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Precision Study on $t\bar{t}H$ production

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Outline

- Introduction
- Details of the calculation
- Results
- Summary

Introduction

Background

- Discovery of Higgs boson 2012:

  ⇒ Standard Model completed no direct evidence for physics beyond SM

- Future tasks:
  - ➢ precise investigation of Higgs boson
  - ➢ precise study of other SM processes
  - ➢ search for physics beyond SM
- Decent predictions require higher-order corrections

Automation of NLO QCD corrections

- Feynarts&Formcalc
- BLACKHAT
- NJET
- HELACNLO
- GOSAM
- OPENLOOPS
- MadGraph5_aMC@NLO

Relevance NLO Electroweak (EW) corrections

- Naively: $O(\alpha) \sim O(\alpha_s^2) \sim$ few %
- EW corrections can be enhanced:

  high energy scales, $E \gg M_W$

  $\Rightarrow$ Sudakov logarithms $\sim \ln^2\left(\frac{E^2}{M_W^2}\right)$

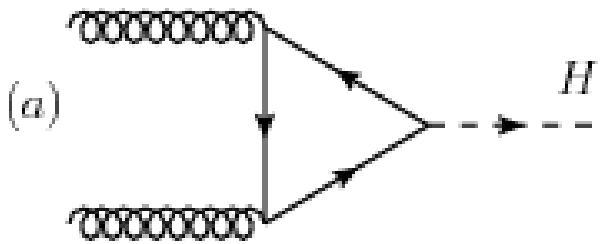
  $\Rightarrow$ corrections of several 10% for $E \sim$ 1TeV tails of distributions
- Les Houches wishlist 2013:

  NNLO QCD and NLO EW for various processes desired

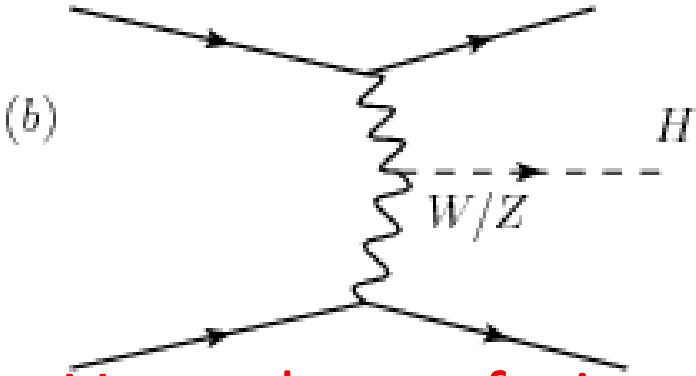
Automation of NLO EW corrections

- RECOLA
- GOSAM
- OPENLOOPS
- MadGraph5_aMC@NLO
- Feynarts&Formcalc

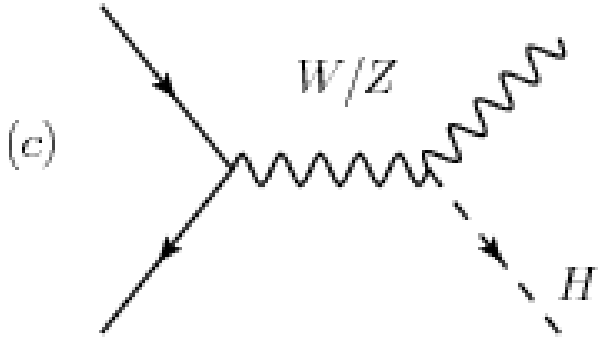
Main Higgs production channels



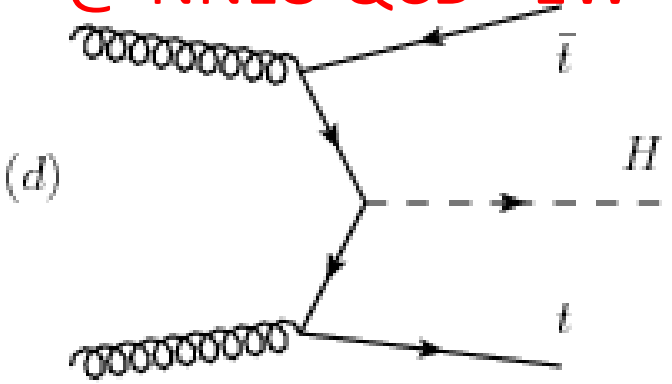
gluon-gluon fusion
@ NNLO QCD+ EW



Vector boson fusion
@ NNLO QCD+ EW



VH associated production
@ NNLO QCD+ EW



ttH @ NLO QCD+ EW

Existing results on ttH at NLO

- QCD corrections:
  - ✓L. Reina, S. Dawson, et.al. 2003
  - ✓W. Beenakker, S. Dittmaier, et.al 2003
- parton-shower matching:
  - ✓R. Frederix , S. Frixione, et.al. 2011
  - ✓M.V. Garzelli, A. Kardos, et.al. 2011
- EW corrctions: part of Les Houches wish list 2013
  - ✓Y. Zhang, W. Ma, et.al. 2014 (EW)
  - ✓S. Frixione, V. Hirschi, et.al. 2014,2015 (weak, EW)

Motivation

- probing the top-Higgs Yukawa coupling
- nontrivial study case for (automatized) calculation of EW NLO corrections
- part of Les Houches wish list 2013

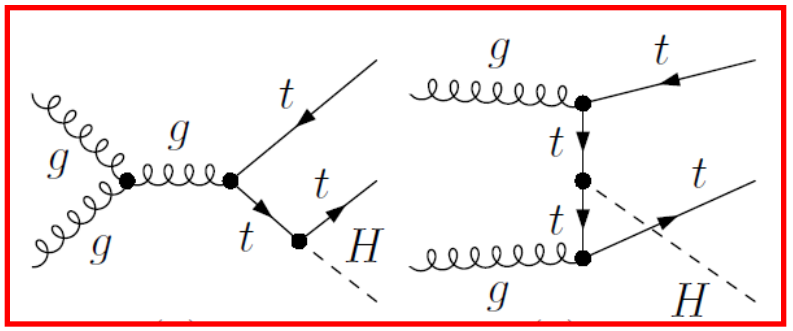
Details of the calculation

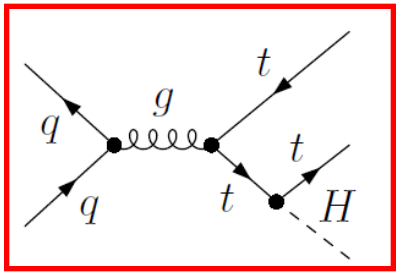
Tree level

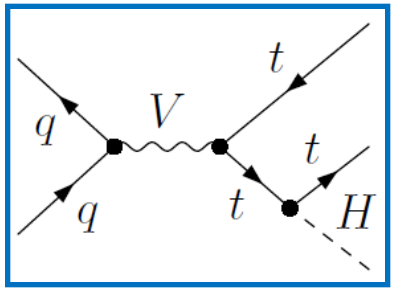
Sample diagrams:

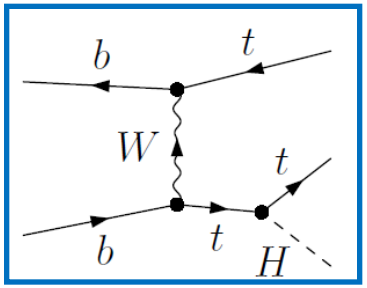
QCD, $O(\alpha_s\, \alpha^{1/2})$ and

EW, $O(\alpha^{3/2})$









Subprocess	$\mathcal{O}(\mathcal{M})$	$\mathcal{O}(\sigma)$
$gg \to t\bar{t}H$	$\alpha_s\alpha^{1/2}$	$\alpha_s^2\alpha$
$q\bar{q} \to t\bar{t}H$	$\alpha_s\alpha^{1/2}, \alpha^{3/2}$	$\alpha_s^2\alpha, \alpha^3$
$b\bar{b} \to t\bar{t}H$	$\alpha_s\alpha^{1/2}, \alpha^{3/2}$	$\alpha_s^2\alpha, \alpha_s\alpha^2, \alpha^3$
$g\gamma \to t\bar{t}H$	$\alpha_s^{1/2}\alpha$	$\alpha_s\alpha^2$
$\gamma\gamma \to t\bar{t}H$	$\alpha^{3/2}$	α^3

q=u,d,c,s

CKM matrix is set to be diagonal

$\sqrt{s}$		gg	$q\bar{q}$		$b\bar{b}$			$g\gamma$	$\gamma\gamma$
		$\alpha_s^2\alpha$	$\alpha_s^2\alpha$	α^3	$\alpha_s^2\alpha$	$\alpha_s\alpha^2$	α^3	$\alpha_s\alpha^2$	α^3
14	σ_{tree}(pb)	0.37178	0.12160	0.000828	0.0010382	-0.0015650	0.0033241	0.006196	6×10^{-6}
	$\frac{\sigma_{tree}}{\sigma_{LO}}$(%)	75.20	24.59	0.17	0.21	-0.32	0.67	1.25	0.001
33	σ_{tree}(pb)	2.9058	0.45500	0.003154	0.007844	-0.011778	0.027167	0.028225	1.6×10^{-5}
	$\frac{\sigma_{tree}}{\sigma_{LO}}$(%)	86.26	13.51	0.09	0.23	-0.35	0.81	0.84	0.0005
100	σ_{tree}(pb)	25.078	1.8325	0.012769	0.06237	-0.09333	0.2449	0.14016	4.4×10^{-5}
	$\frac{\sigma_{tree}}{\sigma_{LO}}$(%)	92.97	6.79	0.05	0.23	-0.35	0.91	0.52	0.0002

$$\sigma_{LO} = \sigma_0(\alpha_s^2\alpha) = \sigma_0^{gg}(\alpha_s^2\alpha) + \sum_q \sigma_0^{q\bar{q}}(\alpha_s^2\alpha) + \sigma_0^{b\bar{b}}(\alpha_s^2\alpha).$$

ttH at NLO

Tower of contributions to σ:

- $O(\alpha_s^3\alpha)$: QCD corrections to QCD diagrams 2003
- $O(\alpha_s^2\alpha^2)$: this talk
  - EW corrections to QCD diagrams
  - QCD corrections to EW–QCD interferences
- $O(\alpha_s\alpha^3)$:
  - QCD corrections to EW diagrams
  - EW corrections EW–QCD to interferences
- $O(\alpha^4)$: EW corrections to EW diagrams

General setup

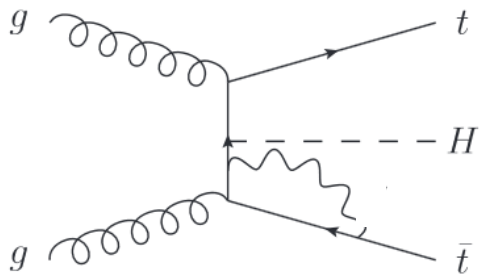
- G_μ scheme for electromagnetic coupling:

$$\alpha_{G_\mu} = \frac{\sqrt{2} G_\mu M_{\mathrm{W}}^2}{\pi} \left(1 - \frac{M_{\mathrm{W}}^2}{M_{\mathrm{Z}}^2} \right)$$

- massless light fermions
- ’t Hooft–Feynman gauge
- $\Delta\sigma_{NLO}^{EW} = \sigma^{gg}(\alpha_s^2\alpha^2) + \sum_q \sigma^{q\bar{q}}(\alpha_s^2\alpha^2) + \sigma^{b\bar{b}}(\alpha_s^2\alpha^2).$
- matrix elements with FeynArts/FormCalc
- loop integrals with LoopTools

$O(\alpha_s^2\alpha^2)$ contributions for the gluon fusion

- $\Delta\sigma = \Delta\sigma_{virt} + \Delta\sigma_{real}$
- $\Delta\sigma_{virutal} \sim 2Re(\mathcal{M}^*_{tree}\mathcal{M}_{loop})$

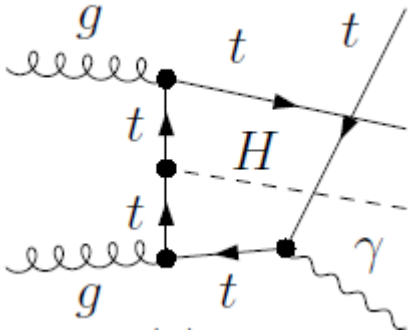


UV divergent ⟹ canceled exactly after performing the **renormalization** procedure

IR divergent ⟹ canceled exactly with $\Delta\sigma_{real}$

- $\Delta\sigma_{real} \sim |\mathcal{M}_{real}|^2$

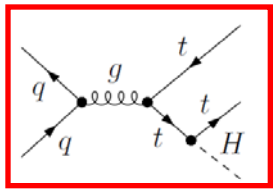
  - the two cutoff phase space slicing (TCPSS) method
  - the dipole subtraction (**DS**) method



$O(\alpha_s^2\alpha^2)$ contributions for $q\bar{q}$ annihilation

- $\Delta\sigma = \Delta\sigma_{virt} + \Delta\sigma_{real}$
- $\hat{\sigma}^{q\bar{q}}_{virt}(\alpha_s^2\alpha^2) \sim$

$$\left\{ 2Re\{\mathcal{M}^{q\bar{q}*}_{0,g}\mathcal{M}^{q\bar{q}}_{1,EW}\} + \right.$$



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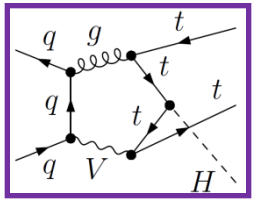
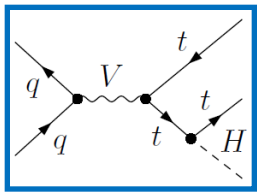


$O(\alpha_s\,\alpha^{1/2})$ $O(\alpha_s\,\alpha^{3/2})$

$$\left. 2Re\{\mathcal{M}^{q\bar{q}*}_{0,Z/\gamma}\mathcal{M}^{q\bar{q}}_{1,QCD}\} \right\}$$



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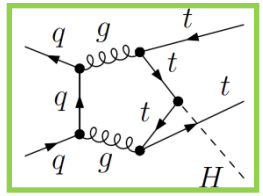
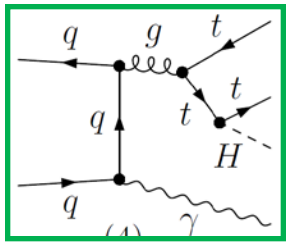


$O(\alpha^{3/2})$ $O(\alpha_s^{\,2}\,\alpha^{1/2})$

- $\Delta\sigma_{real} = \Delta\sigma_{realr} + \Delta\sigma_{realg} + \Delta\sigma_{realq}$

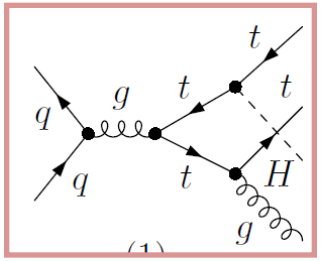
$O(\alpha_s^2\alpha^2)$ contributions for $q\bar{q}$ annihilation

- real photon emission



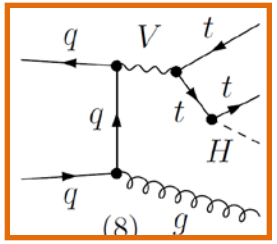
$O(\alpha_s\alpha)$

- real gluon emission



$O(\alpha_s^{3/2}\,\alpha^{1/2})$

×



$O(\alpha_s^{1/2}\,\alpha^{3/2})$

- real quark emission

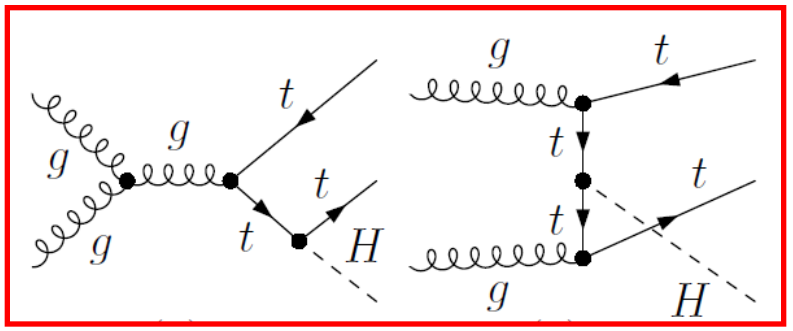
$$q(p_1) + \gamma(p_2) \to t(p_3) + \bar{t}(p_4) + H(p_5) + q(p_6),$$
$$q(p_1) + g(p_2) \to t(p_3) + \bar{t}(p_4) + H(p_5) + q(p_6),$$

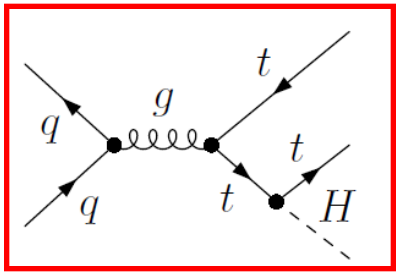
Tree level

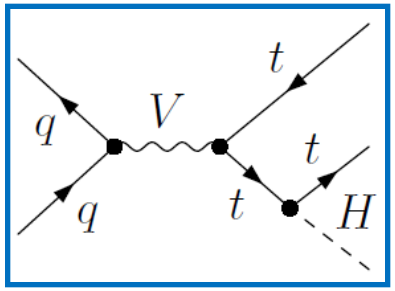
Sample diagrams:

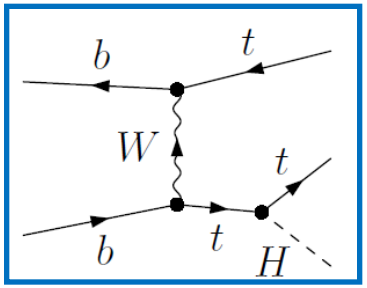
QCD, $O(\alpha_s\, \alpha^{1/2})$ and

EW, $O(\alpha^{3/2})$









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$q\bar{q} \to t\bar{t}H$	$\alpha_s\alpha^{1/2}, \alpha^{3/2}$	$\alpha_s^2\alpha, \alpha^3$
$b\bar{b} \to t\bar{t}H$	$\alpha_s\alpha^{1/2}, \alpha^{3/2}$	$\alpha_s^2\alpha, \alpha_s\alpha^2, \alpha^3$
$g\gamma \to t\bar{t}H$	$\alpha_s^{1/2}\alpha$	$\alpha_s\alpha^2$
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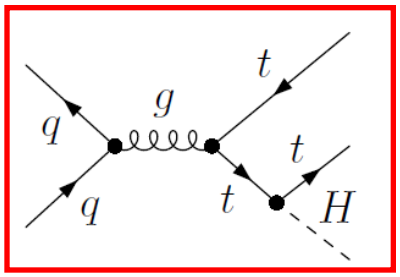
q=u,d,c,s

CKM matrix is set to be diagonal

$O(\alpha_s^2\alpha^2)$ contributions for $b\bar{b}$ annihilation



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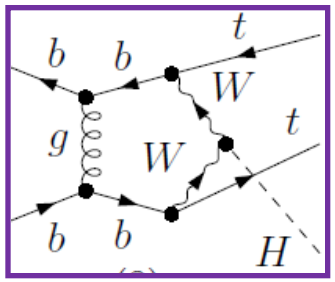
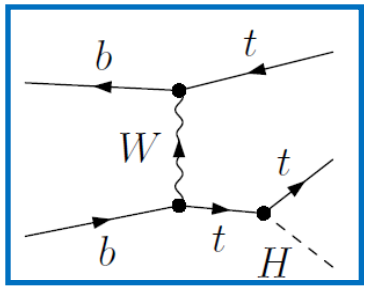


$O(\alpha_s\,\alpha^{1/2})$ $O(\alpha_s\,\alpha^{3/2})$



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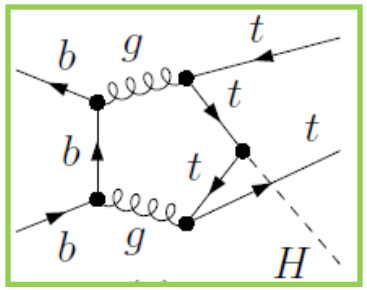


$O(\alpha^{3/2})$ $O(\alpha_s^2\,\alpha^{1/2})$

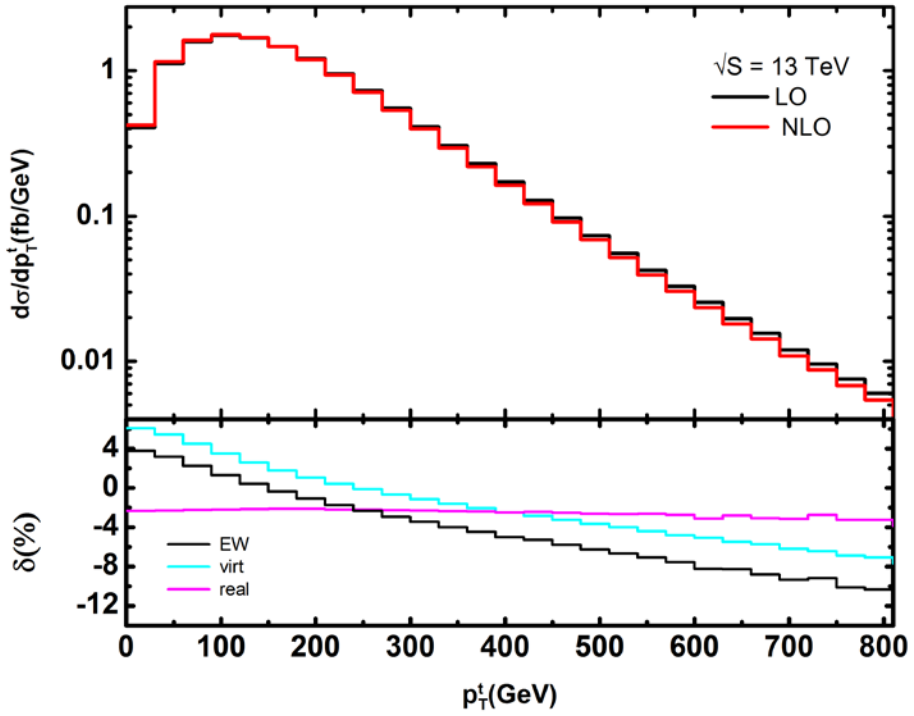
QCD corrections to EW–QCD interferences

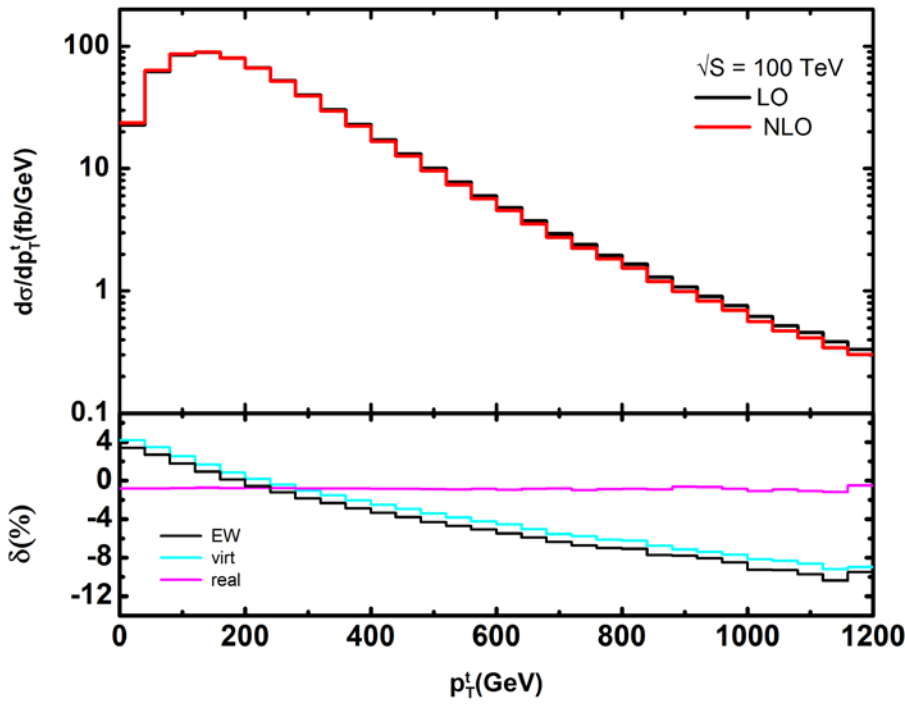
Results

Result for total cross section

	σ_{LO}（pb）	δ(%)
13	0.39381(4)	-0.2
100	25.200(5)	-0.5

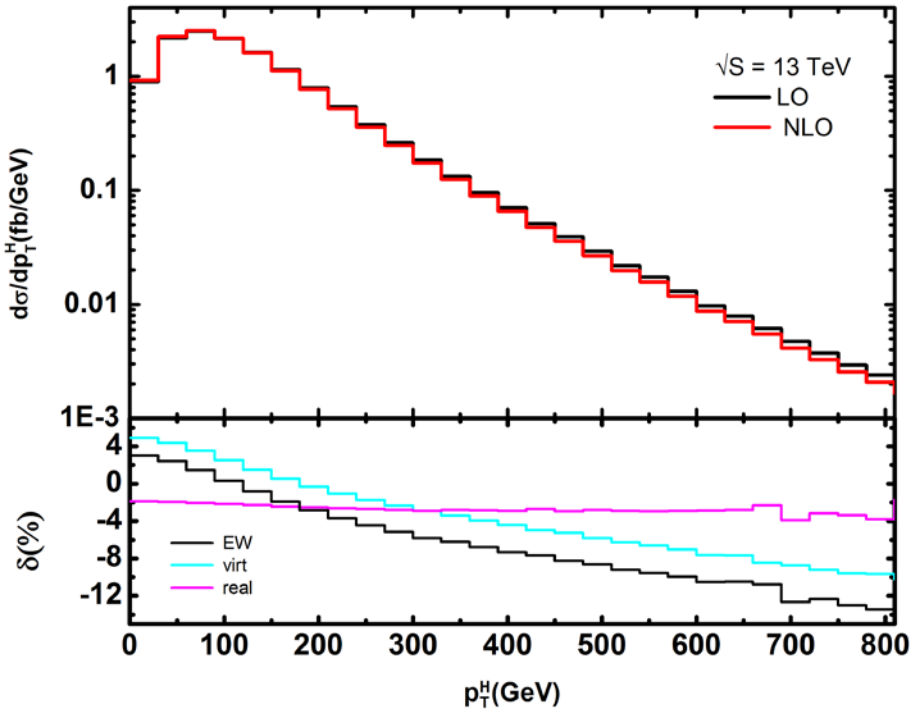
Distribution in p_T of top

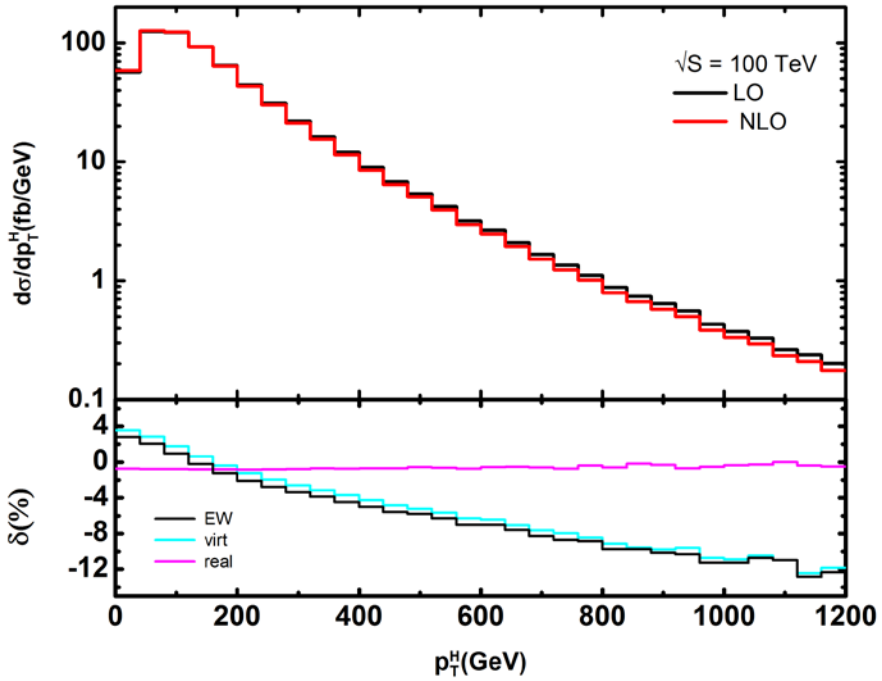




- EW corrections sizeable for large p_T dominated by virtual corrections (Sudakov logarithms)
- subtracted real photonic corrections small and flat

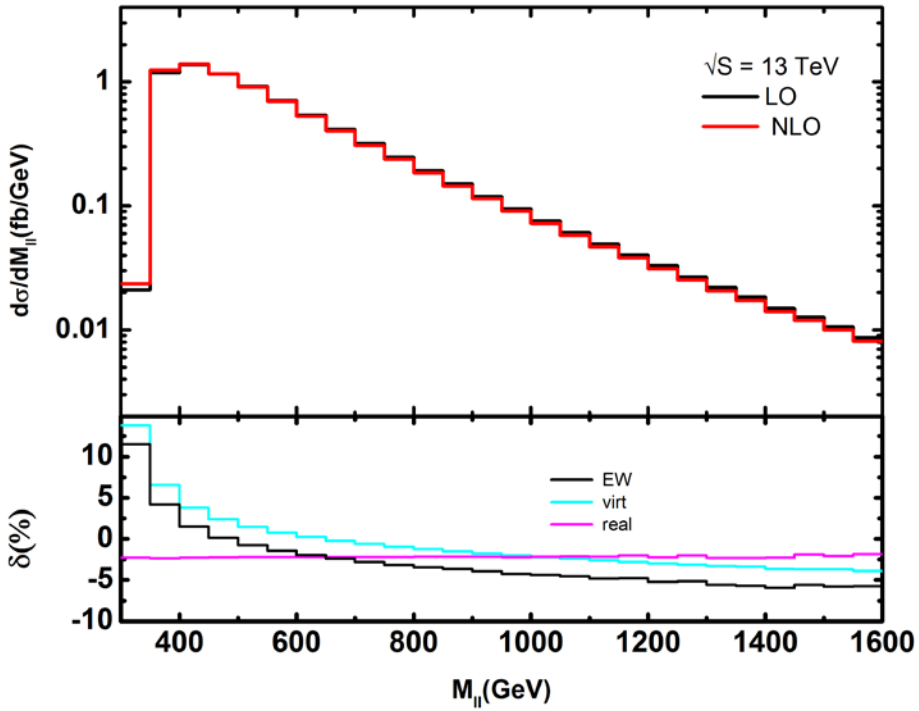
Distribution in p_T of Higgs

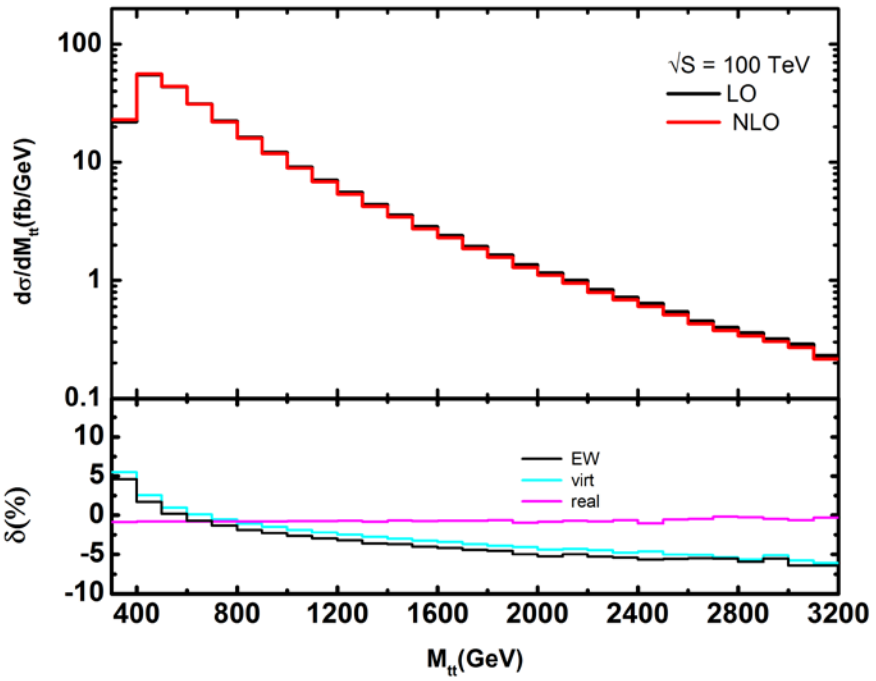




- EW corrections −13% when p_T^H =0.8TeV for HC13 and 1.2TeV for HC100 dominated by virtual corrections (Sudakov logarithms)
- subtracted real corrections small (<4% for HC13 and 1% for HC100)

Distribution in invariant mass of top pair





- EW corrections are positive near the threshold

Summary

Summary

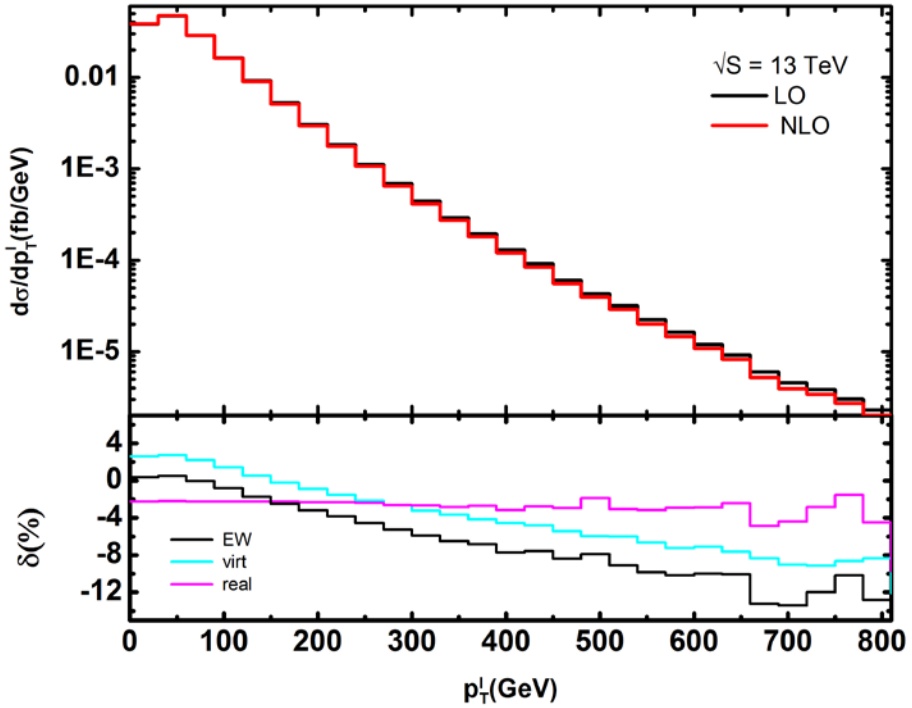
- Automation of QCD/EW corrections
- EW corrections to pp→ttH
  - $O(\alpha_s^2\alpha^2)$ corrections calculated

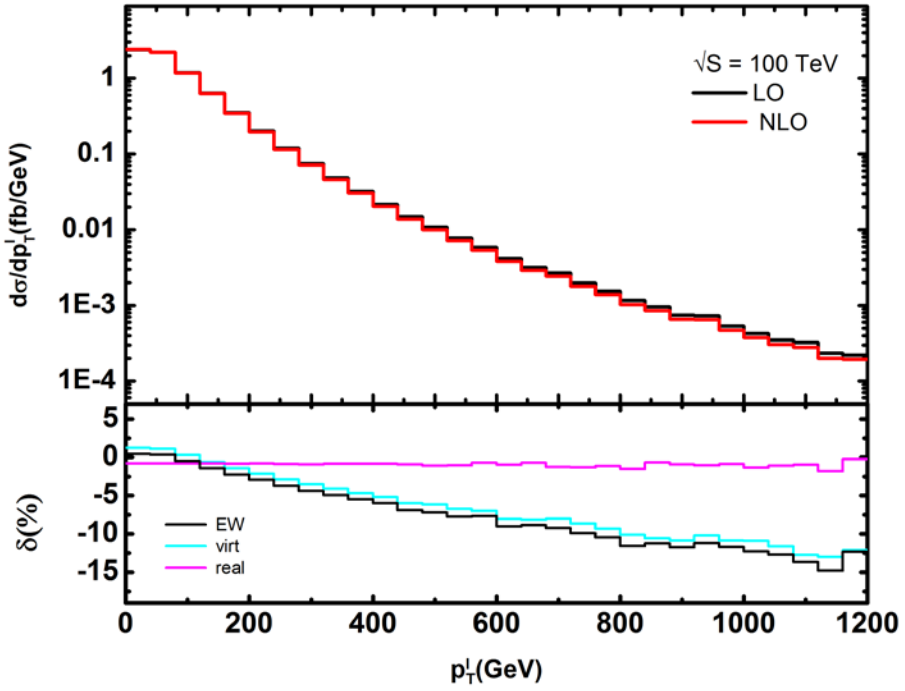
  (EW corrections to LO QCD diagrams,

  QCD corrections to LO EW-QCD interferences)
  - corrections to total cross section less than per-cent
  - corrections of more than ten per cent in high-energy tails of distributions from virtual Sudakov logarithms
  - real corrections small and stable

Backup

Distribution in p_T of lepton





$$pp \to t\bar{t}H \to W^+bW^-bH + X \to l^+l^-b\bar{b}\nu\bar{\nu}H + X$$

Distribution in invariant mass of lepton pair