DNN confusion matrix



JJ = continuum  $\gamma\gamma + \text{jets}$

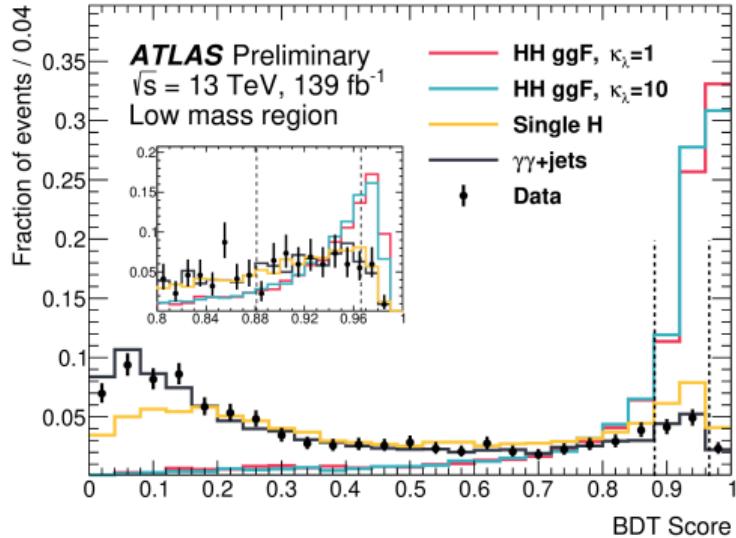
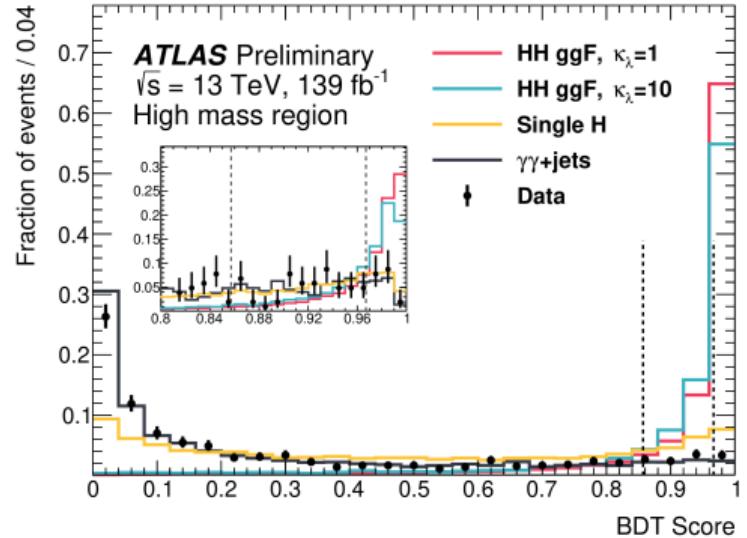
# $d_{HH}$ distribution



## DNN significance breakdown

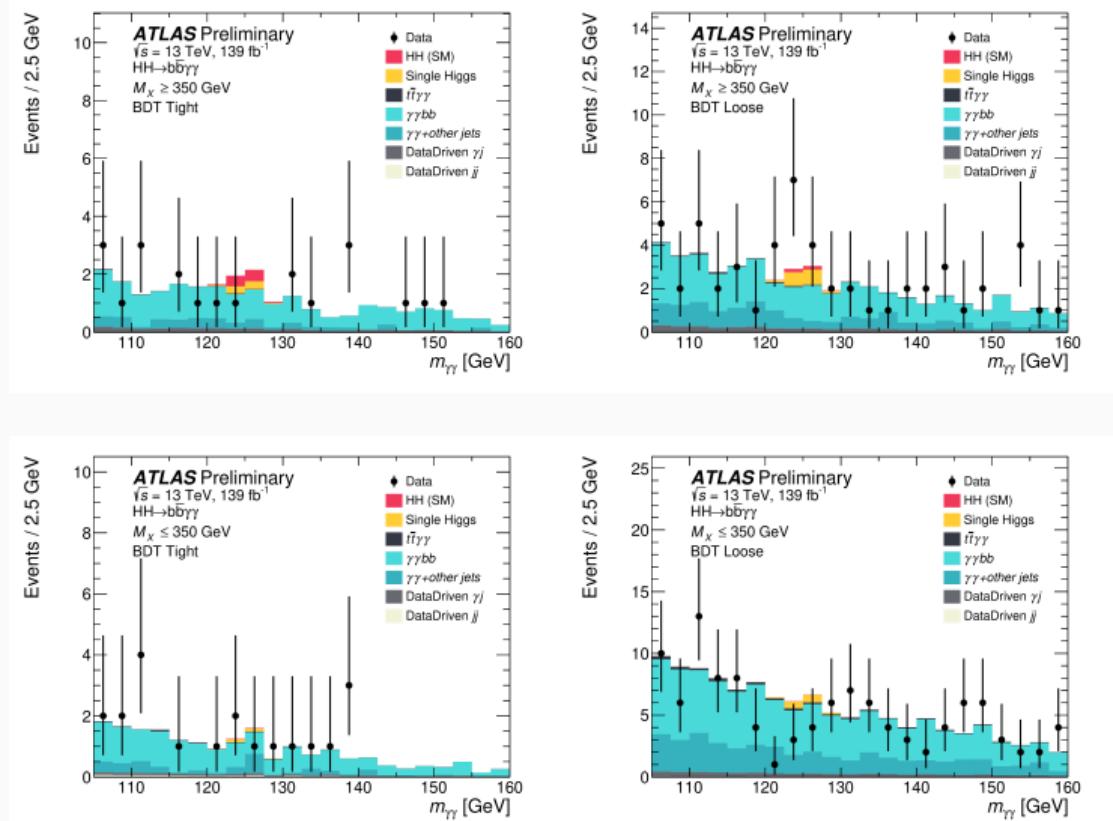
Categories	SM ggF HH	BSM $\kappa_\lambda=10$ ggF HH
High mass, High $d_{HH}$	0.53	2.45
High mass, Low $d_{HH}$	0.11	0.94
Low mass, High $d_{HH}$	0.03	2.21
Low mass, Low $d_{HH}$	0.01	0.54
Combined	$0.54\sigma$	$3.47\sigma$

# BDT categories



Category	Selection criteria
High mass BDT tight	$m_{b\bar{b}\gamma\gamma}^* \geq 350 \text{ GeV}$ , BDT score $\in [0.967, 1]$
High mass BDT loose	$m_{b\bar{b}\gamma\gamma}^* \geq 350 \text{ GeV}$ , BDT score $\in [0.857, 0.967]$
Low mass BDT tight	$m_{b\bar{b}\gamma\gamma}^* < 350 \text{ GeV}$ , BDT score $\in [0.966, 1]$
Low mass BDT loose	$m_{b\bar{b}\gamma\gamma}^* < 350 \text{ GeV}$ , BDT score $\in [0.881, 0.966]$

# Analysis categories



## Statistical model

$$\mathcal{L} = \prod_c \left( Pois(n_c | N_c(\theta)) \cdot \prod_{i=1}^{n_c} f_c(m_{\gamma\gamma}^i, \theta) \cdot G(\theta) \right),$$

$$N_c(\theta) = \mu \cdot N_{\text{HH,c}}(\theta_{yield}) + N_{\text{H,c}}(\theta_{yield}) + N_{\text{SS,c}} \cdot \theta_{\text{SS,c}} + N_{\text{continuum,c}},$$

$$\tilde{q}_\mu = \begin{cases} -2 \log \frac{L(\mu, \hat{\theta}(\mu))}{L(0, \hat{\theta}(0))} & \hat{\mu} < 0 \\ -2 \log \frac{L(\mu, \hat{\theta}(\mu))}{L(\hat{\mu}, \hat{\theta})} & 0 \leq \hat{\mu} \leq \mu \\ 0 & \hat{\mu} > \mu \end{cases}$$

# Modelling and Spurious Signal

- Biases related to the choice quantified through the Spurious Signal (SS) method:
  - Measure residual fitted  $N_{SS}$  in continuum MC:  $n_{sig} \times PDF_{sig} + n_{bkg} \times PDF_{bkg}$
  - $N_{SS} = \max |n_{sig}(m_H)|$  :  $m_H$  vary from 121 to 129 with step of 1 GeV
  - Relaxed SS criteria (allowing  $2\sigma$  local statistical fluctuation) is used because of lack of statistics.

$$\zeta_{SS} = \begin{cases} N_{SS} + 2\Delta_{MC}, & N_{SS} + 2\Delta_{MC} < 0 \\ N_{SS} - 2\Delta_{MC}, & N_{SS} - 2\Delta_{MC} > 0 \\ 0, & otherwise \end{cases}$$

- Functional form chosen: **Exponential**
- The fitted  $N_{SS}$  are used as systematic uncertainties on the signal yield

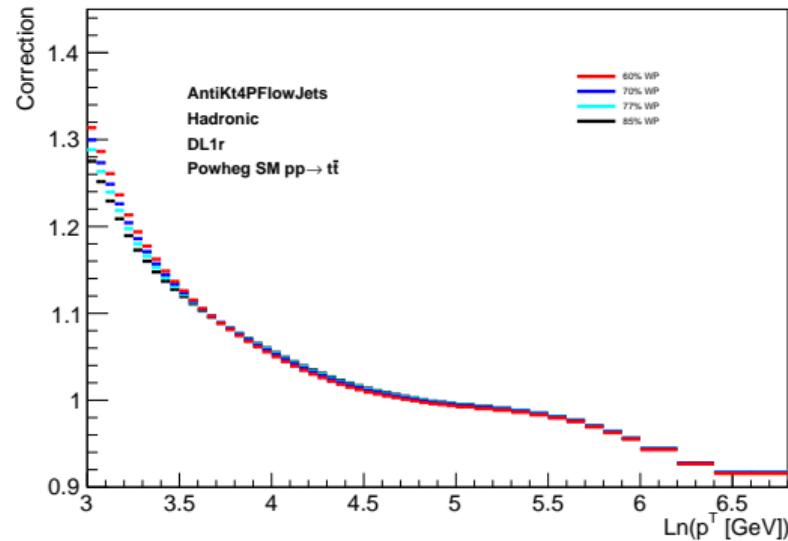
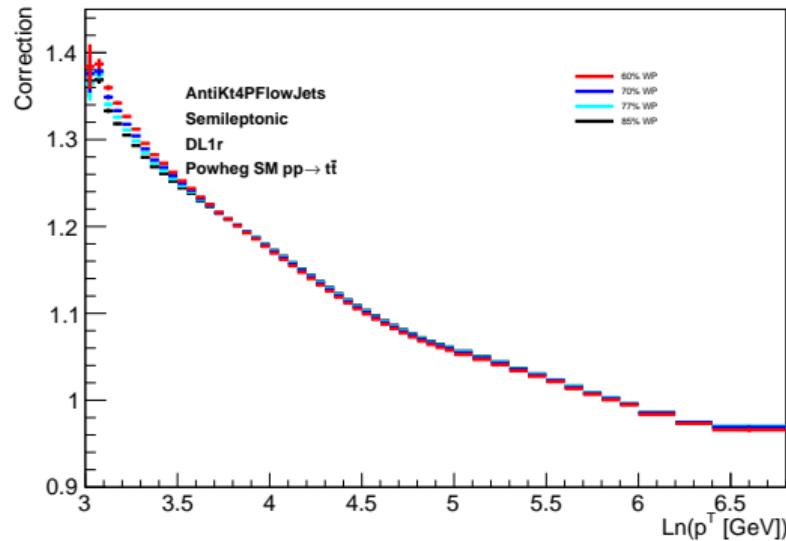
Category	$N_{SS}$
High mass BDT tight	0.688
High mass BDT loose	0.990
Low mass BDT tight	0.594
Low mass BDT loose	1.088

## *b*-jet energy calibration systematic

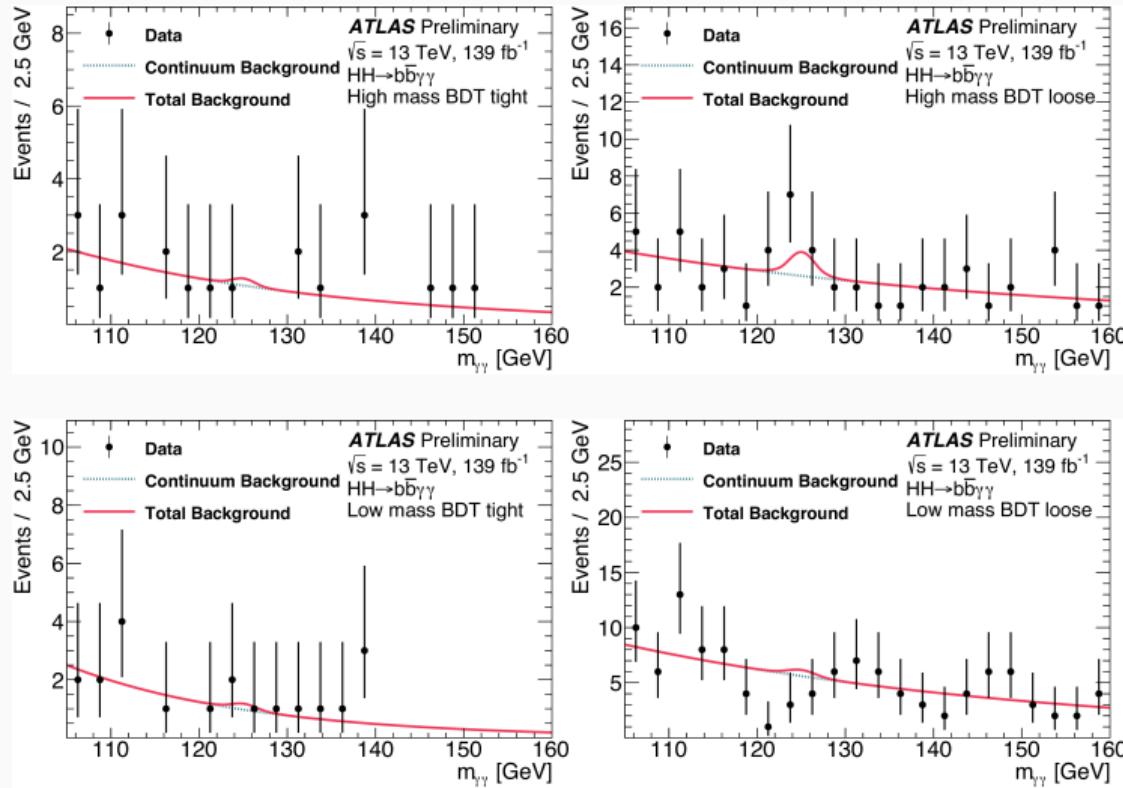
- $\mu$ -in-jet systematic negligible from Run-1 in ZH
- Impact of *b*-tagging WP on  $p_T$  Reco, as systematic
  - three variations of the  $p_T$  Reco correction, using 60%, 70% and 85% *b*-tagging WP.
  - relative impact on the yield → systematic uncertainty
  - largest systematic, same order as the flavour tagging uncertainty

$p_T$ -Reco variation	% relative effect to nominal
60% WP	$\pm 0.094$
70% WP	$\pm 0.065$
85% WP	$\pm 0.12$

# $p_T$ Reco as function of $b$ -tagging WPs



# background-only fit



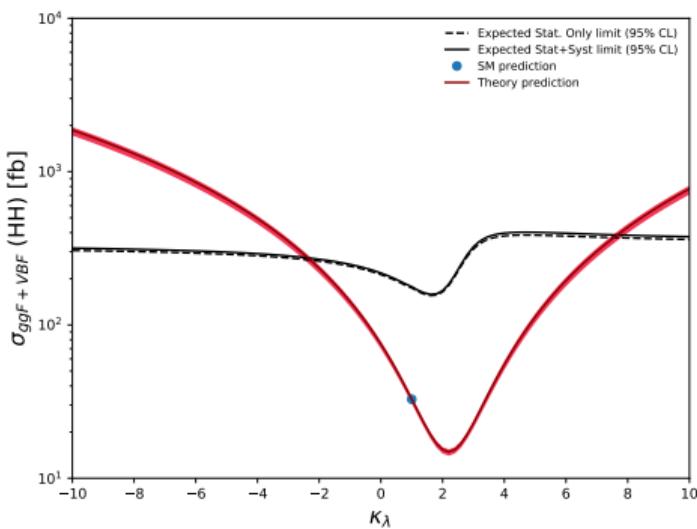
# Observed events

	High mass BDT tight	High mass BDT loose	Low mass BDT tight	Low mass BDT loose
Continuum background	$4.9 \pm 1.1$	$9.5 \pm 1.5$	$3.7 \pm 1.0$	$24.9 \pm 2.5$
Single Higgs boson background	$0.670 \pm 0.032$	$1.57 \pm 0.04$	$0.220 \pm 0.016$	$1.39 \pm 0.04$
ggF	$0.261 \pm 0.028$	$0.44 \pm 0.04$	$0.063 \pm 0.014$	$0.274 \pm 0.030$
<i>t</i> <i>tH</i>	$0.1929 \pm 0.0045$	$0.491 \pm 0.007$	$0.1074 \pm 0.0033$	$0.742 \pm 0.009$
ZH	$0.142 \pm 0.005$	$0.486 \pm 0.010$	$0.04019 \pm 0.0027$	$0.269 \pm 0.007$
Rest	$0.074 \pm 0.012$	$0.155 \pm 0.020$	$0.008 \pm 0.006$	$0.109 \pm 0.016$
SM <i>HH</i> signal	$0.8753 \pm 0.0032$	$0.3680 \pm 0.0020$	$(49.4 \pm 0.7) \cdot 10^{-3}$	$(78.7 \pm 0.9) \cdot 10^{-3}$
ggF	$0.8626 \pm 0.0032$	$0.3518 \pm 0.0020$	$(46.1 \pm 0.7) \cdot 10^{-3}$	$(71.8 \pm 0.9) \cdot 10^{-3}$
VBF	$0.01266 \pm 0.00016$	$0.01618 \pm 0.00018$	$(3.22 \pm 0.08) \cdot 10^{-3}$	$(6.923 \pm 0.011) \cdot 10^{-3}$
Alternative <i>HH</i> ( $\kappa_\lambda = 10$ ) signal	$6.36 \pm 0.05$	$3.691 \pm 0.038$	$4.65 \pm 0.04$	$8.64 \pm 0.06$
Data	2	17	5	14

# Systematic impact

Relative impact of the systematic uncertainties in %			
Source	Type	Non-resonant analysis	Resonant analysis
		$HH$	$m_X = 300 \text{ GeV}$
Experimental			
Photon energy scale	Norm. + Shape	5.2	2.7
Photon energy resolution	Norm. + Shape	1.8	1.6
Flavor tagging	Normalization	0.5	< 0.5
Theoretical			
Heavy flavor content	Normalization	1.5	< 0.5
Higgs boson mass	Norm. + Shape	1.8	< 0.5
PDF+ $\alpha_s$	Normalization	0.7	< 0.5
Spurious signal	Normalization	5.5	5.4

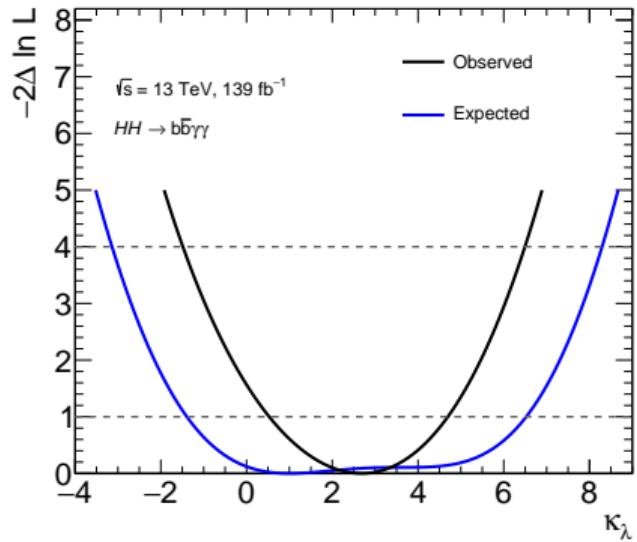
# Expected limit: Stat. Only vs Stat.+Syst.



	Stat. Only	Stat.+Syst.
$\sigma_{HH}/\sigma_{HH}^{SM}$ limit	5.3	5.5
$\kappa_\lambda$ interval	[-2.3, 7.6]	[-2.4, 7.7]

Category	$\sigma_{HH}/\sigma_{HH}^{SM}$ limit
High mass, High BDT	5.8
High mass, Low BDT	21.0
Low mass, High BDT	102.9
Low mass, Low BDT	125.6
Combined	5.5

## $\kappa_\lambda$ likelihood scan

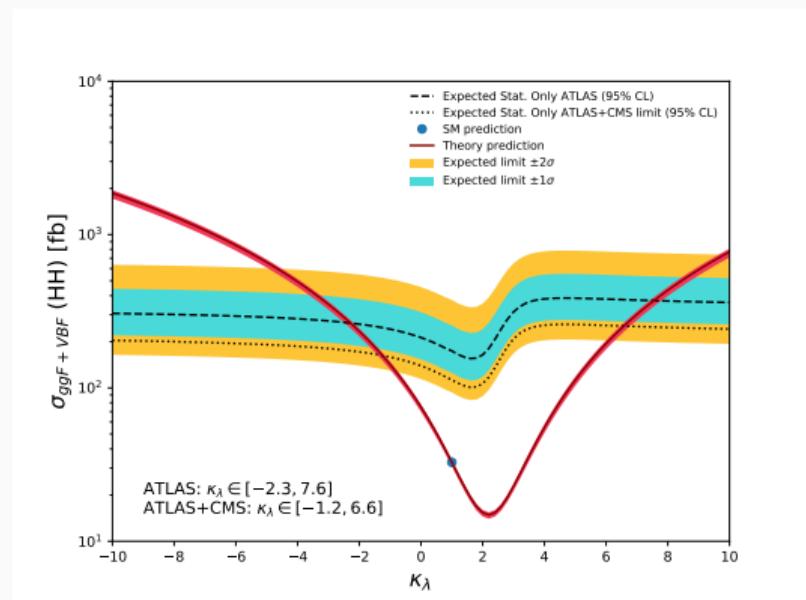


- best-fit  $\kappa_\lambda$  is  $2.7^{+2.1}_{-2.2}$
- $\mu_{HH} = 1 \pm 2.37$  for SM

	$1\sigma$ CI	$2\sigma$ CI
Expected	[-1.4, 6.4]	[-3.1, 8.2]
Observed	[0.5, 4.7]	[-1.4, 6.5]

# Combination with CMS

- ATLAS+CMS  $\sim \times 2$  139  $\text{fb}^{-1}$
- Expected 95% CL limit on  $\sigma_{HH}$  of 3.4



# full Run-2 HH $\rightarrow b\bar{b}\tau^+\tau^-$

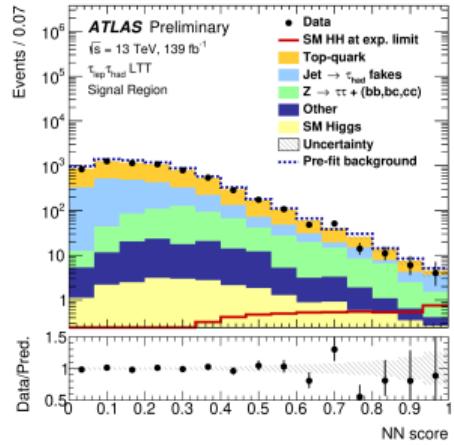
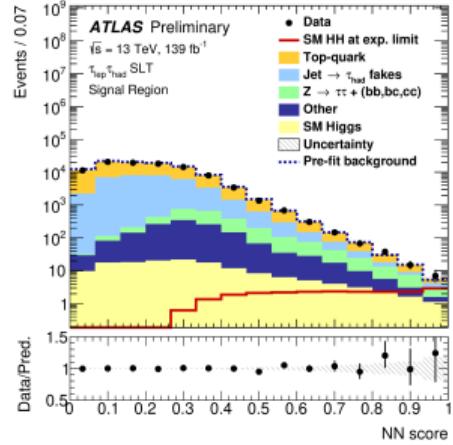
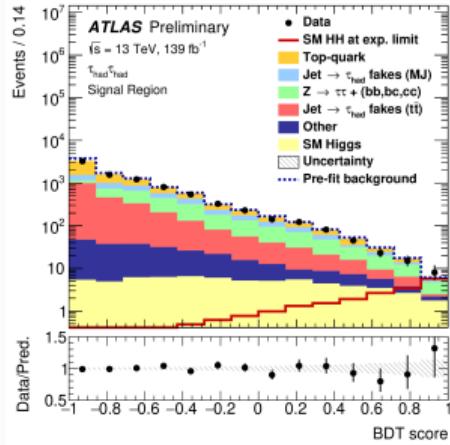
ATLAS-CONF-2021-030

- Relies on:
  - $\tau_{had}\tau_{had}$ : Single and Double tau trigger
  - $\tau_{lep}\tau_{had}$ : Single lepton and lepton+tau trigger
- backgrounds:
  - **true**  $\tau$ :  $t\bar{t}$  and Z+HF, from Monte Carlo and normalization from data
  - **fake**  $\tau$ :  $t\bar{t}$  and multi-jet, data driven
- 3 MVA categories:
  - $\tau_{had}\tau_{had}$
  - $\tau_{lep}\tau_{had}$
  - Z+HF background control
- fit of MVA outputs

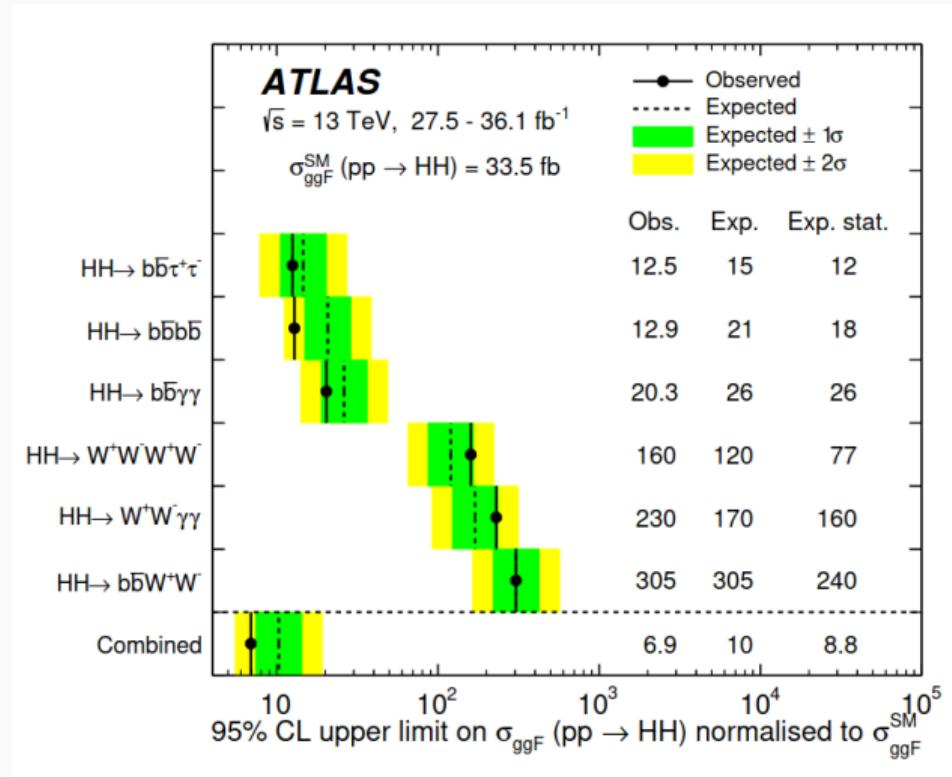
		Observed	$-2\sigma$	$-1\sigma$	Expected	$+1\sigma$	$+2\sigma$
$\tau_{had}\tau_{had}$	$\sigma_{ggF+VBF} [\text{fb}]$	145	70.5	94.6	131	183	245
	$\sigma_{ggF+VBF}/\sigma_{ggF+VBF}^{\text{SM}}$	4.95	2.38	3.19	4.43	6.17	8.27
$\tau_{lep}\tau_{had}$	$\sigma_{ggF+VBF} [\text{fb}]$	265	124	167	231	322	432
	$\sigma_{ggF+VBF}/\sigma_{ggF+VBF}^{\text{SM}}$	9.16	4.22	5.66	7.86	10.9	14.7
Combined	$\sigma_{ggF+VBF} [\text{fb}]$	135	61.3	82.3	114	159	213
	$\sigma_{ggF+VBF}/\sigma_{ggF+VBF}^{\text{SM}}$	4.65	2.08	2.79	3.87	5.39	7.22

- $\times 4$  improvement w.r.t early Run-2 (12.7 $\times$ SM)
- large systematic from background modelling

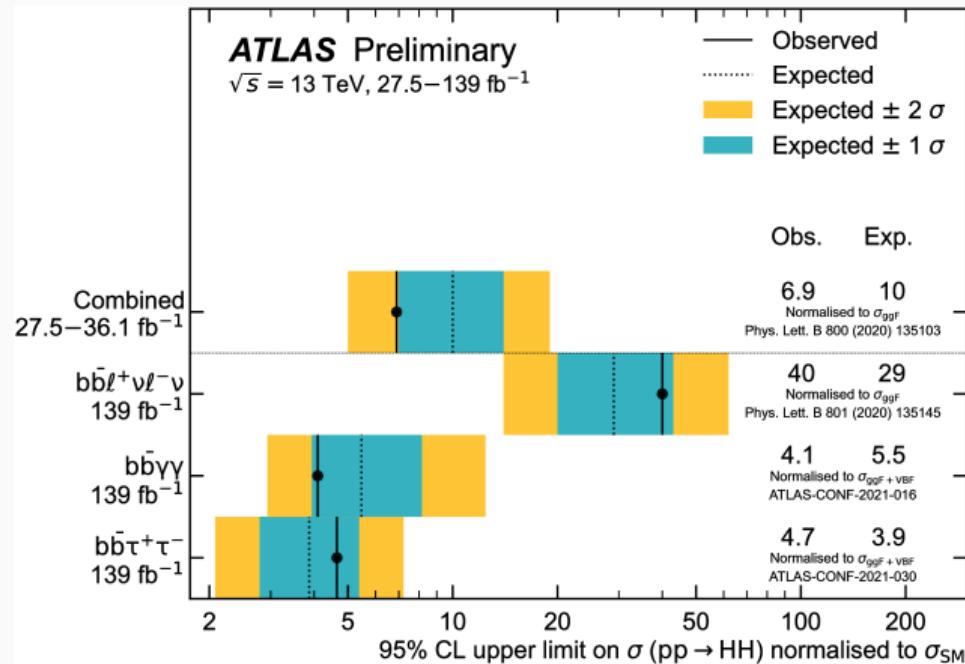
# full Run-2 HH $\rightarrow b\bar{b}\tau^+\tau^-$



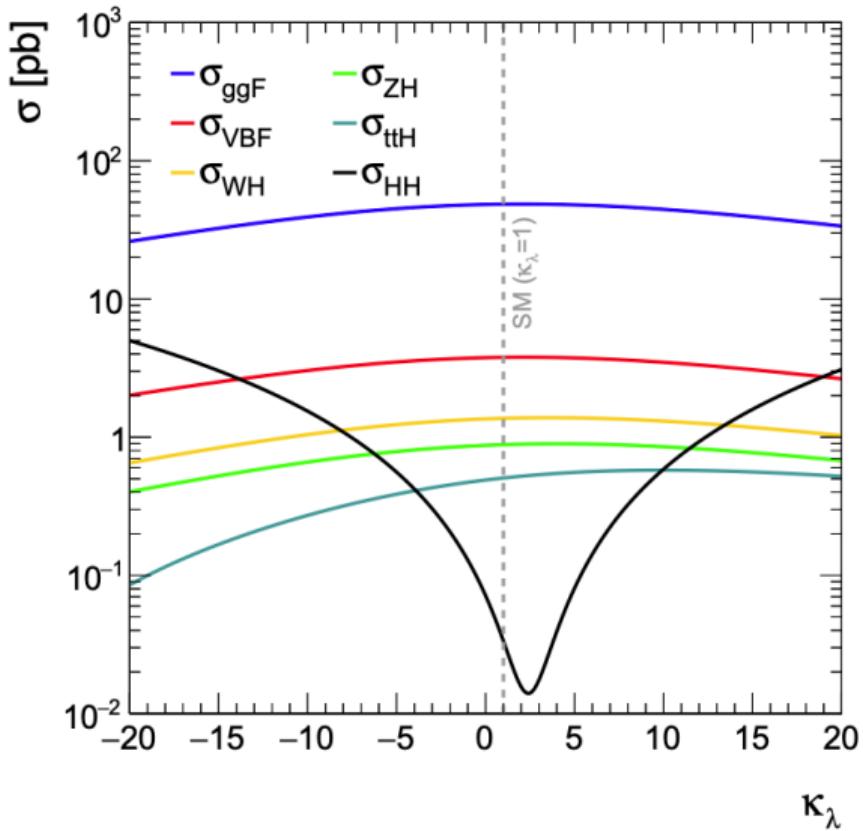
# Early Run-2 combination

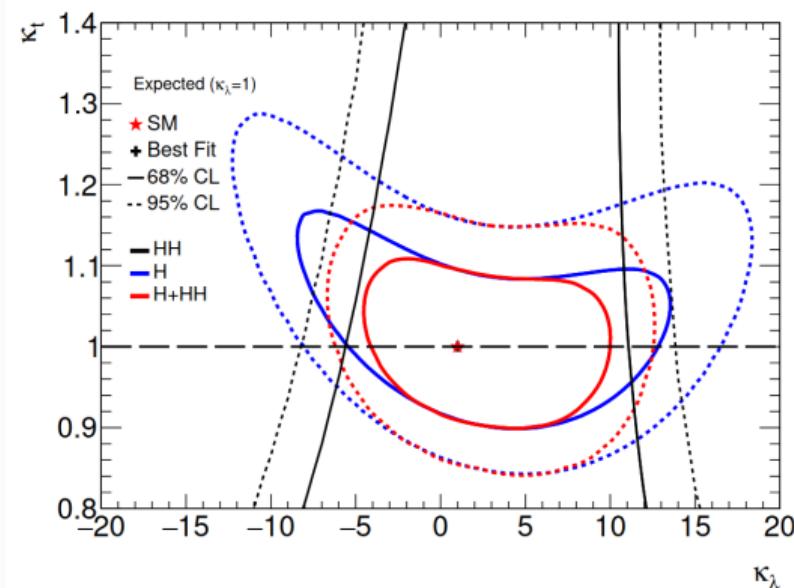
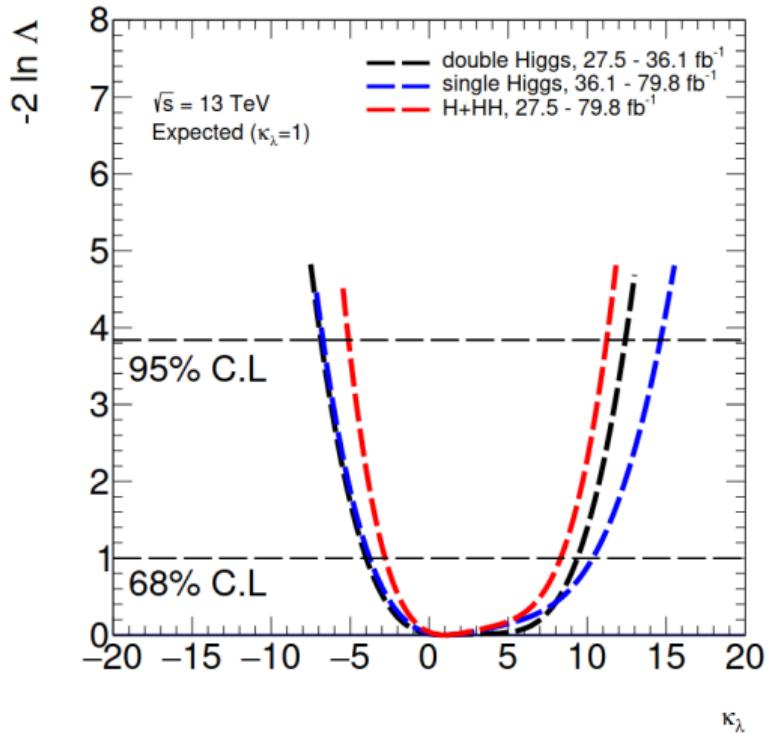


# First full Run-2 combination

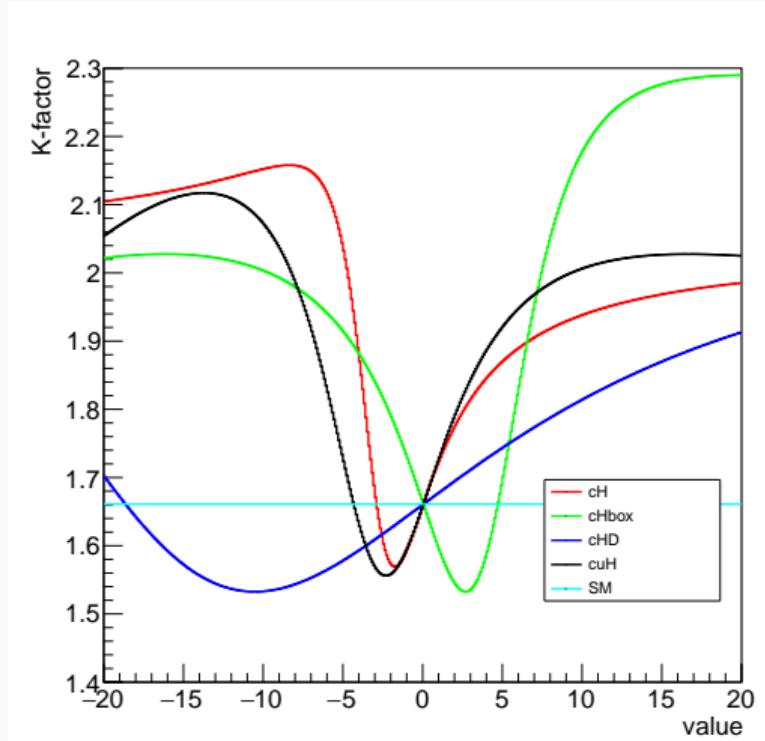
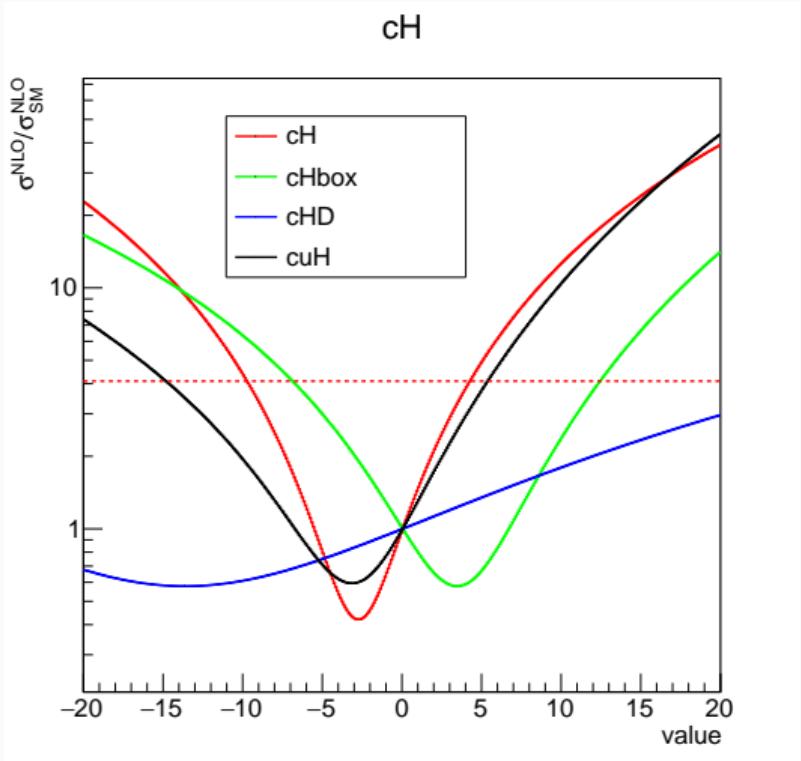


# Single Higgs vs $\kappa_\lambda$



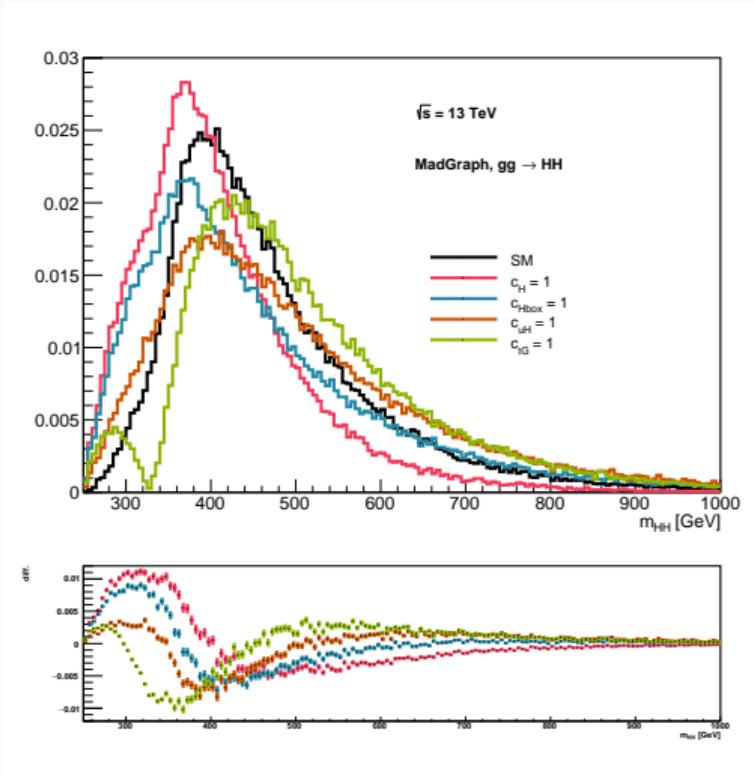


## Cross-section as function of $c_i$

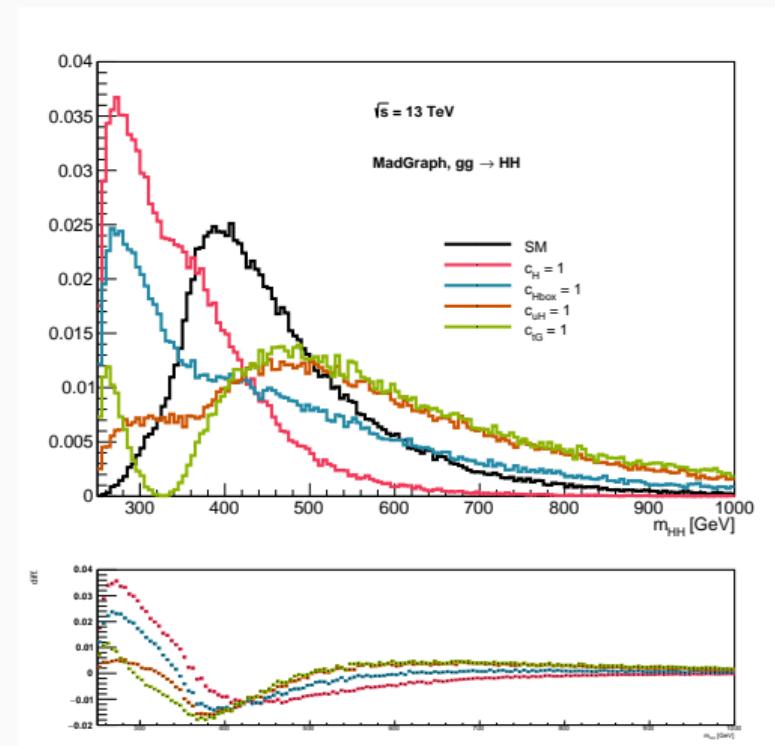


# Linear vs quadratic : $m_{HH}$ distribution

Interference

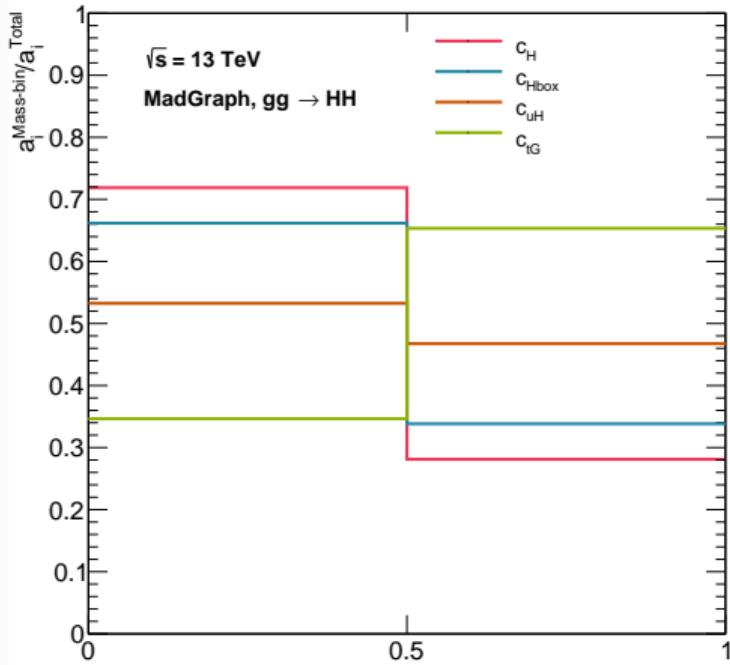


pure BSM

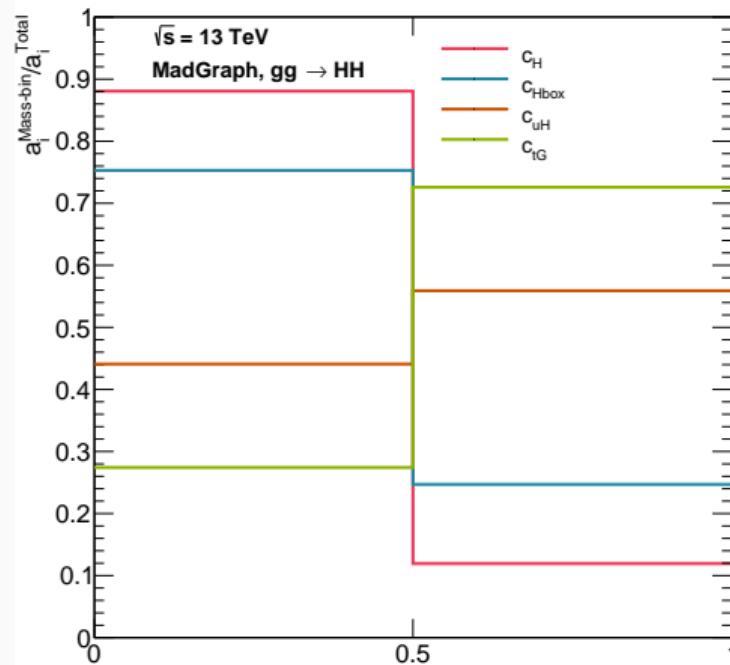


# Linear vs quadratic : Cross-section

Interference



pure BSM



## Cross-section parameterization

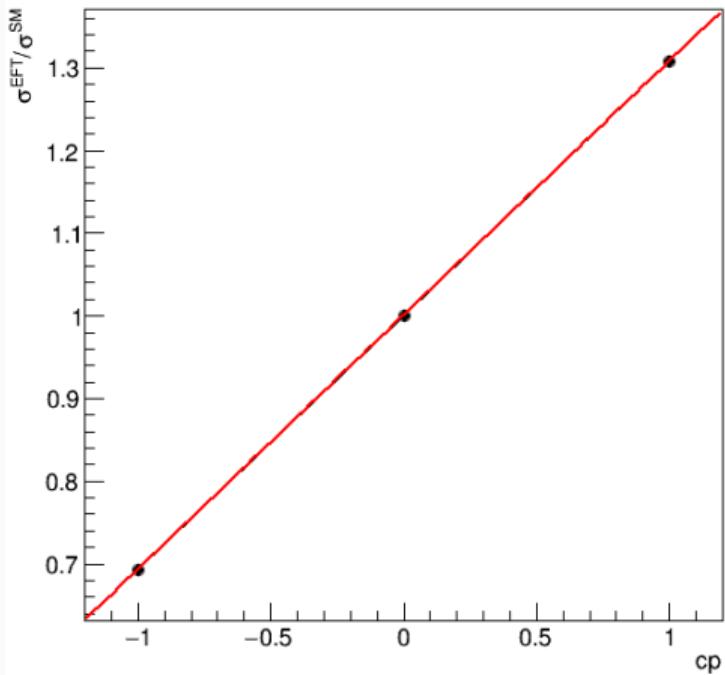
- ggF HH events simulated using MadGraph events generator + SMEFTatNLO feynrules model (using NLO card).
- Each term (linear and quadratic) is generated separately:

Command	term
generate p p > h h QED=2 QCD=2 NP=2 [QCD]	SM only
generate p p > h h NP=2 QCD=2 QED=2 NP <sup>2</sup> =2 [QCD]	Interference
generate p p > h h NP=2 QCD=2 QED=2 NP <sup>2</sup> =4 [QCD]	BSM only

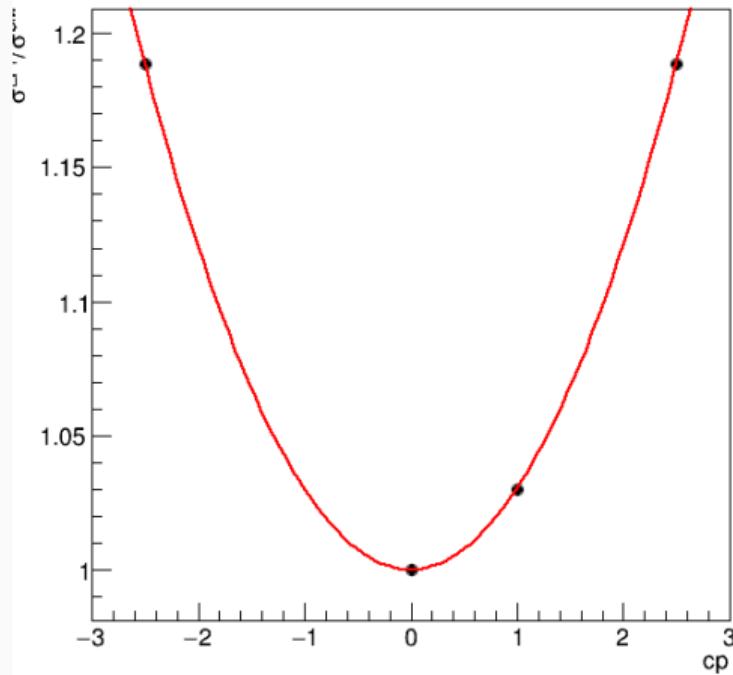
- 4 EFT variations are generated for each operator,  $c_i = \pm 1, \pm 2$
- $\frac{\sigma}{\sigma_{SM}}$  fitted in each mass region (High mass and Low mass) using
- Cross-term effect considered by generating an additional  $c_{i,j} = 1$  BSM sample and subtract individual quadratic contribution.

## $c_H$ parameterization

cp HM



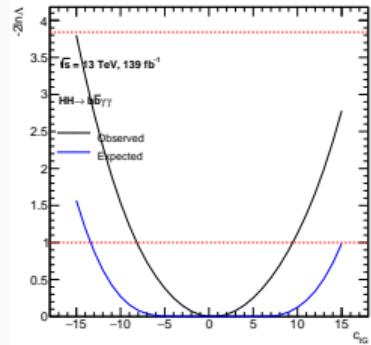
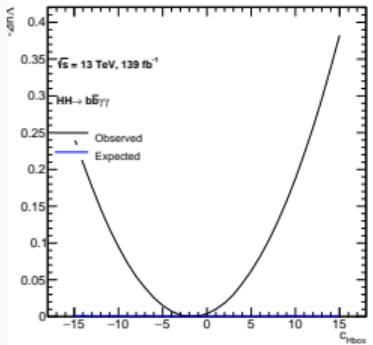
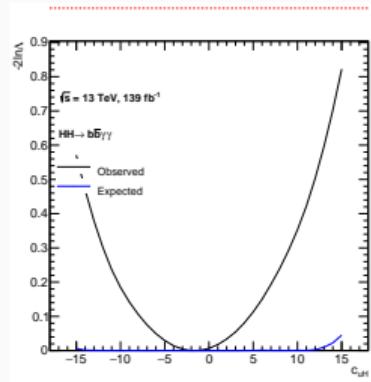
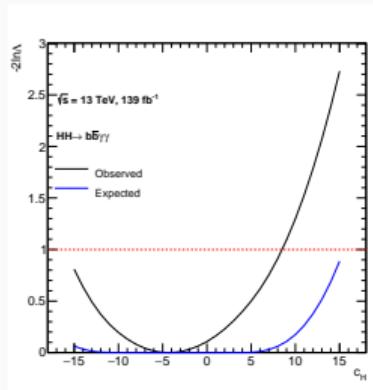
cp HM



# Parametrization

Region	$\sigma / \sigma_{SM}$
High mass	$\begin{aligned} & - 0.19 \cdot c_{H\square} + 0.02 \cdot c_{H\square}^2 + 0.31 \cdot c_H \\ & + 0.03 \cdot c_H^2 + 0.24 \cdot c_{uH} + 0.03 \cdot c_{uH}^2 \\ & - 0.30 \cdot c_{tG} + 0.05 \cdot c_{tG}^2 - 0.04 \cdot c_H \cdot c_{H\square} \\ & + 0.04 \cdot c_H \cdot c_{uH} - 0.06 \cdot c_H \cdot c_{tG} \\ & - 0.05 \cdot c_{H\square} \cdot c_{uH} + 0.04 \cdot c_{H\square} \cdot c_{tG} \\ & - 0.06 \cdot c_{uH} \cdot c_{tG} \end{aligned}$
Low mass	$\begin{aligned} & - 0.38 \cdot c_{H\square} + 0.05 \cdot c_{H\square}^2 + 0.79 \cdot c_H \\ & + 0.22 \cdot c_H^2 + 0.28 \cdot c_{uH} + 0.02 \cdot c_{uH}^2 \\ & - 0.16 \cdot c_{tG} + 0.02 \cdot c_{tG}^2 - 0.21 \cdot c_H \cdot c_{H\square} \\ & + 0.14 \cdot c_H \cdot c_{uH} + 0.09 \cdot c_H \cdot c_{tG} \\ & - 0.07 \cdot c_{H\square} \cdot c_{uH} - 0.03 \cdot c_{H\square} \cdot c_{tG} \\ & + 0.03 \cdot c_{uH} \cdot c_{tG} \end{aligned}$

# likelihood scans



## Sensitivity estimate

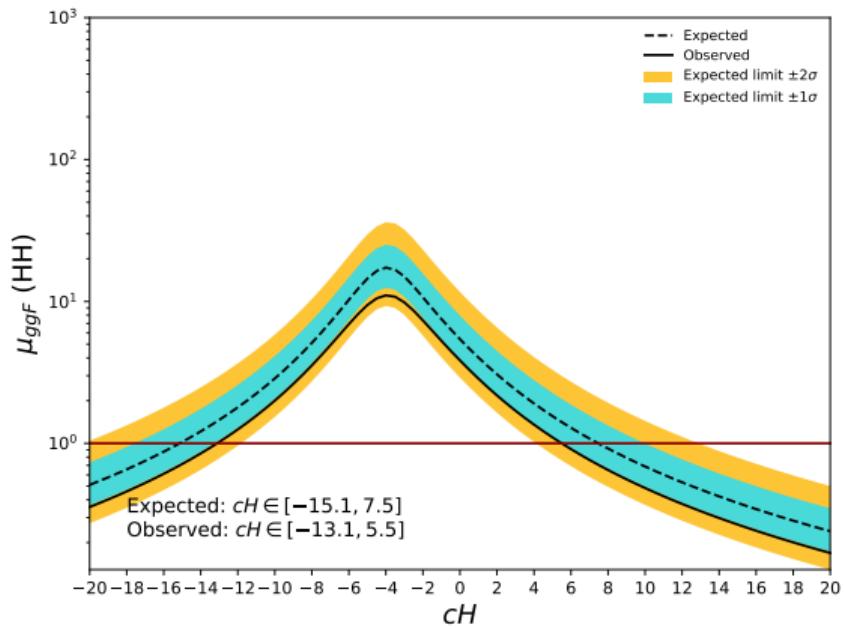
- Looking at the eigenvectors of the inverse covariance matrix of Wilson coefficients

$$C_{EFT}^{-1} = P^T \cdot C_{b\bar{b}\gamma\gamma}^{-1} \cdot P$$

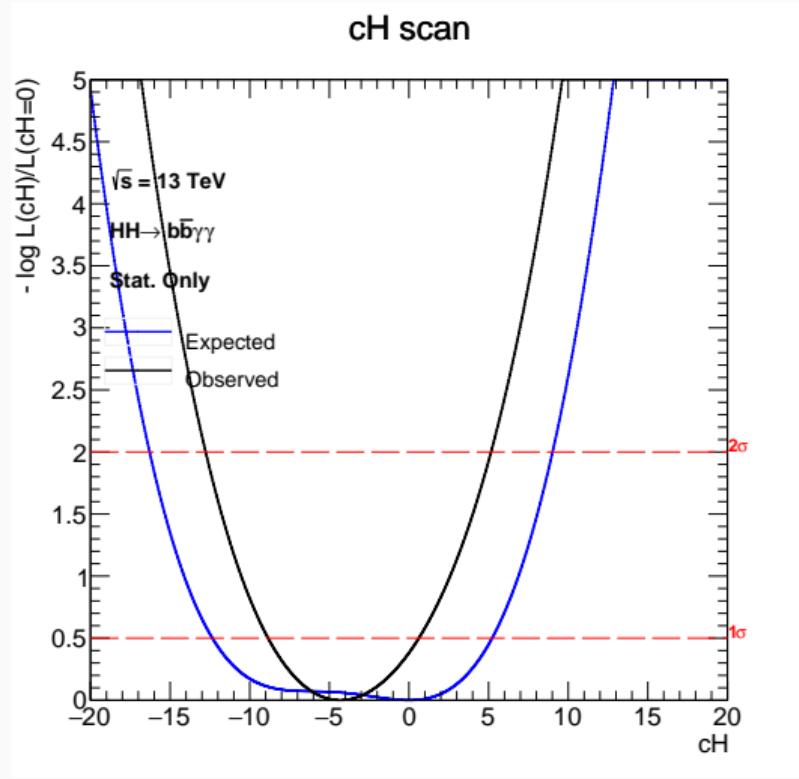
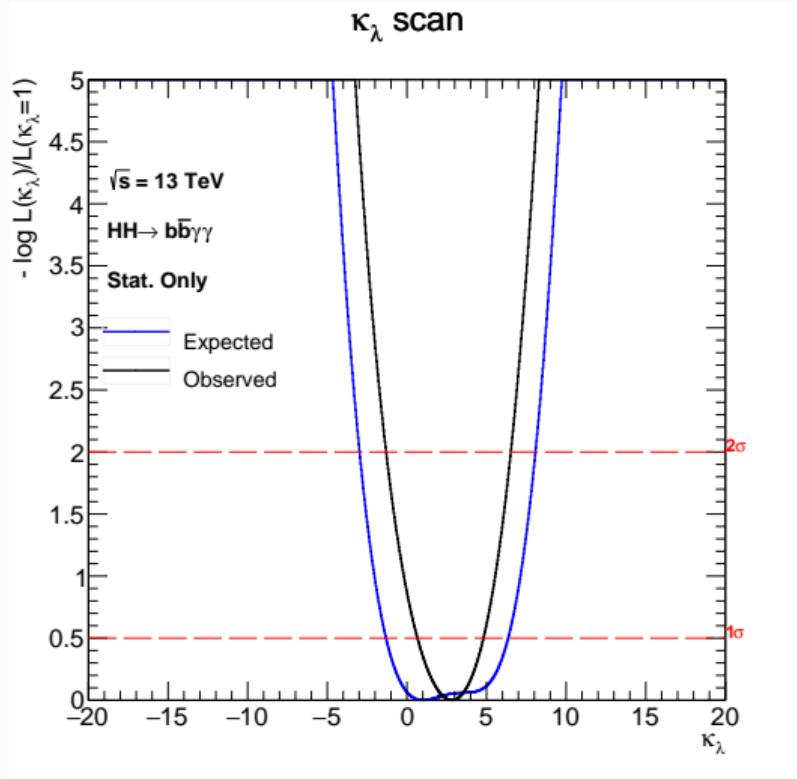
- $P$  is the parameterization matrix considering only linear terms.

Eigenvalue	Eigenvector
0.0523	- 0.582 · $c_H$ + 0.363 · $c_{H\square}$ - 0.456 · $c_{uH}$ + 0.567 · $c_{tG}$
0.0001	- 0.696 · $c_H$ + 0.182 · $c_{H\square}$ + 0.206 · $c_{uH}$ - 0.663 · $c_{tG}$
-0.0000	- 1.025 · $c_H$ - 1.947 · $c_{H\square}$ + 0.702 · $c_{uH}$ + 0.759 · $c_{tG}$
-0.0000	- 0.235 · $c_H$ - 0.006 · $c_{H\square}$ + 0.977 · $c_{uH}$ + 0.549 · $c_{tG}$

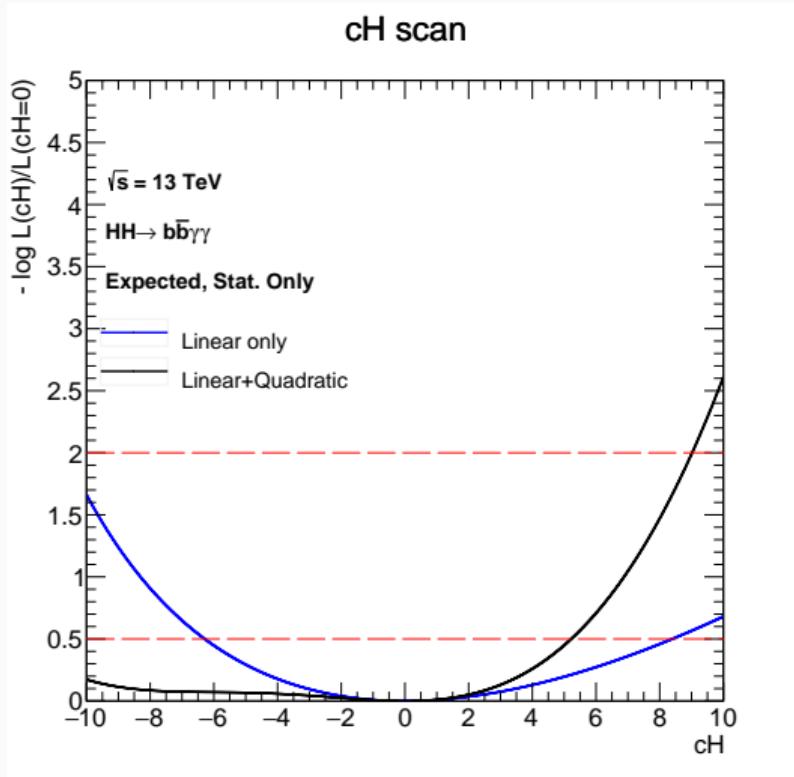
$cH$  only



# $c_H$ vs $\kappa_\lambda$

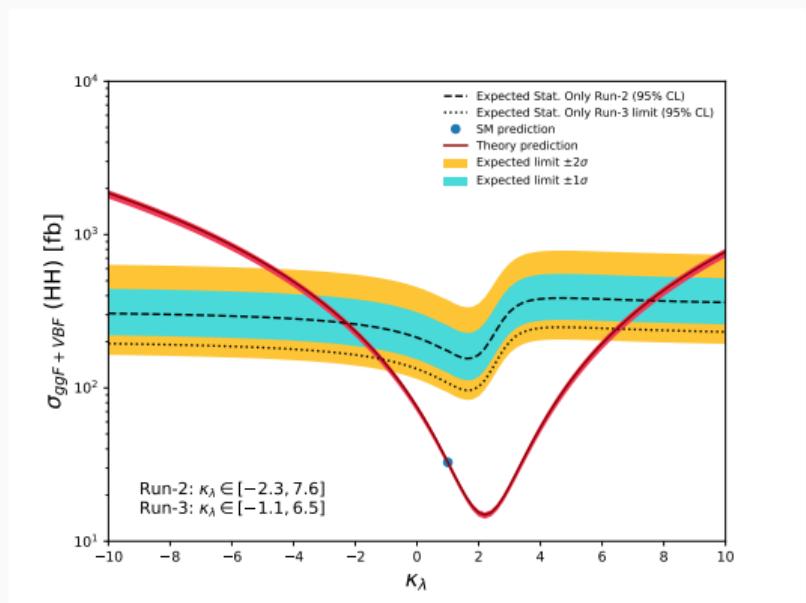


# Linear vs Quadratic



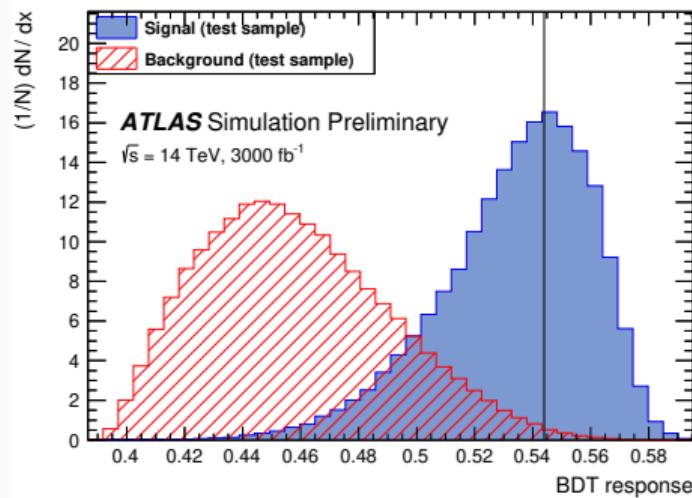
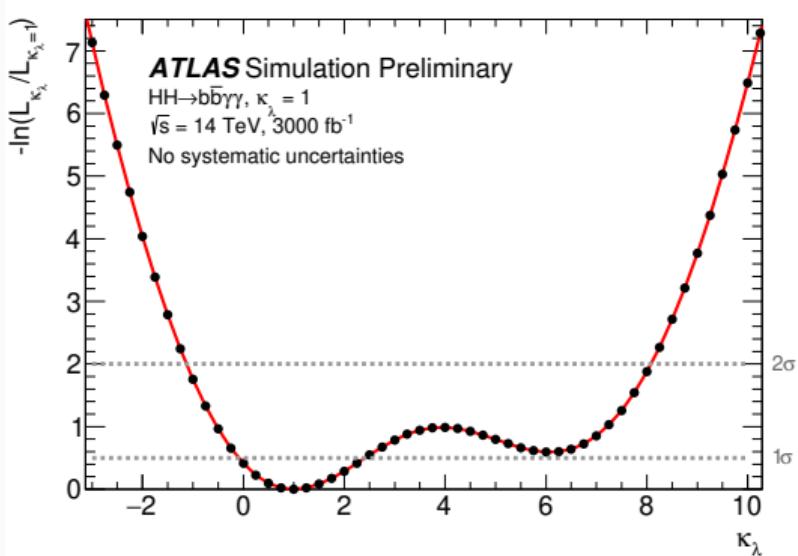
# Extrapolation to Run-3

- Scale Run-2 with  $300/139 \sim 2.16$
- Expected 95% CL limit on  $\sigma_{HH}$  of 3.3
- $\mu_{HH} = 1 \pm 1.52$  for SM
- SM HH significance:  $0.71\sigma$



# European strategy

- Monte Carlo based  $b\bar{b}\gamma\gamma$  analysis
- One BDT category, 40% efficiency and 99% of background rejection
- Signal extracted using  $m_{b\bar{b}\gamma\gamma}$  variable.
- $\mu = 1 \pm 0.6$  with significance of  $2.1\sigma$



Scenario	$1\sigma$ CI	$2\sigma$ CI
Stat.	$-0.1 < \kappa_\lambda < 2.4$	$-1.1 < \kappa_\lambda < 8.1$
Syst.	$-0.2 < \kappa_\lambda < 2.5$	$-1.4 < \kappa_\lambda < 8.2$

## Extrapolation to HL-LHC

Process	ggF HH	VBF HH	ggF H	VBF H	$t\bar{t}H$	WH	ZH	tHjb	tWH	$\gamma\gamma$
Scale	1.19	1.2	1.13	1.13	1.21	1.1	1.11	1.21	1.22	+18%

Scenario	Run-2 Stat. Only	HL-LHC Stat. Only
High mass, High BDT	0.47	2.38
High mass, Low BDT	0.13	0.64
Low mass, High BDT	0.03	0.15
Low mass, Low BDT	0.02	0.10
Combined	$0.48\sigma$	$2.47\sigma$

- $\mu_{HH} = 1 \pm 0.44$

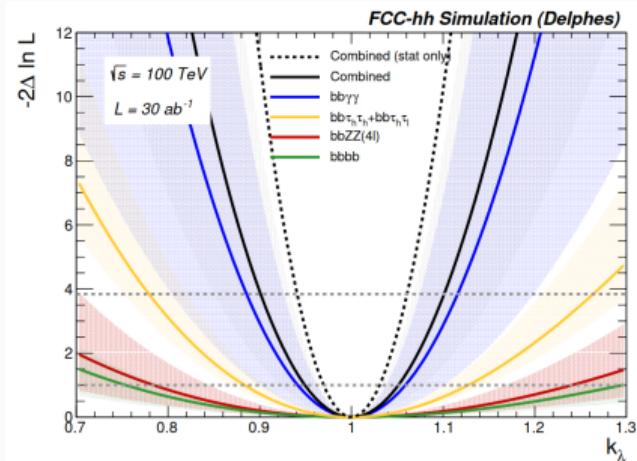
# Prospect in FCC-hh

2004.03505

- $pp$  collider at  $\sqrt{s} = 100$  TeV.
- $\mathcal{L}_{int} = 30 \text{ ab}^{-1}$
- From 14 TeV to 100 TeV,  $\times 30$  increase in cross-section

	@68% CL	scenario I	scenario II	scenario III
$\delta_\mu$	stat only	2.5	3.6	5.6
$\delta_\mu$	stat + syst	2.8	4.4	7.5
$\delta_{\kappa_\lambda}$	stat only	3.4	4.8	7.4
$\delta_{\kappa_\lambda}$	stat + syst	3.8	5.9	10.0

- Sensitivity driven by  $b\bar{b}\gamma\gamma$
- **Systematics limited** (control of systematic needed)



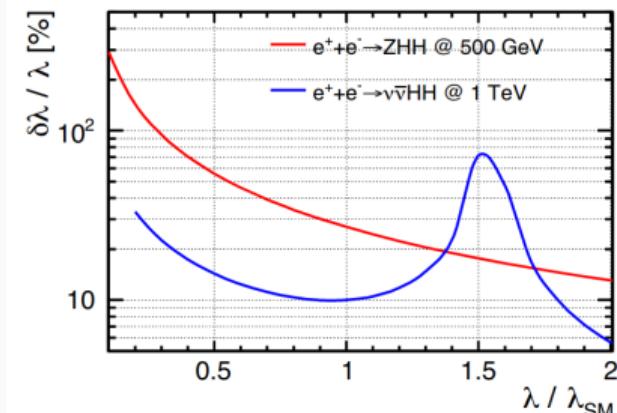
- Scenario I: optimistic, detector performance similar to Run-2
- Scenario II: realistic, intermediate
- Scenario III: conservative (pessimistic), extrapolated from HL-LHC performances

## Systematics scenarios

parameterisation	scenario I	scenario II	scenario III
b-jet ID eff.	82-65%	80-63%	78-60%
b-jet c mistag	15-3%	15-3%	15-3%
b-jet l mistag	1-0.1%	1-0.1%	1-0.1%
$\tau$ -jet ID eff	80-70%	78-67%	75-65%
$\tau$ -jet mistag (jet)	2-1%	2-1%	2-1%
$\tau$ -jet mistag (ele)	0.1-0.04%	0.1-0.04%	0.1-0.04%
$\gamma$ ID eff.	90	90	90
jet $\rightarrow \gamma$ eff.	0.1	0.2	0.4
$m_{\gamma\gamma}$ resolution [GeV]	1.2	1.8	2.9
$m_{bb}$ resolution [GeV]	10	15	20

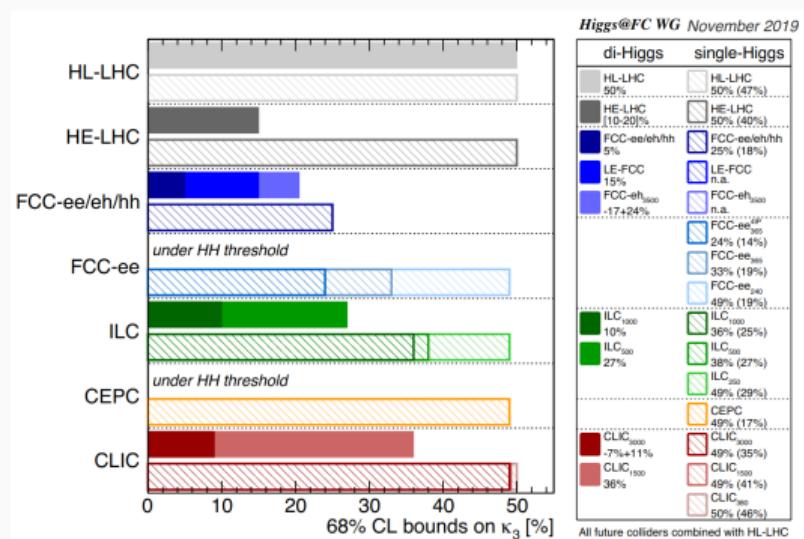
# Prospect in $e^+e^-$ collider

- directly accessible via  $ZHH$  and  $\nu\bar{\nu}HH$
- $\delta^{\text{ILC}}(1 \text{ TeV}) = 10\%$  ,  $\delta^{\text{CLIC}}(3 \text{ TeV}) = 9\%$

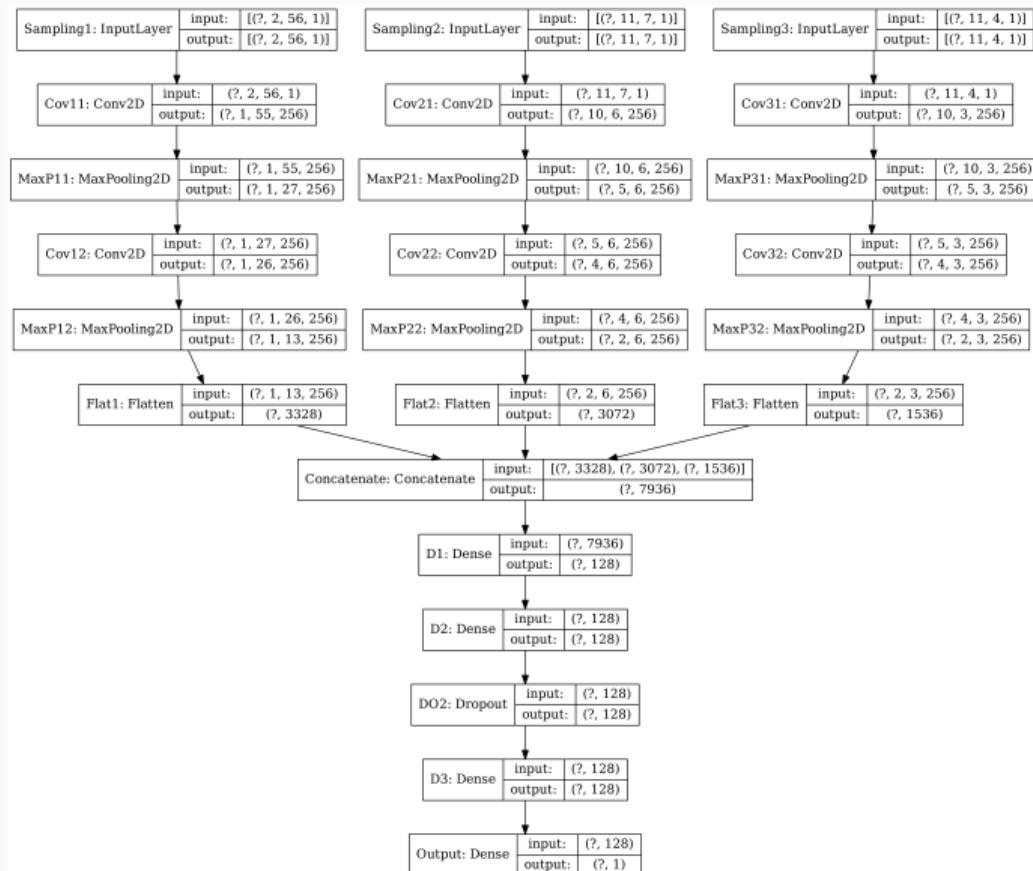


# Knowledge from $\kappa_\lambda$

- **50% sensitivity** → reject  $\kappa_\lambda = 0$  at 95%
- **20% sensitivity** →  $5\sigma$  discovery of SM HH
- **5% sensitivity** → sensitive to quantum corrections to Higgs potential
- Precise measurement of  $\kappa_\lambda$  at FCC-hh requires precise knowledge of  $\kappa_t$
- 1%  $\kappa_t$  leads to 5%  $\kappa_\lambda$
- precise measurement of  $\kappa_t$  needs FCC-ee



# CNN architecture



## CNN images size

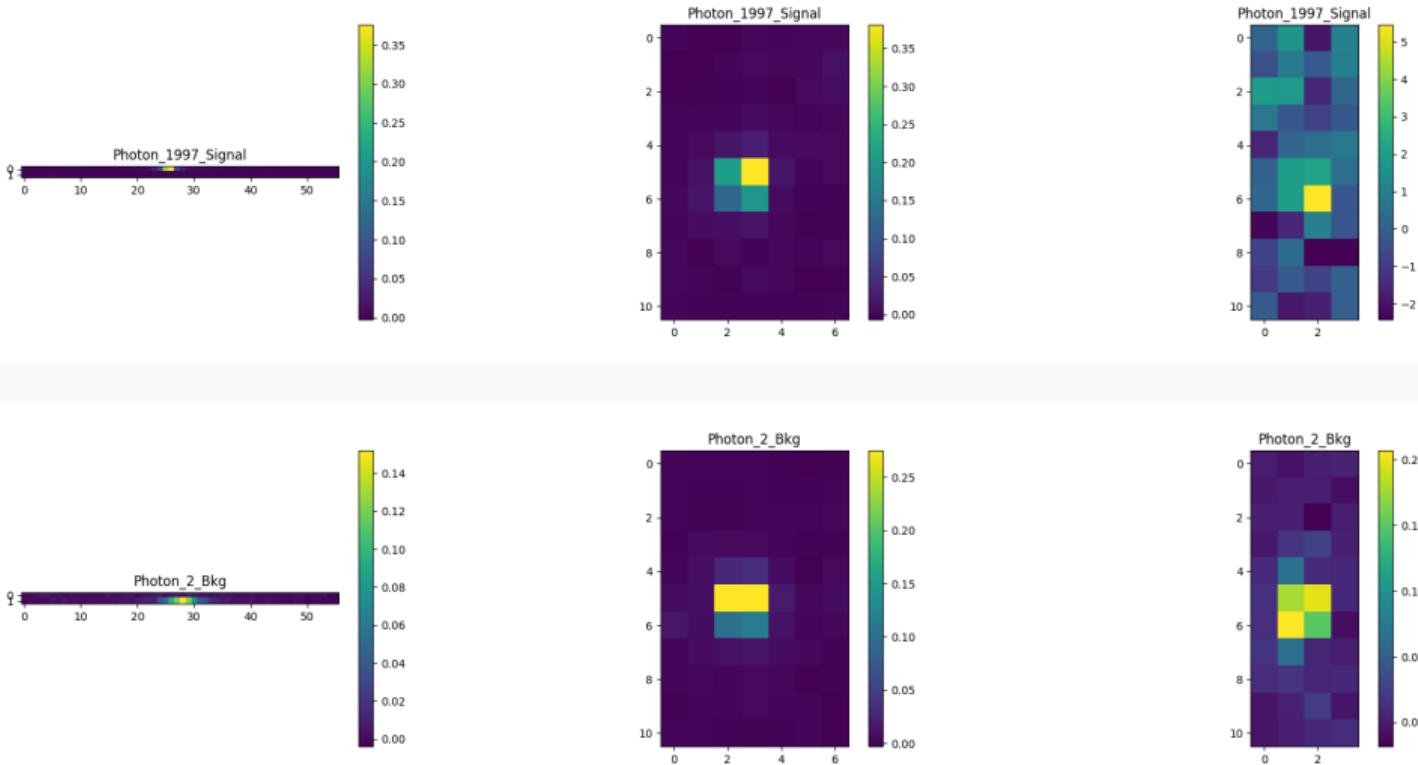
$ \eta $ range	0 to 1.4	1.4 to 1.8	1.8 to 2.0	2.0 to 2.5
Sampling 1	112	112	84	56
Sampling 2	77	77	77	77
Sampling 3	44	44	44	44

**Table 1:** Number of cells in  $7 \times 11$  EM calorimeter windows.

Sampling	Shape
Sampling 1	(56, 2)
Sampling 2	(7, 11)
Sampling 3	(4, 11)

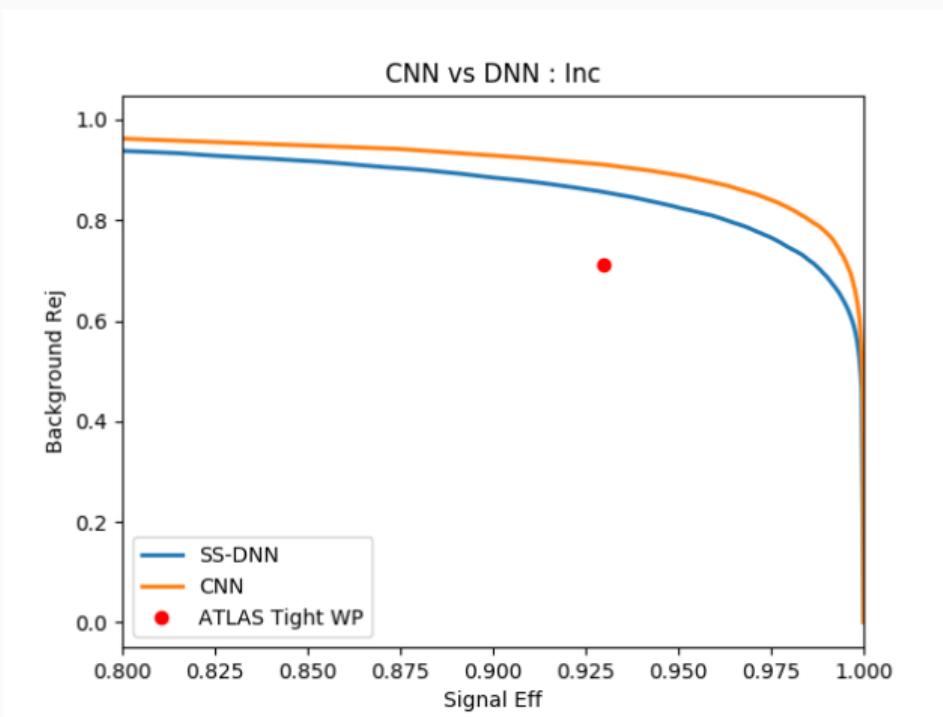
**Table 2:** Image shape of  $7 \times 11$  windows in each sampling in  $(\eta, \phi)$ .

# Example of training images



# CNN vs DNN for photon identification

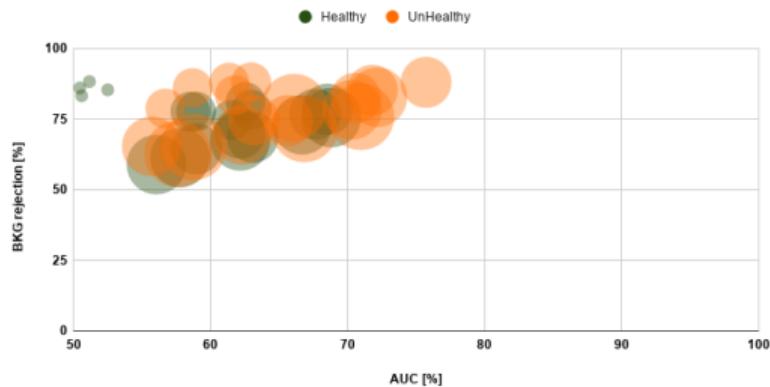
- SS-DNN trained on shower shapes variables
- CNN trained using images



# CNN performance compared to cut-based

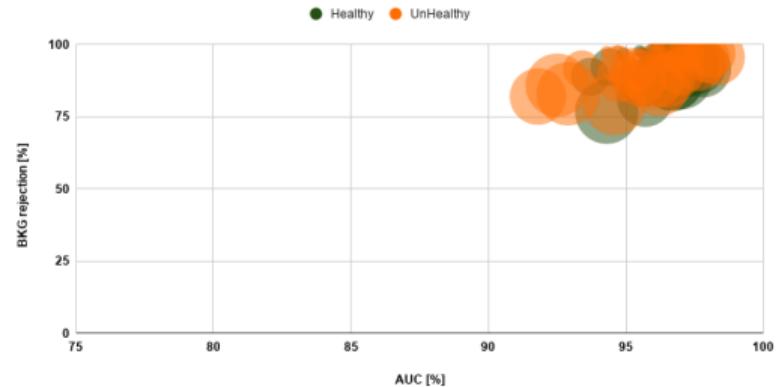
AUC versus BKG rejection

ATLAS Tight WP

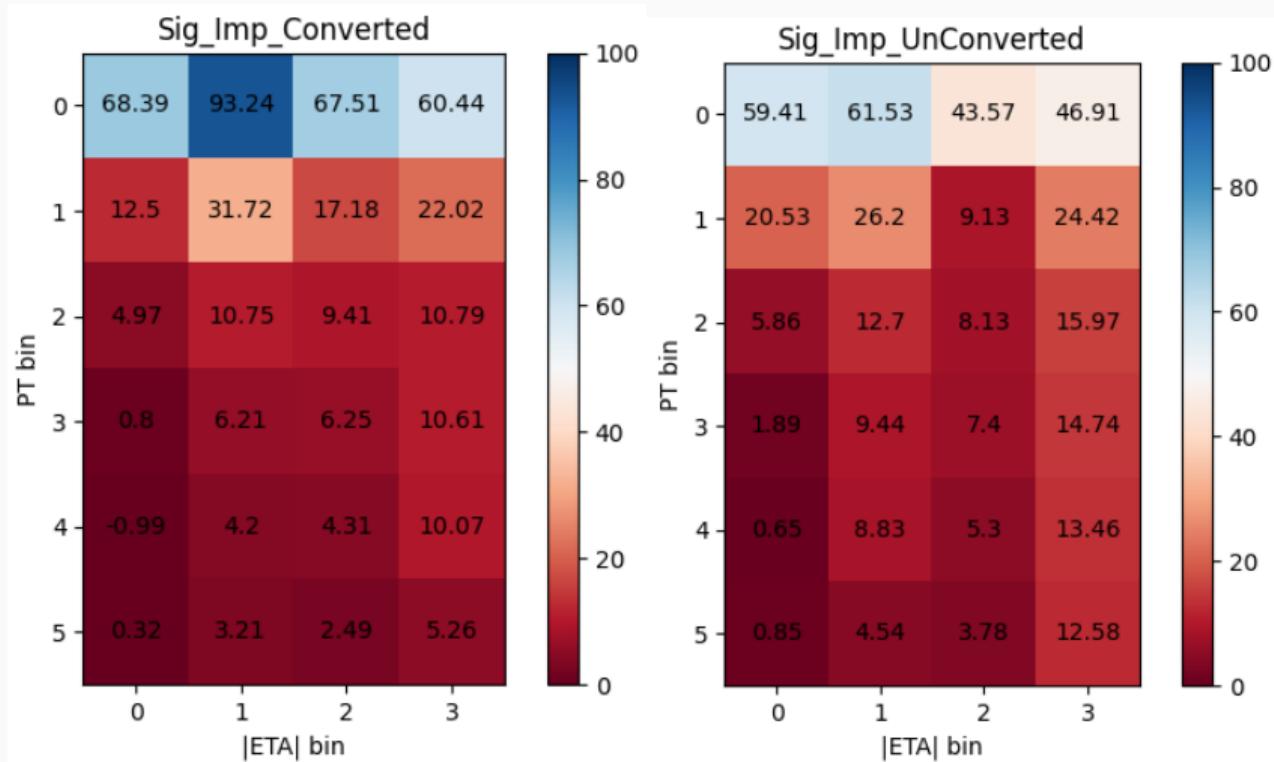


AUC versus BKG rejection

CNN Trained on Mixture

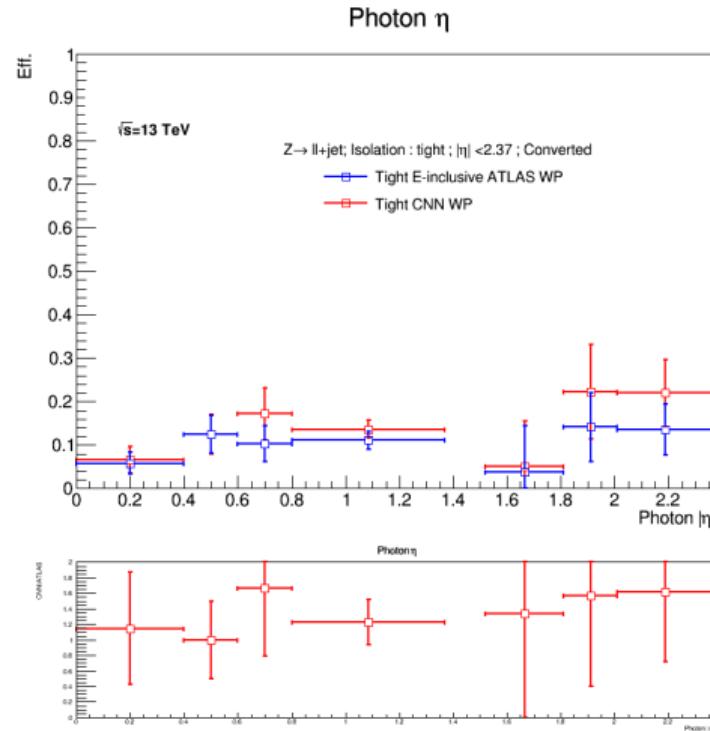
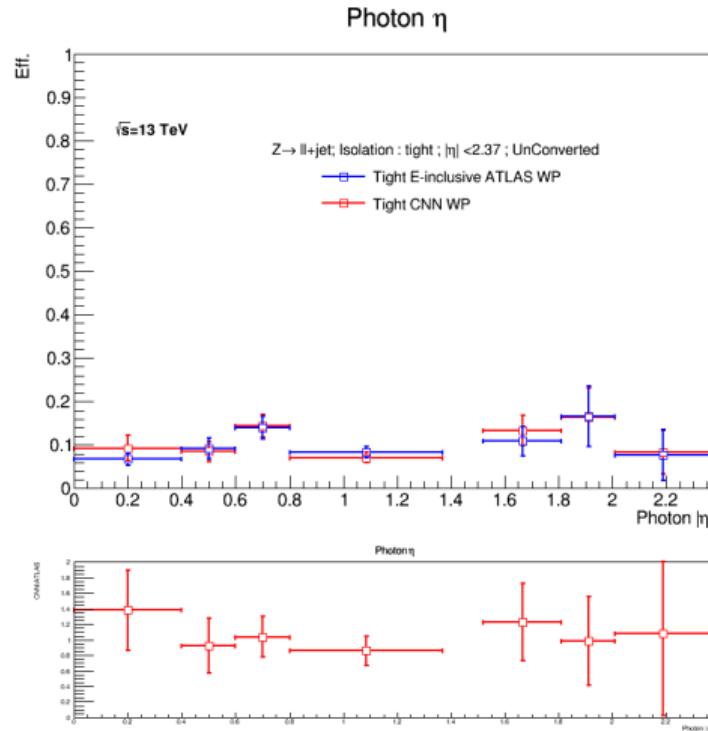


# CNN signal improvement

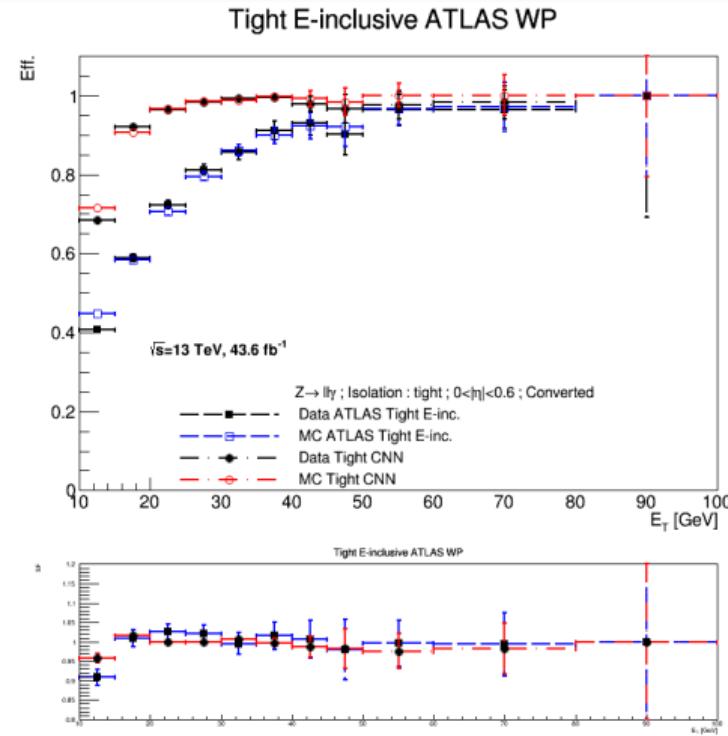
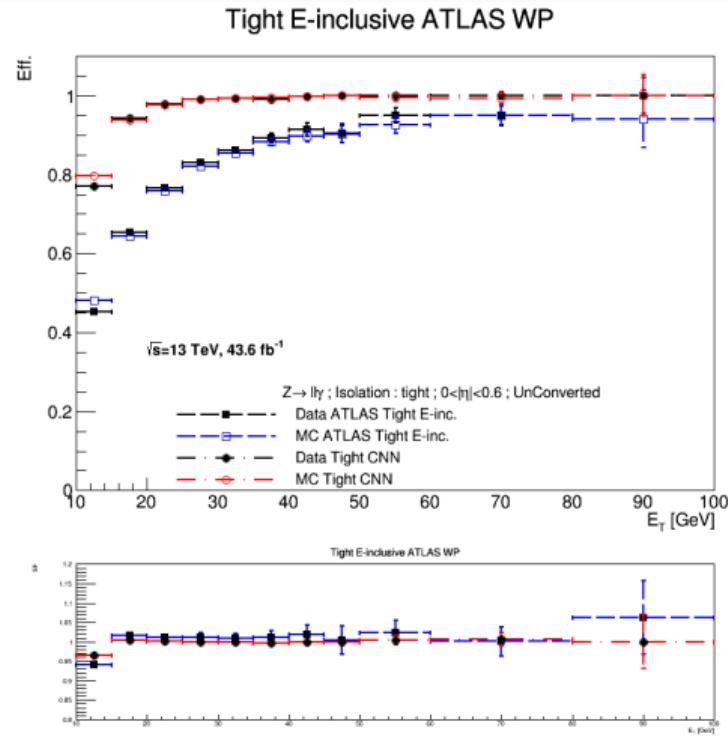


$$p_T = [10, 20, 30, 40, 60, 80, \infty], |\eta| = [0, 0.6, 1.37, 1.52, 1.8, 2.4]$$

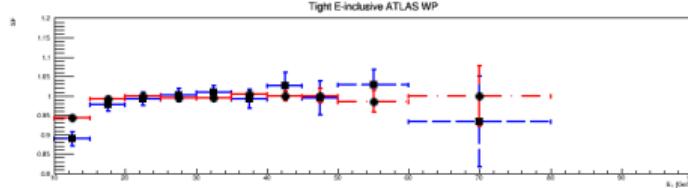
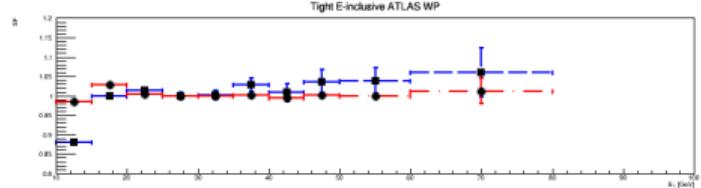
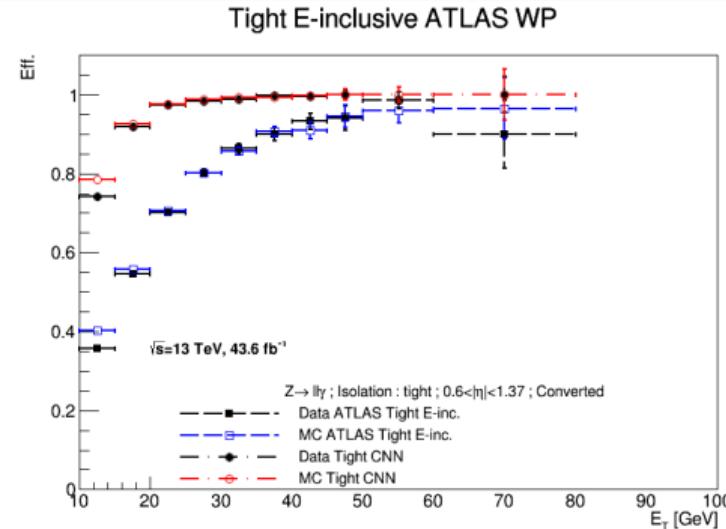
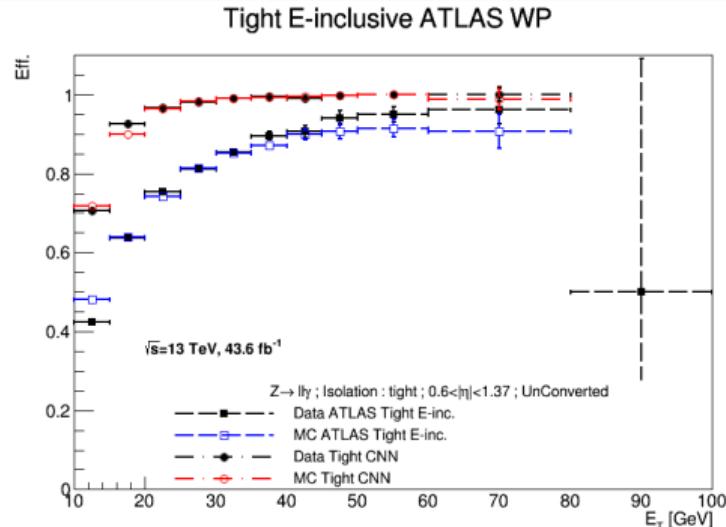
## CNN background rejection



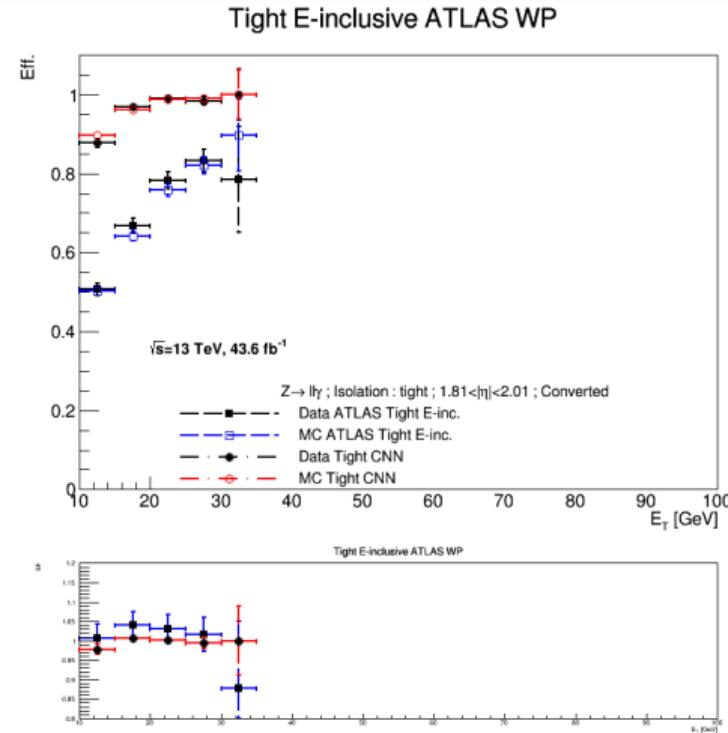
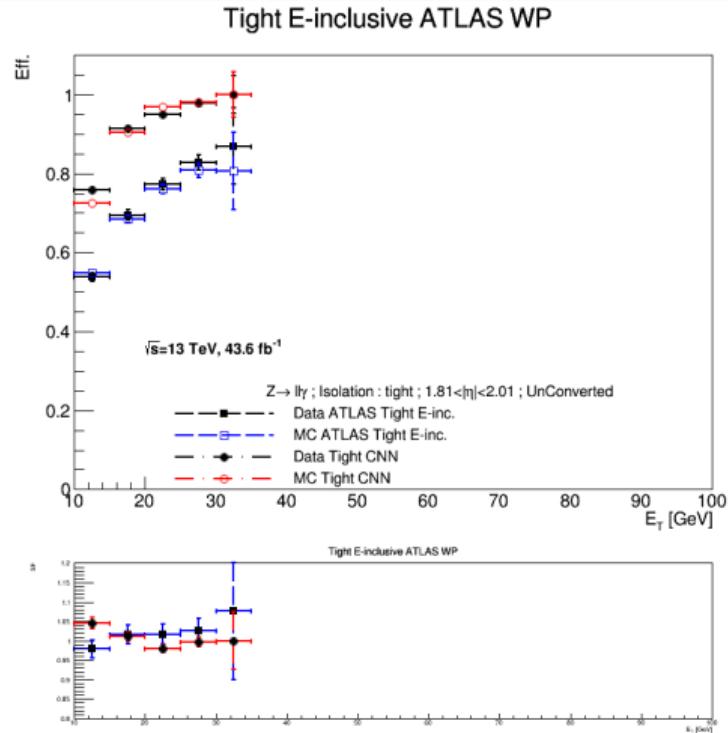
# CNN efficiency, $|\eta| < 0.6$



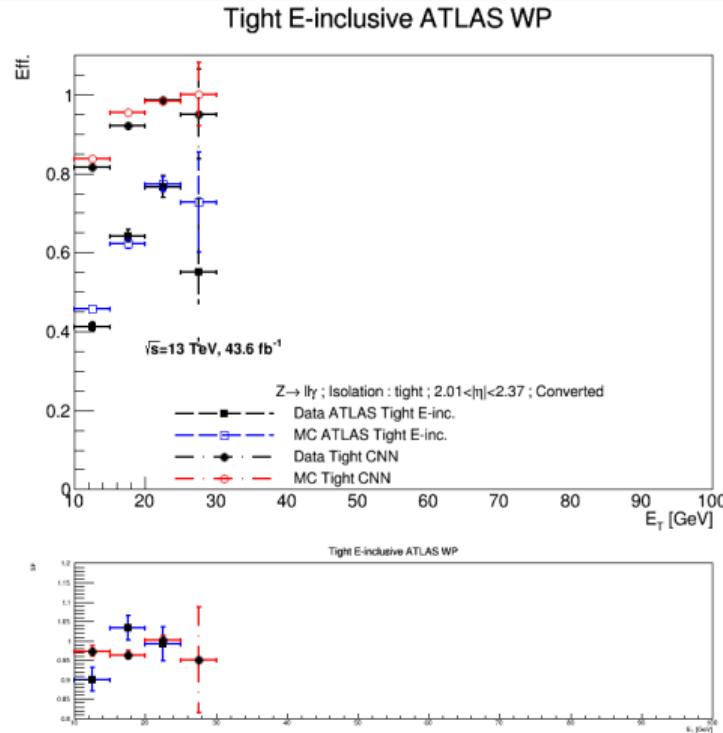
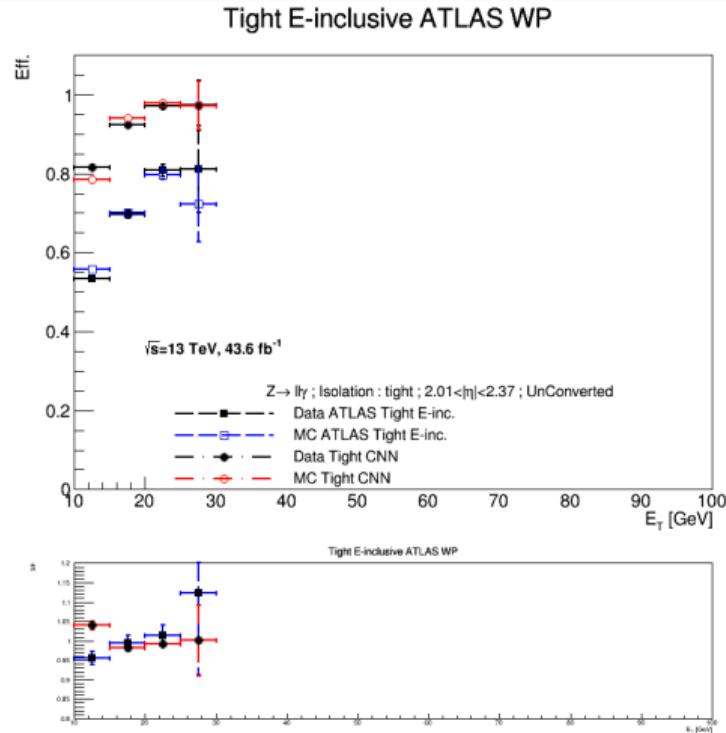
# CNN efficiency, $0.6 < |\eta| < 1.37$



# CNN efficiency, $1.81 < |\eta| < 2.01$



# CNN efficiency, $2.01 < |\eta| < 2.37$



## photon purity before CNN cut

	Unconverted			Converted		
	$e\bar{e}\gamma$	$\mu\bar{\mu}\gamma$	$ll\gamma$	$e\bar{e}\gamma$	$\mu\bar{\mu}\gamma$	$ll\gamma$
$10 < E_T < 15$	$98.1 \pm 4.7$	$96.2 \pm 1.9$	$96.6 \pm 1.8$	$97.8 \pm 7.7$	$95.7 \pm 3.4$	$96.2 \pm 3.1$
$15 < E_T < 20$	$99.4 \pm 12.7$	$99.1 \pm 5.1$	$90.7 \pm 1.9$	$99.3 \pm 20.2$	$98.7 \pm 7.5$	$98.8 \pm 6.9$
$20 < E_T < 25$	$99.5 \pm 24.2$	$99.6 \pm 10.3$	$99.6 \pm 9.5$	$99.2 \pm 29.4$	$99.4 \pm 13.3$	$99.2 \pm 11.2$
$25 < E_T < 30$	$99.4 \pm 33.8$	$99.7 \pm 15.2$	$99.7 \pm 14.5$	$99.3 \pm 51.4$	$99.5 \pm 19.1$	$99.5 \pm 18.2$
$30 < E_T < 100$	$99.1 \pm 33$	$99.7 \pm 17.8$	$99.7 \pm 16.5$	$99.1 \pm 50.8$	$99.6 \pm 23.4$	$99.5 \pm 21.4$

**Table 3:** Fitted photon purity in % of all probes, before tight CNN WP. The uncertainties are only statistical.

## photon purity after CNN cut

	Unconverted			Converted		
	$e e \gamma$	$\mu \mu \gamma$	$l l \gamma$	$e e \gamma$	$\mu \mu \gamma$	$l l \gamma$
$10 < E_T < 15$	$99.6 \pm 11.2$	$98.9 \pm 4.1$	$99.1 \pm 3.8$	$99.3 \pm 16.1$	$98.5 \pm 6.4$	$98.7 \pm 6.02$
$15 < E_T < 20$	$99.8 \pm 23.1$	$99.7 \pm 8.9$	$99.7 \pm 8.1$	$99.7 \pm 34.1$	$99.6 \pm 13.2$	$99.6 \pm 12.0$
$20 < E_T < 25$	$99.8 \pm 38.1$	$99.8 \pm 15.2$	$99.8 \pm 14.1$	$99.7 \pm 46.6$	$99.6 \pm 17.9$	$99.7 \pm 18.1$
$25 < E_T < 30$	$99.7 \pm 49.1$	$99.8 \pm 18.8$	$99.8 \pm 18.5$	$99.6 \pm 66.1$	$99.7 \pm 25.6$	$99.7 \pm 25.$
$30 < E_T < 100$	$99.5 \pm 45.6$	$99.8 \pm 21.2$	$99.8 \pm 20.7$	$98.9 \pm 49.4$	$99.7 \pm 28.5$	$99.7 \pm 25.8$

**Table 4:** Fitted photon purity in % of all probes, after tight CNN WP. The uncertainties are only statistical.

## scale factors for unconverted

	$0 <  \eta  < 0.6$	$0.6 <  \eta  < 1.37$	$1.81 <  \eta  < 2.01$	$2.01 <  \eta  < 2.37$
$10 < E_T < 15$	$0.965 \pm 0.0046$	$0.984 \pm 0.0051$	$1.045 \pm 0.0155$	$1.04 \pm 0.011$
$15 < E_T < 20$	$1.01 \pm 0.0032$	$1.03 \pm 0.0036$	$1.01 \pm 0.0114$	$0.982 \pm 0.008$
$20 < E_T < 25$	$1.002 \pm 0.0026$	$1.003 \pm 0.003$	$0.980 \pm 0.0099$	$0.992 \pm 0.0093$
$25 < E_T < 30$	$0.999 \pm 0.0025$	$0.998 \pm 0.003$	$0.997 \pm 0.0114$	$1.001 \pm 0.091$
$30 < E_T < 35$	$0.999 \pm 0.0032$	$0.999 \pm 0.0032$	$1 \pm 0.0746$	
$35 < E_T < 40$	$0.996 \pm 0.0051$	$1.002 \pm 0.0043$		
$40 < E_T < 45$	$0.999 \pm 0.0067$	$0.995 \pm 0.0077$		
$45 < E_T < 50$	$1 \pm 0.0086$	$1.001 \pm 0.0093$		
$50 < E_T < 60$	$1.004 \pm 0.0114$	$1 \pm 0.0097$		
$60 < E_T < 80$	$1.006 \pm 0.0179$	$1.012 \pm 0.0326$		
$80 < E_T < 100$	$1 \pm 0.07$			

**Table 5:** Scale factors for tight CNN WP efficiency measured with unconverted photons from  $Z \rightarrow ll\gamma$  decays, in various bins of pseudorapidity and transverse energy. The uncertainty includes only statistical components.

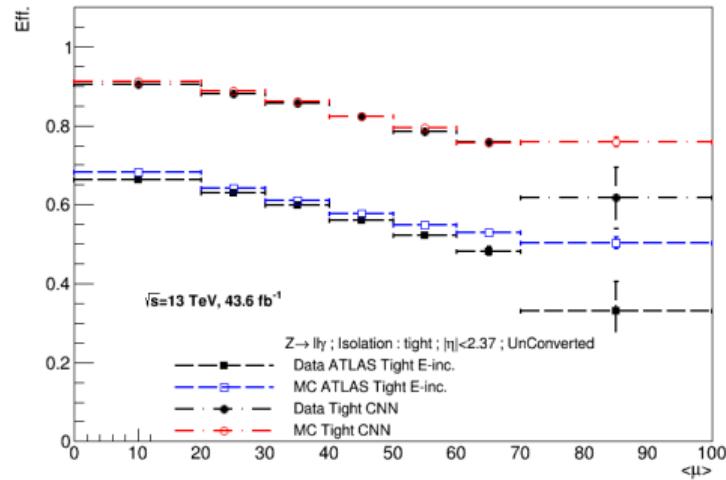
## scale factors for converted

	$0 <  \eta  < 0.6$	$0.6 <  \eta  < 1.37$	$1.81 <  \eta  < 2.01$	$2.01 <  \eta  < 2.37$
$10 < E_T < 15$	$0.96 \pm 0.012$	$0.944 \pm 0.0085$	$0.978 \pm 0.013$	$0.973 \pm 0.013$
$15 < E_T < 20$	$1.02 \pm 0.008$	$0.99 \pm 0.006$	$1.008 \pm 0.01$	$0.963 \pm 0.011$
$20 < E_T < 25$	$0.999 \pm 0.0067$	$0.99 \pm 0.0044$	$1.001 \pm 0.008$	$1.003 \pm 0.012$
$25 < E_T < 30$	$0.999 \pm 0.0063$	$0.995 \pm 0.0044$	$0.994 \pm 0.014$	$0.95 \pm 0.137$
$30 < E_T < 35$	$1.007 \pm 0.0079$	$0.995 \pm 0.0054$	$1 \pm 0.089$	
$35 < E_T < 40$	$0.997 \pm 0.0114$	$1.004 \pm 0.0066$		
$40 < E_T < 45$	$0.987 \pm 0.0277$	$0.998 \pm 0.012$		
$45 < E_T < 50$	$0.983 \pm 0.0508$	$1. \pm 0.018$		
$50 < E_T < 60$	$0.976 \pm 0.0455$	$0.99 \pm 0.0279$		
$60 < E_T < 80$	$0.983 \pm 0.0654$	$1. \pm 0.078$		
$80 < E_T < 100$	$1 \pm 0.37$			

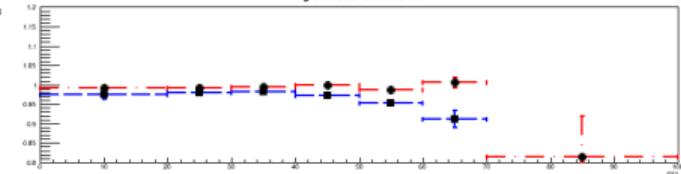
**Table 6:** Scale factors for tight CNN WP efficiency measured with converted photons from  $Z \rightarrow ll\gamma$  decays, in various bins of pseudorapidity and transverse energy. The uncertainty includes only statistical components.

# Pile-up effect on CNN

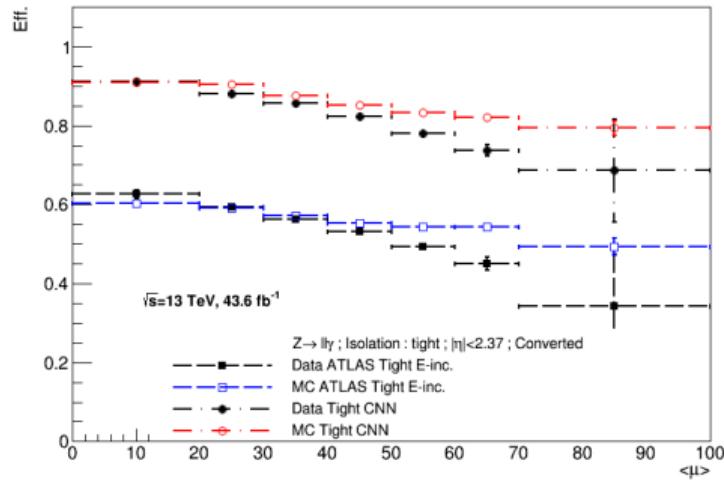
Tight E-inclusive ATLAS WP



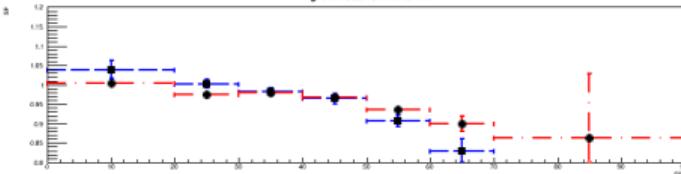
Tight E-inclusive ATLAS WP



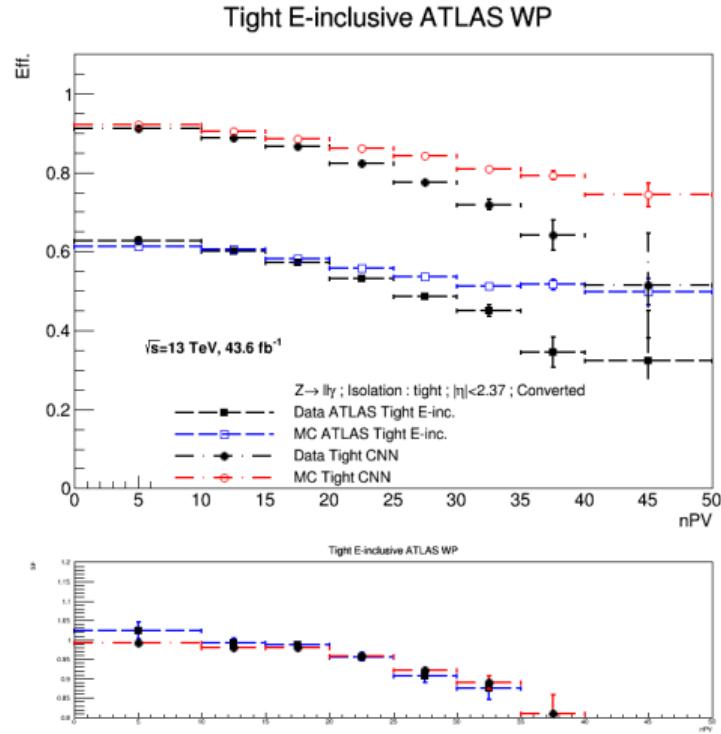
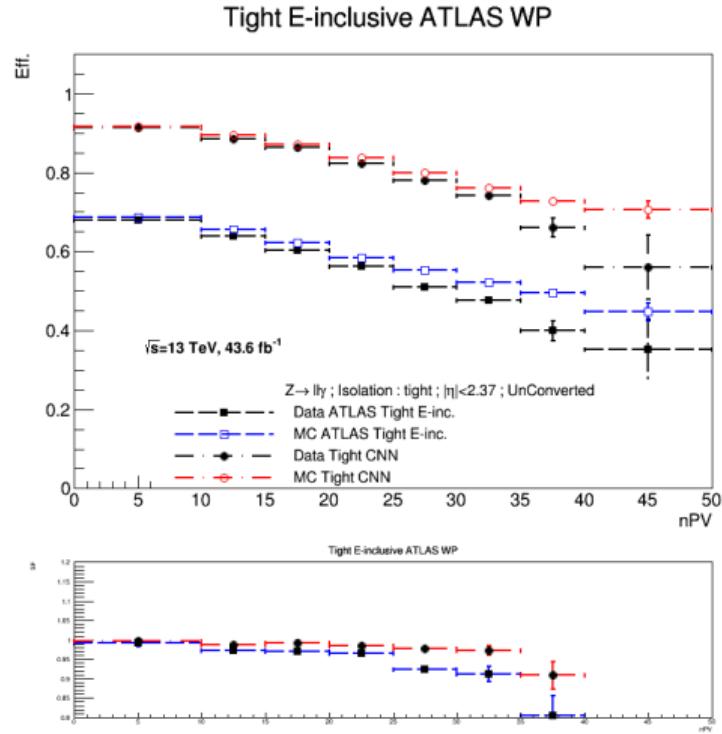
Tight E-inclusive ATLAS WP



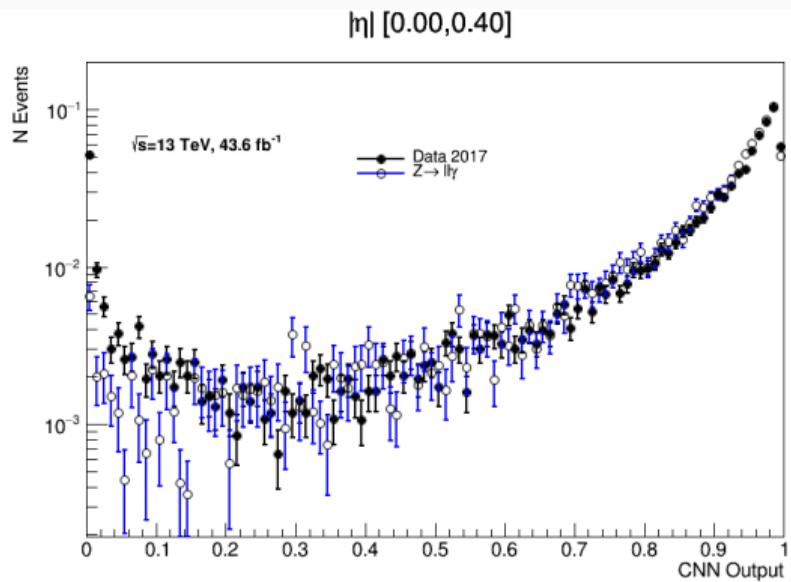
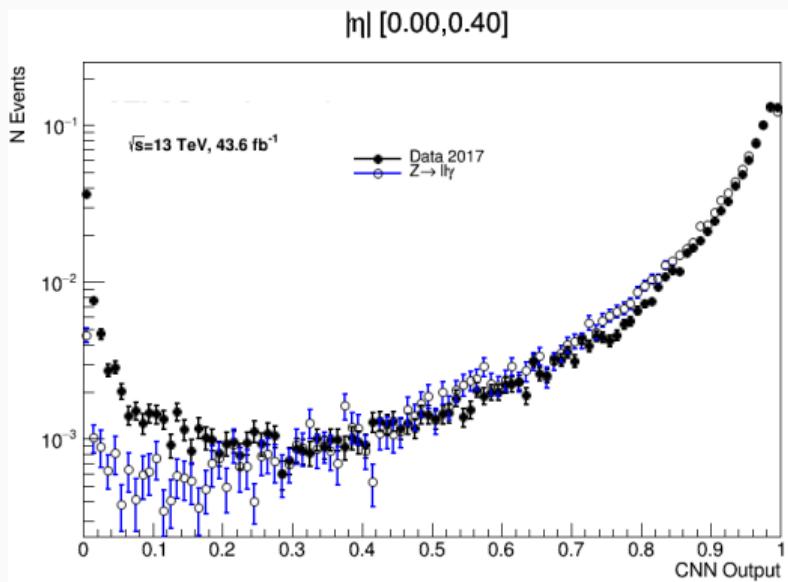
Tight E-inclusive ATLAS WP



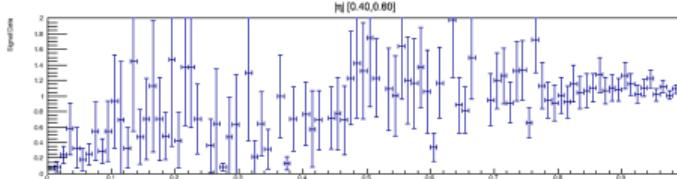
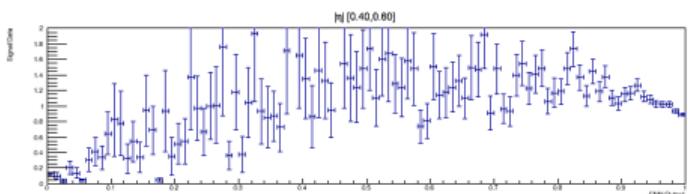
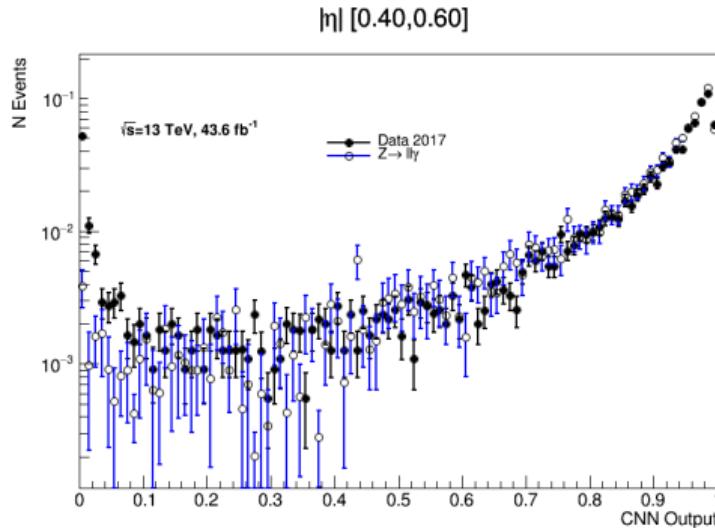
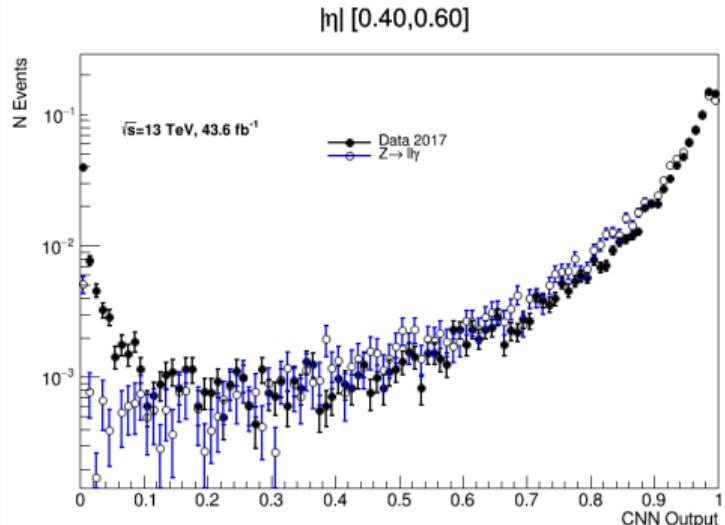
# Primary vertices effect on CNN



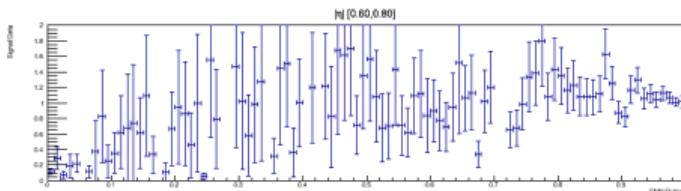
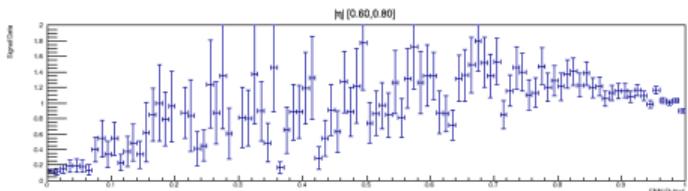
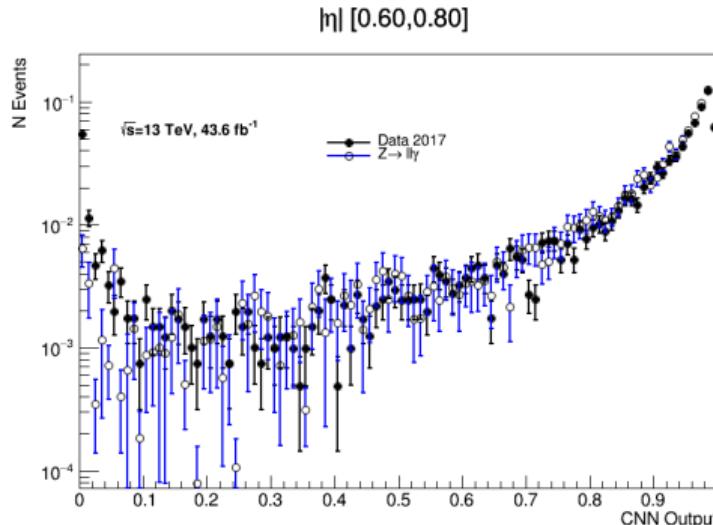
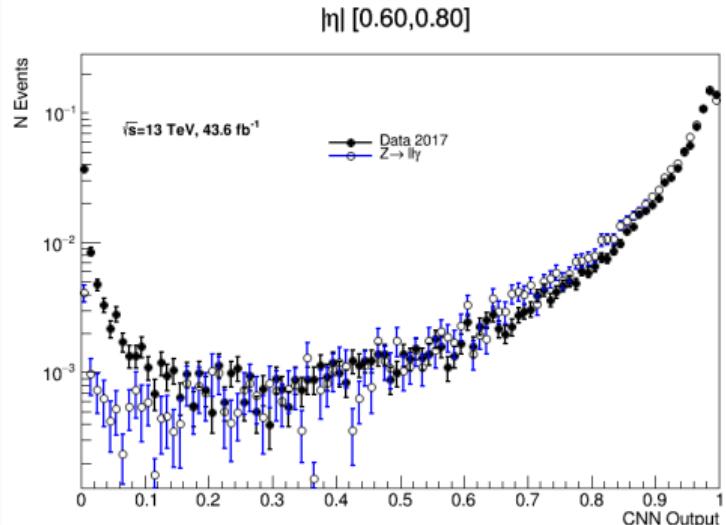
# CNN output distribution, $|\eta| < 0.4$



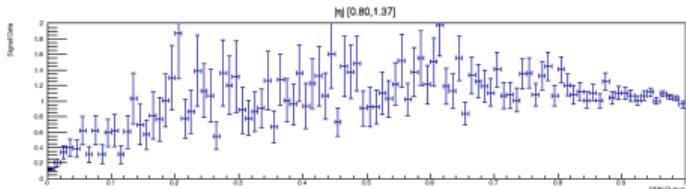
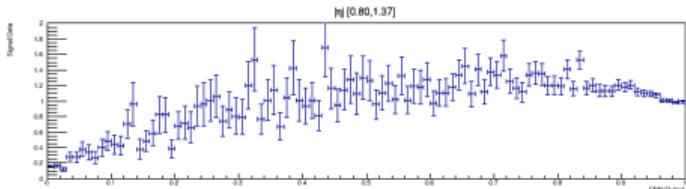
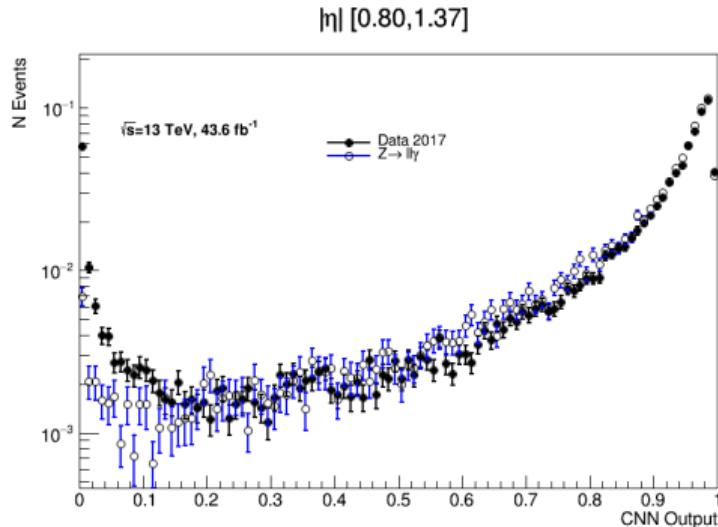
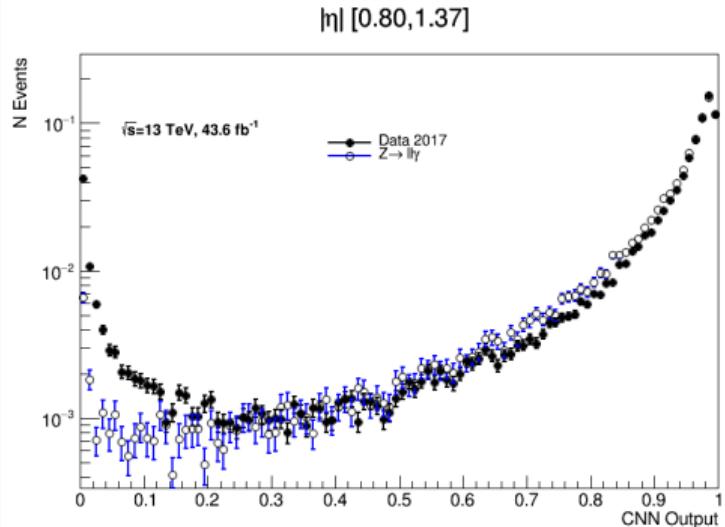
# CNN output distribution, $0.4 < |\eta| < 0.6$



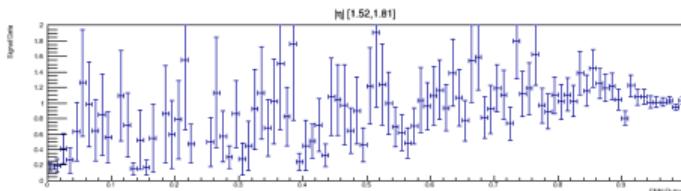
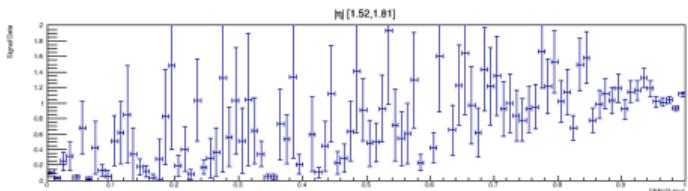
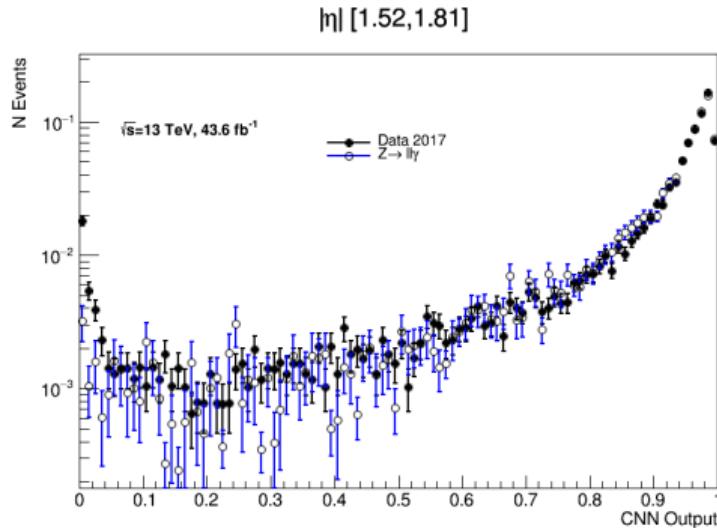
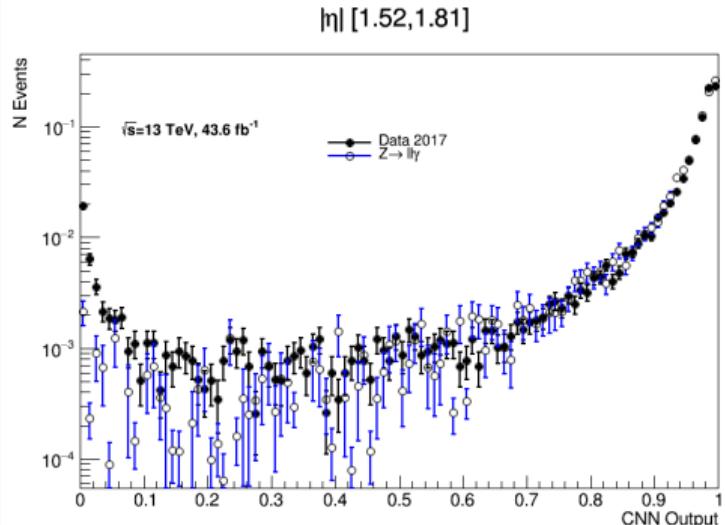
# CNN output distribution, $0.6 < |\eta| < 0.8$



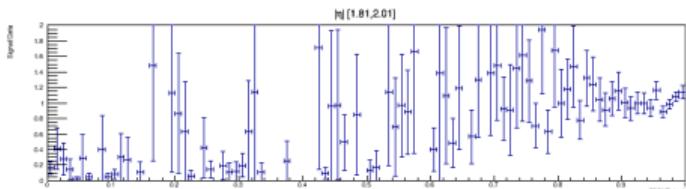
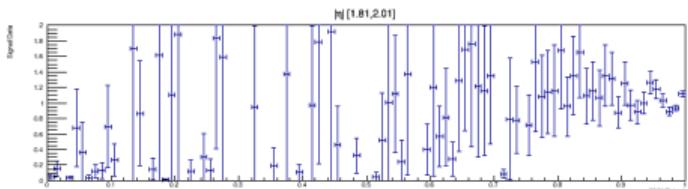
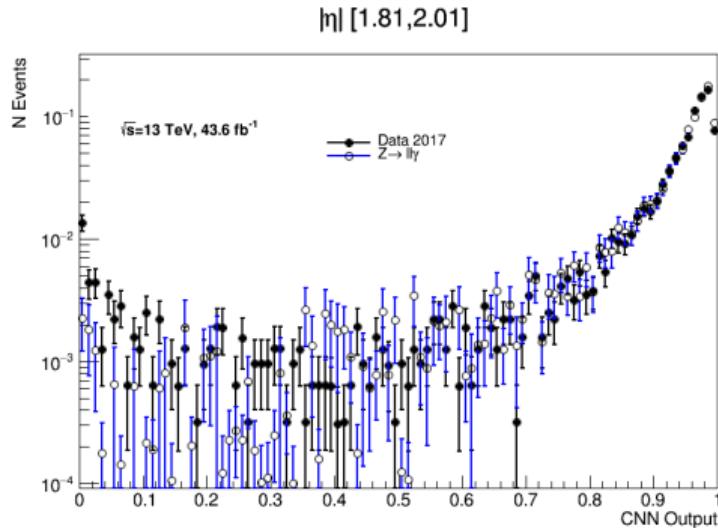
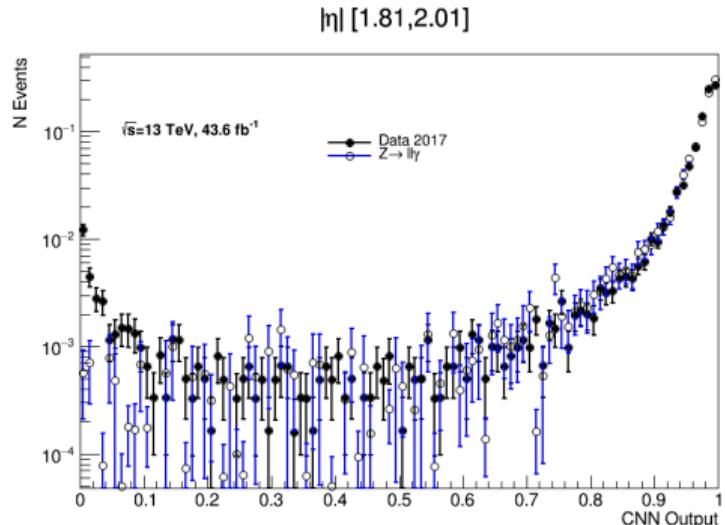
# CNN output distribution, $0.6 < |\eta| < 1.37$



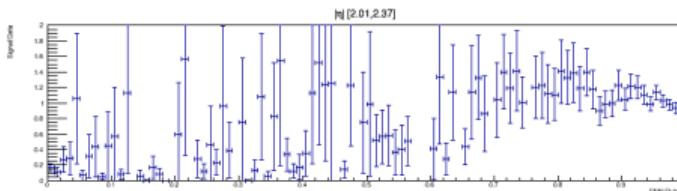
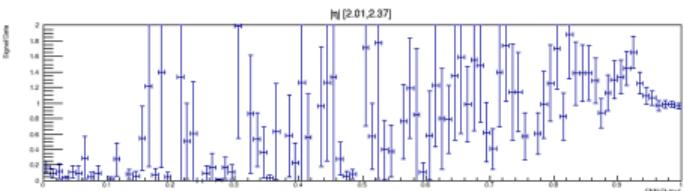
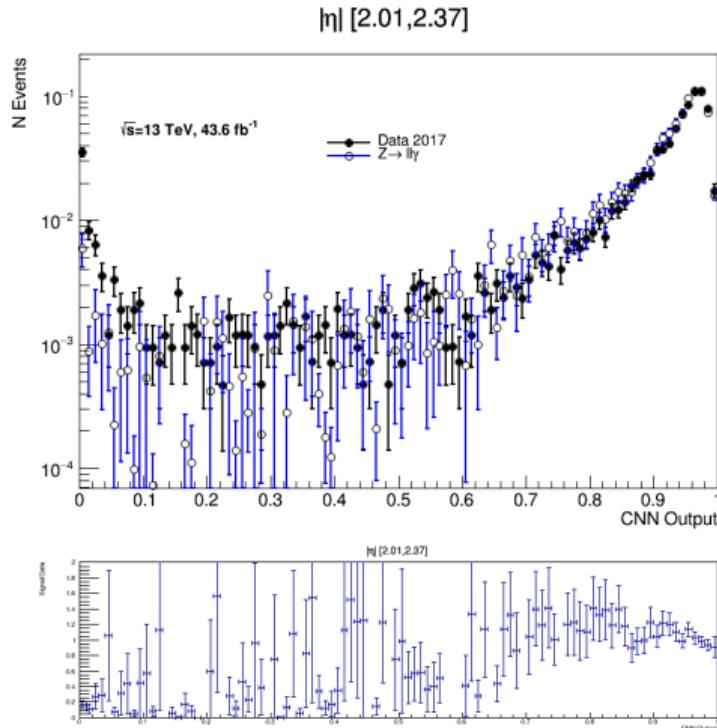
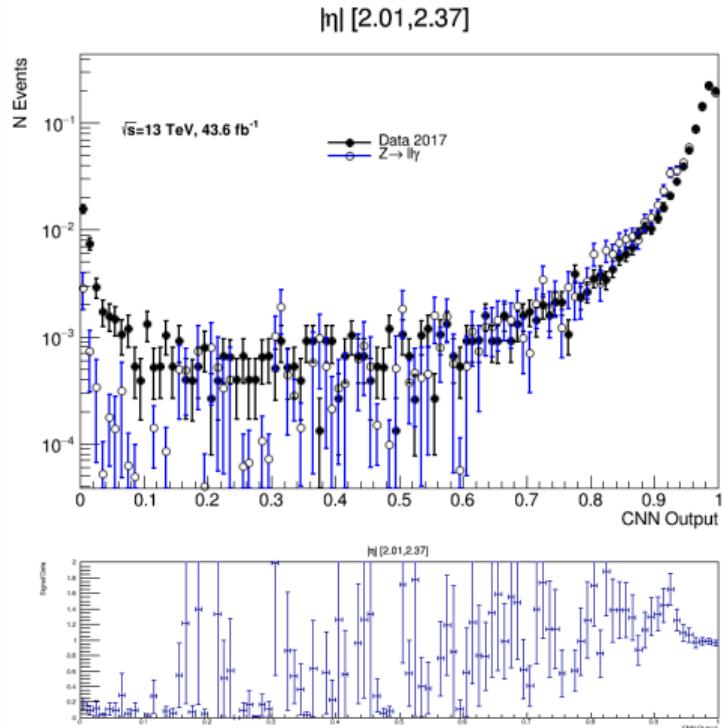
# CNN output distribution, $1.52 < |\eta| < 1.81$



# CNN output distribution, $1.81 < |\eta| < 2.01$

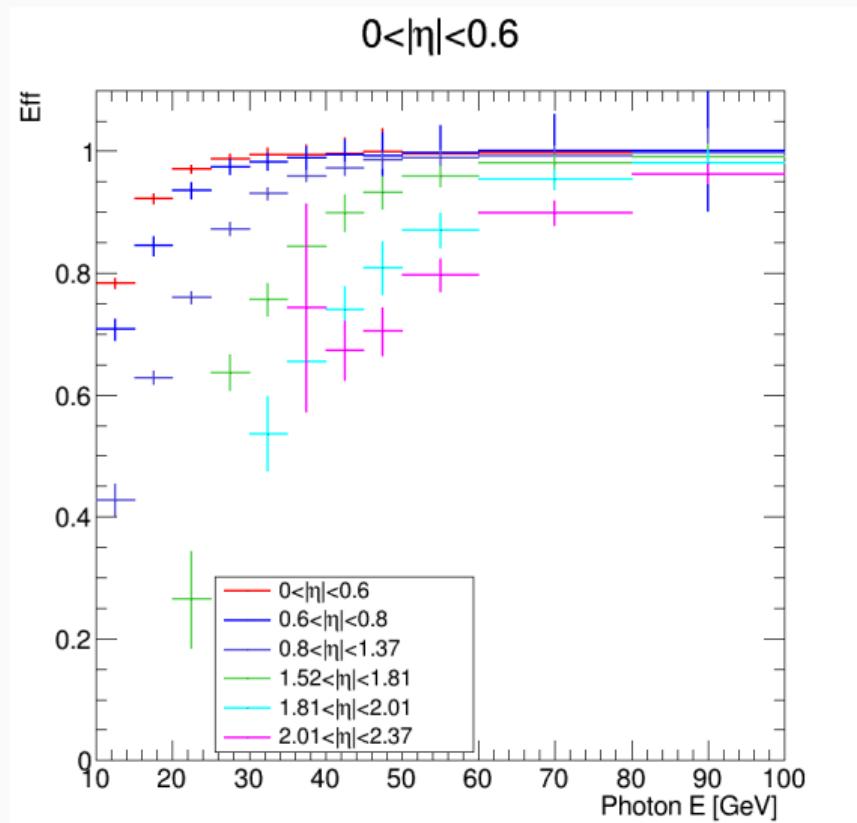


# CNN output distribution, $2.01 < |\eta| < 2.37$



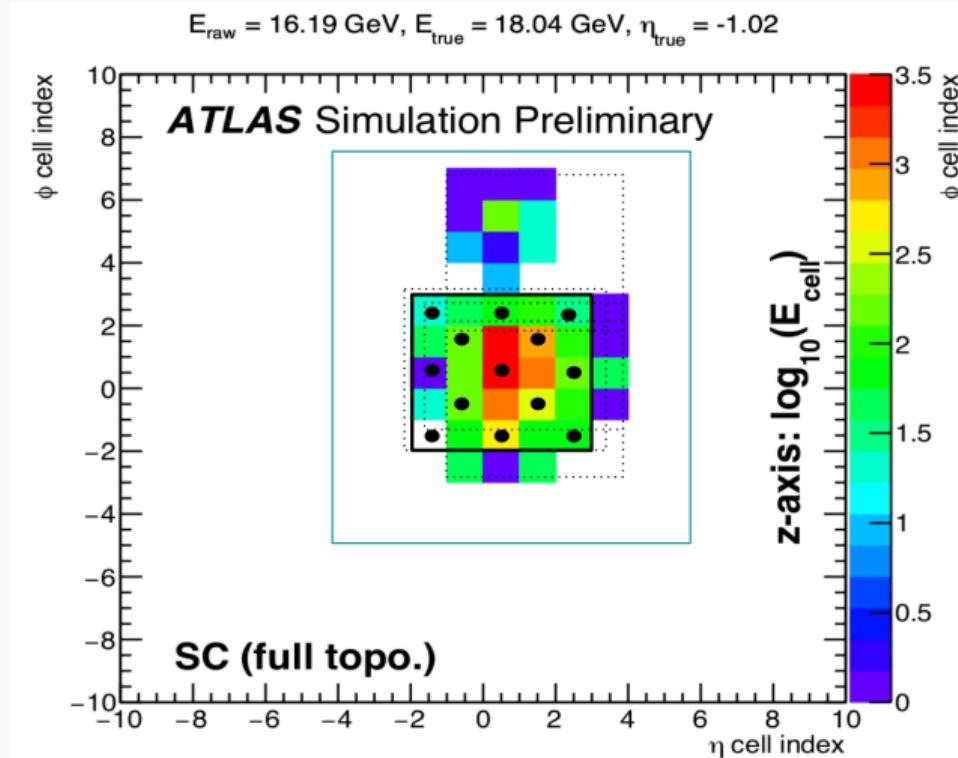
# Low efficiency at High $|\eta|$

- CNN performances degrades at low  $p_T$  and high  $|\eta|$ :
  - low energy photons deposit more energy in the first layer.
  - first layer granularity at high  $|\eta|$ .
- Take into account  $\eta$  during the training



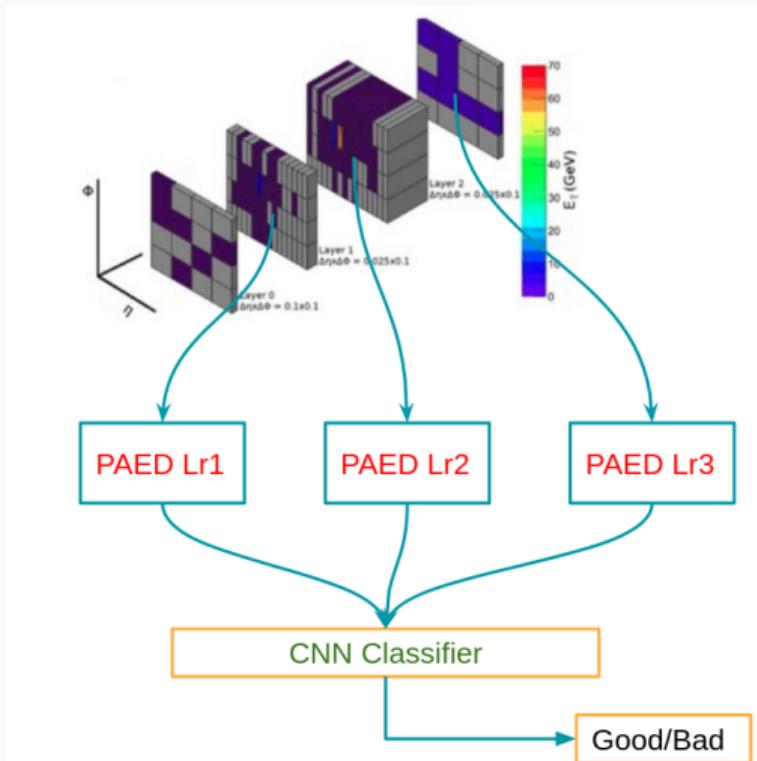
# Multi-Task Cascade Convolutional Network (MTCNN)

- Alternative solution for considering photons direction.
- Used in face detection.
- Can be used with topological clusters.

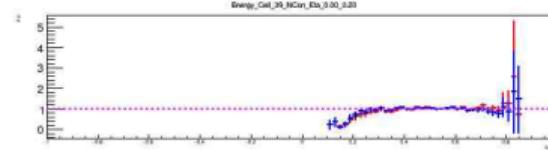
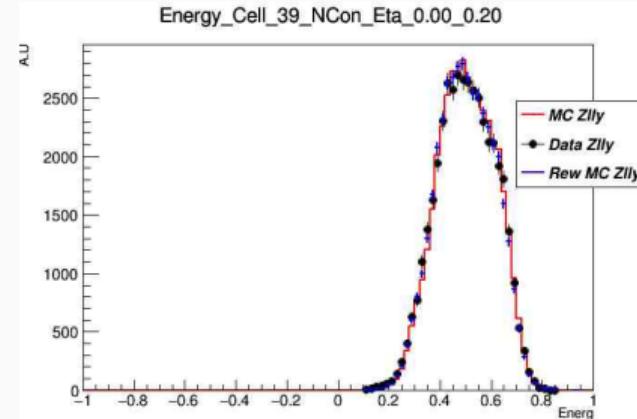
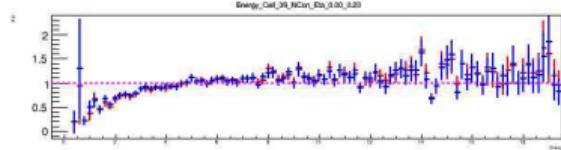
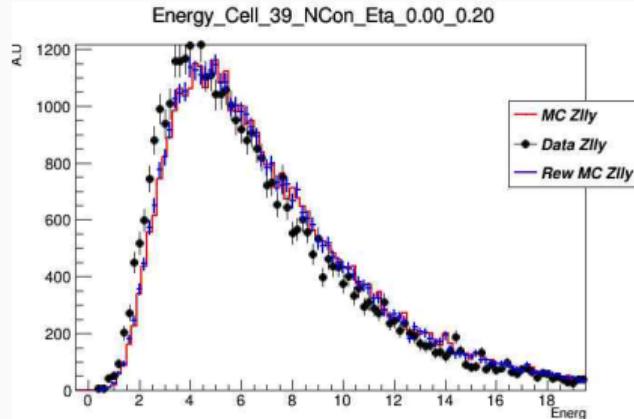


# Pile-Up Auto-Encoder Denoising

- Efficiency degradation for increasing the Pile-Up (crucial at HL-LHC).
- Medicine (image denoising) → ATLAS (pile-up denoising).
- Learn the latent representation of the image using an Auto-Encoder.

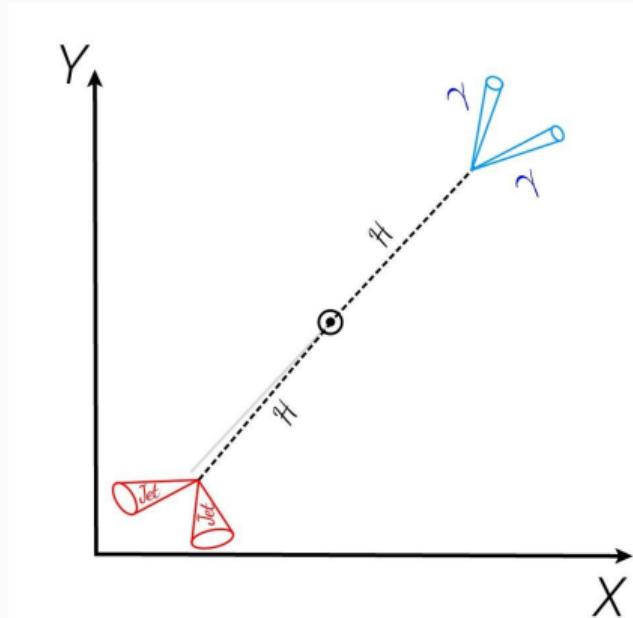


# Cell energy vs Cell energy fraction



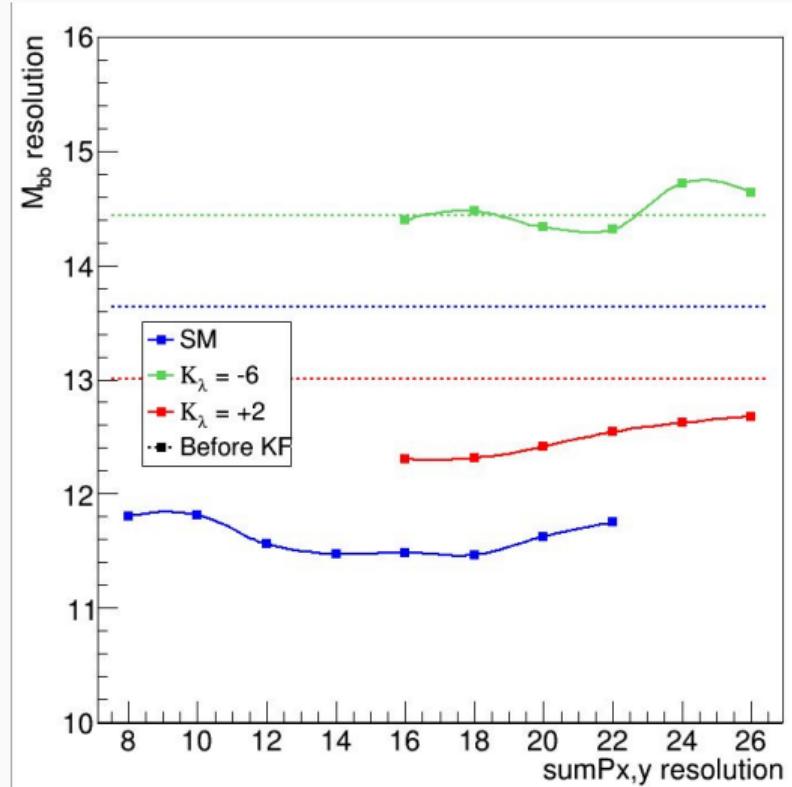
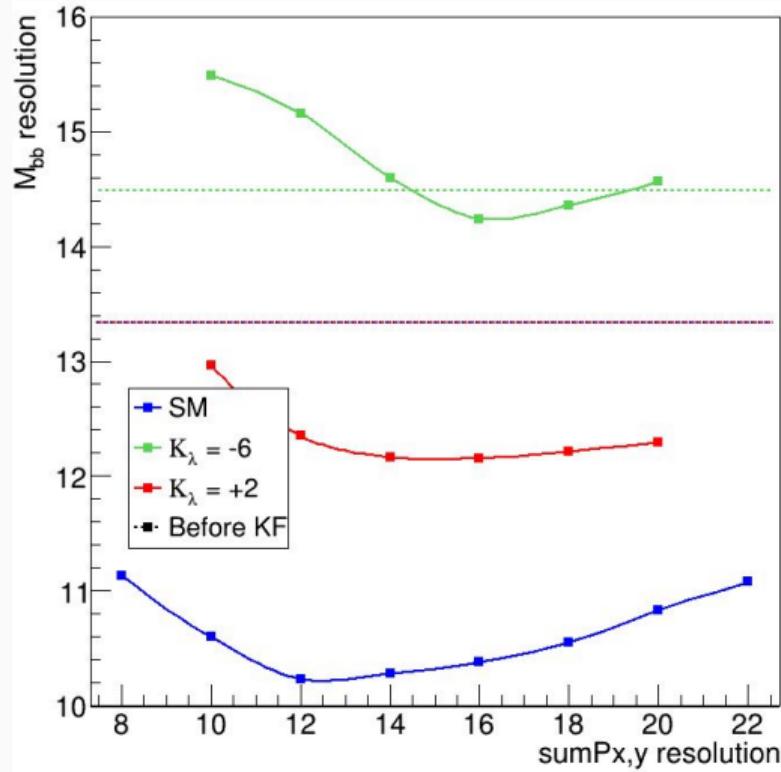
# Kinematic Fit

- Consist of calibration of the HH system balance in the transverse plan.
- Profit from  $m_{\gamma\gamma}$  resolution to improve  $m_{bb}$  resolution.
- Constrain the  $P_{x,y}^{HH+jets}$ , using a likelihood, since additional jets are an important part of HH system.

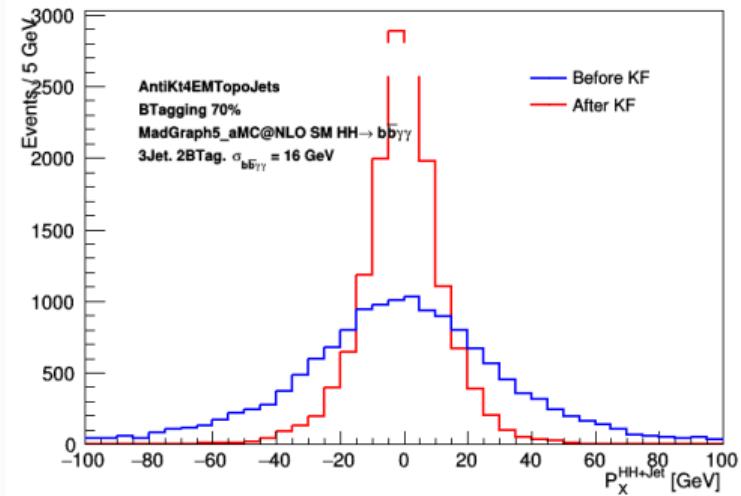
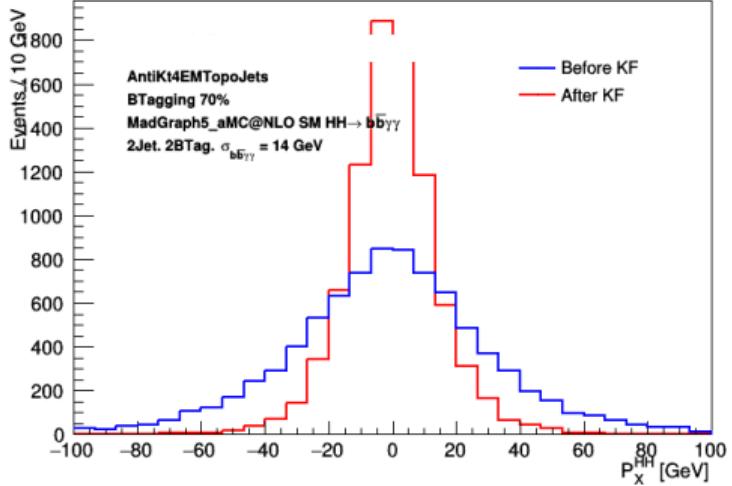


$$-2 \log(\mathcal{L}) = \sum_i \left( \frac{\Omega_i^* - \Omega_i}{\sigma_{\Omega_i}} \right)^2 - 2 \log(L(p_T)) + \left( \frac{\sum p_x^* - 0}{\sigma_{\sigma_{bb}\gamma\gamma}} \right)^2 + \left( \frac{\sum p_y^* - 0}{\sigma_{\sigma_{b\bar{b}}\gamma\gamma}} \right)^2$$

# $\sigma_{b\bar{b}\gamma\gamma}$ determination



# HH system balance



# $m_{bb}$ improvement

