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Electroweak corrections to double Higgs production at the LHC

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中山大學
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Based on: arvix: 2311.16963

In cooperation with:
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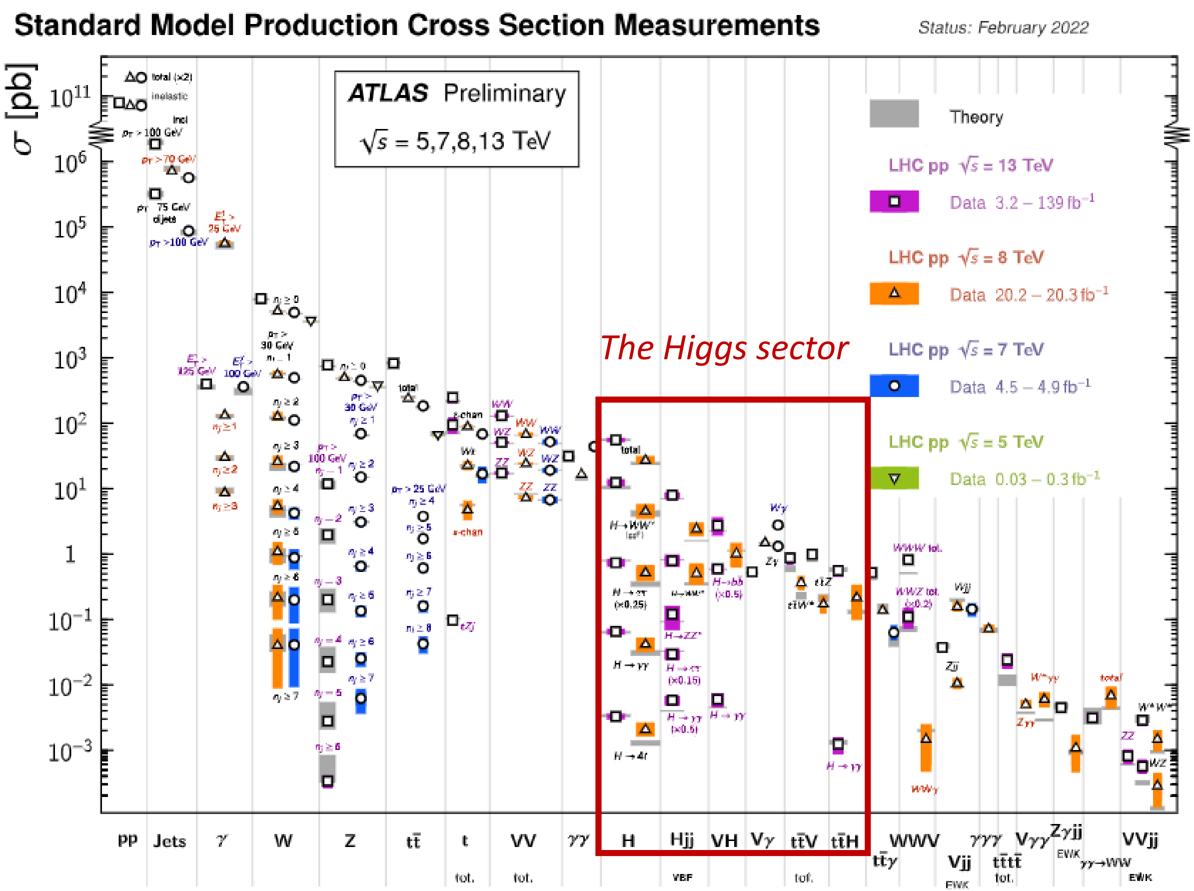
Introduction to Higgs

- Discovery of Higgs boson(2012,LHC): the last found elementary particle in SM
- Experiments at the ALTAS and CMS: consistent with the results predicted by SM

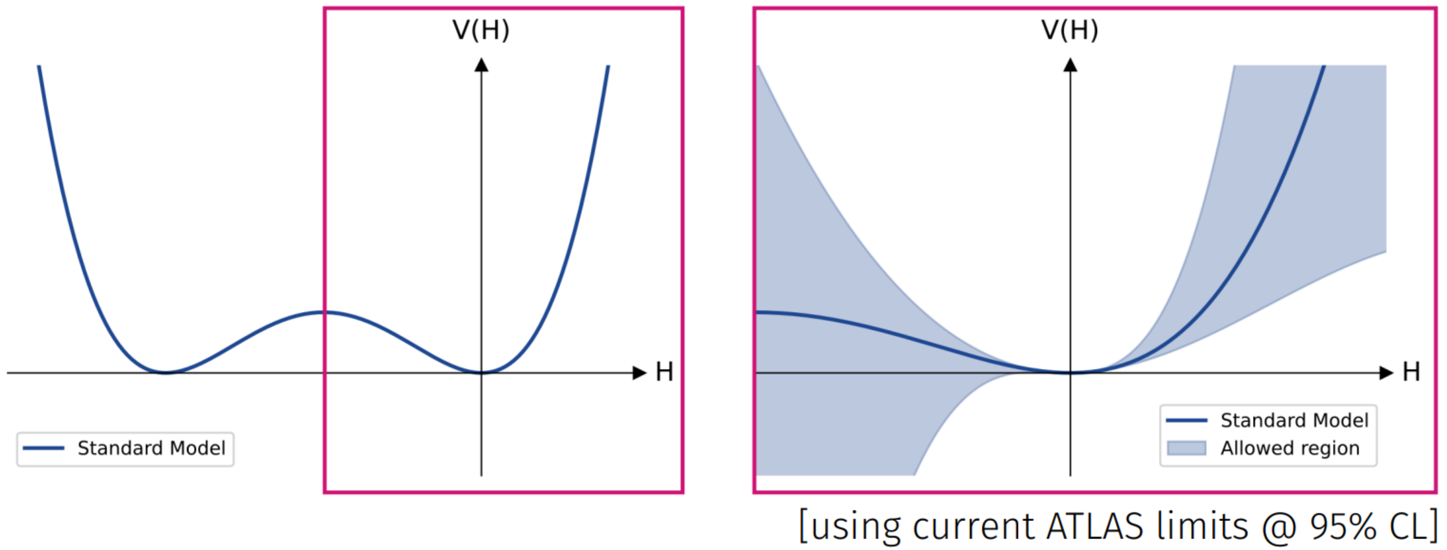
Azzurri: *Int.J.Mod.Phys.A* 38 (2023) 09n10, 23300077



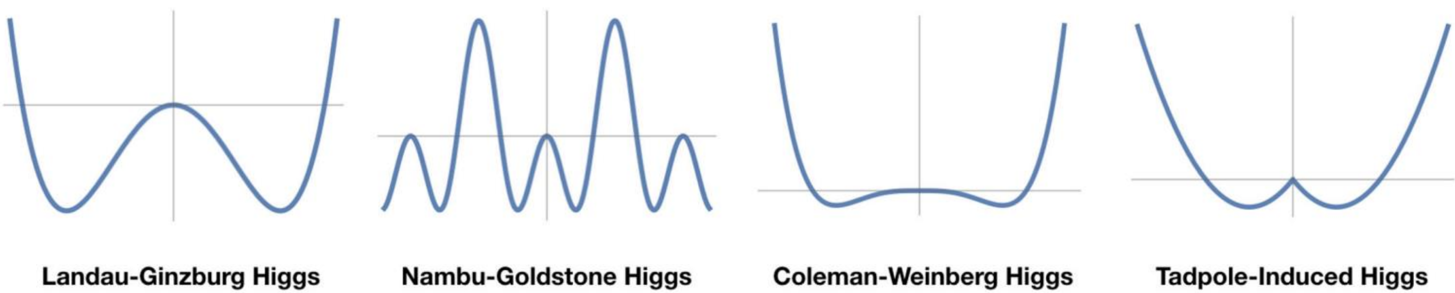
Higgs Potential

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

Plot taken from Moser: Higgs 2023



Agrawal et al: 1907.02078

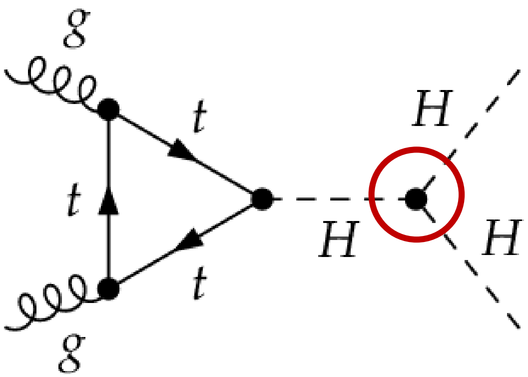


Higgs potential predicted by other BSM theories.

Higgs trilinear coupling

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

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



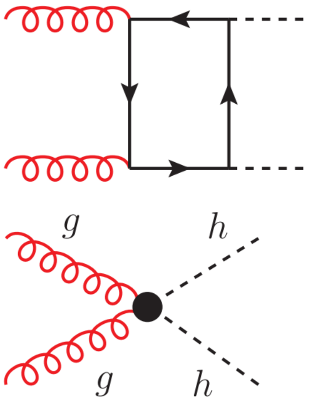
- Experiment constraints on Higgs boson self-interactions:

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

- QCD corrections
  - 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 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 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



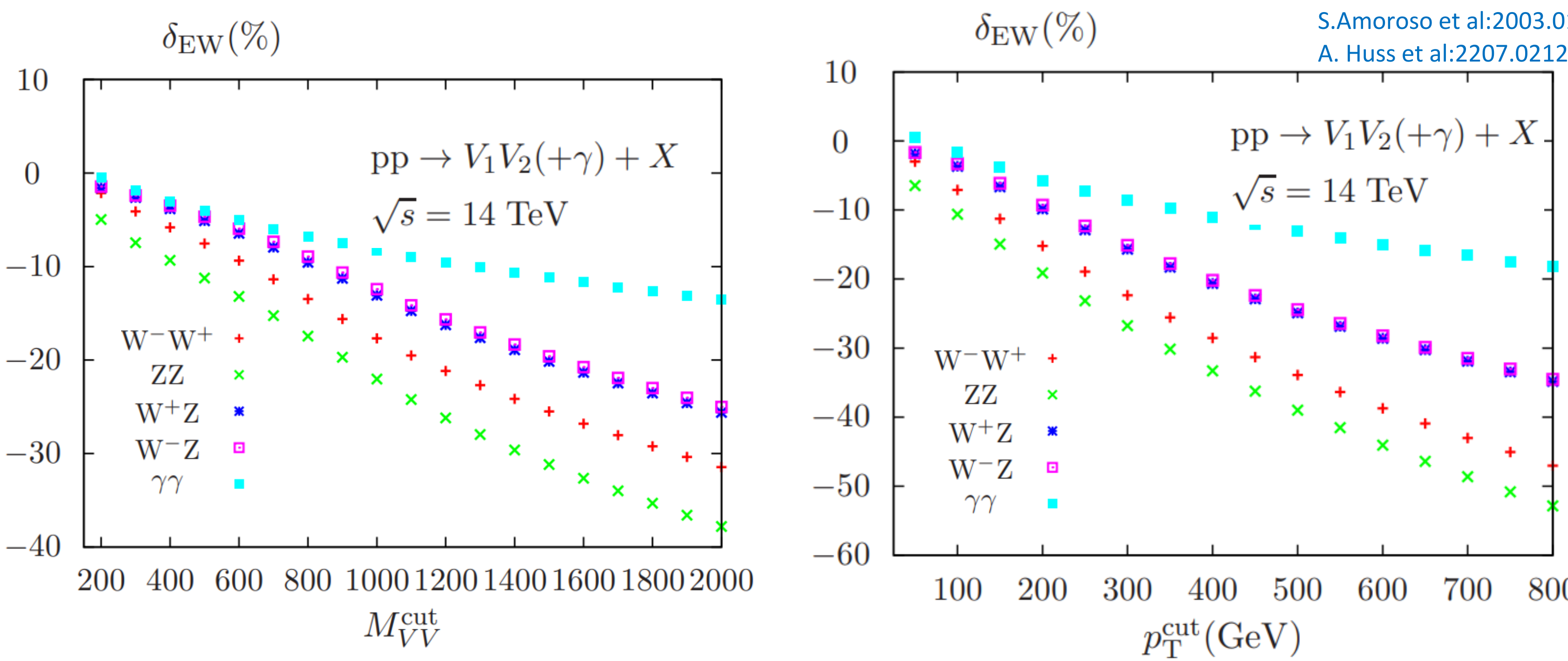
- Current theoretical uncertainties: $\mathcal{O}(1\%)$ Jones: LHEP 2023 (2023) 442

Process	QCD	$\sigma_{th}[pb]$	$\delta_{th}[\%]$
HH production via gg fusion	N^3LO_{HTL} 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 at high energy region. A Bierweiler et al:1305.5402
  - NLO EW corrections are crucial, a focal point in 2015, 2017, 2019 and 2021 Les Houches precision wish lists

J.R. Anderson et al:1605. 04692
Les Houches 2017:1803.07977
S.Amoroso et al:2003.01700
A. Huss et al:2207.02122



EW corrections status

- 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
- Most recent work: Davies et al: 2308.01355
  - HTL and the convergent behavior is not good.
  - Neglecting diagrams with massless fermion loops.
  - Only prediction at the matrix element squared level.
- Groups working on this topic: https://indico.ihep.ac.cn/event/18025/
  - See talk by KIT group at Higgs 2023: HTL + partial results
  - See talk by ShanDong University group at Higgs 2023: partial results
  - See talk by Durham University group at Higgs 2023: partial results

Production Rate

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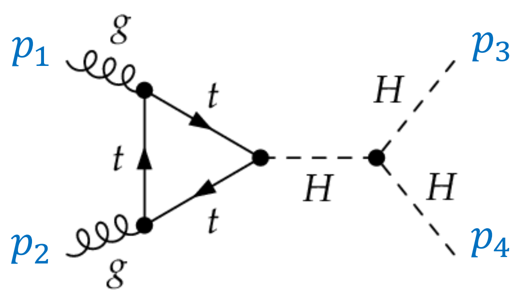
- Di-Higgs production cross section:

gluon PDF

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

  - Kinematics invariants and mass scales include $m_h, m_t, m_W, m_Z, \hat{s},\ \hat{t},$



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

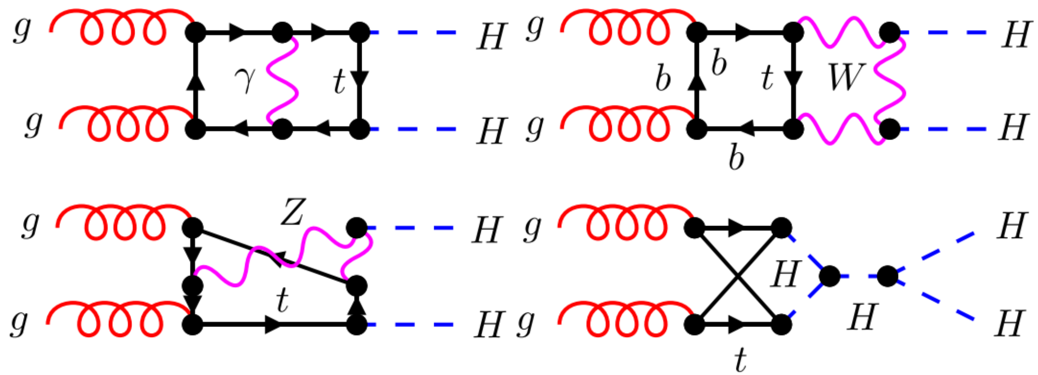
  - Multiple mass scales, analytic result for $\hat{\sigma}$ is challenging.
  - Monte Carlo integration method can be adopted.

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

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

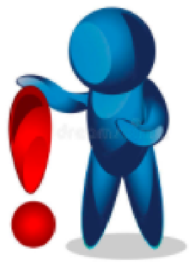
Calculation procedure

- Numerical results for $d\hat{\sigma}/d\hat{t}$ at a phase space point $(\hat{s}_i, \hat{t}_j)$ can be evaluated using following steps:
  - Generate Feynman amplitudes: 8 LO diagrams, 2020 NLO diagrams T. Hahn:0012260



  - Manipulate amplitudes to obtain scalar integrals. CalcLoop
  - Reduce scalar integrals to master integrals. Blade
  - Calculate master integrals. AMFlow
  - Remove divergence via renormalization

ABC trilogy for multi-loop calculation



https://gitlab.com/multiloop-pku

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

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

  - Reduction to master integrals

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

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

Calculate integrals

- Calculate integrals for a phase space point
  - Mass parameters input: $\frac{m_H^2}{m_t^2} = \frac{12}{23}, \frac{m_Z^2}{m_t^2} = \frac{23}{83}, \frac{m_W^2}{m_t^2} = \frac{14}{65}, m_t^2 = 1$
  - Only two dimensional regulator ϵ points ($\epsilon = \pm \frac{1}{1000}$) are required, efficiency enhanced
  - 3000 cpu.h run time
- Calculate integrals for $\mathcal{O}(10^4)$ phase space points
  - 3×10^4 phase space points
  - $\mathcal{O}(10^8)$ cpu.h run time with all points calculated by AMFlow
  - Differential equation running method, $\mathcal{O}(10^5)$ cpu.h run time

Total cross sections

- Input parameters
  - $\alpha = \frac{\sqrt{2}}{\pi} G_\mu m_W^2 \left(1 - \frac{m_W^2}{m_Z^2}\right)$ $m_t = 172.69$ GeV $\alpha = 7.512 \times 10^{-3}$

    $G_\mu = 1.166378 \times 10^{-5}$ GeV^{-2}
  - NNPDF3.1 PDF set
  - NNPDF31_nlo_αs_0118 for both LO and NLO calculations
- Renormalization
  - On-shell renormalization for masses and fields
  - G_μ-scheme renormalization for electromagnetic coupling A. Denner: 1912.06823
- Results: 1.8×10^4 events
  - observed differences with varying μ are around 20%
  - Correction factor $[-4.6\%, -4.3\%]$ for different μ, $\mathcal{O}(0.1\%)$ EW corrections beyond NLO
  - -4% NLO EW corrections

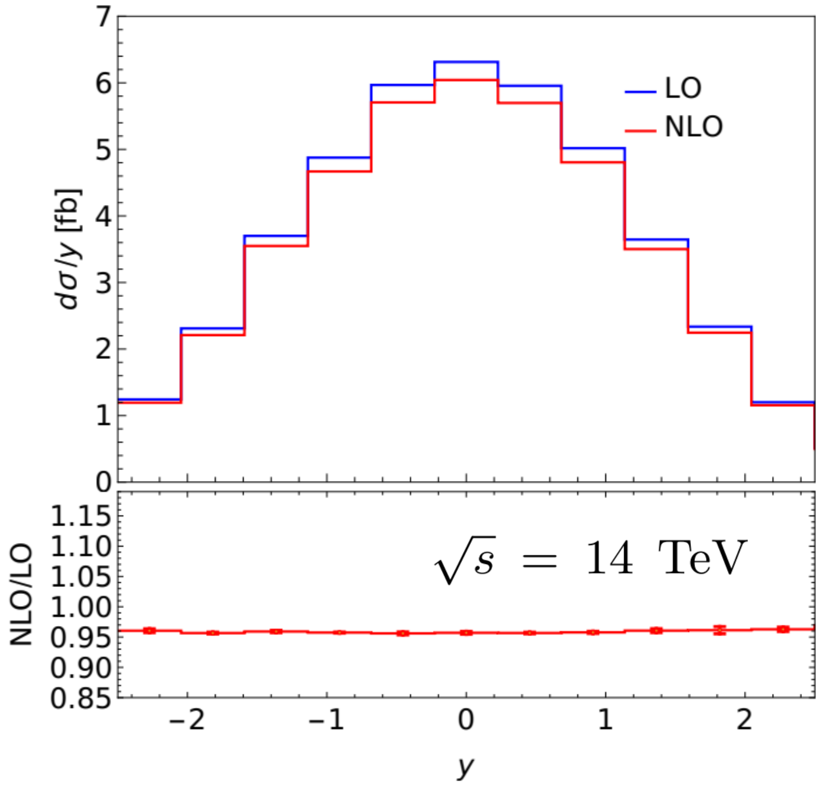
μ	$M_{HH}/2$	$\sqrt{p_T^2 + m_H^2}$	m_H
LO	19.96(6)	21.11(7)	25.09(8)
NLO	19.12(6)	20.21(6)	23.94(8)
$\mathcal{K}$-factor	0.958(1)	0.957(1)	0.954(1)

y differntial distribution

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

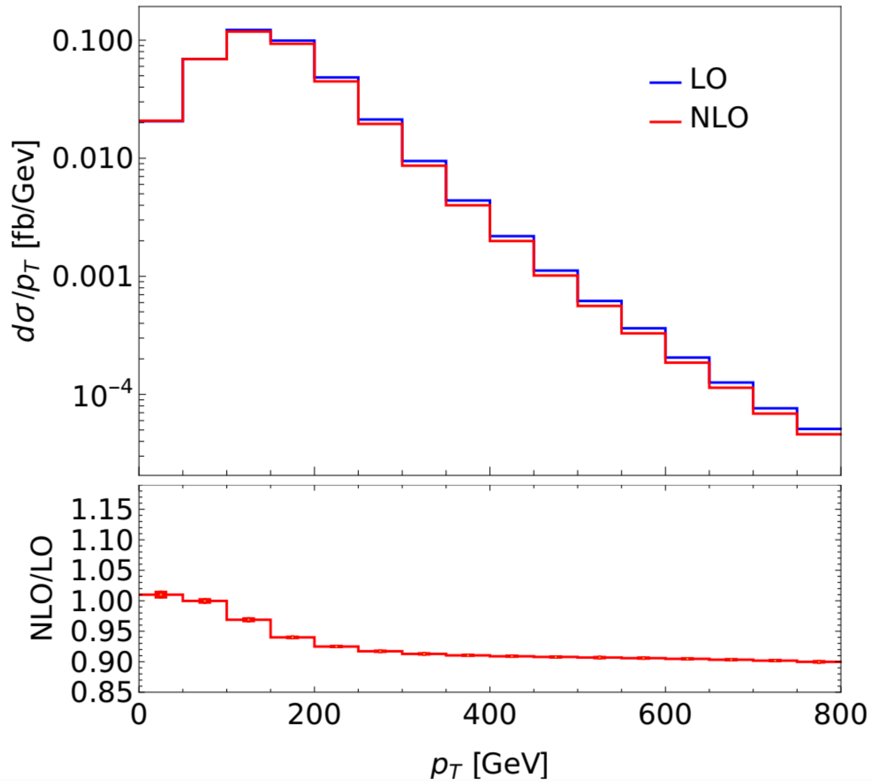
$$\sigma^{\mathrm{NLO}} = \mathrm{K} \times \sigma^{\mathrm{LO}}$$

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

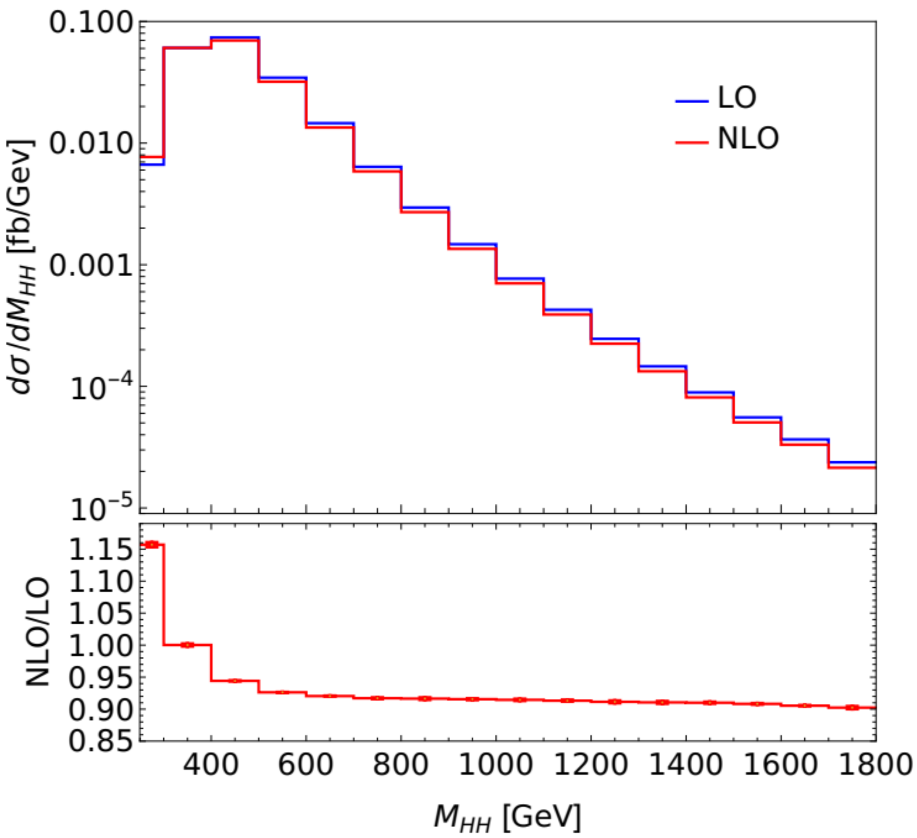


p_T differntial distribution

- -10% NLO corrections in the tail



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

Summary

- Higgs trilinear coupling is important
- Differential equation running method is efficient
- NLO EW corrections 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
- The uncertainties from $\mathrm{N^2LO}$ EW corrections are overall about $\mathcal{O}(0.1\%)$, sufficient precision from current QCD corrections and NLO EW corrections for measurements at HL-LHC

Thanks for your attention!