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Electroweak corrections to double Higgs production at the LHC

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Introduction to Higgs

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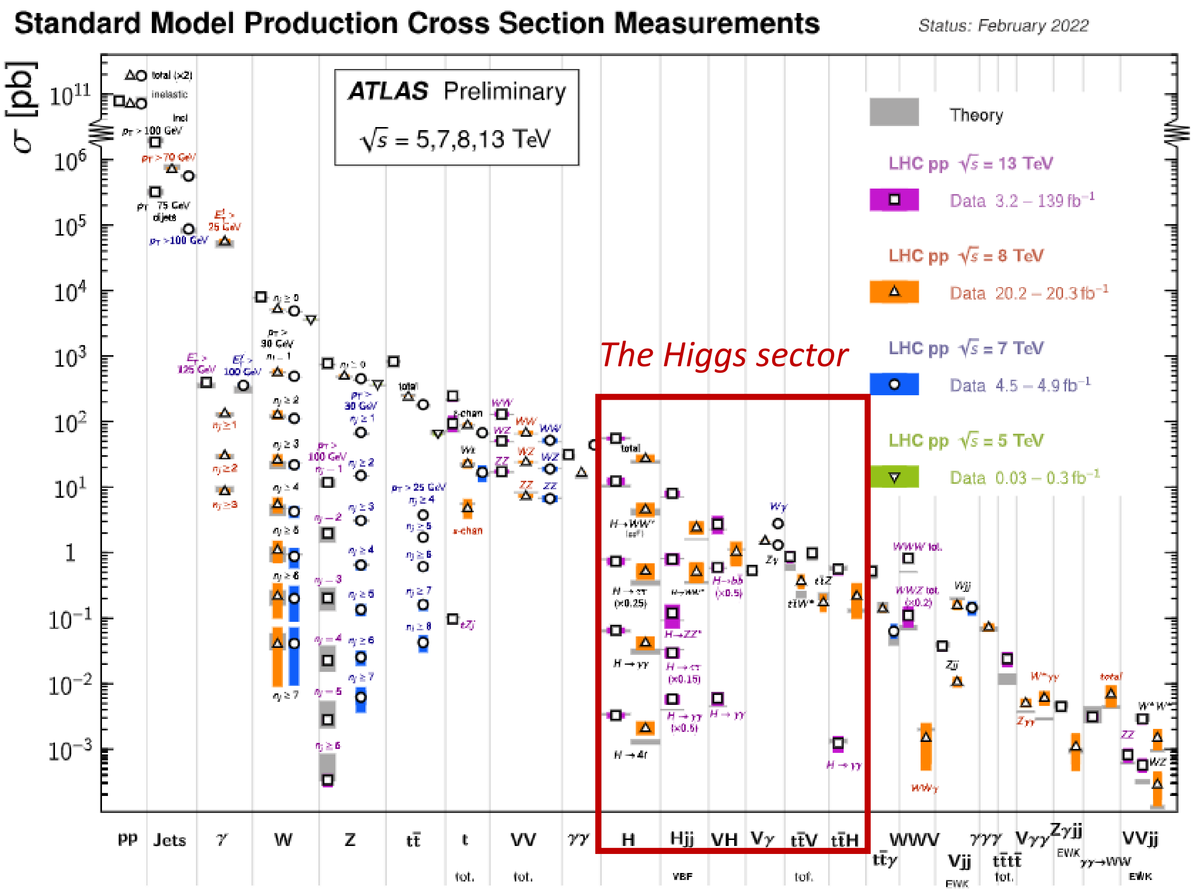
- Discovery of Higgs boson(2012,LHC): the last found elementary particle in SM.

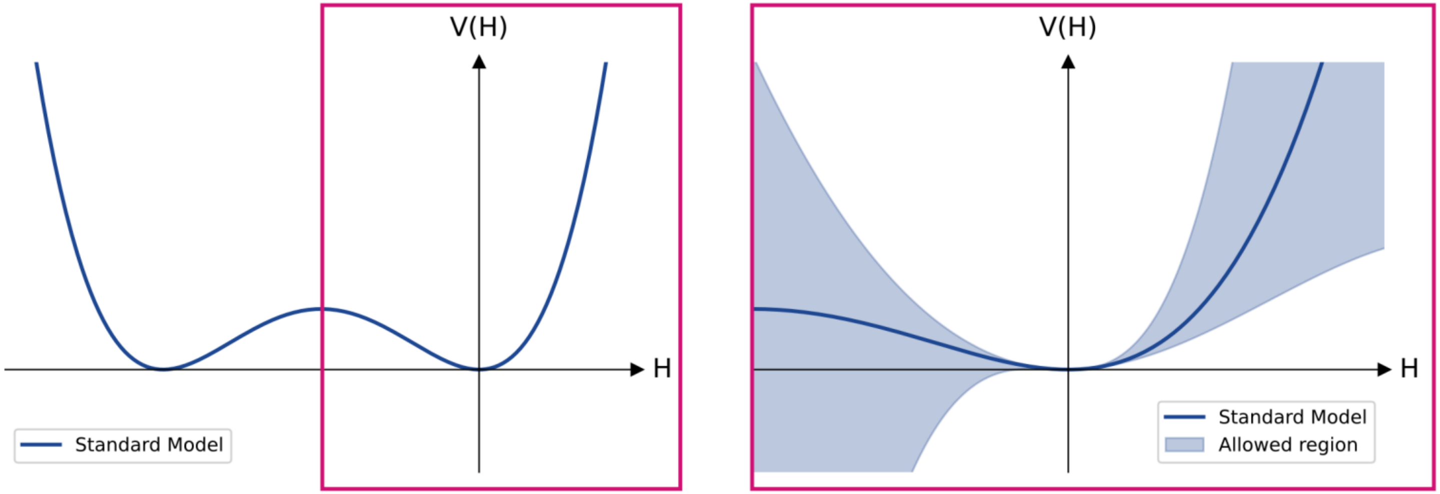
Azzurri: *Int.J.Mod.Phys.A* 38 (2023) 09n10, 23300077



Higgs Potential

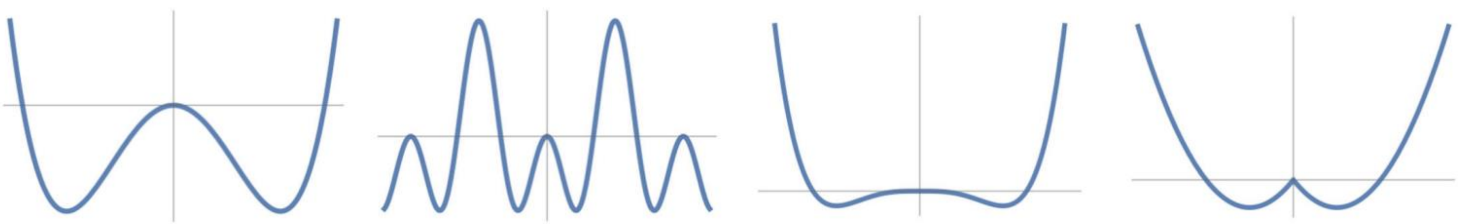
- Problems not clear: shape of Higgs potential, new physics beyond SM…

Plot taken from B. Moser: Higgs 2023



[using current ATLAS limits @ 95% CL]

Agrawal et al: 1907.02078



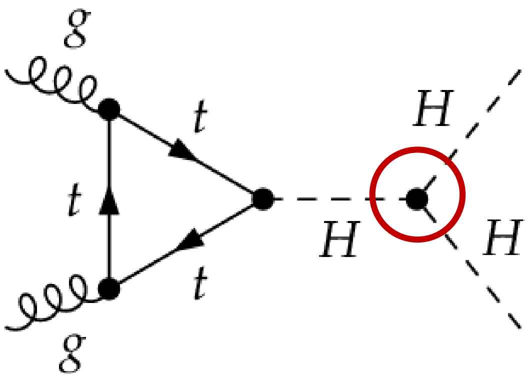
Landau-Ginzburg Higgs | Nambu-Goldstone Higgs | Coleman-Weinberg Higgs | Tadpole-Induced Higgs

Higgs potential predicted by other BSM theories.

Higgs trilinear coupling

- Higgs potential is probed through determining the strength of Higgs boson self-interactions in searches for HH production. $(\lambda^{SM} \approx 1/8)$

$$V(h) = \frac{m_h^2}{2}h^2 + \lambda^{SM} v h^3 + \frac{1}{4}\lambda^{SM} h^4$$



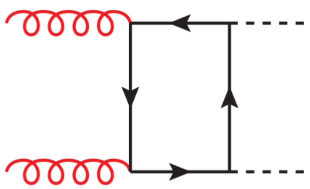
- Experiment constraints on Higgs boson self-interactions:

ATLAS: 2007.02873
CMS: 2202. 09617
Jones: LHEP 2023 (2023) 442

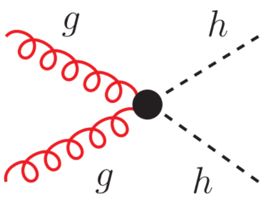
  - Current: $-1.5 < \lambda_{hhh}^{EX}/\lambda^{SM} < 6.7$ for ATLAS, $-2.3 < \lambda_{hhh}^{EX}/\lambda^{SM} < 9.4$ for CMS.
  - Future: a limit of $-0.5 < \lambda_{hhh}^{EX}/\lambda^{SM} < 1.5$ will be achieved.

QCD corrections status

- corrections with full top quark mass dependence
  - NLO corrections keeping top quark mass, Borowka et al:1604.06447
  - NLO corrections matched to parton shower, Heinrich et al:1703.09252
  - NLO corrections with soft-gluon resummation, Ferrera et al: 1609.01691



- corrections in heavy top limit (HTL) approximation
  - $\mathrm{N^2LO}$ in HTL, Florian et al:1305.5206
  - $\mathrm{N^3LO}$ in HTL, Chen et al:1909.06808
  - $\mathrm{N^2LO}$ in HTL+ NLO with full top-quark mass dependence, Florian et al:2106.14050
  - $\mathrm{N^3LO}$ in HTL include the top-quark mass effects, Chen et al:1912.13001
  - $\mathrm{N^2LO}$ in HTL matched to parton shower, Alioli et al: 2212.10489
  - $\mathrm{N^3LO}$ in HTL+ NLO with full top-quark mass dependence + soft-gluon resummation, Ajjath et al:2209.03914



- Current QCD corrections uncertainties: $\mathcal{O}(1\%)$ Jones: LHEP 2023 (2023) 442

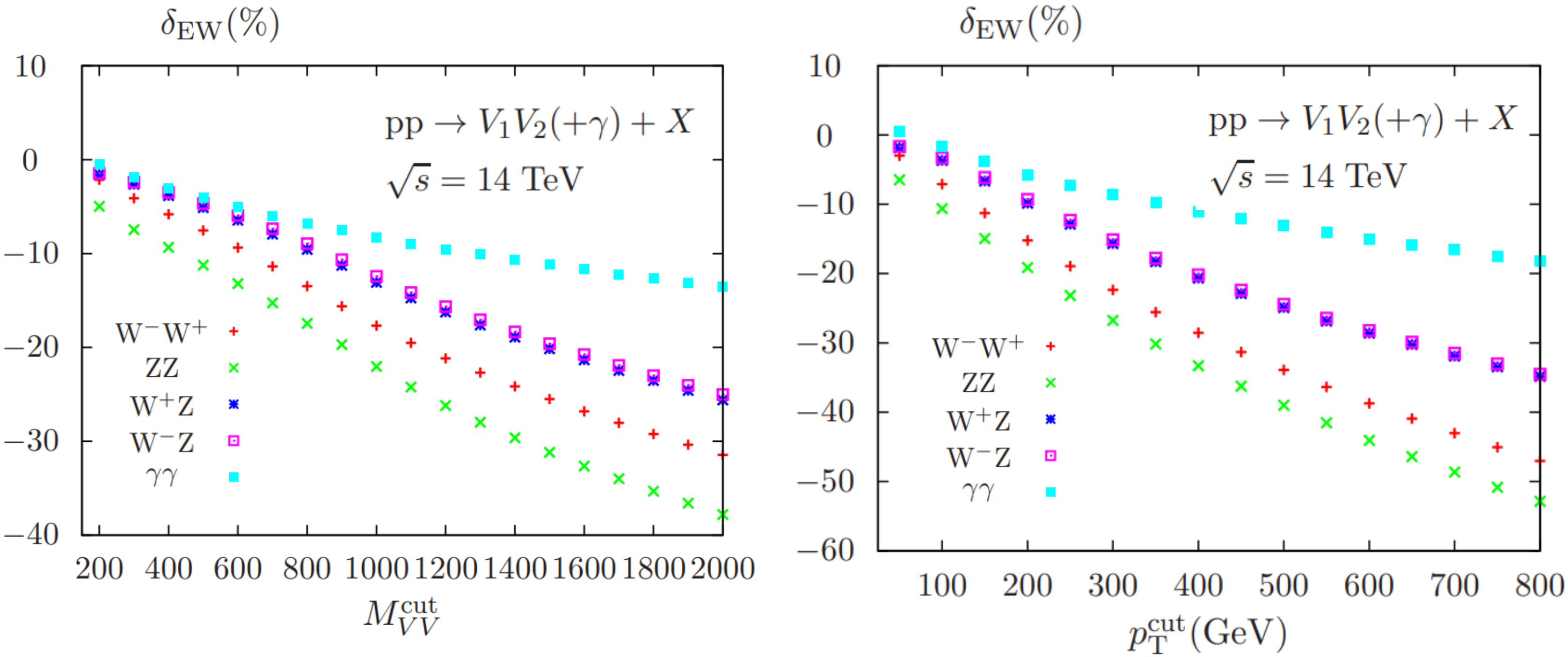
Process	QCD	$\sigma_{th}[pb]$	$\delta_{th}[\%]$
HH production via gg fusion	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NLO_{QCD}}$	0.03105	+2.2 -5.0

Why EW corrections

- EW corrections
  - $\alpha \sim \mathcal{O}(1\%)$, the biggest uncertainty from theoretical side!
  - Sudakov enhancement, $\mathcal{O}(10\% \sim 30\%)$ corrections in high energy region.

Bierweiler et al:1305.5402

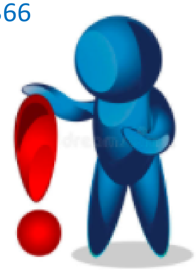
Anderson et al:1605. 04692



- NLO EW corrections are crucial, a focal point in 2015, 2017, 2019 and 2021 Les Houches precision wish lists. Les Houches 2017:1803.07977 Amoroso et al:2003.01700 Huss et al:2207.02122

EW corrections status

- Multiple scales make reduction of scalar integrals and calculation of master integrals difficult.
  - Four mass scales m_H, m_t, m_W, m_Z, two Mandelstam variables $\hat{s}$, $\hat{t}$.
- Recent developments on this topic :
  - Higgs self-coupling corrections in SMEFT, Borowka et al: 1811.12366
  - two-loop box diagrams, Davies et al:2207.02587
  - top-quark Yukawa corrections, Muhlleitner et al:2207.02524
  - NLO EW corrections in large-m_t limit, Davies et al:2308. 01355
  - Yukawa and Higgs self-coupling corrections, Heinrich et al:2407. 04653, Li et at:2407, 14716
  - Comprehensive NLO EW corrections, Bi et al:2311. 16963 — This talk



- A series of developments and efforts have paved the way for full calculation of NLO EW corrections.

Production Rate

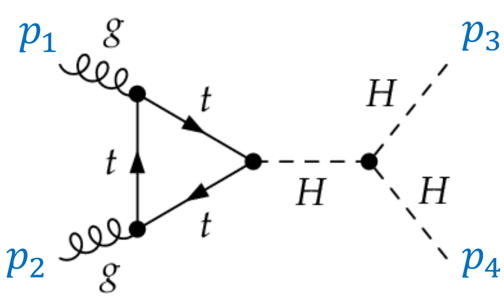
- Di-Higgs production cross section:

gluon PDF

$$\sigma(\mathrm{pp} \to \mathrm{HH}) = \int dx_1\, dx_2 f_g(x_1) f_g(x_2) \hat{\sigma}_{gg\to HH}(\hat{s}, m^2)$$

  - Multiple mass scales, analytic result for $\hat{\sigma}$ is challenging.
  - Monte Carlo integration method can be adopted.

$$\int dx_1\, dx_2 f_g(x_1) f_g(x_2) d\hat{t} \frac{d\hat{\sigma}}{d\hat{t}}(\hat{s}, \hat{t}) = \sum_{i,j} \Delta_{i,j} \times \frac{d\hat{\sigma}}{dt}(\hat{s}_i, \hat{t}_j)$$



$$\begin{cases} \hat{s} = (p_1 + p_1)^2 \\ \hat{t} = (p_1 - p_3)^2 \end{cases}$$

- Lots of numerical results for $d\hat{\sigma}/d\hat{t}$ at different phase space points are required.

Feynman Diagrams

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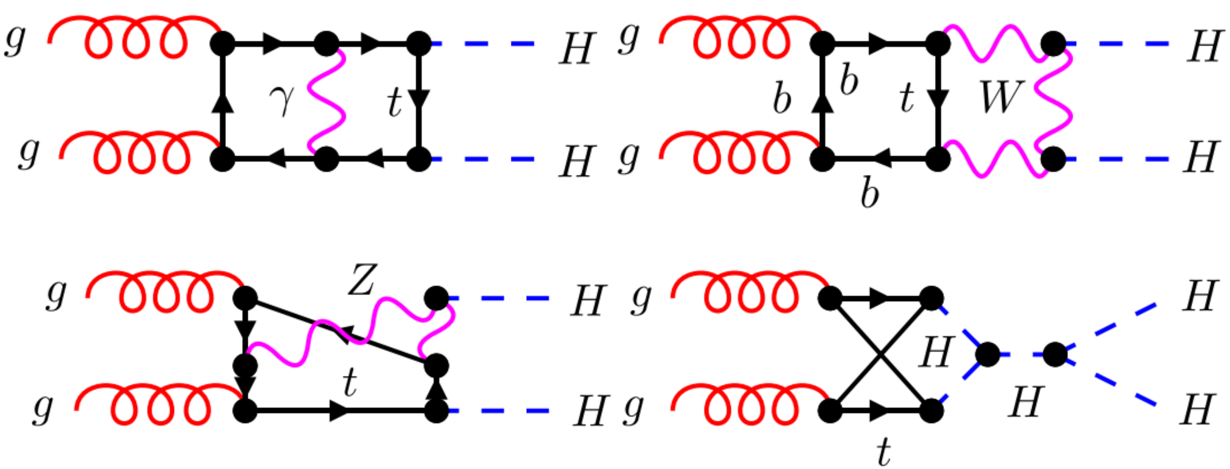
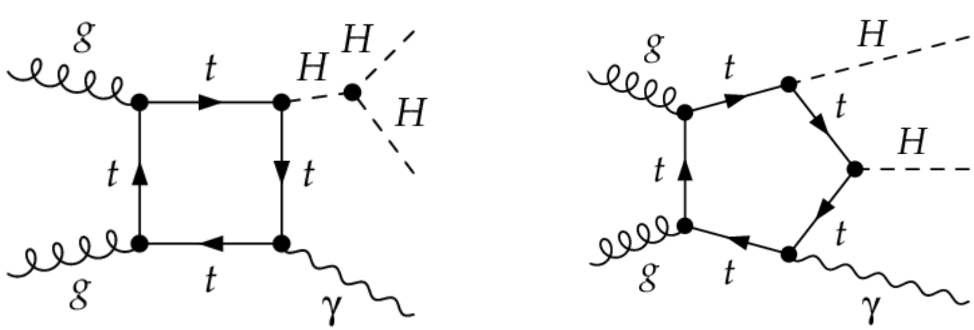
- Generate Feynman diagrams and amplitudes using FeynArts Package.

T. Hahn:0012260

  - 2020 NLO virtual correction diagrams, some typical Feynman diagrams.



  - NLO real corrections are forbidden due to Furry theorem.



Manipulate amplitudes

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- Amplitudes for $g(p_1)g(p_2) \to H(p_3)H(p_4)$, $M_{ab} = \delta_{ab}\epsilon_1^{\mu}\epsilon_2^{\nu}M_{\mu\nu}$
  - Decomposition to form factor:

$$M_{\mu\nu} = F_1(\hat{s},\hat{t},m^2)T_1^{\mu\nu} + F_2(\hat{s},\hat{t},m^2)T_2^{\mu\nu}$$

  - Decomposition to scalar integrals:

To be reduced

$$F_i(\hat{s},\hat{t},m^2) = \sum_j C_{i,j}(\hat{s},\hat{t},m^2) \times \boxed{FI_{i,j}(\hat{s},\hat{t},m^2)}$$

  - Reduction to master integrals using integration-by-part identity, implemented by Blade package.

Guan et al:2405. 14621

https://gitlab.com/multiloop-pku

$$FI_{i,j}(\hat{s},\hat{t},m^2) = \sum_k P_{i,j,k}(\hat{s},\hat{t},m^2) \times \boxed{I_{i,j,k}(\hat{s},\hat{t},m^2)}$$

Key point !

To be calculated, numerical results for $\mathcal{O}(10^4)$ $(\hat{s}_\mathrm{i},\hat{t}_\mathrm{i})$ are required.

Calculate integrals

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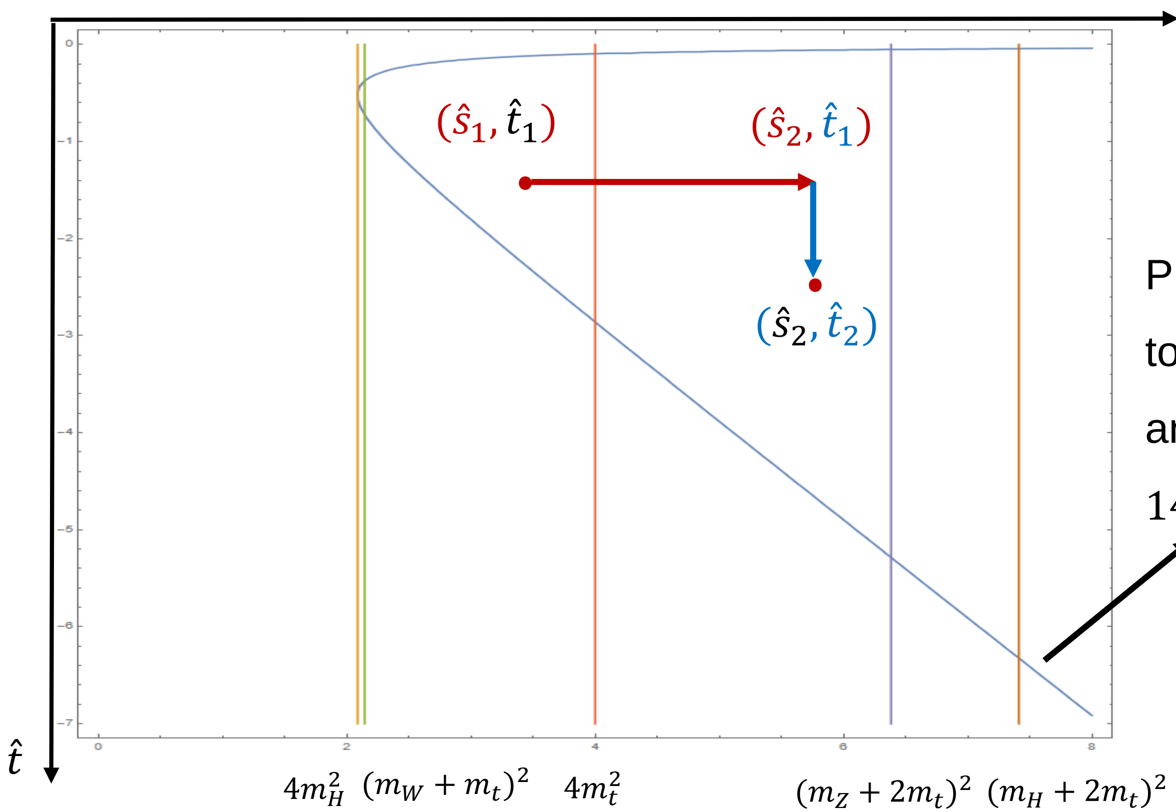
- Calculate integrals for a phase space point:
  - Two dimensional regulator ϵ points ($\epsilon = \pm\frac{1}{1000}$) are sufficient to confirm the cancelation of divergences.
  - 3000 cpu.h run time using AMFlow program package. https://gitlab.com/multiloop-pku Liu et al:2201.11636
- Calculate integrals for 30000 phase space points:
  - $\mathcal{O}(10^8)$ cpu.h run time with all points calculated by AMFlow.
- Calculate integrals using differential equation:
  - Analytical differential equation $\frac{\partial}{\partial\hat{s}}\vec{I} = A_{\hat{s}}\vec{I}, \frac{\partial}{\partial\hat{t}}\vec{I} = A_{\hat{t}}\vec{I}$ provided by Blade.
  - Numerical boundary $\vec{I}(\hat{s}_0, \hat{t}_0)$ provided by AMFlow.
  - Differential equation running method required $\mathcal{O}(10^5)$ cpu.h run time.

DE running

- Physical singularities occur only in $\hat{s}$ direction: $4m_H^2, (m_W+m_t)^2, 4m_t^2, (m_z+2m_t)^2,$ $(m_z+2m_t)^2$.
- Continuation direction for $\hat{s}$ is $+i\delta$.
- Asymptotic expansion at singularities is required in the $\hat{s}$ direction and Taylor expansion is performed in the $\hat{t}$ direction.



Physical boundary corresponds to parallelization between p_1 and p_3.

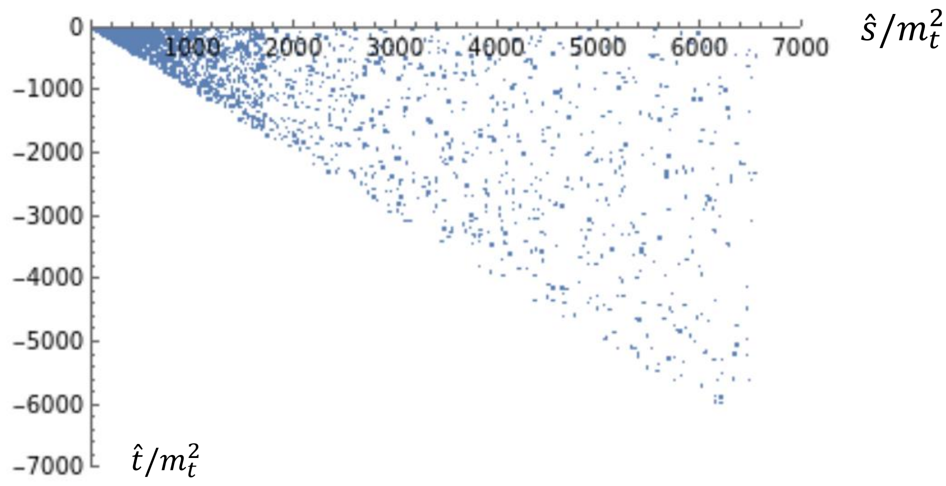
$$144 - 552\hat{t} + 529\hat{s}\hat{t} + 529\hat{t}^2 = 0$$

MC samples

- LO production cross section:

$$\sigma_{\mathrm{LO}} = \sum_{i=1}^{N} \frac{1}{\mathrm{flux}_i} f_g(x_1^i, \mu) f_g\left(x_2^i, \mu\right) |\overline{M_{\mathrm{LO}}^i}(\hat{s}, \hat{t})|^2 \, \Delta x_1^i \, \Delta x_2^i \Delta \Phi_2^i$$

  - μ is factorization scale and $\Delta\Phi_2$ corresponds to the element of phase space integral, $\Delta\Phi_2 \sim \Delta\hat{t}$.
  - Importance sampling based on LO cross section:



  - Samples are sparse at high energy region due to the suppression of gluon PDFs.

Total cross sections

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- Input parameters
  - $\alpha = \frac{\sqrt{2}}{\pi} G_\mu m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right), \frac{m_H^2}{m_t^2} = \frac{12}{23}, \frac{m_Z^2}{m_t^2} = \frac{23}{83}, \frac{m_W^2}{m_t^2} = \frac{14}{65}, m_t = 172.69 \text{ GeV}$

    $G_\mu = 1.166378 \times 10^{-5} \text{ GeV}^{-2}, \alpha = 1/133.12$
  - NNPDF3.1 PDF set
- Renormalization
  - On-shell renormalization for masses and fields.
  - G_μ-scheme renormalization for electromagnetic coupling.
- Results: 1.8×10^4 events
  - K factor is stable. Differences are around 20% at LO and NLO cross sections.
  - -4% NLO EW corrections.

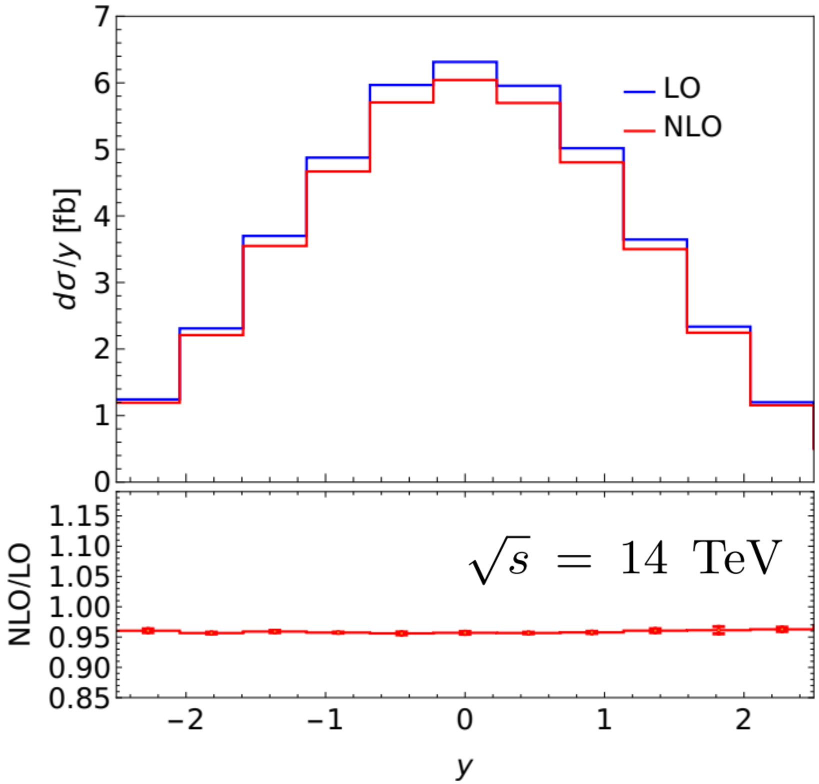
μ	$M_{HH}/2$	$\sqrt{p_T^2 + m_H^2}$	m_H
LO	19.96(6)	21.11(7)	25.09(8)
NLO	19.12(6)	20.21(6)	23.94(8)
$\mathcal{K}$-factor	0.958(1)	0.957(1)	0.954(1)

y differntial distribution

- The differential K factor can get a controllable error with far fewer events

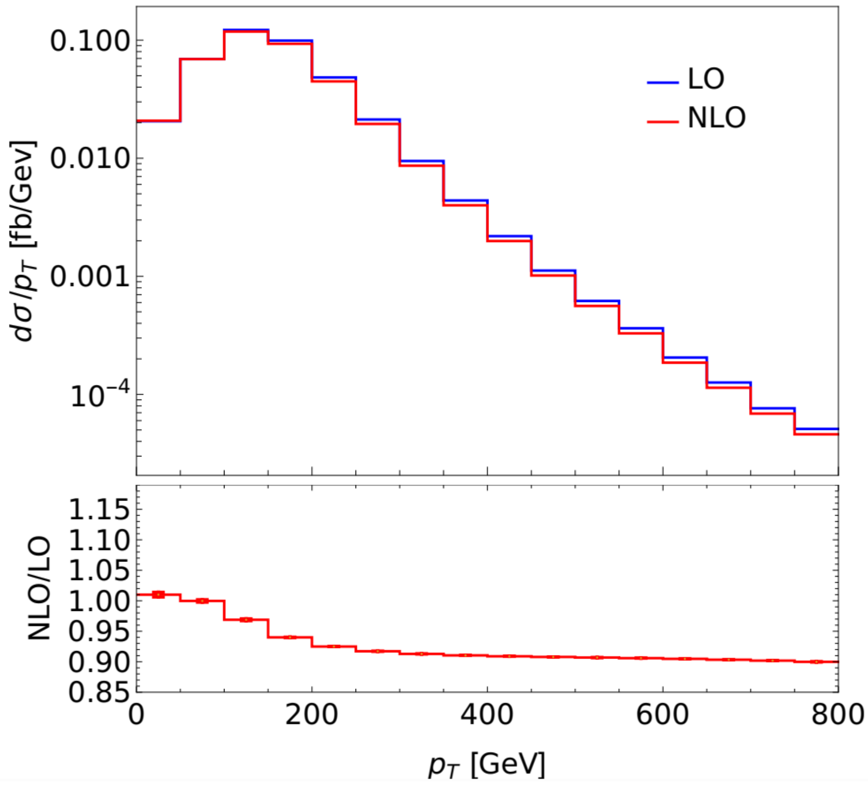
$$\Delta\sigma^{\mathrm{NLO}} = \Delta\sigma^{\mathrm{LO}} \times \Delta\mathrm{K}$$

- $\Delta\sigma^{\mathrm{LO}}$ uses 3×10^5 events.
- $\Delta\mathrm{K}$ uses 1.8×10^4 events for σ and additional 400 events for each bin.
- Up to NLO, $\mathrm{K} \approx 0.96$.

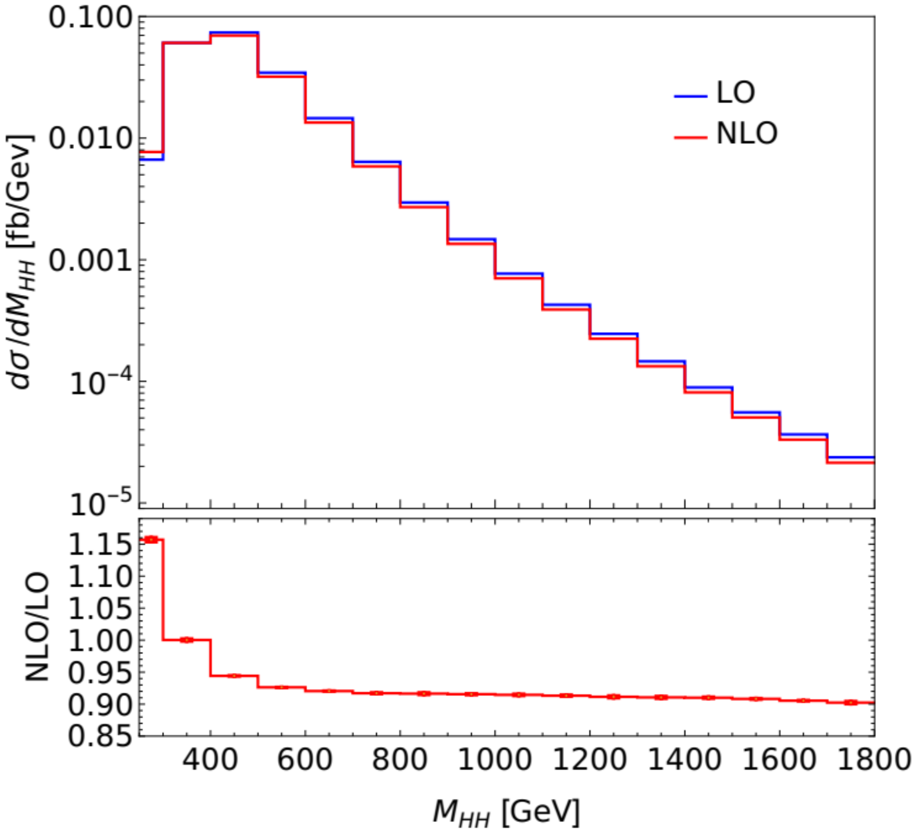


p_T differntial distribution

- -10% NLO corrections at the tail, Sudakov enhancement.



M_{HH} differntial distribution



- $+15\%$ NLO corrections at the beginning of spectrum.
- -10% corrections in the tail, similar to p_T differential distribution. Sudakov enhancement.

Cross Check

- NLO EW corrections in large-m_t limit: Davies et al:2308. 01355
  - Performed a $1/m_t$ expansion in the heavy top limit.
  - Expansion results converge well for a top mass above 200 GeV.
  - We choose a non-physical top-quark mass m_t=244.22 GeV to compare with their results of NLO corrections.

PKU group	KIT group
316.1%	316.3%

- Yukawa and Higgs self-coupling corrections: Li et at:2407, 14716

	PKU group	SDU group
Higgs-Higgs	-1.395%	-1.401%
Higgs-Yukawa	2.345%	2.355%

  - These minor differences can be attributed to variations in input parameters.

Summary

- Higgs trilinear coupling is important.
- NLO EW correction to total cross sections is about -4%.
- -4% NLO EW corrections to rapidity distribution.
- $+15\%$ NLO corrections at the beginning of spectrum for the $\mathrm{M_{HH}}$, Sudakov effect was observed for both p_T and $\mathrm{M_{HH}}$ distribution.
- Sufficient precision from current QCD corrections and NLO EW corrections for measurements at the HL-LHC.

Thanks for your attention!