Improving the sensitivity of the trilinear Higgs boson self-coupling measurement at the (HL-LHC and) FCC-hh

16-week internship under the supervision of Claude Charlot
Laboratoire Leprince-Ringuet (LLR), École polytechnique & IN2P3

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Higgs/top performance meeting
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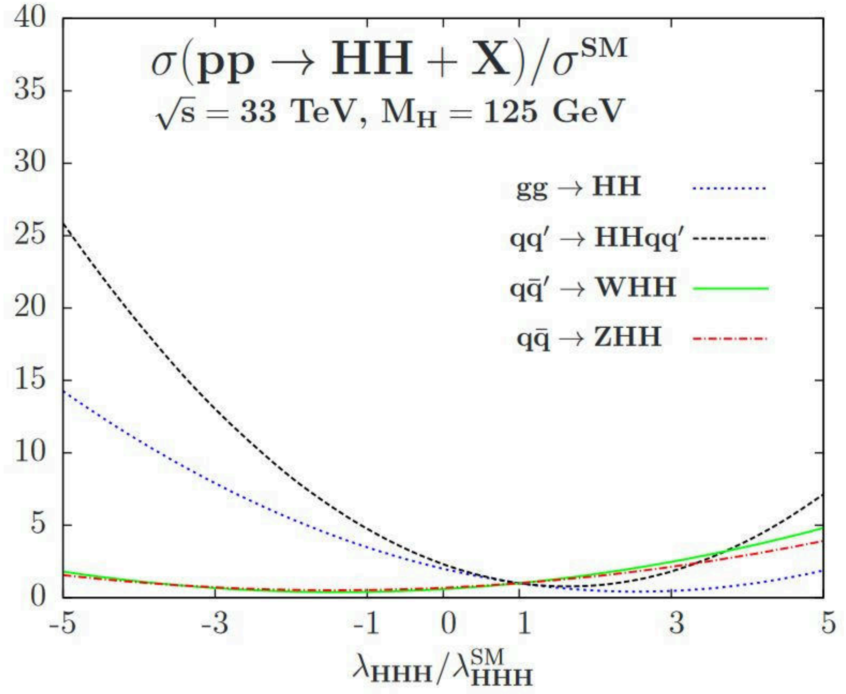
λ can be measured via Higgs boson pair production involving the trilinear Higgs boson self-coupling at the FCC-hh

Sensitivity of gluon-gluon fusion (ggF) vs. vector boson fusion (VBF) to the trilinear Higgs boson self-coupling

The VBF HH production cross section is known to be more sensitive to the trilinear Higgs boson self-coupling λ “out of the box”, but does it hold if we enhance the λ_{hhh} contribution in ggF HH using kinematical cuts?



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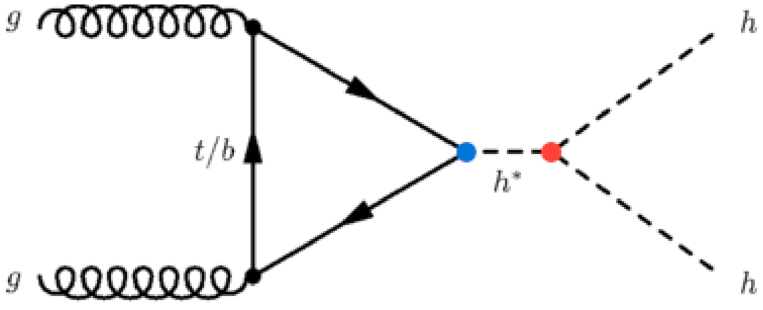
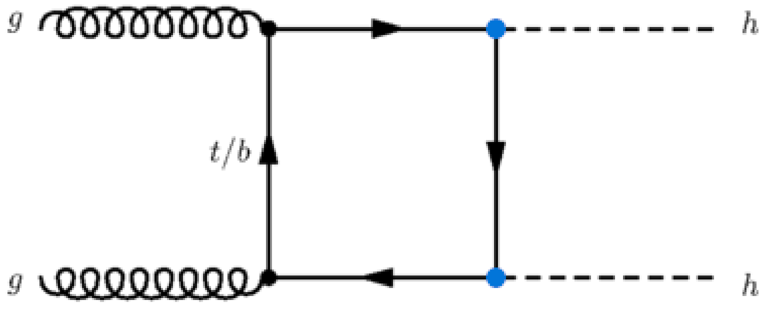


(a)

"Box" amplitude $\mathcal{M}_{\square} \propto y_t^2$



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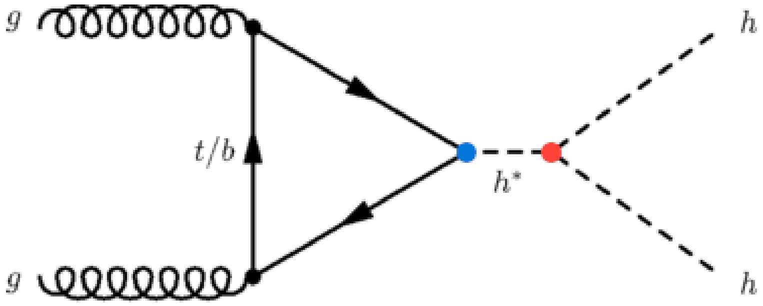

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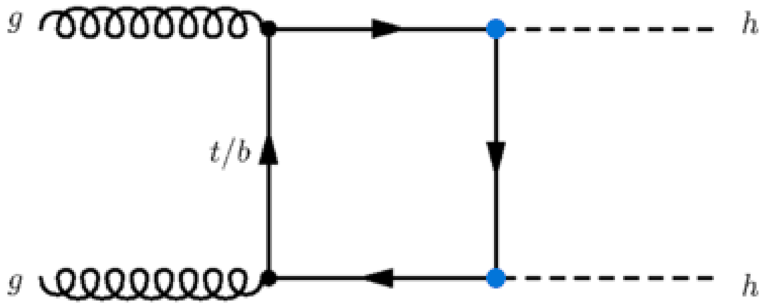

(b)

Higgs-top Yukawa coupling modifier $\kappa_t \equiv y_t / y_t^{\text{SM}}$, trilinear Higgs self-coupling modifier $\kappa_\lambda \equiv \lambda_{hhh} / \lambda_{hhh}^{\text{SM}}$

$$\sigma^{\text{LO}}_{gg\to hh}(\kappa_t, \kappa_\lambda) = \kappa_t^4 \sigma_{\square}^{\text{SM}} + 2\kappa_t^3 \kappa_\lambda \cos\theta \sqrt{\sigma_{\square}^{\text{SM}} \sigma_{\triangleright}^{\text{SM}}} + \kappa_t^2 \kappa_\lambda^2 \sigma_{\triangleright}^{\text{SM}} \qquad \theta \equiv \left|\arg(\mathcal{M}_{\triangleright}) - \arg(\mathcal{M}_{\square})\right|$$

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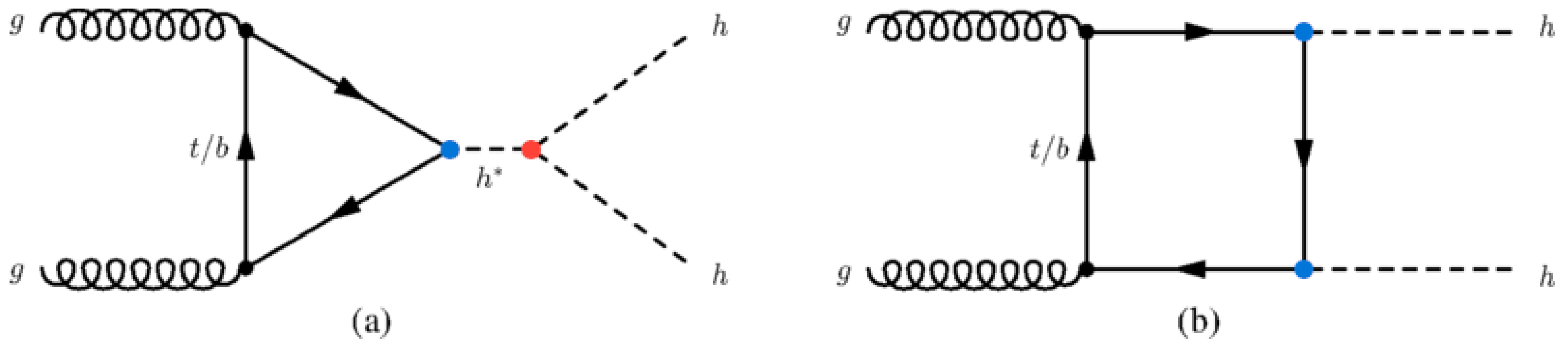

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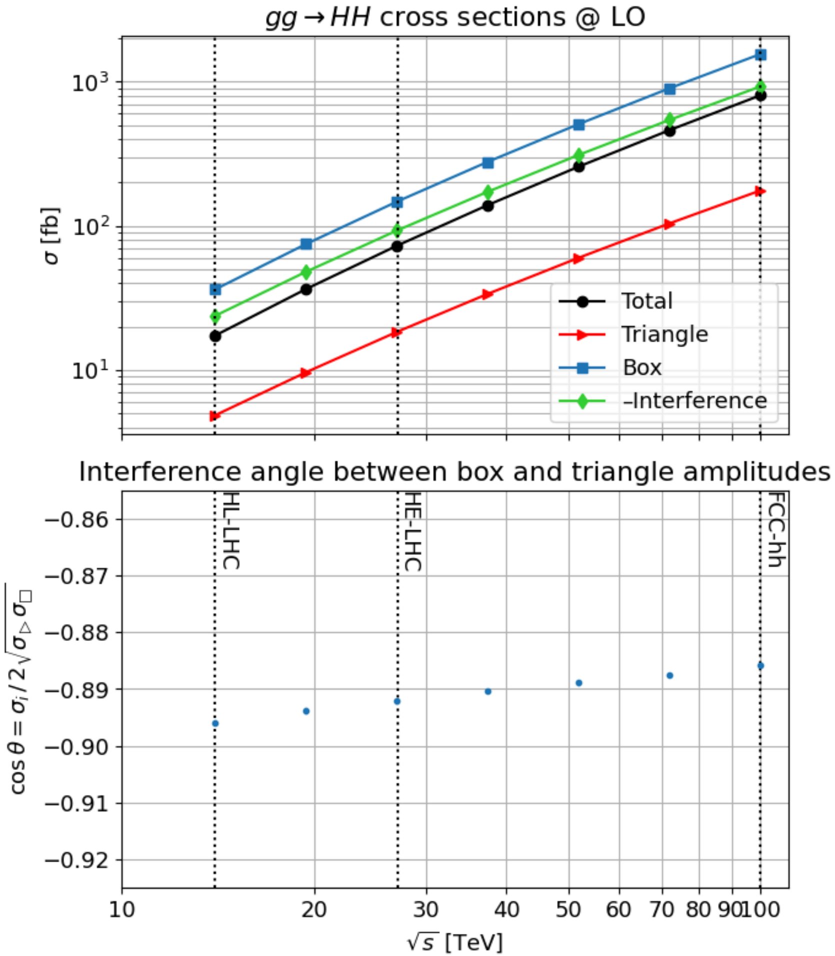
Highly destructive interference ($\cos\theta \approx -0.89$) $\Longrightarrow$ small cross section (only 17.3 fb @ 14 TeV)

Idea: use HH kinematics to improve the sensitivity of the trilinear Higgs self-coupling measurement

LO cross sections vs. center-of-mass energy $\sqrt{s}$

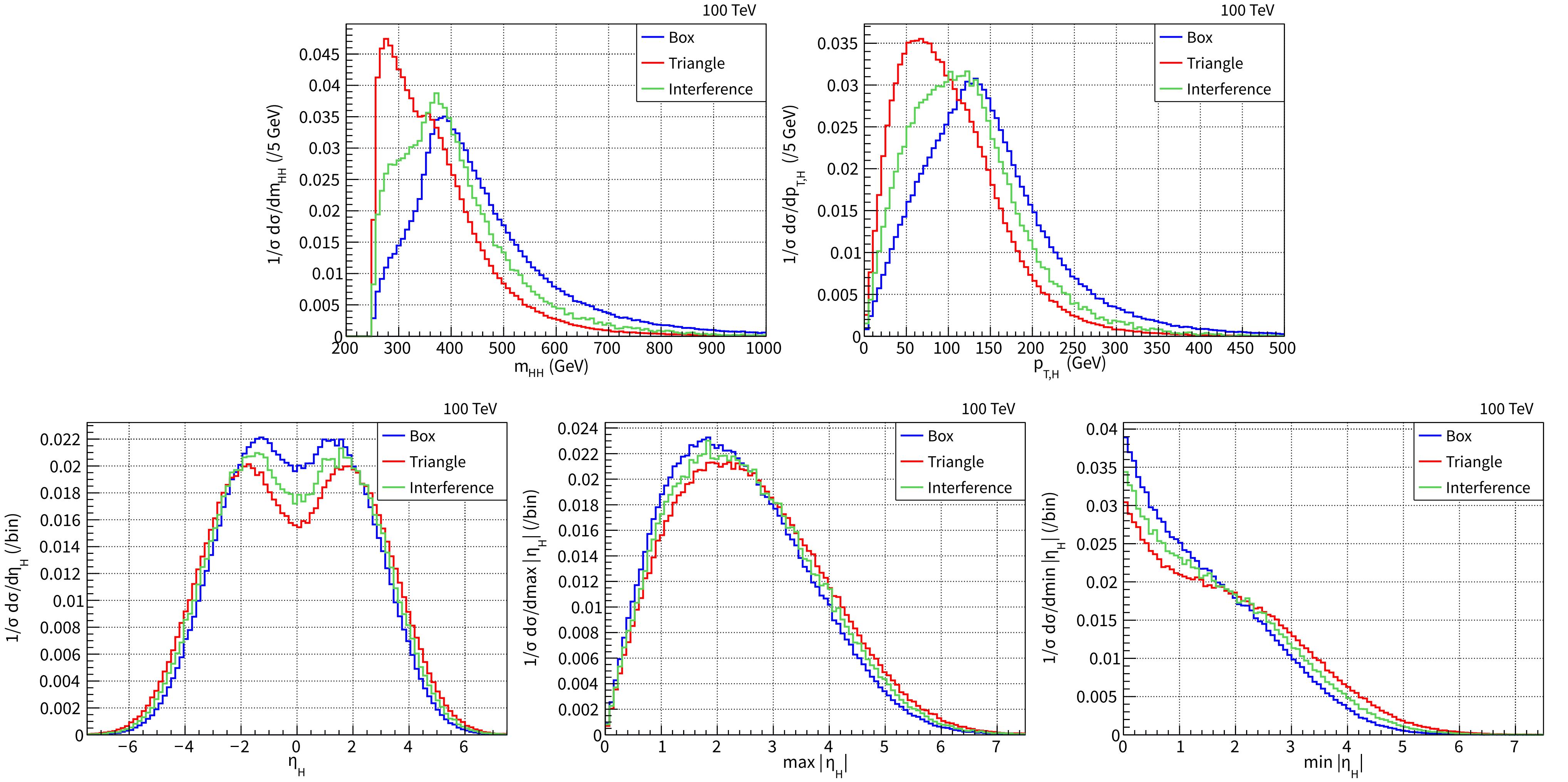


- We use MadGraph5_aMC@NLO to generate $gg \rightarrow hh$ events at the Leading Order
- All 3 contributions to the total cross section steadily increase and keep the **same relative ordering** (box > |interference| > total > triangle)
- Between 14 TeV and 100 TeV, the total ggF HH production cross section increases from **17.3 fb** to **806 fb** @ LO and from **36.7 fb** to **1224 fb** including the available QCD corrections according to the recommendations of the LHC Higgs Cross Section Working Group
- The **interference angle** θ is pretty much **constant** over the 14 TeV to 100 TeV range ($\cos\theta \approx -0.89$)

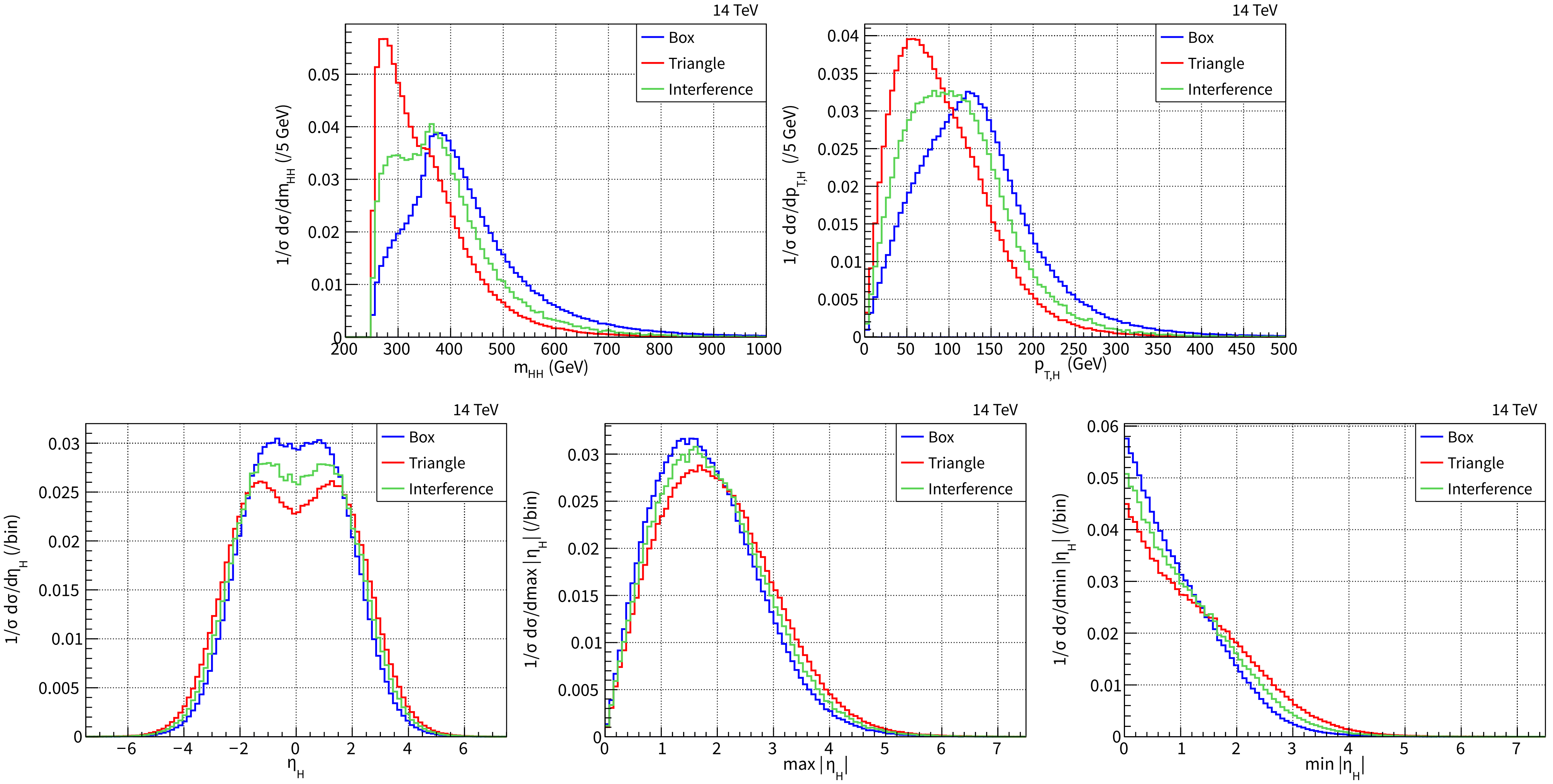
Kinematic distributions for the two final state Higgs bosons

- Invariant mass m_{hh}
- Transverse momenta $p_{\mathrm{T},h} = \min p_{\mathrm{T},h} = \max p_{\mathrm{T},h}$ (hh final state $\Longrightarrow$ same p_{T} @ LO)
- Rapidities y_h, y_{hh}
- Pseudorapidities $\eta_h, \min|\eta_h|, \max|\eta_h|$
- Angular separation $\Delta R_{hh} \equiv \sqrt{\Delta\phi_{hh}^2 + \Delta\eta_{hh}^2}$
- Helicity angle θ^* (between one h in the hh rest frame, and the hh direction)

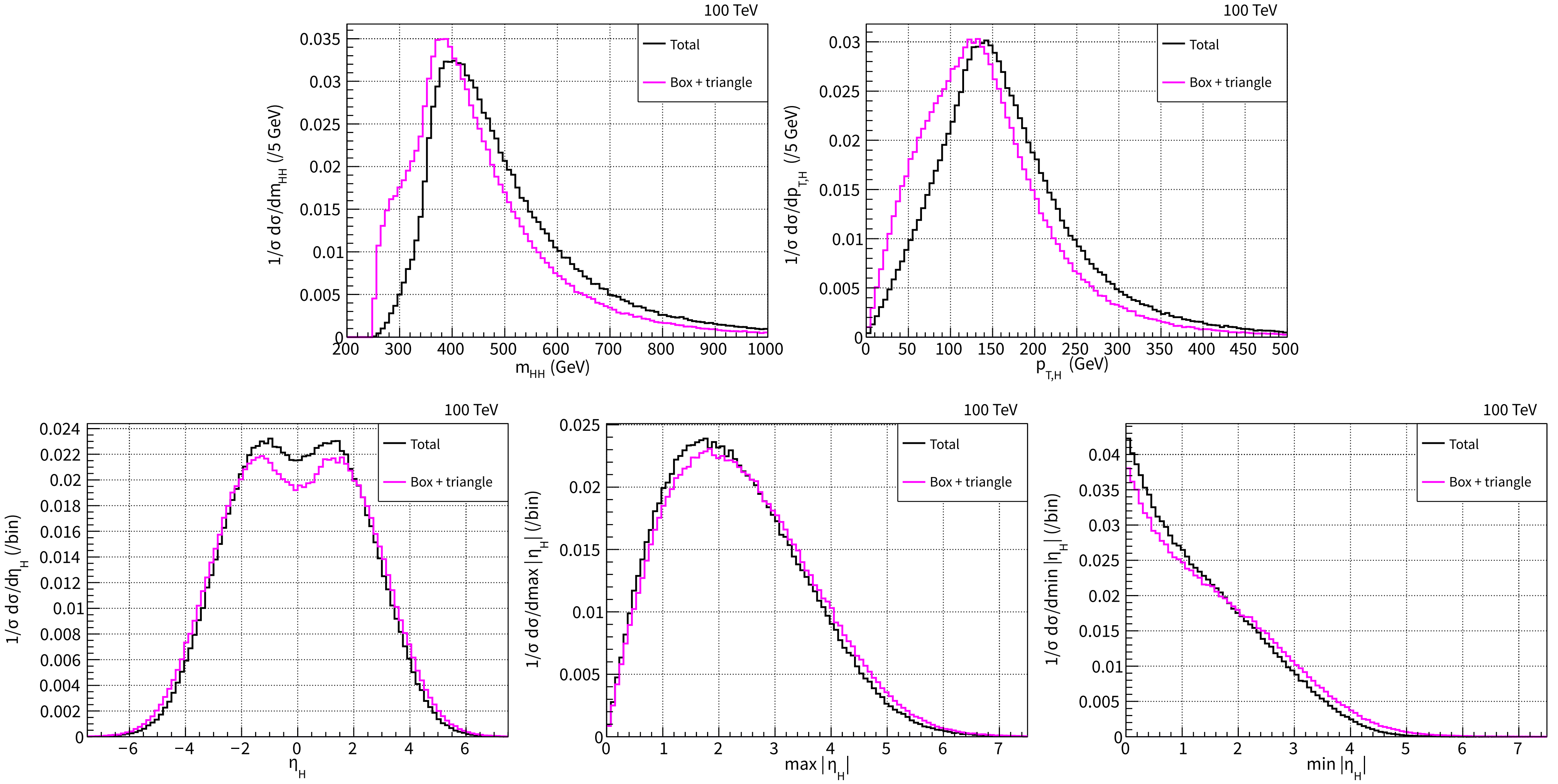
100 TeV (FCC-hh)



14 TeV (HL-LHC)


14 TeV
Box
Triangle
Interference
1/σ dσ/dm_HH (/5 GeV)
m_HH (GeV)
1/σ dσ/dp_T,H (/5 GeV)
p_T,H (GeV)
1/σ dσ/dη_H (/bin)
η_H
1/σ dσ/dmax |η_H| (/bin)
max |η_H|
1/σ dσ/dmin |η_H| (/bin)
min |η_H|

100 TeV (FCC-hh)



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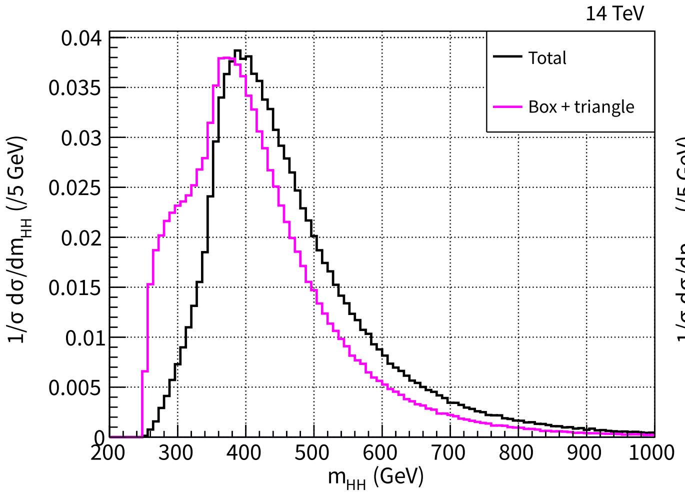
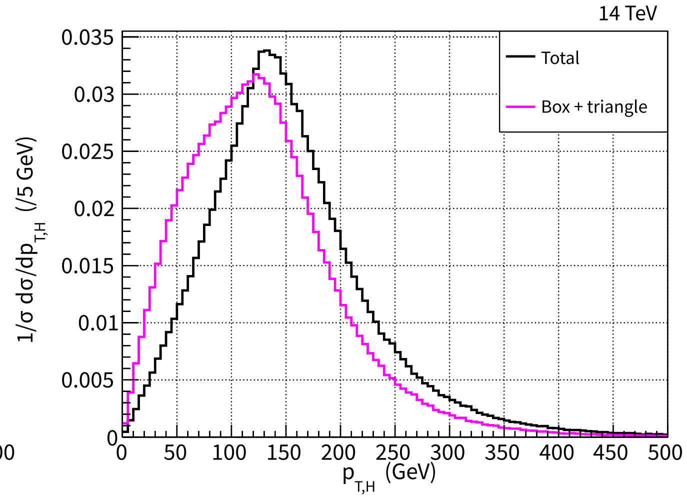
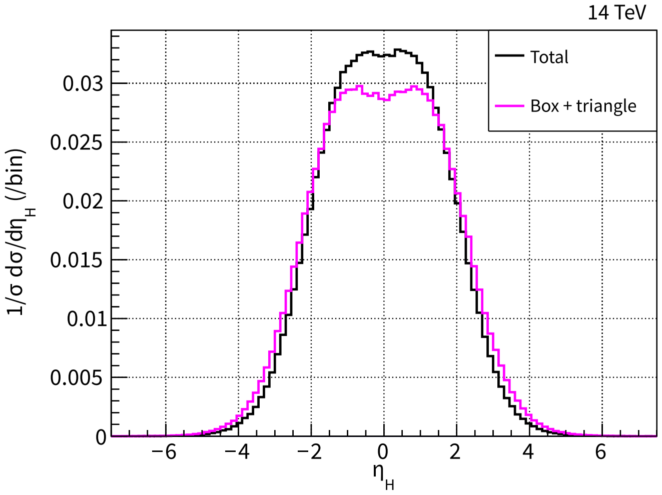
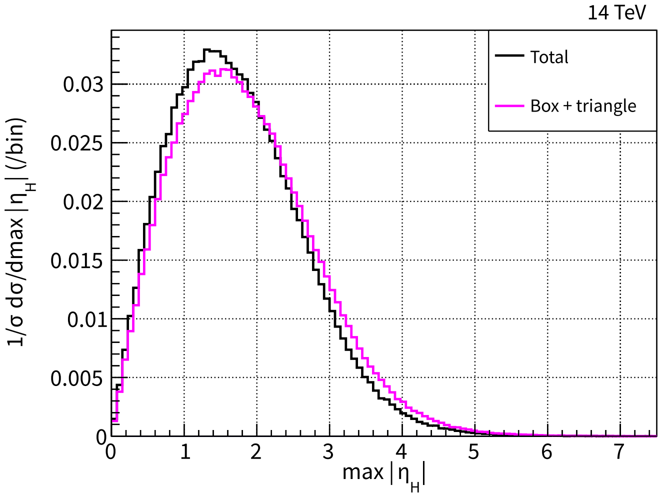
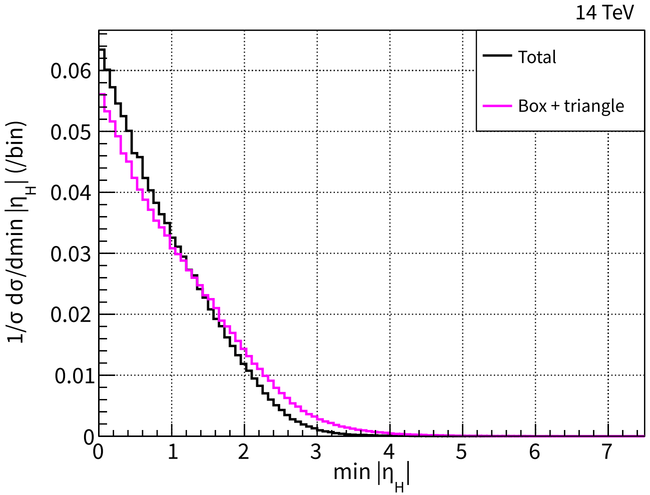

14 TeV
Total
Box + triangle
1/σ dσ/dm_HH (/5 GeV)
m_HH (GeV)
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0.04
200
300
400
500
600
700
800
900
1000

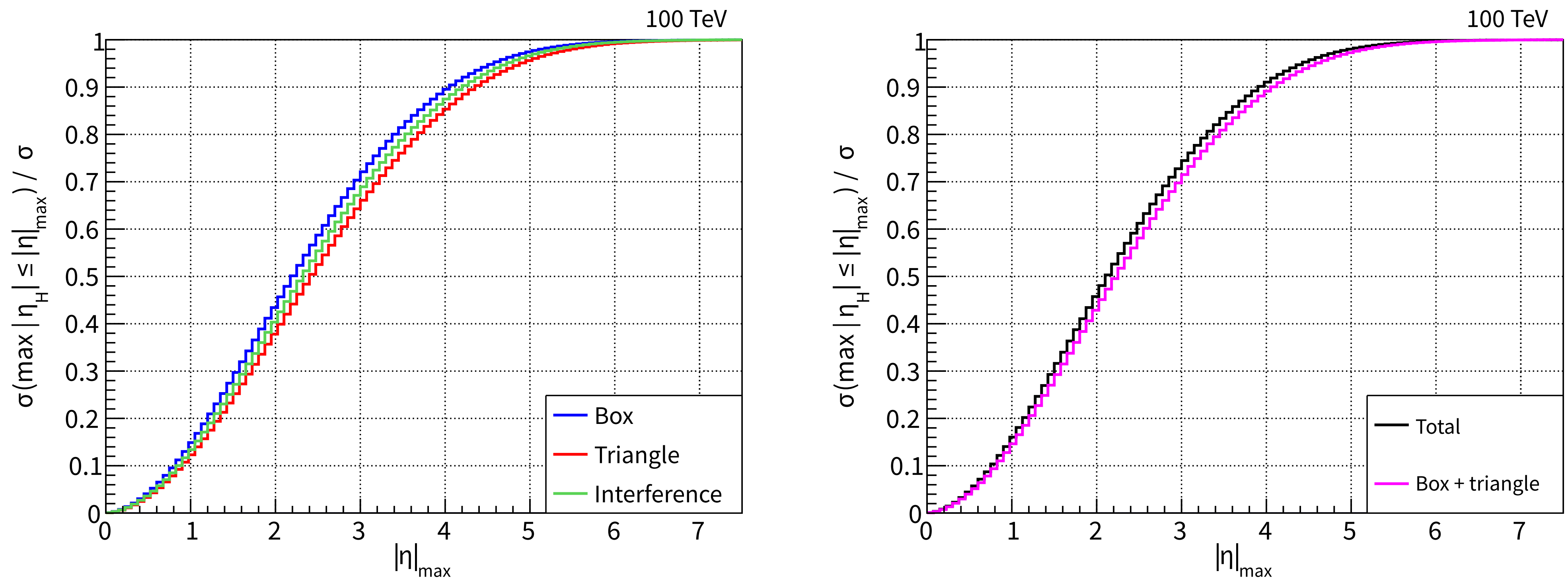

14 TeV
Total
Box + triangle
1/σ dσ/dp_T,H (/5 GeV)
p_T,H (GeV)
0
0.005
0.01
0.015
0.02
0.025
0.03
0.035
0
50
100
150
200
250
300
350
400
450
500


14 TeV
Total
Box + triangle
1/σ dσ/dη_H (/bin)
η_H
0
0.005
0.01
0.015
0.02
0.025
0.03
−6
−4
−2
0
2
4
6


14 TeV
Total
Box + triangle
1/σ dσ/dmax |η_H| (/bin)
max |η_H|
0
0.005
0.01
0.015
0.02
0.025
0.03
0
1
2
3
4
5
6
7


14 TeV
Total
Box + triangle
1/σ dσ/dmin |η_H| (/bin)
min |η_H|
0
0.01
0.02
0.03
0.04
0.05
0.06
0
1
2
3
4
5
6
7

Relevance of η coverage up to $|\eta| = 5$ (but not beyond) for FCC (100 TeV)



- **90%** of events such that $\max |\eta_h| \leq 4$
- **98%** of events such that $\max |\eta_h| \leq 5$

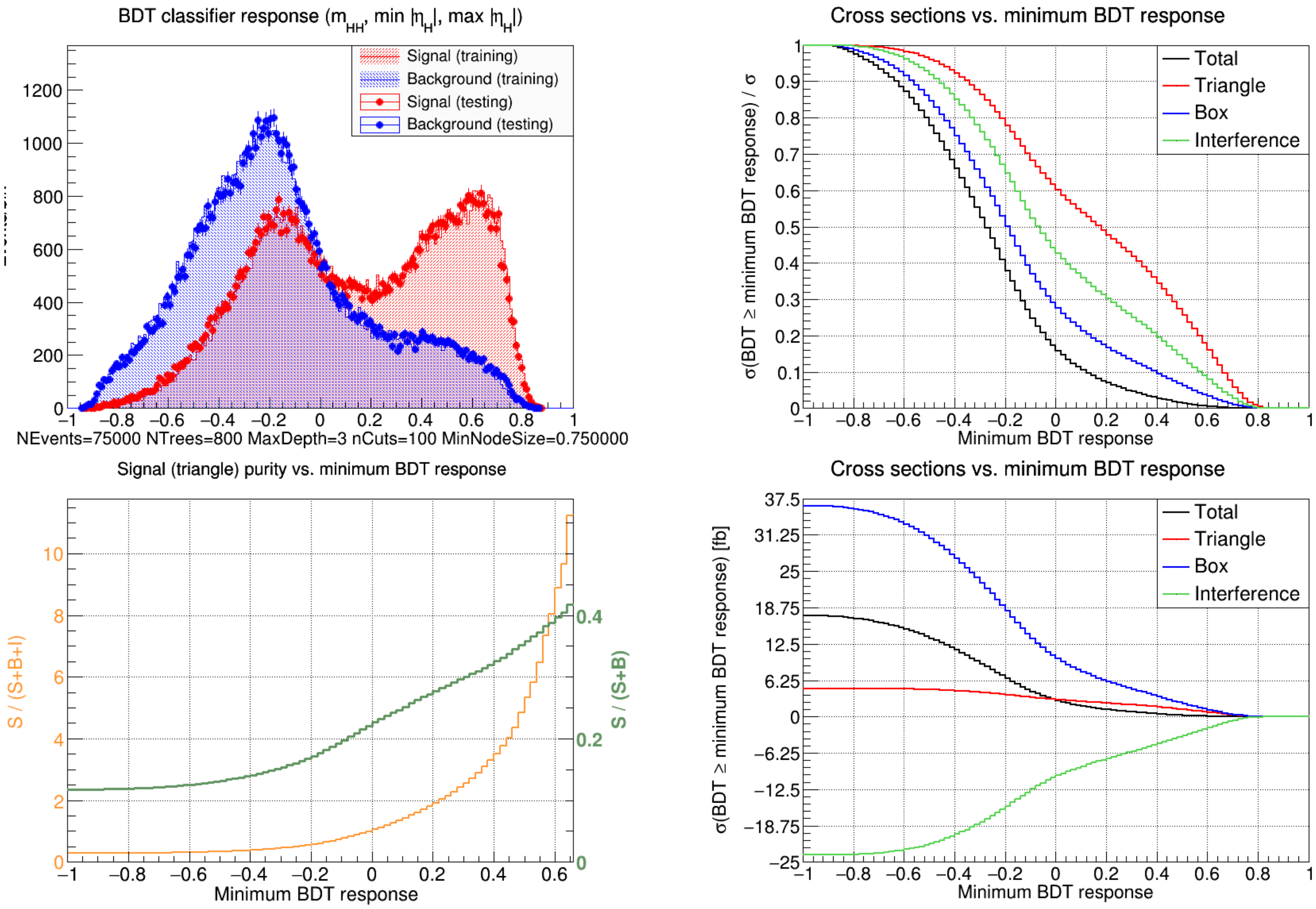
  $\Rightarrow$ only a small gain beyond $|\eta| = 5$

Improving the λ_{hhh} measurement sensitivity using event selections

We'll try to improve the triangle-to-other-contributions (signal-to-background) ratio to increase the variation of $\sigma^{\mathrm{LO}}_{gg\to hh}$ w.r.t. λ_{hhh} using Toolkit for MultiVariate Analysis (TMVA, now in ROOT)

- Train, test, evaluate a Boosted Decision Tree
  Input variables are m_{hh}, $\min|\eta_h|$, $\max|\eta_h|$
- Plot the BDT response histograms
  (for signal = triangle and background = box)
- Apply the trained BDT to a given dataset (the total ggF HH production), give a score to each event

100 TeV (FCC-hh)



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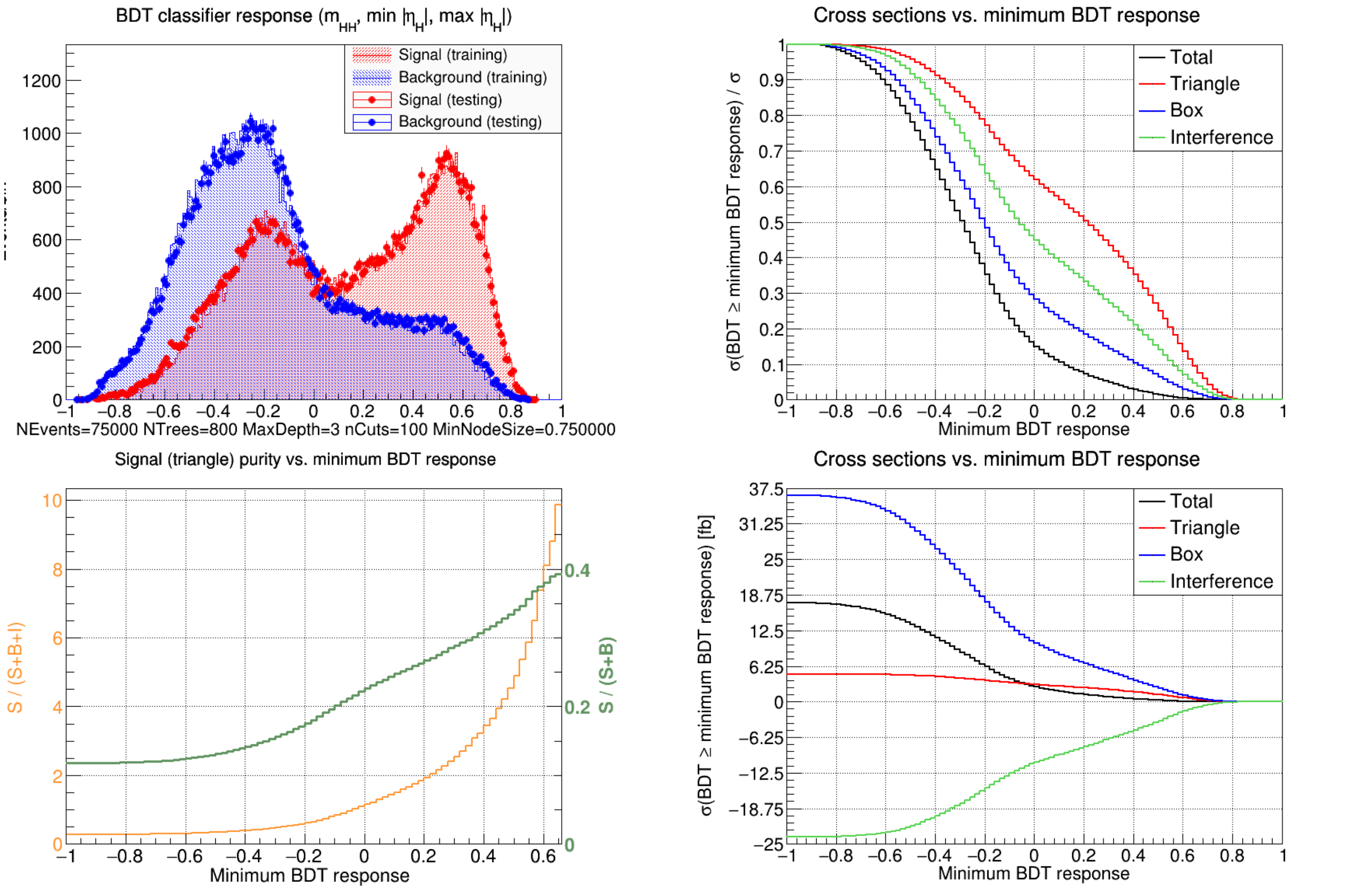
BDT classifier response (m_{HH}, min $|\eta_H|$, max $|\eta_H|$)
Signal (training)
Background (training)
Signal (testing)
Background (testing)
NEvents=75000 NTrees=800 MaxDepth=3 nCuts=100 MinNodeSize=0.750000
Cross sections vs. minimum BDT response
σ(BDT ≥ minimum BDT response) / σ
Total
Triangle
Box
Interference
Minimum BDT response
Signal (triangle) purity vs. minimum BDT response
S / (S+B+I)
S / (S+B)
Minimum BDT response
Cross sections vs. minimum BDT response
σ(BDT ≥ minimum BDT response) [fb]
Total
Triangle
Box
Interference
Minimum BDT response

We plot the ratio between $\sigma^{\mathrm{LO,cut}}_{gg\to hh}(\kappa_t, \kappa_\lambda)$ and $\sigma^{\mathrm{LO,SM,cut}}_{gg\to hh}$ (a quadratic function in κ_λ)

$$\hat{\sigma}(\kappa_t, \kappa_\lambda) = \frac{\kappa_t^4 \sigma_\square^{\mathrm{SM,cut}} + 2\kappa_t^3 \kappa_\lambda \cos\theta \sqrt{\sigma_\square^{\mathrm{SM,cut}} \sigma_\triangleright^{\mathrm{SM,cut}}} + \kappa_t^2 \kappa_\lambda^2 \sigma_\triangleright^{\mathrm{SM,cut}}}{\sigma_\square^{\mathrm{SM,cut}} + 2\cos\theta \sqrt{\sigma_\square^{\mathrm{SM,cut}} \sigma_\triangleright^{\mathrm{SM,cut}}} + \sigma_\triangleright^{\mathrm{SM,cut}}}$$

for different values of the cut on the BDT response

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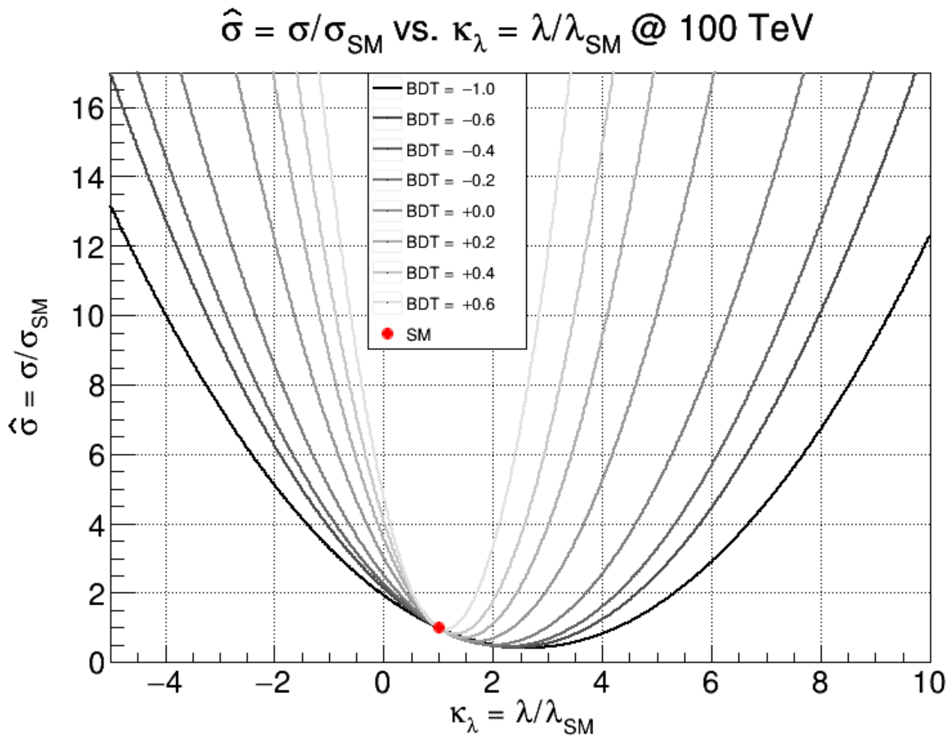
for different values of the cut on the BDT response

- The minimum $-\kappa_t \cos\theta \sqrt{\sigma_\square^{\text{SM,cut}} / \sigma_\triangleright^{\text{SM,cut}}}$ shifts towards $\kappa_\lambda \approx 1$ as we reduce the interference
- The plot is sharper and sharper
  σ is more and more sensitive to κ_λ



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4. Next: more thorough/realistic FCC-hh study

14 TeV (HL-LHC) 200 PU