

The logo for CEA (Commissariat à l'énergie atomique et aux énergies alternatives), consisting of the lowercase letters 'cea' in white on a red square background.The logo for IRFU (Institut de Recherche Nucléaire de Strasbourg), consisting of the lowercase letters 'irfu' in red.The logo for P&I (Physique et Ingénierie), consisting of the letters 'P&I' in red.

Faculté

de **physique et ingénierie**

Université de Strasbourg

The logo for the CMS experiment, featuring the letters 'CMS' in white above a stylized white graphic of particle tracks.

# Study of Higgs boson pair production in the $b\bar{b}\tau\tau$ channel with CMS Experiment

Léa-Maria Ravour

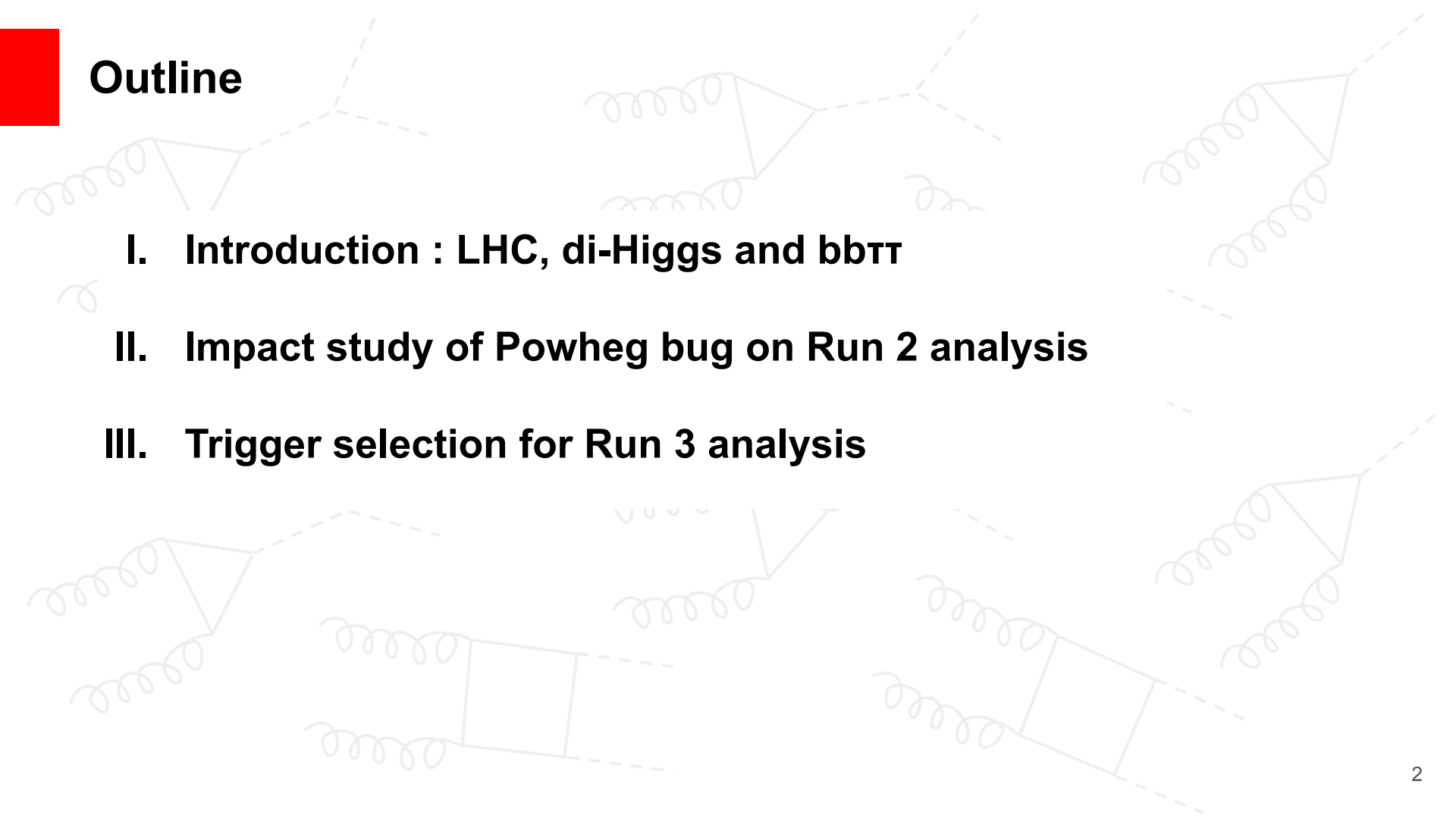
Under the supervision of Louis Portalès

20/06/2024

1



# Outline

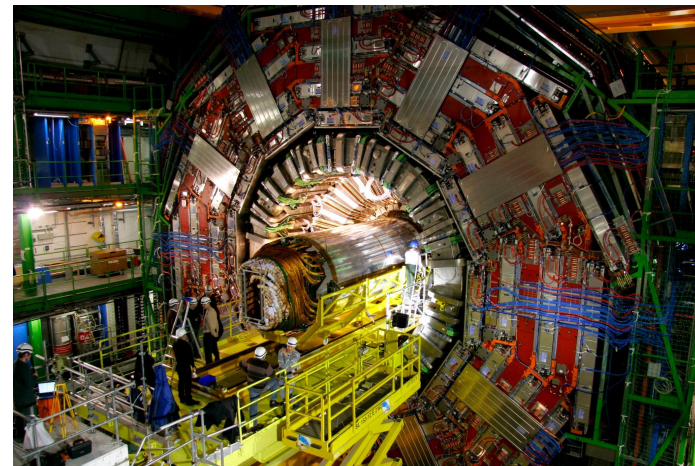
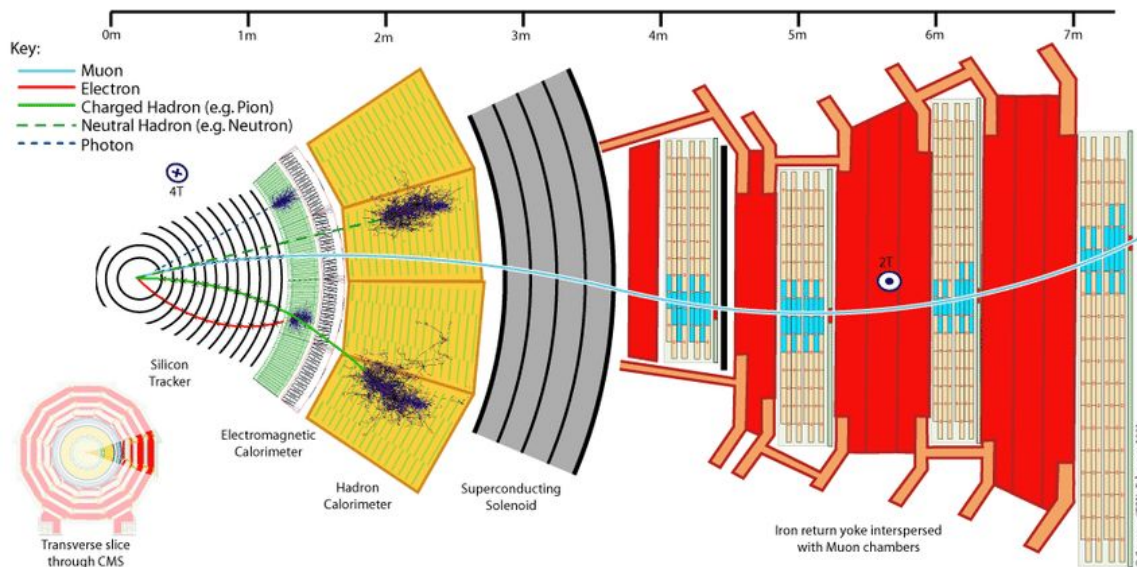
- 
- I. Introduction : LHC, di-Higgs and  $bb\tau\tau$
- II. Impact study of Powheg bug on Run 2 analysis
- III. Trigger selection for Run 3 analysis

The background of the slide is filled with a repeating pattern of light gray Feynman diagrams. These diagrams represent particle interactions, featuring wavy lines for photons and solid lines for fermions. The diagrams include a triangle loop, a square loop, and a box loop, each with external wavy lines and dashed lines representing incoming and outgoing particles.

# Introduction



# CMS Experiment at LHC



CMS : 22x15x15 m, 14000 t

# Higgs boson : discovered in 2012 and studied since

masse →	$\approx 2.3 \text{ MeV}/c^2$	$\approx 1.275 \text{ GeV}/c^2$	$\approx 173.07 \text{ GeV}/c^2$	0	$\approx 126 \text{ GeV}/c^2$
charge →	2/3	2/3	2/3	0	0
spin →	1/2	1/2	1/2	1	0
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b>g</b> gluon	<b>H</b> boson de Higgs
<b>QUARKS</b>	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b><math>\gamma</math></b> photon	
	$0.511 \text{ MeV}/c^2$	$105.7 \text{ MeV}/c^2$	$1.777 \text{ GeV}/c^2$	$91.2 \text{ GeV}/c^2$	
	-1	-1	-1	0	
	1/2	1/2	1/2	1	
	<b>e</b> électron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b><math>Z^0</math></b> boson $Z^0$	
<b>LEPTONS</b>	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	$80.4 \text{ GeV}/c^2$	
	0	0	0	$\pm 1$	
	1/2	1/2	1/2	1	
	<b><math>\nu_e</math></b> neutrino électronique	<b><math>\nu_\mu</math></b> neutrino muonique	<b><math>\nu_\tau</math></b> neutrino tauique	<b><math>W^\pm</math></b> boson $W^\pm$	
					<b>BOSONS DE JAUGE</b>

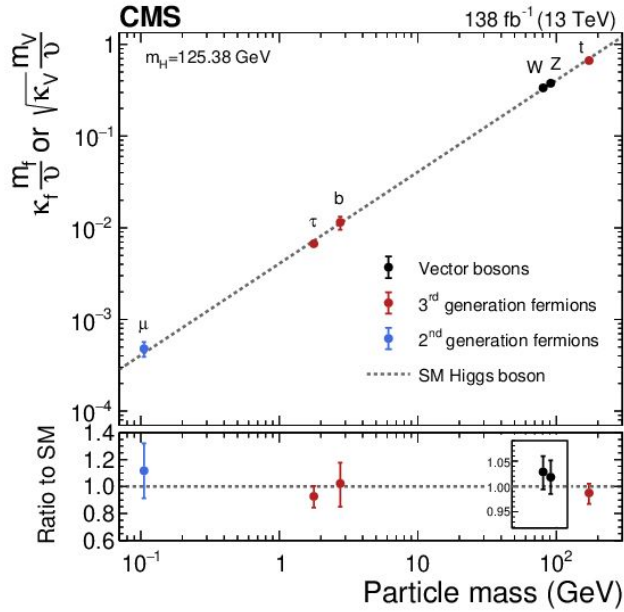
Higgs mechanism explains how elementary particles acquire their mass



Cham, Jorge, PhD Comics



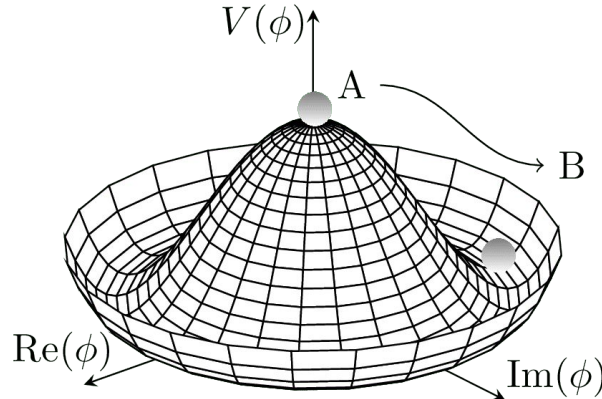
# Higgs potential and self coupling



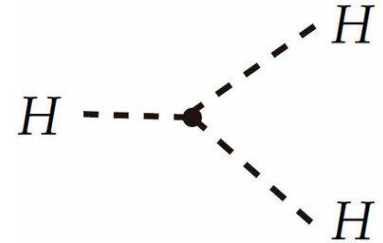
réf: [Nature](#)

$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \lambda_4 H^4 - \frac{1}{8}m_H^2 v^2.$$

**not yet measured!**

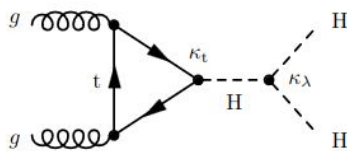
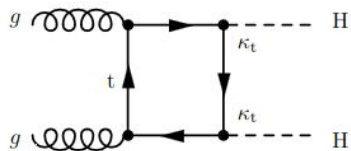


$$\lambda = \frac{m_H^2}{2v^2}$$

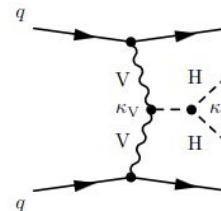
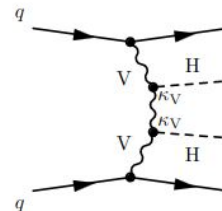
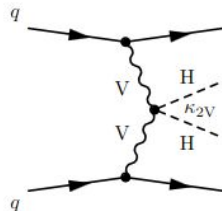


# Higgs boson pair production at LHC

ggF : ~ 90%



VBF : ~ 5%



$\sigma(HH) \sim 30 \text{ fb}$  1000x lower than  $\sigma(H) \sim 40 \text{ pb}$  : **very rare process never measured!**

→  $H_2$

BRs	bb	WW	$\tau\tau$	ZZ	$\gamma\gamma$
bb	34%				
WW	25%	4.6%			
$\tau\tau$	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
$\gamma\gamma$	0.26%	0.10%	0.028%	0.012%	0.0005%

↓  $H_1$

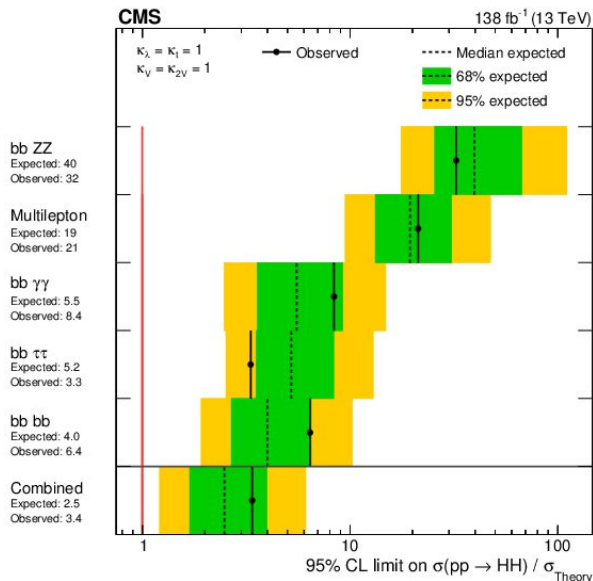
$$\kappa_\lambda = \frac{\lambda}{\lambda_{SM}}$$

Mainly :

- ★ **bbbb** : largest branching ratio but large QCD background
- ★ **bbγγ** : excellent resolution on diphoton H mass but very low branching ratio
- ★ **bbττ** : intermediate branching ratio and background



# Status of HH analyses



We are now starting Run 3 (2022-2025) analysis, and we plan to combine it to Run 2 (2015-2018) for better statistics

Current CMS limits 95%CL :

$$\sigma/\sigma_{\text{SM}} < 3.4 \text{ (expected } \sigma/\sigma_{\text{SM}} < 2.5)$$

$$-1.24 < \kappa_\lambda < 6.49$$

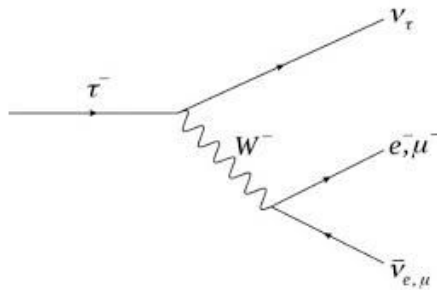
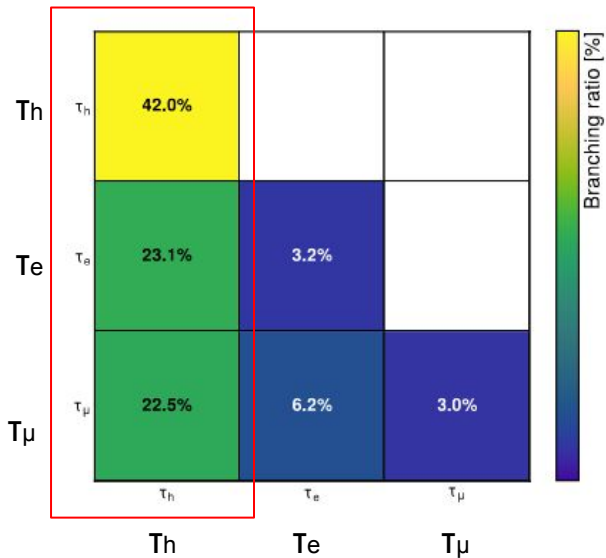
**2 ways to improve statistics :**

- take more data
- improve data selection  $\rightarrow$ triggers

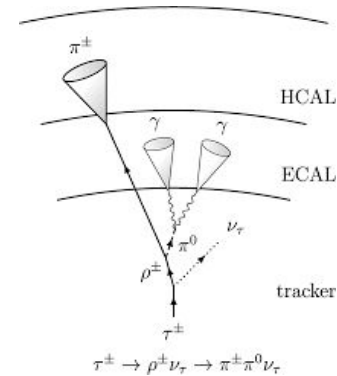


# HH → bbττ

3 channels considered for diTau decays : **eτ** ( $\tau_e \tau_h$ ), **μτ** ( $\tau_\mu \tau_h$ ) & **ττ** ( $\tau_h \tau_h$ )  
(87.6% of all diTau decays)



leptonic tau decay



hadronic tau decay

The background of the slide is filled with several faint, light-gray Feynman diagrams. These diagrams represent particle interactions, specifically showing a top quark loop (a triangle) that couples to a Higgs boson (represented by a wavy line) and a bottom quark (represented by a solid line). The diagrams are arranged in a grid-like pattern across the slide.

**Impact study of Powheg bug on Run 2  
HH→bbττ analysis**

# Impact study of Powheg bug

see [G.Heinrich presentation](#)  
for more details on the bug

Monte Carlo events generators produce simulations used in the analyses

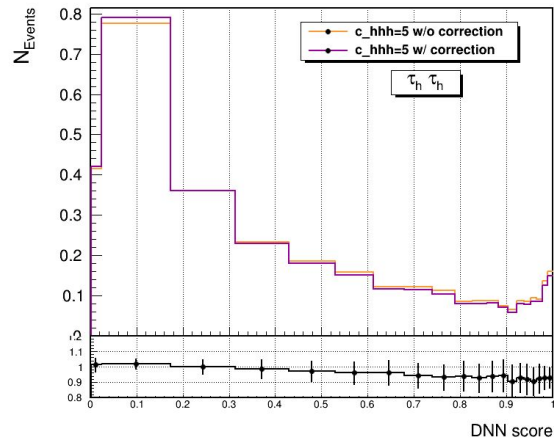
Bug on MC generator POWHEG for ggHH events, used in both CMS and ATLAS Run 2 HH analyses **already published**

→ necessity to study the impact on Run 2  $b\bar{b}\tau\tau$  analysis

→ Impact study on several variables for  $\kappa_\lambda=2.45$  and  $\kappa_\lambda=5$  comparing histograms with and without correction factors in the 3 channels :  $e\tau$ ,  $\mu\tau$ ,  $\tau\tau$ . One of these variables is the score of the DNN used to discriminate signal from background

## Impact on the yield

	$\kappa_\lambda=2.45$	$\kappa_\lambda=5$
$e\tau$	1.4%	1.3%
$\mu\tau$	1.1%	1.2%
$\tau\tau$	2.3%	2.6%



# Impact study of Powheg bug

Available on the CMS information server

CMS AN-20-245



2024/06/05  
 Archive Hash: 3c18bb9-D  
 Archive Date: 2024/06/05

Legacy combination of analyses to search for nonresonant production of Higgs boson pairs in proton proton collisions at  $\sqrt{s} = 13$  TeV

A. Bethani<sup>1</sup>, N. De Filippis<sup>2</sup>, J. M. Duarte<sup>3</sup>, N. Lu<sup>12</sup>, F. Monti<sup>5</sup>, J. Wang<sup>5</sup>, C. Wang<sup>5</sup>, M. Rieger<sup>6</sup>, A. Carvalho<sup>7</sup>, T. Lange<sup>8</sup>, D. F. Guerrero Ibarra<sup>10</sup>, I. Dutta<sup>4</sup>, S. Xie<sup>4</sup>, S. H. Laurila<sup>9</sup>, C. M. Suarez<sup>10</sup>, C. Pena<sup>10</sup>, F. Brivio<sup>11</sup>, C. Yu<sup>12</sup>, C. Zhou<sup>13</sup>, L.M. Rabour<sup>14</sup>, Y. Lai<sup>15</sup>, and C. Palmer<sup>15</sup>

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<sup>11</sup> Università and INFN Milano-Bicocca, Milano (IT)

<sup>12</sup> University of Science and Technology of China, Hefei (CN)

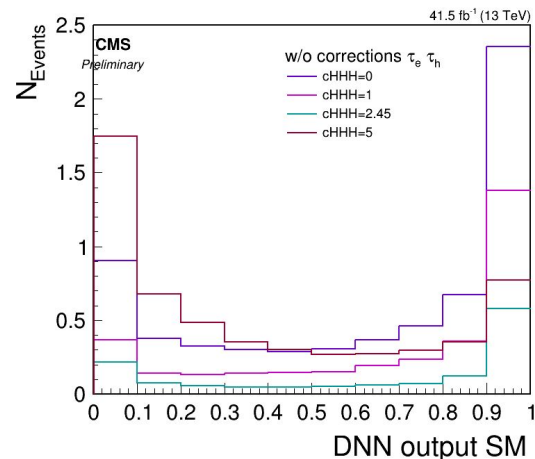
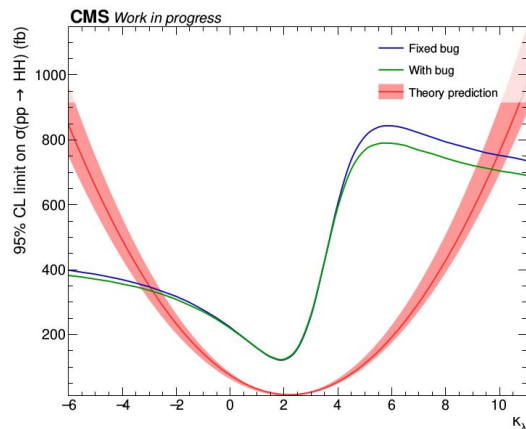
<sup>13</sup> Peking University, Beijing (CN)

<sup>14</sup> CEA Saclay, Saclay (FR)

<sup>15</sup> University of Maryland, College Park, MD (US)

## Results

- Effect on the cross section and kl constraints of less than 3% : negligible
- Study added to an analysis note on HH Run 2 combination
- Proportion of high DNN score for  $\kappa_\lambda=5$  lower than expected since DNN is trained for SM  $\rightarrow$  to be improved for Run 3

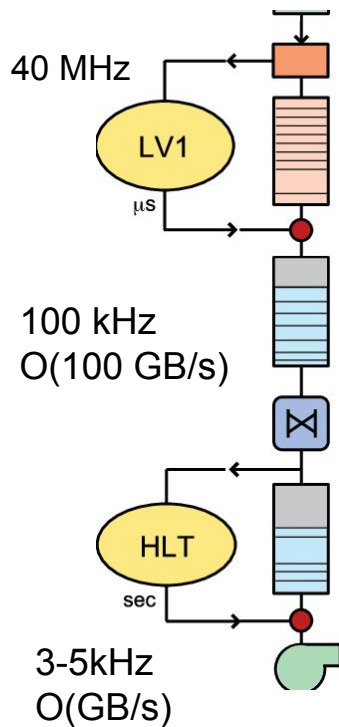




The background of the slide features several faint, light-gray Feynman diagrams. These diagrams represent particle interactions, with wavy lines indicating photons or gluons and solid lines representing fermions. Some diagrams include triangular or square loops, and dashed lines representing external particles or virtual particles. The diagrams are arranged in a grid-like pattern across the slide.

# Trigger selection for Run 3 analysis

# Triggers



Too many data to save all events at LHC : 40M BX/s and 1BX ~ 1MB → O(40TB/s)  
In one year ~200 ZB ie  $10^9$  TB...

→ **Triggers needed to realise a first selection online (reconstruction more limited than during the analysis)**

**HLT : OR logic → more triggers = more data**

**3 Baselines** (triggers we used in Run 2 and will continue using in Run 3) :

**eτ** : isolated e,  $p_T > 32$  GeV OR  
isolated e,  $p_T > 24$  GeV,  $|\eta| < 2.1$  && tau,  $p_T > 30$  GeV,  $|\eta| < 2.1$

**μτ** : isolated μ,  $p_T > 24$  GeV OR  
isolated μ,  $p_T > 20$  GeV,  $|\eta| < 2.1$  && tau,  $p_T > 20$  GeV,  $|\eta| < 2.1$

**ττ** : 2 taus,  $p_T > 35$  GeV,  $|\eta| < 2.1$

# Gain study

**New triggers used in Run 3** : study of the improvement on the selection for  $\kappa_\lambda=0$  and  $\kappa_\lambda=1$  with 2023 samples

- 4 jets among which 2 tagged as b jets (**4jets2b**)
- single hadronic tau with high pT (**single tau**)
- a pair of hadronic taus and a jet (**diTau+jet**)
- missing transverse energy (**MET**)

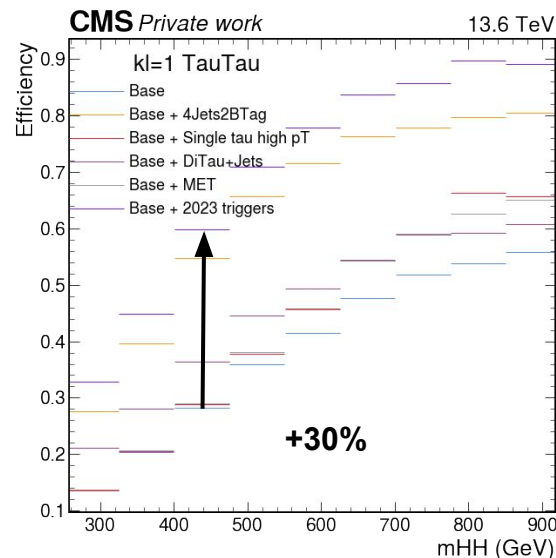
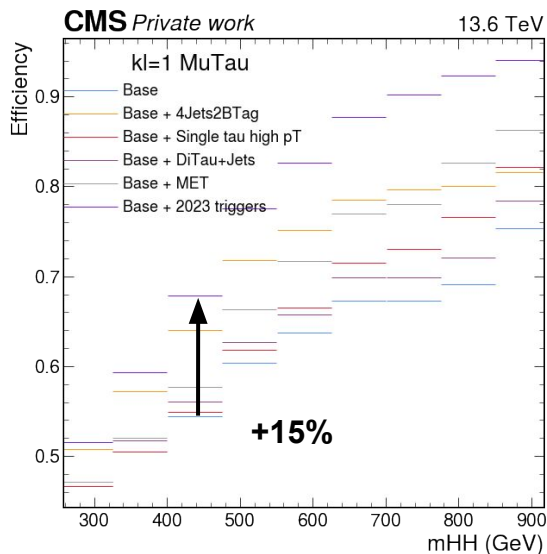
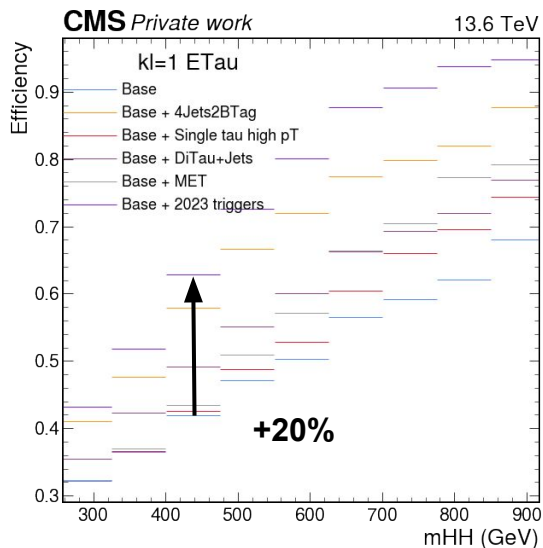
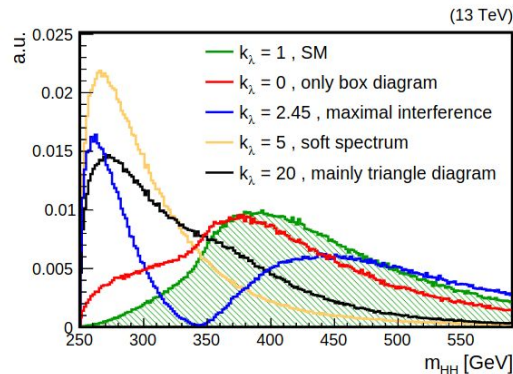
$$gain = \frac{\text{Trigger OR baseline}}{\text{baseline}} - 1$$

$\kappa_\lambda=0$	etau	mutau	tautau
4jets2b	0.35	0.16	0.82
single tau	0.03	0.02	0.05
diTau+jet	0.16	0.03	0.26
MET	0.07	0.08	0.06
all	0.48	0.23	1.01

$\kappa_\lambda=1$	etau	mutau	tautau
4jets2b	0.37	0.16	0.80
single tau	0.04	0.03	0.07
diTau+jet	0.17	0.03	0.25
MET	0.08	0.08	0.07
all	0.50	0.25	0.98

# Acceptance study depending on $m_{HH}$

$$\varepsilon = \frac{\text{Trigger AND Selection}}{\text{Selection}}$$





The background of the slide features a repeating pattern of faint, light-gray Feynman diagrams. These diagrams include various types of loops: a triangle loop with a wavy line on one side, a square loop with wavy lines on two opposite sides, and a pentagon loop with wavy lines on two opposite sides. Dashed lines represent external propagators. A solid red rectangle is positioned on the left side of the slide, partially overlapping the text.

# Summary

# Summary

## Impact study of Powheg bug

- Effect on the cross section and kl constraints of less than 3% → **impact negligible**
- Study added to an analysis note on HH Run 2 legacy combination
- Proportion of high DNN score for kl=5 lower than expected → to be improved for Run 3

## Efficiency study of Run 3 triggers

- Gain up to 80% for 4jets2b trigger
- Overall gain of 100% and +30% absolute efficiency in  $\pi$  channel → **clear improvement for Run 3 analysis!**

## Remaining work :

- Overlaps to be studied
- VBF triggers to be studied
- Implementation in the analysis

The background of the slide is filled with several faint, light-gray Feynman diagrams. These diagrams represent particle interactions, featuring wavy lines (representing photons or gluons) and solid lines (representing fermions like quarks or leptons). Some diagrams show a vertex where a wavy line meets a solid line, while others show more complex loop or exchange structures. The diagrams are scattered across the slide, creating a technical and scientific atmosphere.

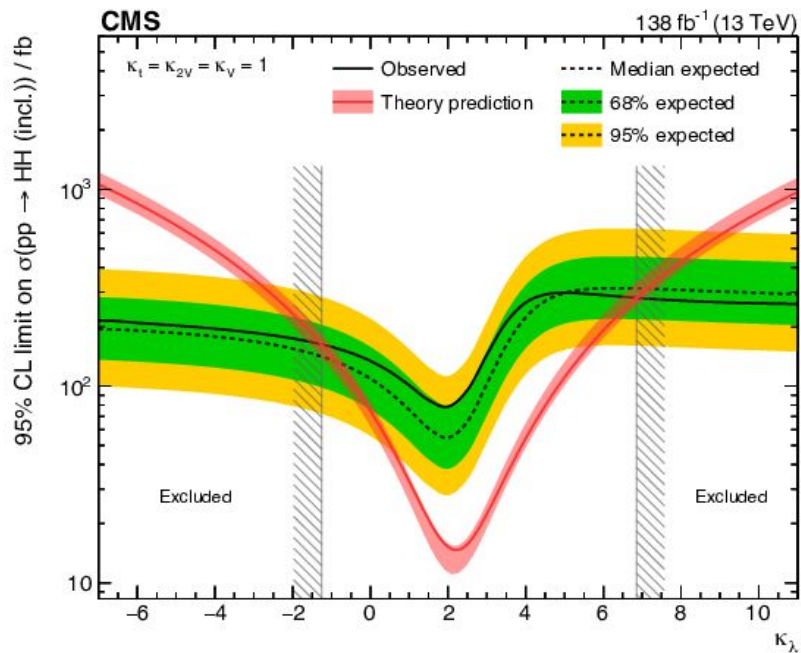
**Thank you!**  
**Questions?**

The background of the slide is filled with a repeating pattern of light gray Feynman diagrams. These diagrams represent particle interactions, specifically showing a fermion loop (a triangle or square) with wavy lines representing photons. The diagrams are arranged in a grid-like fashion, with some overlapping. A solid red rectangle is positioned on the left side of the slide, partially overlapping the text.

# Backup



# Constraints on lambda



# Cuts

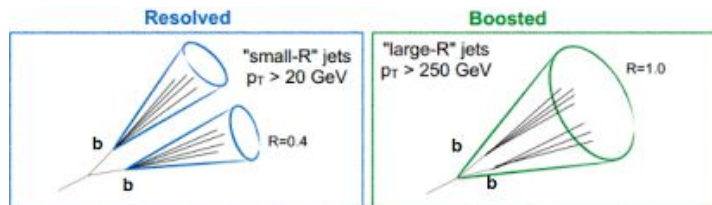
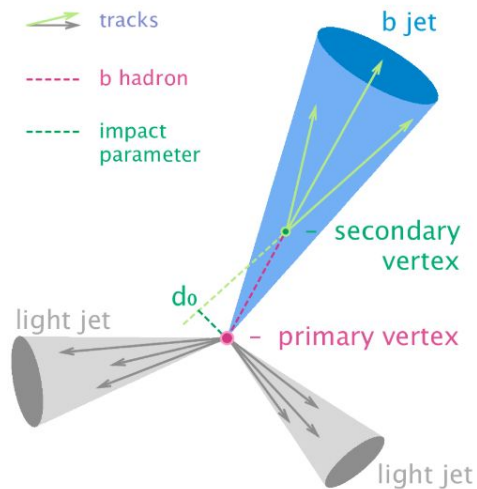
Electron :  $p_T > 10$  GeV,  $|\eta| < 2.5$ ,  $\Delta R(e, \tau) < 0.5$

Muon :  $p_T > 15$  GeV,  $|\eta| < 2.4$ ,  $\Delta R(\mu, \tau) < 0.5$ ,  $dR < 0.15$

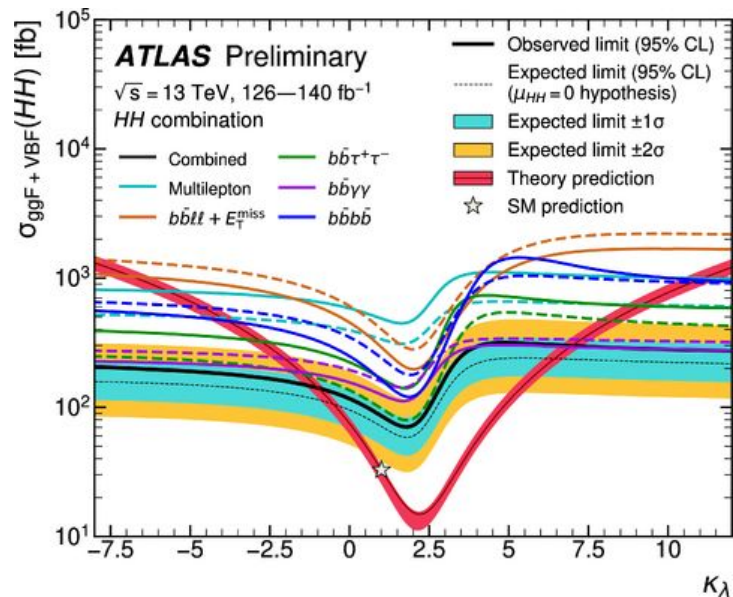
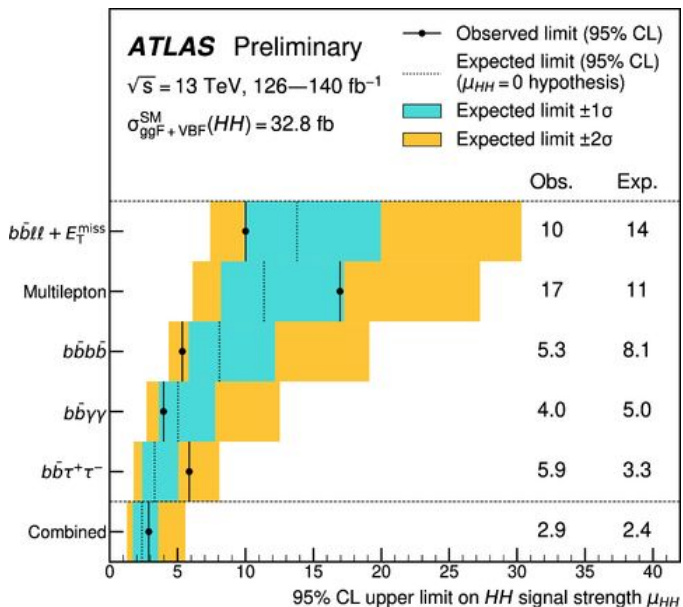
Tau :  $p_T > 20$  GeV,  $|\eta| < 2.3$ , DeepTauVSJet  $> 5$

b jets : 2 jets w/  $p_T > 20$  GeV,  $|\eta| < 2.4$  (not yet identified as b)

# b tagging

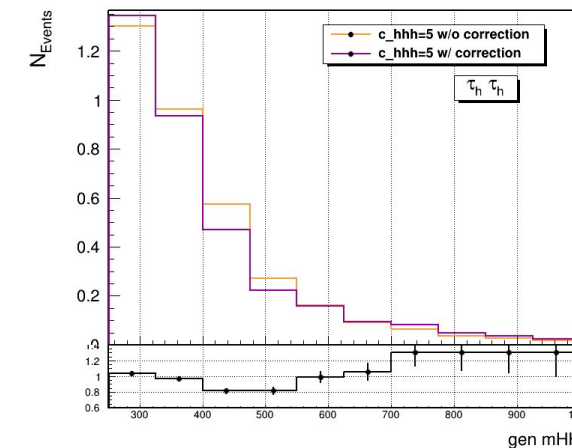
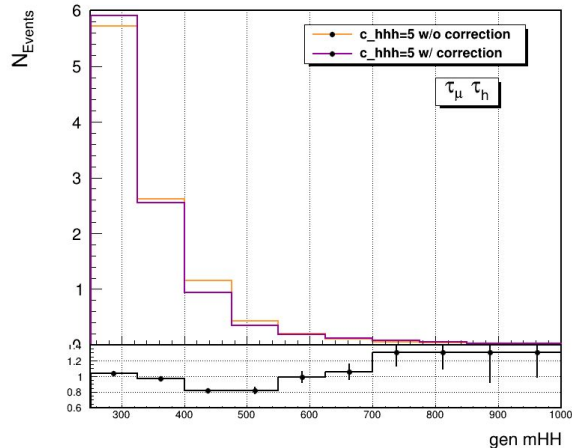
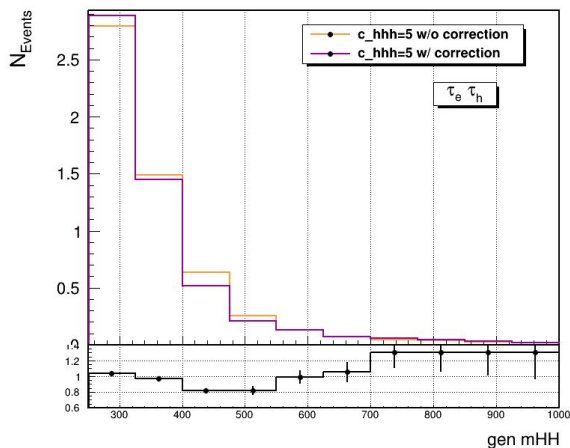
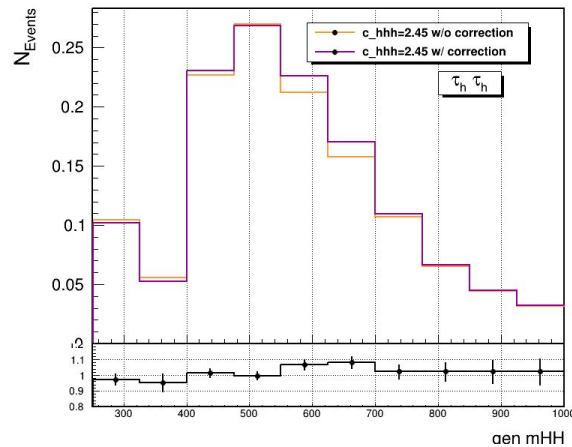
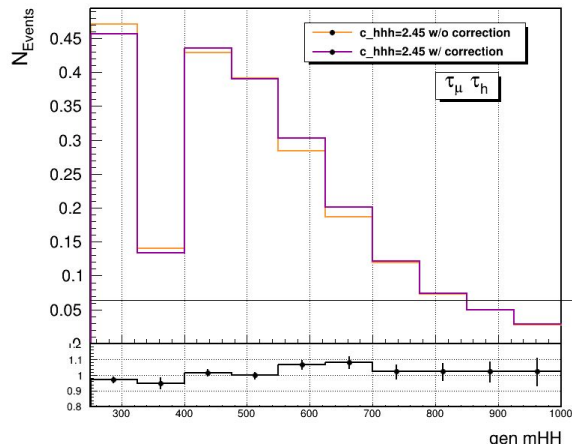
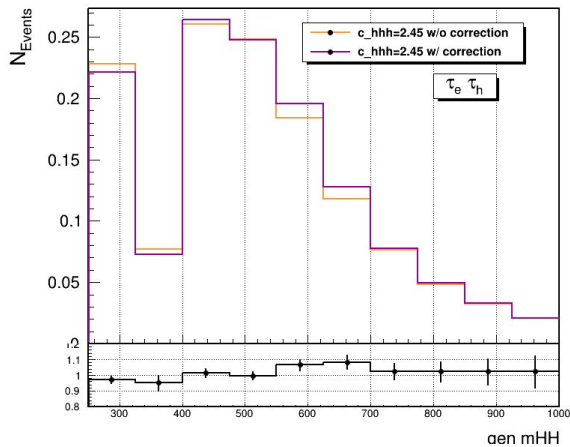


# ATLAS limits

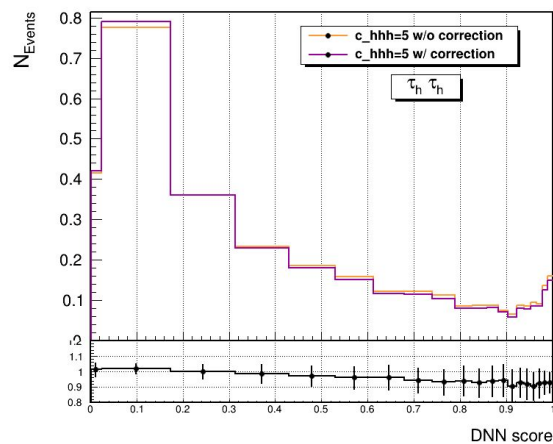
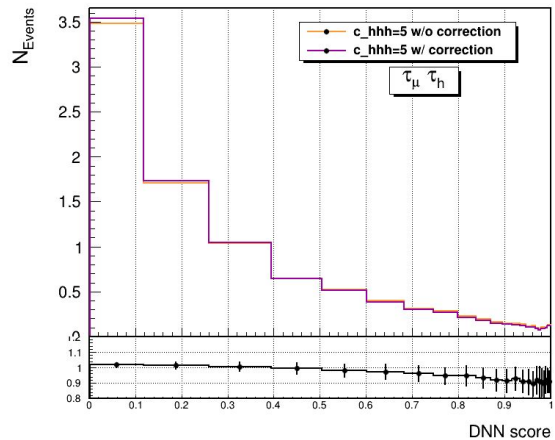
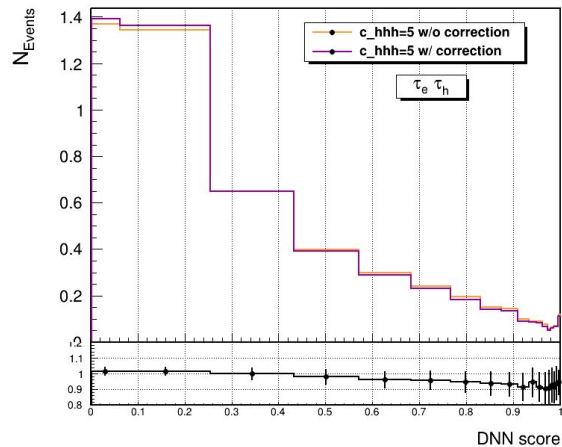
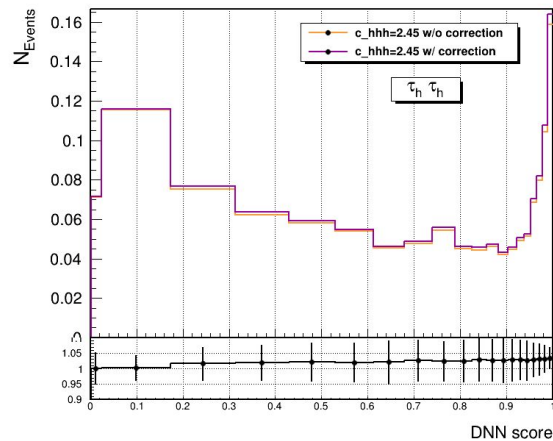
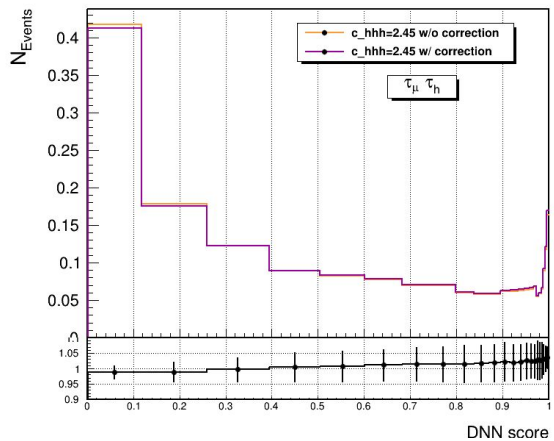
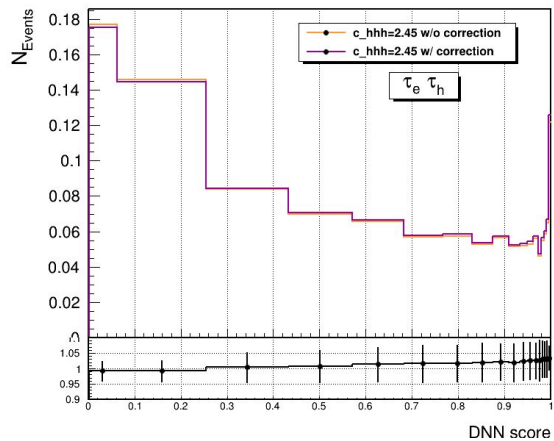




# generated HH mass



# DNN score



# Efficiency study

$K\lambda=0$	etau	mutau	tautau
4jets2b	0.34	0.24	0.38
single tau	0.03	0.02	0.03
diTau+jet	0.28	0.03	0.34
MET	0.05	0.21	0.02
all	0.43	0.55	0.28

$K\lambda=1$	etau	mutau	tautau
4jets2b	0.37	0.28	0.42
single tau	0.04	0.03	0.04
diTau+jet	0.31	0.03	0.38
MET	0.06	0.21	0.03
all	0.44	0.57	0.32