Electroweak corrections to top quark pair production in association with a photon or a Higgs boson at hadron colliders

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18nd December 2016, PKU, Beijing

Based on arXiv:1407.1110, 1612.00248

Outline

- Introduction
- Details of the calculation
- Results
- Summary

Introduction

Background

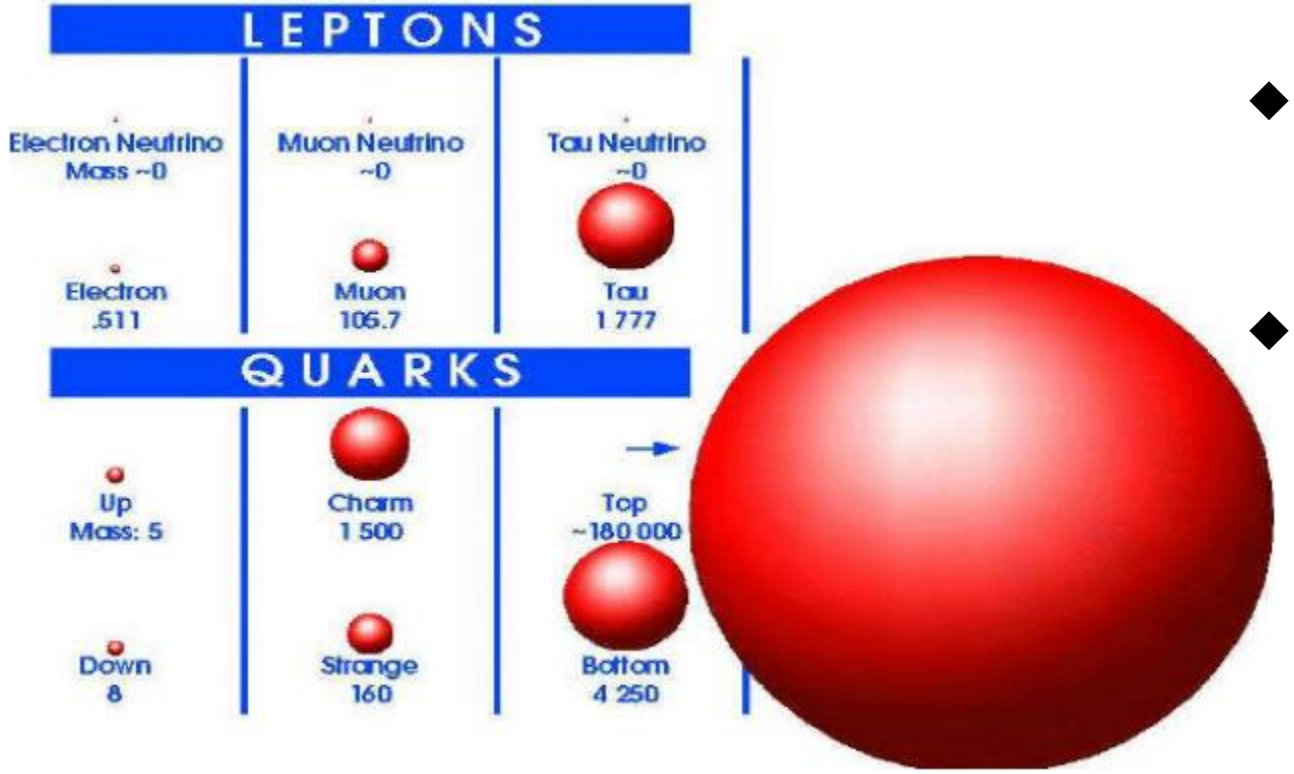
- Discovery of Higgs boson 2012:

  ⇒ 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

Why top?



- The Heaviest known elementary particle.
- Sensitive to new physics.

Higher order predictions for top quark pair in association with bosons

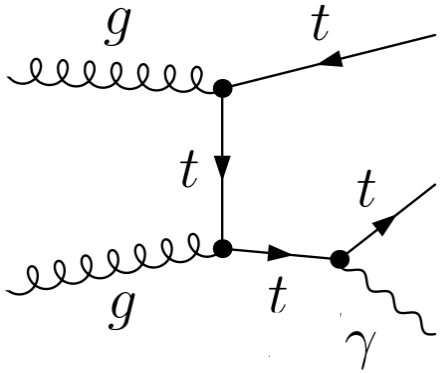
- $t\bar{t}H$
  - NLO QCD corrections
    - Beenakker et al. hep-ph/0107081 & hep-ph/0211352
    - Dawson et al. hep-ph/0211438 & hep-ph/0305087
  - Matching to PS
    - aMC@NLO: Frederix et al. arXiv:1104.5613
    - Powhel: Garzelli et al. arXiv:1108.0387
    - Powheg Box: Hartanto et al. arXiv:1501.04498
  - Weak & Electroweak corrections
    - Frixione et al. arXiv:1407.0823 & arXiv:1504.03446
    - Zhang et al. arXiv:1407.1110
  - Soft gluon resummation
    - Kulesza et al. arXiv:1509.02780
- $t\bar{t}VV$
  - NLO QCD corrections + PS
    - $t\bar{t}\gamma\gamma$ Kardos et al. arXiv:1408.0278
    - all $t\bar{t}VV$ Maltoni et al. arXiv:1507.05640
    - $t\bar{t}\gamma\gamma$ van Deurzen et al. arXiv:1509.02077
- $t\bar{t}V$
  - NLO QCD corrections
    - $t\bar{t}\gamma$ Duan et al. arXiv:0907.1324 &arXiv:1110.2315
    - $t\bar{t}\gamma$ Melnikov et al. arXiv:1102.1967
    - $t\bar{t}W$, $t\bar{t}\gamma^*/Z$, $t\bar{t}\gamma$ Hirschi et al. arXiv:1103.0621
    - $t\bar{t}Z$ Lazopoulos et al. arXiv:0804.2220
    - $t\bar{t}Z$ Kardos et al. arXiv:1111.0610
    - $t\bar{t}W$ Campbell et al. arXiv:1204.5678
  - Matching to PS
    - $t\bar{t}Z$ Garzelli et al. arXiv:1111.1444
    - $t\bar{t}W, t\bar{t}Z$ Garzelli et al. arXiv:1208.2665
  - Weak & Electroweak corrections
    - $t\bar{t}W, t\bar{t}Z$ (and $t\bar{t}H$) Frixione et al. arXiv:1504.03446
    - $t\bar{t}\gamma$ Duan, Zhang et al. arXiv:1612.00248

Motivation of electroweak corrections to $t\bar{t}H$ and $t\bar{t}\gamma$

- $t\bar{t}H$ offers unique direct access to the top-Higgs Yukawa coupling

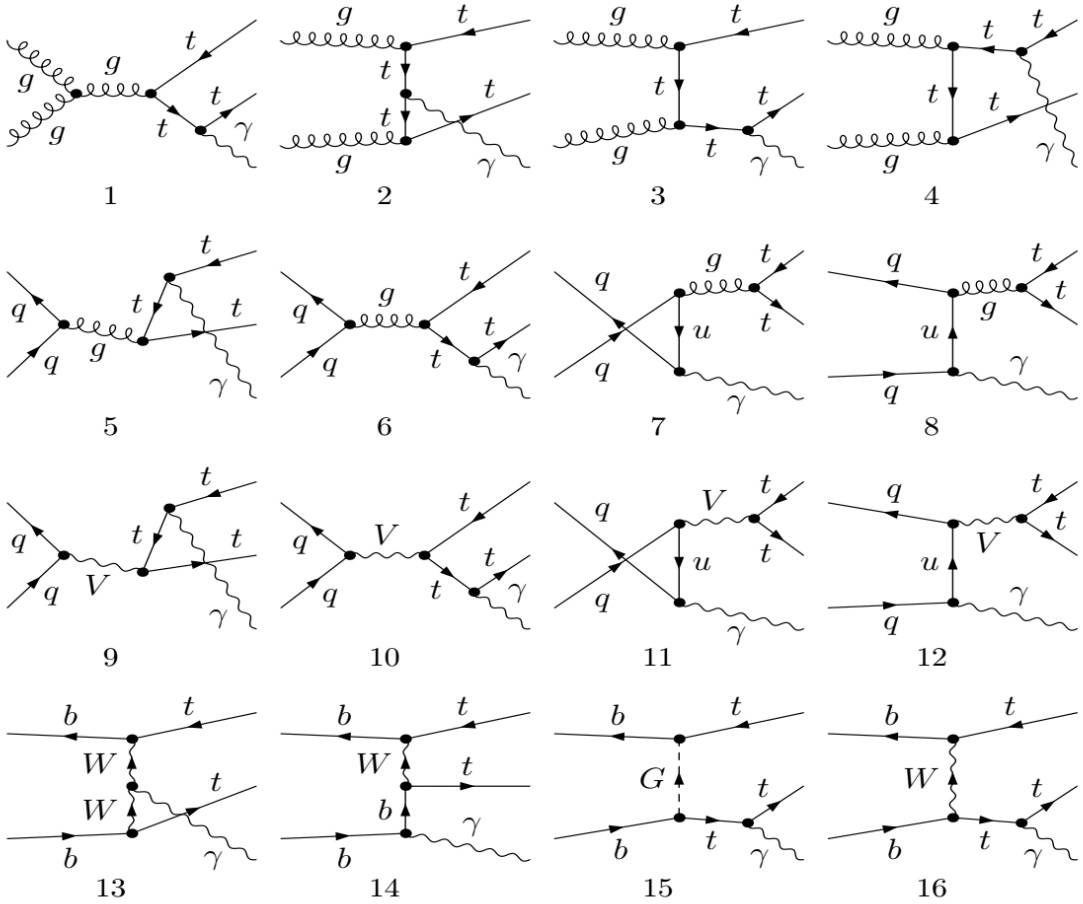
- $t\bar{t}\gamma$ probes the top-photon electromagnetic coupling directly

- Boosted searches: Electroweak corrections enhanced because of Sudakov logs ($\log(Q/M_W)$)



Details of the calculation

Glancing the order of cross section of $pp \to t\bar{t}H/\gamma + X$ at tree level

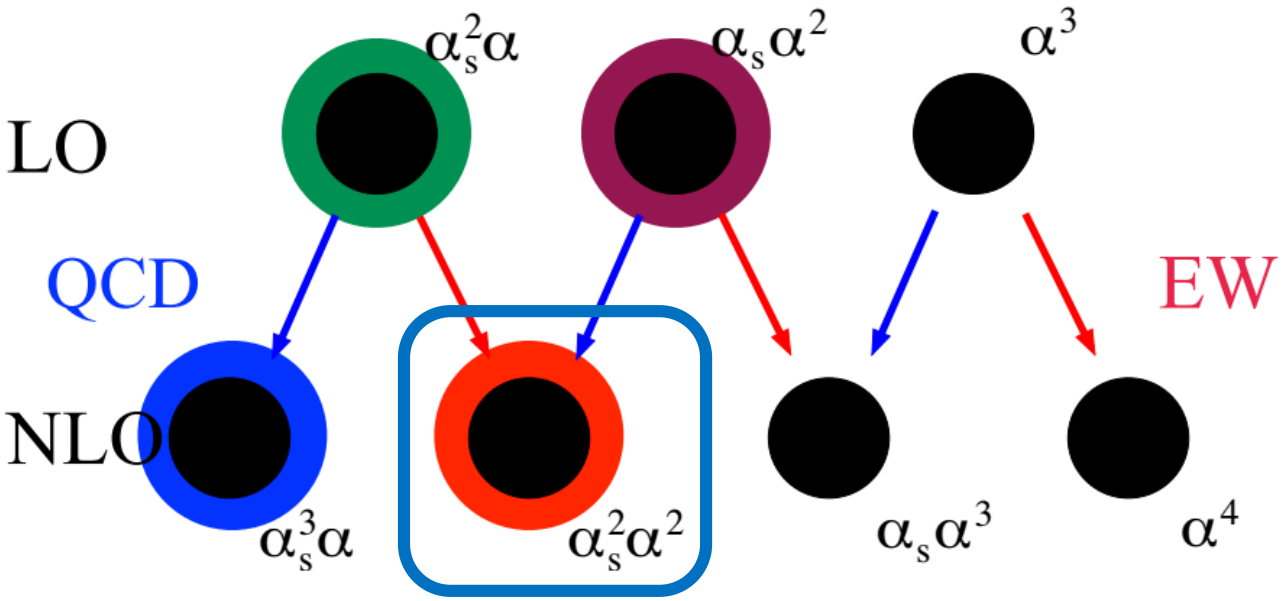


$$\sigma_{tree-level} = \sigma^{gg}(\alpha_S^2\alpha) + \sigma^{q\bar{q}}(\alpha_S^2\alpha) + \sigma^{q\bar{q}}(\alpha^3) + \sigma^{b\bar{b}}(\alpha_S\alpha^2)$$
$$\equiv \sigma_{LO,1}(\alpha_S^2\alpha) + \sigma_{LO,2}(\alpha_S\alpha^2) + \sigma_{LO,3}(\alpha^3)$$

$V = Z, \gamma$

Glancing the order of cross section of $pp \to t\bar{t}H/\gamma + X$ at one loop level

$$\Delta\sigma_{one-loop-level} \equiv \Delta\sigma_{NLO,1}(\alpha_S^3\alpha) + \Delta\sigma_{NLO,2}(\alpha_S^2\alpha^2) + \Delta\sigma_{LO,3}(\alpha_S\alpha^3) + \Delta\sigma_{LO,4}(\alpha^4)$$



Ack. to M. Zaro

Technology of the calculation at NLO

$$\Delta\sigma_{NLO} = \Delta\sigma_{virtual} + \Delta\sigma_{real}$$

虚修正

实辐射

实辐射：红外发散——与虚修正相消

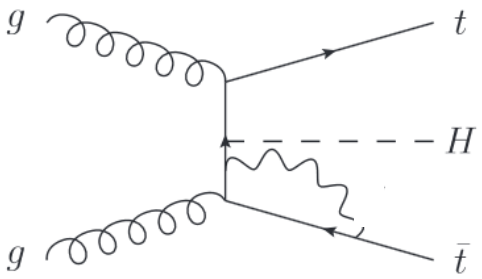
相空间分割法、双极点翦除法

虚修正：紫外发散——通过重整化消除

红外发散——与实辐射部分完全抵消

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

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

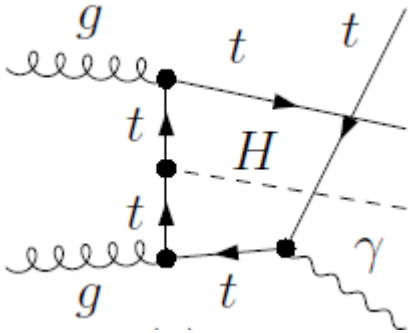


UV divergent ⟹ canceled exactly after performing the **renormalization** procedure

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

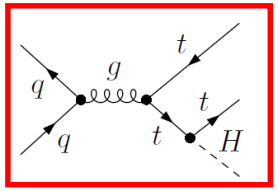
- $$\Delta\sigma_{real} \sim |\mathcal{M}_{real}|^2$$

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



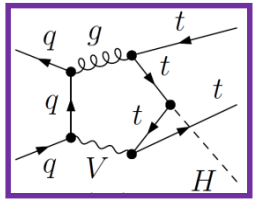
$O(\alpha_s^2\alpha^2)$ contributions for $q\bar{q}$ annihilation

- $\Delta\sigma = \Delta\sigma_{virt} + \Delta\sigma_{real}$
- $$\hat{\sigma}^{q\bar{q}}_{virt}(\alpha_s^2\alpha^2) \sim \left\{2Re\{\mathcal{M}^{q\bar{q}*}_{0,g}\mathcal{M}^{q\bar{q}}_{1,EW}\} + 2Re\{\mathcal{M}^{q\bar{q}*}_{0,Z/\gamma}\mathcal{M}^{q\bar{q}}_{1,QCD}\}\right\}$$

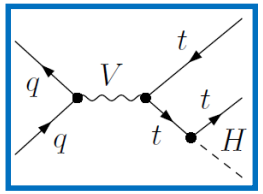


$O(\alpha_s\,\alpha^{1/2})$

×

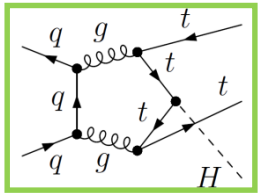


$O(\alpha_s\,\alpha^{3/2})$



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

×

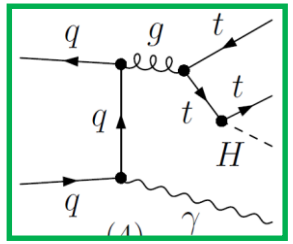


$O(\alpha_s^2\,\alpha^{1/2})$

- $\Delta\sigma_{real} = \Delta\sigma^{\gamma}_{real} + \Delta\sigma^{g}_{real}$

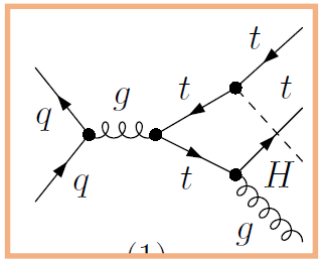
$O(\alpha_s^2\alpha^2)$ contributions for $q\bar{q}$ annihilation

- real photon emission



$O(\alpha_s\alpha)$

- real gluon emission



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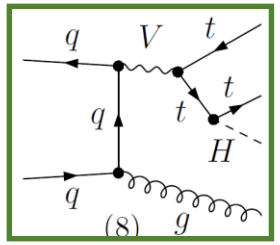


$O(\alpha_s^{3/2}\,\alpha^{1/2})$

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

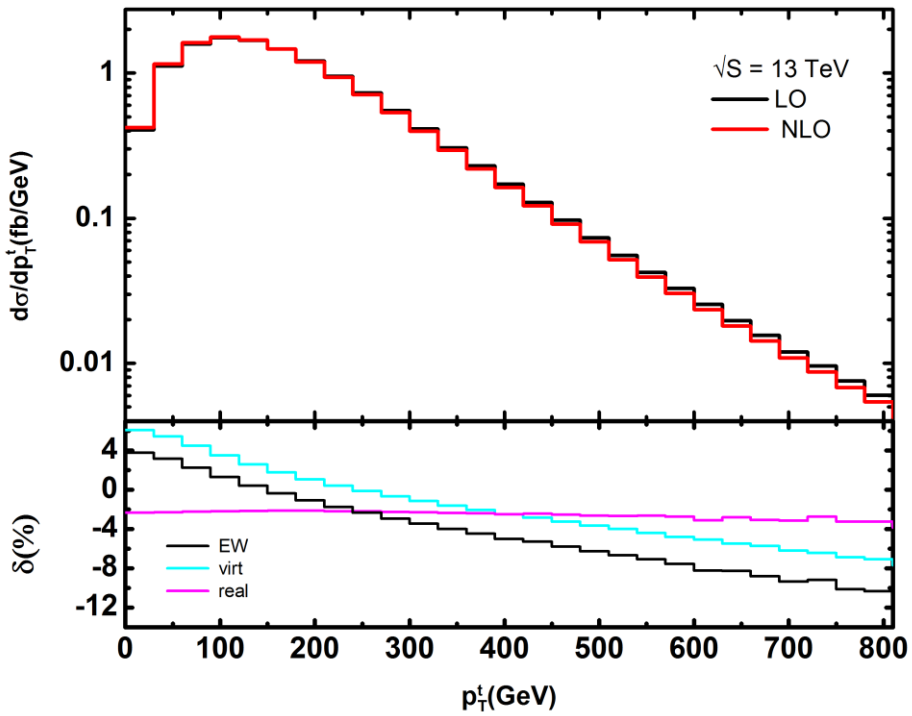
Results

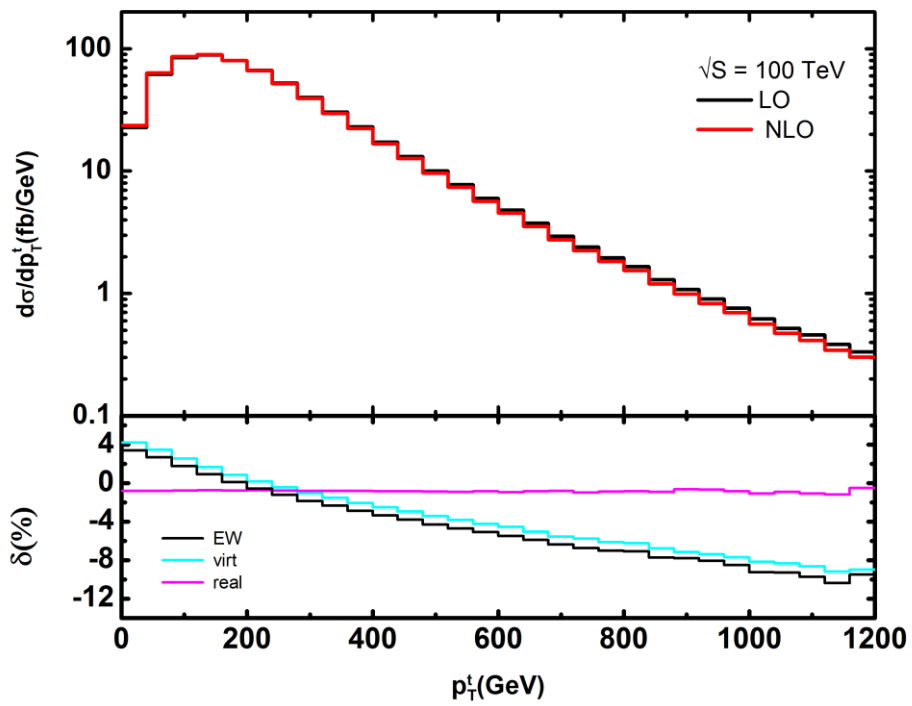
Results for $pp \to t\bar{t}H + X$

Results of total cross section for $pp \to t\bar{t}H + X$

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

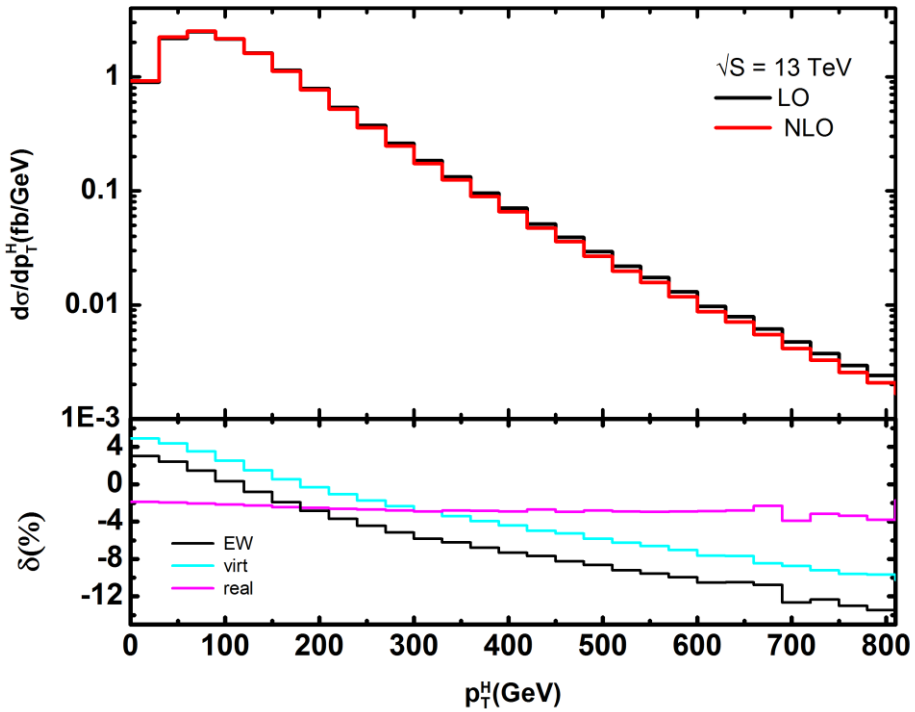
Distribution in p_T of top for $pp \to t\bar{t}H + X$

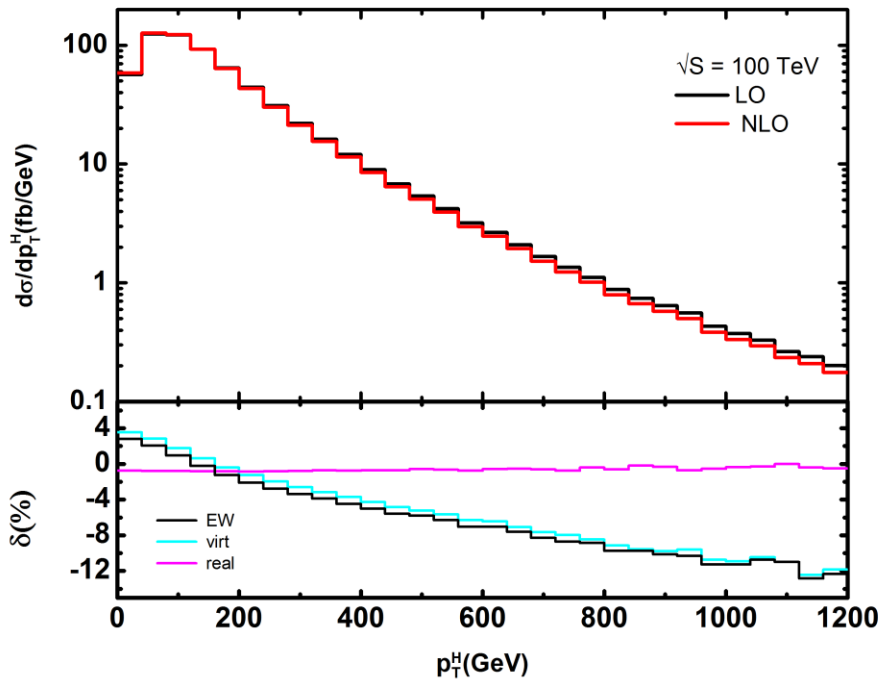




- EW corrections sizeable for large p_T
  dominated by virtual corrections (Sudakov logarithms)
- subtracted real photonic corrections small and flat

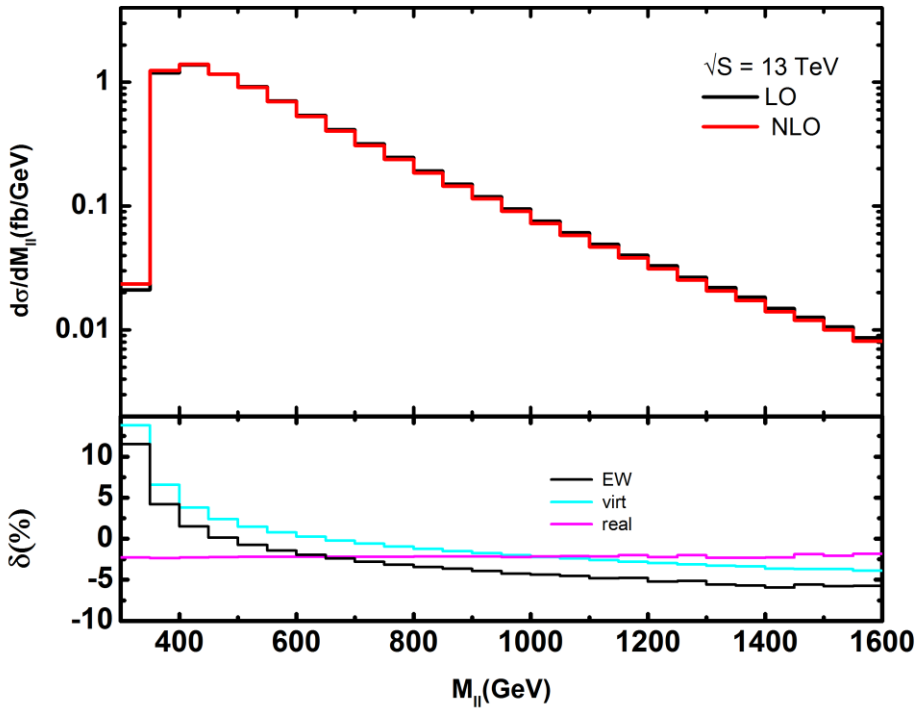
Distribution in p_T of Higgs for $pp \to t\bar{t}H + X$

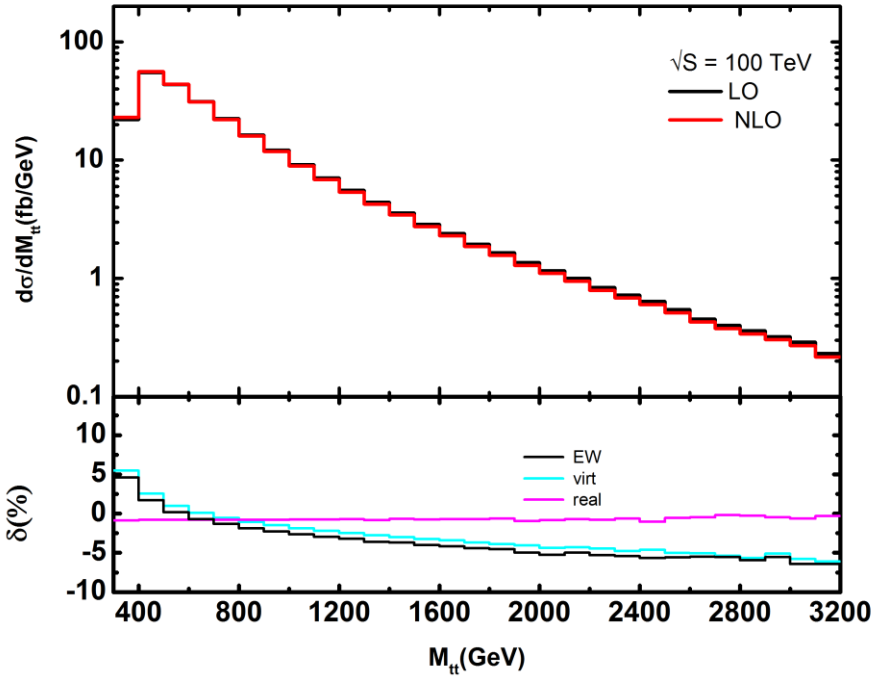




- −13% when p_T^H =0.8TeV for HC13 and 1.2TeV for HC100 dominated by virtual corrections (Sudakov logarithms)
- subtracted real corrections small (<4% for HC13 and 1% for HC100)

Distribution in invariant mass of top pair for $pp \to t\bar{t}H + X$





- EW corrections are positive near the threshold

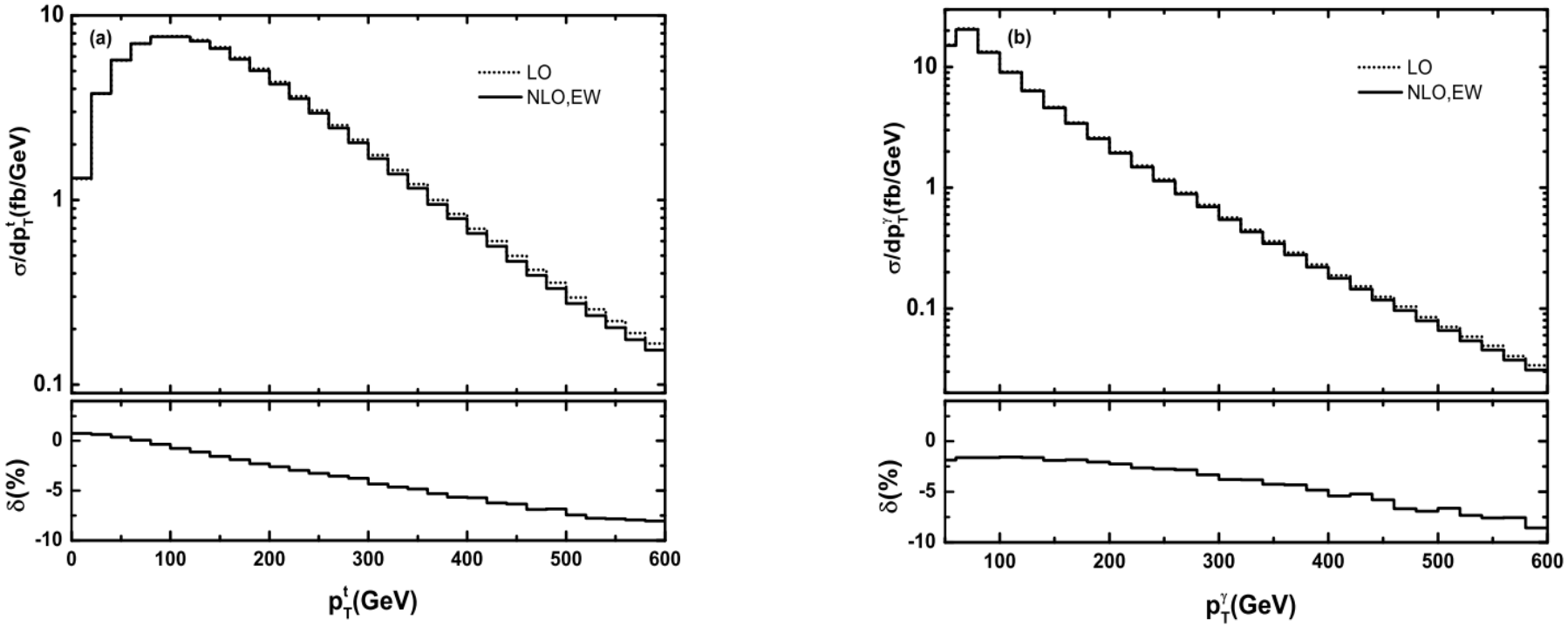
Results for $pp \to t\bar{t}\gamma + X$

Results of total cross section for $pp \to t\bar{t}\gamma + X$

$p_T^{\gamma,cut}$ [GeV]		50	100	200	500	1000
$\sigma_{\rm LO}$	13 TeV [fb]	851.4(3)	356.1(2)	93.12(4)	4.596(2)	0.14778(4)
	100 TeV [pb]	61.42(2)	30.47(2)	10.616(6)	1.1123(7)	0.10661(7)
$\sigma_{\rm NLO,\,EW}$	13 TeV [fb]	835.4(4)	348.4(3)	89.92(5)	4.205(3)	0.1259(4)
	100 TeV [pb]	60.04(3)	29.69(3)	10.205(8)	1.0158(9)	0.09068(9)
$\delta_{\rm NLO,\,EW}$ [%]	13 TeV	-1.9	-2.2	-3.4	-8.5	-14.8
	100 TeV	-2.2	-2.6	-3.9	-8.7	-14.9

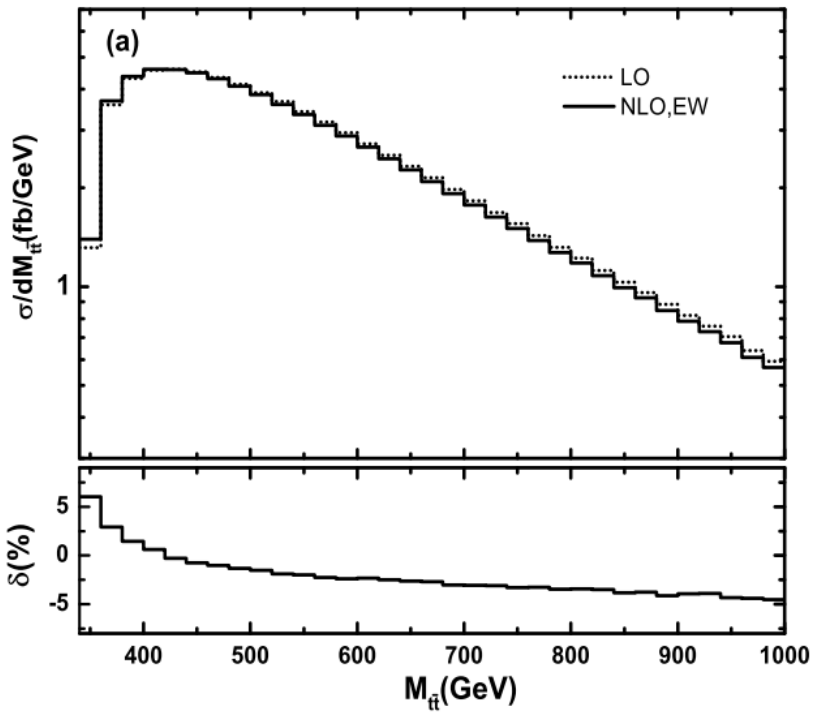
In order to exclude the inevitably IR divergence at tree level, we require the final state photon tagged hard with $p_T^{\gamma} > p_T^{\gamma,cut}$.

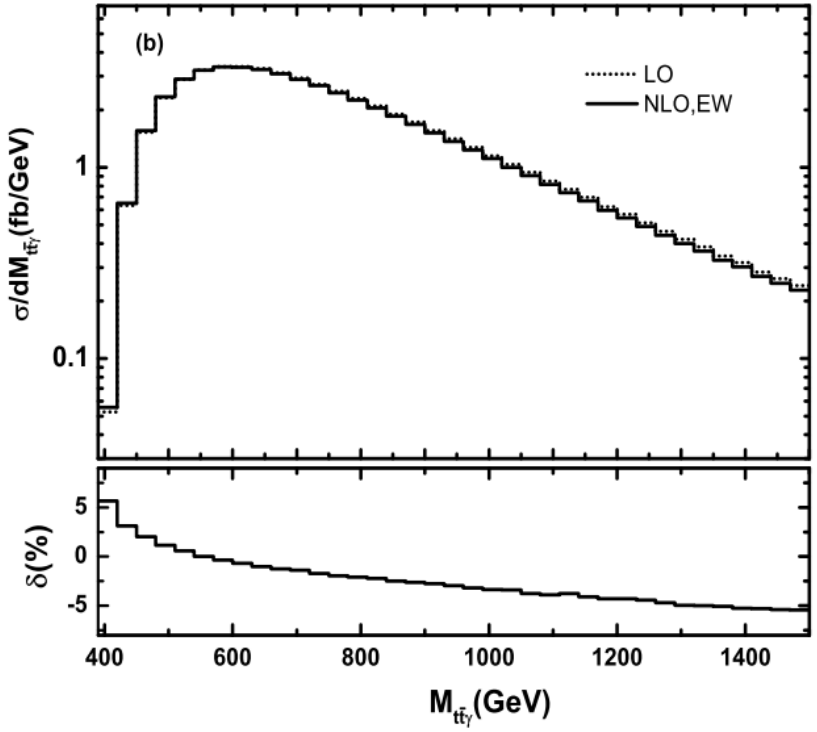
Distribution in p_T of $\boldsymbol{t}$ and $\boldsymbol{\gamma}$ at LHC13



- EW corrections sizeable for large p_T
- -8.0% when p_T^t = 600 GeV
- -8.6% when p_T^γ = 600 GeV

Distribution in $M_{t\bar{t}}$ and $M_{t\bar{t}\gamma}$ at LHC13





- EW corrections are positive near the threshold

Summary

Summary

- EW corrections for $\boldsymbol{t\bar{t}+H}$ and $\boldsymbol{t\bar{t}+\gamma}$ productions at LHC and futher hadron collider.

- Due to the Sudakov logs, EW corrections can be significant especially in high energy region.