

Electroweak corrections to double Higgs production at the LHC

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Introduction



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- Introduction
- Calculation strategy
- Results
- Summary

Introduction to Higgs Boson



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Standard Model of Elementary Particles

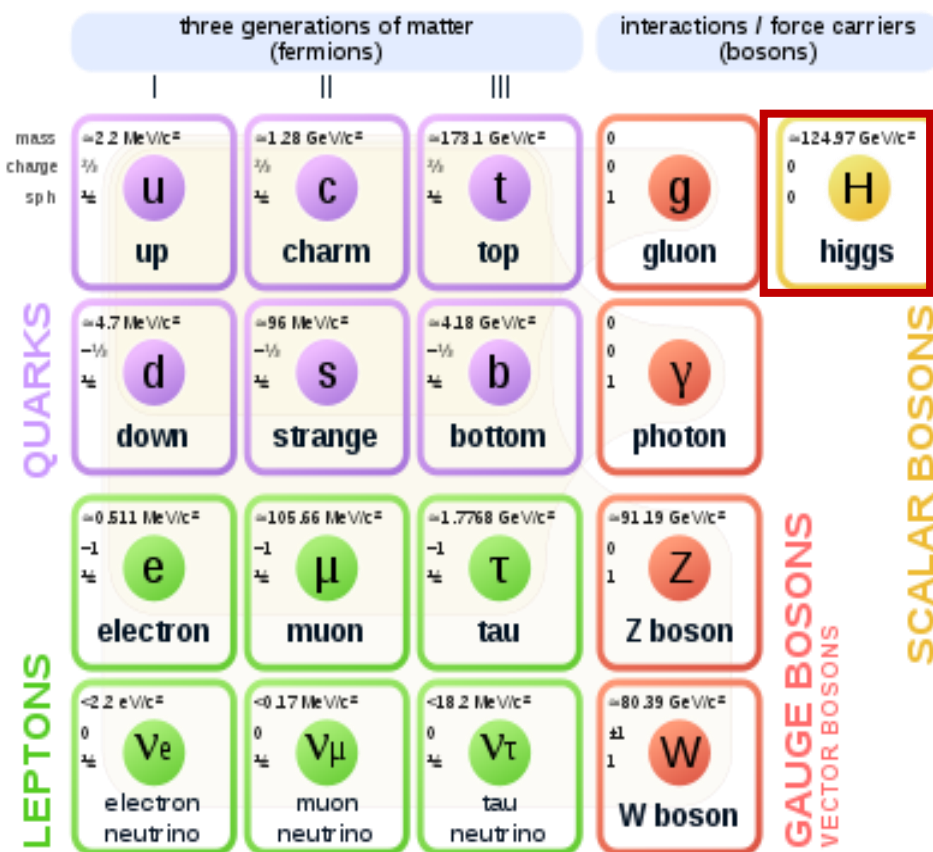


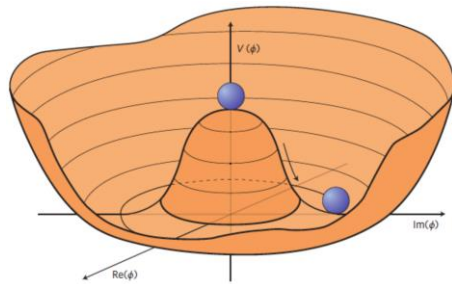
Figure taken from Wikipedia

- Discovery of Higgs boson(2012,LHC): last fundamental particle in SM.
- Experiments at the **ALTA**S and **CMS**: agrees with result SM predicted.
- Problems not solved**: electroweak symmetry breaking, Higgs coupling to SM particles/DM, hierarchy problem... Require new physics beyond SM.
- One promising way probing new physics**: precision measurements of the properties of H (for e.g. **Higgs self coupling**).

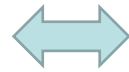
Higgs self coupling



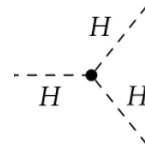
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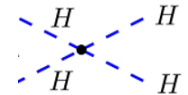
Plot taken from Ellis: [1312.5672](#)



$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_{HHH}^{SM} v H^3 + \frac{1}{4} \lambda_{HHHH}^{SM} H^4$$



Feasible
at HL-LHC



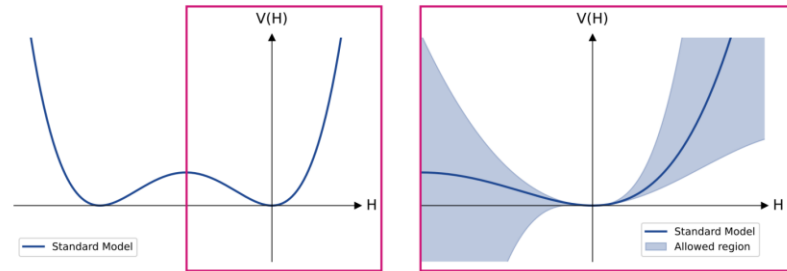
20??



What the SM predicts

vs

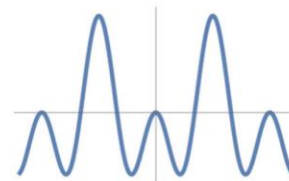
what we know experimentally



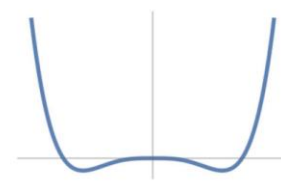
[using current ATLAS limits @ 95% CL]



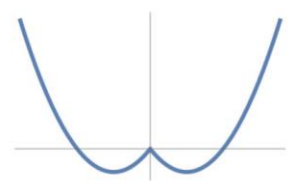
New physics



Nambu-Goldstone Higgs

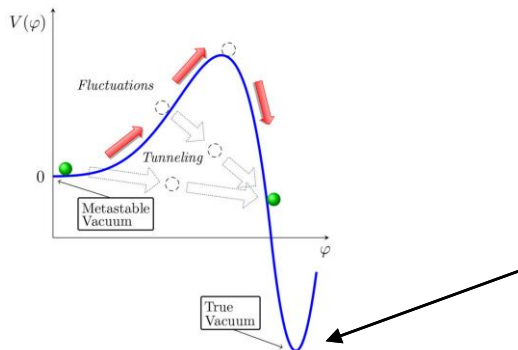


Coleman-Weinberg Higgs



Tadpole-Induced Higgs

Plot taken from Moser: [Higgs 2023](#)



What would
Universe be
like in such
vacuum?



big consequences
for the Universe

Markkanen et al: [1809.06923](#)

Measurements of Higgs boson coupling



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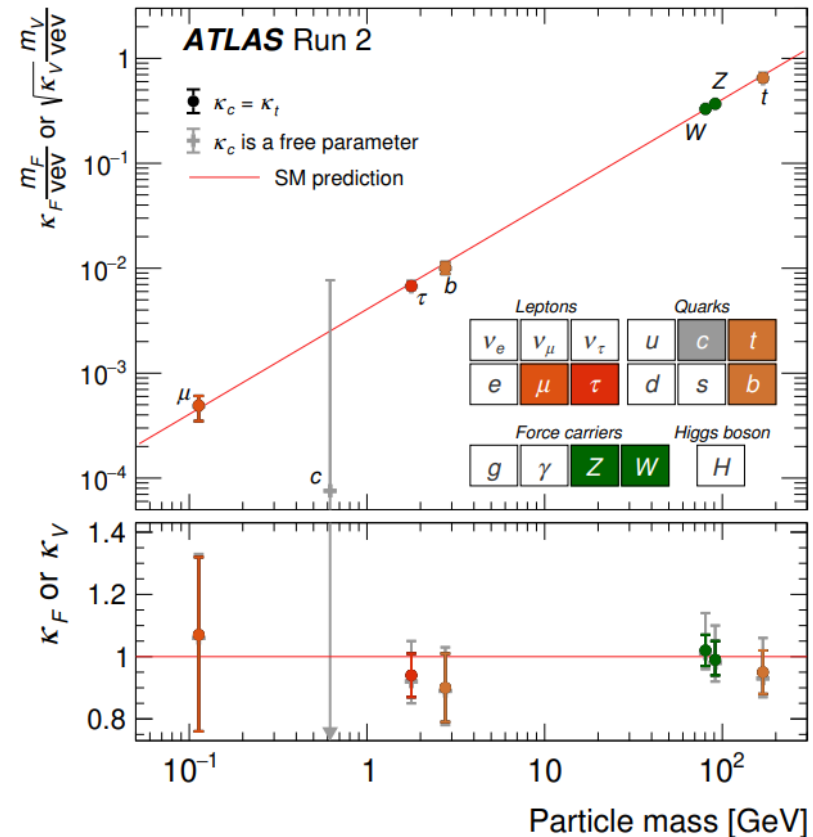
g_{Hff}, g_{HVV}

- can be measured with high precision.



$\lambda_{HHH}, \lambda_{HHHH}$

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



ATLAS:2207.00092

Run 2 δ_μ^{tot} [%]	HL-LHC $\delta_\mu^{\text{tot}} (\delta_\mu^{\text{th}})$ [%]
-------------------------------------	---

$-1.0 < \lambda/\lambda_{\text{SM}} < 6.6$ $0.5 < \lambda/\lambda_{\text{SM}} < 1.5$ Jones: LHEP 2023 (2023) 442

Status of QCD corrections



- 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](#)

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

Importance of EW corrections

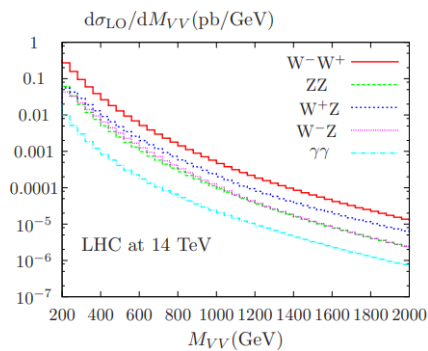


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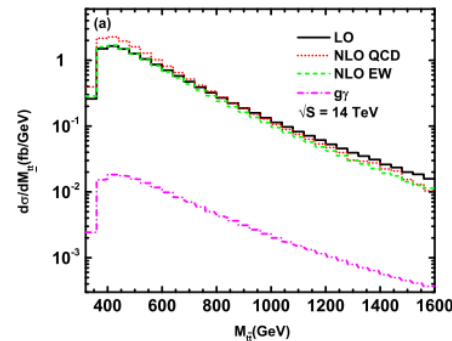
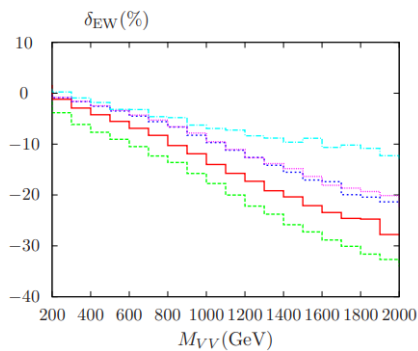


- Unknown size of EW corrections
 - Biggest uncertainties from theoretical side
- NLO EW corrections are notably significant at high energy region

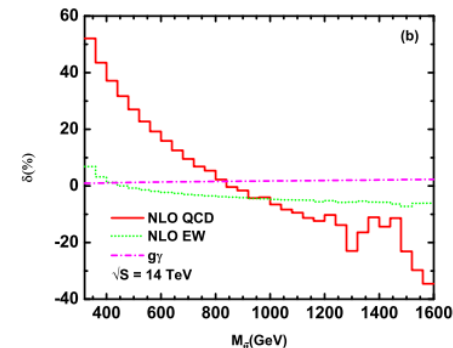
➤ Sudakov enhancement: $\alpha \sim 0.7\% \rightarrow \frac{\alpha}{4\pi \sin^2 \theta_W} \log^2 \left(\frac{s}{m_Z^2} \right) \Big|_{s=2000^2} \sim 10\% \sim \alpha_s$



A Bierweiler et al:1305.5402

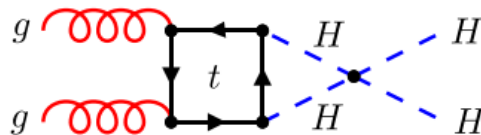


Zhang et al: 1407.1110



- Higgs quartic coupling only emerges at the NLO EW level

➤ Constrained on λ_{HHHH}^{SM} indirectly from NLO EW correction



Status of NLO EW corrections



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- Partial results

- Two-loop box diagrams, [Davies et al:2207.02587](#)
- Top-quark Yukawa corrections, [Muhlleitner et al:2207.02524](#)
- Higgs self-coupling corrections, [Borowka et al: 1811.12366](#)
- HTL and Neglecting diagrams with massless fermion loops, [Davies et al: 2308.01355](#)

- Groups working on this topic:

- See Hantian Zhang's talk at Higgs 2023: [HTL + partial results](#)
- See Xiao Zhang's talk at Higgs 2023: [partial results](#)
- See Thomas Stone's talk at Higgs 2023: [partial results](#)

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

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

Calculation strategy



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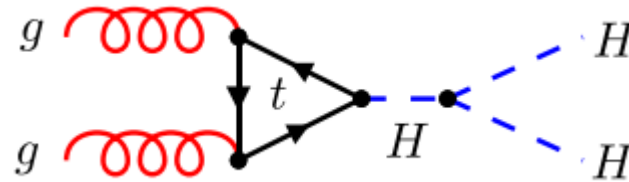
EW corrections to double H production at the LHC



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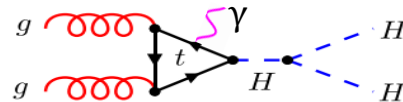
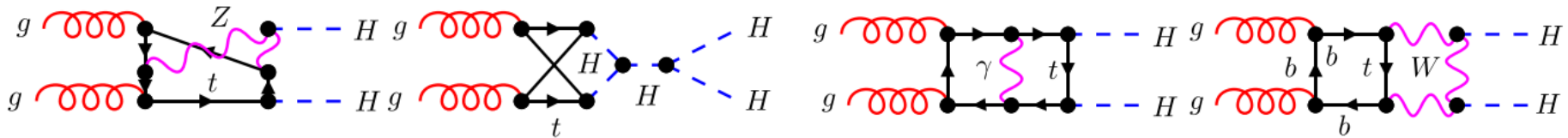


LO diagrams:



Typical Feynman diagrams at LO

NLO diagrams:



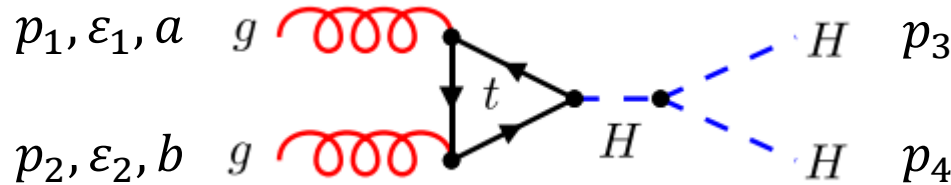
Forbidden due to Furry Theorem

Typical Feynman diagrams at NLO EW

Amplitudes of $gg \rightarrow HH$



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● Amplitude Structure:

$$\mathcal{M}_{ab} = \delta_{ab} \epsilon_1^\mu \epsilon_2^\nu \mathcal{M}_{\mu\nu}$$

$$\mathcal{M}^{\mu\nu} = F_1 T_1^{\mu\nu} + F_2 T_2^{\mu\nu} + \Delta_0^{\mu\nu} + \Delta_5^{\mu\nu}$$

- General decomposition at any number of loop.
- $\Delta_0^{\mu\nu}$: depends on p_1^μ or p_2^ν . No contribution at the matrix element level.
- $\Delta_5^{\mu\nu}$: depends on Levi-Civita tensor. No contribution at the matrix element squared level at NLO EW.
- F_1, F_2 : Form factors.

Calculation of form factors



- Form factors can be decomposed into:

$$F_{1,2}(x) = \sum_i d_i(x) FI_i(x)$$

$$\begin{aligned} x: m_H, m_t, m_W, m_Z, \\ \hat{s} &= (p_1 + p_2)^2, \\ \hat{t} &= (p_1 - p_3)^2. \end{aligned}$$

- Reduce $FI_i(\hat{s})$ to master integrals (IBP):

$$\{FI_i(x)\} = \left\{ \sum_k c_{i,k}(x) I_k(x) \right\}$$

- $d_i(x)$ and $c_{i,k}(x)$ are analytic.
- A huge number of I_k need to be calculated.
- The number of $\{I_k\} < \{FI_i\}$.
- The number of I_k is finite.
- We can construct the different equations for I_k and solve them.

Different equations for I_k



Construct differential equations (DEs): $\vec{I}(x) = \{I_1(x), I_2(x) \dots I_N(x)\}$

$$\frac{dI_m(x)}{dx} = \sum_n A_{m,n}(x) I'_n(x) \xrightarrow{\text{IBP}} \frac{d\vec{I}(x)}{dx} = A(x) \vec{I}(x)$$

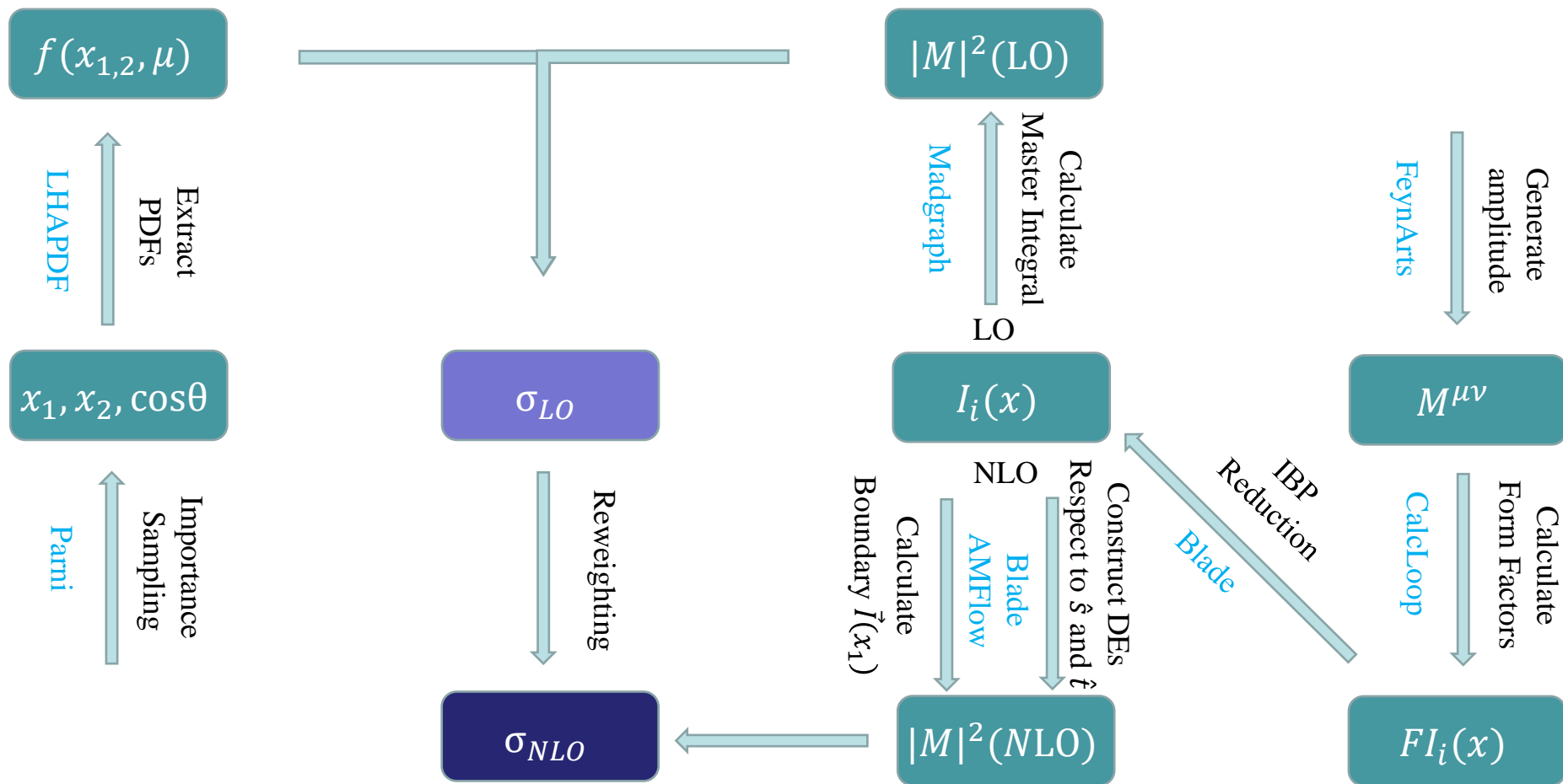
- $\vec{I}(x)$ can be expanded as a **power expansion near x_0** ,

- regular: $S = \{0\}, k_0 = 0$,
- singular: $S = \{-2\epsilon, 1 + \epsilon \dots\}, k_\mu \geq 0$,

$$I_i(x) = \sum_{\mu \in S} (x - x_0)^\mu \sum_{k=0}^{k_\mu} \log(x - x_0)^k \sum_{n=0}^m c_{i,\mu,k,n} (x - x_0)^n$$

- $c_{i,\mu,k,n}$ can be determined once any boundary $\vec{I}(x_1)$ are provided.
- $\vec{I}(x_1)$ can be determined by AMFlow
- Taking adequate **expansion order m** , we can eventually achieve predictions with high precision.
- $\vec{I}(x)$ can be evaluated at any points of x efficiently.

Calculation flowchart



Calculation strategy



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- **Results**
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Input Parameters



$$m_t = 172.69 \text{ GeV}$$

PDG2022

$$\frac{m_H^2}{m_t^2} = \frac{12}{23}, \quad \frac{m_Z^2}{m_t^2} = \frac{23}{83}, \quad \frac{m_W^2}{m_t^2} = \frac{14}{65},$$

$$G_\mu = 1.166378 \times 10^{-5} \text{ GeV}^{-2}$$

$$\alpha = \frac{\sqrt{2}}{\pi} G_\mu m_W^2 \left(1 - \frac{m_W^2}{m_Z^2} \right)$$

CKM=1

PDFs: NNPDF31_nlo_as_0118

on-shell renormalization: masses and fields; G_μ -scheme: Electromagnetic coupling

[Denner et al:1912.06823](#)

$$D=4-2\varepsilon, \quad \varepsilon = \pm 1/1000$$

$$\sigma(\varepsilon) = a_0 + a_1 \varepsilon + a_3 \varepsilon^2 + \dots$$

$$\sigma(0) \sim \frac{\sigma(+1/1000) + \sigma(-1/1000)}{2} = a_0 + a_3 \varepsilon^2 + \dots$$

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: Differential cross sections



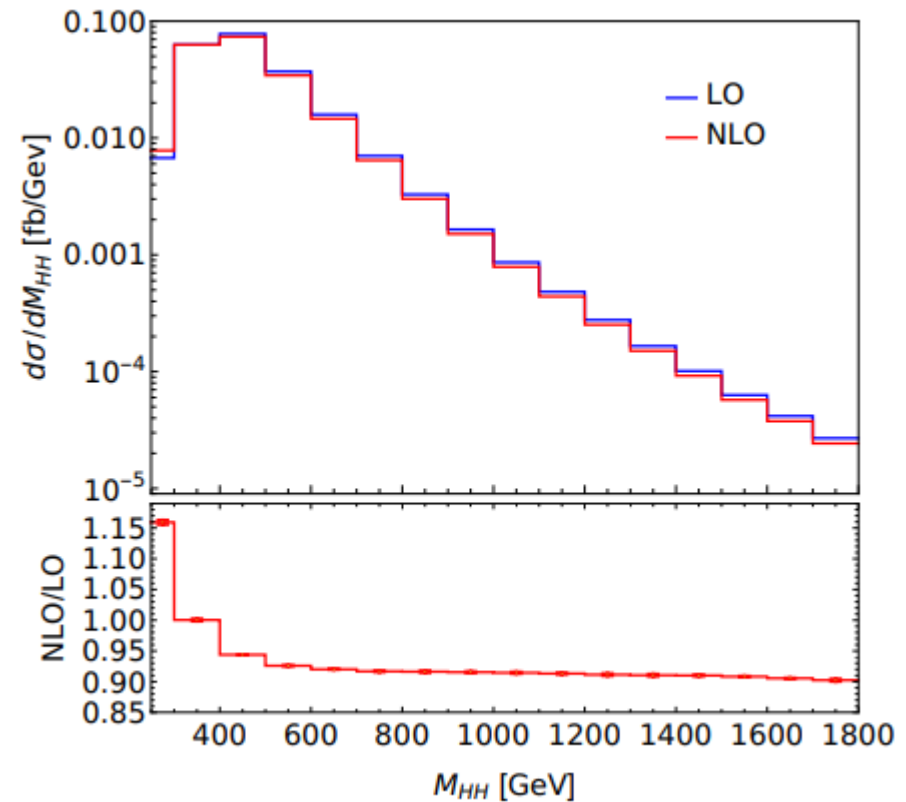
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$$\Delta\sigma^{\text{NLO}} = \Delta\mathcal{K}\Delta\sigma^{\text{LO}}$$

$\Delta\sigma_{LO}$: based on 300k events

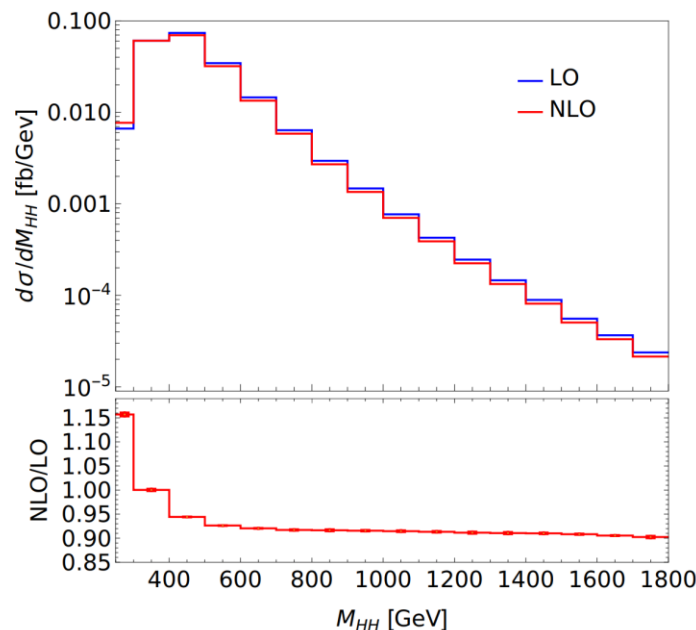
$\Delta\mathcal{K}$: based on 30k events



Results: Differential cross sections



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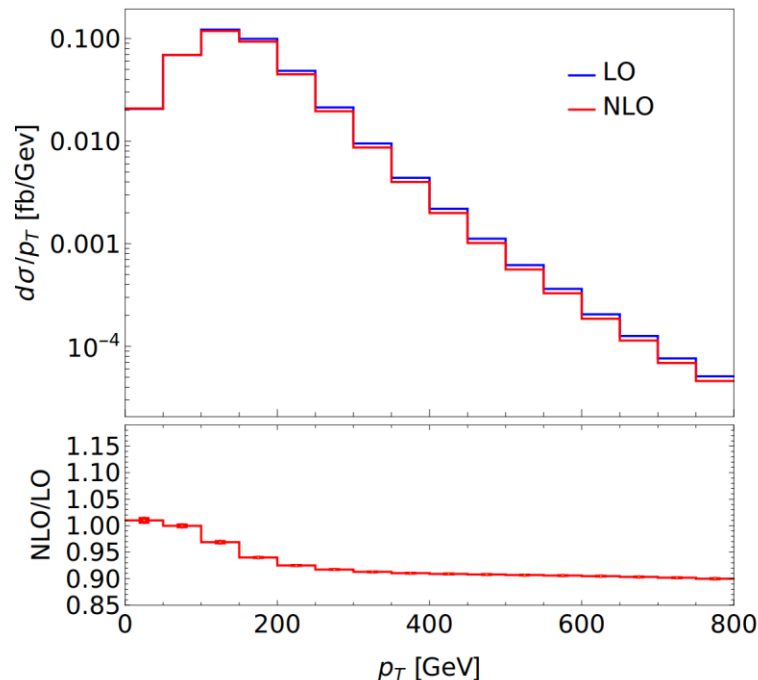


- Big positive corrections at the HH threshold.
 - Enhancement due to $\sigma_{LO}(\sqrt{\hat{s}} = 2m_H) \sim 0$. It is explained in 2207.02524.
- -10% correction at high energy region.
 - EW Sudakov effects.
- Tiny cross section at high energy region
 - Gluon PDFs are highly suppressed at high energy region.

Results: Differential cross sections



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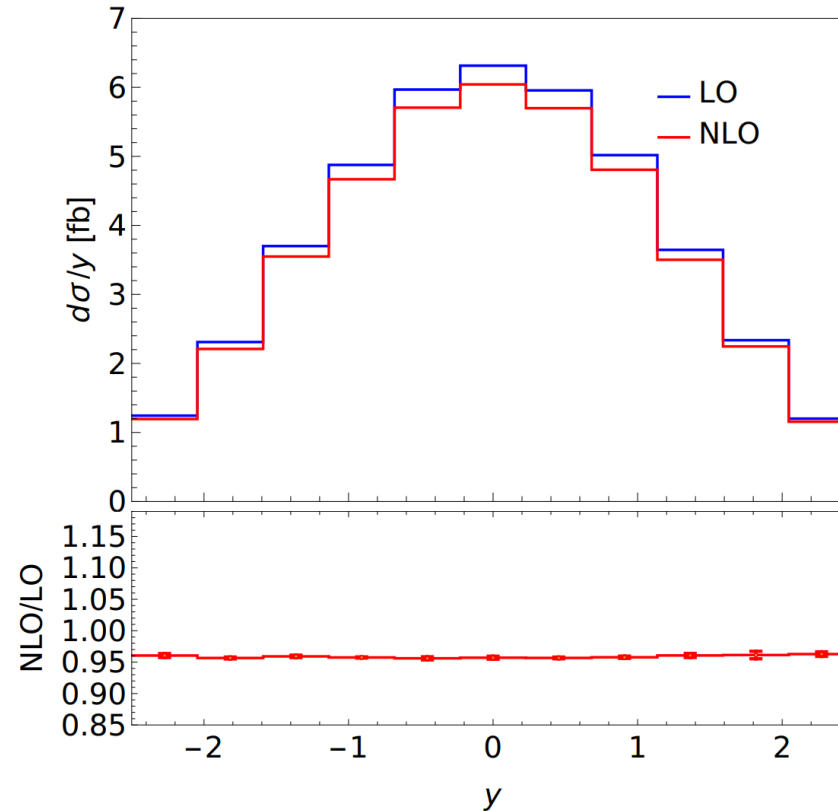


- Positive corrections at the beginning of the spectrum.
 - The events in this region are mixed with high $\sqrt{\hat{s}}$ and low $\sqrt{\hat{s}}$.
- -10% correction at high energy region.
 - EW Sudakov effects.

Results: Differential cross sections



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

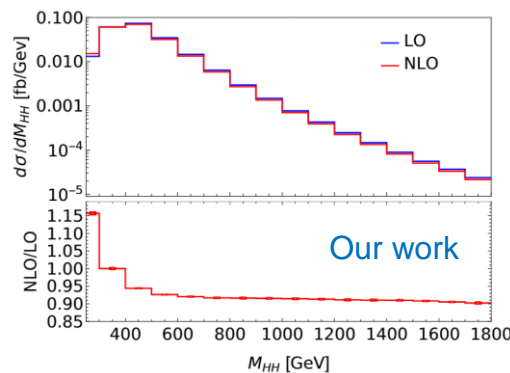
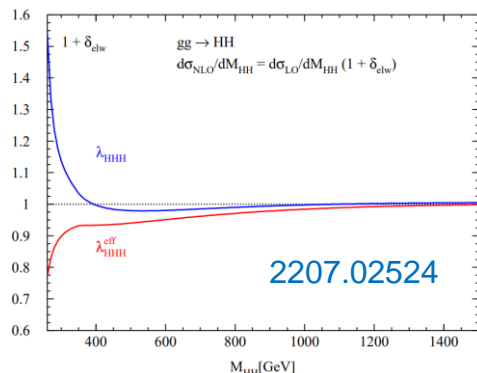
Results: comparisons with other publication



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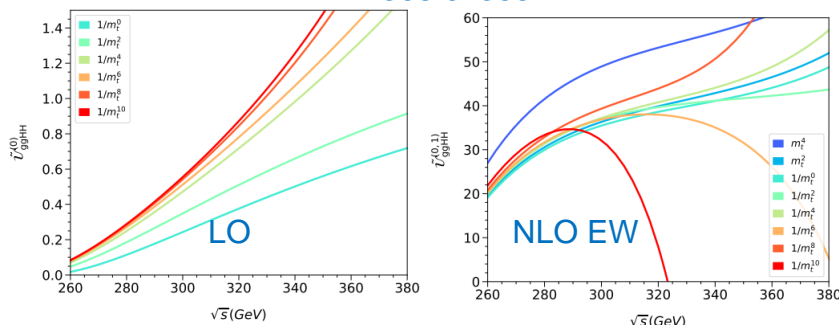
- Top-quark Yukawa corrections, [Muhlleitner et al:2207.02524](#)



- Similar Enhancement at Threshold
- Differences appear at the tail

- HTL and neglecting diagrams with massless fermion loops, [Davies et al: 2308.01355](#)

2308.01355



- ~65% corrections at $\sqrt{s}=260$ GeV
- Our full results reveal the correction is 34% and 57% once neglect the diagram contains only mass less fermion

- Xiao Zhang's talk at Higgs 2023

- ~+1% corrections when only considering Top-Yukawa corrections and Higgs self coupling corrections.
- Our full results reveal the correction is ~-4%.

Summary



- **Higgs self coupling** is important to identify the Higgs potential and to probe new physics.
- The study of $\sigma(\text{HH})$ 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!