IUEP

Di-Higgs day @ Konkuk University
2019. 06. 27. Thursday

Probing the trilinear Higgs boson coupling in the di-Higgs production at the LHC and its performance improvement using machine learning

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Ref : 1. An exploratory study of Higgs-boson pair production **(JHEP 1508(2015) 133)**

2. Higgs-boson-pair production H(→ $b\bar{b}$)H(→ γγ) from gluon fusion at the HL-LHC and HL-100 TeV hadron collider **(Arxiv :1804.07130)**

3. Higgs-boson-pair production H(→$b\bar{b}$)H(→γγ) from gluon fusion with multivariate techenique **(Work in Progress)**

4. Introduction to Machine Learning with Python (Andreas Muller)

Contents

- Higgs in the SM (Prof. Song's presentation)
- How to probe it ? : Higgs pair production
  (From the experimental view, Dr. Yu's presentation)
  (From the intermediate(?), this talk)
  (From the theoretical view, Prof. M. Park's and Prof. S. Park's talks
- Simulation
- Analysis (TMVA, BDT)
  BDTL1 scenario
- Expected yields and significance(Z)
- Conclusion
- Recent updates

Preliminary

Recent updates

- HH NLO generator – POWHEG BOX V2
  Use of NLO kinematic distributions (or variables)
- Improved yields and significance(Z)
- Improved Likelihood fit using the M_{HH} kinematic distribution

Higgs In the SM

- Higgs field (h) : responsible for
  ① the spontaneous EW symmetry breaking
  ② the generation of masses of all the SM particle

- The potential is characterized by only two parameters :
  ① vacuum expectation value v
  ② the Higgs mass m_H

$$v = \frac{1}{\sqrt{\sqrt{2}\, G_F}} \approx 246 \text{ GeV} \qquad V_{SM}(h) = \frac{1}{2} m_H^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

Trilinear and Quartic Higgs boson coupling in the SM

$$\lambda_3^{SM} = \lambda_4^{SM} = \frac{m_H^2}{2\,v^2}$$

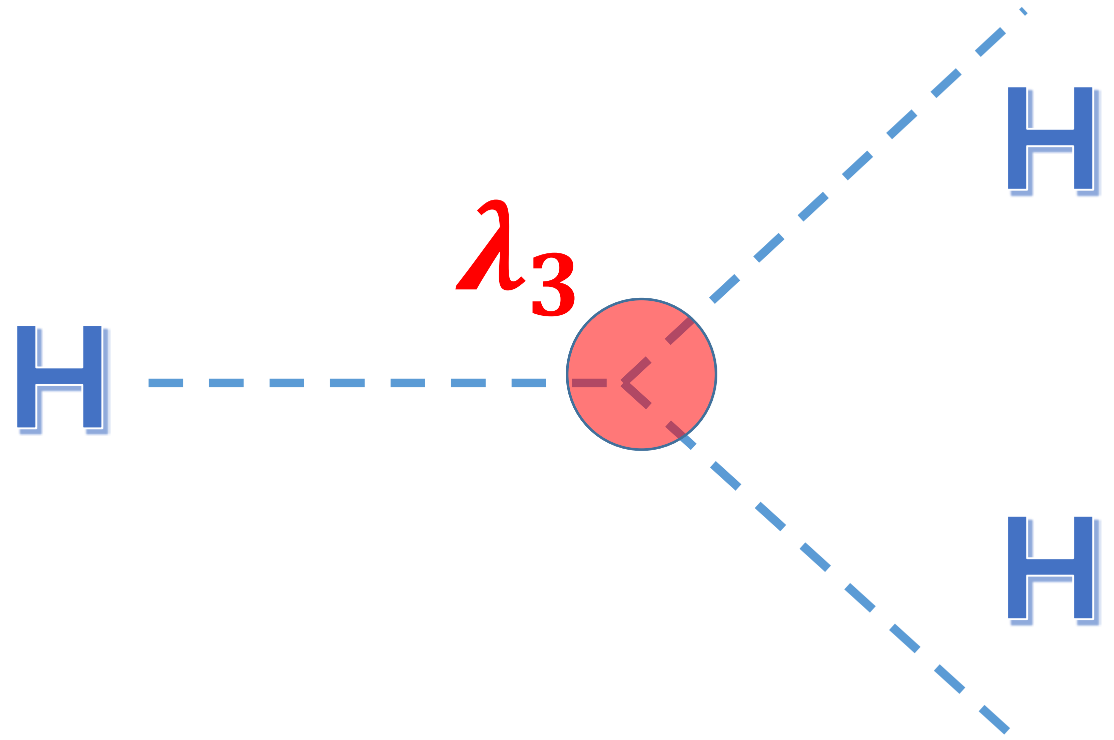
New Physics can affect the Higgs potential form

⟹ Sizeable departures from the SM form

⟹ $\lambda_3 = \lambda_3^{SM} + \delta\lambda_3^{SM}$, $\lambda_4 = \lambda_4^{SM} + \delta\lambda_4^{SM}$

Trilinear Higgs boson coupling

$$\lambda_3 = \lambda_3^{SM} + \delta\lambda_3^{SM}$$



How to probe it ?

Higgs pair production !

We now focus on

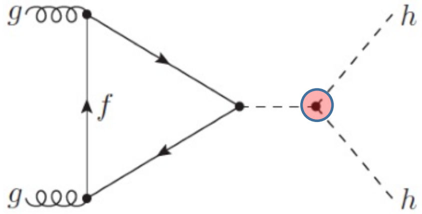
Higgs pair production

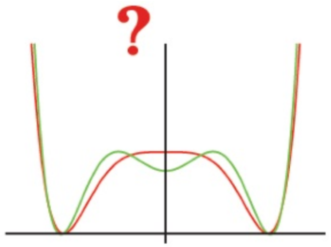
at the **Hadron collider**

Why Higgs pair production so interesting ?

Allows accessing crucial components of the Higgs sector !!!

can probe the Higgs self-coupling





can help to reconstruct the electroweak symmetry breaking potential

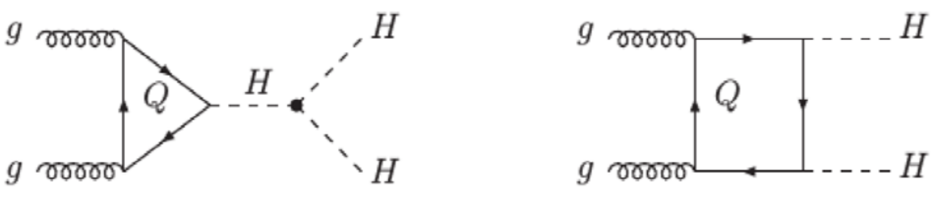
may reveal the doublet nature of the Higgs by means of the hhVV coupling

∴ A high priority goal on the physics program at the future collider

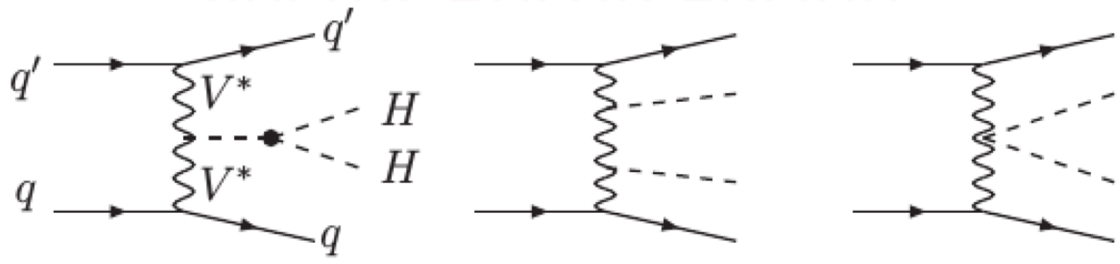
Higgs pair productions at the LHC

Production modes

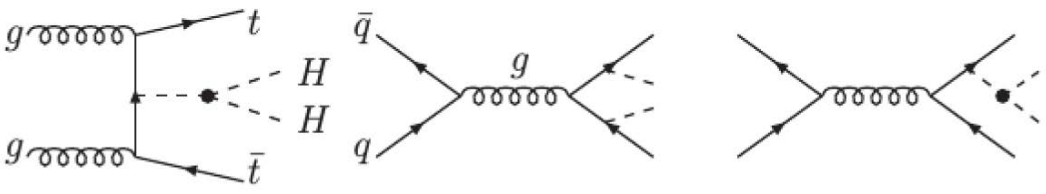
Gluon Fusion



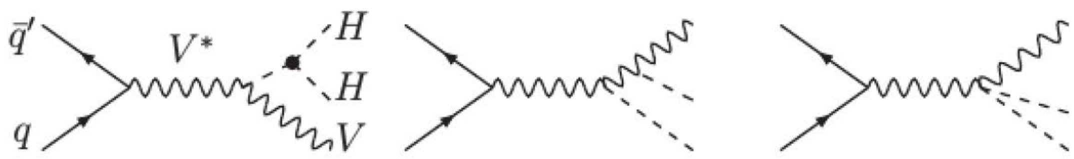
Vector Boson Fusion



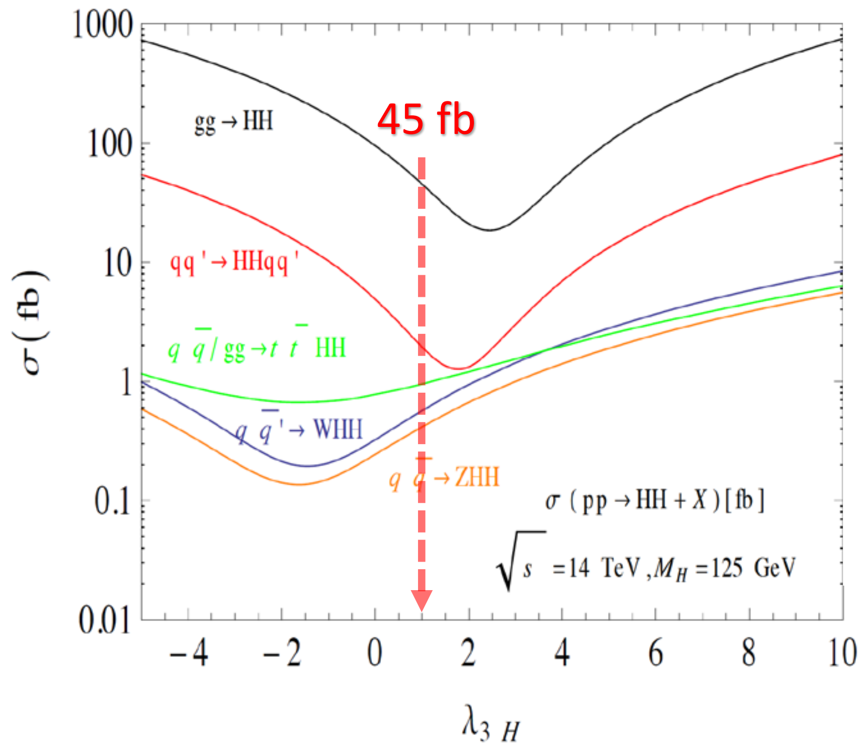
Top associated productions

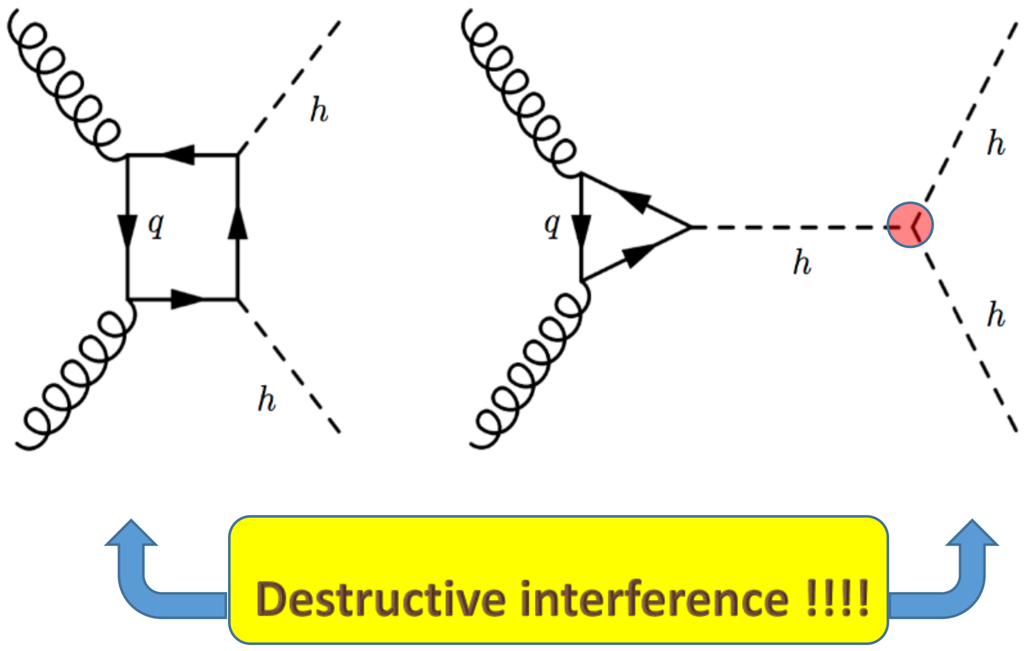


Higgs strahlung



Why Higgs pair production so difficult ?





In the leading gluon fusion production mode,
the cross section at 14 TeV is only 45 fb (in the SM),
further suppressed by each decay branching fractions.

45 fb ↔ NNLO accuracy including NNLL gluon resummation in the infinite top quark mass approximation.

Why **Higgs pair production** so difficult ?

Full top-quark mass effect at the NLO

45.05 fb → **36.69 fb**

Recently, the NLO corrections considering full top-quark mass dependence have been available. We observe that **20 % reduction** at 14 TeV compared to the cross sections used.

Strong QCD backgrounds

→ Which search mode would be better to use?

Search channels for Higgs pair production at Collider

Our Channel reconstruct τ / W b-tagging, QCD BG

Decay channels	$HH \to bb\gamma\gamma$	$HH \to bb\tau\tau$	$HH \to bbWW$	$HH \to bbbb$	$\cdots$
Branching ratios	0.263%	7.29%	24.8%	33.3%	

small BR
relatively clean channel
dominate BGs comes from
fake photon or b-jet

Huge $t\bar{t}$ BG

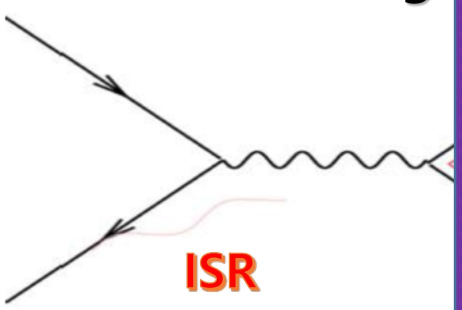
Huge hadronic BG

Decay channels	$HH \to bb\gamma\gamma$	$HH \to bb\tau\tau$	$HH \to bbWW$	$HH \to bbbb$	$\cdots$
Expected events with 3 ab^{-1}	**290**	**8000**	**27000**	**37000**	$\cdots$

Simulation

Outline of Simulations

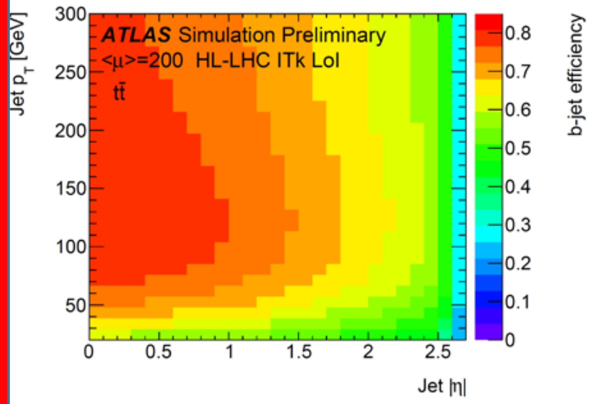
Hard Scattering



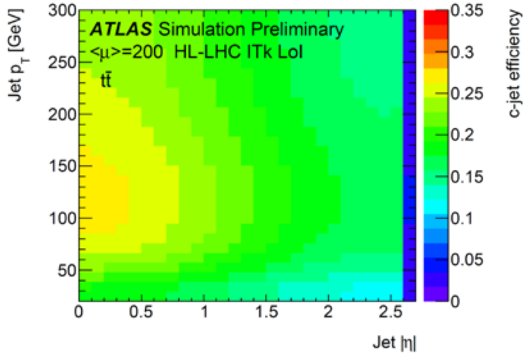
Parton level

LHE files

b-jet efficiency



c-jet efficiency



ATL-PHYS-PUB-2016-026

① Updated Signal Cross Section (about 20% reduction)

$\sigma \cdot Br(H \to \gamma\gamma)Br(H \to b\bar{b})$=0.119 fb → 0.096 fb

Signal

Signal process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
$gg \to HH \to b\bar{b}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	0.096	NNLO	NNPDF2.3LO

Backgrounds

Background(BG)	Process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
Single-Higgs associated BG	$ggH(\to \gamma\gamma)$	POWHEG-BOX/PYTHIA6	1.20×10^2	NNNLO	CT10
	$t\bar{t}H(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	1.37	NLO	
	$ZH(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	2.24	NLO	
	$b\bar{b}H(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	1.26	NLO	
Non-resonant BG	$b\bar{b}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.12×10^2	LO	CT14LO
	$c\bar{c}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.08×10^3	LO	
	$jj\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.40×10^4	LO	
	$b\bar{b}j\gamma$	MG5_aMC@NLO/PYTHIA8	2.72×10^5	LO	
	$c\bar{c}j\gamma$	MG5_aMC@NLO/PYTHIA8	9.17×10^5	LO	
	$b\bar{b}jj$	MG5_aMC@NLO/PYTHIA8	3.00×10^8	LO	
	$Z(\to b\bar{b})\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	5.03	LO	
$t\bar{t}$ and $t\bar{t}\gamma$ BG ($\geq$ 1 lepton)	$t\bar{t}$	POWHEG − BOX/PYTHIA8	5.30×10^5	NNLO +NNLL	CT10
	$t\bar{t}\gamma$	MG5_aMC@NLO/PYTHIA8	1.60×10^3	NLO	CTEQ6L1

② Updated non-resonant BG with the recent PDF

CTEQ6L1 PDF → CT14LO PDF (+ about 20% reduction)

Signal

Signal process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
$gg \to HH \to b\bar{b}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	0.096	NNLO	NNPDF2.3LO

Backgrounds

Background(BG)	Process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
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	$t\bar{t}H(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	1.37	NLO	
	$ZH(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	2.24	NLO	
	$bbH(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	1.26	NLO	
Non-resonant BG	$bb\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.12×10^2	LO	CT14LO
	$c\bar{c}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.08×10^3	LO	
	$jj\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.40×10^4	LO	
	$bbj\gamma$	MG5_aMC@NLO/PYTHIA8	2.72×10^5	LO	
	$c\bar{c}j\gamma$	MG5_aMC@NLO/PYTHIA8	9.17×10^5	LO	
	$bbjj$	MG5_aMC@NLO/PYTHIA8	3.00×10^8	LO	
	$Z(\to bb)\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	5.03	LO	
$t\bar{t}$ and $t\bar{t}\gamma$ BG ($\geq$ 1 lepton)	$t\bar{t}$	POWHEG − BOX/PYTHIA8	5.30×10^5	NNLO +NNLL	CT10
	$t\bar{t}\gamma$	MG5_aMC@NLO/PYTHIA8	1.60×10^3	NLO	CTEQ6L1

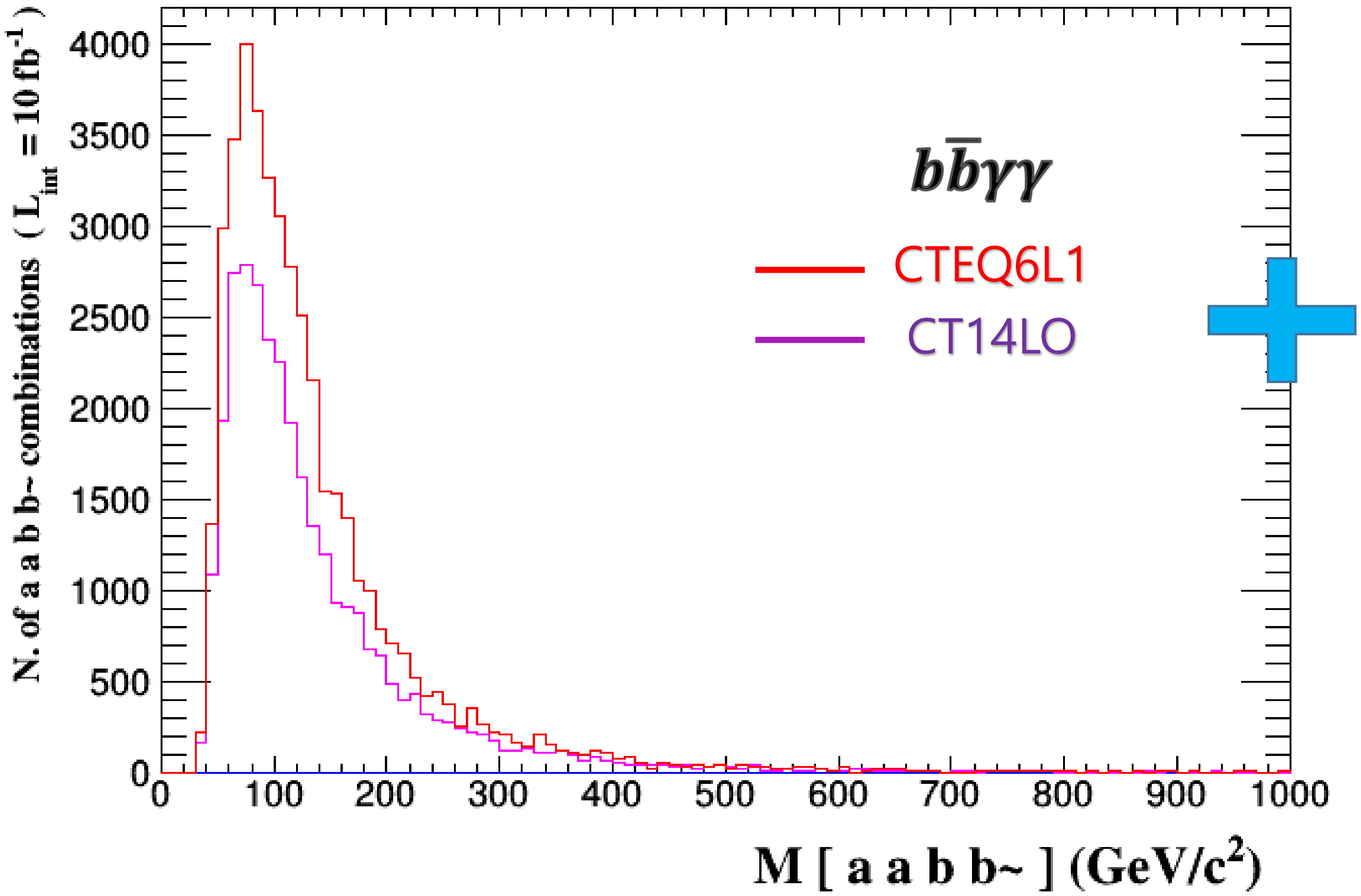
Cuts at the generator level on the non-resonant BGs

$$P_{T_j} > 20 \;\; \mathrm{GeV},\;\; P_{T_b} > 20 \;\; \mathrm{GeV},\;\; P_{T_\gamma} > 25 \;\; \mathrm{GeV},\;\; P_{T_l} > 10 \;\; \mathrm{GeV},$$
$$|\eta_j| < 5,\;\; |\eta_\gamma| < 2.7,\;\; |\eta_l| < 2.5,\;\; \Delta R_{jj,ll,\gamma\gamma,\gamma j,jl,\gamma l} > 0.4,$$
$$M_{jj} > 25 \; \mathrm{GeV},\;\; M_{bb} > 45 \; \mathrm{GeV},\;\; 60 < M_{\gamma\gamma} < 200 \; \mathrm{GeV}.$$

CTEQ6L1 v.s. CT14LO

CT14LO contains the LHC RUN I results

They show similar kinematic distributions.



CTEQ6L1 PDF → CT14LO PDF

approximately 20% reduced cross sections.

Analysis

Analysis Methods

- Cut Based Analysis

- Machine Learning

  Multi-Variate Analysis : BDT (Boosted Decision Tree)
  (work in progress)

TMVA (Toolkit for Multivariate Data Analysis with ROOT)

A. Hoecker, P. Speckmayer, J. Stelzer, J. Therhaag, E. von Toerne, and H. Voss,
TMVA - Toolkit for Multivariate Data Analysis,
PoS ACAT 040 (2007), arXiv:physics/0703039

Machine Learning

TMVA package

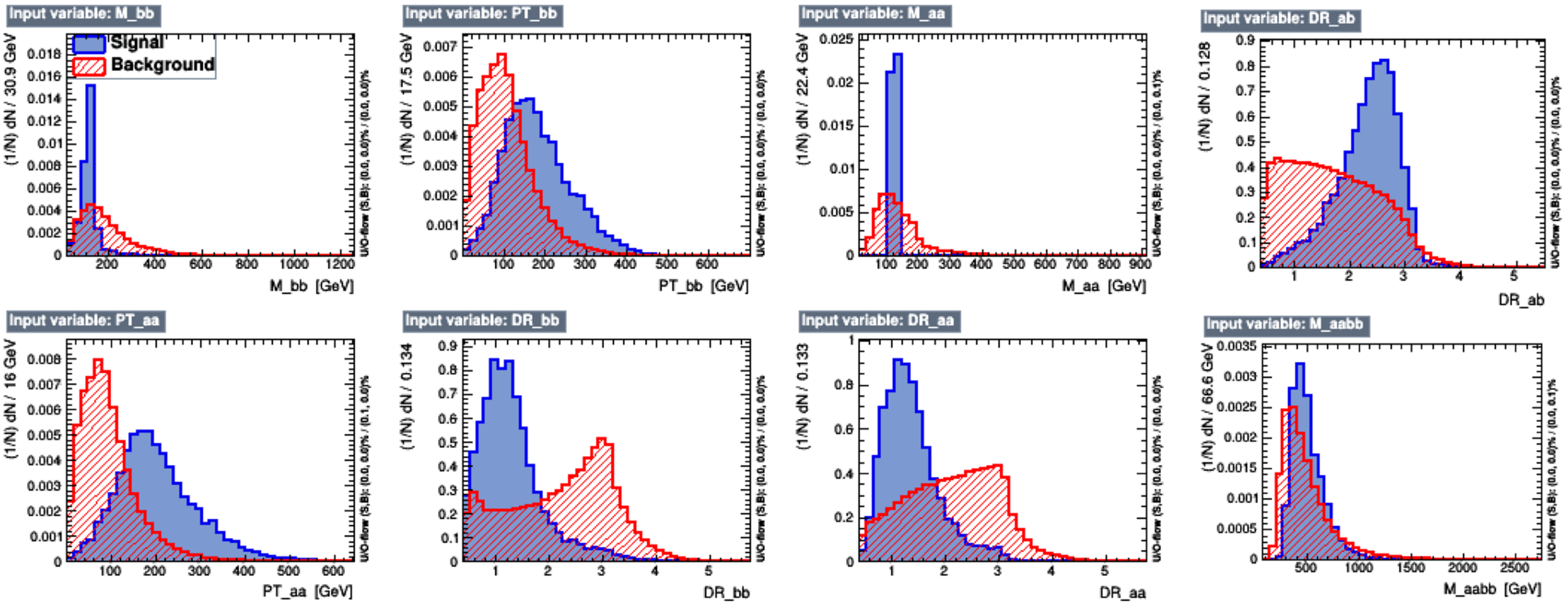
Pre-selection cuts for TMVA study

Sequence	Event Selection Criteria at the HL-LHC
1	Di-photon trigger condition, ≥ 2 isolated photons with $P_T > 25$ GeV, $\|\eta\| < 2.5$
2	≥ 2 isolated photons with $P_T > 30$ GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.37$, $\Delta R_{j\gamma} > 0.4$
3	≥ 2 jets identified as b-jets with leading(subleading) $P_T > 40(30)$ GeV, $\|\eta\| < 2.4$
4	Events are required to contain ≤ 5 jets with $P_T > 30$ GeV within $\|\eta\| < 2.5$
5	No isolated leptons with $P_T > 25$ GeV, $\|\eta\| < 2.5$

We use TMVA analysis to improve our previous result

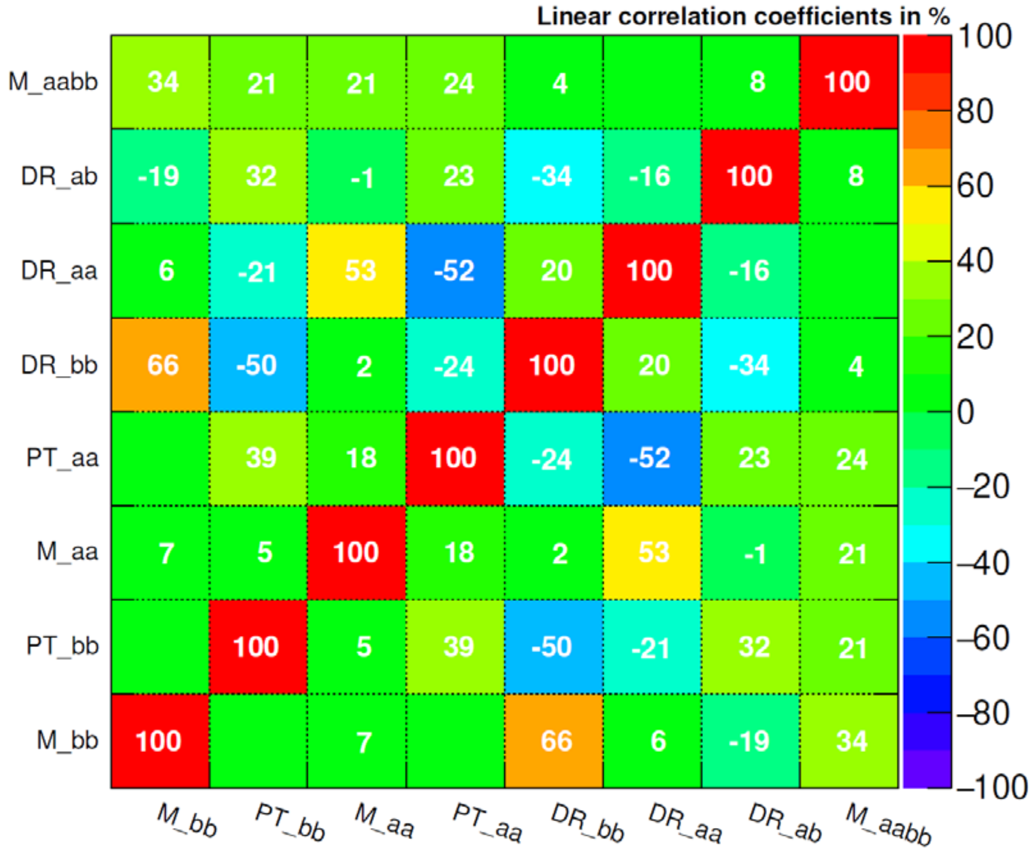
TMVA Inputs : 8 (kinematic) variables

$$P_{T\_\gamma\gamma}\,, P_{T\_bb}\,, M_{\gamma\gamma}\,, M_{bb}\,, M_{\gamma\gamma bb}\,, \Delta R_{\gamma\gamma}\,, \Delta R_{bb}\,, \Delta R_{\gamma b}$$

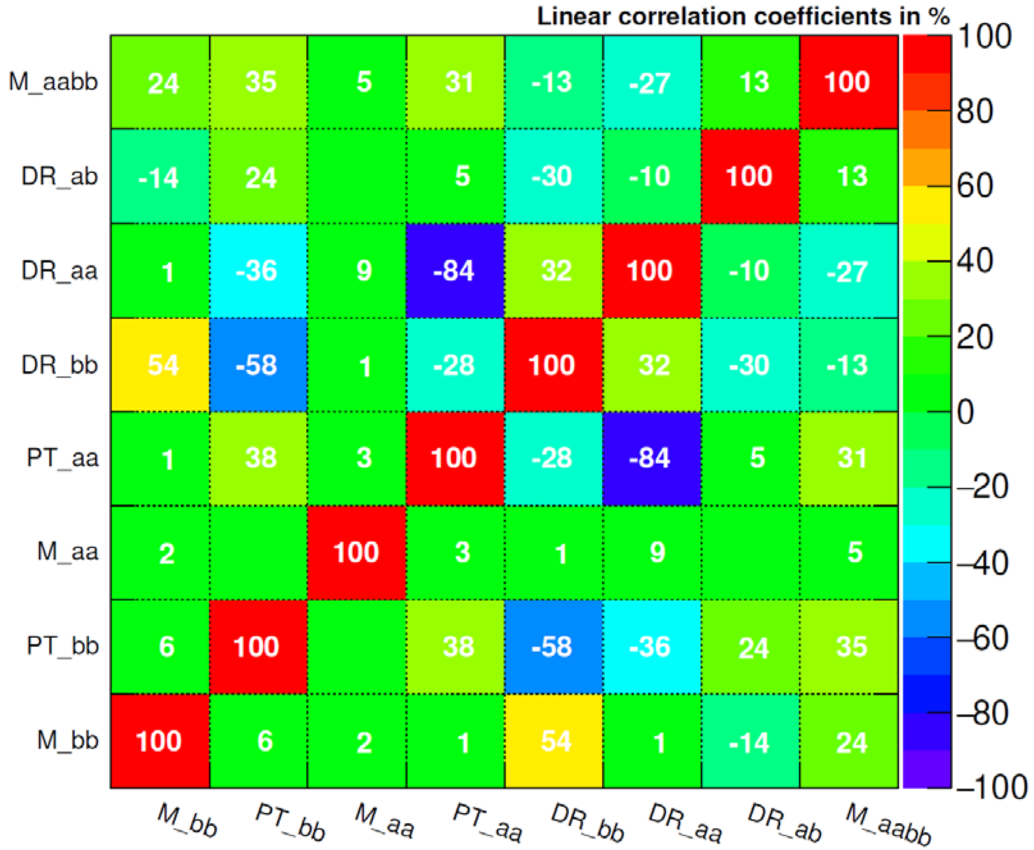


Correlation Matrix among variables

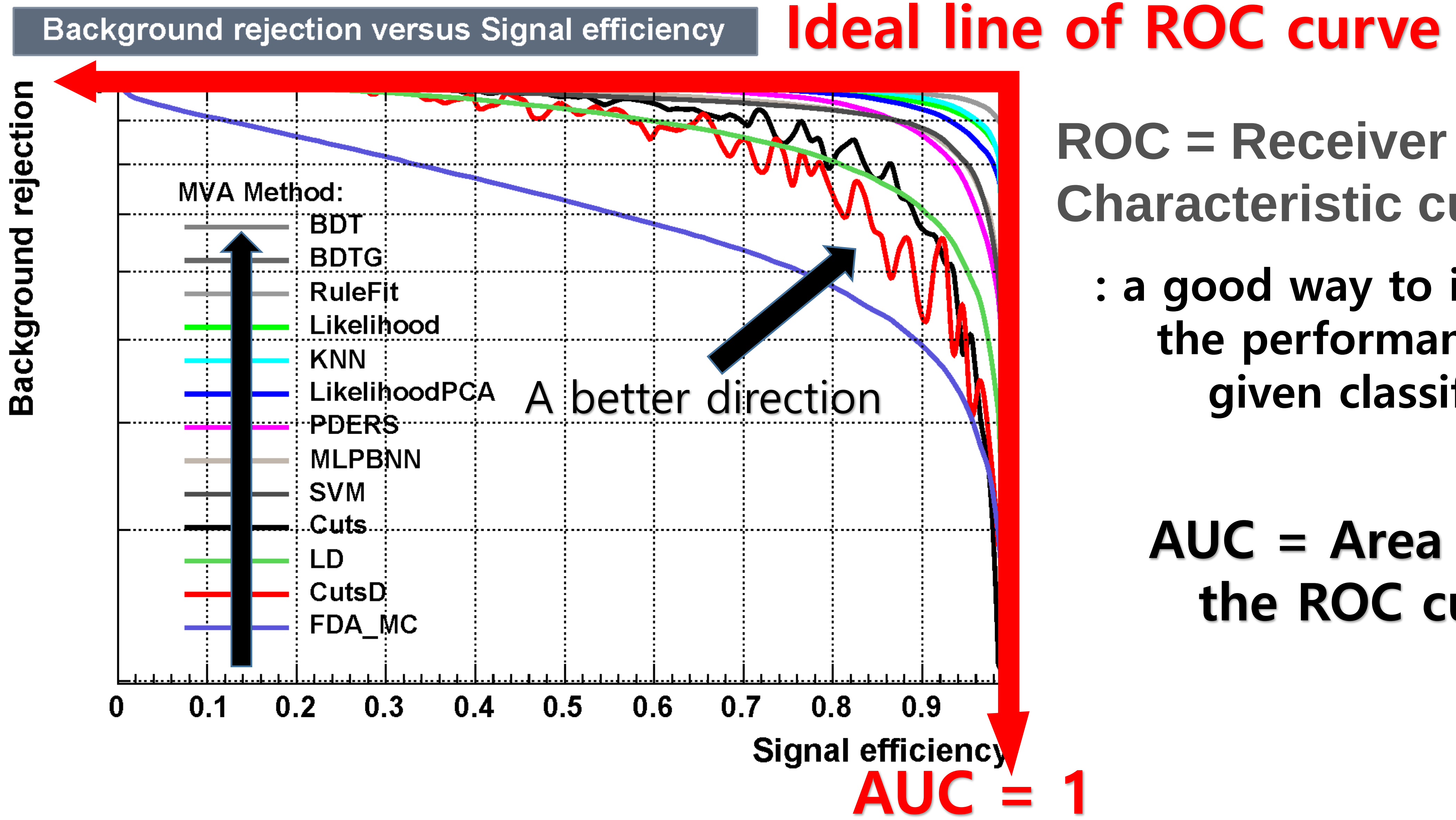
Correlation Matrix (background)



Correlation Matrix (signal)



Various ML methods in TMVA

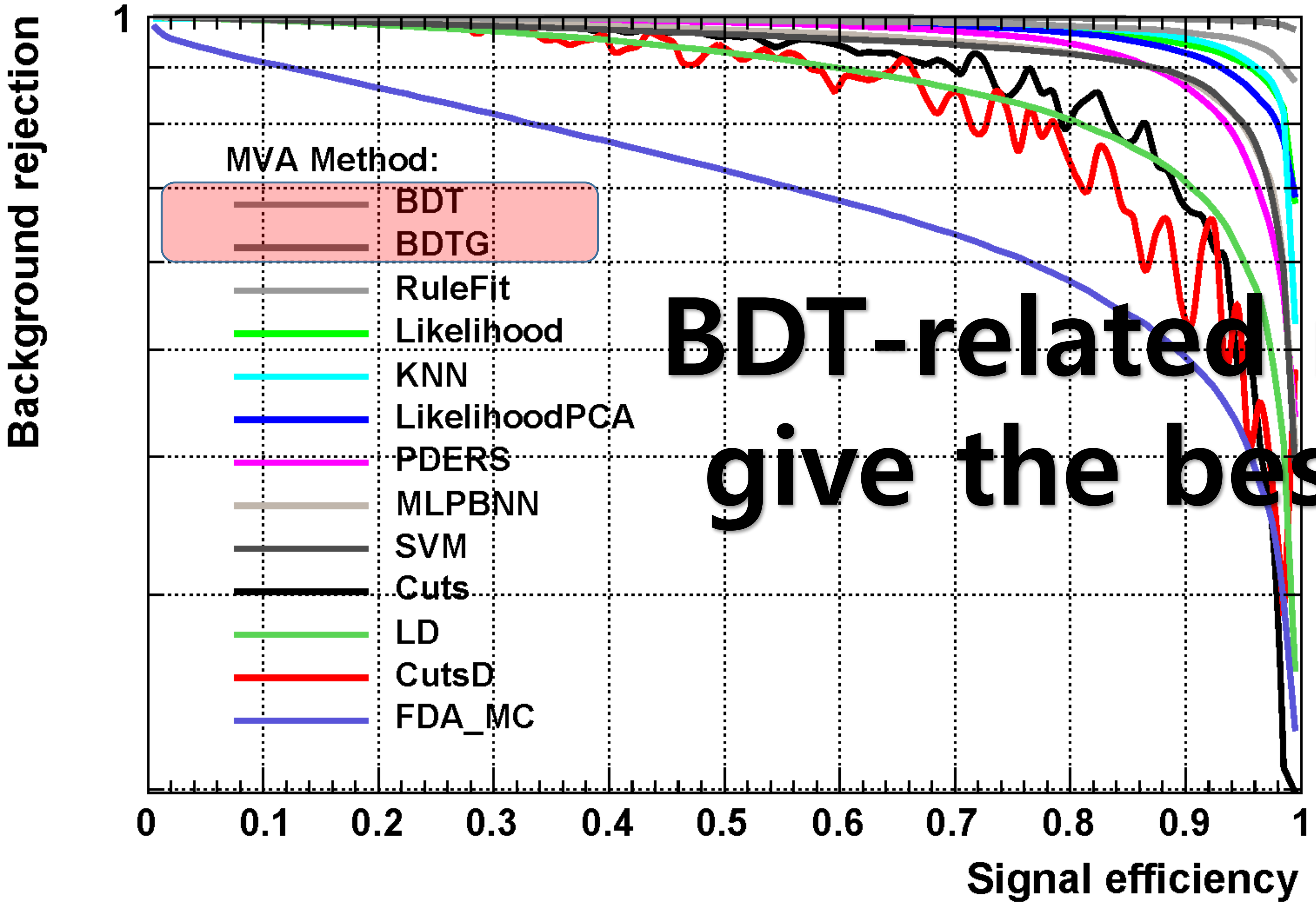


ROC = Receiver Operating Characteristic curve

: a good way to illustrate the performance of given classifier

AUC = Area under the ROC curve

Background rejection versus Signal efficiency

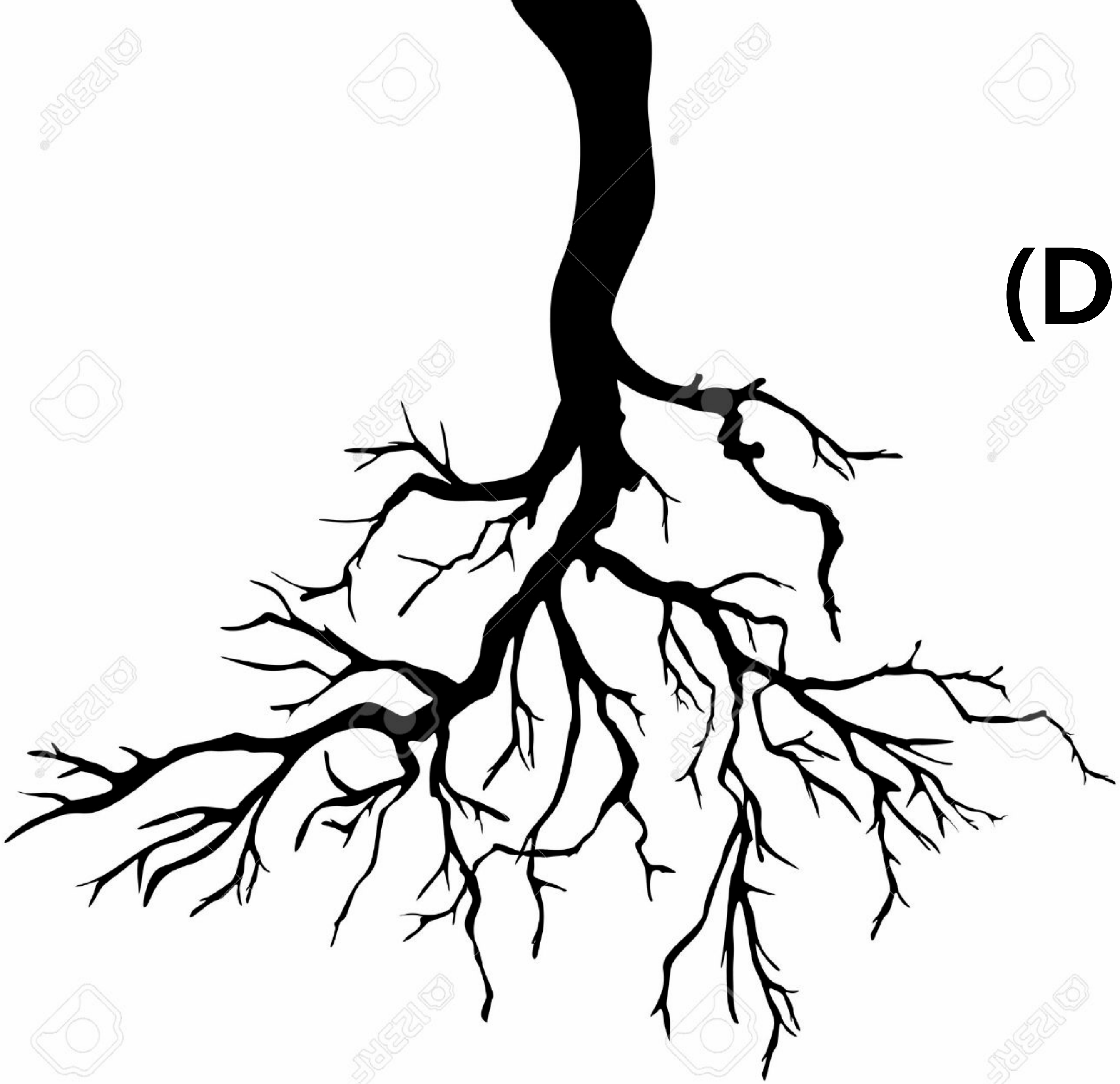


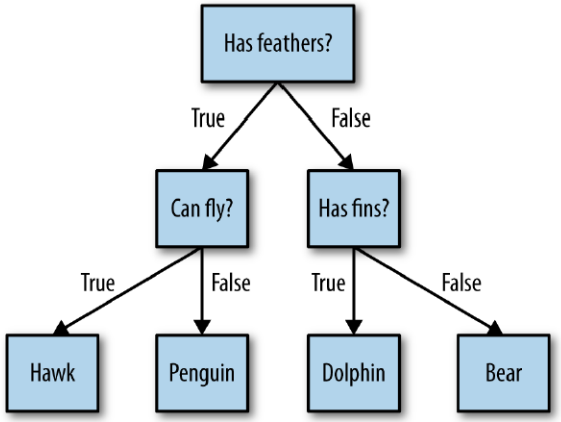
BDT-related methods give the best results

BDT

(Boosted Decision Tree)

DT
(Decision Tree)





2. A decision tree to distinguish among several animals

Decision Trees

- Decision trees are widely used models for classification and regression tasks. Essentially, they learn a hierarchy of if/else questions, leading to a decision.

- This series of questions can be expressed as a decision tree, as shown in

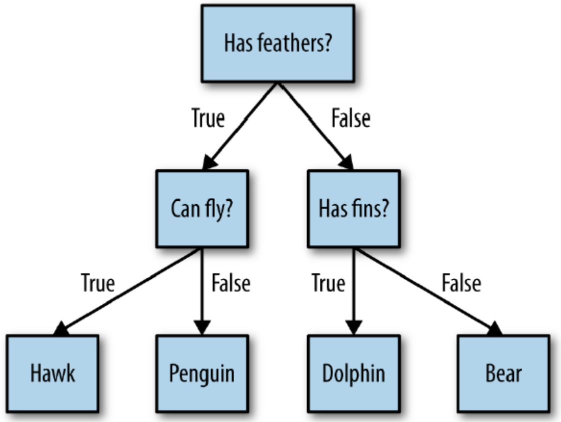


Figure 2-22. A decision tree to distinguish among several animals

<One example>

How to classify this set ?

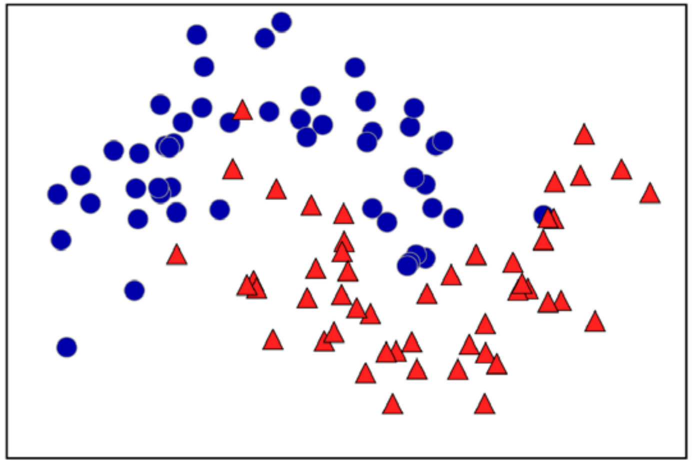
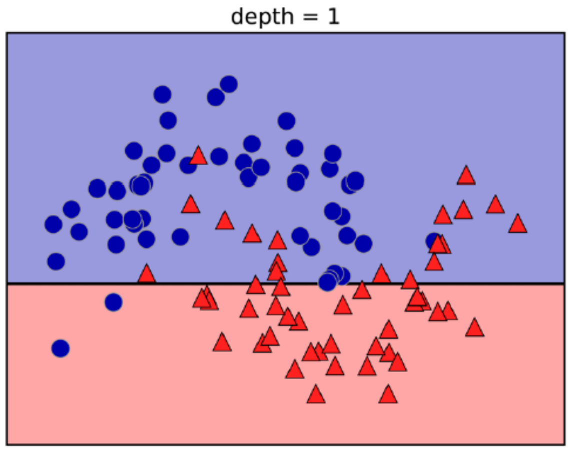
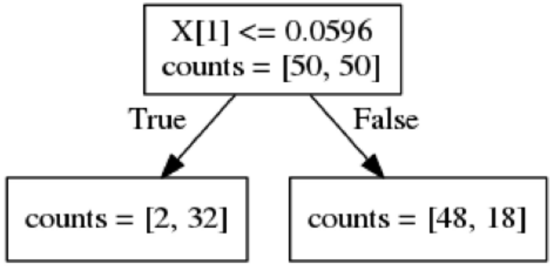
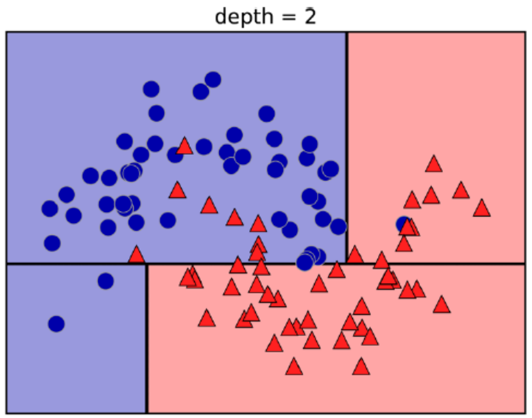


Figure 2-23. Two-moons dataset on which the decision tree will be built







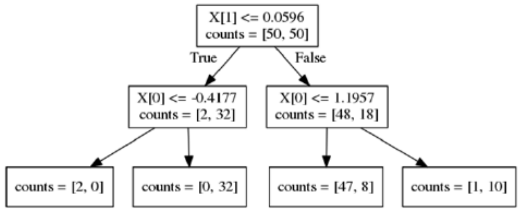


Figure 2-25. Decision boundary of tree with depth 2 (left) and corresponding decision tree (right)

Finally.....

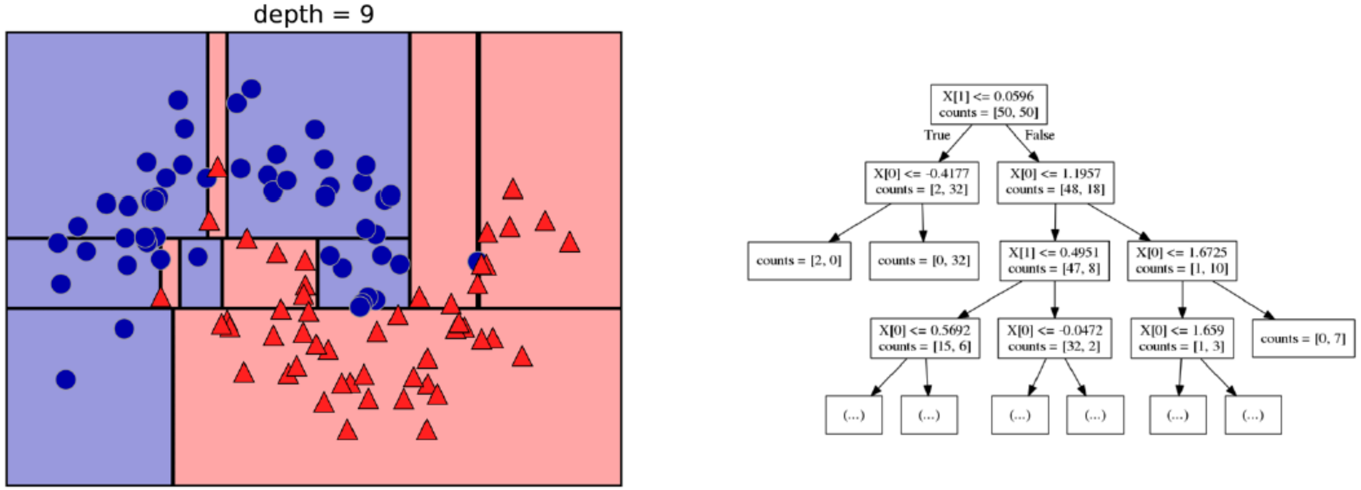


Figure 2-26. Decision boundary of tree with depth 9 (left) and part of the corresponding tree (right); the full tree is quite large and hard to visualize

However,

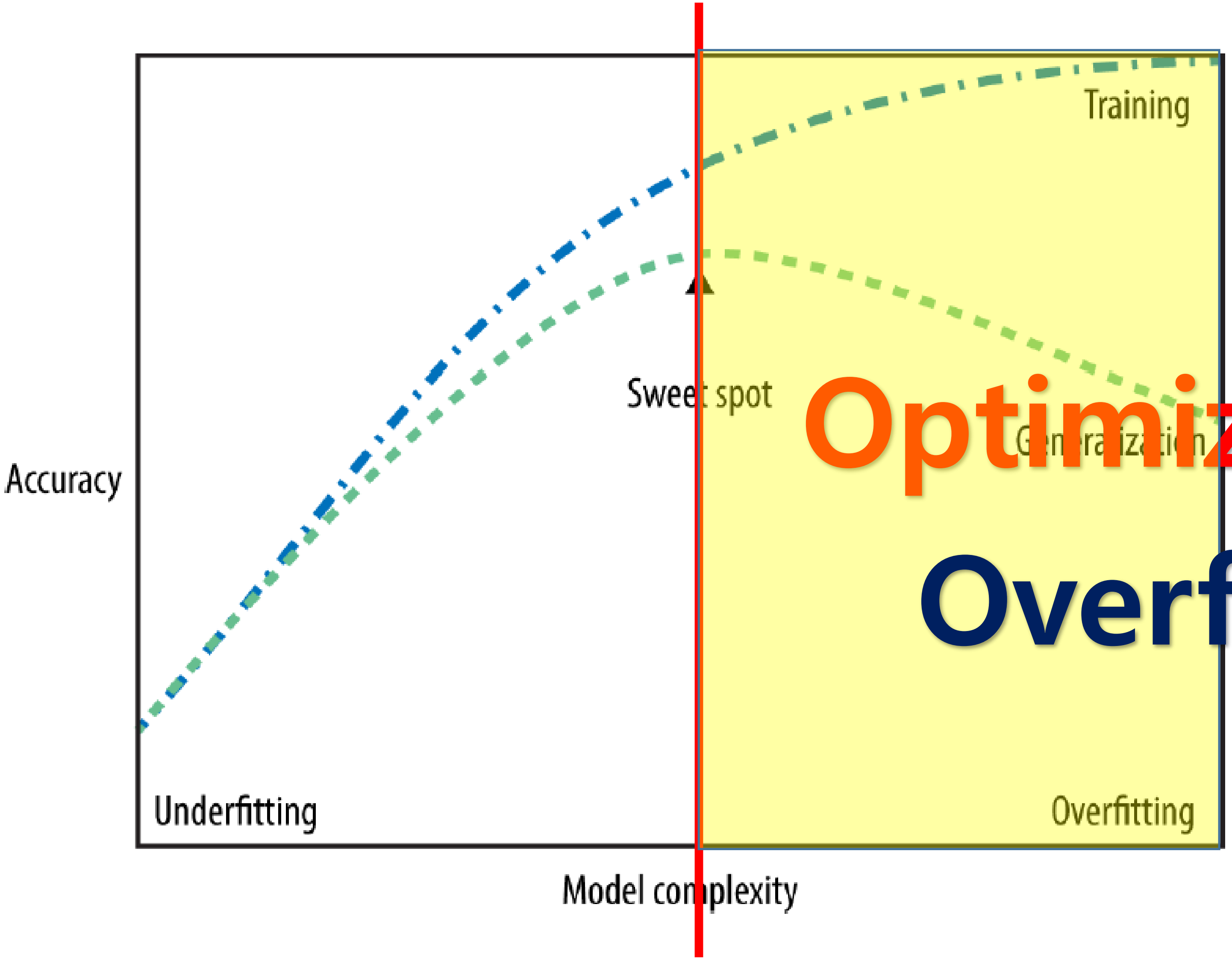
If we don’t restrict the depth of a decision tree, the tree can become arbitrarily deep and complex.

↓

Easily Overfitting !!

Supervised Learning

- Classification and Regression
- Generalization, Overfitting, and Underfitting



Optimized Machine

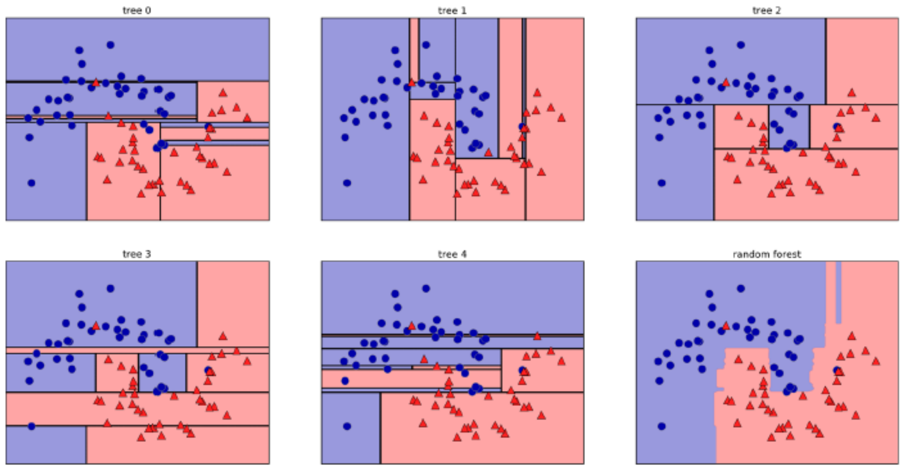
Overfitting !!!

To avoid the overfitting,

Ensembles of Decision Trees

- There are two ensemble models that have proven to be effective on a wide range of datasets for classification and regression, both of which use decision trees as their building blocks: **random forests** and **gradient boosted decision trees**.

Use the **ensemble average** !



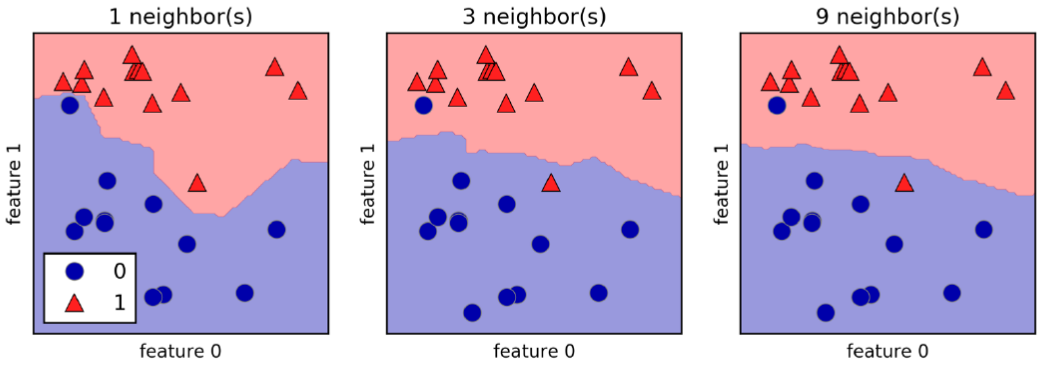
Use the **strong pre-pruning** !

Gradient boosted trees often use very shallow trees, of depth one to five,

Shallow tree + Shallow tree + Shallow tree + ...

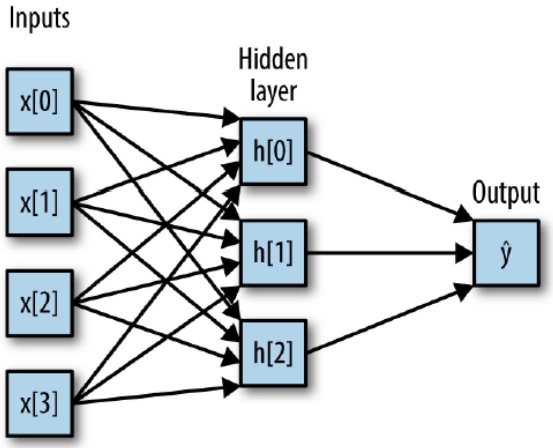
Other methods (algorithms)

- k-Nearest Neighbors
- Linear Models (Linear Fitting)
- Decision Trees
- Support Vector Machines
- Neural Networks (Deep Learning)
- ……



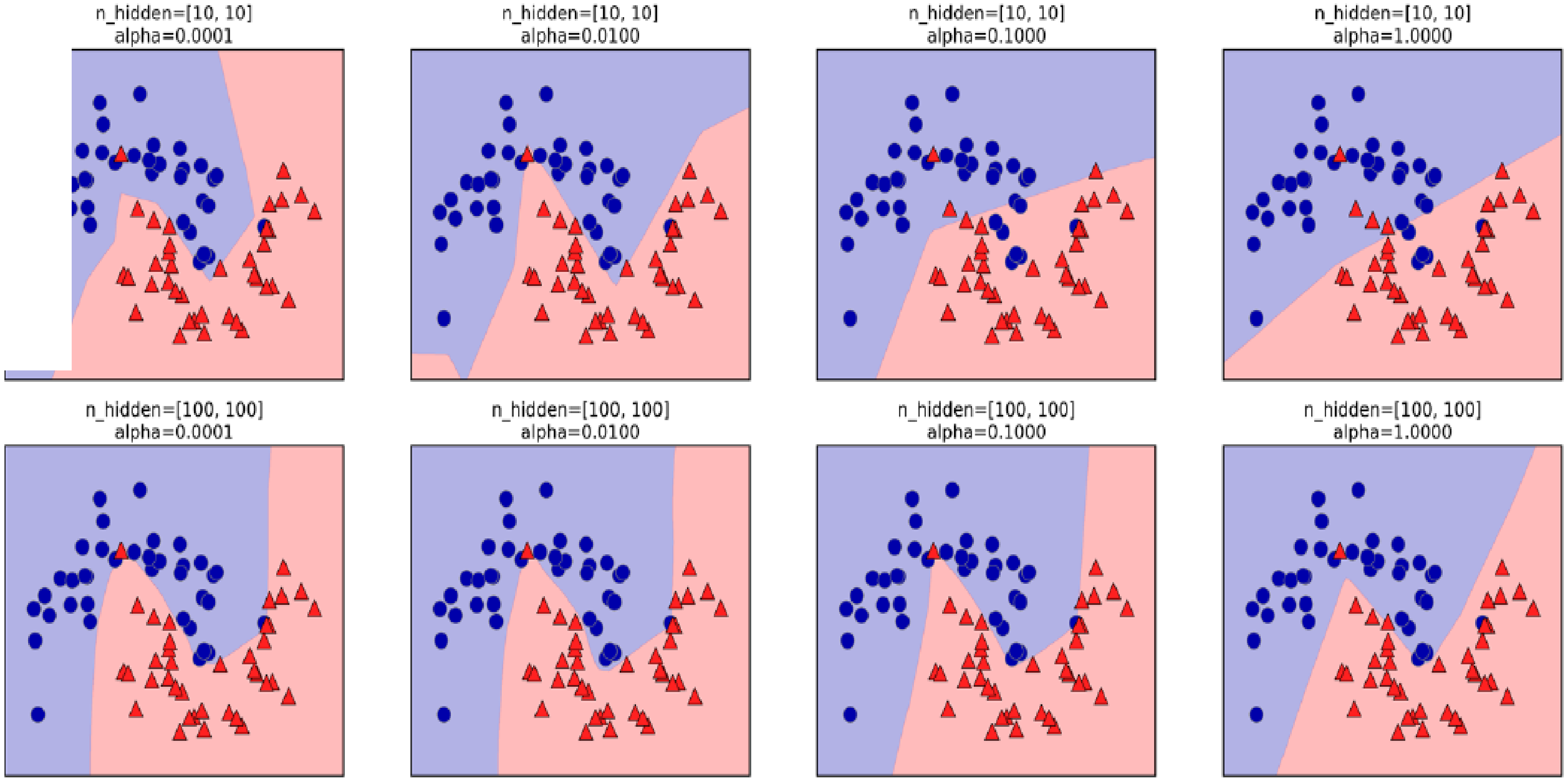
Decision boundaries created by the nearest neighbors model for different values of n_neighbors

Neural Network (Briefly……)



multilayer perceptron(MLP) with a single hidden layer

With 2 hidden layers (N_1, N_2)



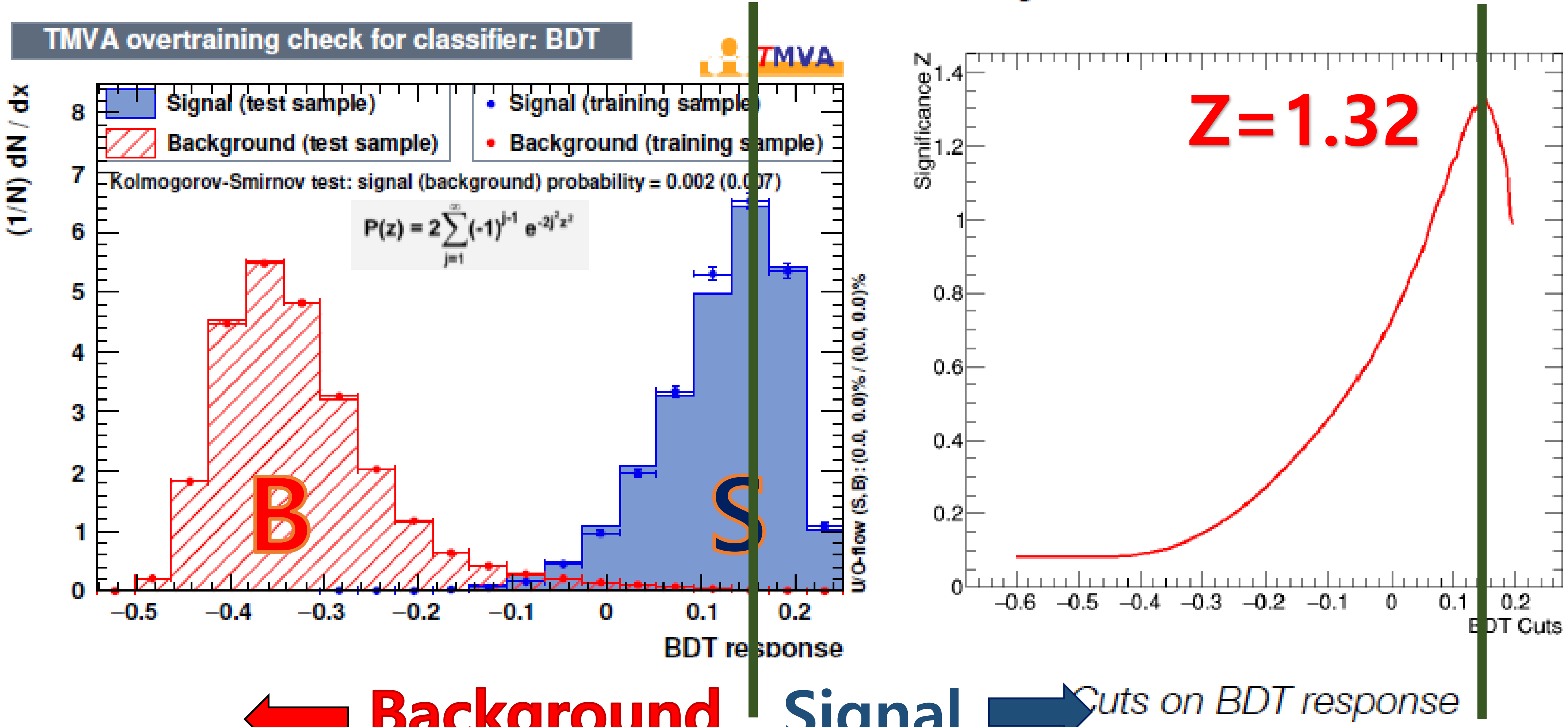
Decision functions for different numbers of hidden units and different settings of the alpha parameter

BDT setup in TMVA

- Pre-Selection Cuts (1) – (5) ⟹ TMVA inputs
- NTrees=800
- MinNodeSize=2.5%
- MaxDepth=4
- BoostType=AdaBoost
- AdaBoostBeta=0.5
- UseBaggedBoost
- BaggedSampleFraction=0.5
- SeparationType=GiniIndex
- nCuts=20

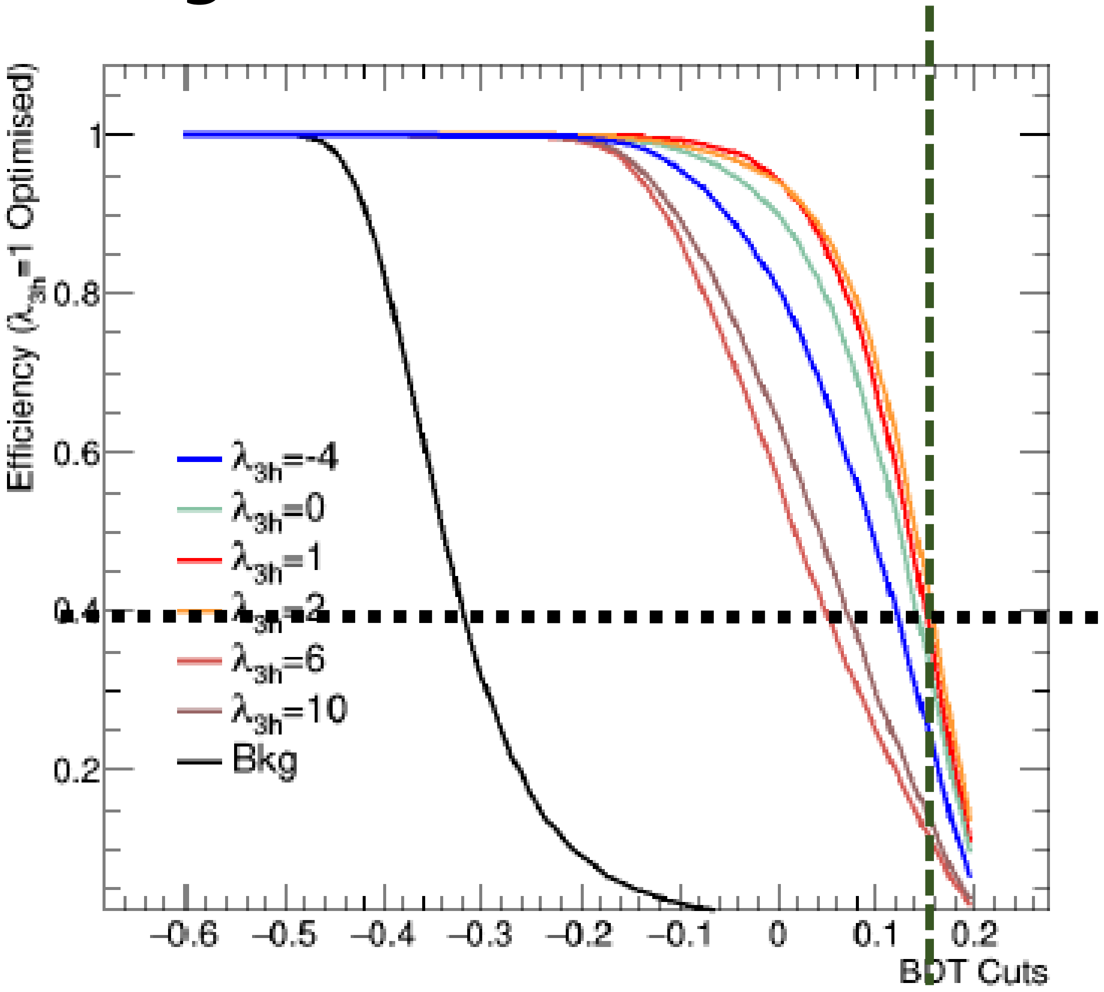
BDT machine optimized with $\lambda_{3H} = 1$

AUC = 0.996 : Area under ROC (receiver operating characteristic curve) curve

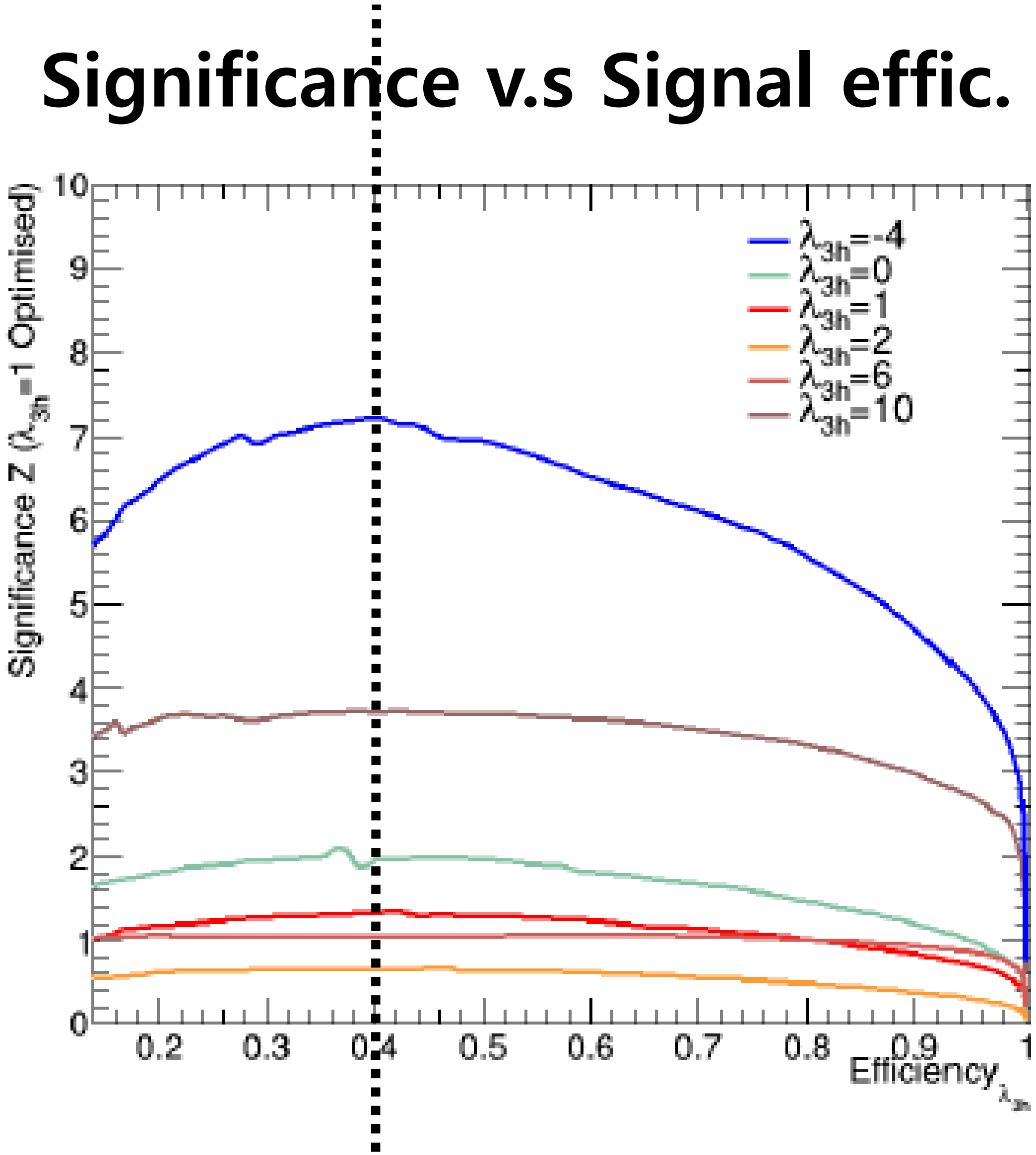


Background Signal Cuts on BDT response

Signal effic. v.s BDT Cuts



Significance v.s Signal effic.



Expected Yields and Significance(Z)

	Expectd yields (3000 fb^{-1})		
Signal and Backgrounds	Pre-BDT Cuts	Cut based	BDT, Z_{Max}
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H}=0$	34.31	16.14	12.86
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H}=1$	17.71	9.15	7.64
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H}=2$	8.93	4.79	4.17
$gg\,H(\gamma\gamma)$	68.76	6.60	4.86
$t\bar{t}\,H(\gamma\gamma)$	158.14	13.21	7.97
$Z\,H(\gamma\gamma)$	23.89	3.62	2.67
$b\bar{b}\,H(\gamma\gamma)$	2.52	0.15	0.11
$b\,b\,\gamma\,\gamma$	7055.47	15.28	5.72
$c\,\bar{c}\,\gamma\,\gamma$	7058.43	7.14	2.27
$j\,j\,\gamma\,\gamma$	1113.20	3.17	0.58
$b\,\bar{b}\,j\,\gamma$	10607.63	14.73	2.85
$c\,\bar{c}\,j\,\gamma$	4716.52	4.82	1.51
$b\,\bar{b}\,j\,j$	2606.49	3.53	0.74
$Z(b\bar{b})\,\gamma\gamma$	179.33	0.86	0.35
$t\,\bar{t}$ ($\geq$ 1 leptons)	5433.74	4.98	0.61
$t\,\bar{t}\,\gamma$ ($\geq$ 1 leptons)	1916.50	3.61	1.04
Total Background		81.70	31.27
Significance Z, $\lambda_{3H}=0$		1.73	2.16
Significance Z, $\lambda_{3H}=1$		0.99	1.32
Significance Z, $\lambda_{3H}=2$		0.52	0.73

C&C

of signal = 9.15

# of bg = 81.70

∴ significance Z = 0.99

BDTλ_1

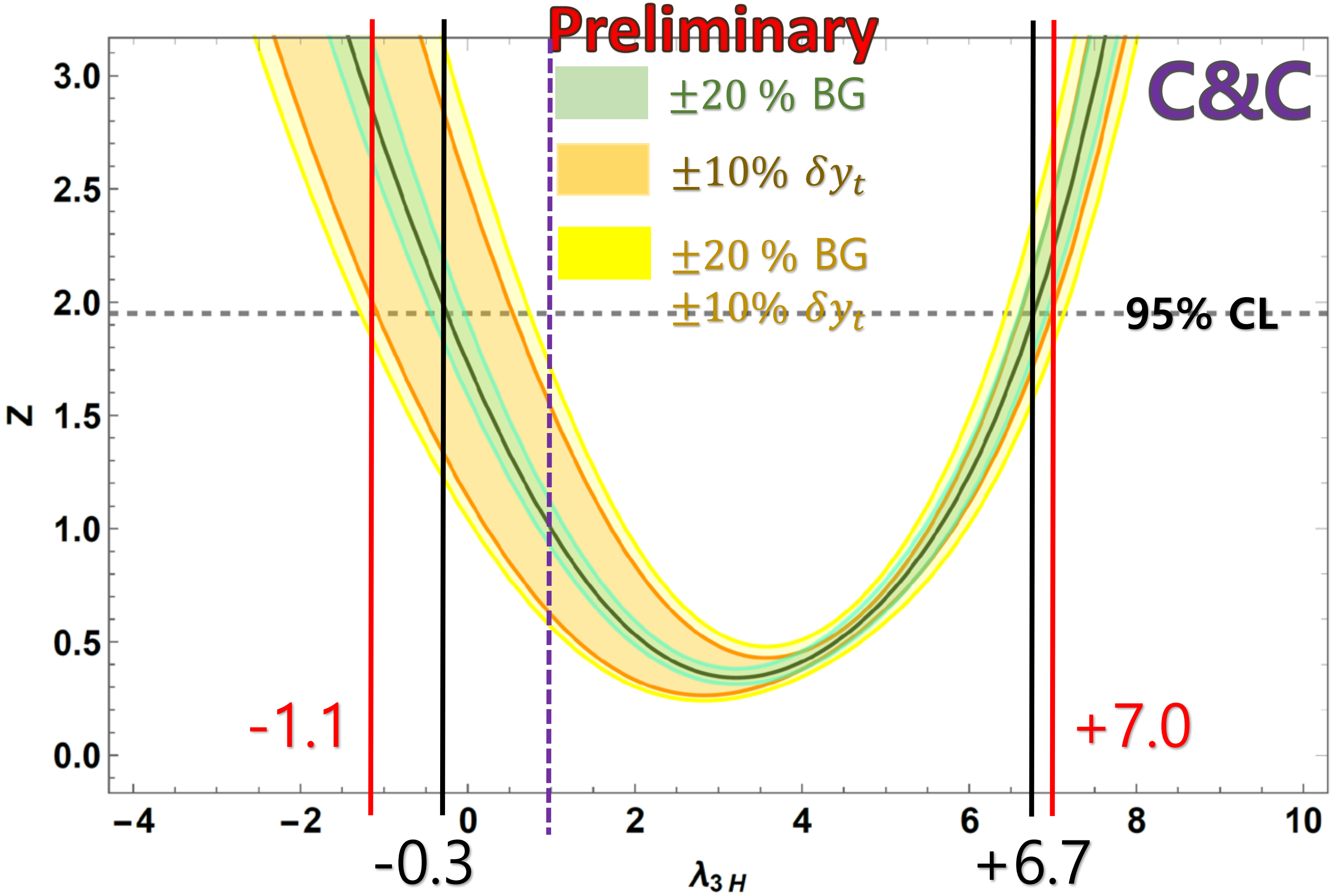
of signal = 7.64

# of bg = 31.27

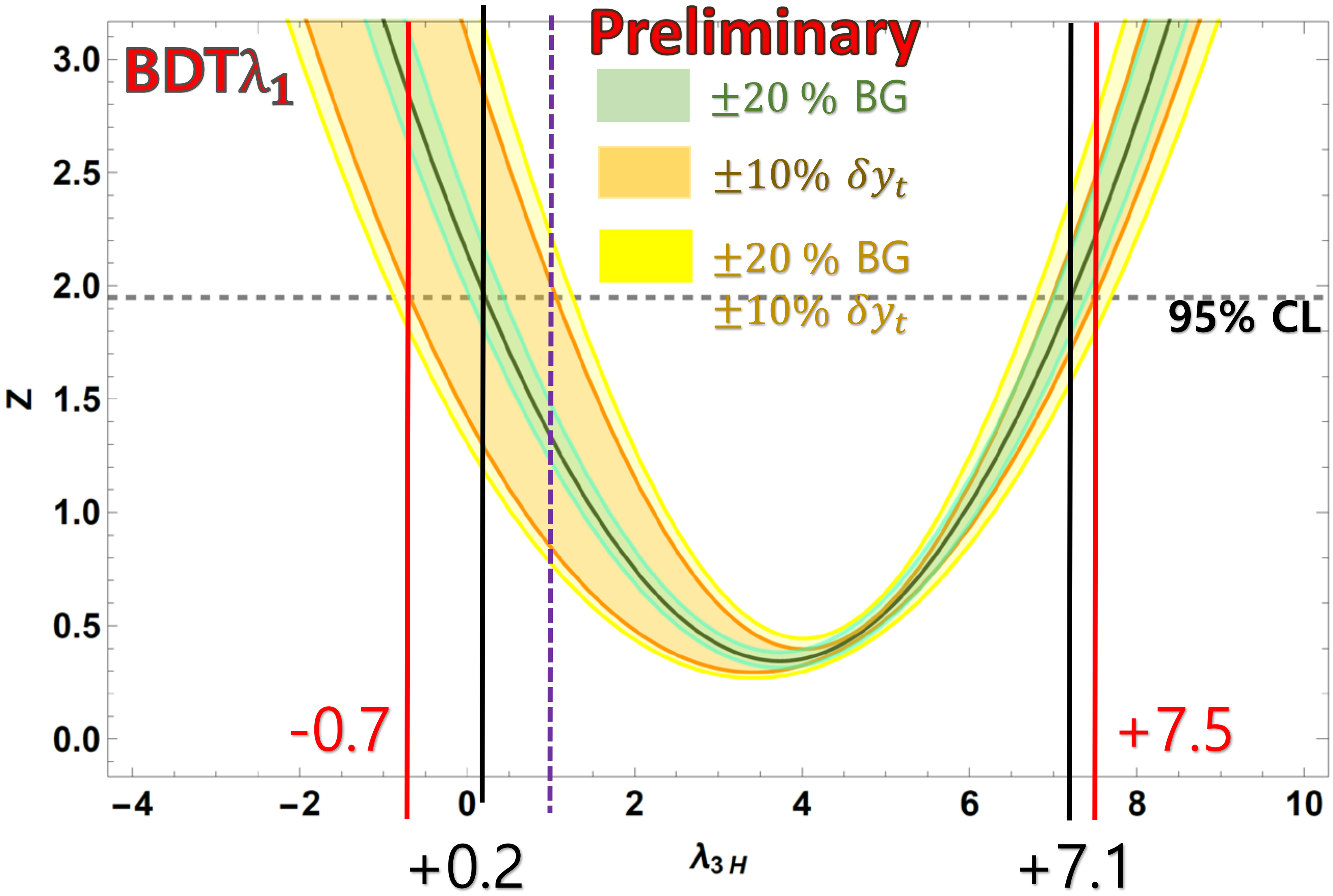
∴ BDT-improved Z = 1.32

33% enhancement on Z

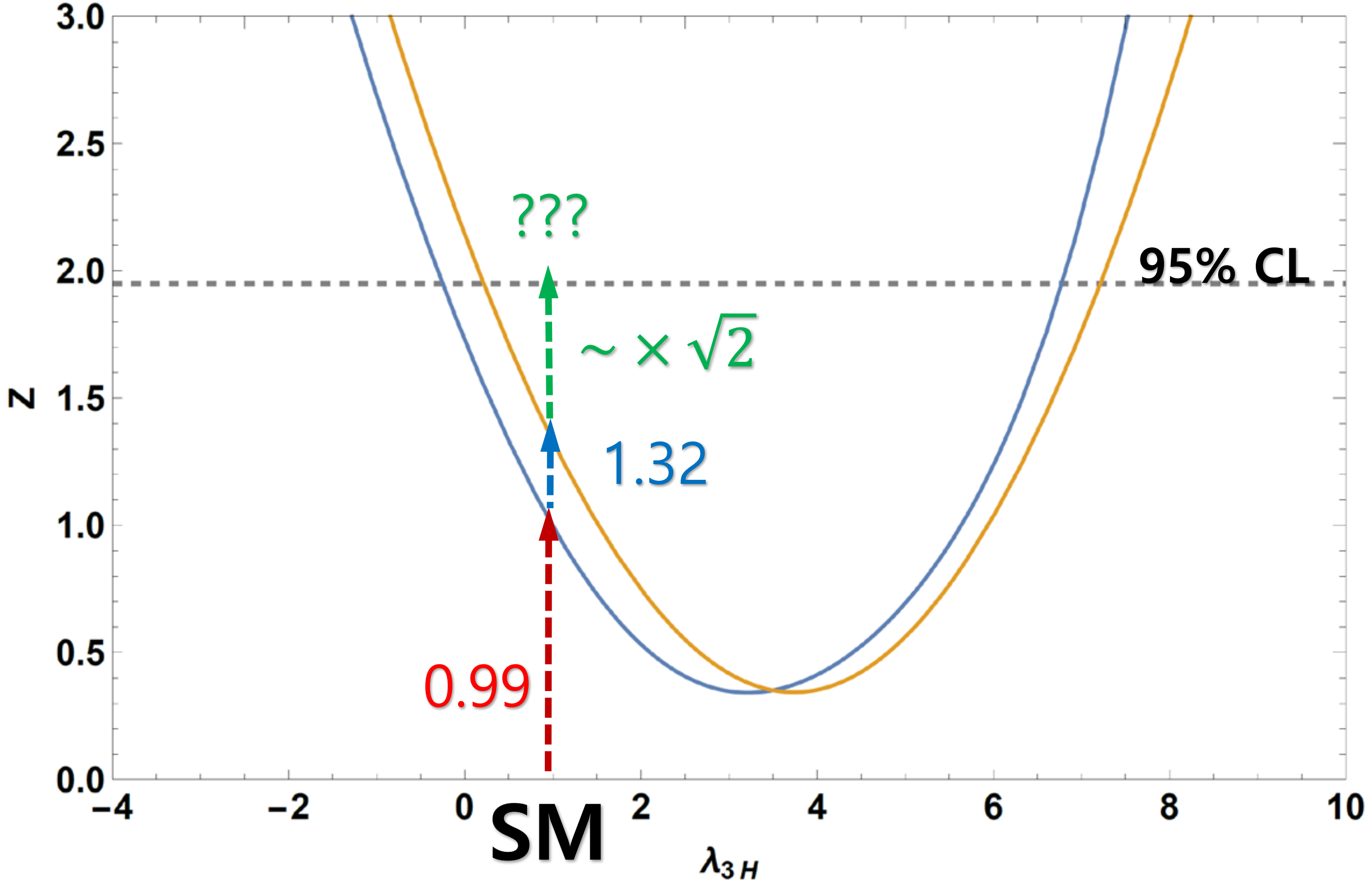
Significance of the signal over the background versus λ_{3H} at the HL-LHC



Significance of the signal over the background versus λ_{3H} at the HL-LHC



Z v.s. λ_{3H}=1 in the cases of C&C and BDTL1



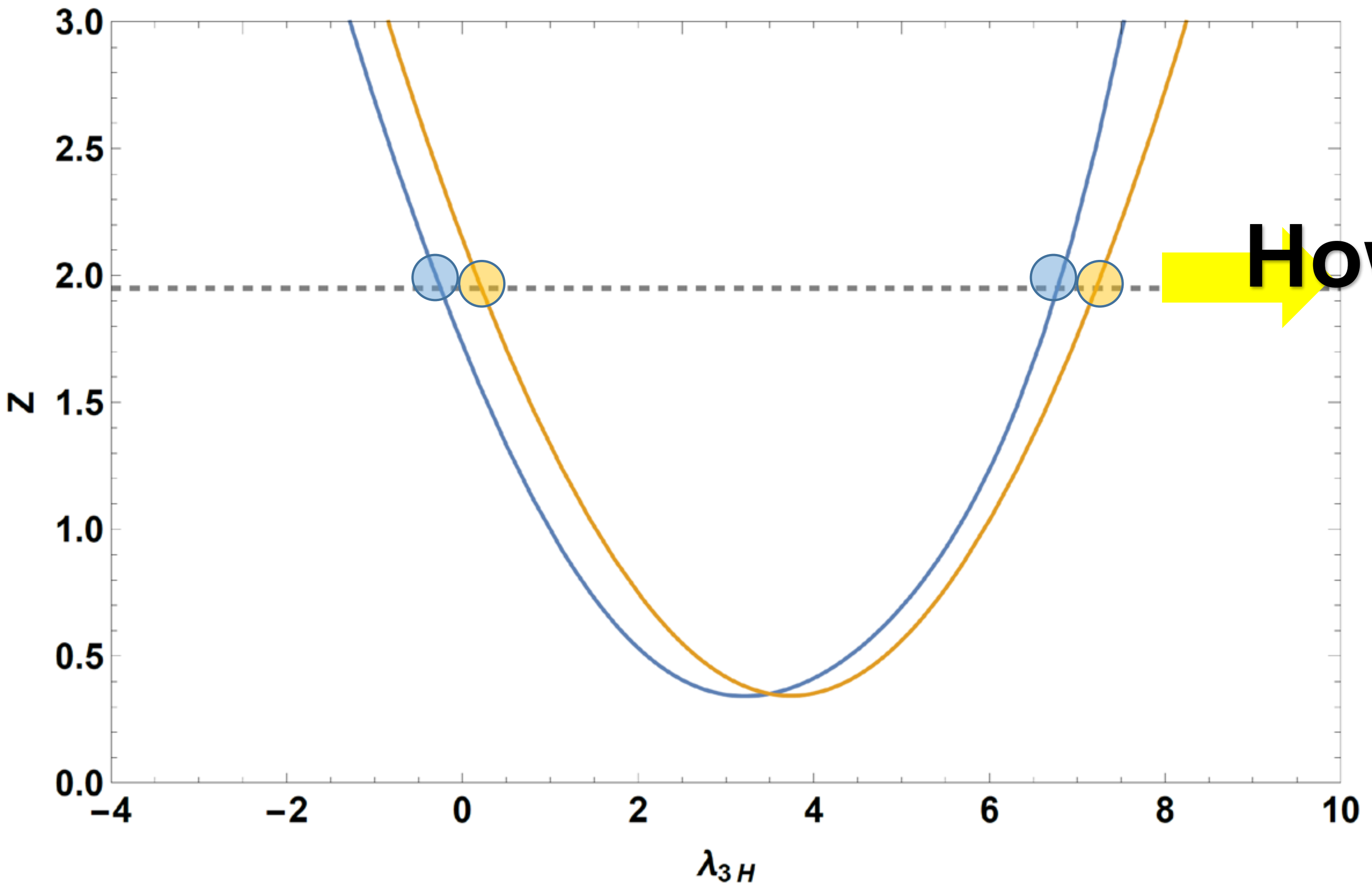
HL-LHC
with Lumi.= $6\ ab^{-1}$
Ref. arxiv:1902.00134

BDTL1 Z=1.32

C&C Z=0.99

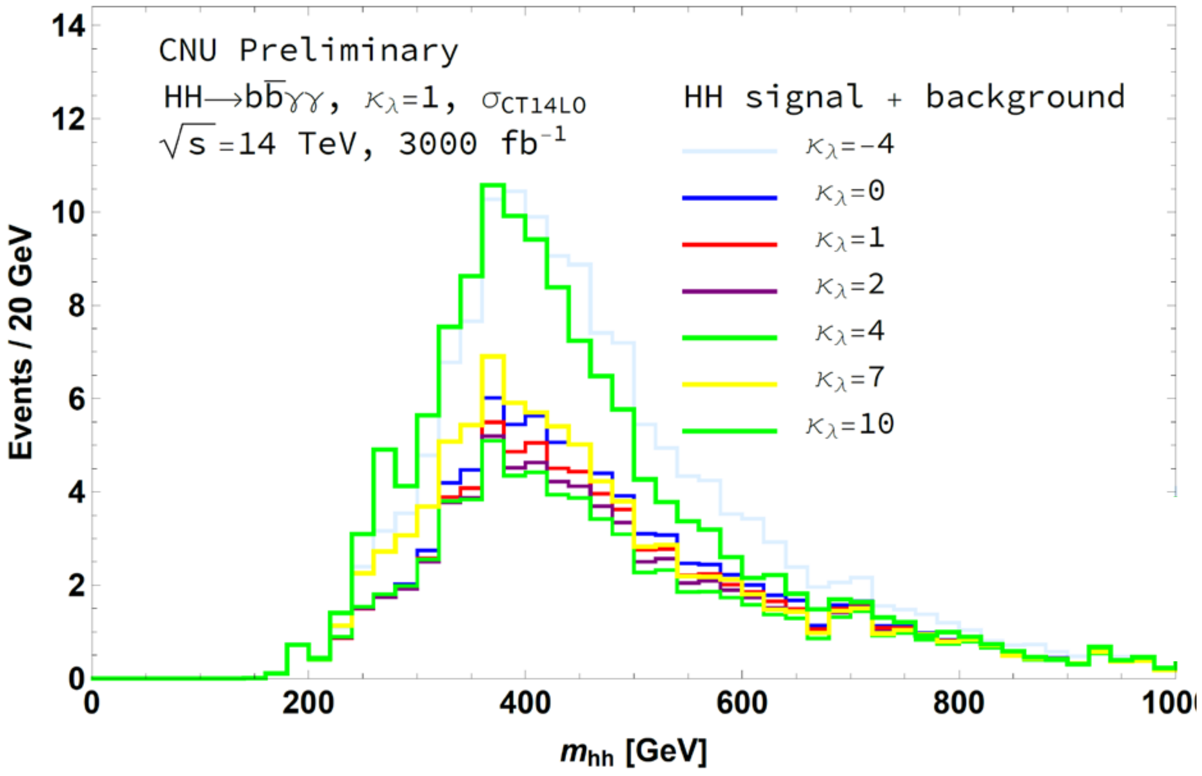
$\therefore$ It may be possible to measure at the LH-LHC with $6\ ab^{-1}$.

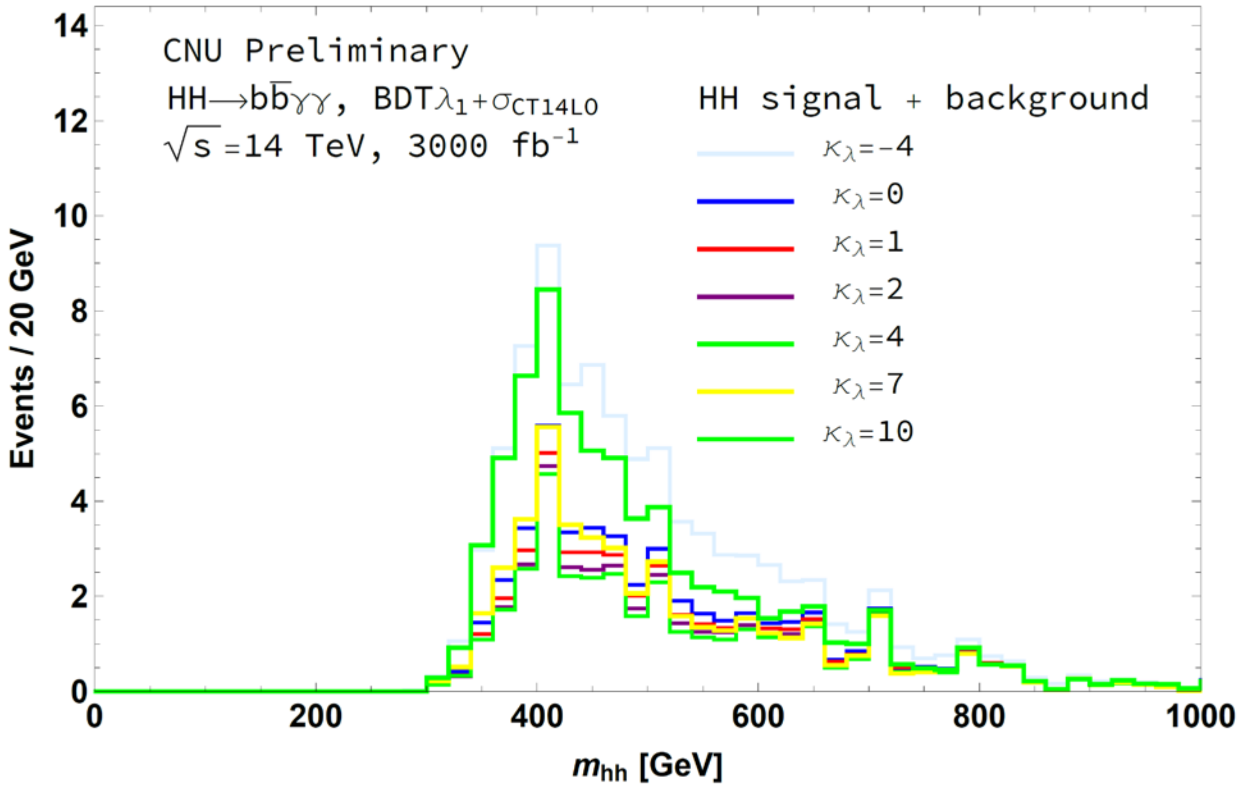
If we can measure(?) the signal and bg. numbers for the case of $\lambda_{3H} = 1$ at the LH-LHC with $\mathbf{6\ ab^{-1}}$



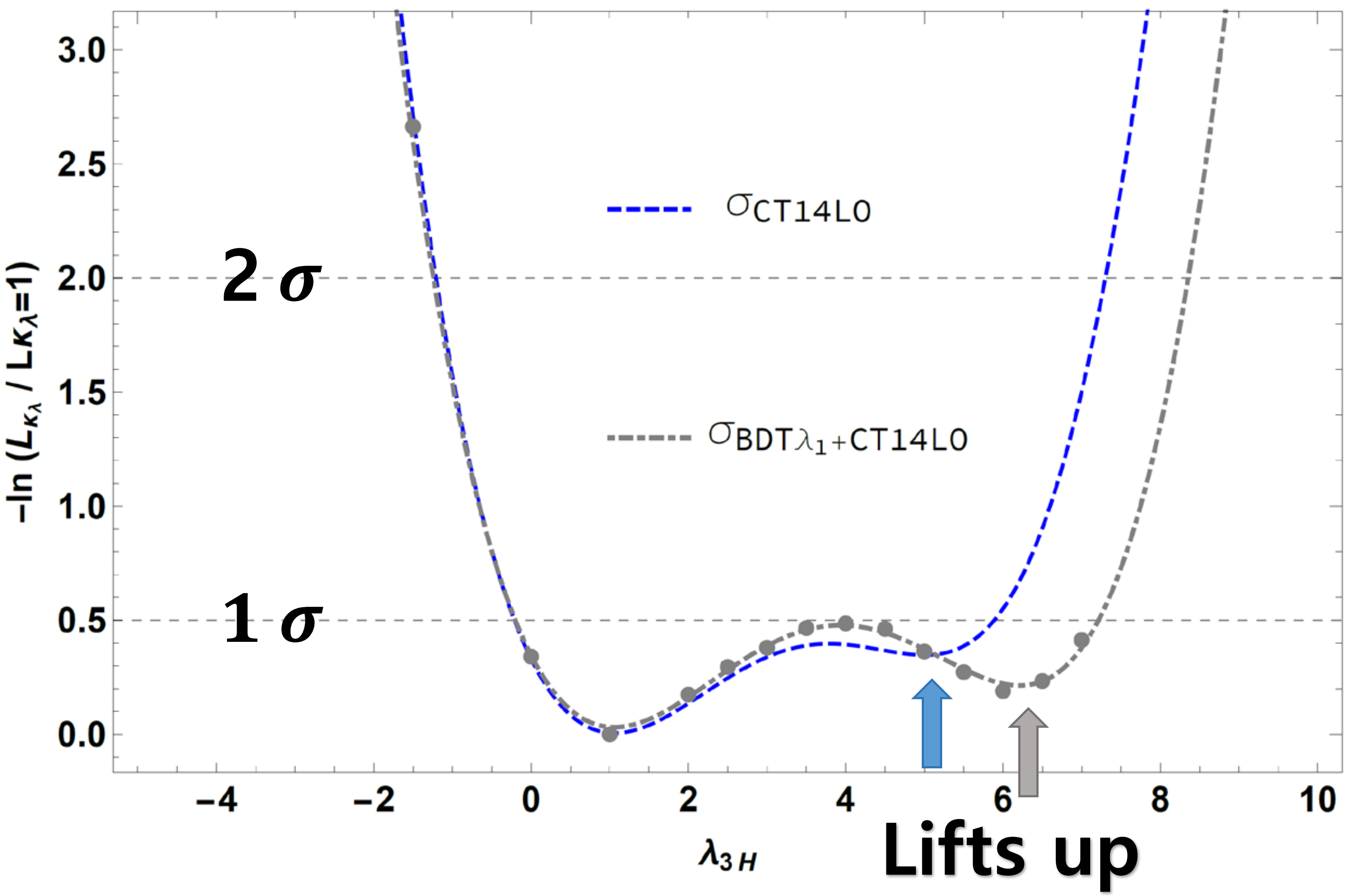
How can we distinguish these values ?

M_{hh} kinematic distributions





Log-Likelihood Ratios with the $\lambda_{3H} = 1$ nominal data set and the different λ_{3H} template sets



Impact of NLO

Preliminary

Recent updates

- HH NLO generator – POWHEG BOX V2
  Use of NLO kinematic distributions (or variables)
- Improved (NLO) yields and significance(Z)
- Improved Likelihood fit
  using the (NLO) M_{HH} kinematic distribution

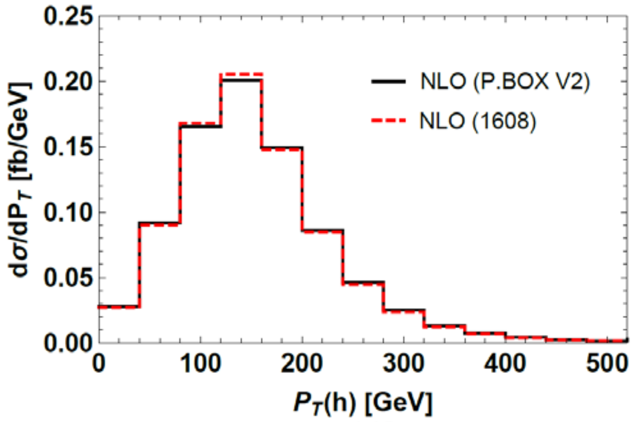
Preliminary

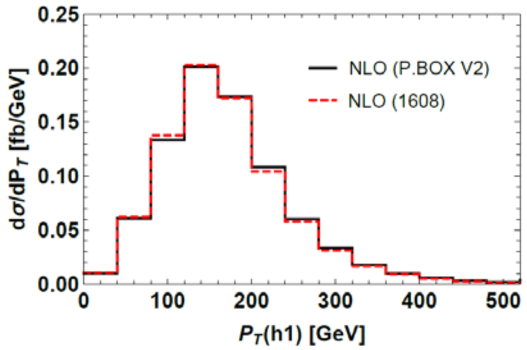
HH NLO generator – POWHEG BOX V2

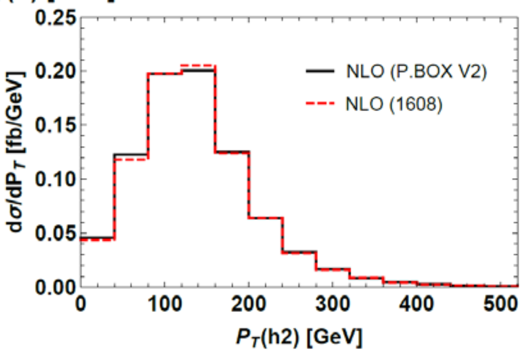
Signal process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
$gg \to HH \to bb\gamma\gamma$	POWHEG-BOX-V2/PYTHIA8	0.096	NNLO	PDF4LHC15_nlo

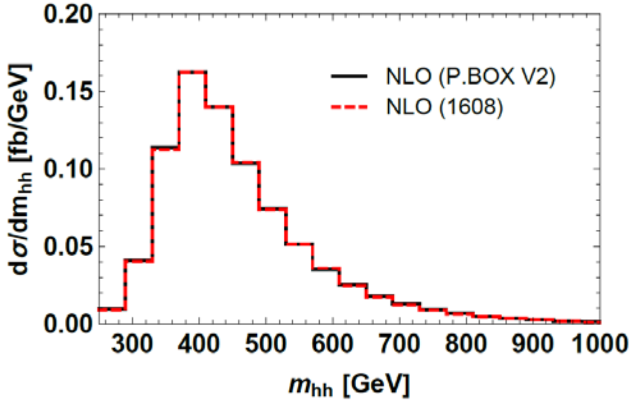
Validation of the NLO sample

At the parton level

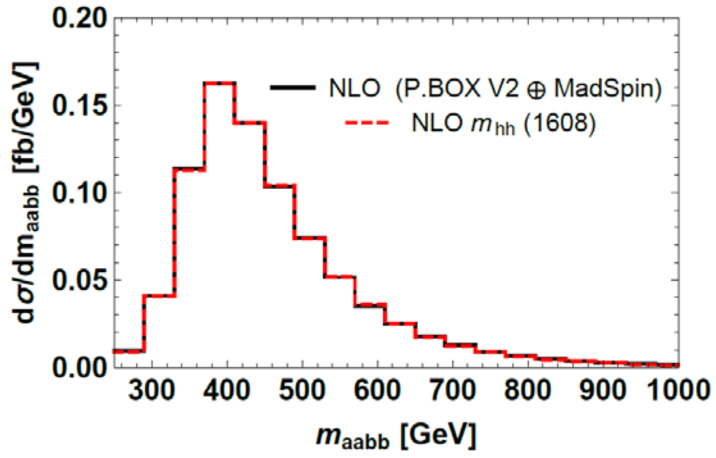






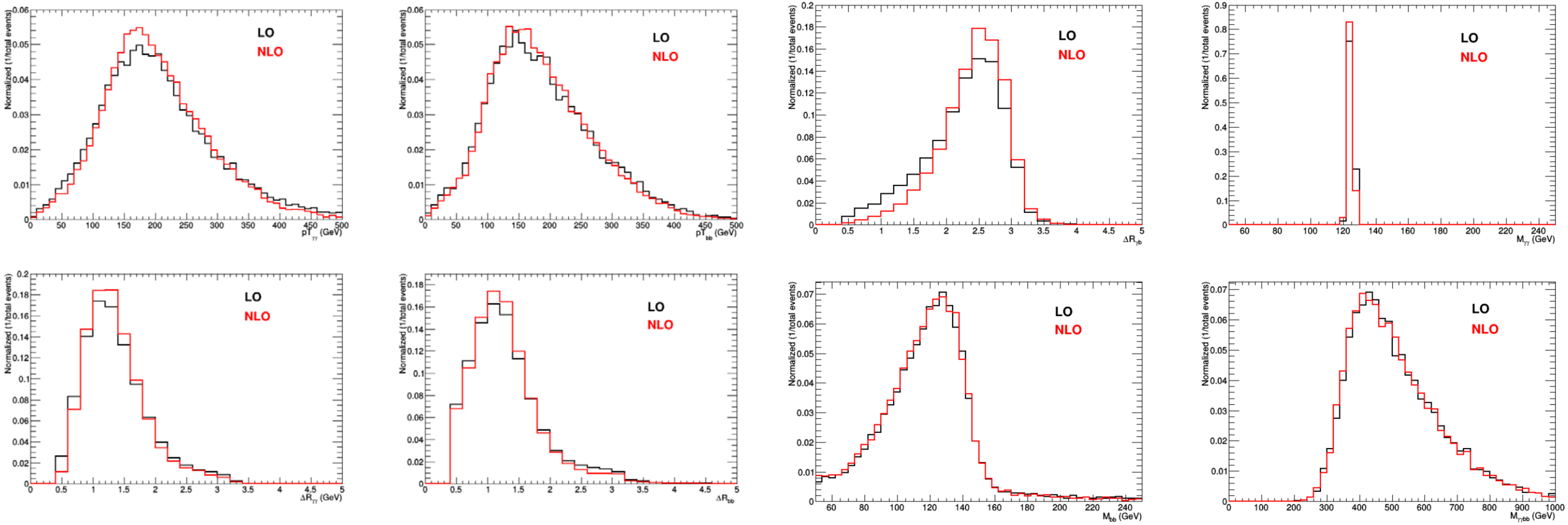


After the decay of the Higgs boson

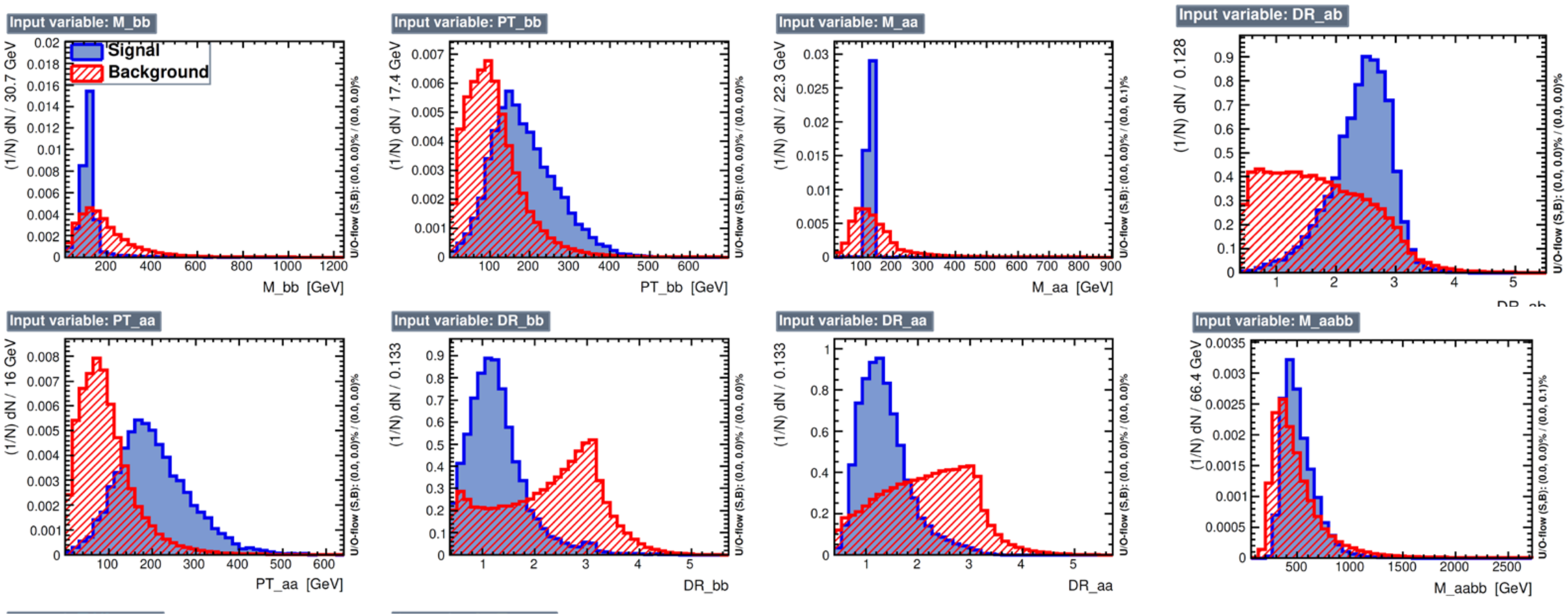


Validation of the NLO sample

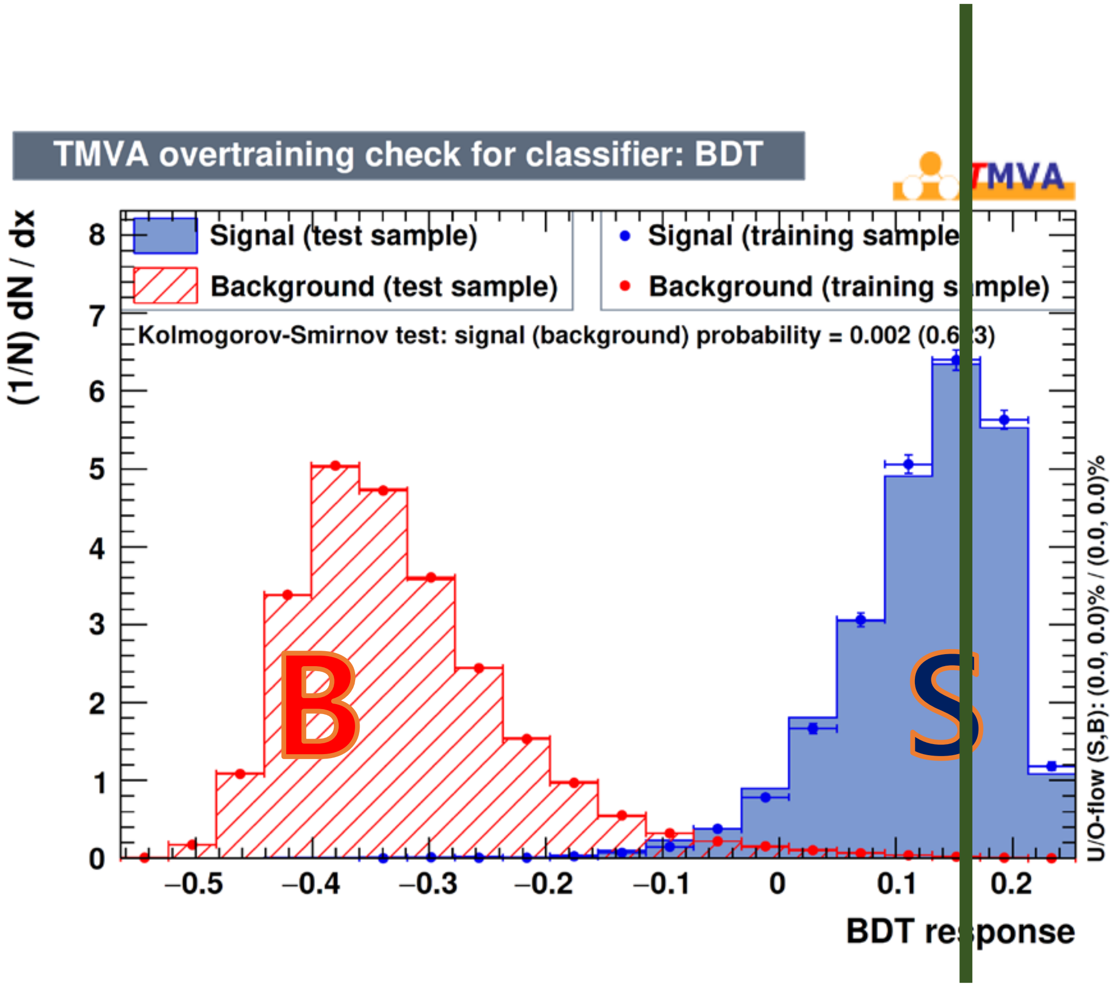
At the detector level

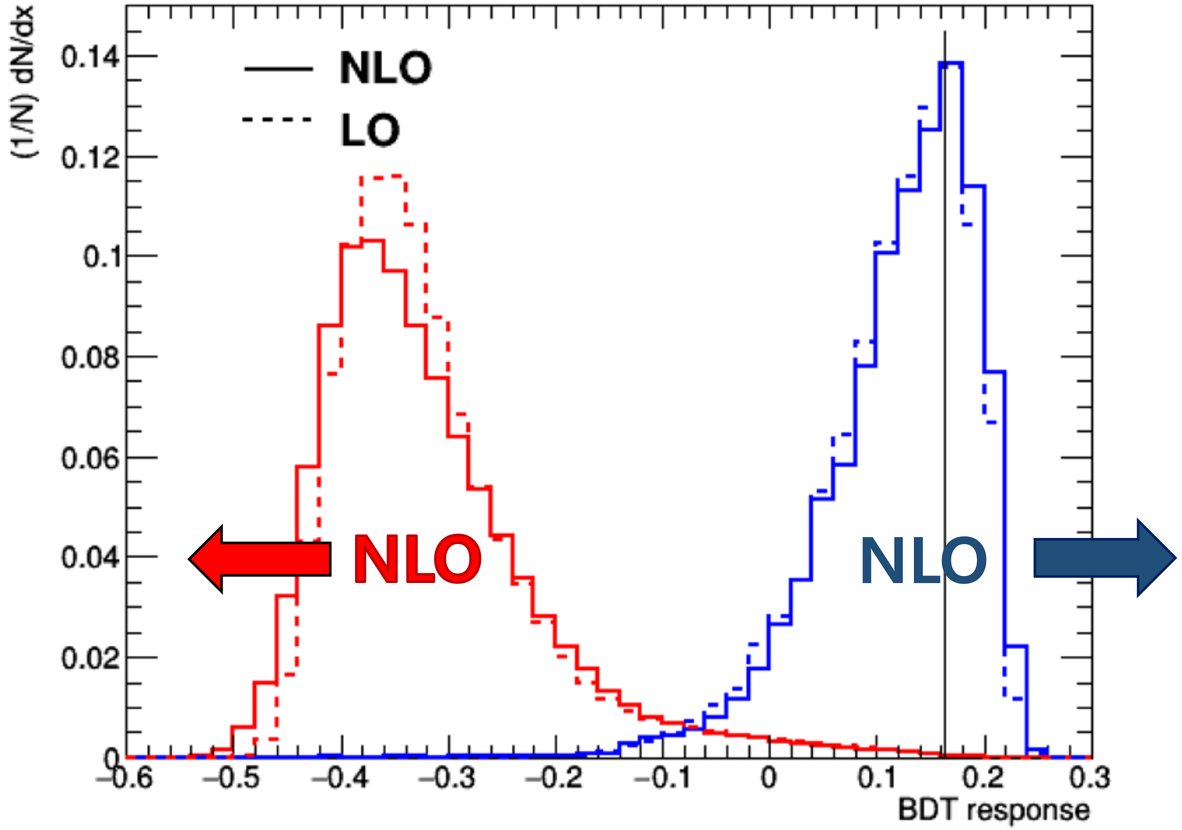


TMVA (NLO) input variables



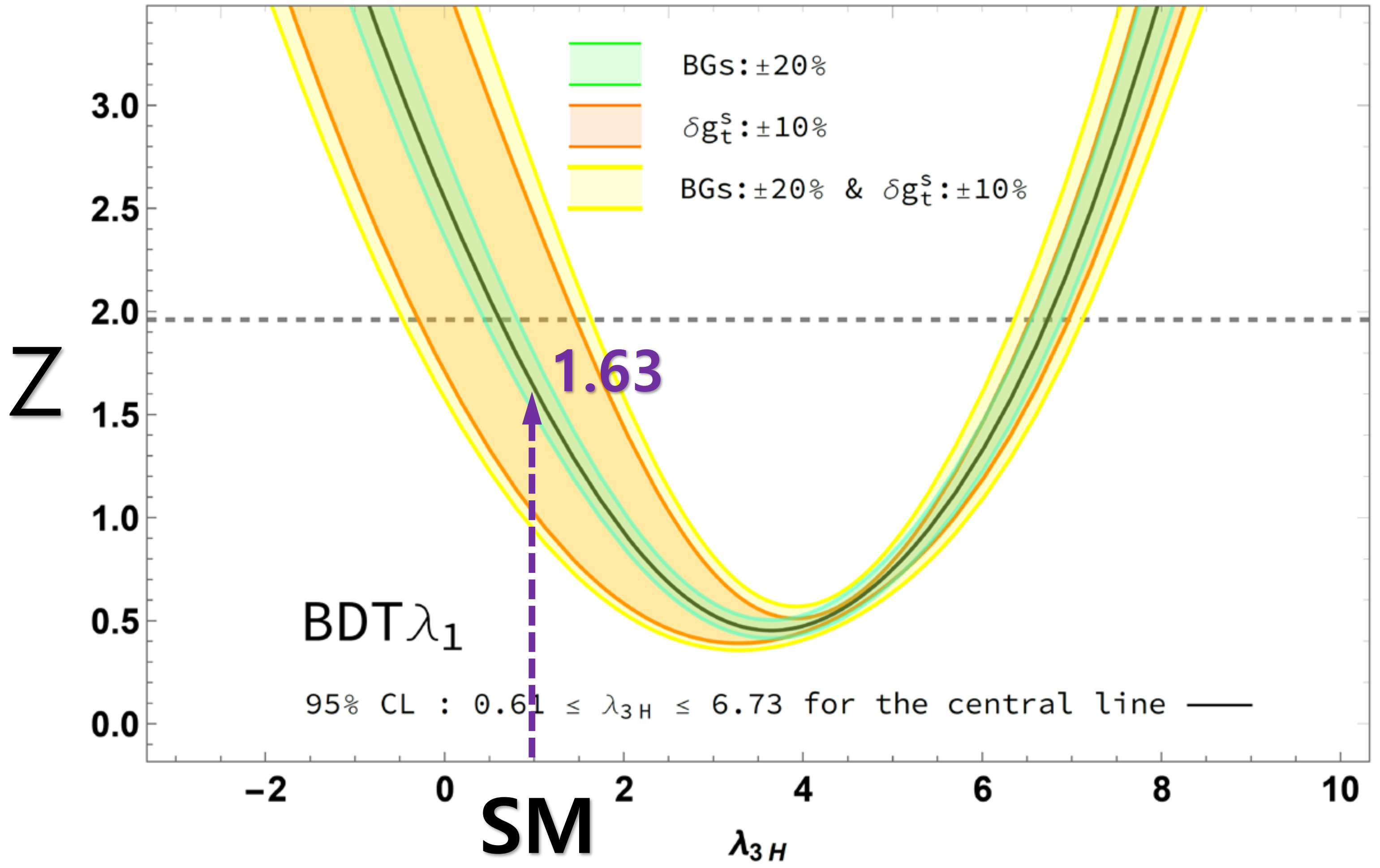
BDTL1 scenario



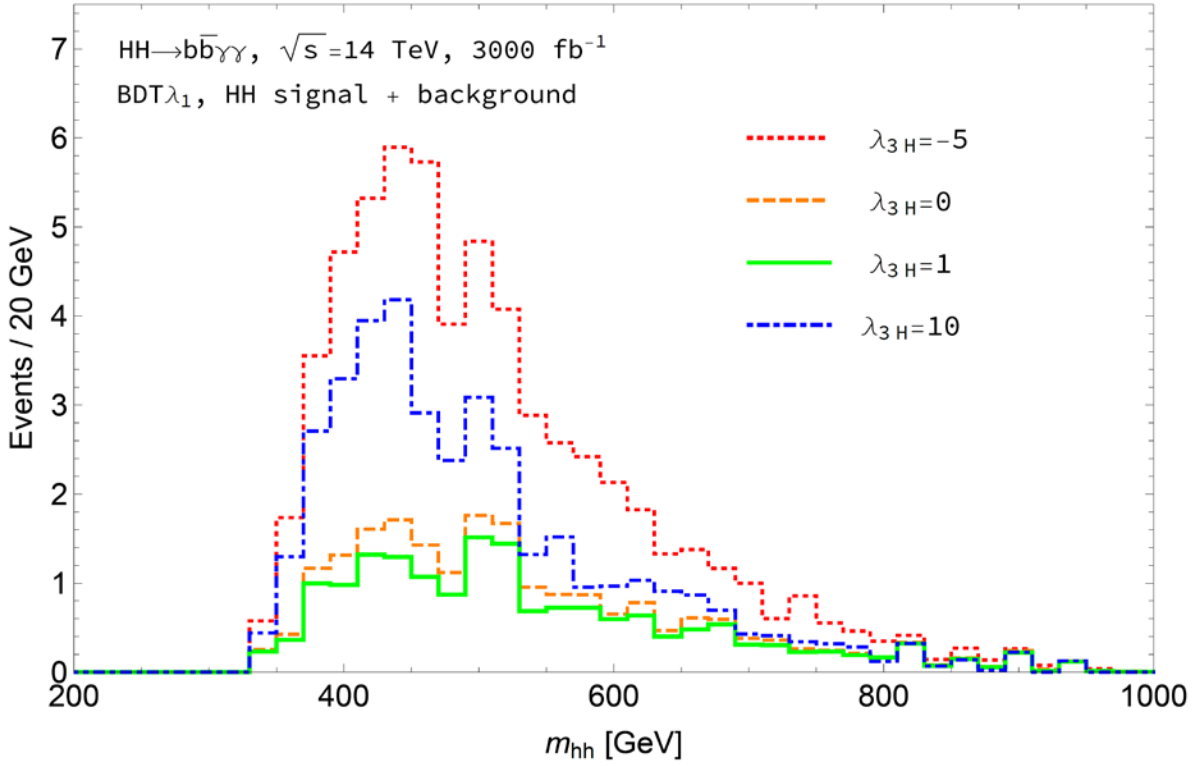


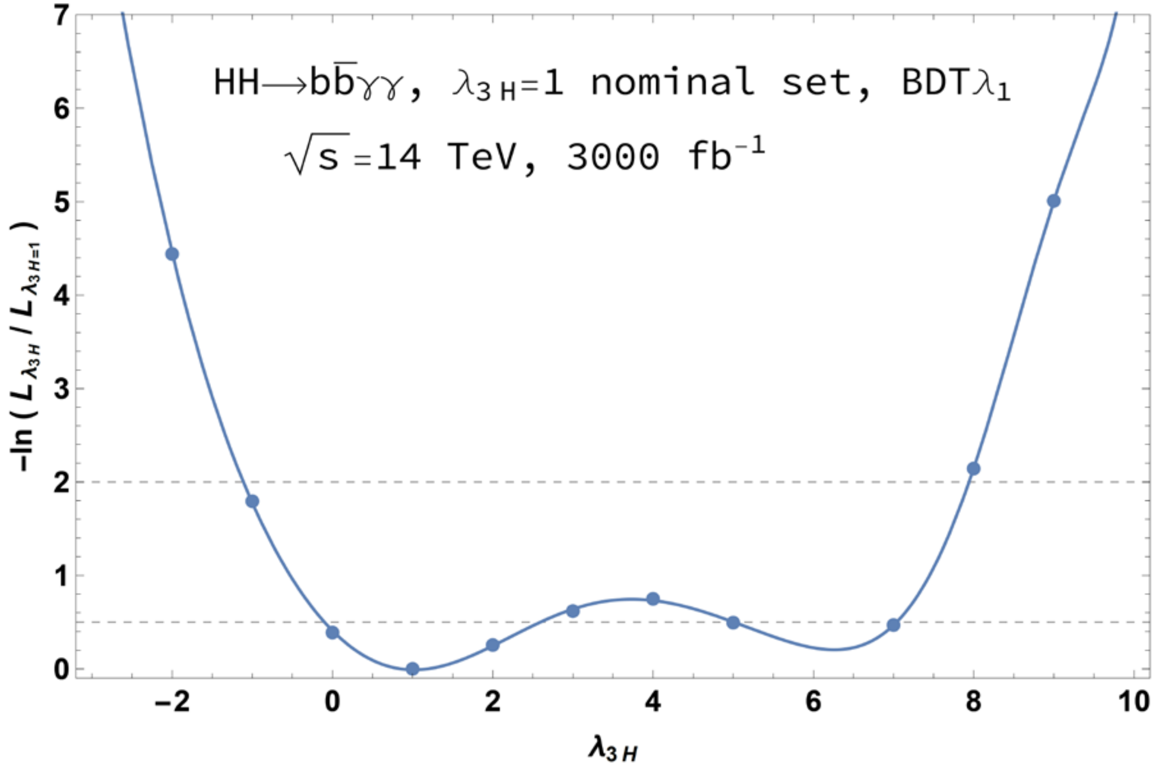
Improved (NLO) yields and significance(Z)

Signal and Backgrounds	BDTλ_1
$H(b\,b)\,H(\gamma\,\gamma),\ \lambda_{3H}=-5$	49.98
$H(b\,\bar{b})\,H(\gamma\,\gamma),\ \lambda_{3H}=0$	9.59
$\mathbf{H(b\,\bar{b})\,H(\gamma\,\gamma),\ \lambda_{3H}=1}$	**5.91**
$H(b\,\bar{b})\,H(\gamma\,\gamma),\ \lambda_{3H}=5$	2.65
$gg\,H(\gamma\,\gamma)$	1.68
$t\,\bar{t}\,H(\gamma\,\gamma)$	3.41
$Z\,H(\gamma\,\gamma)$	1.16
$b\,\bar{b}\,H(\gamma\,\gamma)$	0.076
$b\,\bar{b}\,\gamma\,\gamma$	2.38
$c\,\bar{c}\,\gamma\,\gamma$	0.00
$j\,j\,\gamma\,\gamma$	0.26
$b\,\bar{b}\,j\,\gamma$	0.98
$c\,\bar{c}\,j\,\gamma$	0.27
$b\,\bar{b}\,j\,j$	0.36
$Z(b\,\bar{b})\,\gamma\gamma$	0.15
$t\,\bar{t}$ ($\geq$ 1 leptons)	0.32
$t\,\bar{t}\gamma$ ($\geq$ 1 leptons)	0.31
Total Background	11.36
Significance $Z,\ \lambda_{3H}=1$	**1.63**



Improved Likelihood fit using the (NLO) M_{HH} kinematic distribution





Scenario	1σ CI	2σ CI
$\lambda_{3H} = 1$ nominal set	$-0.1 < \lambda_{3H} < 2.6$ and $5.0 < \lambda_{3H} < 7.0$	$-1.1 < \lambda_{3H} < 7.9$
$\lambda_{3H} = 0$ nominal set	$-0.9 < \lambda_{3H} < 1.1$ and $6.4 < \lambda_{3H} < 7.5$	$-1.8 < \lambda_{3H} < 2.8$ and $4.6 < \lambda_{3H} < 8.5$

Conclusion

1. We examine the impact of the full NLO corrections considering full top-quark mass dependence, and the recent CT14LO PDF.

2. (CT14LO) At 14 TeV with 3000 fb^-1, the trilinear coupling is constrained to be -1.1 < λ_{3H} < 7.0 at 95% CL taking account of the uncertainties associated with the top-Yukawa coupling and the estimation of backgrounds.

3. (CT14LO) Taking the central line, the 95% CL sensitivity region for λ_{3H} is -0.3 < λ_{3H} < 6.7

4. (BDTL1) The trilinear coupling is constrained to be -0.7< λ_{3H} < 7.5 at 95% CL taking account of the uncertainties associated with the top-Yukawa coupling and the estimation of backgrounds.

5. (BDTL1) Taking the central line, the 95% CL sensitivity region for λ_{3H} is 0.2 < λ_{3H} < 7.1

6. (BDTL1 + NLO) Taking the central line, the 95% CL sensitivity region for λ_{3H} is 0.6 < λ_{3H} < 6.7

• HL-LHC : constraint the λ_{3H}

1. Cut-Based Analysis : $-1.1 < \lambda_{3H} < 7.0$ at 95% CL,

   $Z = 0.99$ ($\lambda_{3H}=1$)

33% enhancement on Z

2. BDT Analysis : $0.2 < \lambda_{3H} < 7.1$ at 95% CL,

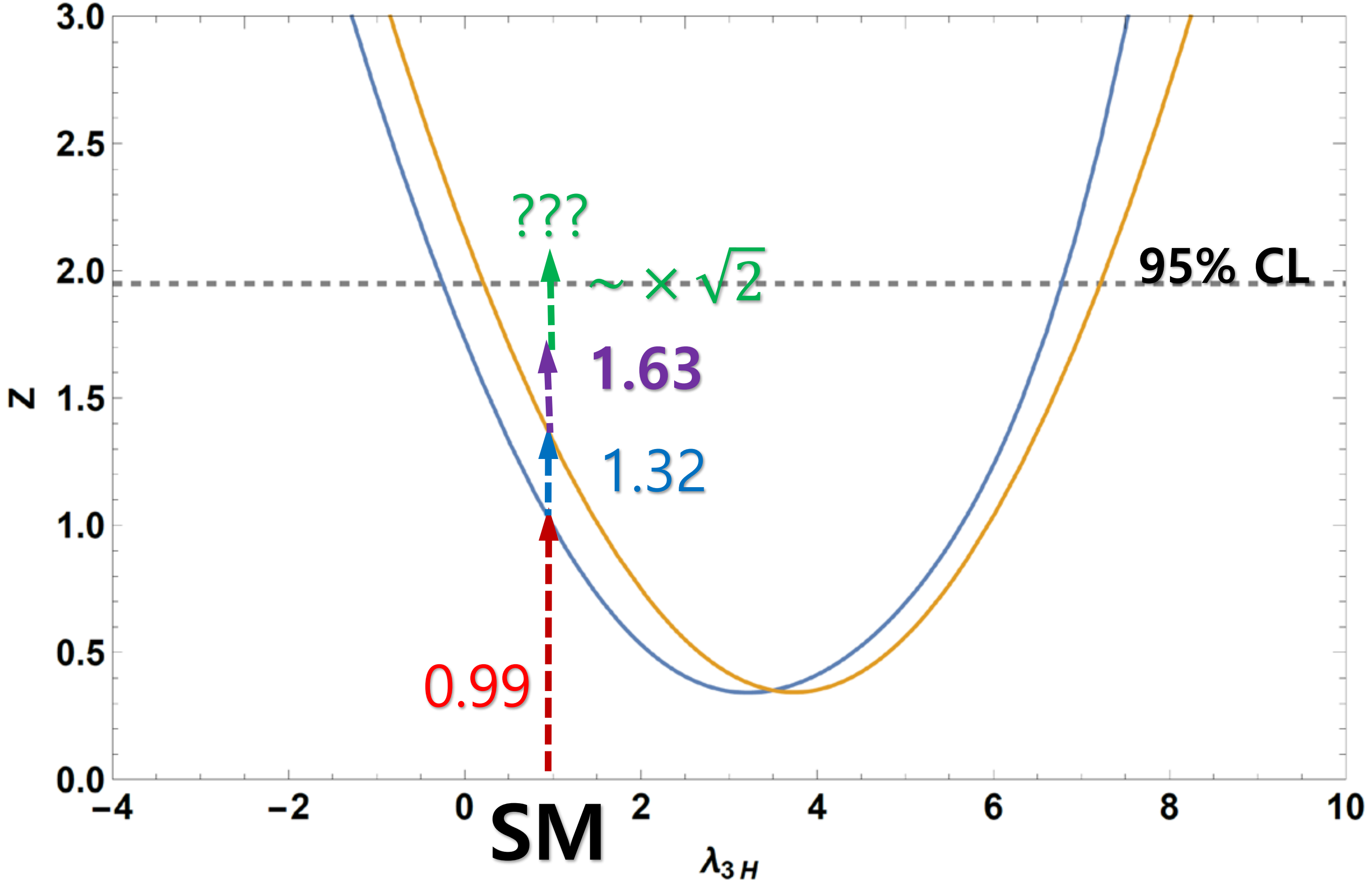
   $Z = 1.32$ ($\lambda_{3H}=1$)

23% enhancement on Z

3. BDT Analysis + NLO : $0.6 < \lambda_{3H} < 6.7$ at 95% CL,

   $Z = 1.63$ ($\lambda_{3H}=1$)

Z v.s. λ_{3H}=1 in the cases of C&C and BDTL1



HL-LHC
with Lumi.= $6\ ab^{-1}$

Ref. arxiv:1902.00134

BDTL1 + NLO, Z=1.63

BDTL1, Z=1.32

C&C, Z=0.99

Last, but not least

- **Combined analysis** : $b\bar{b}b\bar{b}$ + $b\bar{b}\gamma\gamma$ + $b\bar{b}\tau\tau$ → Z (≥ 3σ)

ATL-PHYS-PUB-2018-053

- **Advanced technology in the future** …
  Increased luminosity, improved tagging efficiency, improved resolution and so on….

- **More precise simulation, higher order QCD correction ..**
  Improved MC Event generators (at the NLO, NNLO QCD order),
  QCD NLO, NNLO, NNNLO corrections …
  ….

• HL-LHC : constraint the λ_{3H}

1. Cut-Based Analysis : $-1.1 < \lambda_{3H} < 7.0$ at 95% CL,

   $Z = 0.99$ ($\lambda_{3H} = 1$)

2. BDT Analysis : $0.2 < \lambda_{3H} < 7.1$ at 95% CL,

   $Z = 1.32$ ($\lambda_{3H} = 1$)

3. BDT Analysis + NLO : $0.6 < \lambda_{3H} < 6.7$ at 95% CL,

   $Z = 1.63$ ($\lambda_{3H} = 1$)

33% enhancement on Z

23% enhancement on Z

Thank you for your attention !!!!!

END

Backup Slides I

Further improvements to be made

- New low and high-level kinematic variables : ex. 8 var. -> 22 var.
- Finding the optimized pre-selection cuts (Hyperopt)

Impurity

Purity : $p = S/(S+B)$

Impurity function :

Gini Index : $p \cdot (1-p)$

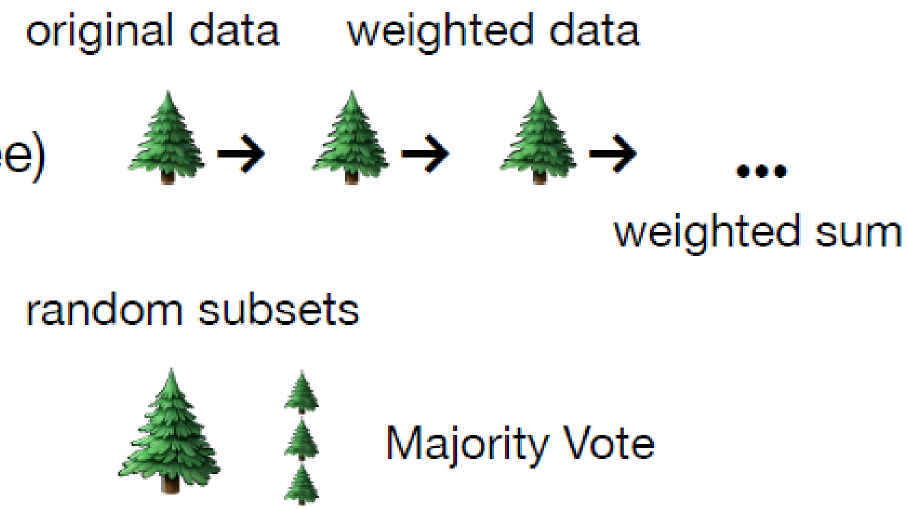
Cross entropy : $-p \cdot ln(p) - (1-p) \cdot ln(1-p)$

Misclassification error : $1 - max(p, 1-p)$

Statistical significance : $S/\sqrt{S+B}$

Boost and Bagging

- A way of enhancing the classification performance
- Increasing the stability with respect to statistical fluctuations in the training sample
- TMVA Provides :
  - Boosting
    - Adaptive Boost (boosting tree)
    - Gradient Boost (GBDT)
  - Bagging (random forest)



TMVA Users Guide

Adaptive Boost

- Starting with the original event weights when training the first decision tree

- Subsequent tree is trained using a modified event sample (previous misclassified events multiplied by a boost weight α)

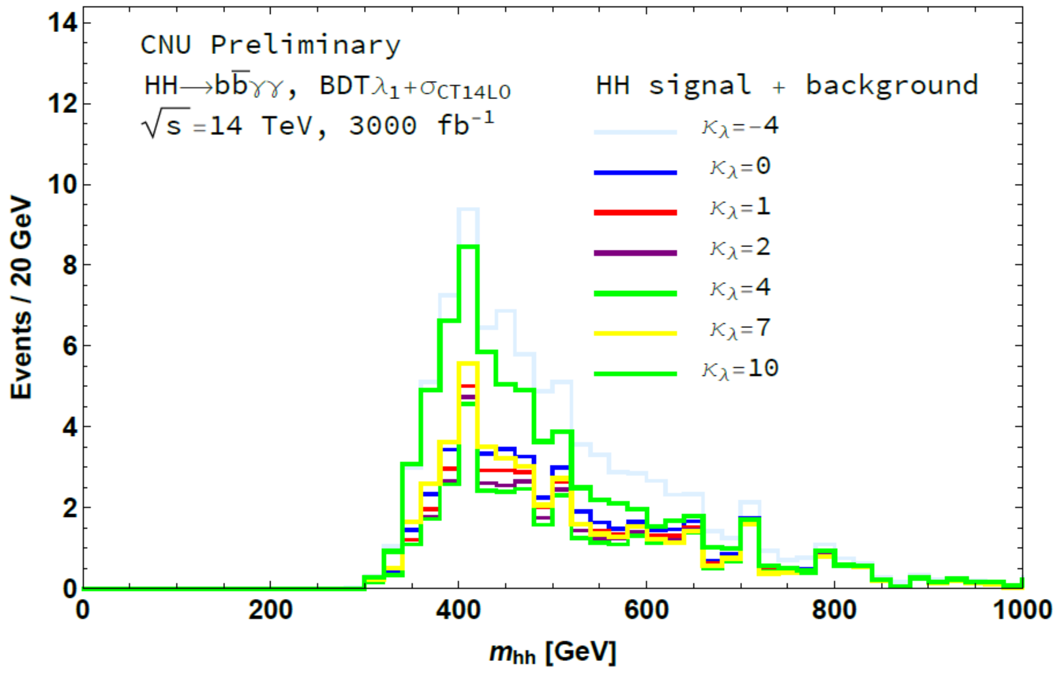
$$\alpha = \frac{1 - \text{err}}{\text{err}}$$ **err = misclassified / tot.**

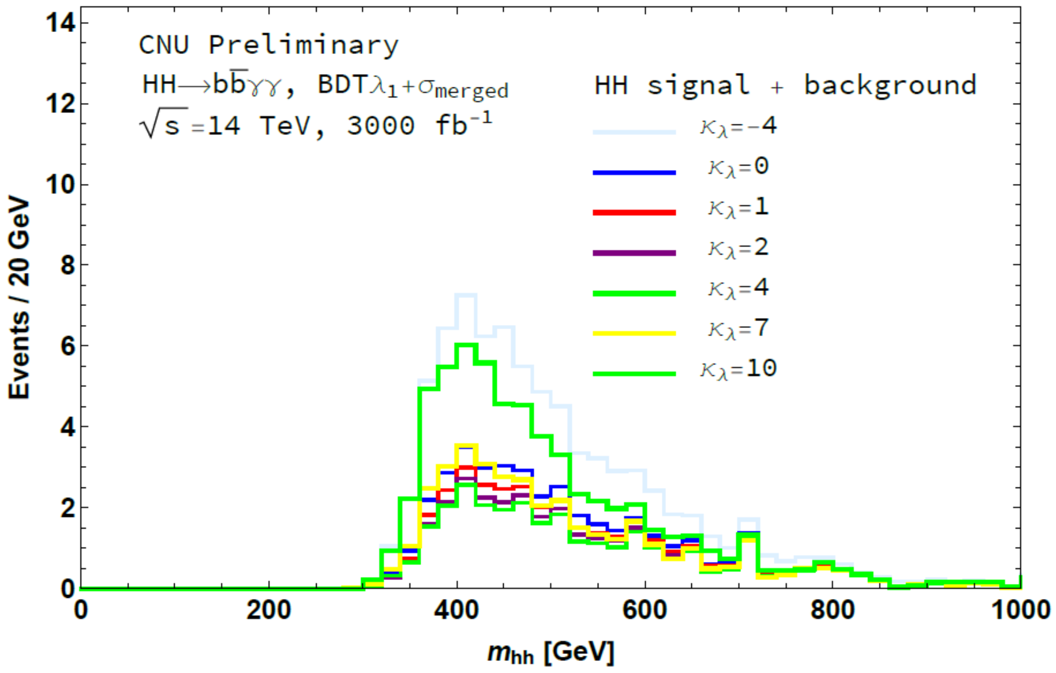
- The boosted event classification :
  (small — background-like; large — signal-like event)

$$y_{\text{Boost}}(\mathbf{x}) = \frac{1}{N_{\text{collection}}} \cdot \sum_{i}^{N_{\text{collection}}} \ln(\alpha_i) \cdot h_i(\mathbf{x}) \qquad h(x) = \pm 1$$ **signal** **Bkg**

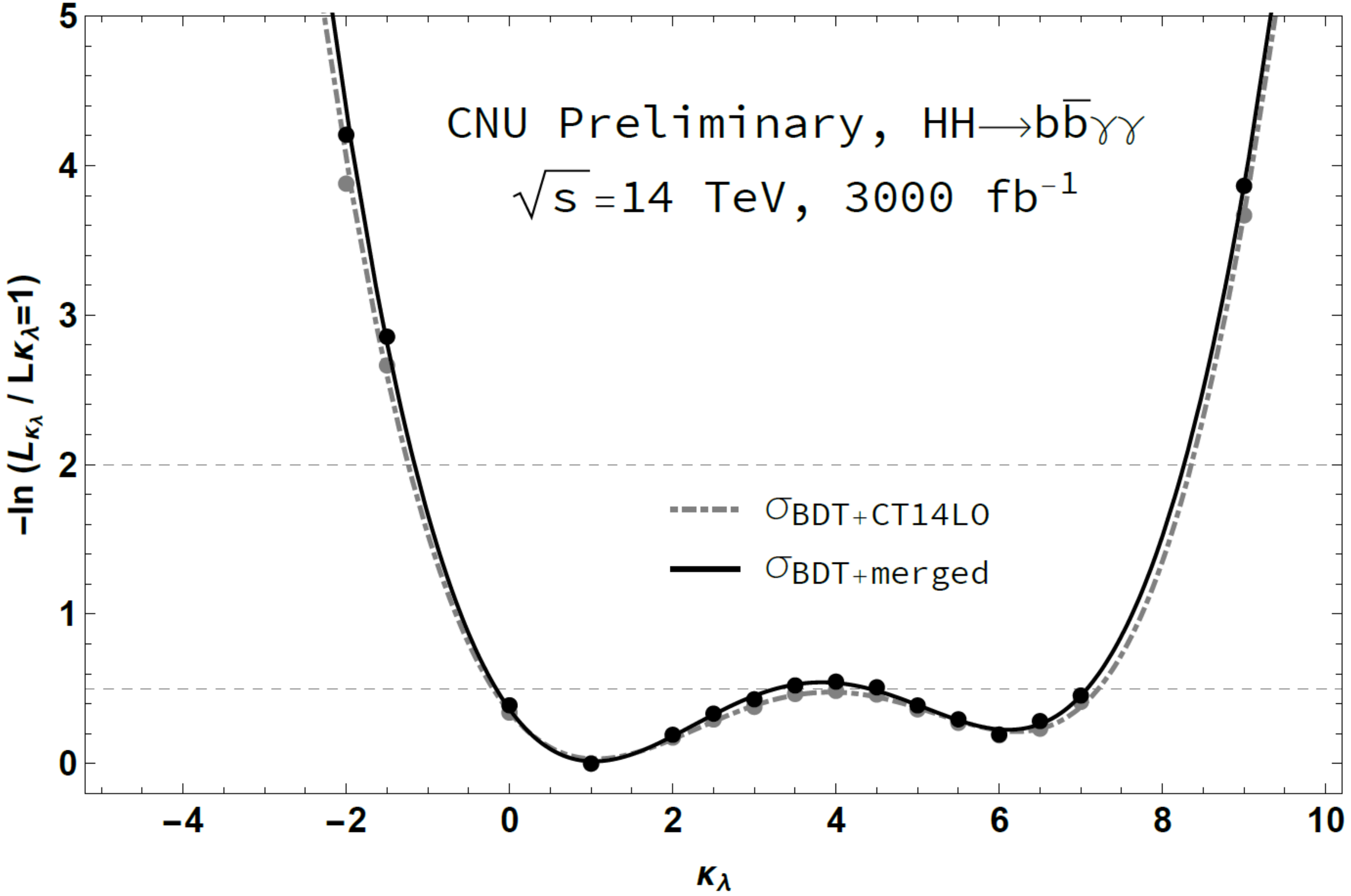
- The learning rate $\alpha \rightarrow \alpha^{\beta}$

M_hh distributions II

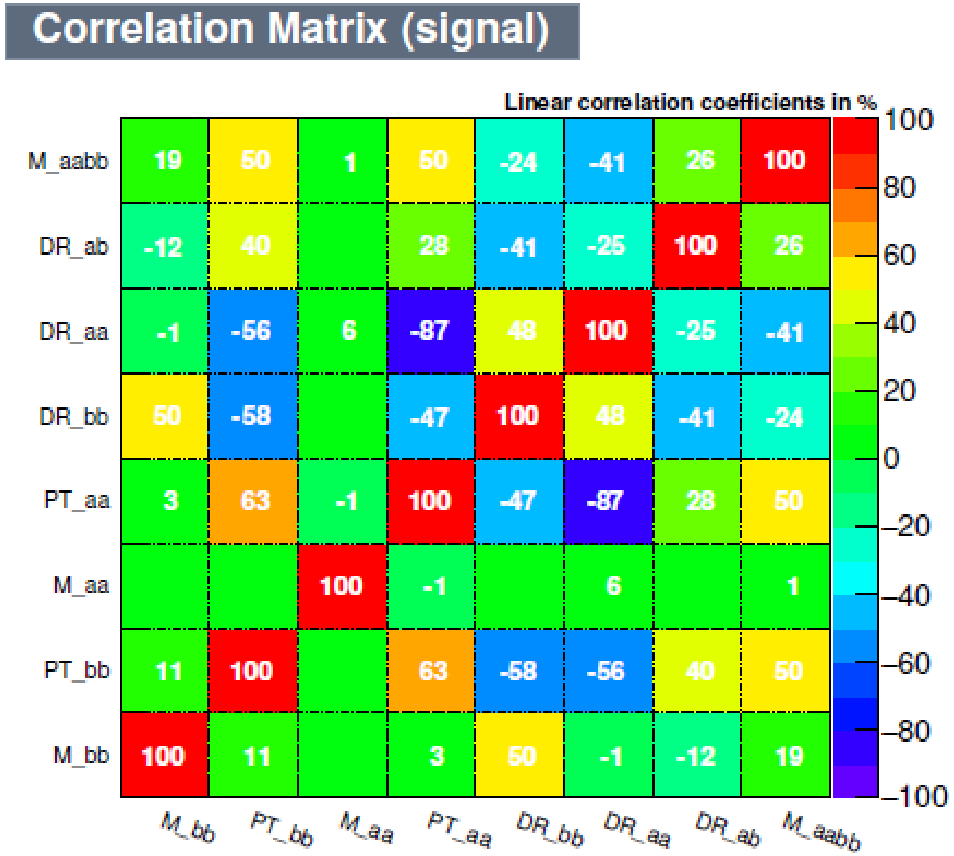


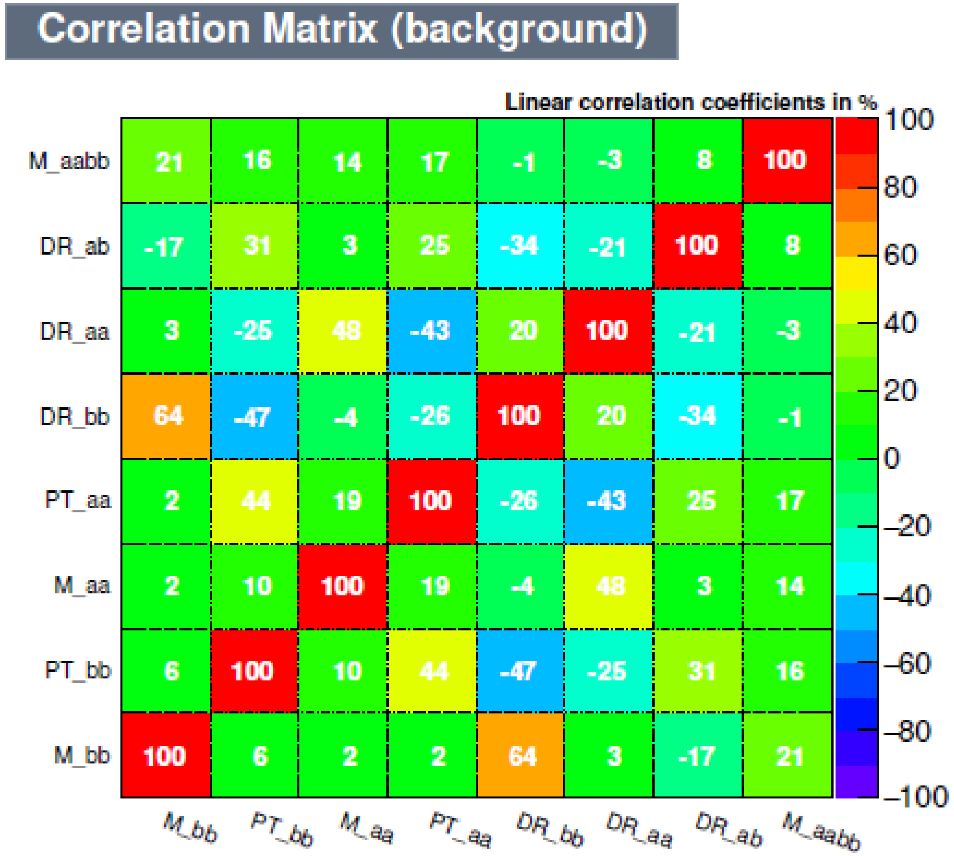


Log-Likelihood Ratios v.s Lambda_3H



(NLO-) Correlation Matrix





Event selection on Cut-and-Count Analysis

Sequence	Event Selection Criteria at the HL-LHC
1	Di-photon trigger condition, ≥ 2 isolated photons with $P_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
2	≥ 2 isolated photons with $P_T > 30$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$, $\Delta R_{j\gamma} > 0.4$
3	≥ 2 jets identified as b-jets with leading(subleading) $P_T > 40(30)$ GeV, $\lvert\eta\rvert < 2.4$
4	Events are required to contain ≤ 5 jets with $P_T > 30$ GeV within $\lvert\eta\rvert < 2.5$
5	No isolated leptons with $P_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
6	$0.4 < \Delta R_{b\bar{b}} < 2.0$, $0.4 < \Delta R_{\gamma\gamma} < 2.0$
7	$122 < M_{\gamma\gamma}/\text{GeV} < 128$ and $100 < M_{b\bar{b}}/\text{GeV} < 150$
8	$P_T^{\gamma\gamma} > 80$ GeV, $P_T^{b\bar{b}} > 80$ GeV

These red conditions of cuts were very important
to distinguish signal and background on the Cut-and-Count Analysis !

HL-LHC 14 TeV

Signal

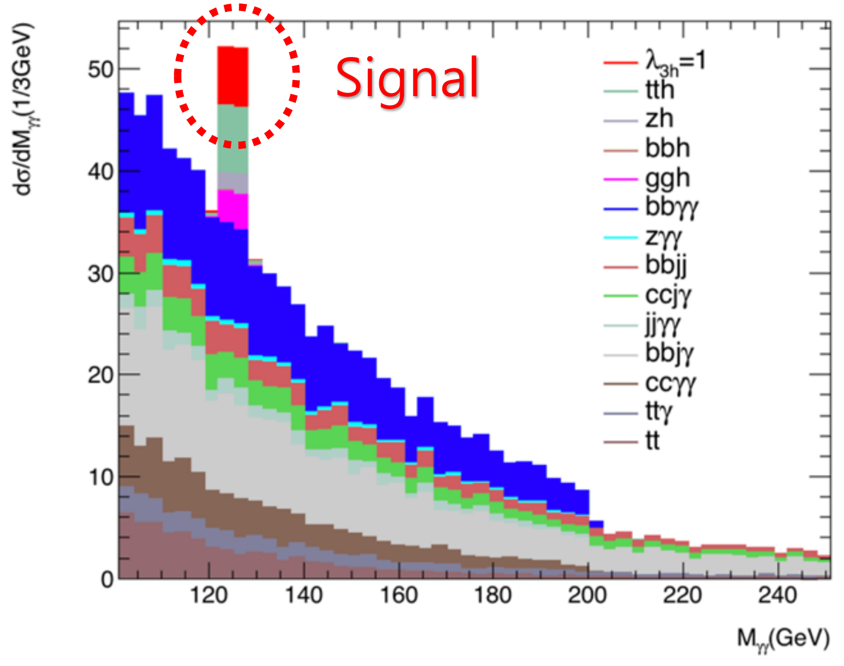
Signal process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
$gg \to HH \to b\bar{b}\gamma\gamma$ [15]	MG5_aMC@NLO/PYTHIA8	0.119	NNLO +NNLL	NNPDF2.3LO

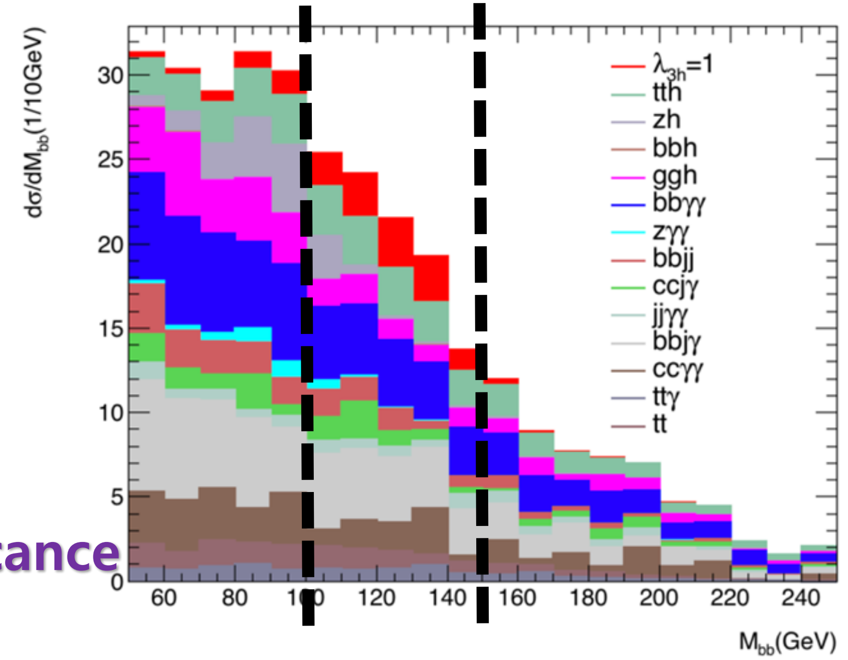
Backgrounds

Background(BG)	Process	Generator/Parton Shower	$\sigma \cdot BR$ [fb]	Order in QCD	PDF used
Single-Higgs associated BG [15]	$ggH(\to \gamma\gamma)$	POWHEG – BOX/PYTHIA6	1.20×10^2	NNNLO	CT10
	$t\bar{t}H(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	1.37	NLO	
	$ZH(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	2.24	NLO	
	$b\bar{b}H(\to \gamma\gamma)$	PYTHIA8/PYTHIA8	1.26	NLO	
Non-resonant BG	$b\bar{b}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.40×10^2	LO	CTEQ6L1
	$c\bar{c}\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.14×10^3	LO	
	$jj\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	1.62×10^4	LO	
	$b\bar{b}j\gamma$	MG5_aMC@NLO/PYTHIA8	3.67×10^5	LO	
	$c\bar{c}j\gamma$	MG5_aMC@NLO/PYTHIA8	1.05×10^6	LO	
	$b\bar{b}jj$	MG5_aMC@NLO/PYTHIA8	4.34×10^8	LO	
	$Z(\to b\bar{b})\gamma\gamma$	MG5_aMC@NLO/PYTHIA8	5.17	LO	
$t\bar{t}$ and $t\bar{t}\gamma$ BG	$t\bar{t}$ [18]	POWHEG – BOX/PYTHIA8	5.30×10^5	NNLO +NNLL	CT10
(≥ 1 lepton)	$t\bar{t}\gamma$ [19]	MG5_aMC@NLO/PYTHIA8	1.60×10^3	NLO	CTEQ6L1

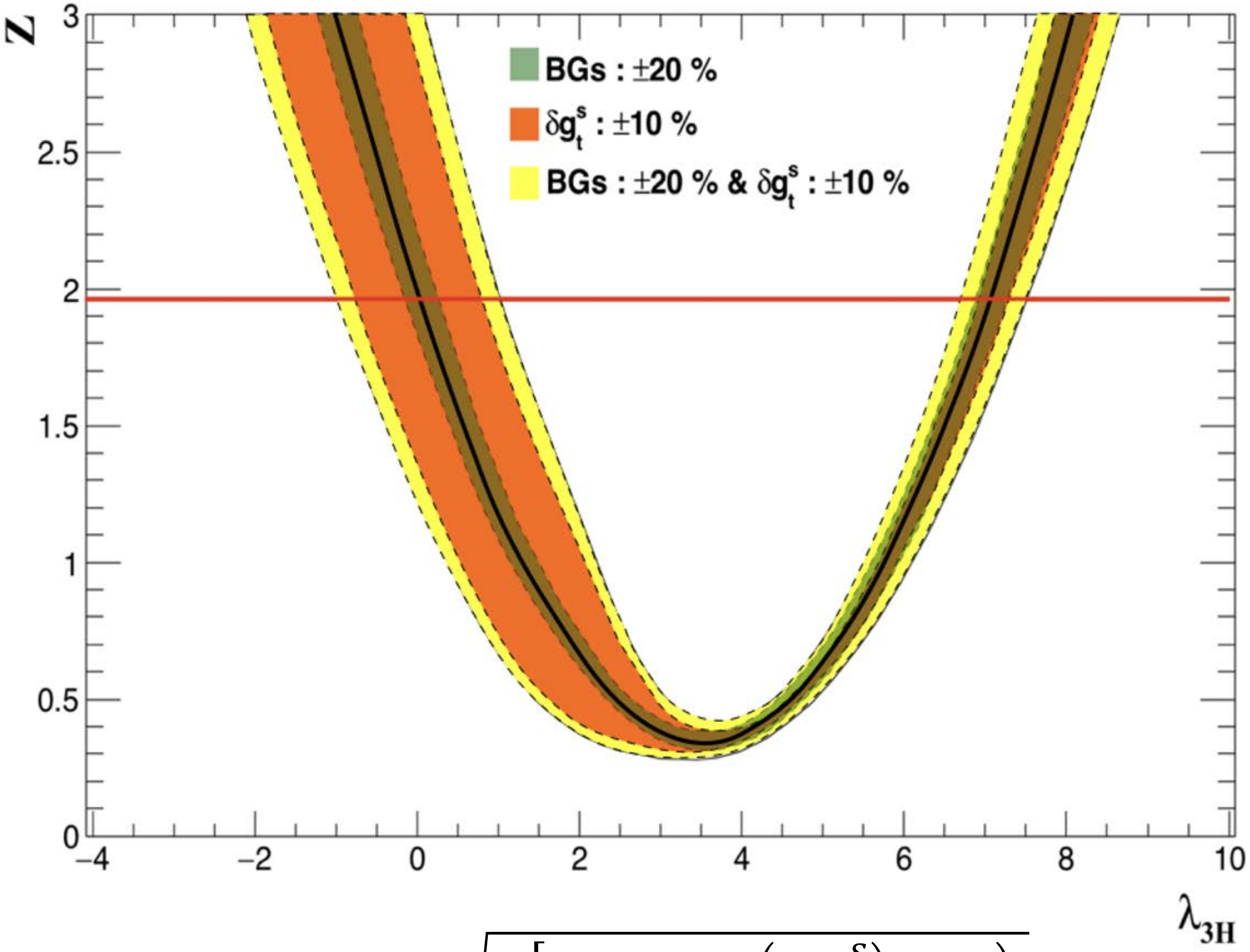
Expected yields (3000 fb^{-1}) Samples	Total	Barrel-barrel	Other (End-cap)	Ratio (O/B)
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = -4$	77.14	57.03	20.11	0.35
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 0$	19.50	14.33	5.17	0.36
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 1$	11.42	8.53	2.89	0.34
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 2$	6.82	5.14	1.68	0.33
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 6$	11.03	7.91	3.12	0.39
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 10$	57.46	41.94	15.52	0.37
$gg\,H(\gamma\gamma)$	6.60	4.50	2.10	0.47
$t\bar{t}\,H(\gamma\gamma)$	13.21	9.82	3.39	0.35
$Z\,H(\gamma\gamma)$	3.62	2.44	1.18	0.48
$b\bar{b}\,H(\gamma\gamma)$	0.15	0.11	0.04	0.40
$b\bar{b}\gamma\gamma$	18.86	11.15	7.71	0.69
$c\bar{c}\gamma\gamma$	7.53	4.79	2.74	0.57
$jj\gamma\gamma$	3.34	1.59	1.75	1.10
$b\bar{b}j\gamma$	18.77	10.40	8.37	0.80
$c\bar{c}j\gamma$	5.52	3.94	1.58	0.40
$b\bar{b}jj$	5.54	3.81	1.73	0.45
$Z(b\bar{b})\gamma\gamma$	0.90	0.54	0.36	0.67
$t\bar{t}$ ($\geq$ 1 leptons)	4.98	3.04	1.94	0.64
$t\bar{t}\gamma$ ($\geq$ 1 leptons)	3.61	2.29	1.32	0.58
Total Background	92.63	58.42	34.21	0.59
Significance Z	1.163	1.090	0.487	
Combined significance		1.194		

Combined significance = 1.194



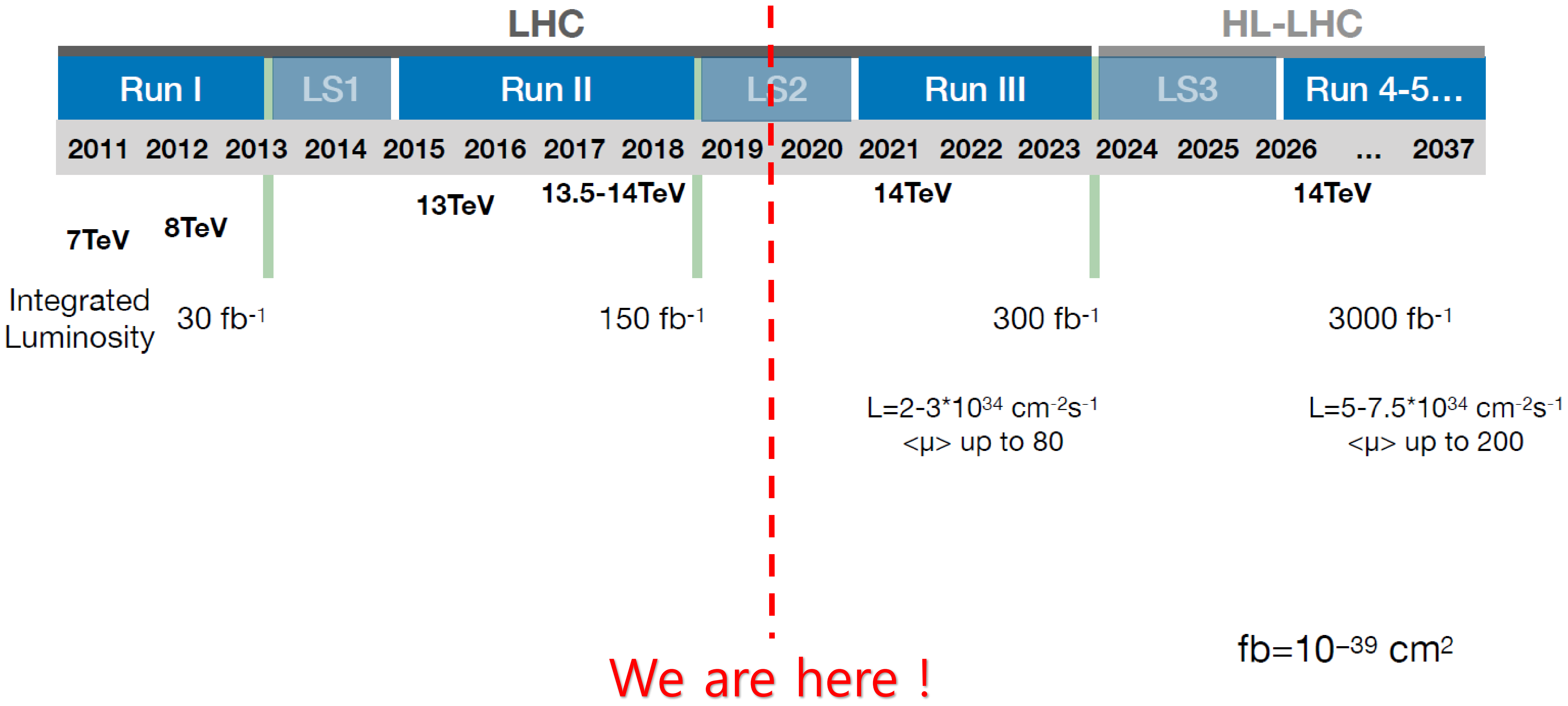


Result at the HL-LHC

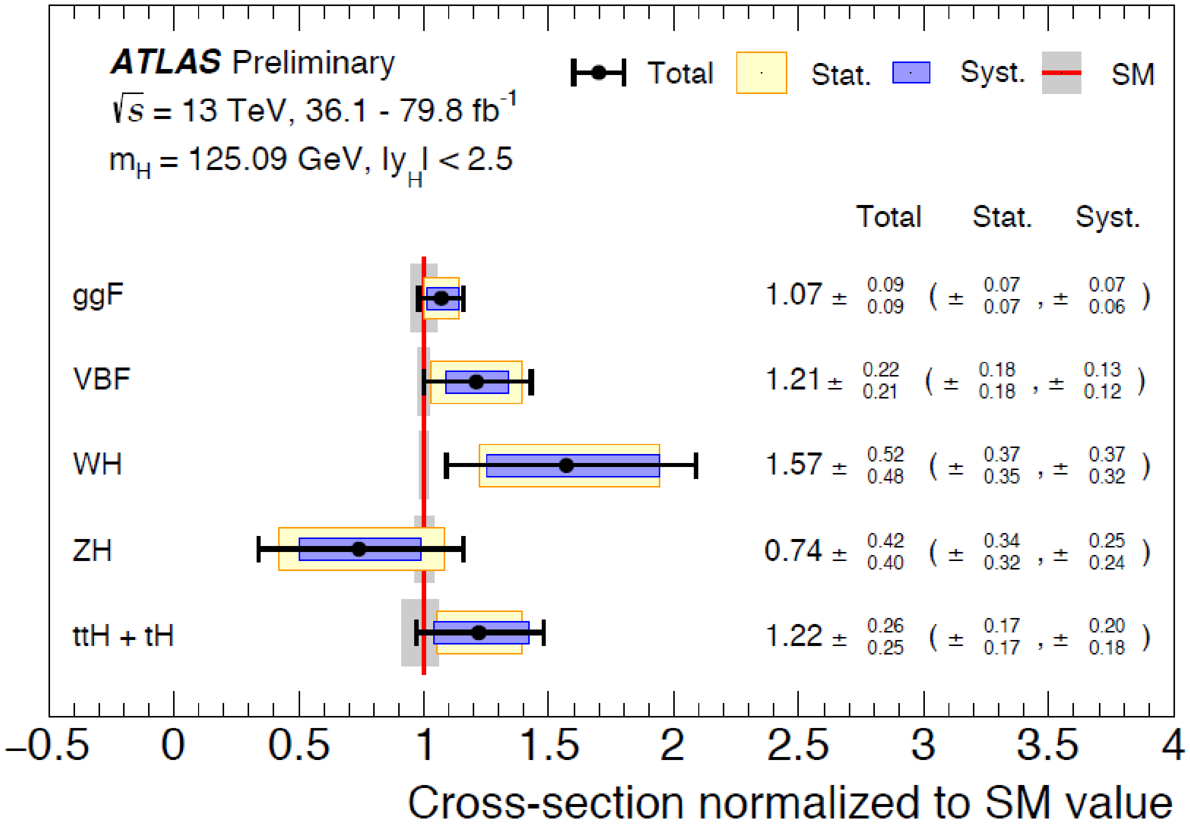


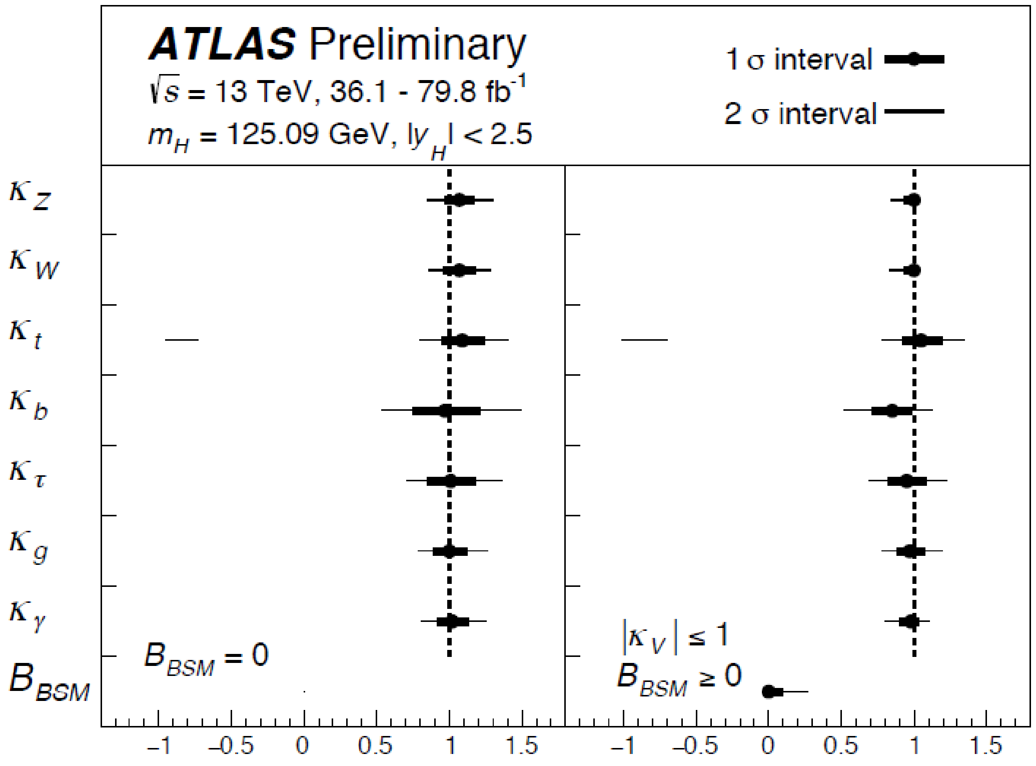
$$Z = \sqrt{2\left[\left(\left(s+b\right)\ln\left(1+\frac{s}{b}\right)-s\right)\right]}$$

Timeline of LHC



LHC RUN II





All parameters except κt are assumed to be positive.

ATLAS Collaboration, ATLAS-CONF-2018-031

Machine Learning

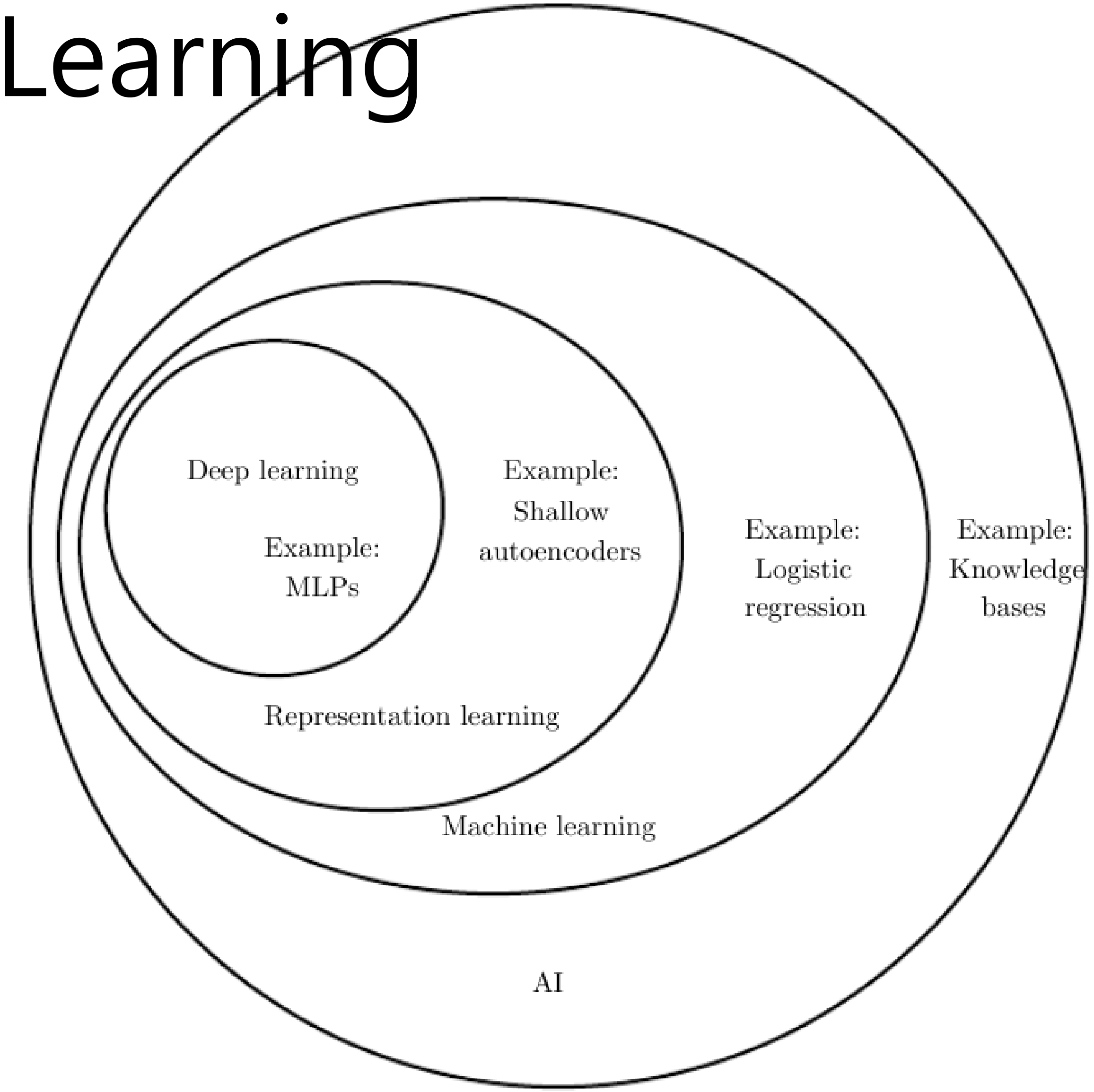
From Wikipedia

- **Machine learning** (ML) is a field of artificial intelligence that uses statistical techniques to give computer systems the ability to "learn" (e.g., progressively improve performance on a specific task) from data, without being explicitly programmed.[2]

- The name *machine learning* was coined in 1959 by Arthur Samuel.[1] Machine learning explores the study and construction of algorithms that can learn from and make predictions on data[3] – such algorithms overcome following strictly static program instructions by making data-driven predictions or decisions,[4]:2 through building a model from sample inputs. Machine learning is employed in a range of computing tasks where designing and programming explicit algorithms with good performance is difficult or infeasible; example applications include email filtering, detection of network intruders, and computer vision.

- …………

Machine Learning



[Ian Goodfellow, Yoshua Bengio a nd Aaron Courville] 'Deep Learning'

(In machine learning language)

“**machine**” = ‘model (from data)’

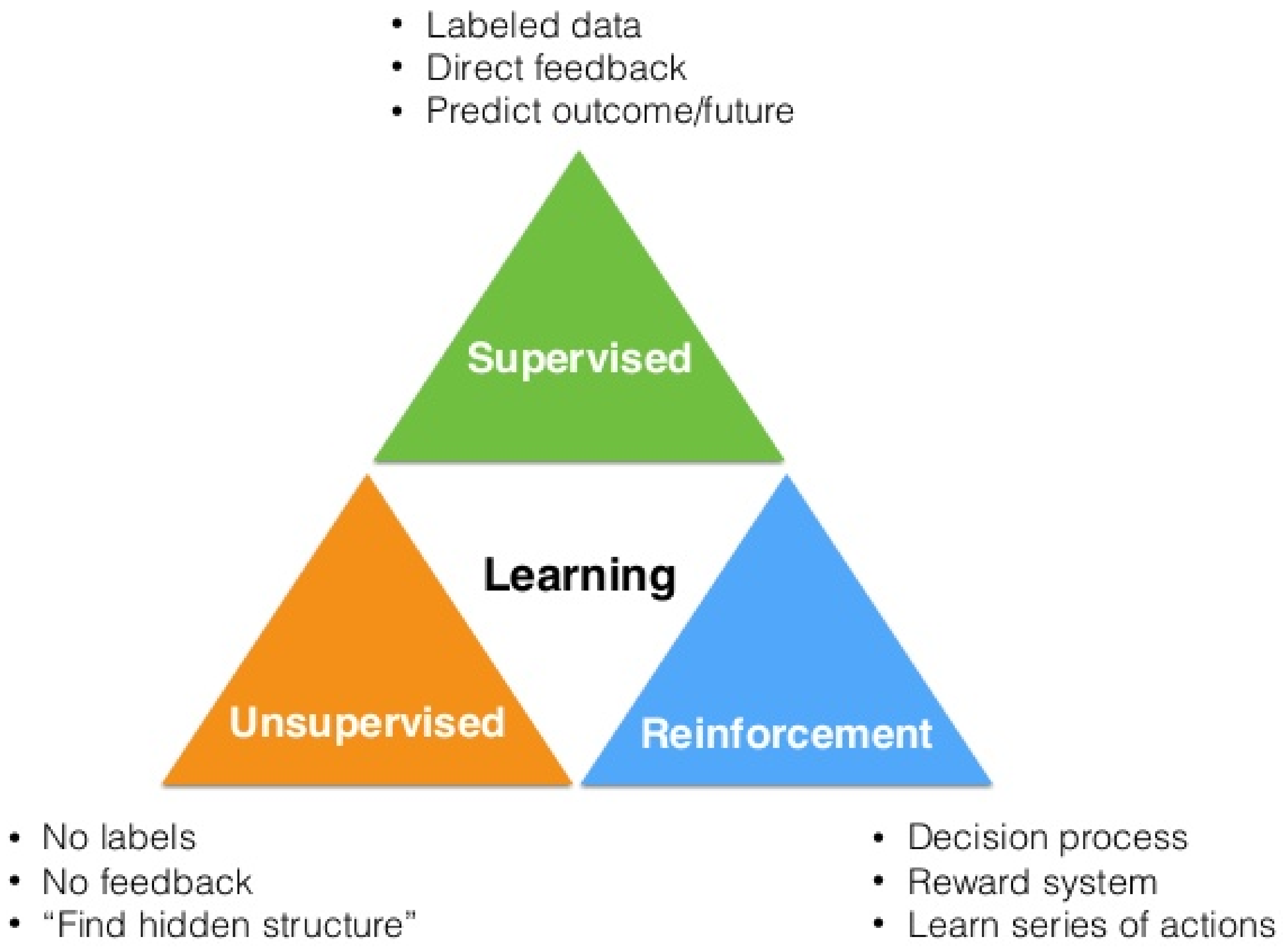
Learning = Improving performance at a task (ex) with experience

(In machine learning language)

“**Learning**” = Optimization of (machine’s/model’s) parameters of a proper error function which represents performance at a task.

Therefore, “**I am training a machine**

= I am building a new model (from data)



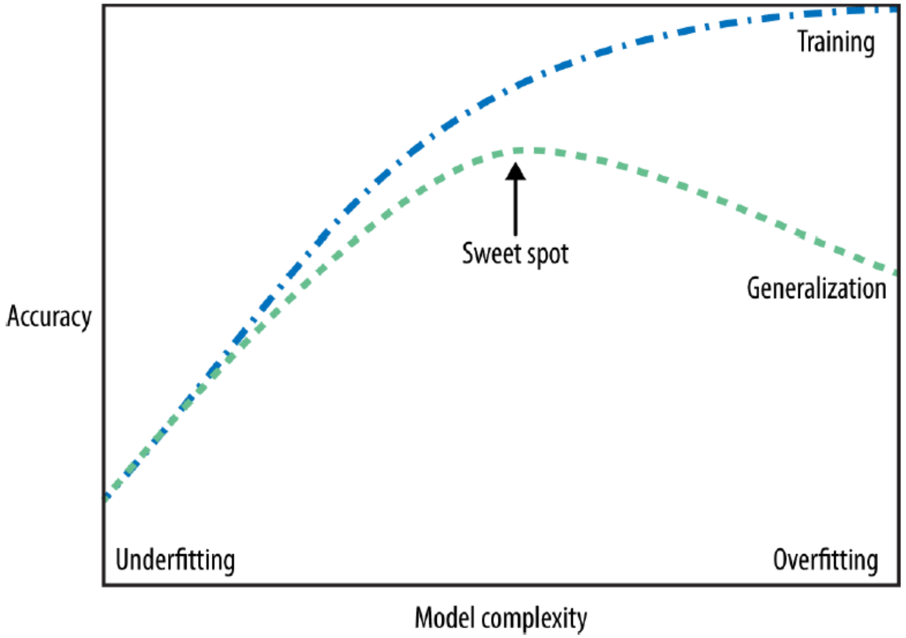
http://solarisailab.com/archives/1785, 솔라리스의 인공지능 연구실

Supervised Learning

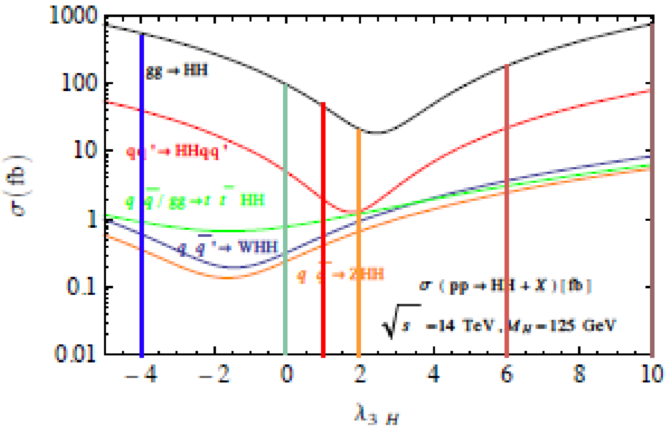
Supervised Learning

- Classification and Regression
- Generalization, Overfitting, and Underfitting

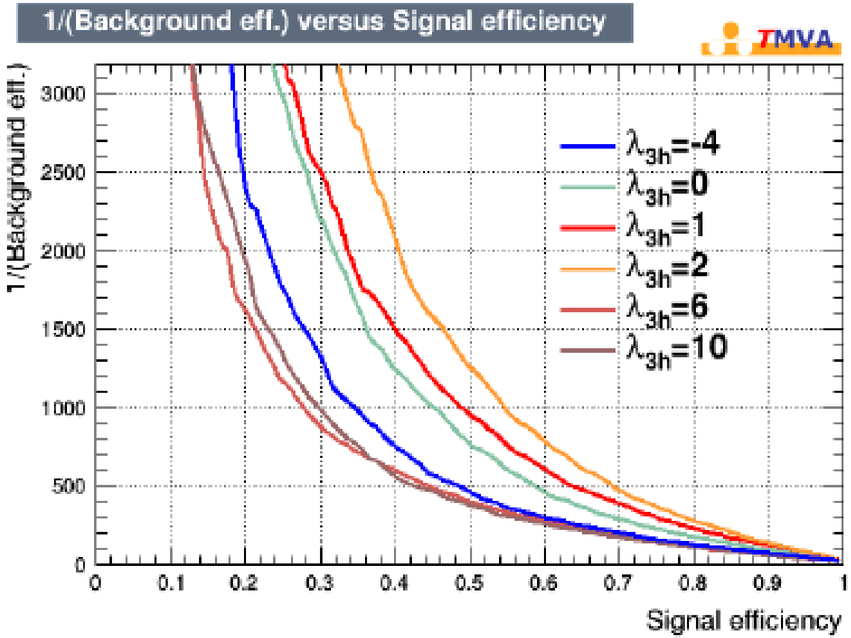
This figure is really important !!!

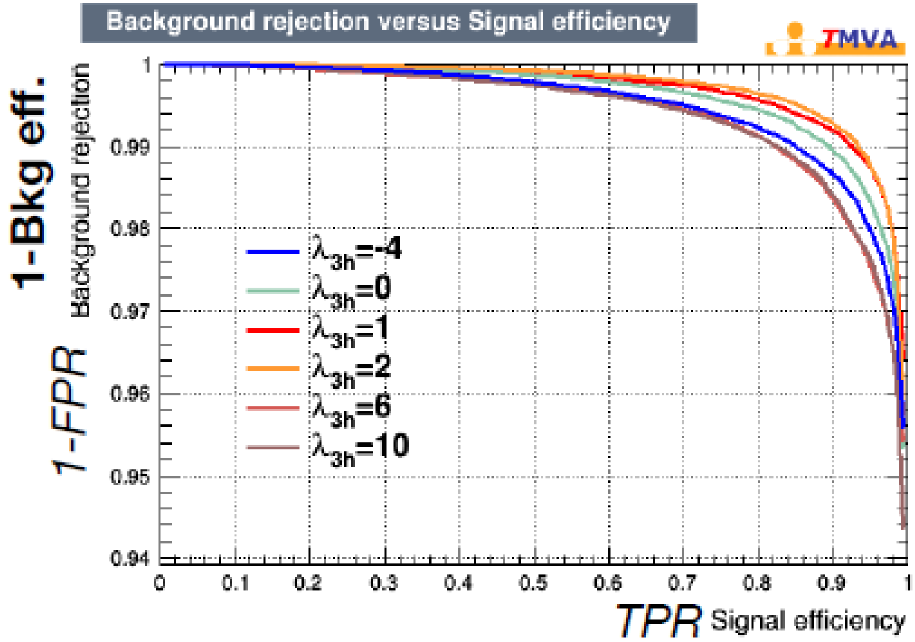


Each λ_{3H} optimized BDT machine



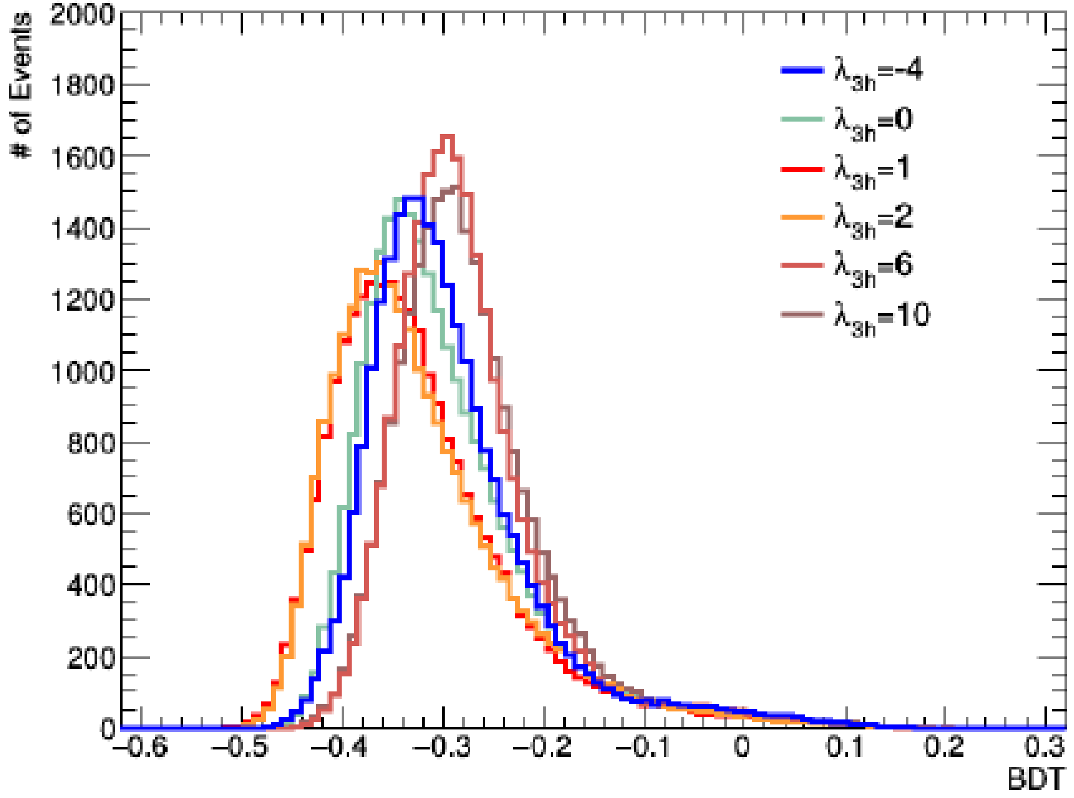
$$\sigma \times \mathcal{L} \times a \times \epsilon$$

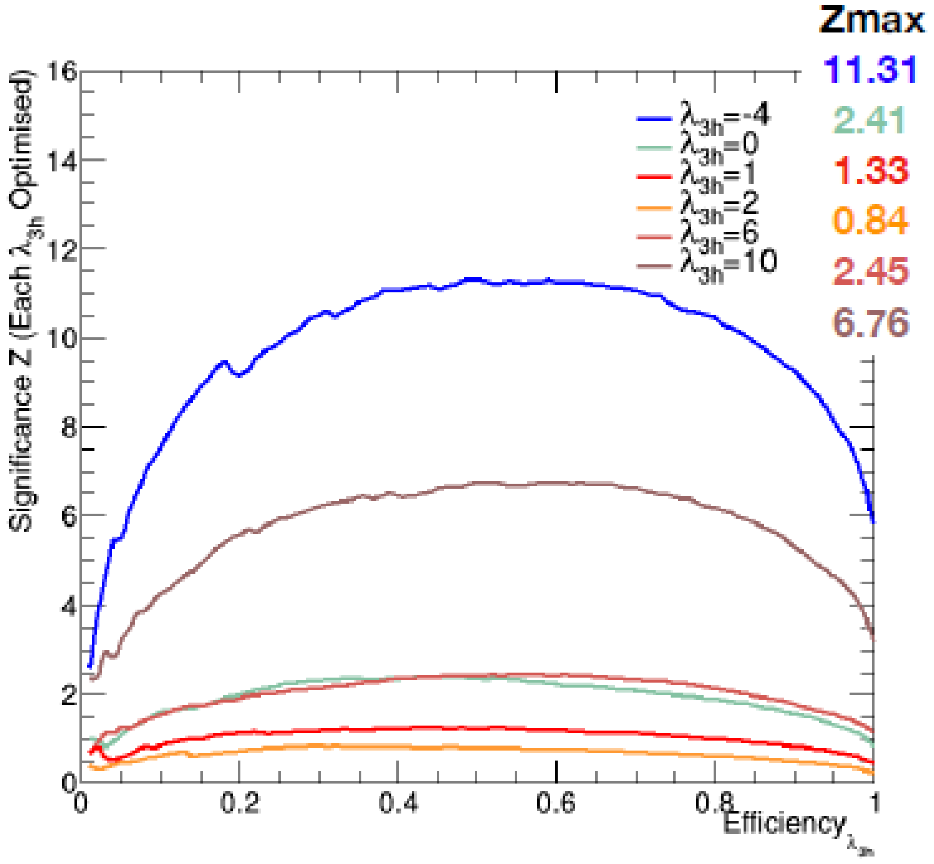




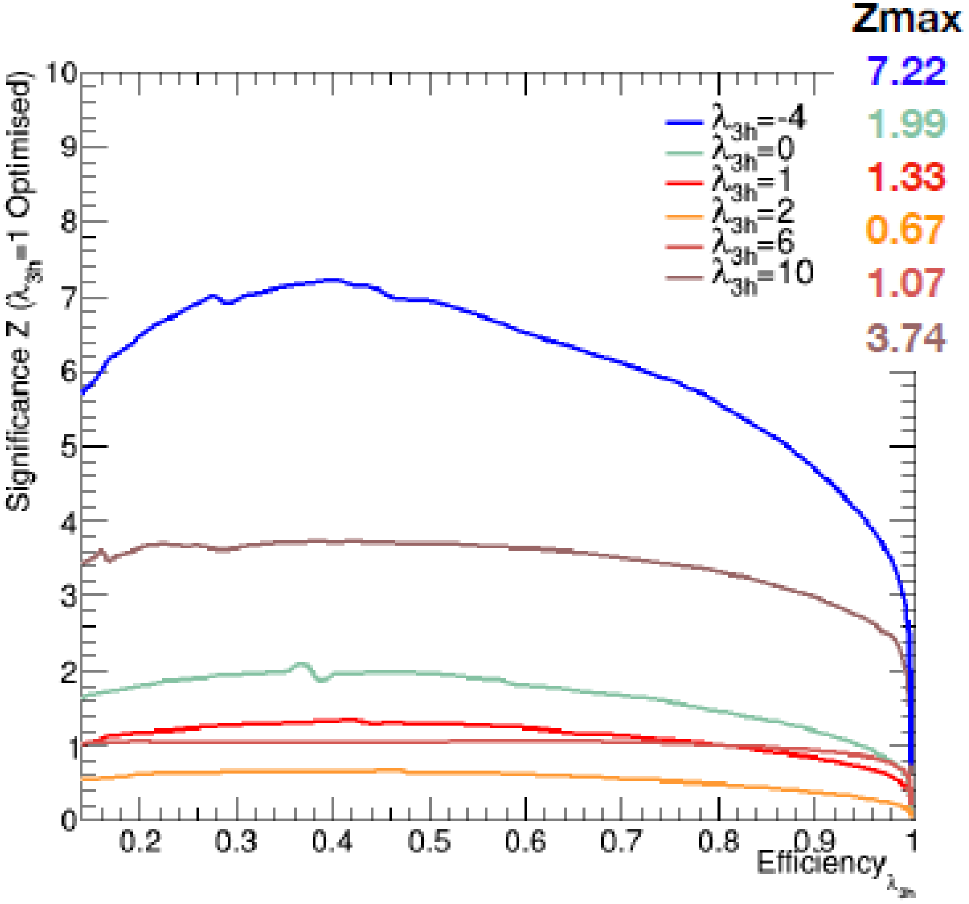
Each λ_{3H} optimized BDT machine

AUC = 0.992-0.996

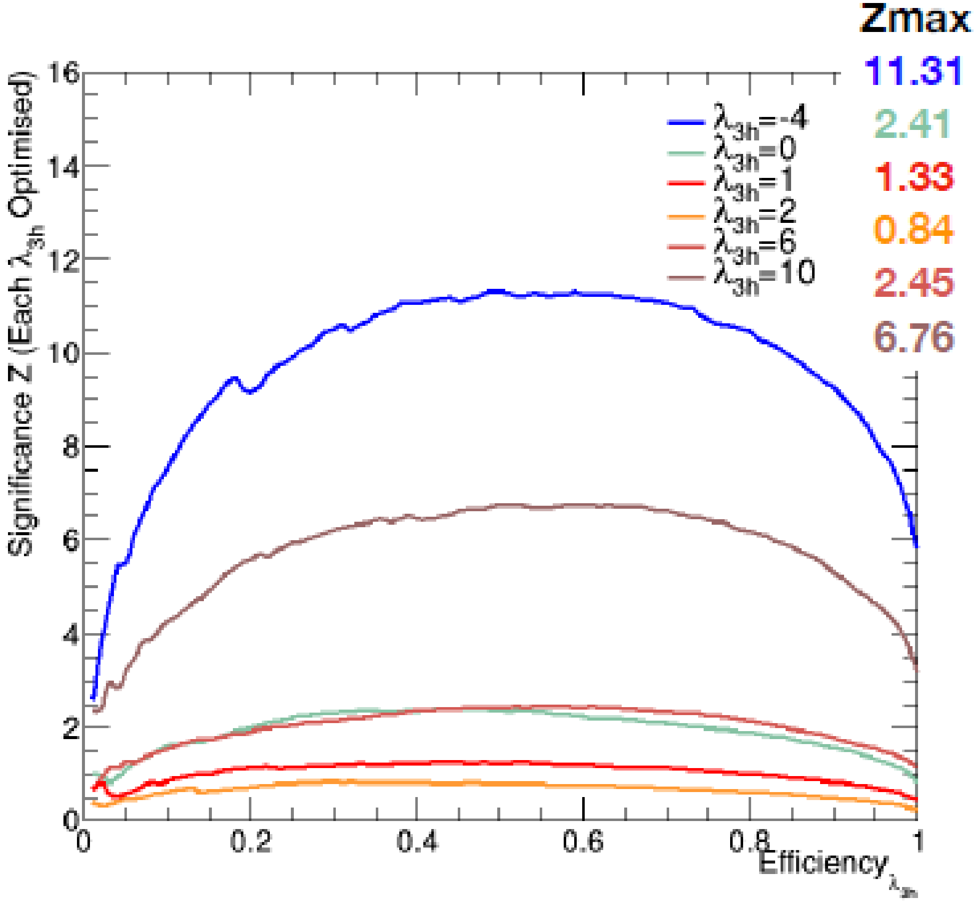




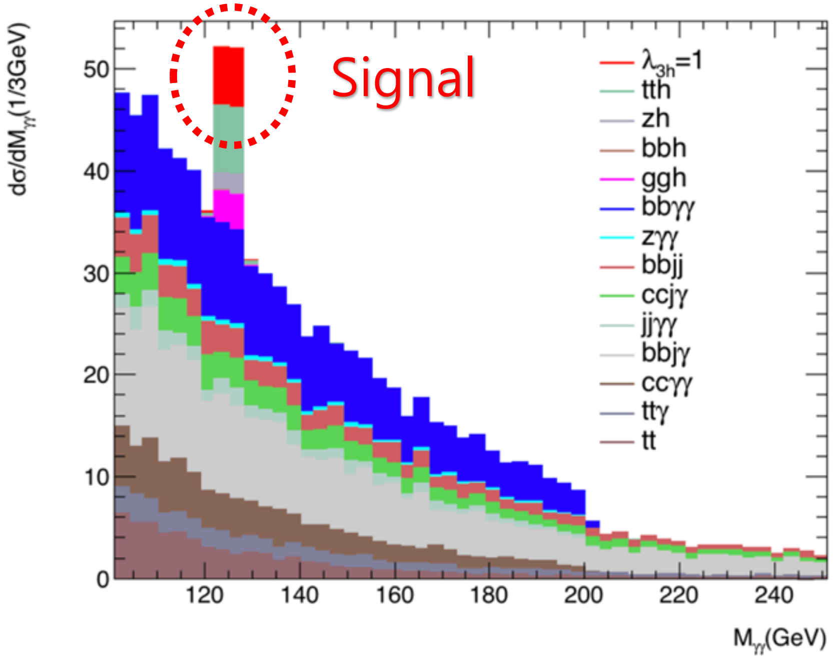
- $\lambda_{3h} = 1$ Optimized



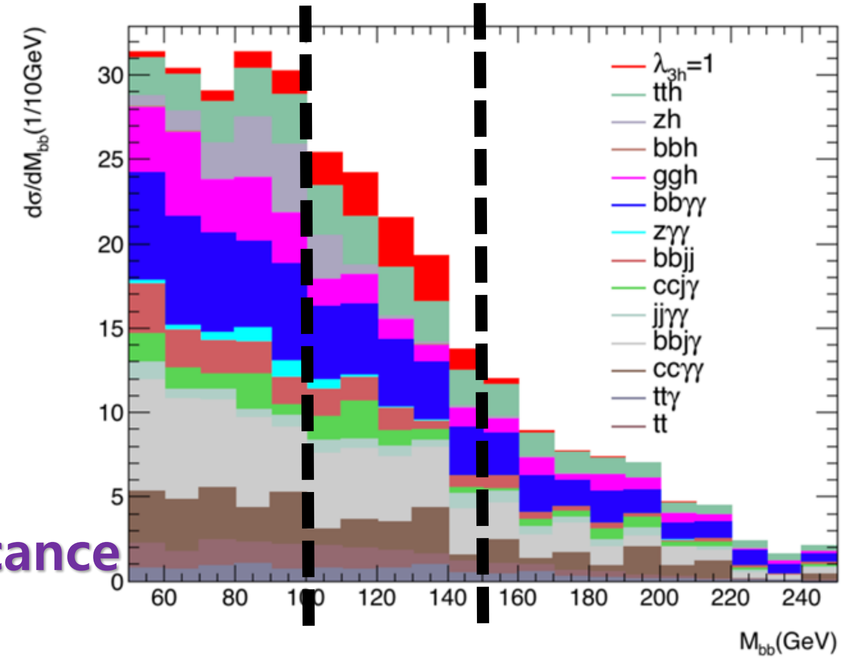
- λ_{3h} Optimized



Expected yields (3000 fb^{-1}) Samples	Total	Barrel-barrel	Other (End-cap)	Ratio (O/B)
$H(b\bar{b})\,H(\gamma\gamma),\ \lambda_{3H} = -4$	77.14	57.03	20.11	0.35
$H(b\bar{b})\,H(\gamma\gamma),\ \lambda_{3H} = 0$	19.50	14.33	5.17	0.36
$H(b\bar{b})\,H(\gamma\gamma),\ \lambda_{3H} = 1$	11.42	8.53	2.89	0.34
$H(b\bar{b})\,H(\gamma\gamma),\ \lambda_{3H} = 2$	6.82	5.14	1.68	0.33
$H(b\bar{b})\,H(\gamma\gamma),\ \lambda_{3H} = 6$	11.03	7.91	3.12	0.39
$H(b\bar{b})\,H(\gamma\gamma),\ \lambda_{3H} = 10$	57.46	41.94	15.52	0.37
$gg\,H(\gamma\gamma)$	6.60	4.50	2.10	0.47
$t\bar{t}\,H(\gamma\gamma)$	13.21	9.82	3.39	0.35
$Z\,H(\gamma\gamma)$	3.62	2.44	1.18	0.48
$b\bar{b}\,H(\gamma\gamma)$	0.15	0.11	0.04	0.40
$b\bar{b}\gamma\gamma$	18.86	11.15	7.71	0.69
$c\bar{c}\gamma\gamma$	7.53	4.79	2.74	0.57
$jj\gamma\gamma$	3.34	1.59	1.75	1.10
$b\bar{b}j\gamma$	18.77	10.40	8.37	0.80
$c\bar{c}j\gamma$	5.52	3.94	1.58	0.40
$b\bar{b}jj$	5.54	3.81	1.73	0.45
$Z(b\bar{b})\gamma\gamma$	0.90	0.54	0.36	0.67
$t\bar{t}$ ($\geq$ 1 leptons)	4.98	3.04	1.94	0.64
$t\bar{t}\gamma$ ($\geq$ 1 leptons)	3.61	2.29	1.32	0.58
Total Background	92.63	58.42	34.21	0.59
Significance Z	1.163	1.090	0.487	
Combined significance		1.194		



Combined significance = 1.194



Recent Update I (on the signal)

- 1. We examine the impact of the NLO corrections considering full top-quark mass dependence.

Previously,

(gg -> HH) = 45.05 fb (14 TeV),
(gg -> HH) = 1749 fb (100 TeV)

NNLO accuracy including NNLL gluon resummation in the infinite top quark mass approximation.

Full top-quark mass effect at the NLO

1. Recently, the NLO corrections considering full top-quark mass dependence have been available.
2. We observe that 20 (30) % reduction at 14 (100) TeV compared to the cross sections used.

(gg -> HH) = 36.69 fb (14 TeV),
(gg -> HH) = 1224 fb (100 TeV)

Double counting problem and their cross sections

- We have also checked the double counting problems between ME and PS on the non-resonant backgrounds.

- The final merged cross sections are reduced by
  about 20~30% (bbaa, zaa),
  about 30~40% (ccaa),
  about 50~60% (bbja, ccja),
  about > 60% (jjaa).

- However, the merged cross section of the “bbjj” is not reliable.

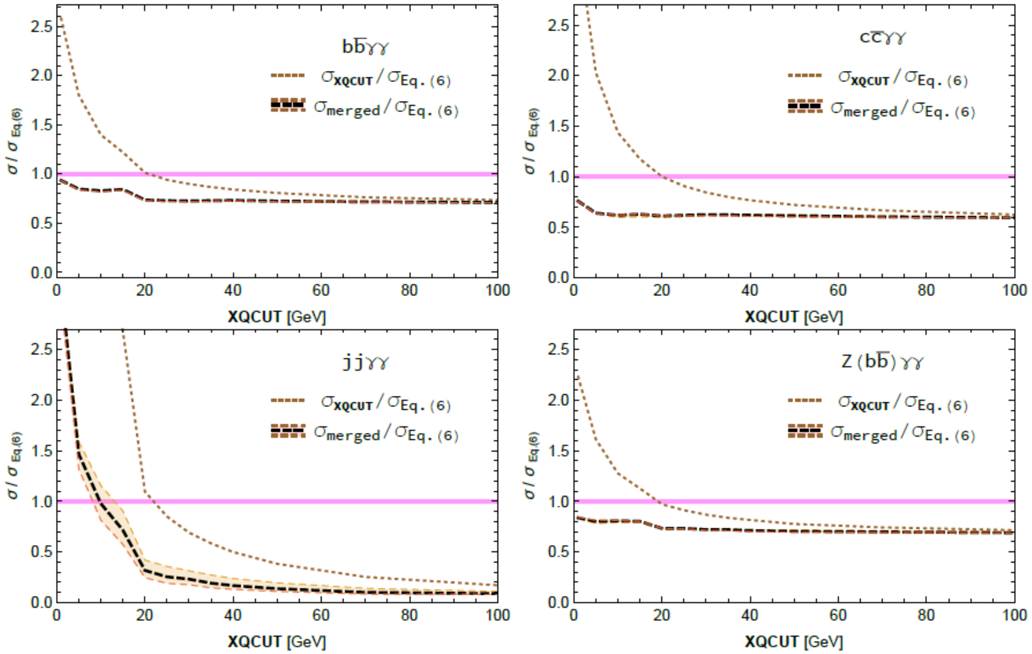
Faking Processes and rates

Background(BG)	Process	Fake Process	Fake rate
Non-resonant BG	$b\bar{b}\gamma\gamma$	N/A	N/A
	$c\bar{c}\gamma\gamma$	$c \to b,\ \bar{c} \to \bar{b}$	$(P_{c\to b})^2$
	$jj\gamma\gamma$	$c_s \to b,\ \bar{c_s} \to \bar{b}$	**1/8** $(P_{c_s \to b})^2$
	$b\bar{b}j\gamma$	$j \to \gamma$	5×10^{-4}
	$c\bar{c}j\gamma$	$c \to b,\ \bar{c} \to \bar{b},\ j \to \gamma$	$(P_{c\to b})^2 \cdot (5 \times 10^{-4})$
	$b\bar{b}jj$	$j \to \gamma,\ j \to \gamma$	$(5 \times 10^{-4})^2$
	$Z(\to b\bar{b})\gamma\gamma$	N/A	N/A
$t\bar{t}$	Leptonic decay	$e \to \gamma,\ e \to \gamma$	$(0.02)^2/0.02 \cdot 0.05/(0.05)^2$
	Semi-leptonic decay	$e \to \gamma,\ j \to \gamma$	$(0.02) \cdot 5 \times 10^{-4}/(0.05) \cdot 5 \times 10^{-4}$
$t\bar{t}\gamma$	Leptonic decay	$e \to \gamma$	$0.02/0.05$
	Semi-leptonic	$e \to \gamma$	$0.02/0.05$

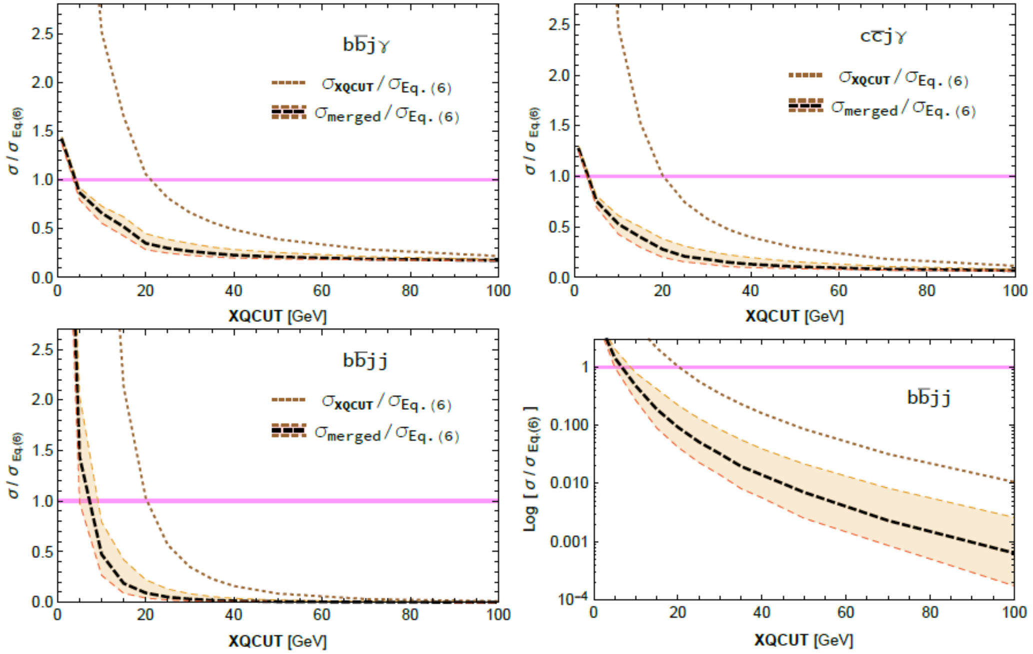
Preliminary

PDF	Cross Section [fb]	$b\bar{b}\gamma\gamma$	$c\bar{c}\gamma\gamma$	$jj\gamma\gamma$	$b\bar{b}j\gamma$	$c\bar{c}j\gamma$	$b\bar{b}jj$	$z(b\bar{b})\gamma\gamma$
CTEQ6L1	σ	140	1140	1.62×10^4	3.67×10^5	1.05×10^6	4.34×10^8	5.17
CT14LO	σ	112	1081	1.40×10^4	2.72×10^5	0.91×10^6	3.00×10^8	5.03
CT14LO	σ_{XQCUT}	113	1082	1.54×10^4	2.88×10^5	0.92×10^6	3.10×10^8	4.89
CT14LO	σ_{merged}	82.5	647	0.59×10^4	1.22×10^5	0.35×10^6	0.67×10^8	3.65
		82.3	662	0.44×10^4	0.96×10^5	0.25×10^6	0.28×10^8	3.68
		81.5	662	0.34×10^4	0.78×10^5	0.18×10^6	0.13×10^8	3.68

Preliminary



Preliminary



Understanding the process

in the effective Lagrangian

$$-\mathcal{L} = \frac{1}{3!}\left(\frac{3M_H^2}{v}\right)\lambda_{3H}\,H^3 + \frac{m_t}{v}\,\bar{t}\left(g_t^S + i\gamma_5 g_t^P\right)t\,H + \frac{1}{2}\frac{m_t}{v^2}\bar{t}\left(g_{tt}^S + i\gamma_5 g_{tt}^P\right)t\,H^2$$

★ In the SM, $\lambda_{3H} = g_t^s = 1$ and $g_{tt}^s = g_{tt}^P = 0$

SM Higgs self couplings

$$\mathcal{L} = -\frac{1}{2}m_H^2 H^2 - \frac{g_{HHH}}{3!}H^3 - \frac{g_{HHHH}}{4!}H^4$$

$$g_{HHH} = \frac{3m_H^2}{v}\,,\; g_{HHHH} = \frac{3m_H^2}{v^2}$$

In the gluon fusion process at the hadron collide

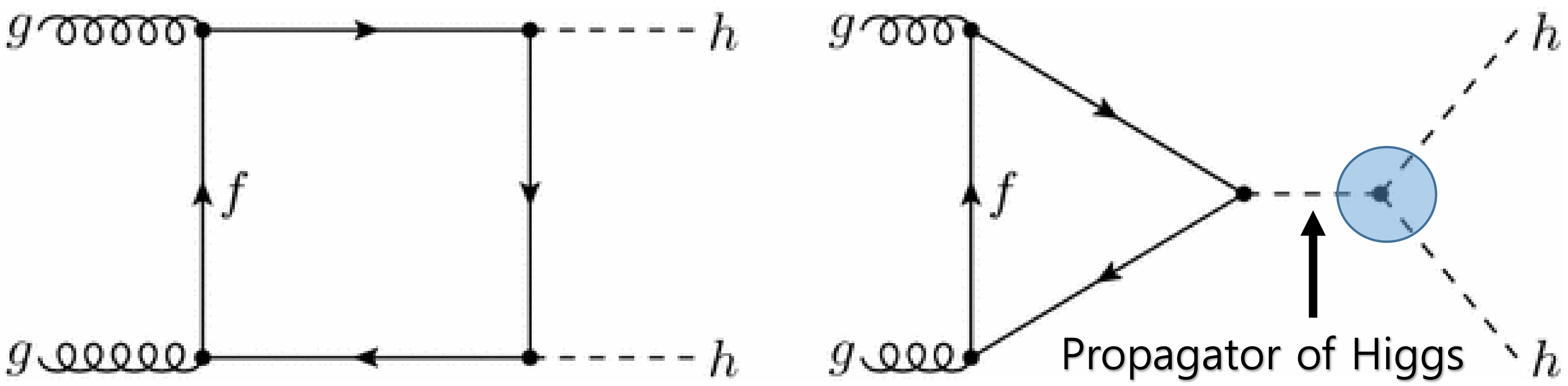
$$g(p_1)g(p_2) \to H(p_3)H(p_4)$$

The differential cross section is given by

$$\frac{d\hat{\sigma}(gg \to HH)}{d\hat{t}} = \frac{G_F^2\alpha_s^2}{512(2\pi)^3}\left[\left|\lambda_{3H}g_t^S D(\hat{s})F_\triangle^S + (g_t^S)^2 F_\square^{SS}\right|^2 + \left|(g_t^S)^2 G_\square^{SS}\right|^2\right]$$

Feynman diagrams

Only QCD Leading Order (LO)



$$D(\hat{s}) = \frac{3M_H^2}{\hat{s} - M_H^2 + iM_H\Gamma_H}$$

$$\frac{d\hat{\sigma}(gg \to HH)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left[\left| \lambda_{3H} g_t^S D(\hat{s}) F_\triangle^S + (g_t^S)^2 F_\square^{SS} \right|^2 + \left| (g_t^S)^2 G_\square^{SS} \right|^2 \right]$$

Important Interference term !!! $\leftrightarrow$ λ_{3H}^{Non-SM}

$$\frac{d\hat{\sigma}(gg \to HH)}{d\hat{t}} = \frac{G_F^2 \alpha_s^2}{512(2\pi)^3} \left[\left| \lambda_{3H} g_t^S D(\hat{s}) F_\triangle^S + (g_t^S)^2 F_\Box^{SS} \right|^2 + \left| (g_t^S)^2 G_\Box^{SS} \right|^2 \right]$$

In the heavy quark limit

$$F_\triangle^S = +\frac{2}{3} + \mathcal{O}(\hat{s}/m_Q^2)\,, \qquad F_\Box^{SS} = -\frac{2}{3} + \mathcal{O}(\hat{s}/m_Q^2)\,, \quad F_\Box^{PP} = +\frac{2}{3} + \mathcal{O}(\hat{s}/m_Q^2)$$

There is large cancellation between the triangle and box diagrams

The production cross section normalized to the corresponding SM cross section :

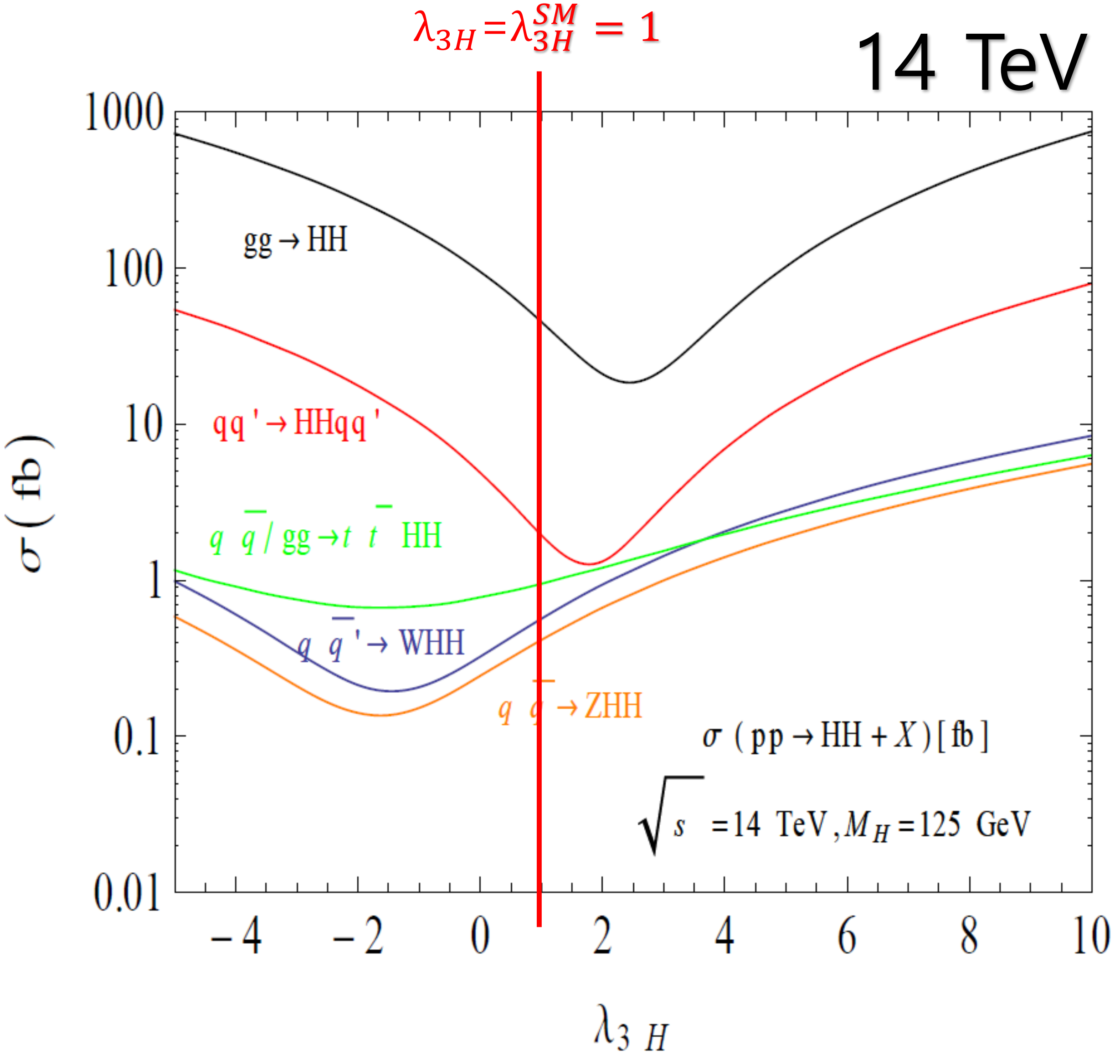
★Interference term

$$\frac{\sigma^{\rm LO}(gg \to HH)}{\sigma^{\rm LO}_{\rm SM}(gg \to HH)} = c_1(s)\,\lambda_{3H}^2\,(g_t^S)^2 + c_2(s)\,\lambda_{3H}\,(g_t^S)^3 + c_3(s)\,(g_t^S)^4$$

$c_1(s)$	$c_2(s)$	$c_3(s)$	
0.263	-1.310	2.047	14 TeV
0.208	-1.108	1.900	100 TeV

JHEP 1508(2015) 133

For the reference, there are various production modes



The gluon fusion production mode is dominant one !

(gg -> HH) = 45.05 fb,

(qq0 -> HHqq0) = 1.94 fb,

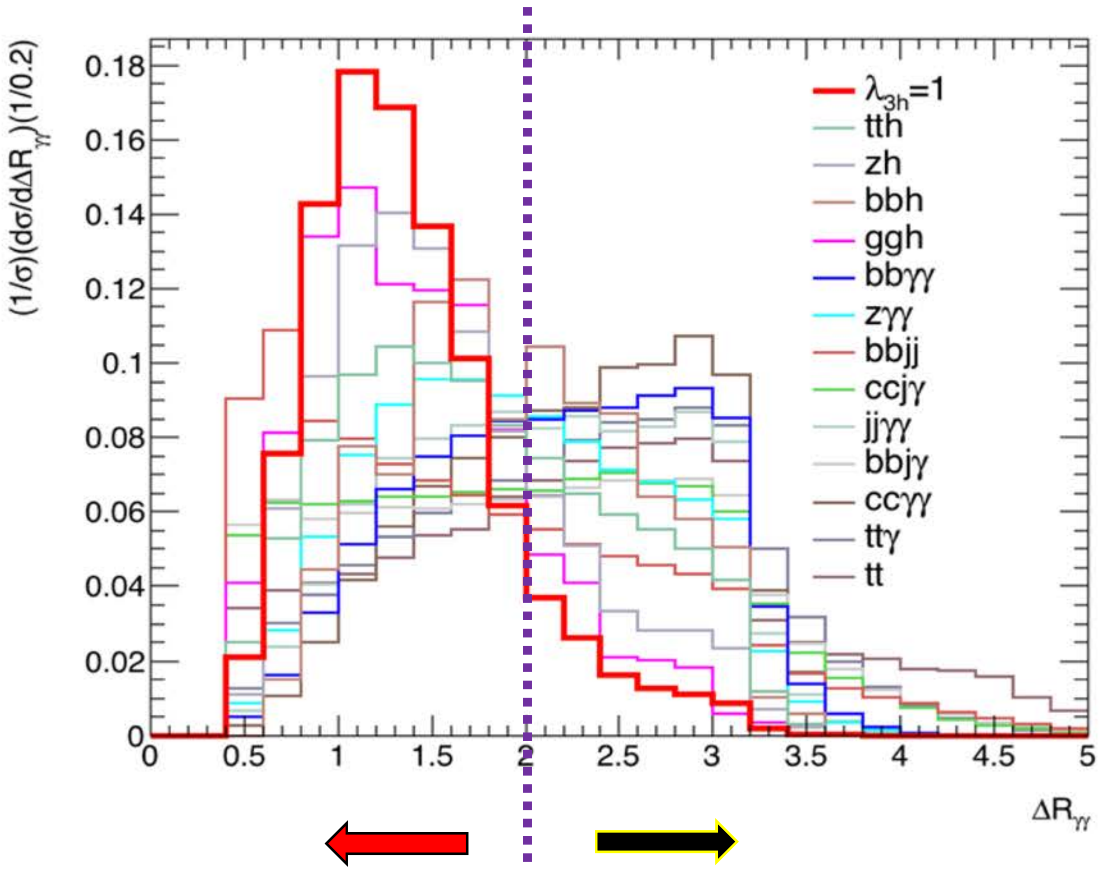
(qq(0) -> V HH =0.567(V = W) =0.415(V = Z) fb,

(gg/qq -> ttHH) = 0.949 fb

are calculated at

NNLO+NNLL, NLO, NNLO, and NLO, respectively

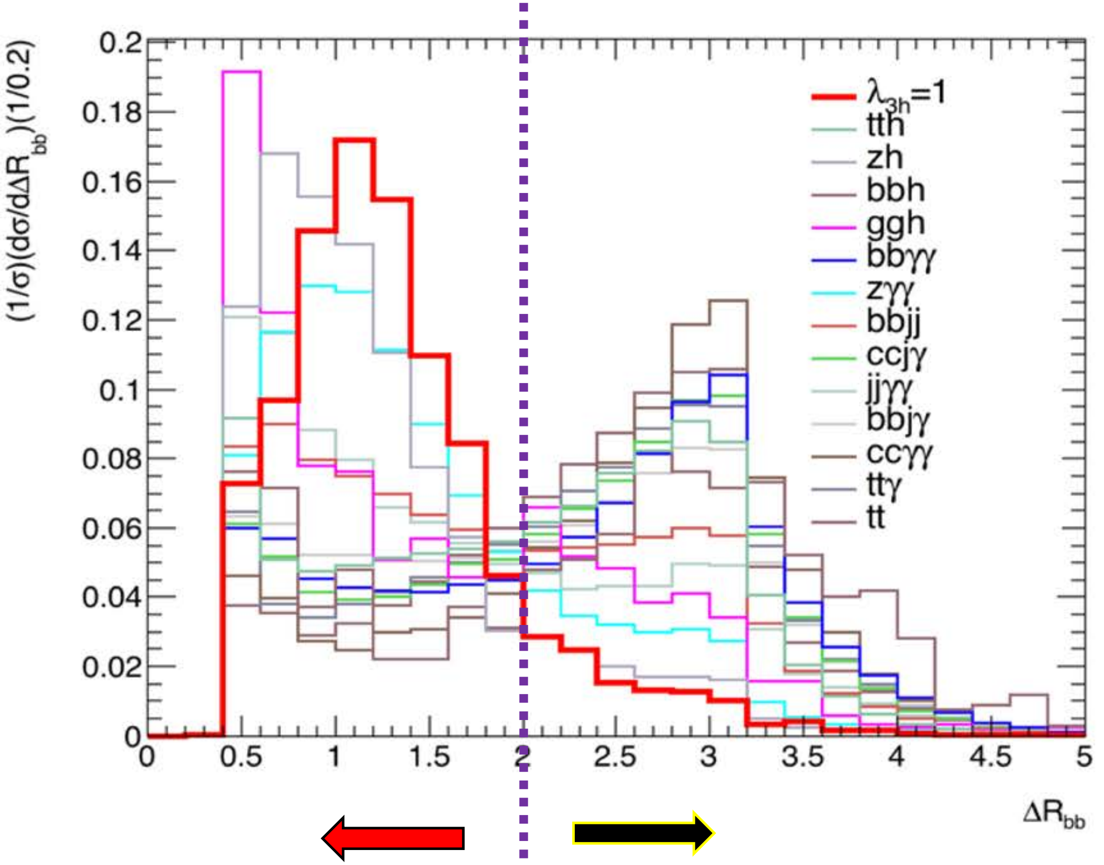
$0.4 < \Delta R_{\gamma\gamma} < 2.0$



Signal-region-like

Background-region-like

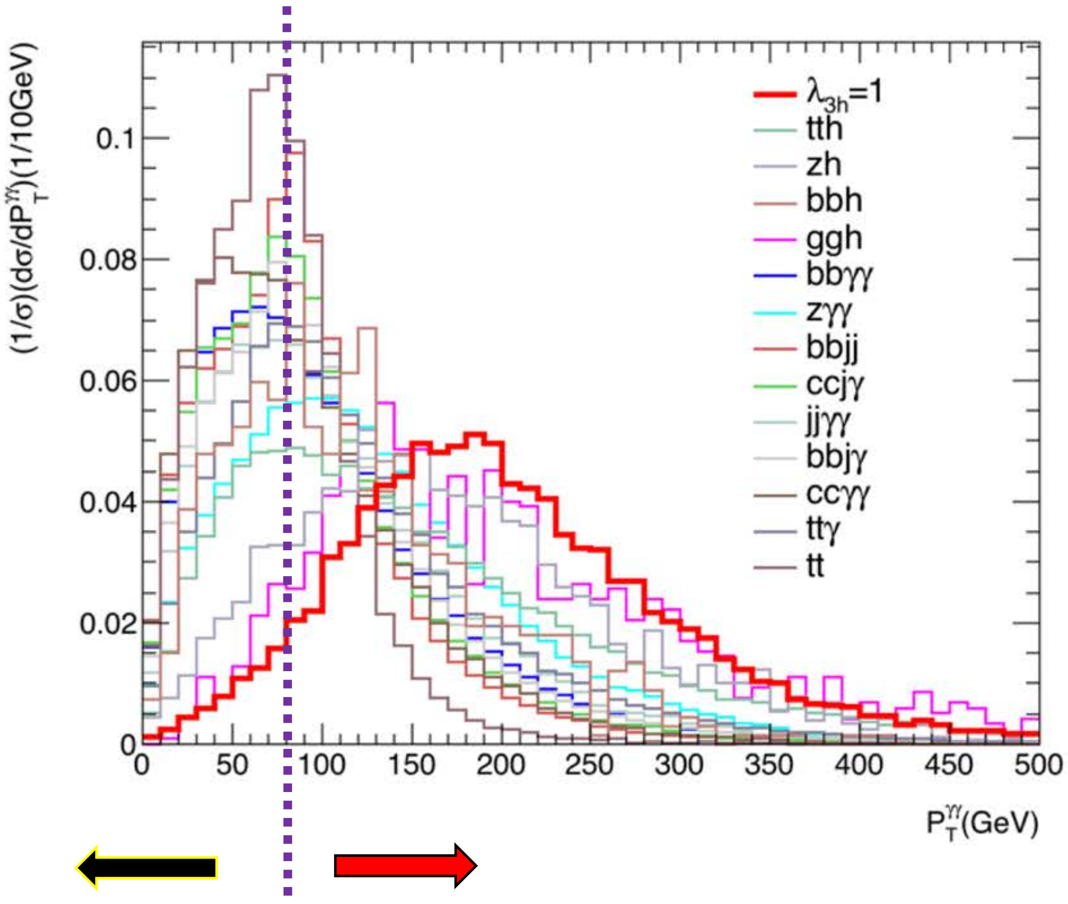
$0.4 < \Delta R_{b\bar{b}} < 2.0$



Signal-region-like

Background-region-like

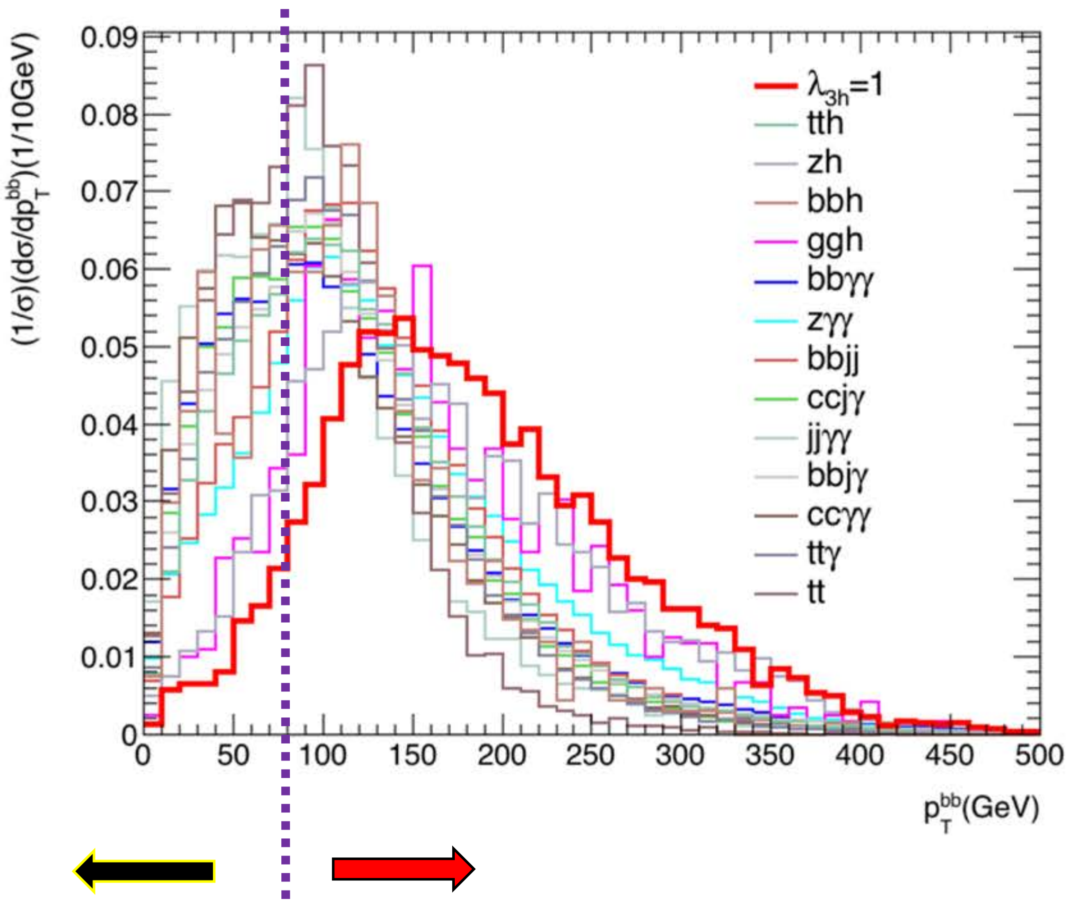
$P_T^{\gamma\gamma} > 80$ GeV



Background -region-like

Signal-region-like

$P_T^{b\bar{b}} > 80$ GeV



Background -region-like

Signal-region-like

Machine Learning approaches to the Higgs boson self coupling

① BDT(Boosted Decision Tree) : bbYY

1. Phys.Rev. D96 (2017) no.3, 035022 (Alves, Alexandre et al.) arXiv:1704.07395 [hep-ph]

BDT + kinematic cuts → 5 σ (4.6 σ) significance with 10 %(20%) systematics and 3 ab^-1

② (Supervising) Deep Neural Networks (DNN) : bbWW + bbττ

1. "Supervising Deep Neural Networks with topological augmentation in search for di-Higgs production at the LHC (Dr. Won Sang Cho)

   5 classes by the number of leptonic taus

   Optimass & its compatibility distance with dim. Of vars ~ 40

→ AUC of ROC = 0.991

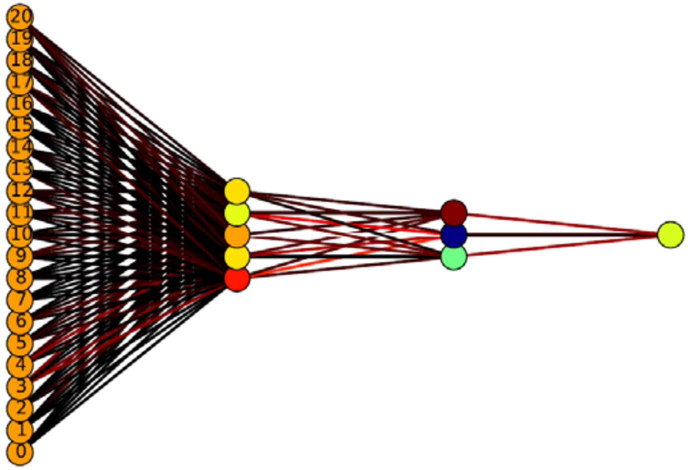
Eff(sig) @(Background purity=0.01) = 0.84

Machine Learning approaches to the Higgs boson self coupling

③ DNN (ANN : a multi-layer feed-forward artificial neural network) : bbbb

1. Eur. Phys. J. C (2016) 76:386 (Katharina Behr, Bortoletto et al.) arXiv:1512.08928 [hep-ph]

DNN + kinematic cuts → $\frac{S}{\sqrt{B}} \sim$ 3 σ significance with 3 ab^-1



Summary Table

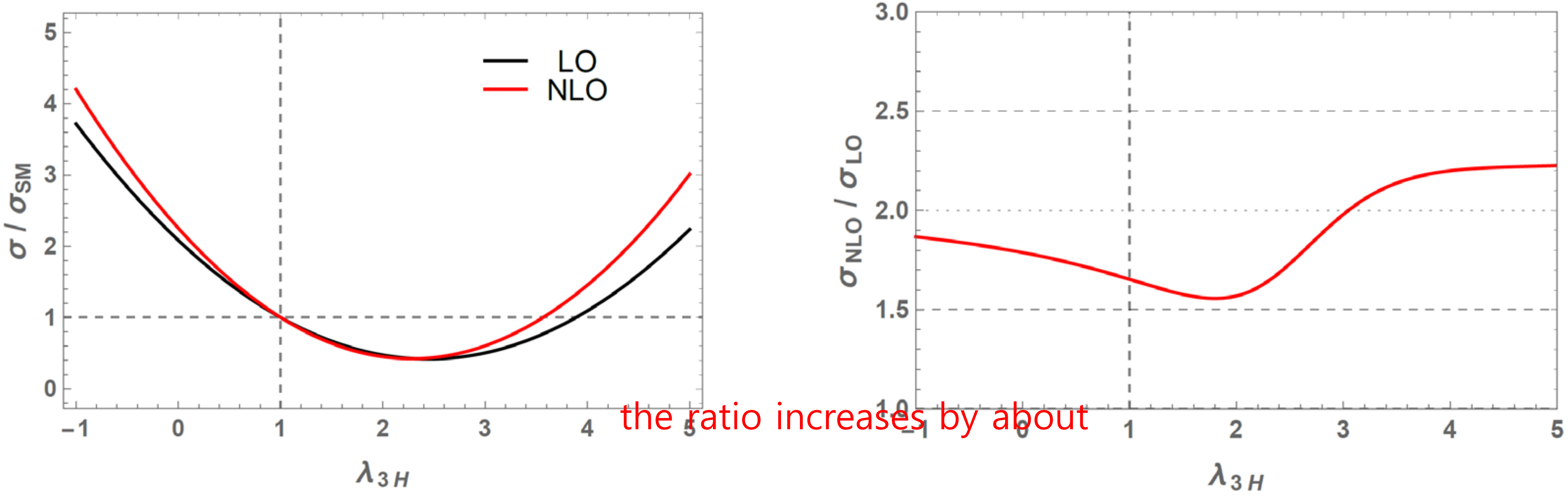
Channel	Achievable Significance (σ)	Methods	Papers	Remarks
bbbb	~ 3	Kinematic Cuts+ DNN	Eur. Phys. J. C (2016) 76:386	HL-LHC (3 ab^-1)
	~ (3.1 ~ 5.7)	DNN DNN	Prof. Park's work Arxiv: 1609.002541	100 TeV FCC (10 ab^-1) HL-LHC (3 ab^-1)
bbWW			Dr. Won Sang Cho's work	
bbττ				
WWWW				
bbYY	~ 5 (4.6)	Kinematic Cuts + BDT	Phys.Rev. D96 (2017) no.3, 035022	HL-LHC (3 ab^-1),
	~ 2.1	Kinematic Cuts + BDT	Preliminary	With full BGs.
bbZZ(eemm)				

Summary Table

Channel	Achievable Significance (σ)	Methods	Papers	Remarks
bbbb	~ 3	Kinematic Cuts+ DNN	Eur. Phys. J. C (2016) 76:386	HL-LHC (3 ab^-1)
bbWW	~ (3.1 ~ 5.7)	DNN DNN	Prof. Park's Work Arxiv: 1609.002541 Dr. Won Sang Cho's Work	100 TeV FCC (10 ab^-1) HL-LHC (3 ab^-1)
bbττ				
WWWW				
bbYY	~ 5 (4.6)	Kinematic Cuts + BDT	Phys.Rev. D96 (2017) no.3, 035022	HL-LHC (3 ab^-1),
	~ 2.1	Kinematic Cuts + BDT	Preriminary	With full BGs.
bbZZ(eemm)				

Summary Table

Channel	Achievable Significance (σ)	Methods	Papers	Remarks
bbbb	~ 3	Kinematic Cuts+ DNN	Eur. Phys. J. C (2016) 76:386	HL-LHC (3 ab^-1)
	~ (3.1 ~ 5.7)	DNN DNN	Prof. Park's talk today morning Arxiv: 1609.002541	100 TeV FCC (10 ab^-1) HL-LHC (3 ab^-1)
bbWW			Next Dr. Won Sang Cho talk	
bbττ				
WWWW				
bbYY	~ 5 (4.6)	Kinematic Cuts + BDT	Phys.Rev. D96 (2017) no.3, 035022	HL-LHC (3 ab^-1),
	~ 2.1	Kinematic Cuts + BDT	Preriminary	With full BGs.
bbZZ(eemm)				

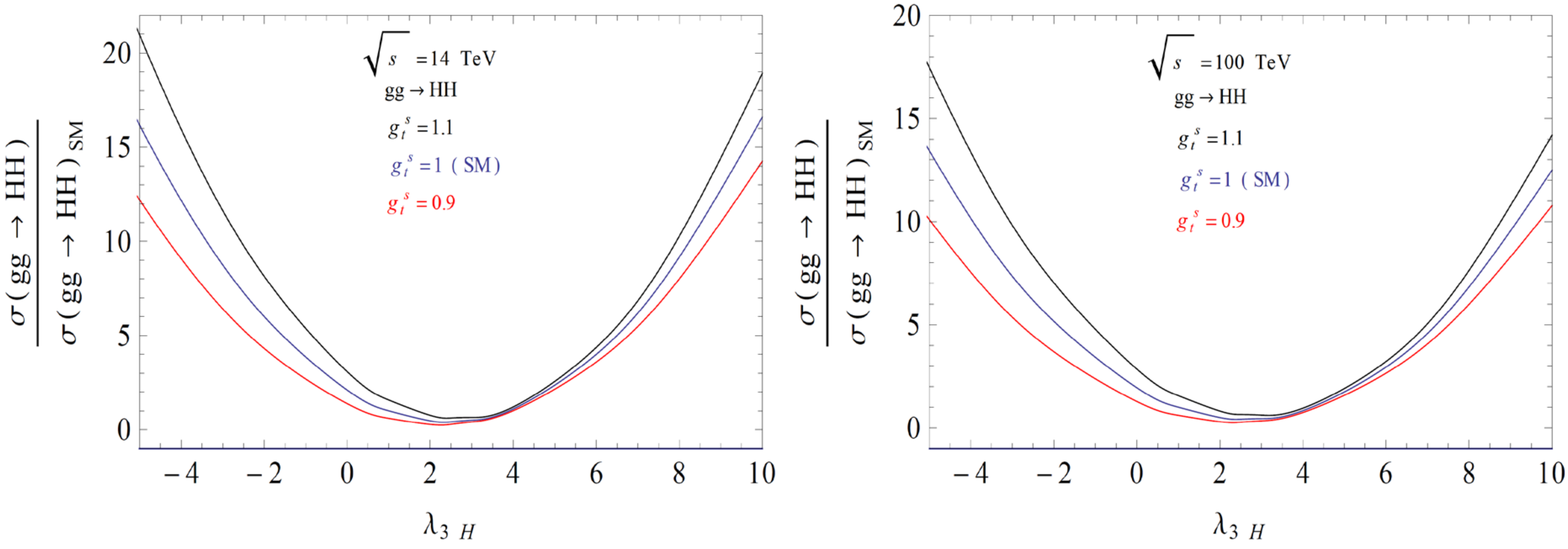


the ratio increases by about

The ratio increases by about 10 (35) % at λ_{3H} =-1 (5) !

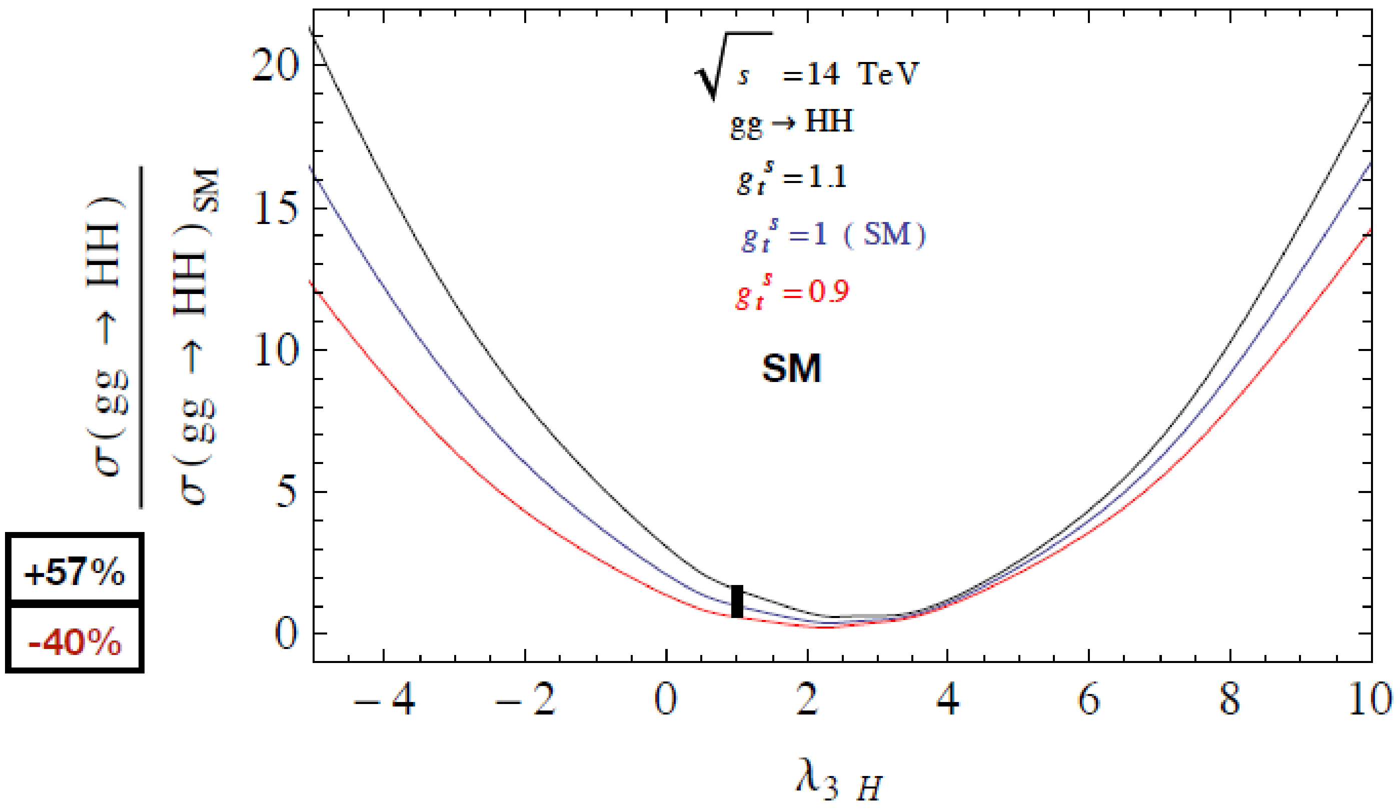
It is clear that the QCD corrections are less significant than the uncertainties associated with the top-Yukawa coupling.

About top Yukawa uncertainty !



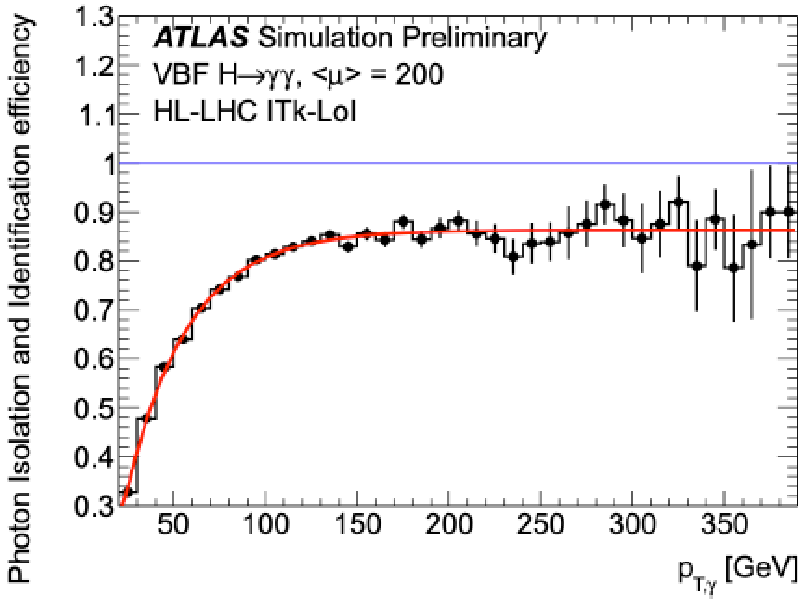
Ratio of cross sections (gg -> HH)=(gg -> HH)SM versus 3H taking account of 10% uncertainty of the top-Yukawa coupling: gSt = 1:1 (black), 1 (blue), and 0:9 (red) for sqrt(s) = 14 TeV (left) and sqrt(s) = 100 TeV (right).

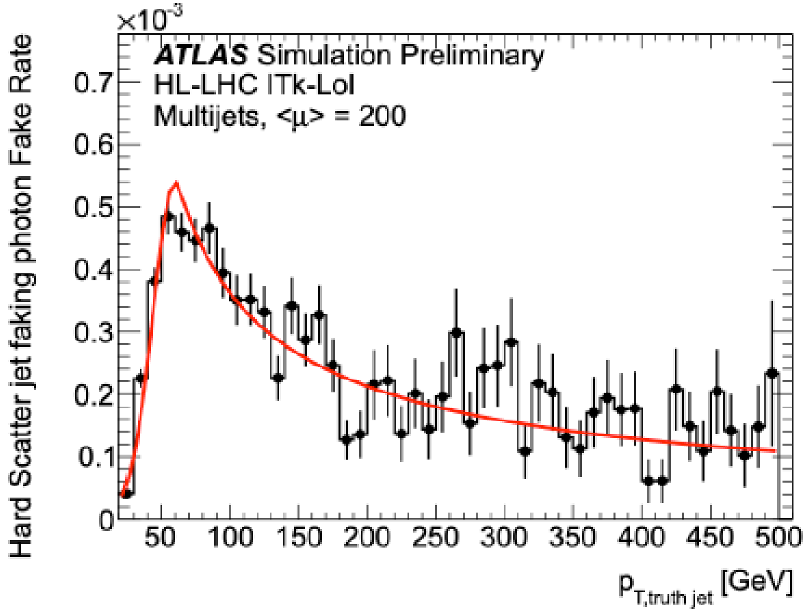
Y_t precision measurement



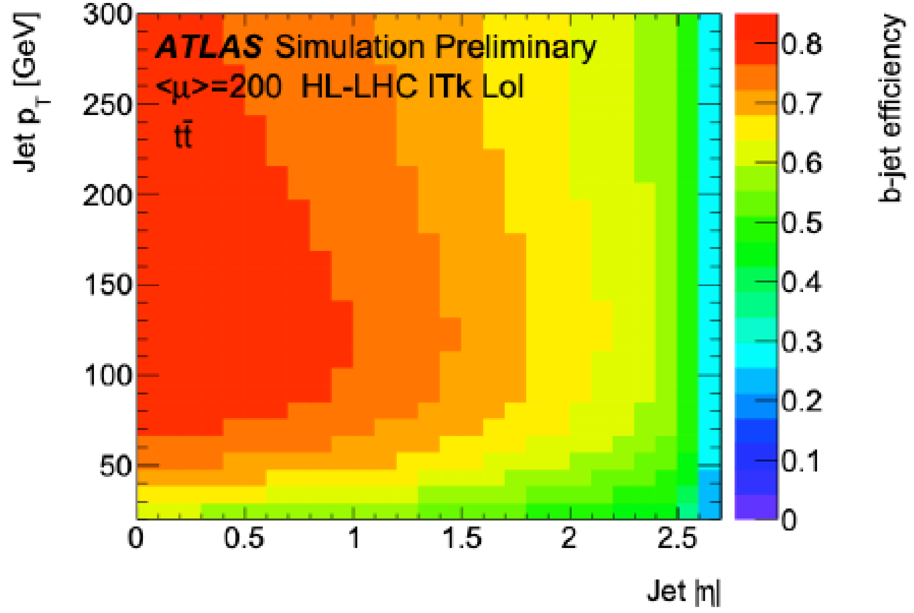
At the HL-LHC, the expected precision of measurement of the top-quark Yukawa coupling (Yt) is 10%.

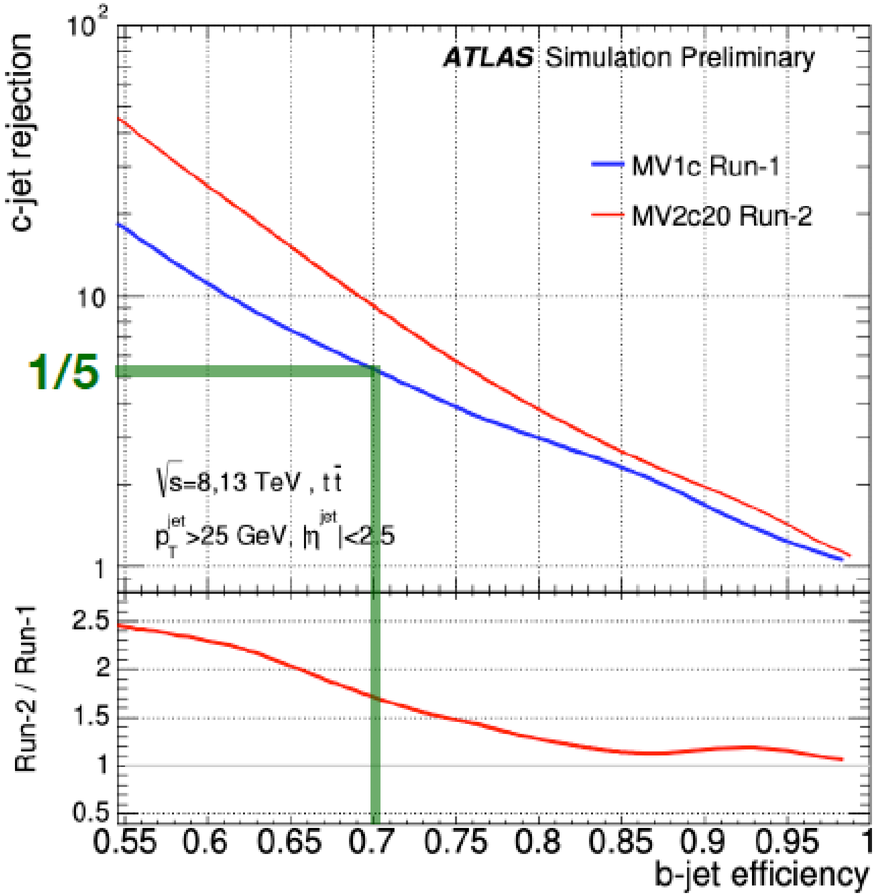
M. Vos, arXiv:1701.06537 [hep-ex].



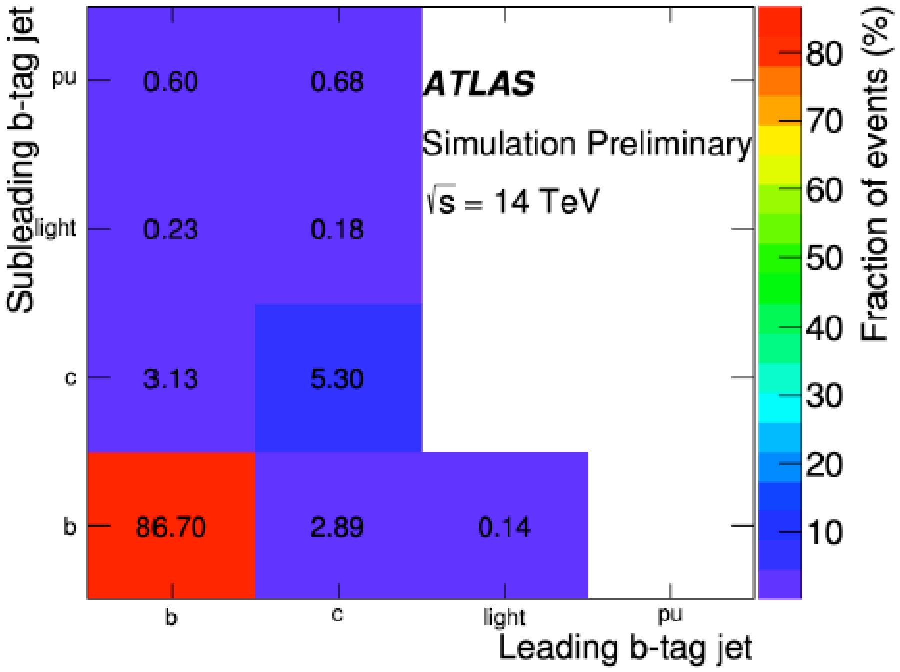


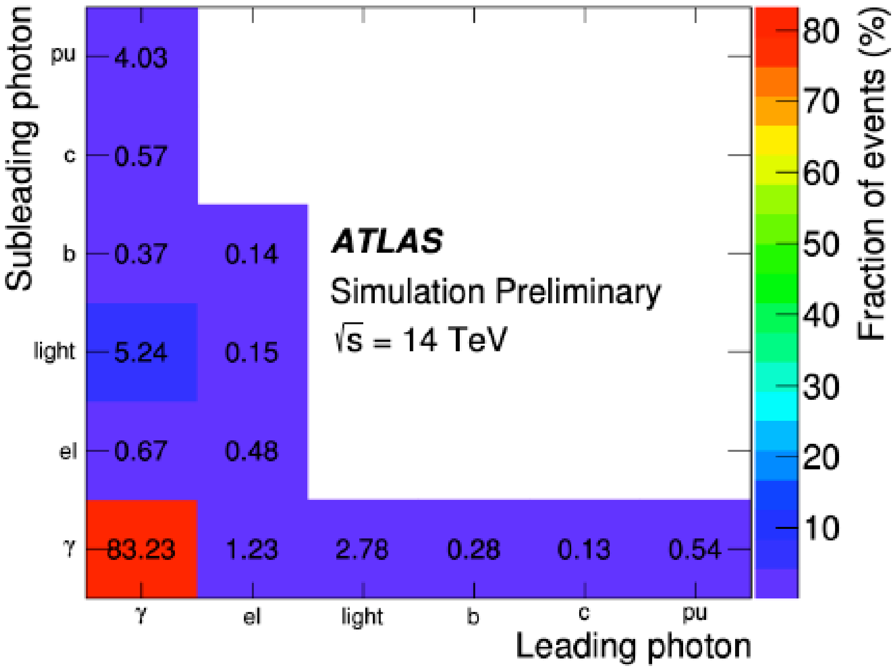
ATLAS Collaboration, ATL-PHYS-PUB-2016-026





ATLAS Collaboration, ATL-PHYS-PUB-2016-026(Left), ATL-PHYS-PUB-2015-022(Right)





ATLAS Collaboration, ATL-PHYS-PUB-2017-001

- Rectangular cut optimisation (binary splits, Sec. 8.1).
- Projective likelihood estimation (Sec. 8.2).
- Multi-dimensional likelihood estimation (PDE range-search – Sec. 8.3, PDE-Foam – Sec. 8.4, and k-NN – Sec. 8.5).
- Linear and nonlinear discriminant analysis (H-Matrix – Sec. 8.6, Fisher – Sec. 8.7, LD – Sec. 8.8, FDA – Sec. 8.9).
- Artificial neural networks (three different multilayer perceptron implementations – Sec. 8.10).
- Support vector machine (Sec. 8.12). • Boosted/bagged decision trees (Sec. 8.13).
- Predictive learning via rule ensembles (RuleFit, Sec. 8.14).
- A generic boost classifier allowing one to boost any of the above classifiers (Sec. 10).
- A generic category classifier allowing one to split the training data into disjoint categories with independent MVAs.