

Associated production of a top-quark pair with vector bosons at NLO

Ioannis Tsinikos

Centre for Cosmology, Particle Physics and Phenomenology (CP3)

Université Catholique de Louvain (UCL)

*In collaboration with
F. Maltoni, D. Pagani*

01-02 June 2015

ERC miniworkshop

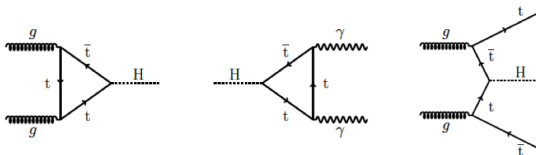


- 1 Introduction
 - Motivation
 - Project
- 2 Processes at FNLO
 - Scale choice
 - σ_{NLO} at 8-100 TeV
 - Focus at 13 TeV
 - Differential K -factors
- 3 $t\bar{t}H$ phenomenology at 13 TeV
 - Analysis selection cuts
 - Diphoton analysis
 - Multilepton analysis
- 4 Conclusions

Motivation

Higgs searches

- High confidence level of a 125 GeV scalar boson discovery by CMS and ATLAS detectors in 2012
- Up to 8 TeV the spin, parity, coupling properties are consistent with the SM Higgs
- Prediction: it has strong coupling to the top quark



- Direct probe of $Y_t = \frac{\sqrt{2}m_t}{v}$: study the coupling, occurring at tree level process
- $t\bar{t}H$ process has irreducible backgrounds from $t\bar{t}V$, $t\bar{t}VV$, $t\bar{t}t\bar{t}$ processes
- Need for high accuracy at 13 TeV requires the best MC simulation for $t\bar{t}V$, $t\bar{t}VV$, $t\bar{t}t\bar{t}$

...but also BSM

The LHC 13 TeV run will provide keys of understanding if not concrete answers to BSM studies :

- SUSY processes
 - 3 lepton signatures : Gaugino production^{ATLAS-CONF-2012-154}
 - 4 leptons : R-parity violating SUSY^{ATLAS-CONF-2012-153}
- Vector like quarks
 - 2 SS leptons, 3 leptons : $b'\bar{b}' \rightarrow tW^-\bar{t}W^+$ CMS PAS B2G-12-019
 - multilepton signatures : $t'\bar{t}' \rightarrow tZ\bar{t}Z$ CMS PAS B2G-12-015
- BSM at NLO accuracy in progress
- $t\bar{t}V$, $t\bar{t}VV$ and $t\bar{t}t\bar{t}$ are irreducible backgrounds

Full study of $t\bar{t}$ +vector bosons at NLO

- Independent study of $t\bar{t}H$, $t\bar{t}V$ and $t\bar{t}VV$, $t\bar{t}t\bar{t}$ processes
 - MADGRAPH5_AMC@NLO
- Study of different scale choices
- Allow for subsequent decays
 - MADSPIN , PYTHIA8
- Perform full MC simulation at 13 TeV
 - PYTHIA8 , MADANALYSIS 5
- Use them as backgrounds to $t\bar{t}H$

Considering three different scales

- Dynamical scales

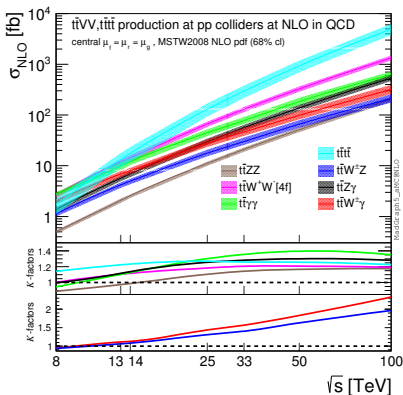
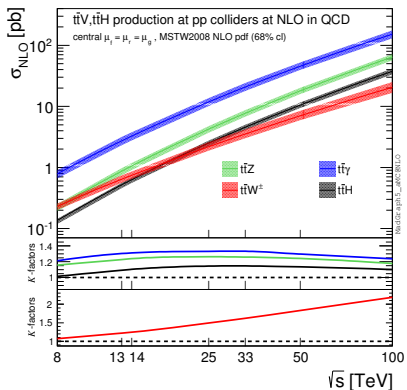
$$\mu^c = \mu_a = \frac{H_T}{N} := \frac{1}{N} \sum_{i=1, N(+1)} m_{T,i}$$

$$\mu^c = \mu_g := \left(\prod_{i=1, N} m_{T,i} \right)^{1/N}$$

- Fixed scale

$$\mu^c = m_t$$

- Independent scale variation in the interval $\{\frac{\mu^c}{2}, \mu^c, 2\mu^c\}$
- We chose the μ_g as reference scale for the comparison

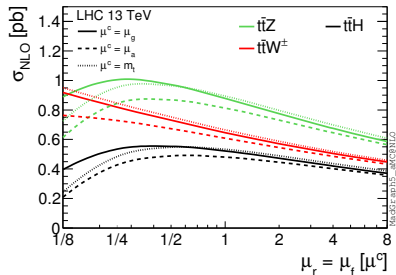
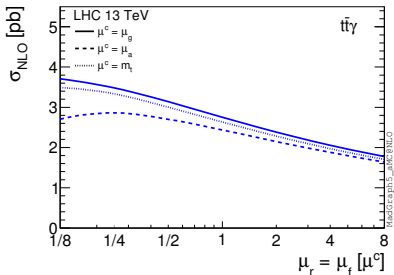


- Different cross section energy dependence
- Different behavior of the K -factor depending on gg channel at LO

Focus at 13 TeV

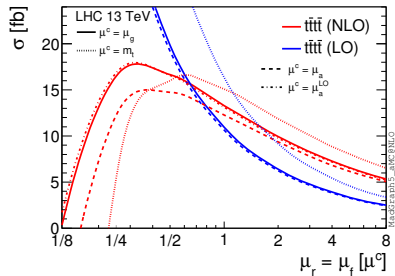
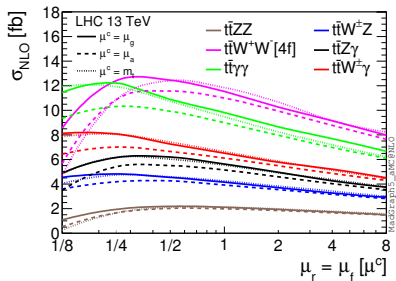
 $t\bar{t}H, t\bar{t}V$

- Diagonal scale variation in the interval $\{\mu^c/8, \mu^c, 8\mu^c\}$



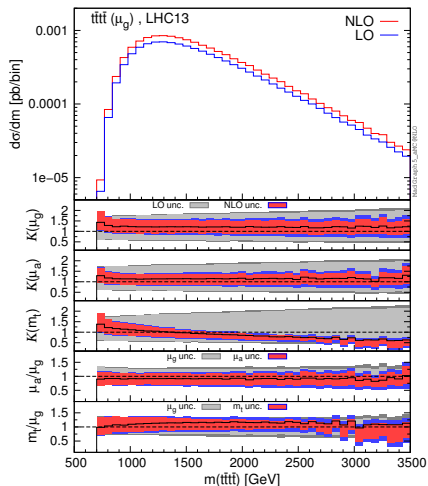
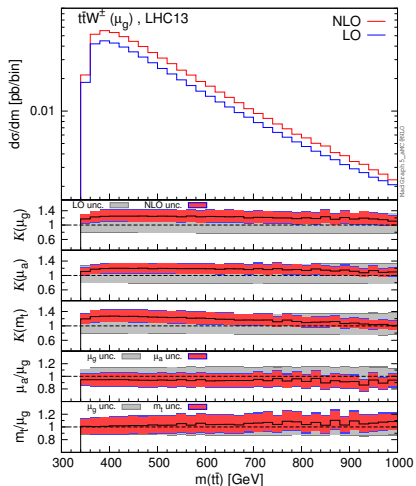
13 TeV σ [fb]	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}W$	$t\bar{t}\gamma$
NLO	522.2 ^{+6.0%} _{-9.4%} ^{+2.1%} _{-2.6%}	873.6 ^{+10.3%} _{-11.7%} ^{+2.0%} _{-2.5%}	644.8 ^{+13.0%} _{-11.6%} ^{+1.7%} _{-1.3%}	2746 ^{+14.2%} _{-13.5%} ^{+1.6%} _{-1.9%}
LO	476.6 ^{+35.5%} _{-24.2%} ^{+2.0%} _{-2.1%}	710.3 ^{+36.1%} _{-24.5%} ^{+2.0%} _{-2.1%}	526.9 ^{+28.1%} _{-20.4%} ^{+1.7%} _{-1.8%}	2100 ^{+36.2%} _{-24.5%} ^{+1.8%} _{-1.9%}
K-factor	1.10	1.23	1.22	1.31

Focus at 13 TeV

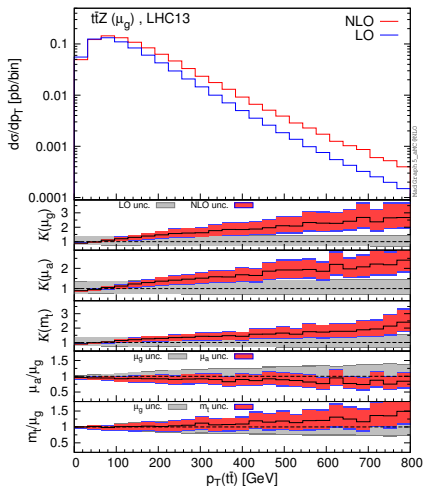
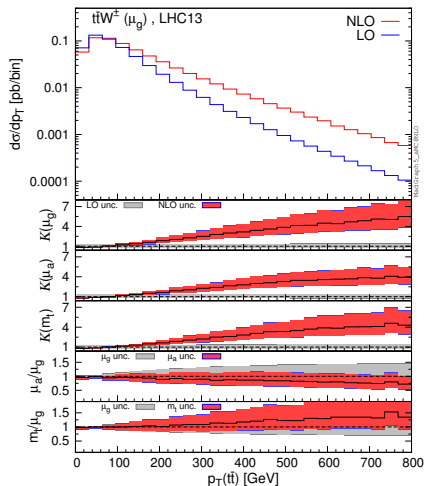
 $t\bar{t}t\bar{t}, t\bar{t}VV$ 

13 TeV σ [fb]	$t\bar{t}ZZ$	$t\bar{t}W^+W^-$ [4f]	$t\bar{t}\gamma\gamma$	$t\bar{t}t\bar{t}$
NLO	$2.117^{+3.8\%}_{-8.6\%}^{+1.9\%}_{-1.8\%}$	$11.84^{+8.3\%}_{-11.2\%}^{+2.3\%}_{-2.4\%}$	$10.26^{+13.9\%}_{-13.3\%}^{+1.3\%}_{-1.3\%}$	$13.31^{+25.8\%}_{-25.3\%}^{+5.8\%}_{-6.6\%}$
LO	$2.137^{+36.1\%}_{-24.4\%}^{+1.9\%}_{-1.9\%}$	$10.78^{+38.3\%}_{-25.4\%}^{+2.2\%}_{-2.2\%}$	$8.838^{+36.5\%}_{-24.5\%}^{+1.5\%}_{-1.6\%}$	$10.94^{+81.1\%}_{-41.6\%}^{+4.8\%}_{-4.7\%}$
K -factor	0.99	1.10	1.16	1.22

13 TeV σ [fb]	$t\bar{t}W^\pm Z$	$t\bar{t}Z\gamma$	$t\bar{t}W^\pm\gamma$
NLO	$4.157^{+9.8\%}_{-10.7\%}^{+2.2\%}_{-1.6\%}$	$5.771^{+10.5\%}_{-12.1\%}^{+1.8\%}_{-1.9\%}$	$6.734^{+12.0\%}_{-11.6\%}^{+1.8\%}_{-1.4\%}$
LO	$3.921^{+32.6\%}_{-22.8\%}^{+2.3\%}_{-2.2\%}$	$5.080^{+38.0\%}_{-25.3\%}^{+1.9\%}_{-1.9\%}$	$6.145^{+32.4\%}_{-22.6\%}^{+2.1\%}_{-2.0\%}$
K -factor	1.06	1.14	1.10

Differential K -factors

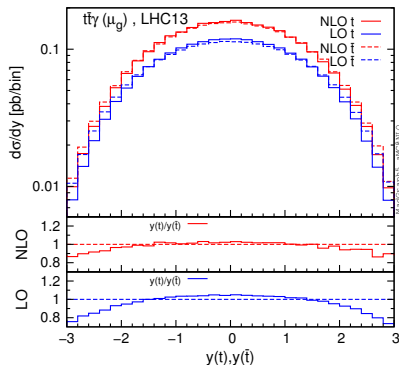
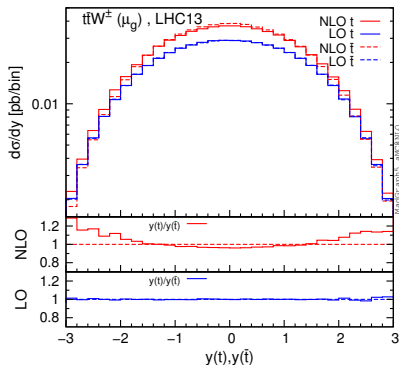
- μ_a systematically lower than μ_g
- K -factor flatter for dynamical scales (important exceptions!)

Differential K -factors

- qg channel opens at NLO, $(qg \rightarrow t\bar{t}Wq') \sim (qg \rightarrow t\bar{t}q) \times (q \rightarrow q'W)$
- $p_T(t\bar{t}) \propto \alpha_s \log^2 [p_T(t\bar{t})/m_W]$

Differential K -factors

$$t\bar{t} \text{ asymmetry, } A_c = \frac{\sigma(|y_t| > |y_{\bar{t}}|) - \sigma(|y_t| < |y_{\bar{t}}|)}{\sigma(|y_t| > |y_{\bar{t}}|) + \sigma(|y_t| < |y_{\bar{t}}|)}$$



13 TeV A_c [%]	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}W$	$t\bar{t}\gamma$
LO	-	$-0.12(3)^{+0.01}_{-0.01} {}^{+0.01}_{-0.02}$	-	$-3.93(3)^{+0.26}_{-0.23} {}^{+0.14}_{-0.11}$
NLO	$1.00(2)^{+0.30}_{-0.20} {}^{+0.06}_{-0.04}$	$0.85(3)^{+0.25}_{-0.17} {}^{+0.06}_{-0.05}$	$2.90(7)^{+0.67}_{-0.47} {}^{+0.06}_{-0.07}$	$-1.79(6)^{+0.50}_{-0.39} {}^{+0.06}_{-0.09}$

Analysis selection cuts

Kinematical cuts in $t\bar{t}H$ analysis arXiv:1408.1682

Particle identification

- Leptons $e(\mu)$: $P_T > 7(5)$ GeV , $|\eta| < 2.5(2.4)$, $\Delta R(\ell, j) > 0.5$
- Jets : anti- k_T , $R = 0.5$, $P_T > 25$ GeV , $|\eta| < 2.4$
- Photons : $|\eta| < 2.5$
- No lepton-jet misidentification, b-tagging efficiency=1

Diphoton \longrightarrow

Leptonic ($t\bar{t}H \rightarrow \ell\nu jjbb\gamma\gamma$, $t\bar{t}H \rightarrow \ell\nu\ell\nu bb\gamma\gamma$)	Diphoton	$2 \gamma, p_T > m_{\gamma\gamma}/2$ (25) GeV for 1 st (2 nd) $\geq 1 e/\mu, p_T > 20$ GeV ≥ 2 jets + ≥ 1 b-tags, $p_T > 25$ GeV
---	----------	---

Multilepton \longrightarrow

Same-Sign Dilepton ($t\bar{t}H \rightarrow \ell^\pm \nu \ell^\pm [\nu] jjj[j] bb$)	Dilepton	$2 e/\mu, p_T > 20$ GeV ≥ 4 jets + ≥ 1 b-tags, $p_T > 25$ GeV
3 Lepton ($t\bar{t}H \rightarrow \ell\nu\ell[\nu]\ell[\nu]j[j]bb$)	Dilepton, Trielectron	$1 e/\mu, p_T > 20$ GeV $1 e/\mu, p_T > 10$ GeV $1 e(\mu), p_T > 7(5)$ GeV ≥ 2 jets + ≥ 1 b-tags, $p_T > 25$ GeV
4 Lepton ($t\bar{t}H \rightarrow \ell\nu\ell\nu\ell[\nu]\ell[\nu]bb$)	Dilepton, Trielectron	$1 e/\mu, p_T > 20$ GeV $1 e/\mu, p_T > 10$ GeV $2 e(\mu), p_T > 7(5)$ GeV ≥ 2 jets + ≥ 1 b-tags, $p_T > 25$ GeV

Diphoton analysis

 $t\bar{t}H(H \rightarrow \gamma\gamma)$ vs $t\bar{t}\gamma\gamma$

Event selection

- $\Delta R(\gamma_1, \gamma_2) > 0.4$, $\Delta R(\gamma_{1,2}, j) > 0.4$, $\Delta R(\gamma_{1,2}, \ell) > 0.4$, $\Delta R(\ell, \ell) > 0.4$
- $100 < m_{\gamma_1\gamma_2} < 180$ GeV

13 TeV σ [fb]	$t\bar{t}H \times BR(H \rightarrow \gamma\gamma)$	$t\bar{t}\gamma\gamma$ (gen. cuts)
NLO	$1.191^{+6.0\%}_{-9.4\%} \quad +2.1\% \quad -2.6\%$	$1.466^{+8.7\%}_{-11.0\%} \quad +1.6\% \quad -1.8\%$
LO	$1.087^{+35.5\%}_{-24.2\%} \quad +2.0\% \quad -2.1\%$	$1.340^{+37.0\%}_{-24.8\%} \quad +1.7\% \quad -1.8\%$
K	1.10	1.09
	$t\bar{t}H(H \rightarrow \gamma\gamma)$	$t\bar{t}\gamma\gamma$
NLO ^{PS}	$0.194^{+5.9\%}_{-9.3\%} \quad +2.0\% \quad -2.6\% \pm 0.002$	$0.374^{+11.4\%}_{-12.2\%} \quad +1.5\% \quad -1.7\% \pm 0.004$
LO ^{PS}	$0.172^{+35.2\%}_{-24.1\%} \quad +2.0\% \quad -02.2\% \pm 0.001$	$0.310^{+36.4\%}_{-24.5\%} \quad +1.7\% \quad -1.8\% \pm 0.002$
K^{PS}	1.13 ± 0.01	1.21 ± 0.01

Signal processes

- $t\bar{t}H(H \rightarrow W^+W^-)$, $t\bar{t}H(H \rightarrow ZZ)$, $t\bar{t}H(H \rightarrow \tau^+\tau^-)$

Background processes

- $t\bar{t}W^\pm$, $t\bar{t}Z/\gamma^*$, $t\bar{t}W^+W^-$, $t\bar{t}ZZ$, $t\bar{t}W^\pm Z$, $t\bar{t}t\bar{t}$

13 TeV $\sigma[\text{fb}]$		SR1	SR2	SR3
$t\bar{t}H(H \rightarrow W^+W^-)$	NLO ^{PS}	$1.54^{+5.1}_{-9.0} {}^{+2.2}_{-2.6} \pm 0.02$	$1.47^{+5.2}_{-9.0} {}^{+2.0}_{-2.4} \pm 0.02$	$0.095^{+7.4}_{-9.7} {}^{+2.0}_{-2.4} \pm 0.002$
	LO ^{PS}	$1.401^{+35.6}_{-24.4} {}^{+2.1}_{-2.2} \pm 0.008$	$1.355^{+35.2}_{-24.1} {}^{+2.0}_{-2.2} \pm 0.008$	$0.0855^{+34.9}_{-24.0} {}^{+2.0}_{-2.2} \pm 0.0007$
$K = 1.10$	K^{PS}	1.10 ± 0.02	1.09 ± 0.02	1.11 ± 0.02
$t\bar{t}Z/\gamma^*$	NLO ^{PS}	$1.61^{+7.7}_{-10.5} {}^{+2.0}_{-2.5} \pm 0.02$	$2.70^{+9.0}_{-11.2} {}^{+2.0}_{-2.5} \pm 0.03$	$0.280^{+9.8}_{-11.0} {}^{+1.9}_{-2.3} \pm 0.003$
	LO ^{PS}	$1.422^{+36.8}_{-24.9} {}^{+2.2}_{-2.3} \pm 0.008$	$2.21^{+36.4}_{-24.7} {}^{+2.1}_{-2.2} \pm 0.01$	$0.221^{+35.8}_{-24.4} {}^{+2.0}_{-2.2} \pm 0.001$
$K = 1.23$	K^{PS}	1.13 ± 0.02	1.23 ± 0.01	1.27 ± 0.01

Multilepton analysis

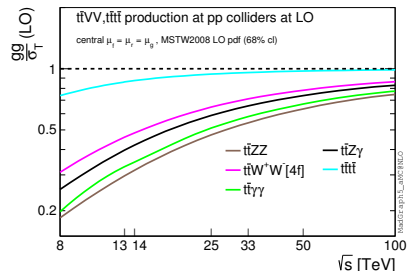
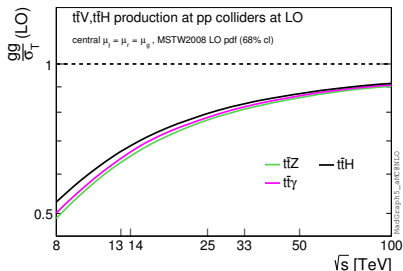
13 TeV $\sigma[\text{fb}]$		SR1	SR2	SR3
$t\bar{t}H(H \rightarrow ZZ)$ $K = 1.10$	NLO ^{PS}	$0.0437^{+5.5}_{-9.2} {}^{+2.3}_{-2.8} \pm 0.0004$	$0.119^{+6.3}_{-9.6} {}^{+2.1}_{-2.5} \pm 0.002$	$0.0170^{+5.0}_{-8.5} {}^{+2.0}_{-2.4} \pm 0.0003$
	LO ^{PS}	$0.0404^{+36.1}_{-24.6} {}^{+2.2}_{-2.3} \pm 0.0002$	$0.1092^{+35.3}_{-24.2} {}^{+2.0}_{-2.2} \pm 0.0008$	$0.0152^{+34.7}_{-23.9} {}^{+1.9}_{-2.1} \pm 0.0001$
	K^{PS}	1.08 ± 0.01	1.09 ± 0.02	1.12 ± 0.02
$t\bar{t}H(H \rightarrow \tau^+ \tau^-)$ $K = 1.10$	NLO ^{PS}	$0.563^{+4.6}_{-8.8} {}^{+2.2}_{-2.7} \pm 0.007$	$0.669^{+6.0}_{-9.4} {}^{+2.1}_{-2.6} \pm 0.008$	$0.0494^{+7.1}_{-9.9} {}^{+2.1}_{-2.5} \pm 0.0007$
	LO ^{PS}	$0.513^{+35.9}_{-24.5} {}^{+2.2}_{-2.3} \pm 0.003$	$0.611^{+35.4}_{-24.2} {}^{+2.1}_{-2.2} \pm 0.003$	$0.0438^{+35.1}_{-24.1} {}^{+2.0}_{-2.2} \pm 0.0003$
	K^{PS}	1.10 ± 0.02	1.10 ± 0.01	1.13 ± 0.02
$t\bar{t}W^\pm$ $K = 1.22$	NLO ^{PS}	$5.77^{+15.1}_{-12.7} {}^{+1.6}_{-1.2} \pm 0.07$	$2.44^{+13.1}_{-11.6} {}^{+1.7}_{-1.4} \pm 0.01$	-
	LO ^{PS}	$4.57^{+27.7}_{-20.2} {}^{+1.8}_{-1.9} \pm 0.03$	$1.989^{+27.5}_{-20.0} {}^{+1.8}_{-1.9} \pm 0.007$	-
	K^{PS}	1.26 ± 0.02	1.23 ± 0.01	-
$t\bar{t}W^+W^-$ $K = 1.10$	NLO ^{PS}	$0.288^{+8.0}_{-11.1} {}^{+2.3}_{-2.6} \pm 0.003$	$0.201^{+7.4}_{-10.7} {}^{+2.1}_{-2.3} \pm 0.003$	$0.0116^{+6.9}_{-10.2} {}^{+2.2}_{-2.3} \pm 0.0002$
	LO ^{PS}	$0.260^{+38.4}_{-25.5} {}^{+2.3}_{-2.3} \pm 0.001$	$0.181^{+38.0}_{-25.3} {}^{+2.2}_{-2.2} \pm 0.001$	$0.01073^{+37.7}_{-25.1} {}^{+2.2}_{-2.2} \pm 0.00008$
	K^{PS}	1.11 ± 0.01	1.11 ± 0.01	1.08 ± 0.02
$t\bar{t}ZZ$ $K = 0.99$	NLO ^{PS}	$(9.60^{+3.5}_{-8.4} {}^{+1.8}_{-1.8} \pm 0.06) \times 10^{-3}$	$(5.02^{+3.7}_{-8.3} {}^{+1.8}_{-1.7} \pm 0.04) \times 10^{-3}$	$(0.249^{+7.2}_{-9.6} {}^{+1.9}_{-1.8} \pm 0.009) \times 10^{-3}$
	LO ^{PS}	$(9.71^{+36.3}_{-24.5} {}^{+1.9}_{-1.9} \pm 0.02) \times 10^{-3}$	$(5.08^{+35.9}_{-24.3} {}^{+1.9}_{-1.9} \pm 0.02) \times 10^{-3}$	$(0.250^{+35.5}_{-24.2} {}^{+1.9}_{-1.9} \pm 0.004) \times 10^{-3}$
	K^{PS}	0.99 ± 0.01	0.99 ± 0.01	1.00 ± 0.04
$t\bar{t}W^\pm Z$ $K = 1.06$	NLO ^{PS}	$0.0620^{+9.0}_{-10.2} {}^{+2.2}_{-1.6} \pm 0.0007$	$0.0279^{+9.2}_{-10.3} {}^{+2.3}_{-1.7} \pm 0.0005$	$(0.91^{+7.2}_{-9.2} {}^{+2.4}_{-1.7} \pm 0.02) \times 10^{-3}$
	LO ^{PS}	$0.0602^{+32.2}_{-22.6} {}^{+2.4}_{-2.3} \pm 0.0003$	$0.0264^{+32.0}_{-22.5} {}^{+2.4}_{-2.2} \pm 0.0002$	$(0.893^{+31.9}_{-22.4} {}^{+2.4}_{-2.2} \pm 0.009) \times 10^{-3}$
	K^{PS}	1.03 ± 0.01	1.06 ± 0.02	1.02 ± 0.02
$t\bar{t}t\bar{t}$ $K = 1.22$	NLO ^{PS}	$0.340^{+27.5}_{-25.8} {}^{+5.5}_{-6.4} \pm 0.004$	$0.211^{+27.4}_{-25.6} {}^{+5.2}_{-6.1} \pm 0.003$	$0.0110^{+27.0}_{-25.5} {}^{+5.0}_{-5.9} \pm 0.0002$
	LO ^{PS}	$0.271^{+80.9}_{-41.5} {}^{+4.6}_{-4.6} \pm 0.001$	$0.166^{+80.3}_{-41.4} {}^{+4.4}_{-4.4} \pm 0.001$	$0.00871^{+79.8}_{-41.2} {}^{+4.2}_{-4.2} \pm 0.00007$
	K^{PS}	1.26 ± 0.02	1.27 ± 0.02	1.26 ± 0.03

Conclusions

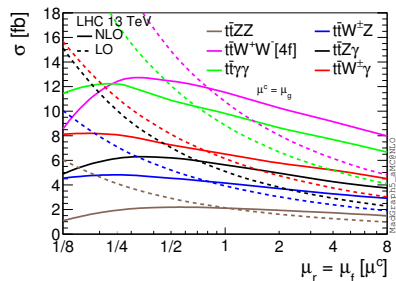
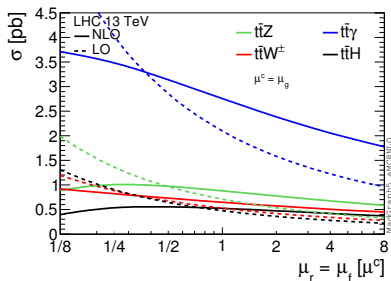
- A general, detailed study is realized on a group of processes
- The behavior of the cross sections with the energy depends on the gg contribution and the new channels entering at NLO
- There is no clear indication of what is the best scale
- The differential K -factors are not flat. Comparison between global K , K^{PS} in the analysis shows that for $t\bar{t}H$ it is $K \sim K^{\text{PS}}$, but this is not true for all the backgrounds ($t\bar{t}\gamma\gamma$, $t\bar{t}Z/\gamma^*$)

...Thank you

• LO gg channel contribution in processes



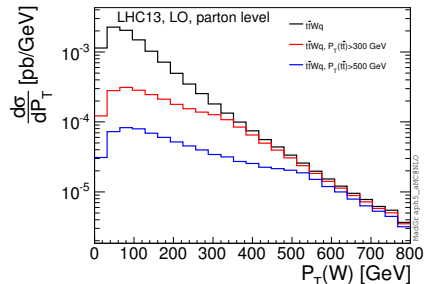
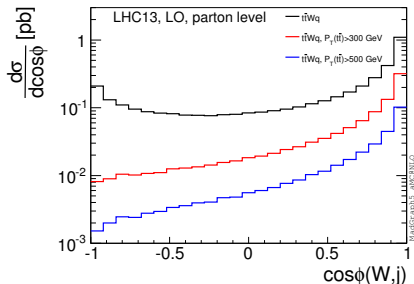
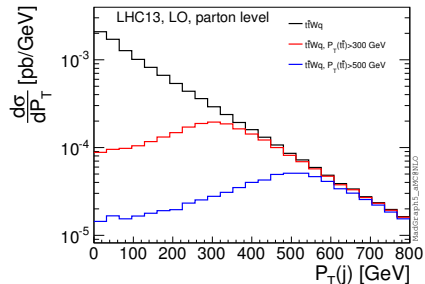
• LO vs NLO cross section scale dependence



- $t\bar{t}Wq$ at LO

High $p_T(t\bar{t})$

- Hard jet
- Soft and collinear W

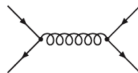
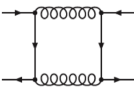
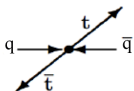


Interferences in QCD corrections \longrightarrow asymmetry

- Interference between amplitudes is not symmetric under $t \leftrightarrow \bar{t}$
- Coulomb-like repulsion/attraction

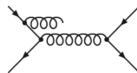
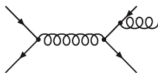
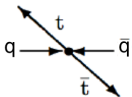
Born (α_s^2) and box (α_s^4) diagrams \longrightarrow positive asymmetry (α_s^3)

- The (anti)top quark prefers to keep the initial (anti)quark direction



ISR (α_s^3) and FSR (α_s^3) diagrams \longrightarrow negative asymmetry (α_s^3)

- The top quark prefers to keep the initial antiquark direction



Total effect \implies Positive asymmetry appearing at α_s^3