HH non-resonant searches at future pp colliders

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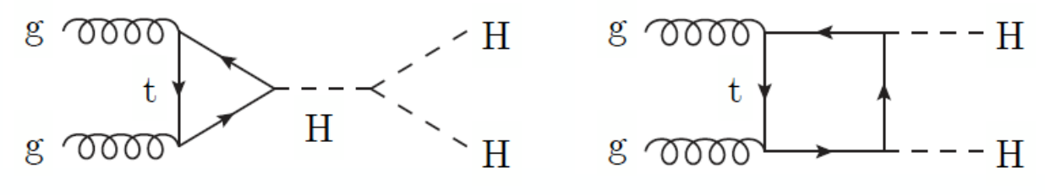
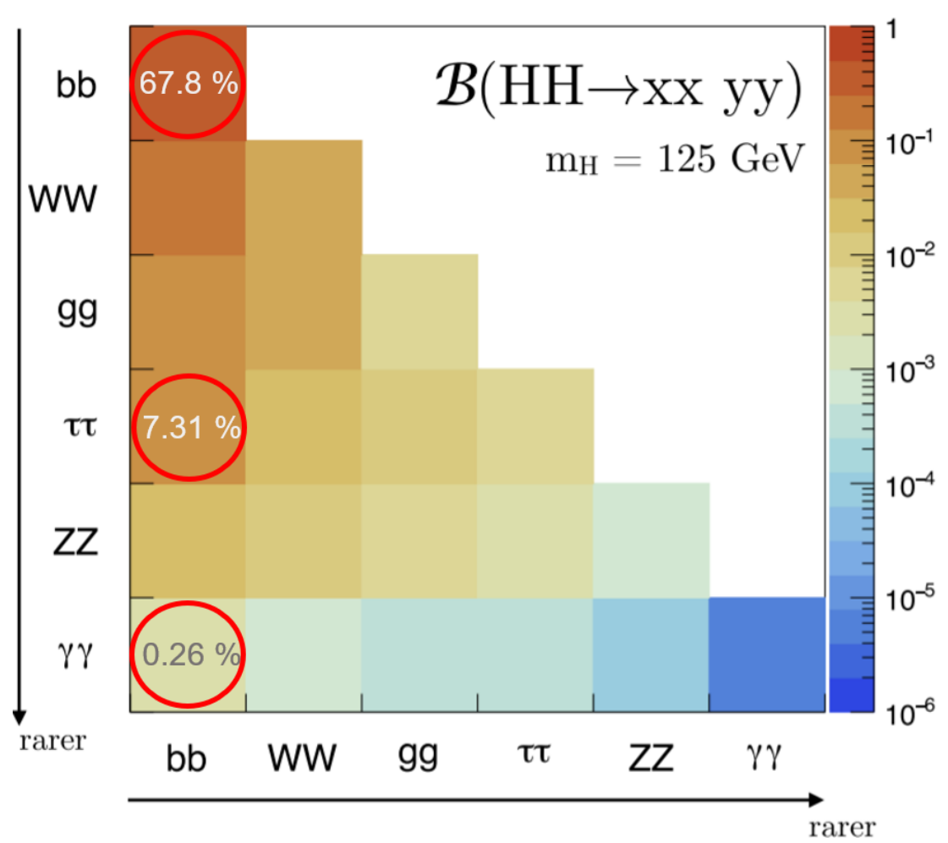
Physics Motivation

- The study of the Higgs boson pair production (HH) is one of the main goals of the scientific program at future colliders.
- It offers a direct experimental access to the Higgs boson trilinear self coupling and hence to the structure of the scalar potential itself, allowing an unprecedented insight in the electroweak symmetry breaking mechanism.
- The di-Higgs phenomenology is dominated by the very tiny cross section of 37 fb in SM at NNLO at result of the destructive interference of the box and triangle diagrams [1][2]

$$V(\mathrm{h}) = \frac{m_{\mathrm{H}}^2}{2}\mathrm{h}^2 + \lambda_{3\mathrm{H}} v \mathrm{h}^3 + \lambda_{4\mathrm{H}} v \mathrm{h}^4$$





- **bbγγ** highest purity, all objects can be reconstructed but very low branching ratio
- **bbττ** second highest branching ratio, trigger leptons, relatively low background
- **bbbb** highest branching ratio but suffers from high QCD- and tt-induced background.

Event, Detector Simulation and Data analysis

- The signal and background processes in proton-proton (pp) collisions at 14 and 100 TeV are modelled using Monte Carlo (MC) event generators; the hadronisation and fragmentation effects are handled by using the PYTHIA8 [3] program.
- Signal processes from gluon-gluon fusion (ggF) HH production are simulated at next-to-leading order (NLO) with POWHEG 2.0 [4–6]
- All the simulated samples are processed with the DELPHES [9] fast simulation program to model the detector response and performances [10][11]
  - simulation accounts also for pileup contributions by overlaying an average of 200 (1000) minimum bias interaction events simulated with PYTHIA8 at center-of-mass energies of 14(100) TeV
- The data analysis for the three aforementioned double Higg decay channels has been done by using the Bamboo framework [12]

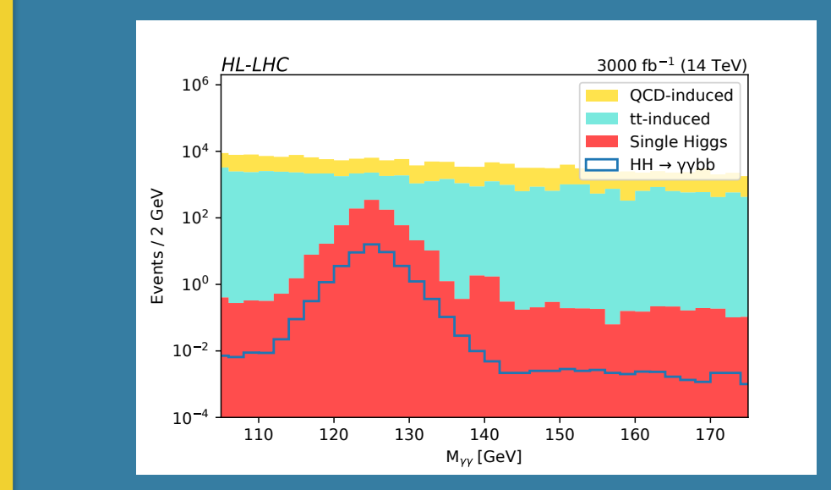
Event Selection

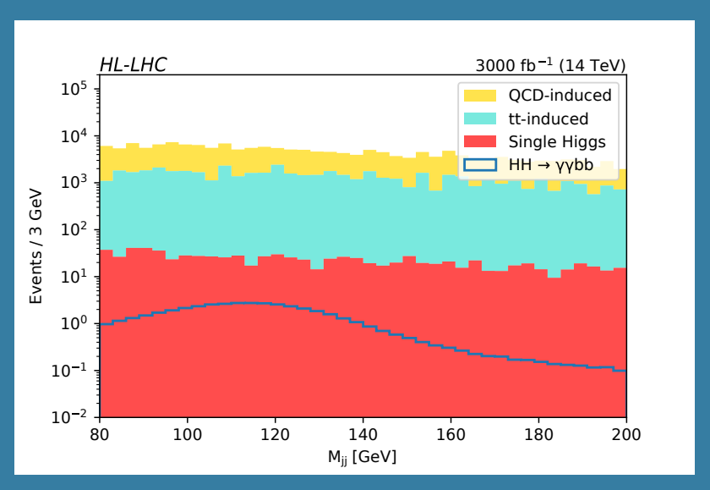
bb$\gamma\gamma$

Variable	Requirement
ID	loose
ISO	tight
$\lvert\eta\rvert$	< 1.44 or in $[1.57, 2.5]$
p_T (sub)lead	> 30 (20) GeV
$p_T/m_{\gamma\gamma}$ (sub)lead	$> 1/3$ (1/4)
$m_{\gamma\gamma}$	in $[100, 180]$ GeV

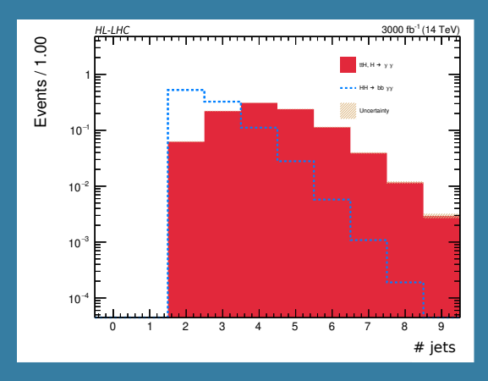
Variable	Requirement
ID	tight
b-tag	loose
$\lvert\eta\rvert$	< 2.5
p_T	> 30 GeV
m_{jj}	in $[80, 200]$ GeV

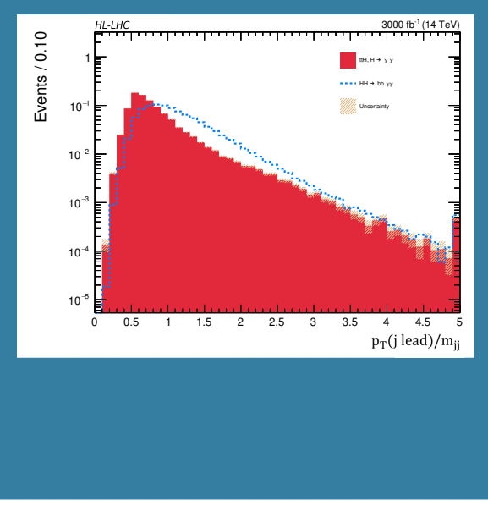
Table 2: Photon (Left) and Jet (Right) kinematic selections

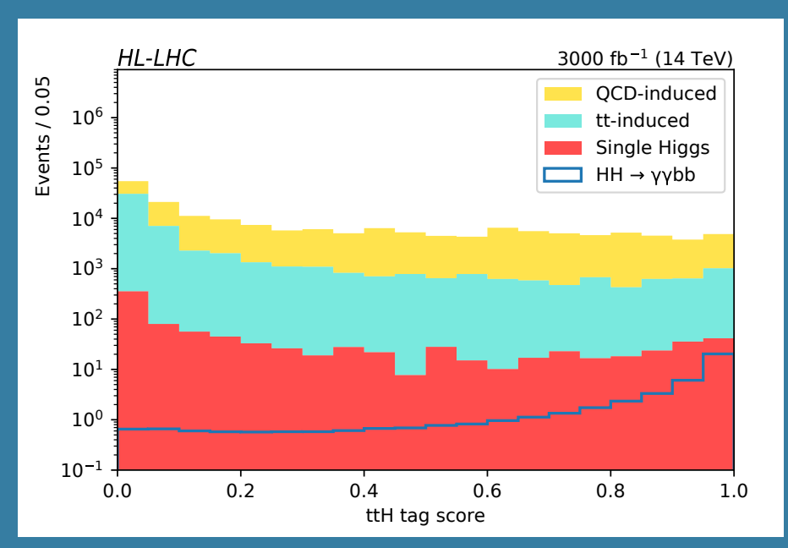




- In order to **discriminate** the signal against the **ttH background**, several variables are combined together into a single powerful tagger







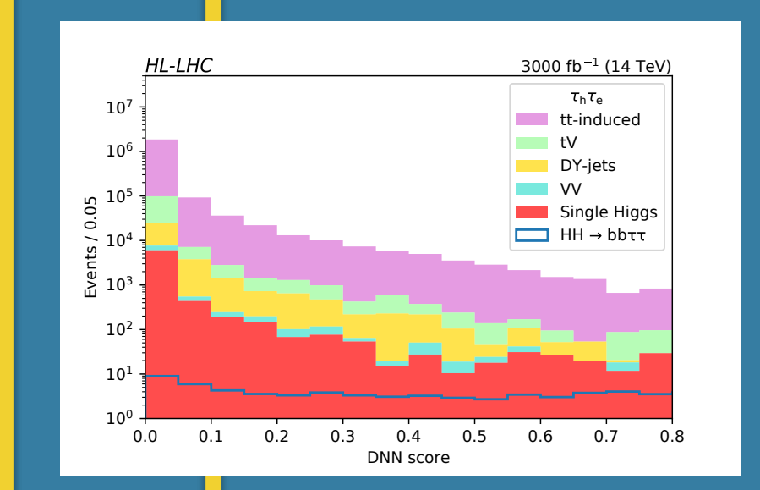
bb$\tau\tau$

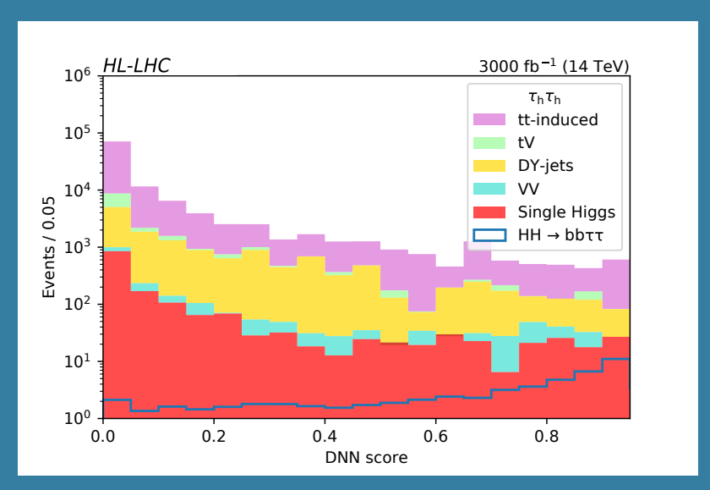
Lepton	Min p_T	Max η	Max iso
Primary muon	23	2.1	0.15
Primary electron	27	2.1	0.1
Veto muon/electron	10	2.4	0.3
Hadronic τ			
$lep\ \tau_h$	20	2.3	
$\tau_h\ \tau_h$	45	2.1	

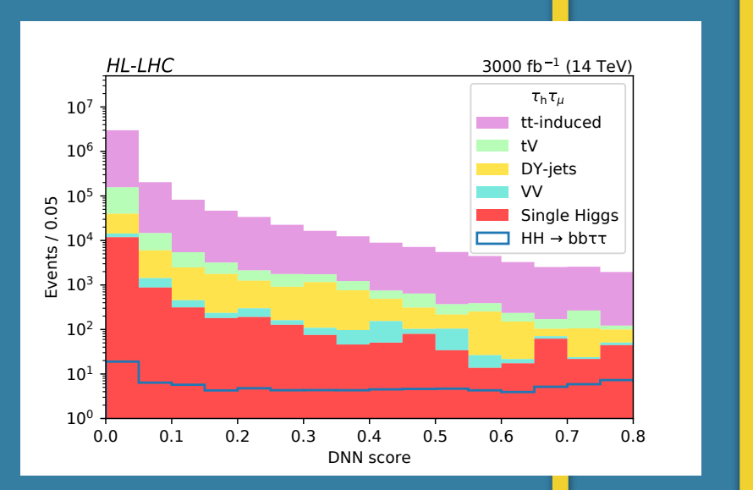
Table 9: Kinematic requirements of leptons and hadronic taus

- **$\mu\tau_h$ ($e\tau_h$)**: exactly one primary muon (electron) and at least one τ_h opposite charged If more pairs, pair with the highest isolation is selected. Exactly 0 veto electrons (muons) are requested;
- **$\tau_h\tau_h$**: exactly zero veto muons or electrons and at least two hadronic taus of opposite charge to one another. In case of multiple choices of hadronic tau, the highest p_T one(s) is/are selected.

- **3 Neural Networks** for the 3 different channels
- different kinematical variables used as inputs







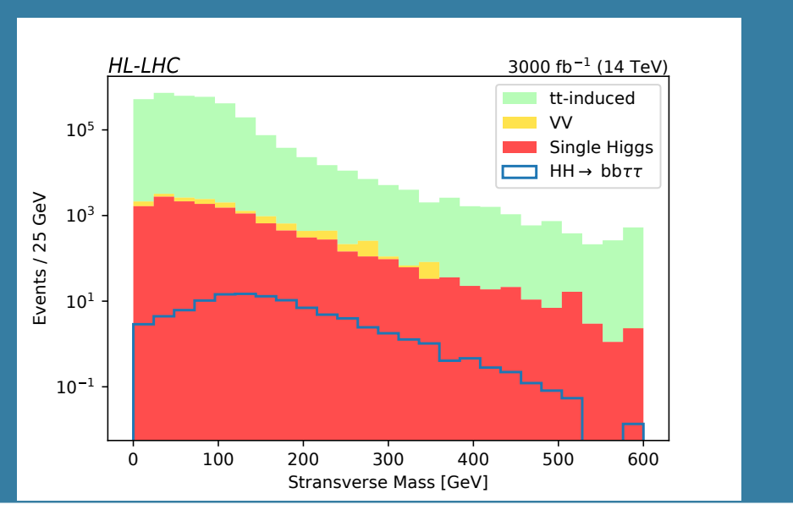
- To cope with the neutrinos coming from taus decay and improve signal and background separation **Stranverse Mass (MT2)** as been used

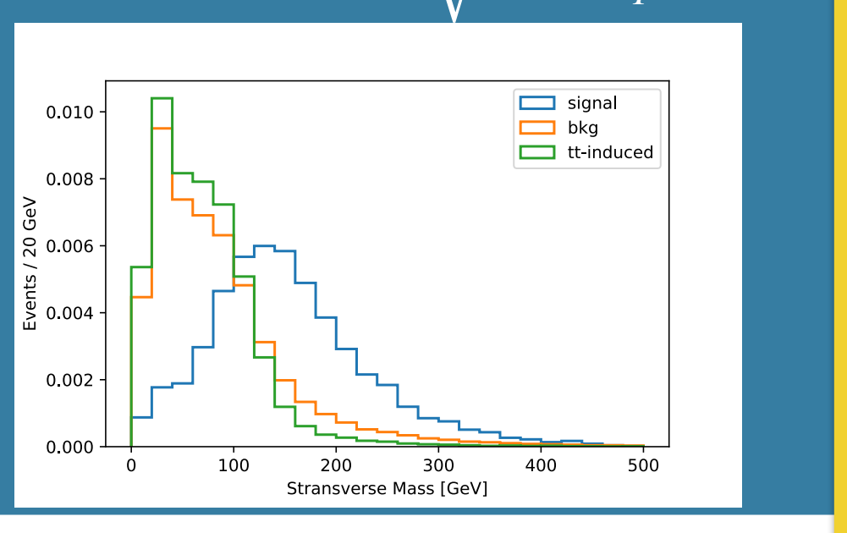
$$M_{T2}(m_B, m_{B'}, b_T, b'_T, p_T^{\Sigma}, m_C, m_{C'}) = \min_{c_T + c'_T = p_T^{\Sigma}} \{\max(m_T, m'_T)\}$$

$$m_T(b_T, c_T, m_b, m_c) = \sqrt{m_b^2 + m_c^2 + 2(e_b e_c - b_T \dot{c}_T)}$$

$$p_T^{\Sigma} = p_T^{vis}(\tau_1) + p_T^{vis}(\tau_2) + p_T^{miss}$$

$$e = \sqrt{m^2 + p_T^2}$$

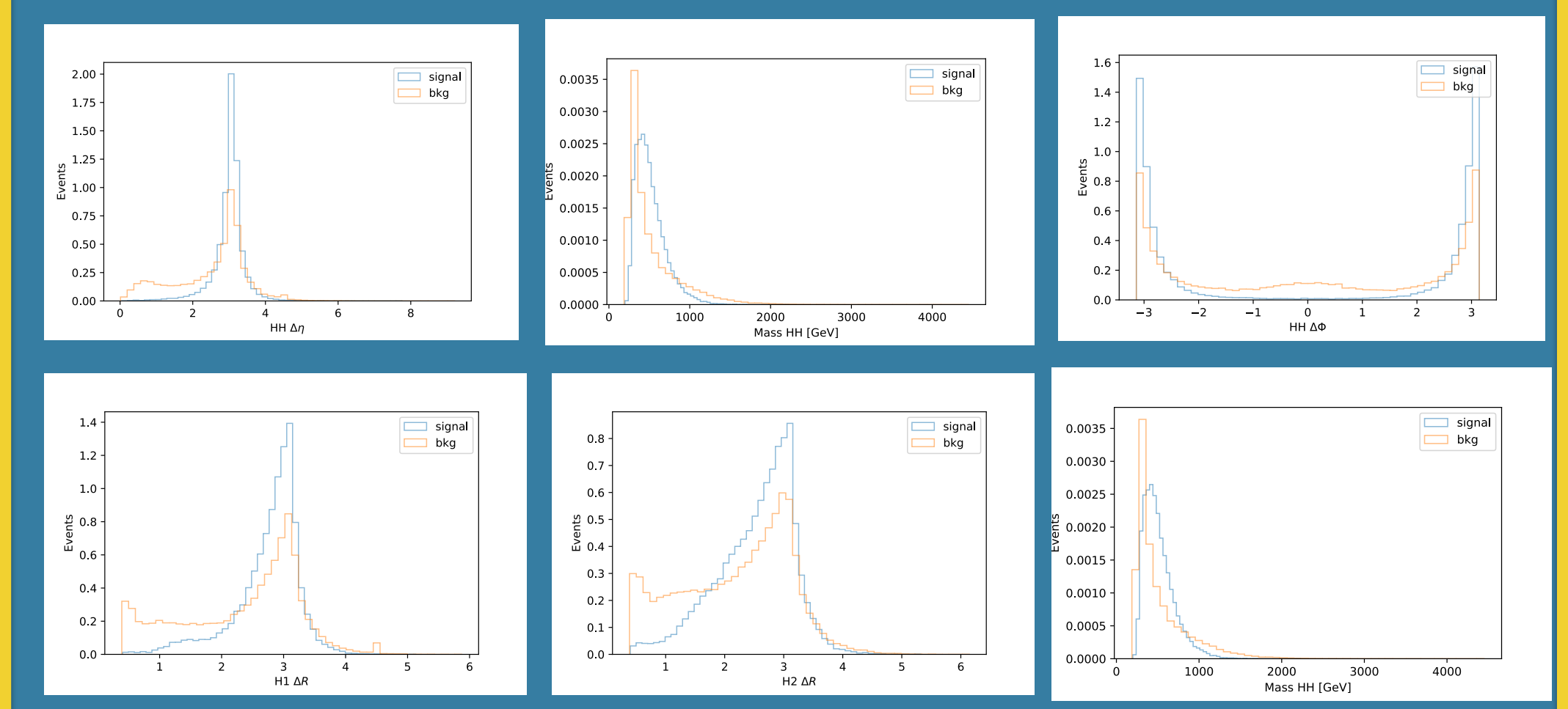


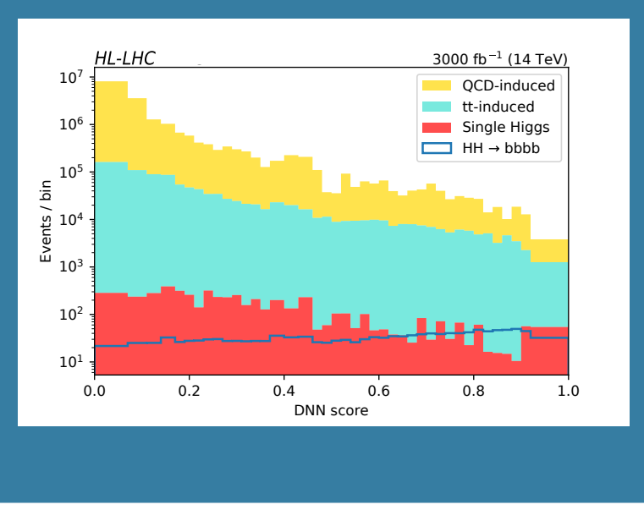


bbbb

- **Four jets** are reconstructed with **p_T > 45 GeV** and **|η| < 3.5** and satisfy the **medium b tagging** working point
- If more than four jets pass that preselection step, the four highest p_T candidates are selected to build the double Higgs pair. The jets are paired in order to minimizes the difference in the invariant mass of the two jet pairs

- **1 Neural Networks** to discriminate against the background
- different kinematical variables used as inputs

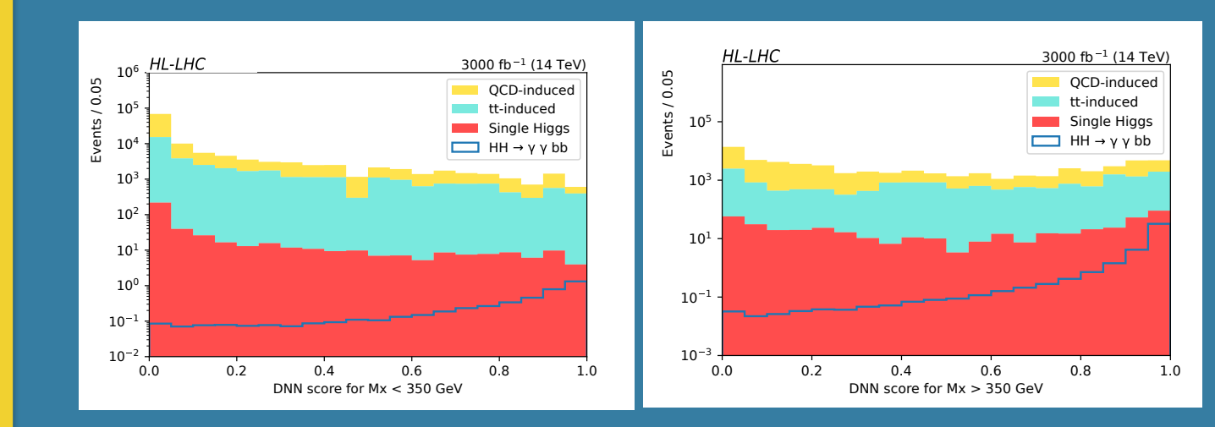




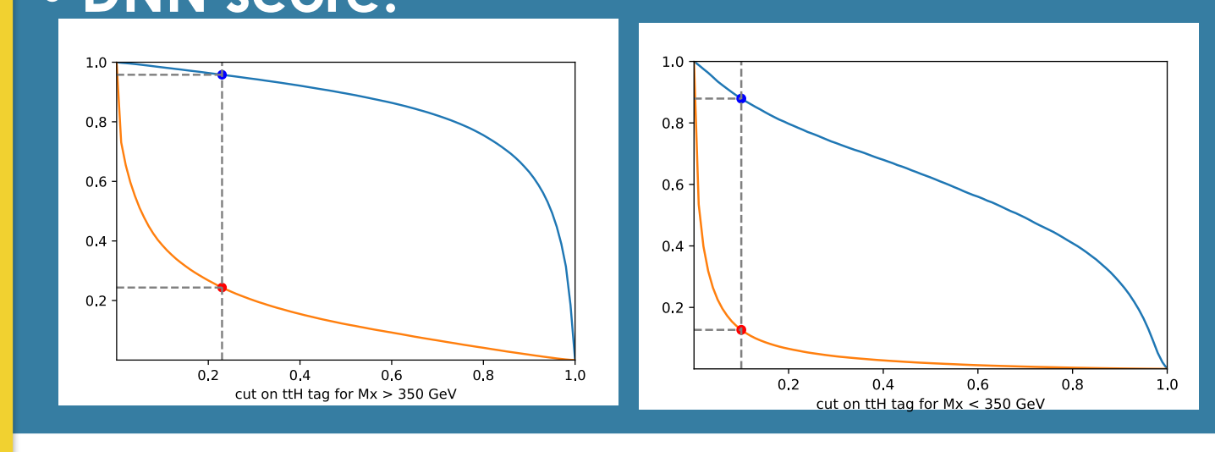
Categories

$$M_X = m_{\gamma\gamma jj} - m_{\gamma\gamma} - m_{jj} + 250\ \mathrm{GeV}$$

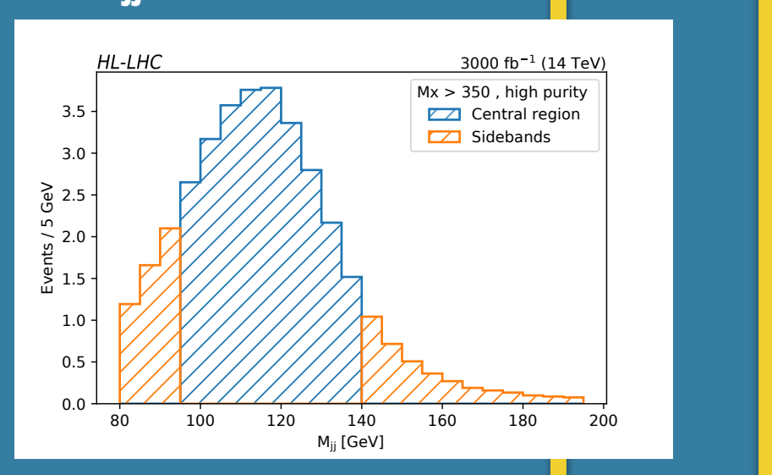
- **M_X < 350 GeV; M_X > 350 GeV**



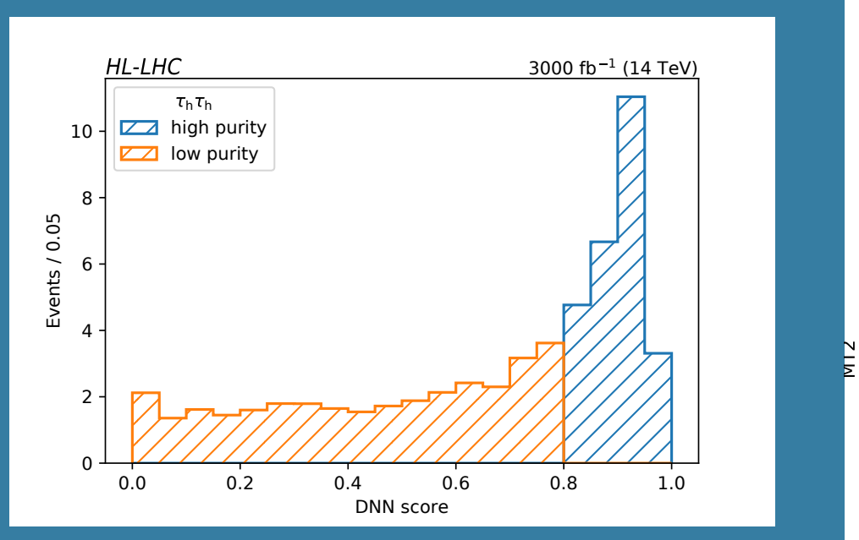
- **DNN score:**

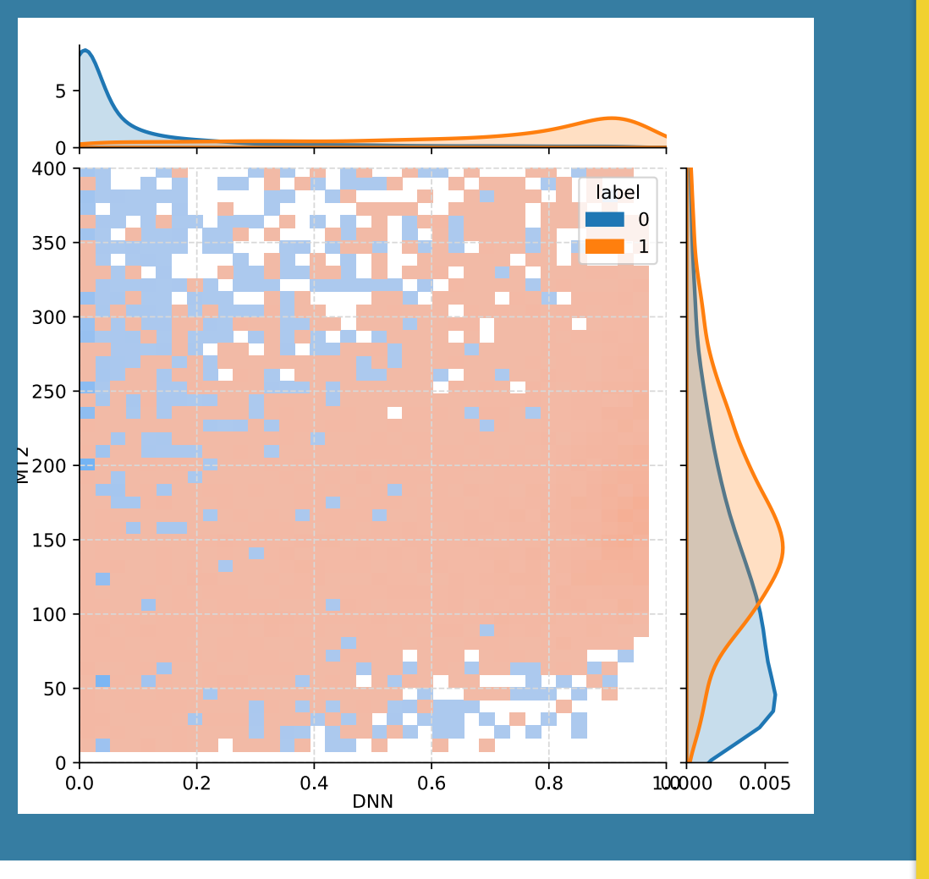


- **m_{jj}**



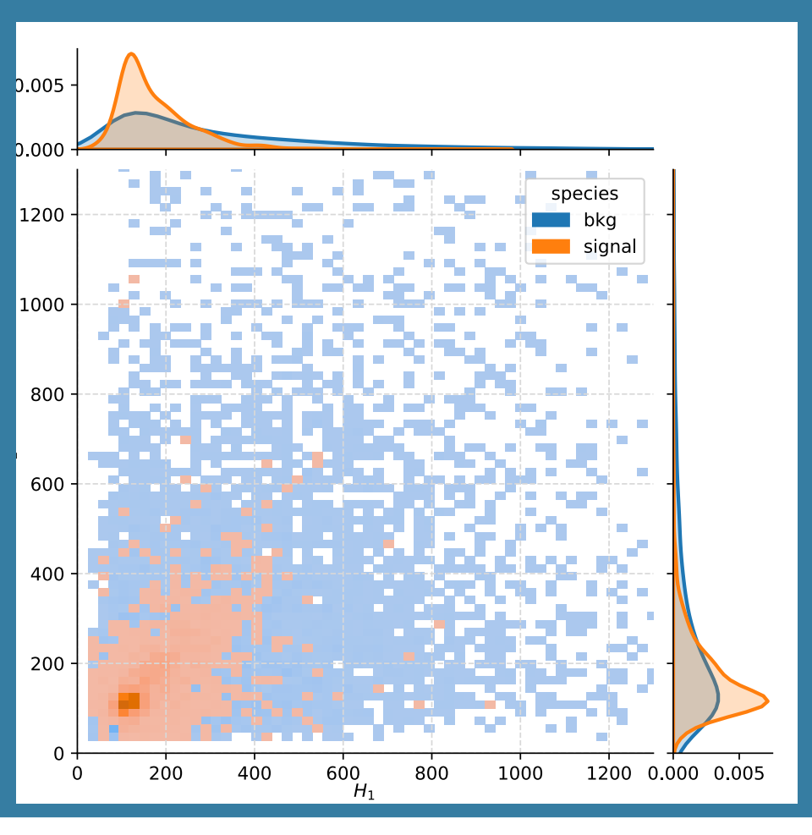
- Events categorized according to the DNN score
- threshold is chosen with a procedure to maximize the signal to background ratio, that is repeated independently for the three different channels





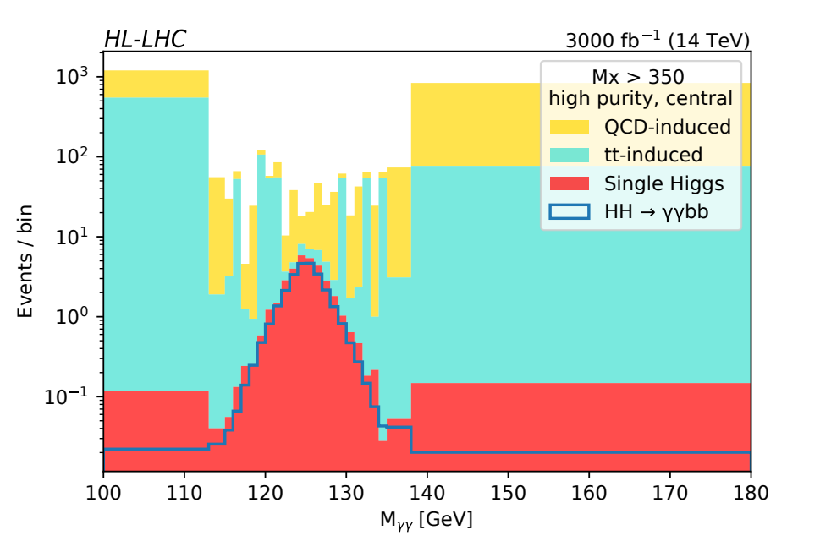
- signal region is defined by considering the events that satisfy a circular cut:

$$\sqrt{(m_{\mathrm{H}_1} - 120\ \mathrm{GeV})^2 + (m_{\mathrm{H}_2} - 120\ \mathrm{GeV})^2} < 40\ \mathrm{GeV}$$



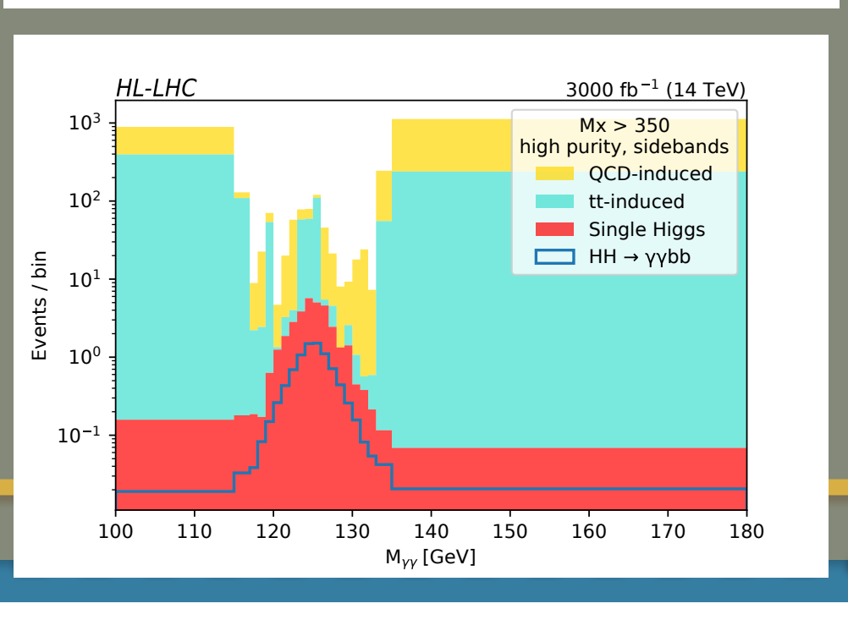
Fit

- **8 Categories**
- **Systematics:**



Systematic uncertainty source	Impact on yields
Luminosity	± 1.0 %
$m_{\gamma\gamma}$ scale	± 0.5 %
Photon energy scale	± 2.0 %
Diphoton trigger	± 2.0%
Photon ID efficiency	± 1.0 %
Jet Energy Scale	± 1.0%
B-tag efficiency	± 1.0%
QCD scale	+4.6% / -6.7% (ggH) +0.4% / -0.7% (VH) +0.5% / -0.3% (VBFH) +6.0% / -9.2% (ttH) +2.4% / -3.6% (tt)
Pdf scale	±3.2% (ggH) ±1.8% (VH) ±2.1% (VBFH) ±3.5% (ttH) ±4.2% (tt)
Signal theoretical uncertainties	+2.1% / -4.9% (QCD scale) ±3.0% (pdf scale) +4.0% / -18.0% (top mass)

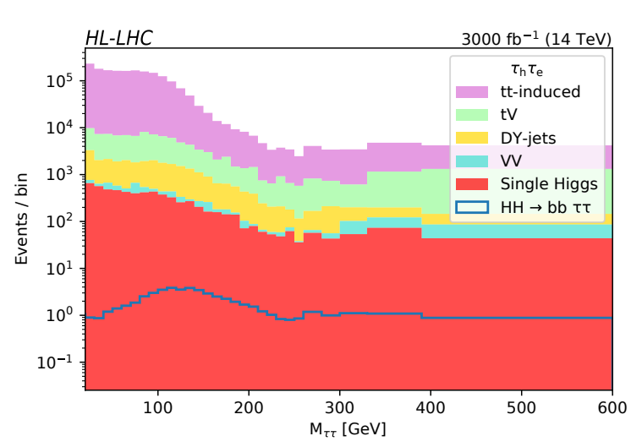
Table 6: Systematic uncertainties for *bbγγ* channel.

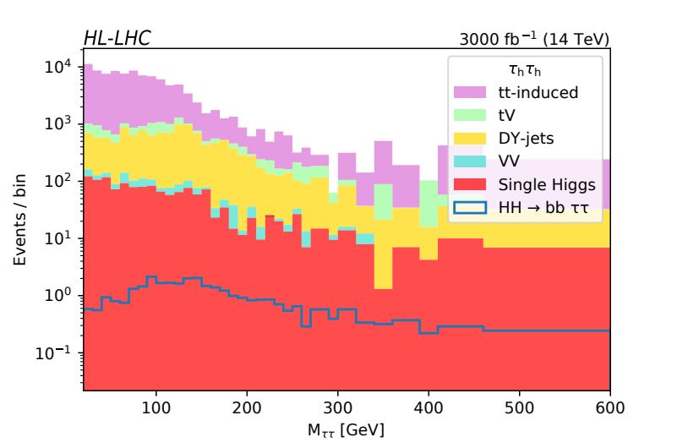


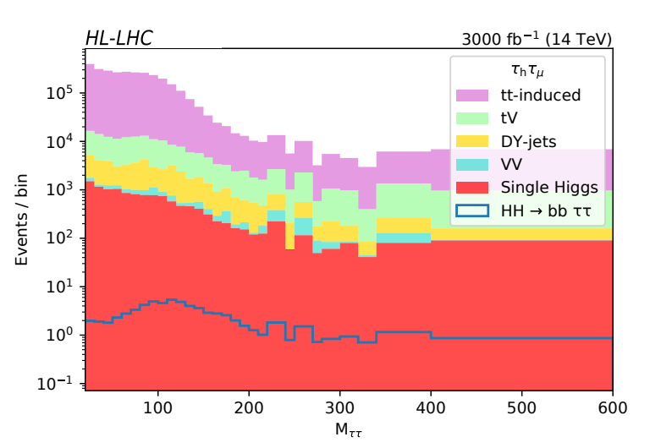
- **6 Categories**
- **Systematics:**

Systematic uncertainty source	Impact on yields
Luminosity	± 1.0 %
Lepton ID efficiency	± 1.0 %
Tau ID efficiency	± 5.0%
Photon ID efficiency	± 1.0 %
Jet Energy Scale	± 1.0%
B-tag efficiency	± 1.0%
QCD scale tt inclusive	+2.4% /-3.6%
Pdf scale tt inclusive	±4.2%
Signal theoretical uncertainties	+2.1% /-4.9% (QCD scale) ±3.0% (pdf scale) +4.0% /-18.0% (top mass)

Table 12: Systematic uncertainties for *bbττ* channel.



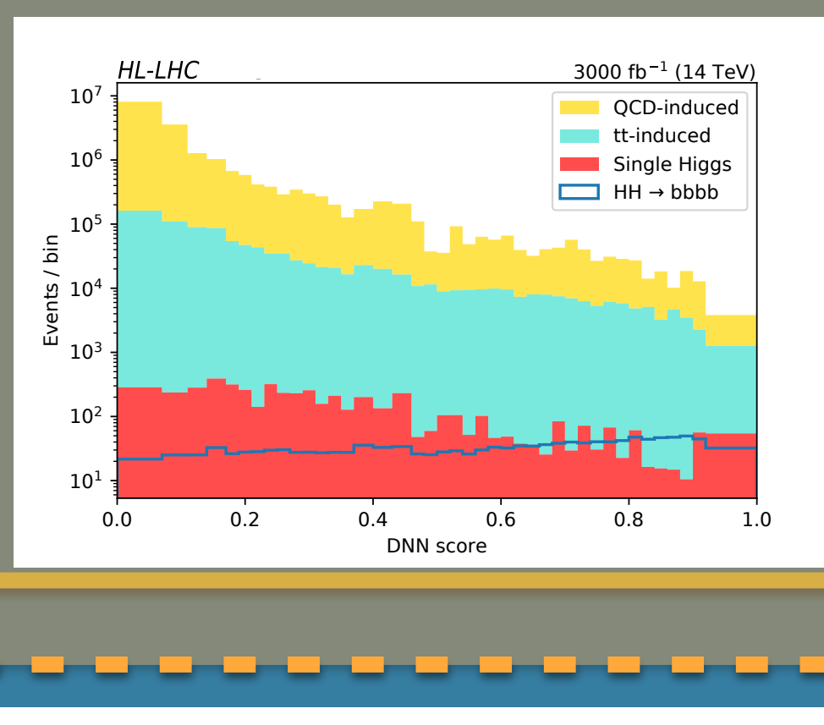




- **1 Category**
- **Systematics:**

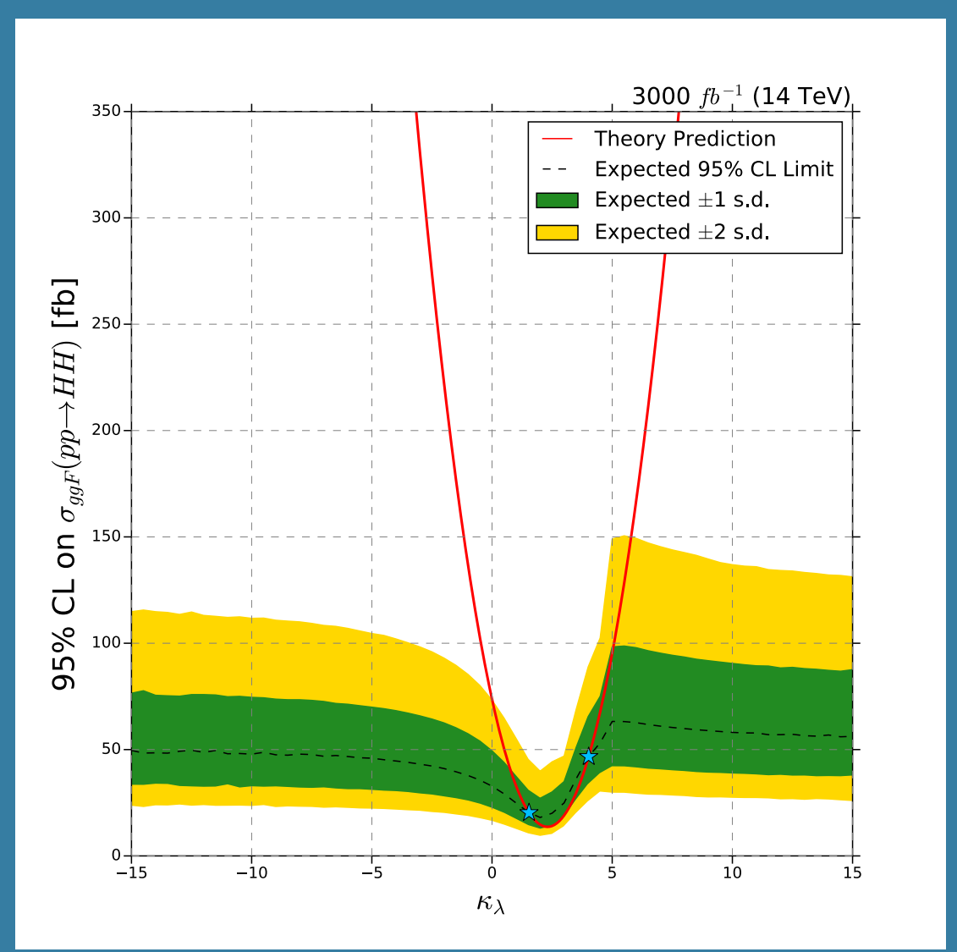
Systematic uncertainty source	Impact on yields
Luminosity	± 1.0 %
Jet Energy Scale	± 1.0%
B-tag efficiency	± 1.0%
QCD scale tt inclusive	+2.4% /-3.6%
Pdf scale tt inclusive	±4.2%
Signal theoretical uncertainties	+2.1% /-4.9% (QCD scale) ±3.0% (pdf scale) +4.0% /-18.0% (top mass)

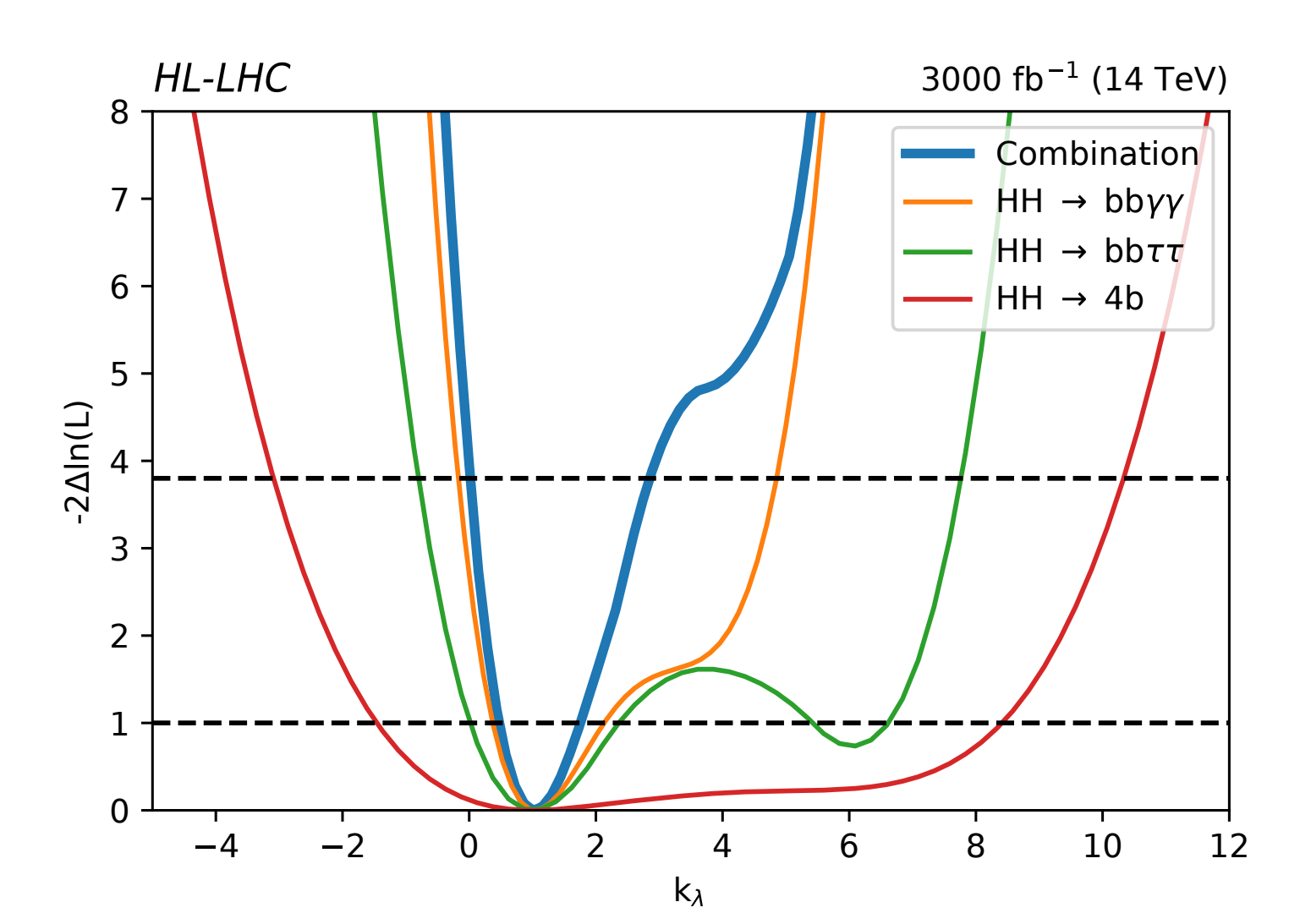
Table 16: Systematic uncertainties for *bbbb* channel.



Results

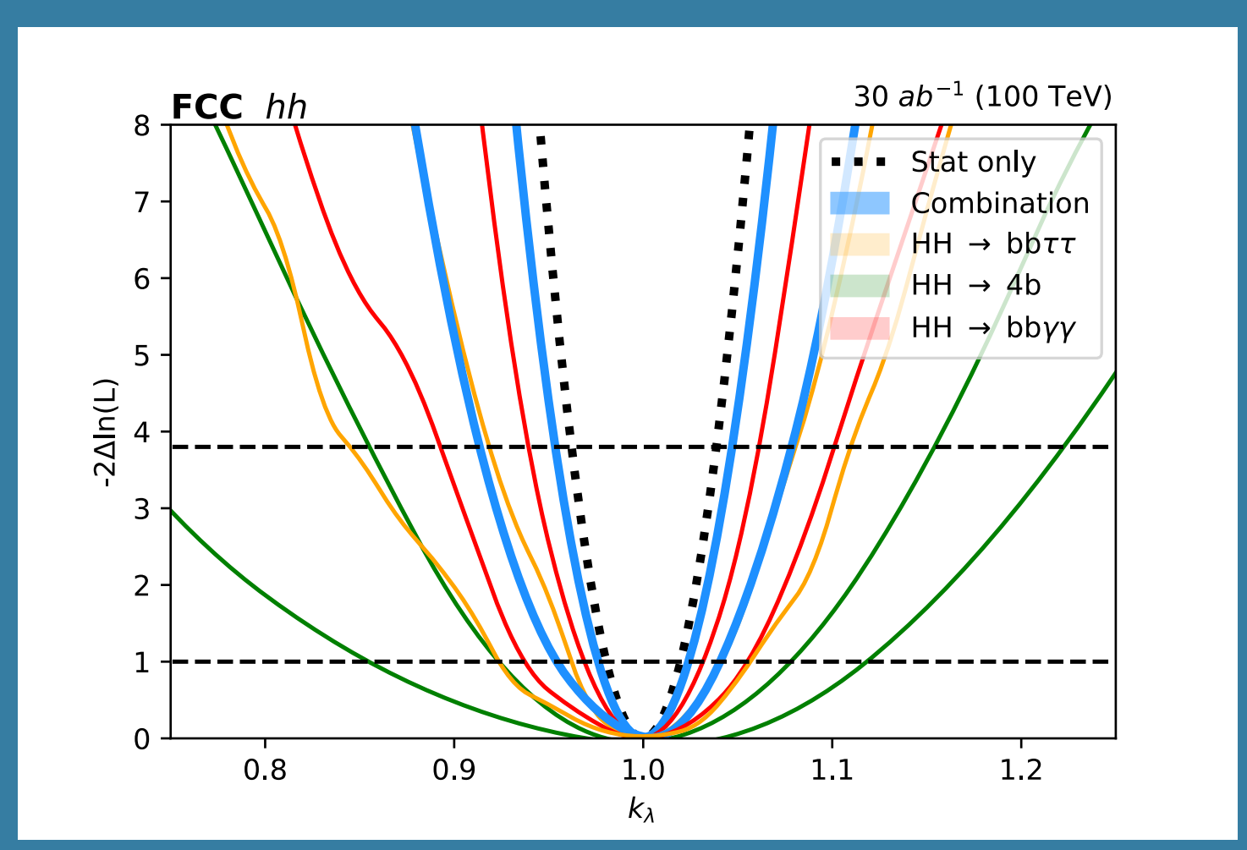
HL-LHC 14 TeV, 3 ab^{-1}

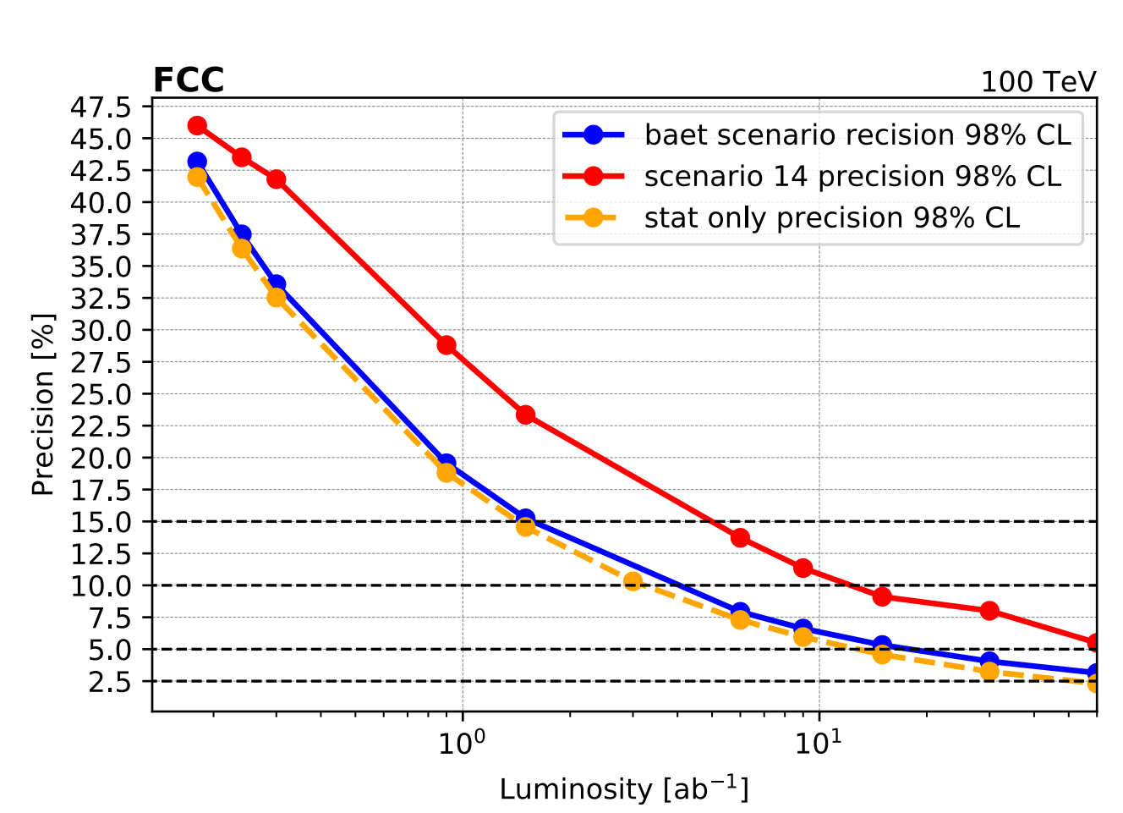




	bb$\gamma\gamma$	bbττ	bbbb	combine
Upper lim. 95% CL	1.09	1.37	2.00	**0.76**
κ_λ constr. 95% CL	[-0.2,4.9]	[-0.84,7.75]	[-3.16,10.41]	**[-0.02,3.05]**
Significance	1.94	1.70	1.06	**2.80**

FCC-hh 100 TeV, 30 ab^{-1}





Systematic uncertainty source	Impact on yields
Luminosity	± 0.5%
Photon ID efficiency	± 1.0 %
B-tag efficiency	± 1.0%
Lepton ID efficiency	± 1.0%
Tau ID efficiency	± 2.0%
Theoretical uncertainties	± 1%

Table 20: Systematic uncertainties in the optimistic scenario.

	bb$\gamma\gamma$	bbττ	bbbb	combine
	Precision on (at 68% CL) κ_λ			
Stat. only	2.6	3.3	8.0	**2.0**
Best scenario	3.1	4.0	9.4	**2.4**
14 TeV scenario	5.6	6.6	13.5	**3.9**

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