25th International Summer Institute on
Phenomenology of Elementary Particles and Cosmology

Probing Trilinear Higgs Self–coupling at the HL-LHC via Multivariate Analysis

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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. Probing Trilinear Higgs Self–coupling at the HL-LHC via Multivariate Analysis **(Arxiv:1908.00753)**

ML : (from SI 2019)

1. Tagging boosted weak gauge bosons with deep learning **– Prof. Cheng-Wei Chiang**

2. A New Architecture of Classification Model with the Abstraction of Physical Symmetry, **- Kayoung Ban**

3. Portraying Double Higgs at the LHC **– Minho Kim** **(bbWW dilepton channel)**

4. Complex-valued Neural Arithmetic Logic Units (CALU) for the Abtraction of Physical Symmetries - **Dr. Won Sang Cho**

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

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

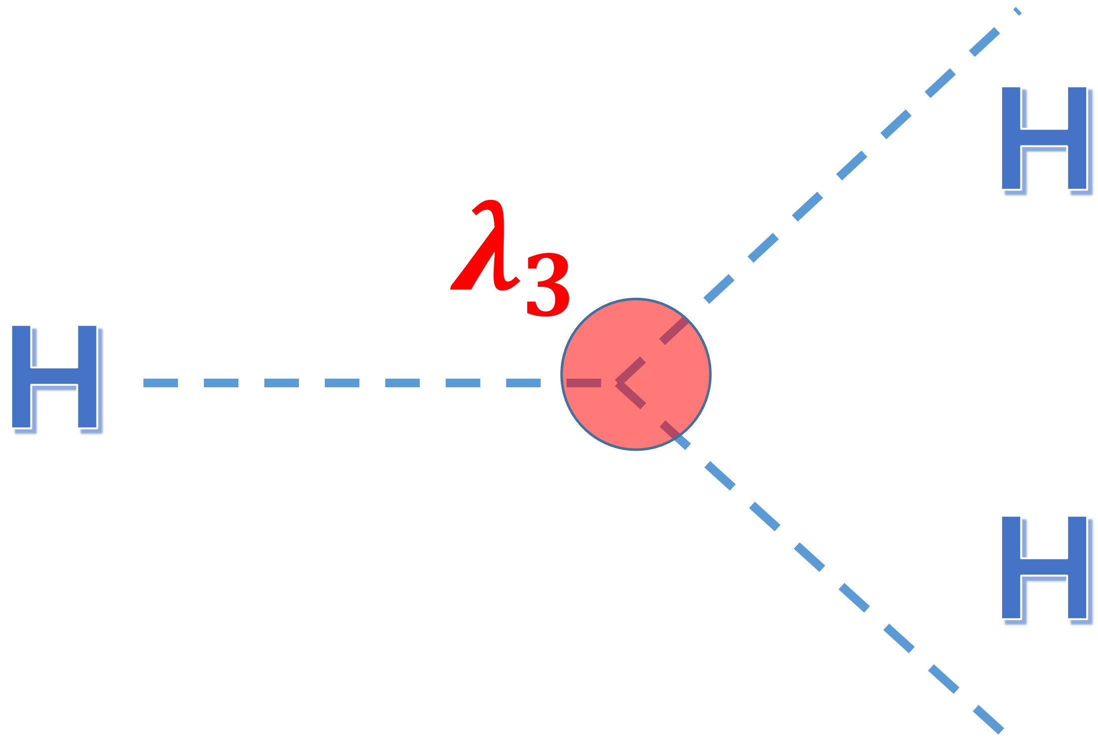
New Physics can affect the Higgs potential form

⟹ 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

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



Therefore,
it is really important to check (or directly measure) this trilinear Higgs coupling λ_3 to verify that SM is correct.

So, how to probe it ?

Higgs pair production !

We now focus on

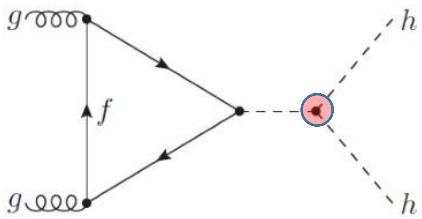
Higgs pair production

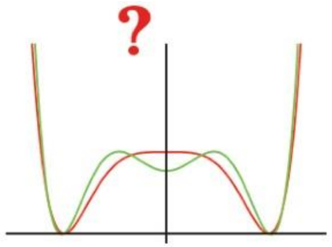
at the **Hadron collider**

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

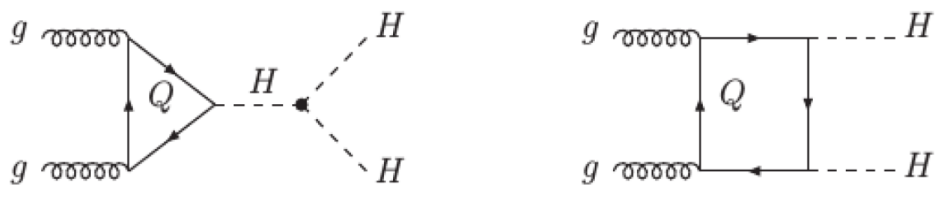
may reveal the doublet nature of the Higgs by means of the hhVV coupling

$\therefore$ A high priority goal on the physics program at the future collider

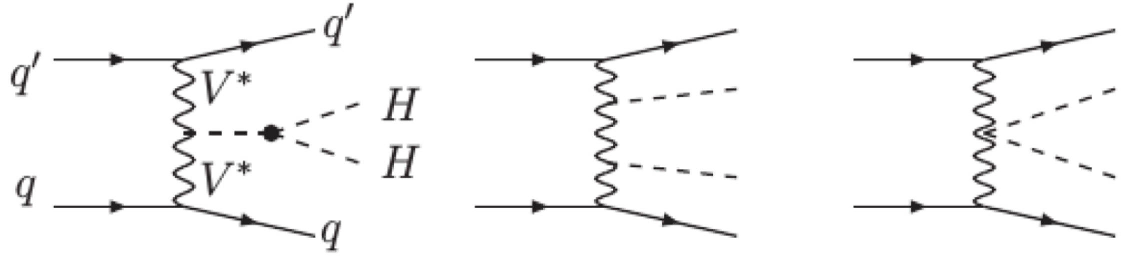
Higgs pair productions at the LHC

Production modes

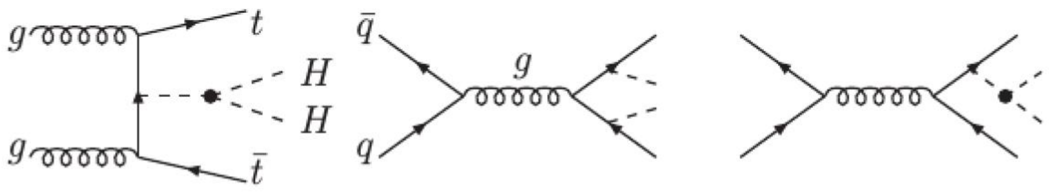
Gluon Fusion



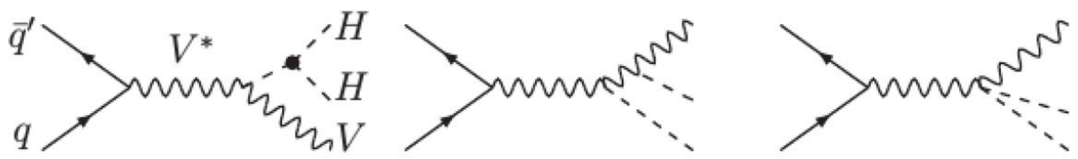
Vector Boson Fusion



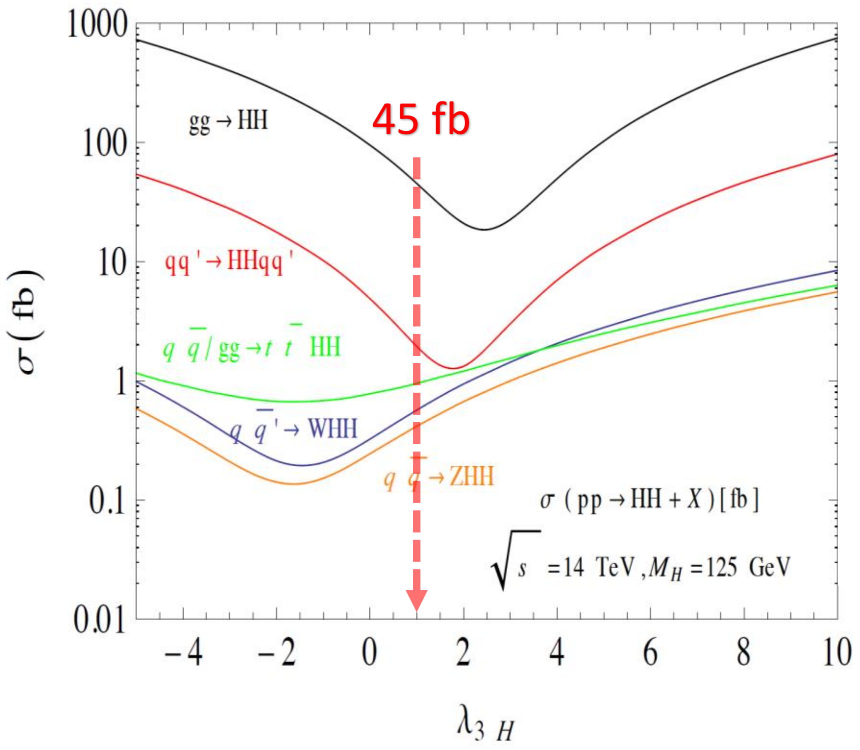
Top associated productions

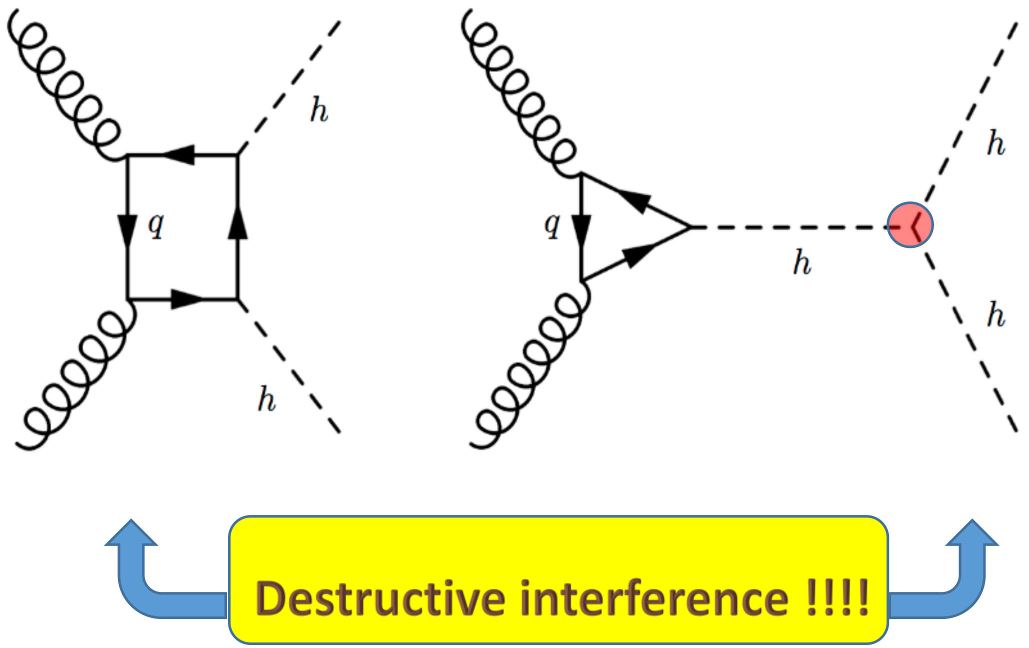


Higgs strahlung



Why **Higgs pair production** so difficult ?





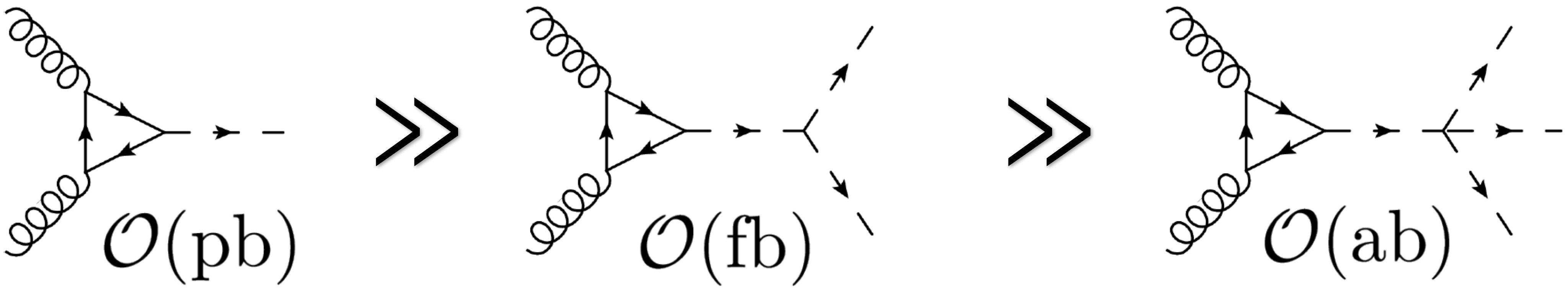
In the leading gluon fusion production mode,
the cross section at 14 TeV is only 45 fb (in the SM),
further suppressed by each decay branching fractions.

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

Direct access to Higgs self-couplings

→ Multi-Higgs production !!!!

However,



Experimentally very challenging !!

So, at the HL-LHC

Higgs pair production
(Double Higgs production)
Challenging !!!

Triple Higgs production
Impossible !!!

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**	$\cdots$

Recent updates

Signal				
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

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	$t\bar{t}$	POWHEG − BOX/PYTHIA8	5.30×10^5	NNLO +NNLL	CT10
(≥ 1 lepton)	$t\bar{t}\gamma$	MG5_aMC@NLO/PYTHIA8	1.60×10^3	NLO	CTEQ6L1

- 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
- Use of the latest multivariate analysis using Toolkit for Multivariate Data Analysis (TMVA) with ROOTv6.18

Analysis Methods

- **Cut Based Analysis**

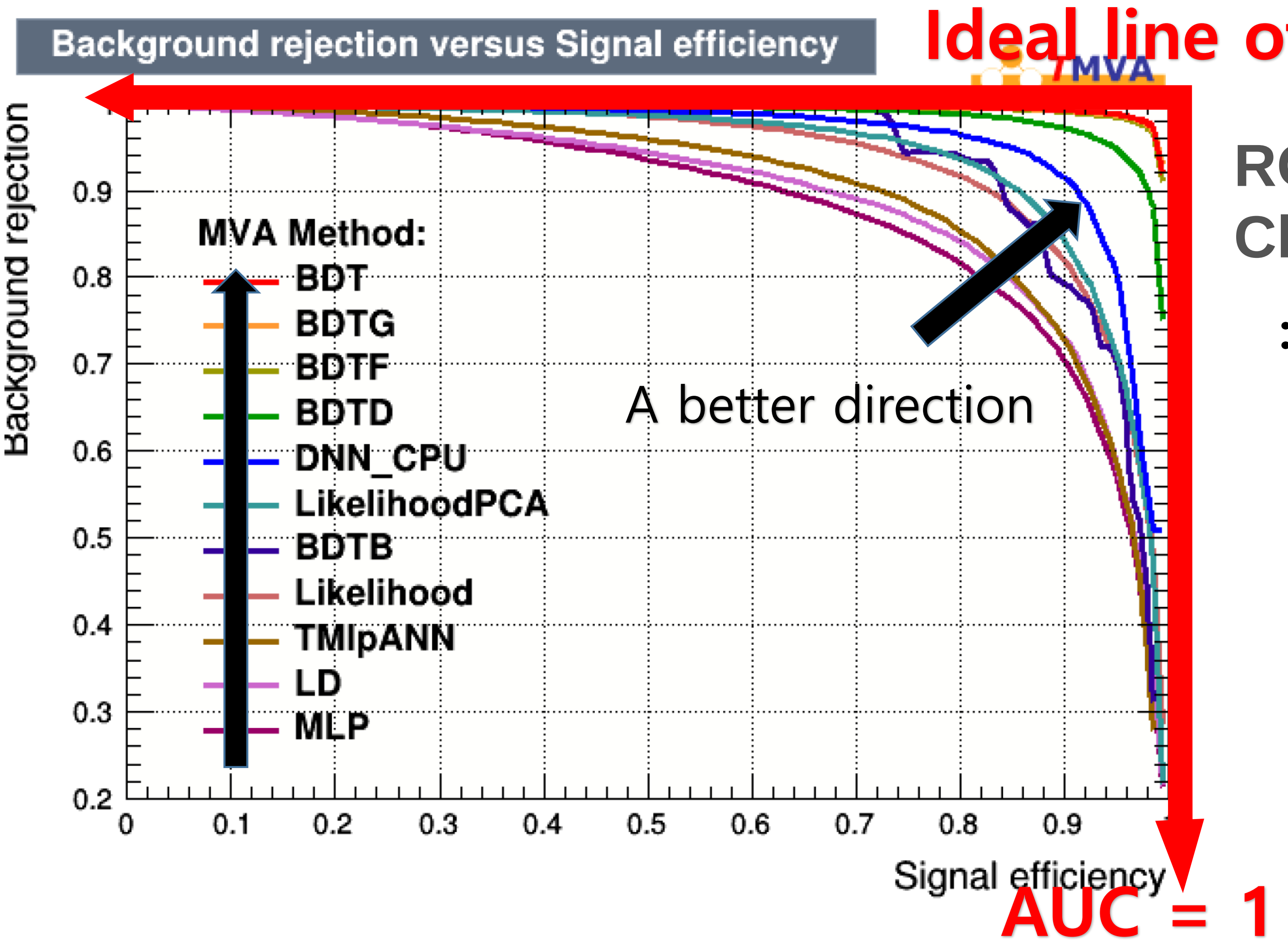
- **Machine Learning**

  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

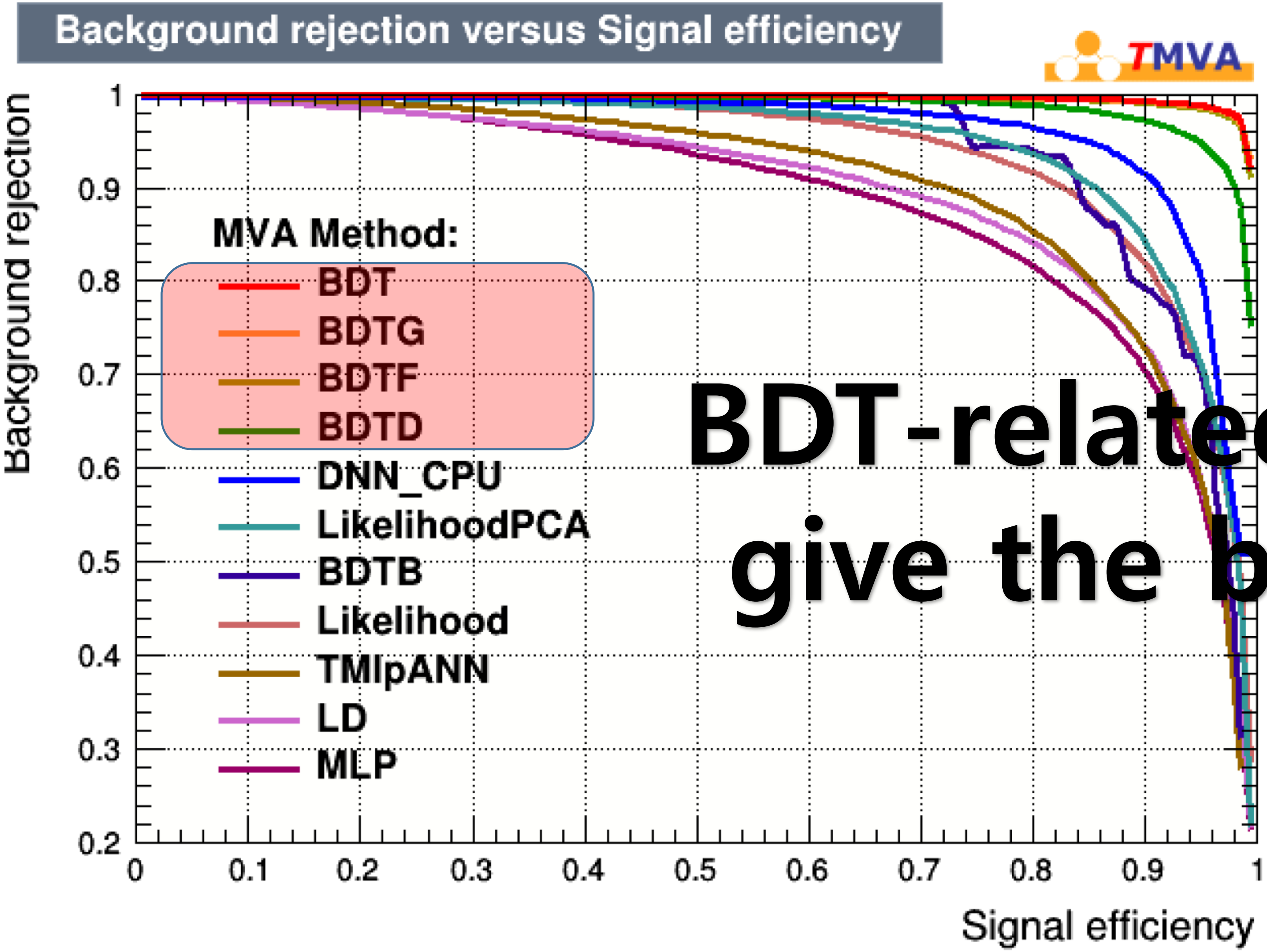
Various ML methods in TMVA



ROC = Receiver Operating Characteristic curve

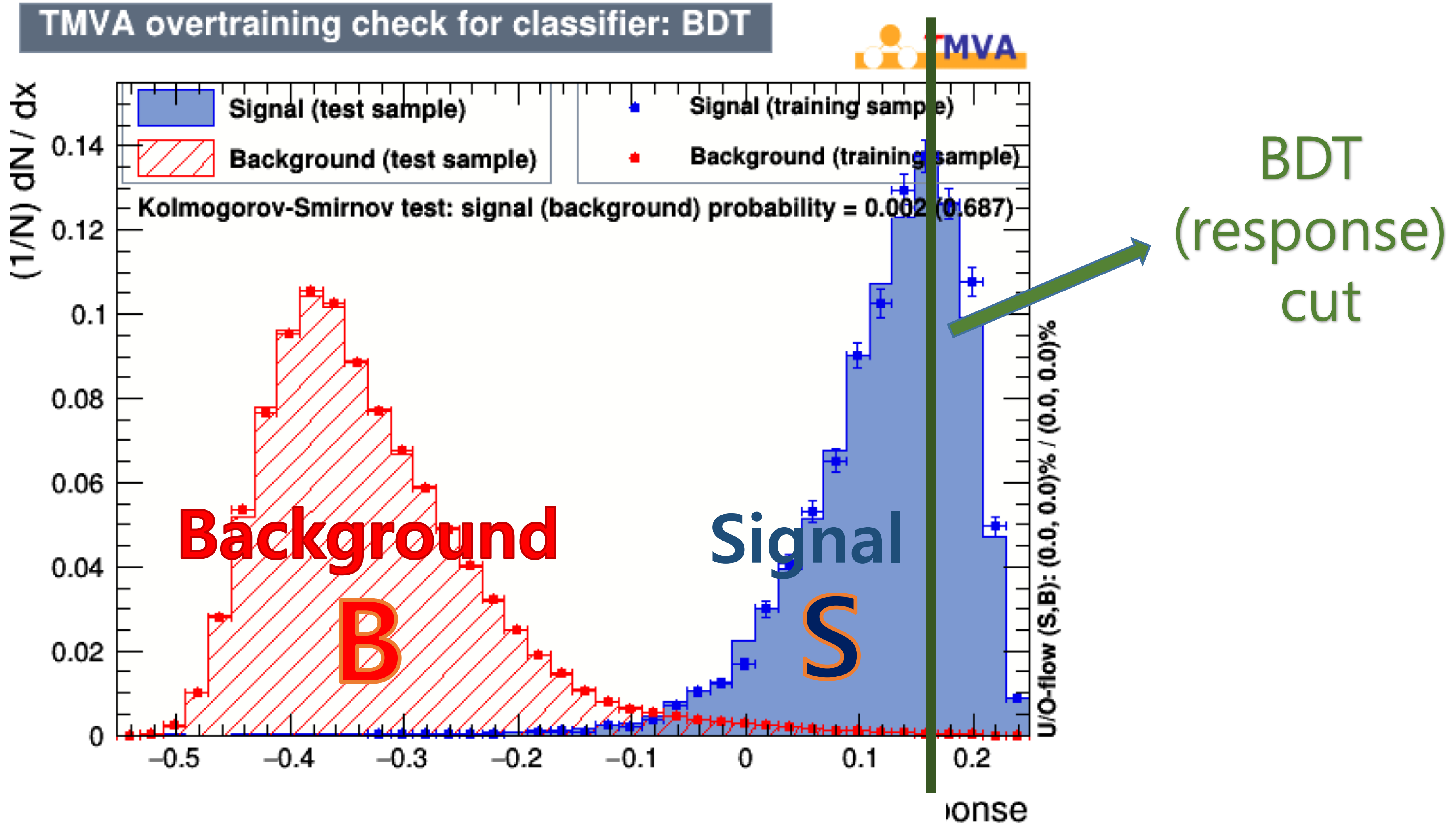
: a good way to illustrate the performance of given classifier

AUC = Area under the ROC curve

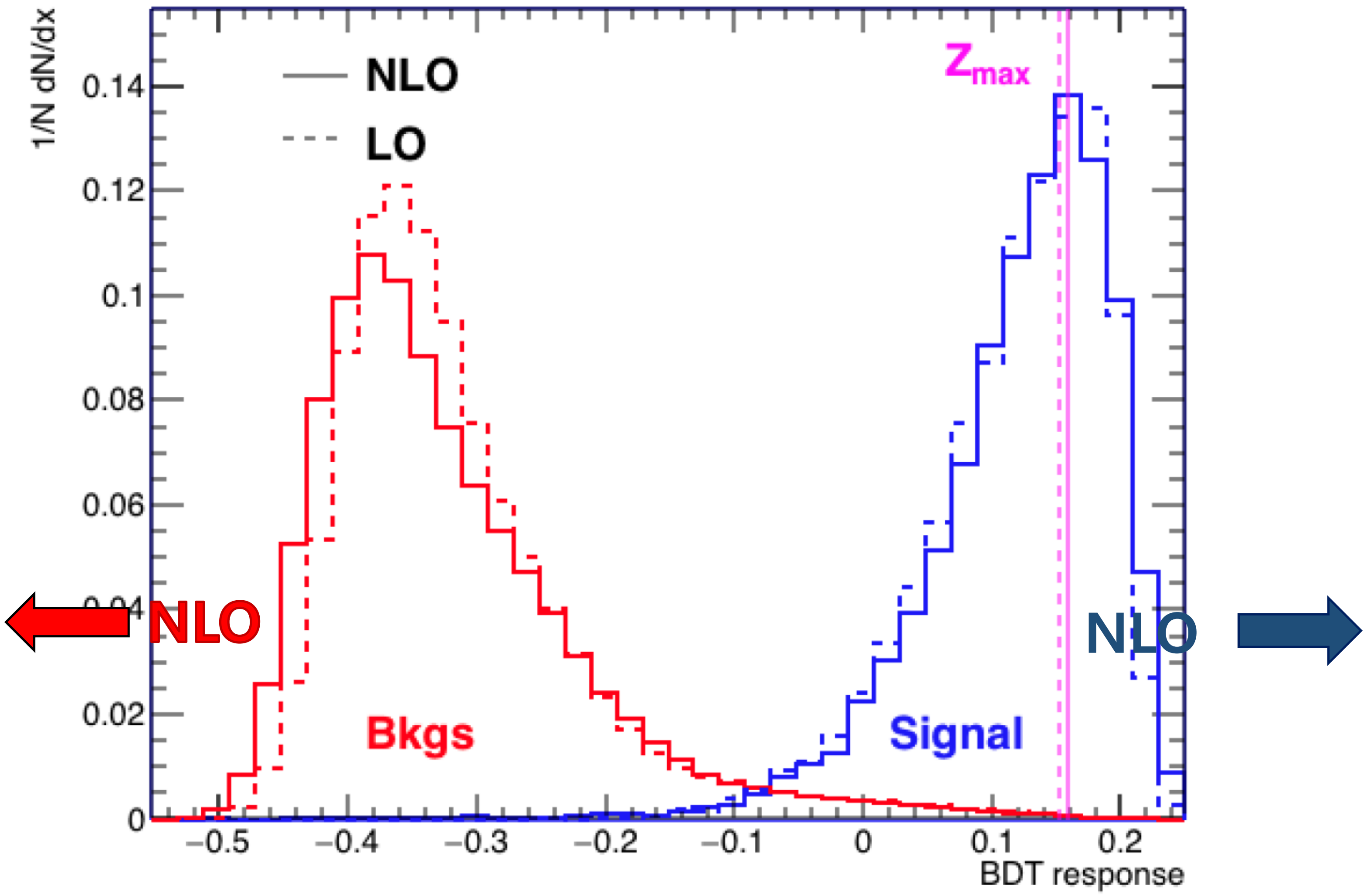


BDT-related methods give the best results

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



Impact of NLO kinematic distributions



Results : Improved Expected Yields and Significance(Z)

	Expected yields (3000 fb^{-1})		
Signal and Backgrounds	Pre-Selection	BDT$_{\rm SM}$	Cut-and-Count
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = -5$	223.22	49.36	90.19
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 0$	33.69	10.22	16.70
$\mathbf{H(b\bar{b})\,H(\gamma\gamma)}$, $\boldsymbol{\lambda_{3H} = 1}$	**17.77**	**6.19**	**9.63**
$H(b\bar{b})\,H(\gamma\gamma)$, $\lambda_{3H} = 5$	26.37	2.76	6.77
$gg\,H(\gamma\gamma)$	68.76	1.92	6.6
$t\bar{t}\,H(\gamma\gamma)$	158.14	3.26	13.21
$Z\,H(\gamma\gamma)$	23.89	1.28	3.62
$b\bar{b}\,H(\gamma\gamma)$	2.52	0.08	0.15
$b\bar{b}\gamma\gamma$	6968.37	2.69	15.09
$c\bar{c}\gamma\gamma$	7051.90	1.30	7.13
$jj\gamma\gamma$	1015.48	0.66	2.89
$b\bar{b}j\gamma$	10018.32	0.82	13.91
$c\bar{c}j\gamma$	4679.49	0.82	4.78
$b\bar{b}jj$	2525.67	0.36	3.42
$Z(b\bar{b})\gamma\gamma$	184.09	0.15	0.88
$t\bar{t}$ ($\geq$ 1 leptons)	5433.74	0.22	4.98
$t\bar{t}\gamma$ ($\geq$ 1 leptons)	1916.50	0.49	3.61
Total Background	40046.87	14.04	80.26
Significance Z, $\lambda_{3H} = 1$		**1.55**	**1.05**

C&C

of signal = 9.63

# of bg = 80.26

∴ significance Z = 1.05

BDT_{SM}

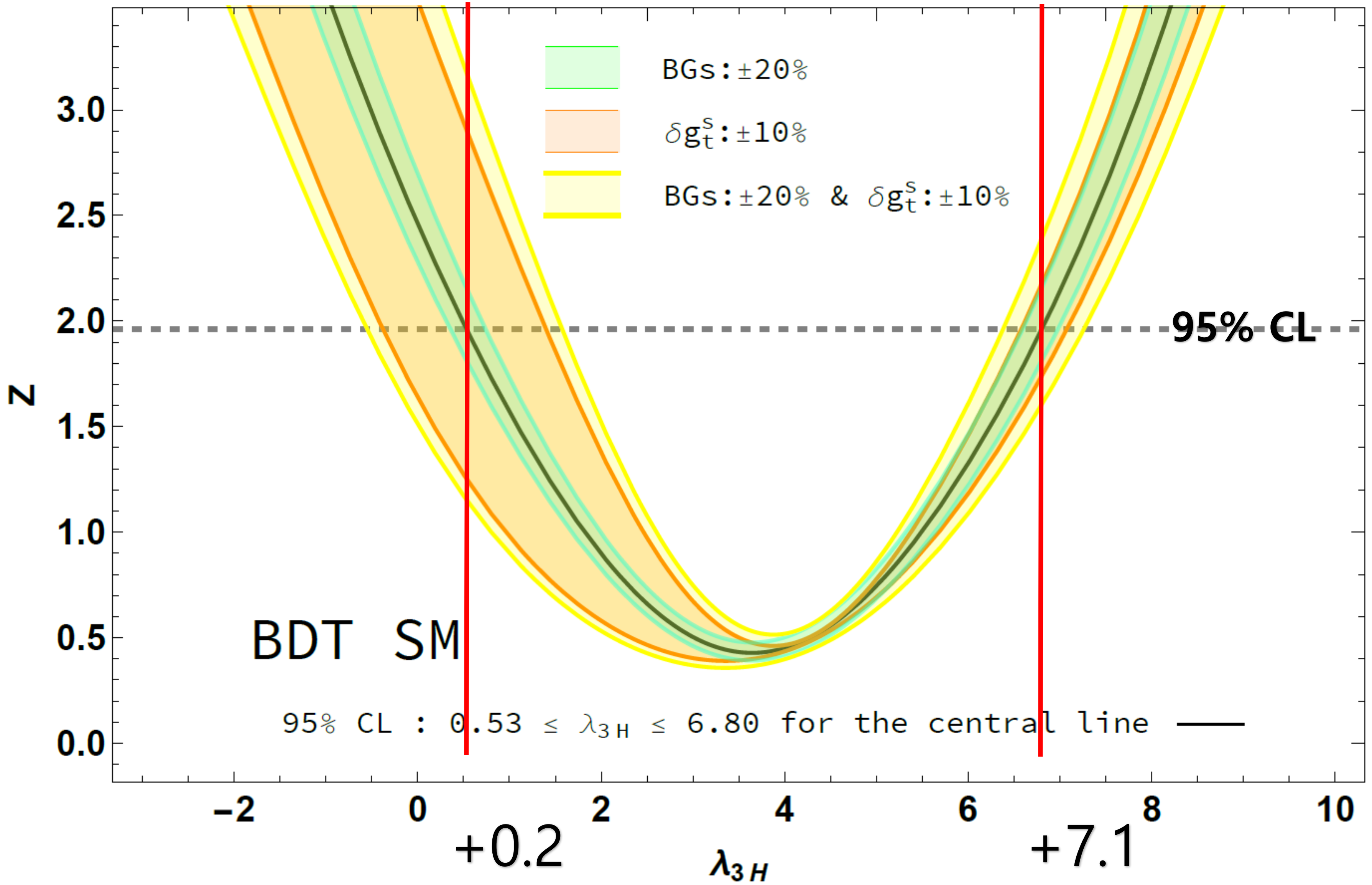
of signal = 6.19

# of bg = 14.04

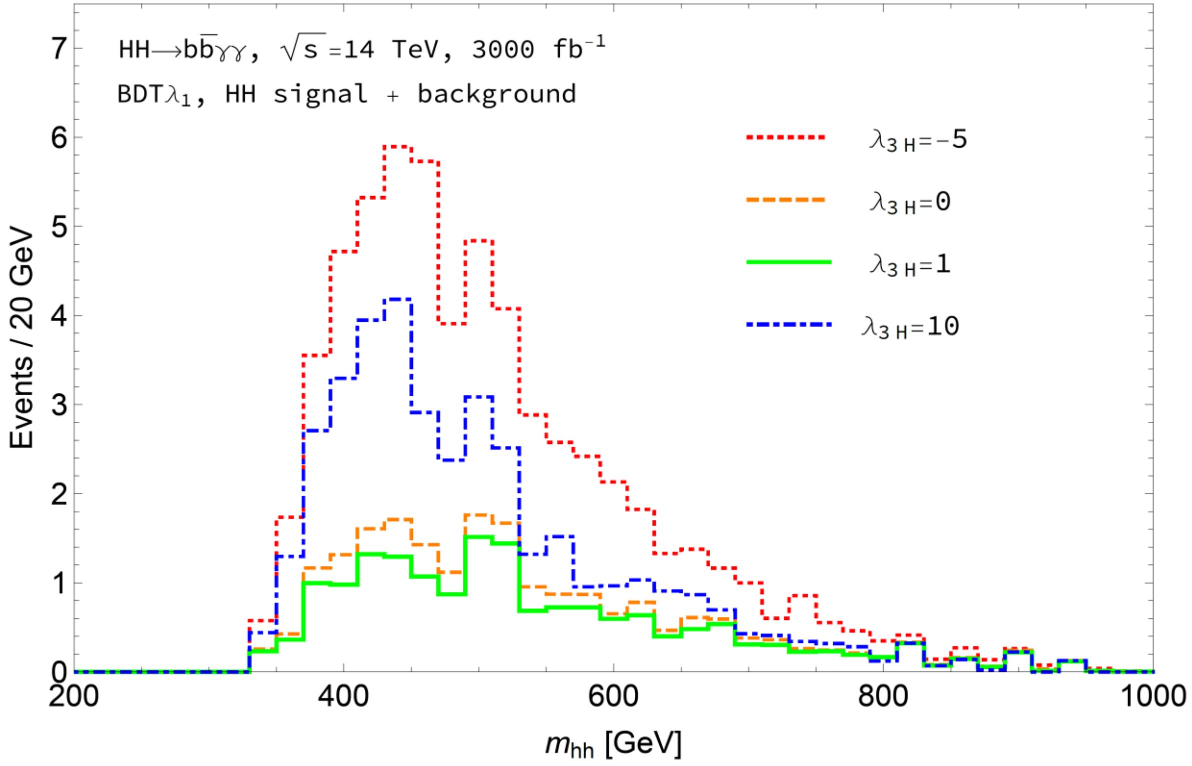
∴ BDT-improved Z = 1.55

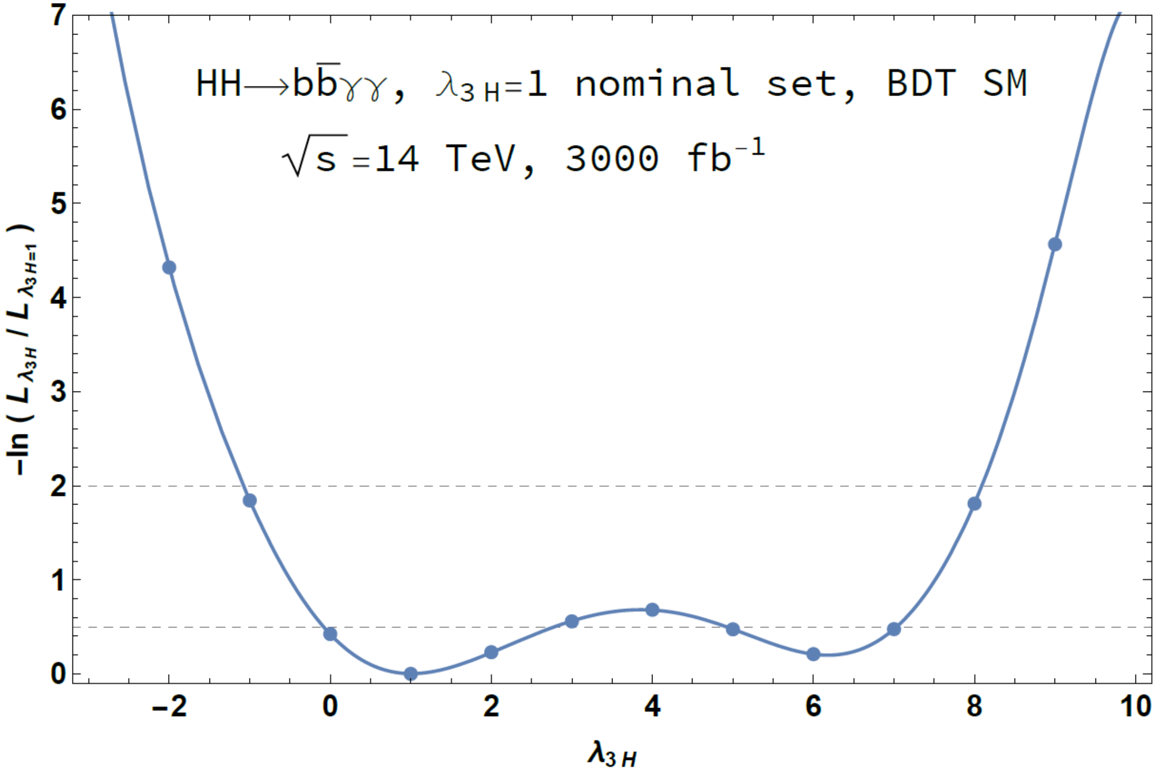
48% enhancement on Z

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

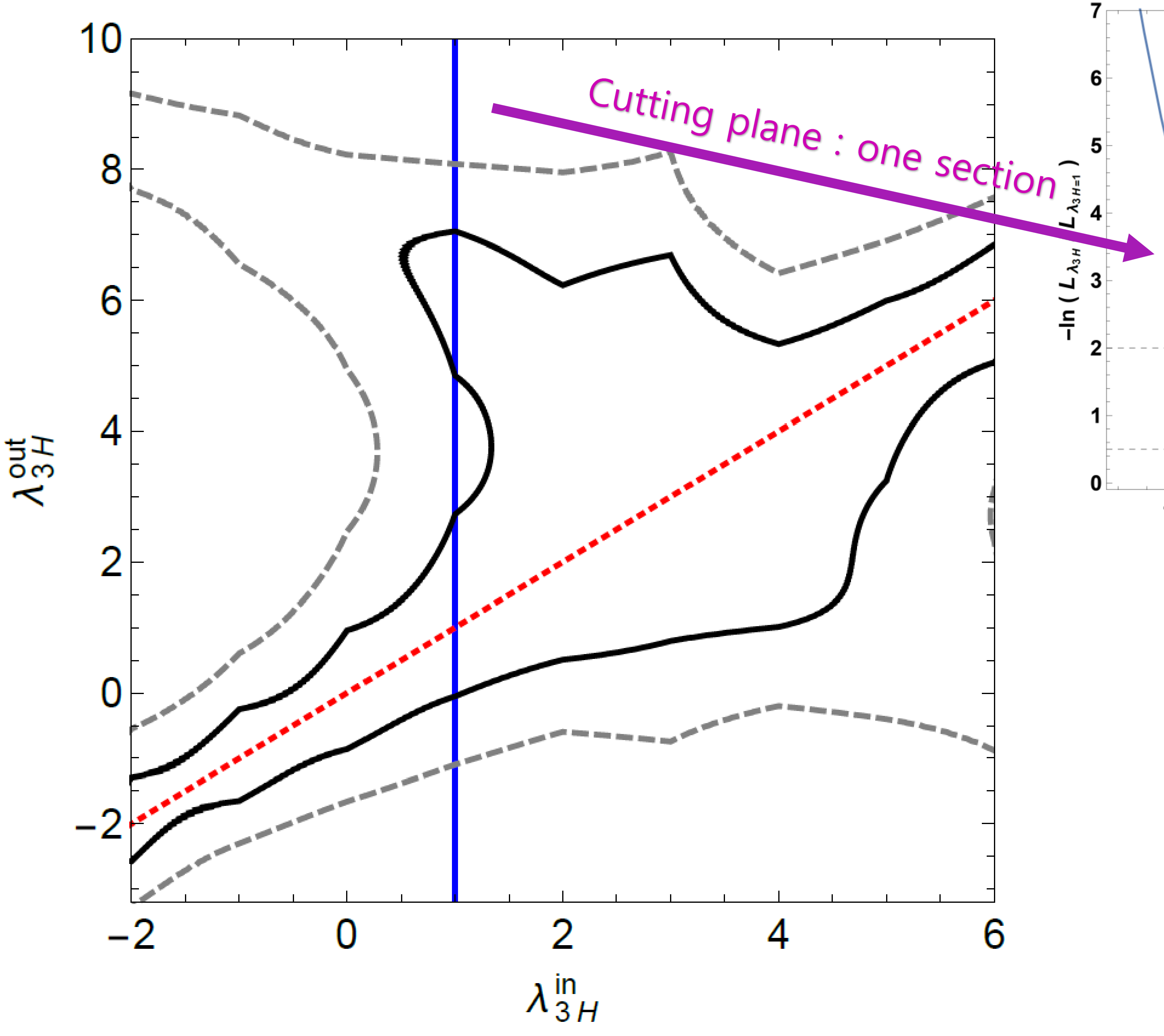


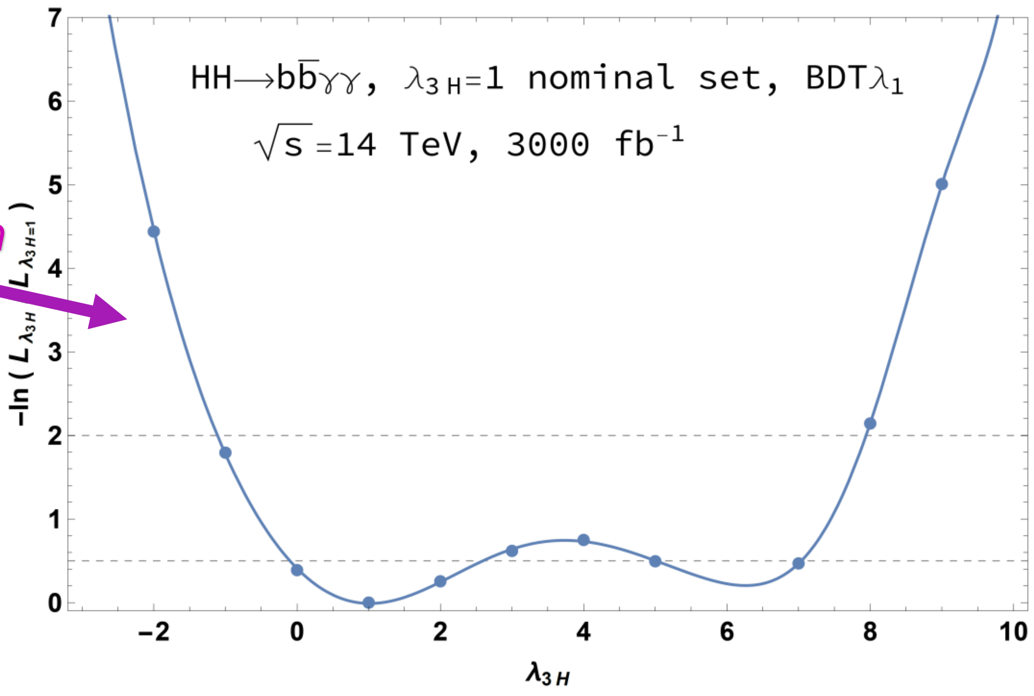
Improved Likelihood fit using the (NLO) M_{HH} kinematic distribution





Scenario	1σ CI	2σ CI
BDTλ SM, $\lambda_{3H} = 1$ nominal set	$-0.1 < \lambda_{3H} < 2.8$ and $4.9 < \lambda_{3H} < 7.0$	$-1.1 < \lambda_{3H} < 8.1$
BDTλ SM, $\lambda_{3H} = 0$ nominal set	$-1.0 < \lambda_{3H} < 1.0$ and $6.5 < \lambda_{3H} < 7.6$	$-1.9 < \lambda_{3H} < 2.9$ and $4.6 < \lambda_{3H} < 8.7$





We find a bulk region of $0.5 \leq \lambda_{3H} \leq 4.5$, where it is hard to pin down the trilinear coupling.

Conclusion

- # HL-LHC : constraint the λ_{3H}

With 3000 fb^{-1}

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

   $Z = 1.05 \ (\lambda_{3H} = 1)$

2. BDT Analysis + NLO_dist : $0.5 < \lambda_{3H} < 6.8$ at 95% CL,

   $Z = 1.55 \ (\lambda_{3H} = 1)$

48% enhancement on Z

3. We find a bulk region of $0.5 \leq \lambda_{3H} \leq 4.5$, where it is hard to pin down the trilinear coupling.

Last, but not least

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

  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 …
  ….

It may be
possible to see(?)
this trilinear Higgs coupling
at the HL-LHC.