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Electroweak corrections to double Higgs production at the LHC

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Dec. 20th, 2024

HIGGS POTENTIAL 2024
HIGGS POTENTIAL AND BSM OPPORTUNITIES

Introduction

- Introduction
- Calculation strategy
- Results
- Summary

Measurements of Higgs boson coupling

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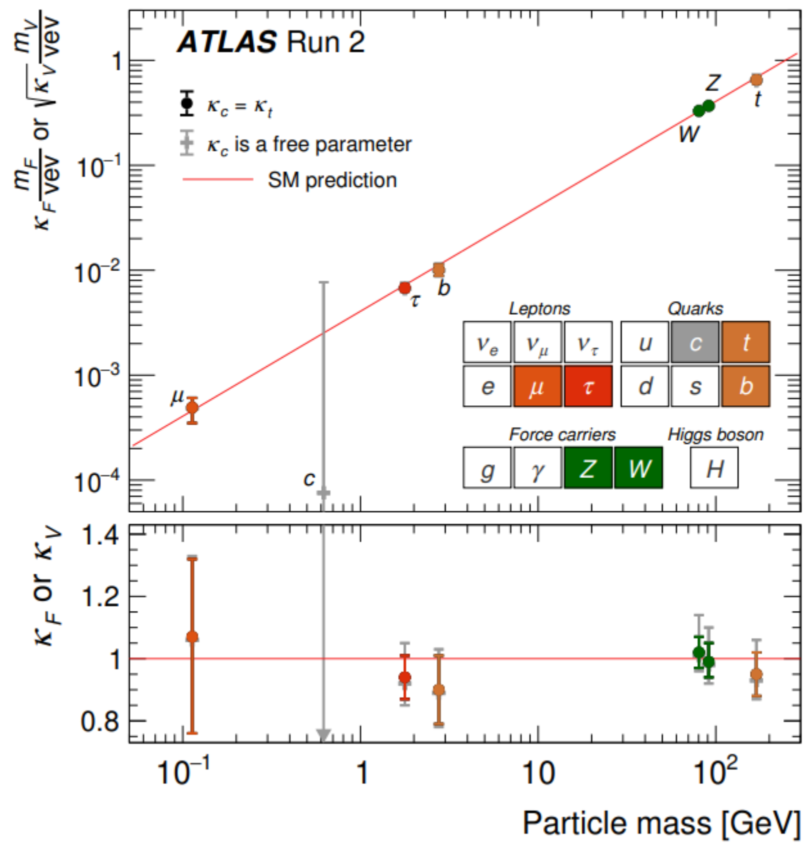
$g_{Hf\bar{f}}$, g_{HVV}

- can be measured with high precision.

λ_{HHH}, λ_{HHHH}

- require multi-Higgs production, small cross sections.
- Mixed with complicated background.



ALTAS:2207.00092

LHC RUN2
$-1.2 < \lambda/\lambda_{SM} < 7.2$ $-1.4 < \lambda/\lambda_{SM} < 6.4$

ATLAS: 2406.09971
CMSPASHIG-20-011

HL-LHC
$-0.5 < \lambda/\lambda_{SM} < 1.5$

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Status of QCD corrections

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- NLO QCD
  - NLO QCD with full top-quark mass dependence, Borowka et al:1604.06447
  - NLO QCD matched to parton shower, Heinrich et al:1703.09252
  - NLO QCD with soft-gluon resummation, Ferrera et al: 1609.01691
- NNLO QCD
  - NNLO QCD in heavy-top limit (HTL) approximation, Florian et al:1305.5206
  - NNLO in HTL+ NLO with full top-quark mass dependence, Florian et al:2106.14050
  - NNLO QCD in HTL matched to parton shower, Alioli et al: 2212.10489
- NNNLO QCD
  - NNNLO QCD in HTL, Chen et al:1909.06808
  - NNNLO in HTL include the top-quark mass effects, Chen et al:1912.13001
  - NNNLO in HTL + NLO with full top-quark mass dependence + soft-gluon resummation, Ajjath et al:2209.03914

Uncertainty from top mass effects are about 5%

Process	Theory	σ_{th} [pb]	δ_{th} [%]	δ_{PDF} [%]	δ_{α_s} [%]
$ggF\ HH$	$\text{N}^3\text{LO}_{\text{HTL}}$ $\otimes$ NLO_{QCD}	0.03105	$^{+2.2}_{-5.0}$	± 2.1	± 2.1

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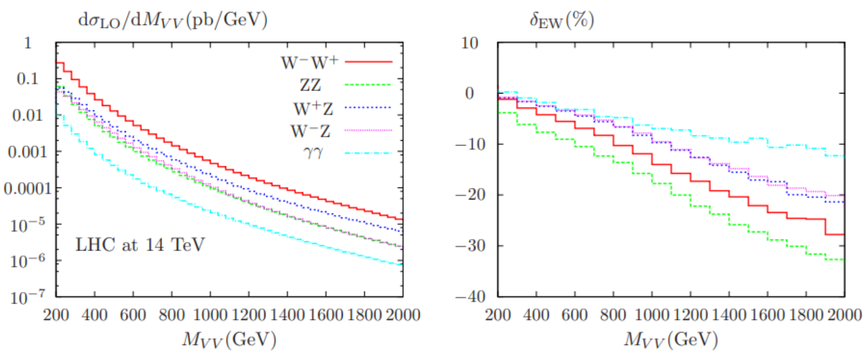
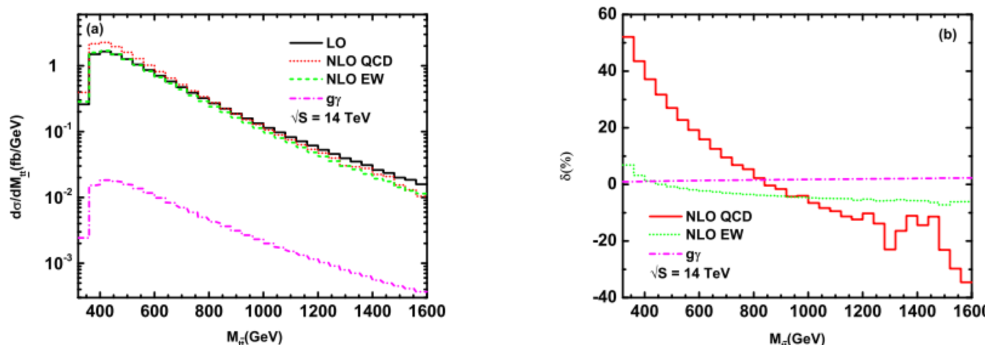
Importance of EW corrections

- Size of EW corrections
  - Most important part in the uncertainty budget
- NLO EW corrections are notably significant at high energy region
  - Sudakov enhancement: $\alpha \sim 0.7\% \to \frac{\alpha}{4\pi \sin\theta_W^2} \log^2(\frac{s}{m_Z^2})|_{s=2000^2} \sim 10\% \sim \alpha_s$

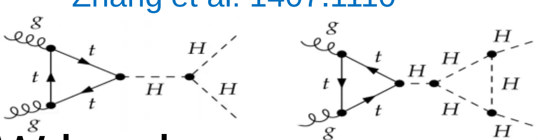


A Bierweiler et al:1305.5402

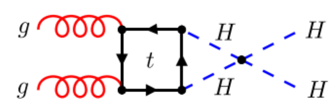


Zhang et al: 1407.1110

- Higgs self couplings receive EW corrections.



- Higgs quartic coupling emerges at the NLO EW level
  - Constrained on λ_{HHHH}^{SM} indirectly from NLO EW correction



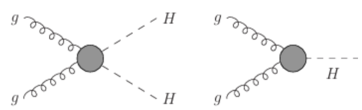
focal point in the 2015, 2017, 2019,and 2021 Les Houches precision wish lists

process	known	desired
$pp \to HH$	$N^3LO_{HTL} \otimes NLO_{QCD}$	NLO_{EW}

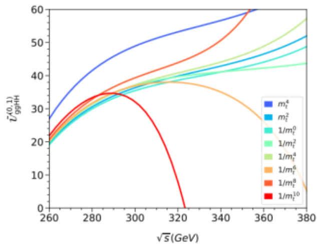
Status of NLO EW corrections

- Results in literature

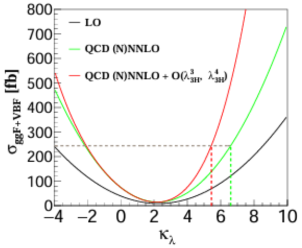
  - Higgs self-coupling corrections in EFT: Borowka et al: 1811.12366
    - EW corrections contains only new physics: $V^{\mathrm{NP}}(\Phi) \equiv \sum_{n=3}^{\infty} \frac{c_{2n}}{\Lambda^{2n-4}} \left(\Phi^\dagger \Phi - \frac{1}{2} v^2\right)^n .$
  - Two-loop Yukawa corrections: Davies et al:2207.02587
    - Higgs boson is exchanged between the top quarks; Master Integrals in the high-energy limit is published.
  - Top-quark Yukawa corrections : Muhlleitner et al:2207.02524
    - Partly in HTL (ggH(H) vertices), Total and differential cross section are presented.



  - HTL and Neglecting diagrams with only massless fermion loops, Davies et al: 2308.01355
    - $|\mathrm{M}|^2$ at particular phase space points ($\frac{p_T}{\sqrt{\hat{s}}}$=0.1) are presented.
    - HTL does not show a convergent behaviour.



  - Full EW corrections: Bi et al:2311.16963
    - Total and differential cross section are presented with full top mass effects.
  - Top-Yukawa and Higgs self-coupling contributions: Heinrich et al:2407.04653
    - Total and differential cross section are presented with full top mass effects.
  - Higgs self-coupling corrections: Li et al:2407.14716
    - Results in κ framework are discussed.
    - Upper limit on the HHH coupling is improved.



Calculation strategy

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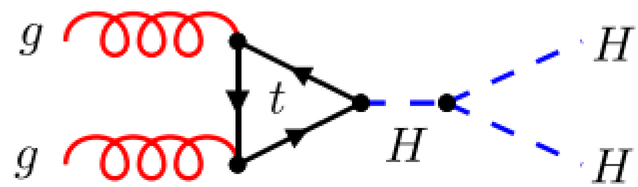
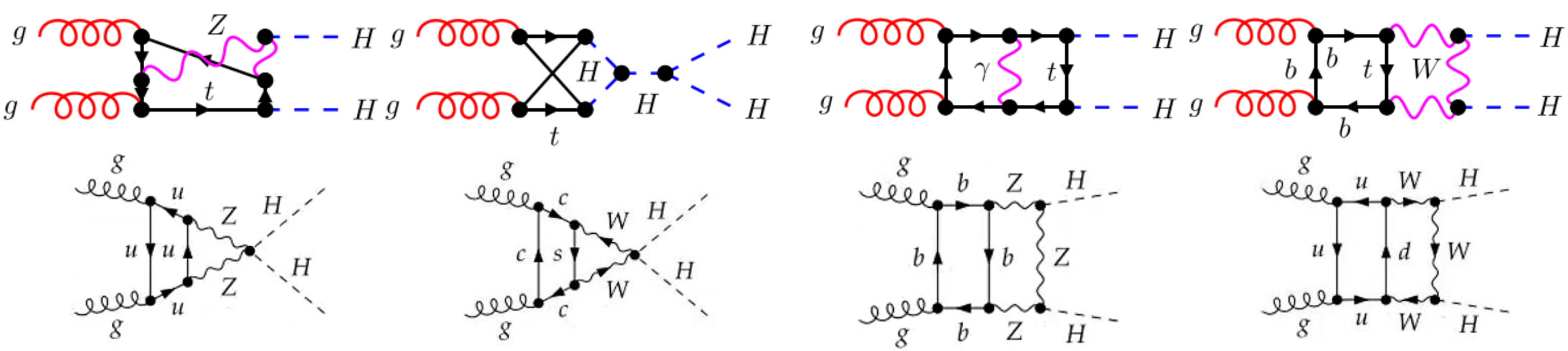
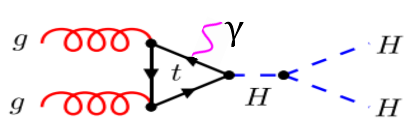
EW corrections to double H production at the LHC

LO diagrams:



NLO diagrams:





Forbidden due to Furry Theorem

Typical Feynman diagrams at NLO EW

Calculations of two loop integrals

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Analytically calculation: (for e.g. Davies et al:2207.02587 and 2308.01355)

Advantage:

- Results can be formulated analytically.

Disadvantage:

- Results are only valid in some particular limit.
  - Results are expressed as an expansion respect to some parameters.
- Only partial sub-diagrams can be calculated analytically.

Numerically calculation: (for e.g. Bi et al:2311.16963; Li et al:2407.14716; Borowka et al: 1811.12366; Heinrich et al:2407.04653)

Advantage:

- MIs are easier to compute.
- Public packages are available: **AMFlow** Liu et al:2201.11669; **pySecDec** Borowka et al: 1703.09692

Disadvantage:

- MIs need to be calculated at a lot of points to obtain cross sections

Calculation strategy

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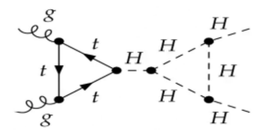
Results: Total cross sections

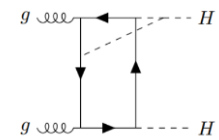
μ	$M_{HH}/2$	$\sqrt{p_T^2+m_H^2}$	m_H
LO	19.96(6)	21.11(7)	25.09(8)
NLO	19.12(6)	20.21(6)	23.94(8)
$\mathcal{K}$-factor	0.958(1)	0.957(1)	0.954(1)

LO and NLO EW corrected integrated cross sections (in fb) 14 TeV LHC.

- Differences with varying scale choices are around 20%.
  - ➢ Huge scale uncertainties. Can be reduced by including QCD corrections.
- K-factor is insensitive to the scale choice.
  - ➢ EW corrections beyond NLO are on the order of a few thousandths.
- The statistical uncertainty for the K-factor is smaller than that of $\sigma_{LO,NLO}$.
  - ➢ K-factor can get a controllable error with far fewer events.

Results: Total cross sections

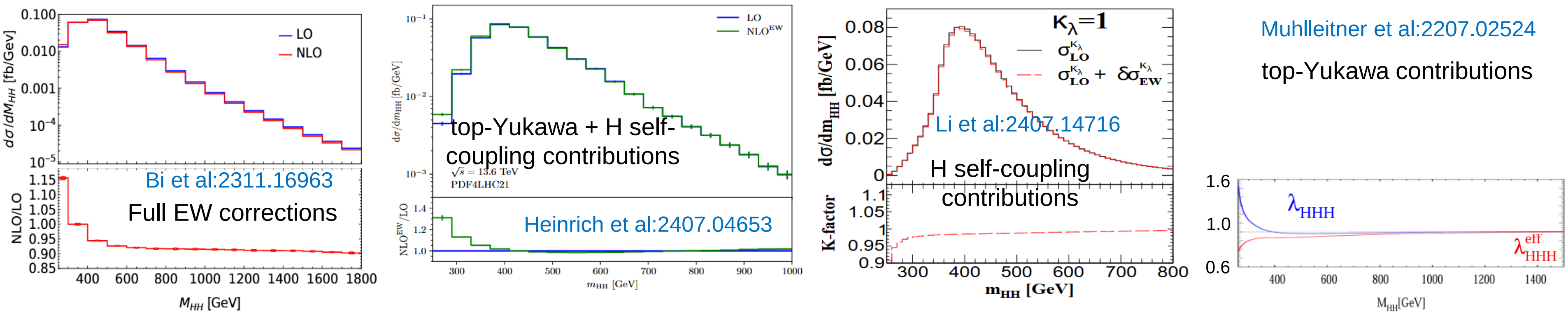




<table>
<tr><th></th><th>Full EW corrections</th><th>H self-coupling contributions</th><th>top-Yukawa contributions</th></tr>
<tr><td rowspan="2">δ^{EW}
Bi et al:2311.16963</td><td rowspan="2">-4.2%</td><td>-1.395%</td><td>2.344%</td></tr>
<tr><td colspan="2">0.949%</td></tr>
<tr><td>δ^{EW}
Heinrich et al:2407.04653</td><td>-</td><td colspan="2">1%</td></tr>
<tr><td rowspan="2">δ^{EW}
Li et al:2407.14716 and Zhang’s talk at Higgs 2023</td><td rowspan="2">-</td><td>-1.401%</td><td>2.355%</td></tr>
<tr><td colspan="2">0.953%</td></tr>
<tr><td>δ^{EW}
Muhlleitner et al:2207.02524</td><td>-</td><td>-</td><td>0.2%</td></tr>
</table>

HTL for ggH(H) vertices

Results: Differential cross sections



- Significant corrections at HH production threshold.
  - The gauge boson contributions included in full EW corrections is negative in the threshold region.
  - Top-Yukawa contributions and H self-coupling contributions have opposite signs in the threshold region.
- Partial results have ~0% corrections at high energy region, while full EW shows -10% corrections at high energy region.
  - The gauge boson contributions included in full EW corrections is negative at high energy region.
- The last plot shows that the M_{HH} is sensitive to the modeling of H self-coupling.
  - The measurement of M_{HH} at HH production threshold is key issue to probe the H self couplings.

Results: Differential cross sections

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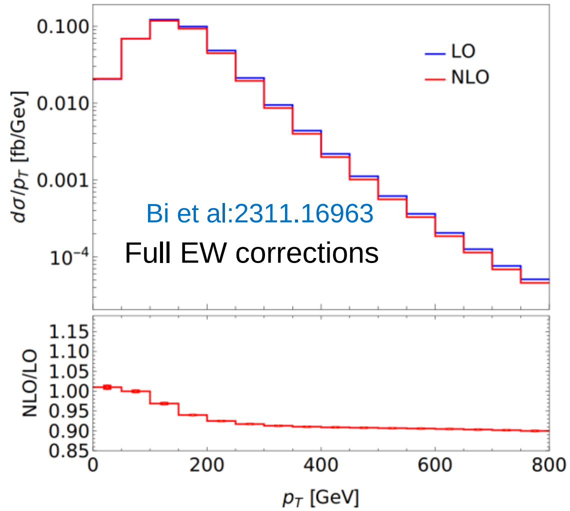
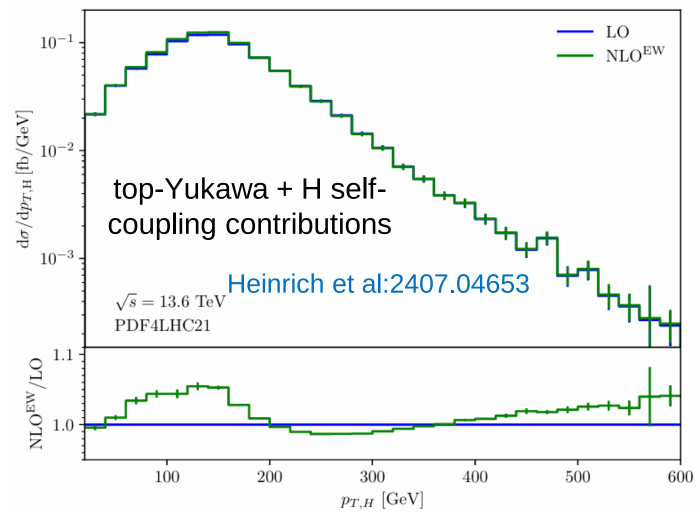
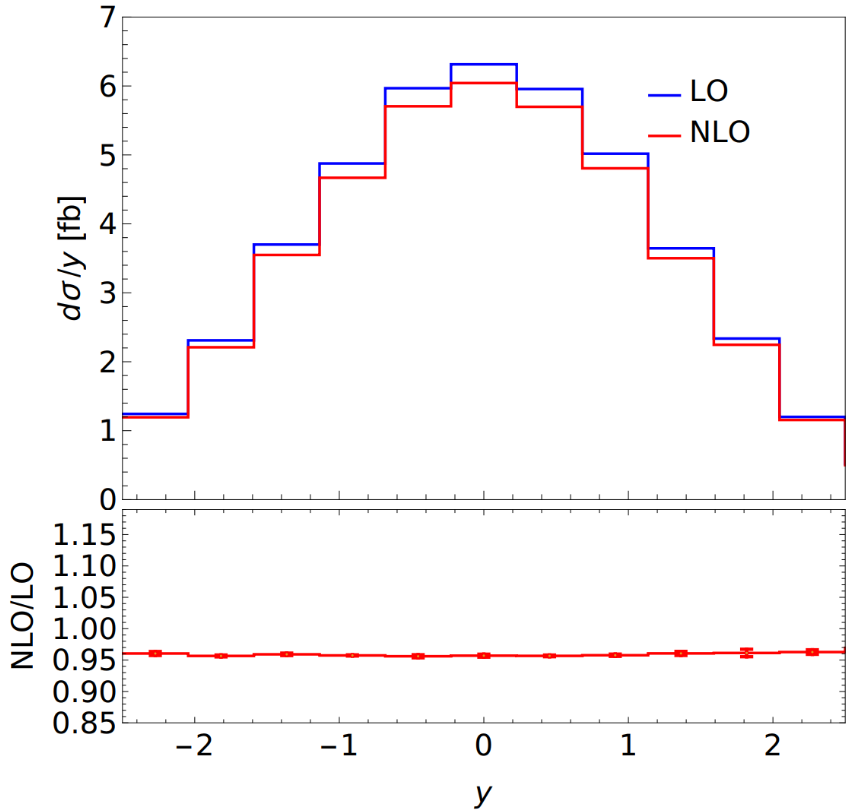




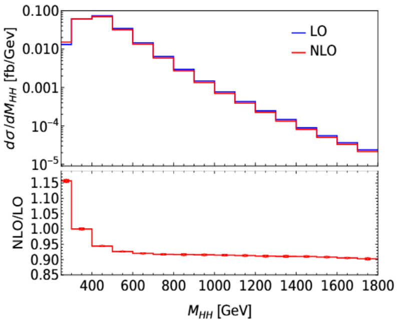
- At High energy region
  - Positive corrections for top-Yukawa + H self-coupling contributions
  - Negative corrections for full EW corrections
  - At high energy region, gauge boson contribution dominates and is negative

Results: Differential cross sections

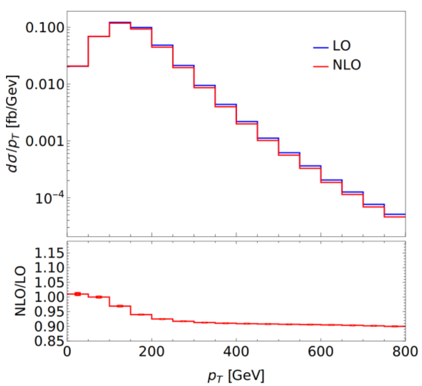


- Flat corrections at around -4%.
  - ➢ Similar to the total cross section

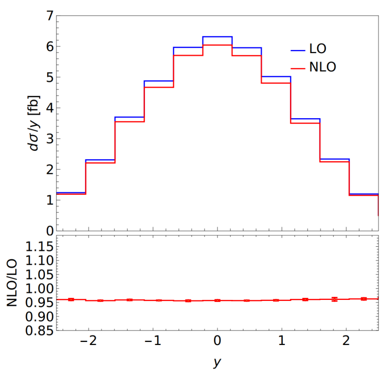
Results



Bin (GeV)	250 - 300	300 - 400	400 - 500	500 - 600	600 - 700	700 - 800	800 - 900	900 - 1000
K-fac	1.157(4)	1.000(2)	0.9442(2)	0.9263(2)	0.9204(3)	0.9171(9)	0.916(2)	0.916(2)
Bin (GeV)	1000 - 1100	1100 - 1200	1200 - 1300	1300 - 1400	1400 - 1500	1500 - 1600	1600 - 1700	1700 - 1800
K-fac	0.915(2)	0.913(2)	0.911(2)	0.911(2)	0.910(1)	0.9082(8)	0.9054(5)	0.902(2)



Bin (GeV)	0 - 50	50 - 100	100 - 150	150 - 200	200 - 250	250 - 300	300 - 350	350 - 400
K-fac	1.010(4)	1.000(2)	0.969(2)	0.9399(4)	0.9249(1)	0.9172(1)	0.9129(1)	0.9104(1)
Bin (GeV)	400 - 450	450 - 500	500 - 550	550 - 600	600 - 650	650 - 700	700 - 750	750 - 800
K-fac	0.9089(1)	0.9079(1)	0.9069(1)	0.9059(1)	0.9047(1)	0.9033(2)	0.9018(1)	0.8999(5)



Bin	-2.5 - -2.04545	-2.04545 - -1.59091	-1.59091 - -1.13636	-1.13636 - -0.681818	-0.681818 - -0.227273	-0.227273 - 0.227273	0.227273 - 0.681818	0.681818 - 1.13636
K-fac	0.960(3)	0.957(2)	0.959(2)	0.957(1)	0.956(2)	0.957(2)	0.957(2)	0.958(2)
Bin	1.13636 - 1.59091	1.59091 - 2.04545	2.04545 - 2.5					
K-fac	0.961(3)	0.961(6)	0.963(4)					

Summary

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- Higgs self coupling is important to identify the Higgs potential and to probe new physics.
- The study of σ(HH) is the best way to extract the Higgs self coupling.
- Our full calculation includes all the diagrams and all the mass effects.
- -4% EW corrections at total cross section level.
- For dimensionful observables, EW corrections reach up to +15% at the beginning of the spectrum and −10% in the tail.
- Our results suggest that the remained uncertainties from theoretical side is overall about few percent and it's precise enough for the measurements at the HL-HLC.

Thanks for your attention!