Top-quark pair production in association with (heavy) bosons at NLO

based on arXiv:1407.0823, arXiv:1504.03446, arXiv:1507.05640.

in collaboration with S. Frixione, V. Hirschi, F. Maltoni,
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Why ttbar + (heavy) bosons at NLO?

Phenomenology

- Measurement of the couplings of the top quark with the Z and H bosons in $t\bar{t}Z$ and $t\bar{t}H$ production
- $t\bar{t}\gamma\gamma$ is an irreducible background to $t\bar{t}H$, with the Higgs into 2 photons
- Leptonic signatures of $t\bar{t}H$ have many ttbar + heavy bosons processes as background: $t\bar{t}W^{\pm}, t\bar{t}Z$ and $t\bar{t}W^{+}W^{-}, t\bar{t}ZZ, t\bar{t}W^{\pm}Z$
- Top-quark central asymmetries in $t\bar{t}V$, at NLO

NLO calculations

"Only" QCD corrections (matched with showers) were available for

$t\bar{t}W^{\pm}$ Garzelli et al '12, Campbell Ellis '12, Maltoni et al '14

$t\bar{t}Z$ Lazopoulos et al '08, Garzelli et al '11, Kardos et al '11

$t\bar{t}H$ Beenakker et al '02, Dawson et al '03, Frederix et al '11, Garzelli et al '11

$t\bar{t}\gamma\gamma$ Kardos Trocsanyi '14

OUTLINE

NLO QCD + PS to $t\bar{t}V$, $t\bar{t}VV$ and $t\bar{t}t\bar{t}$

- Study of scale and PDF uncertainties and energy dependence
- Simulations of searches for $t\bar{t}H$ in leptonic signatures

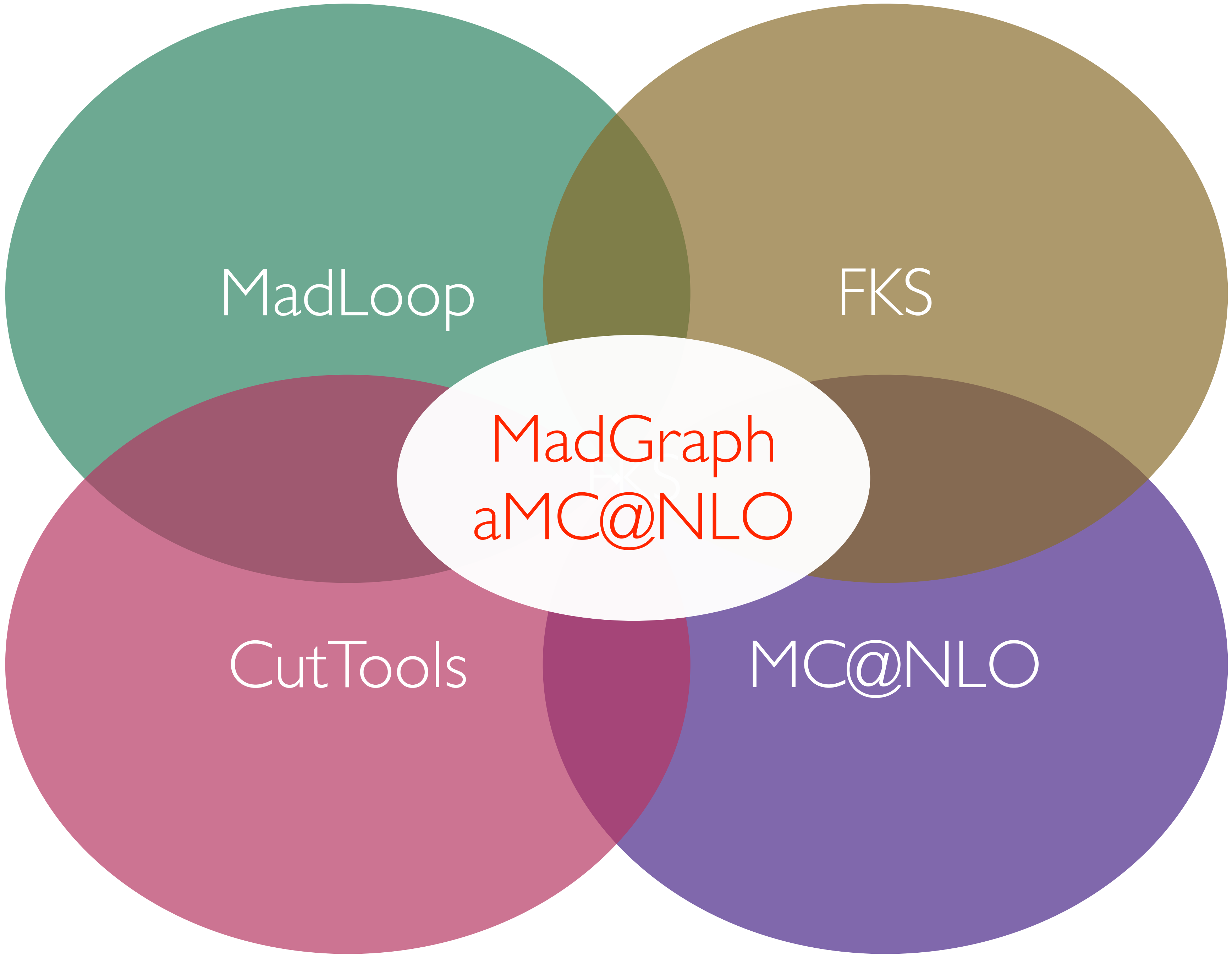
NLO QCD and EW corrections to $t\bar{t}V$

- Completely automated results at 8, 13, 100 TeV and in a boosted regime

Conclusions and Outlook

Automation of NLO corrections in Madgraph5_aMC@NLO

The **complete automation** has already been achieved for **NLO QCD**.



The **automation** for **NLO QCD+EW** is in progress!.

OUTLINE

NLO QCD + PS to $t\bar{t}V$, $t\bar{t}VV$ and $t\bar{t}t\bar{t}$

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Conclusions and Outlook

Processes

$t\bar{t}W^{\pm}$, $t\bar{t}Z$, $t\bar{t}\gamma$, $t\bar{t}H$

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

$t\bar{t}t\bar{t}$

… that is $t\bar{t}H$ and its possible irr. backgrounds

Scale definitions

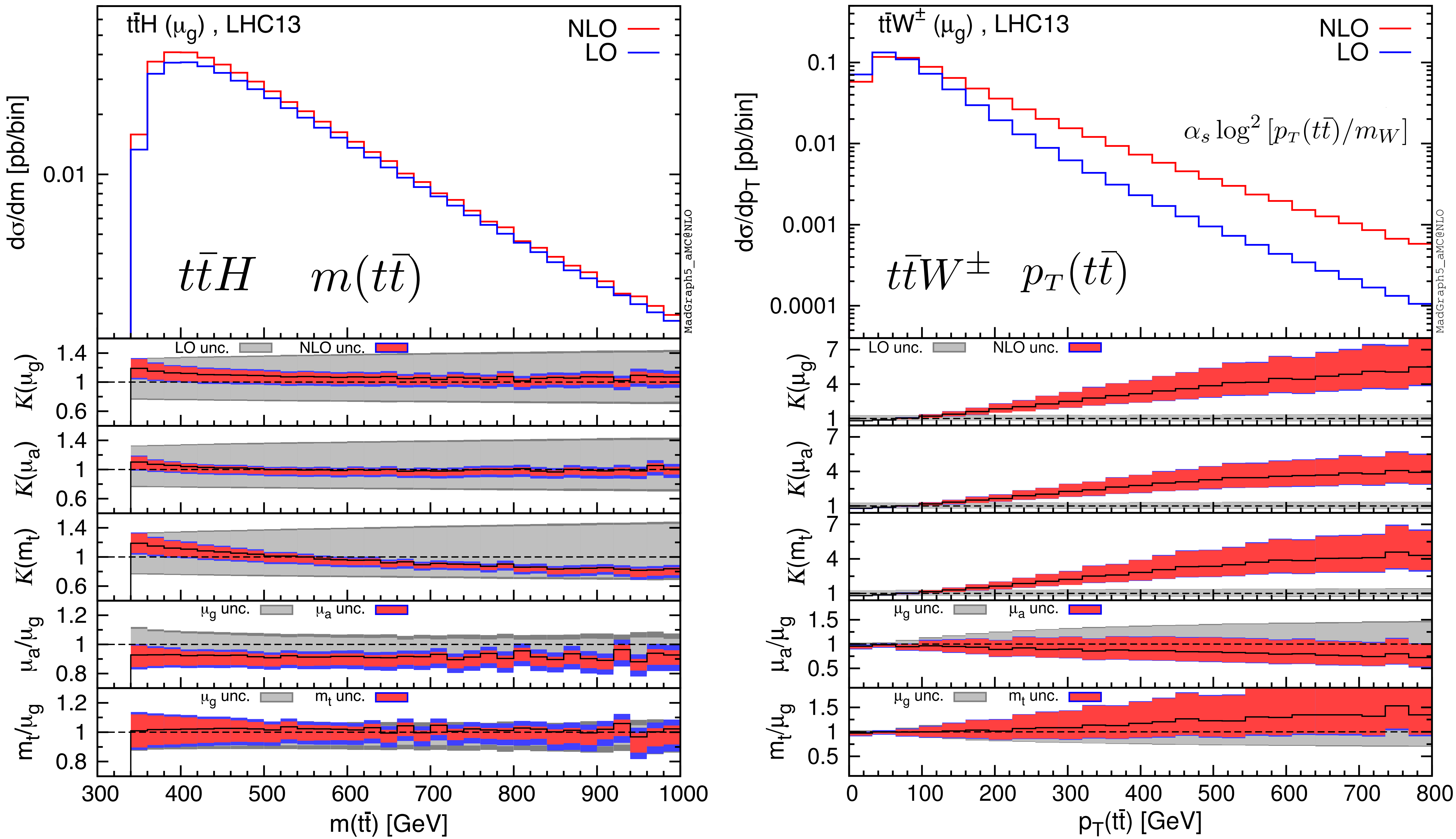
We compare the scale dependencies for the fixed scale and for two (common) definitions of dynamical scales: the **a**rithmetic and **g**eometric mean of final-state transverse masses.

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

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

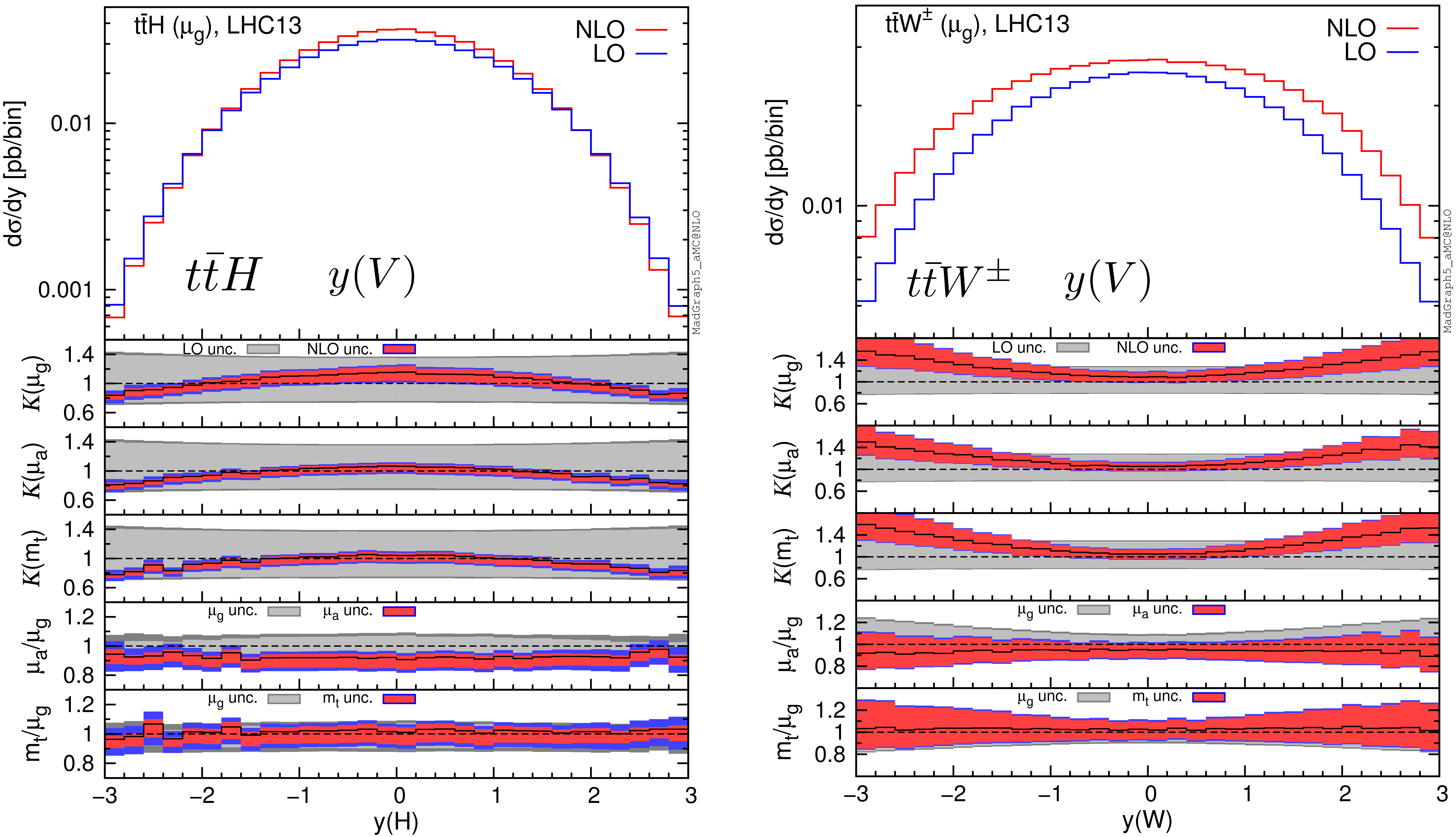
WE DO NOT SEARCH FOR THE BEST SCALE!

Distributions: representative results at fixed order



Maltoni, DP, Tsinikos '15

Distributions: representative results at fixed order



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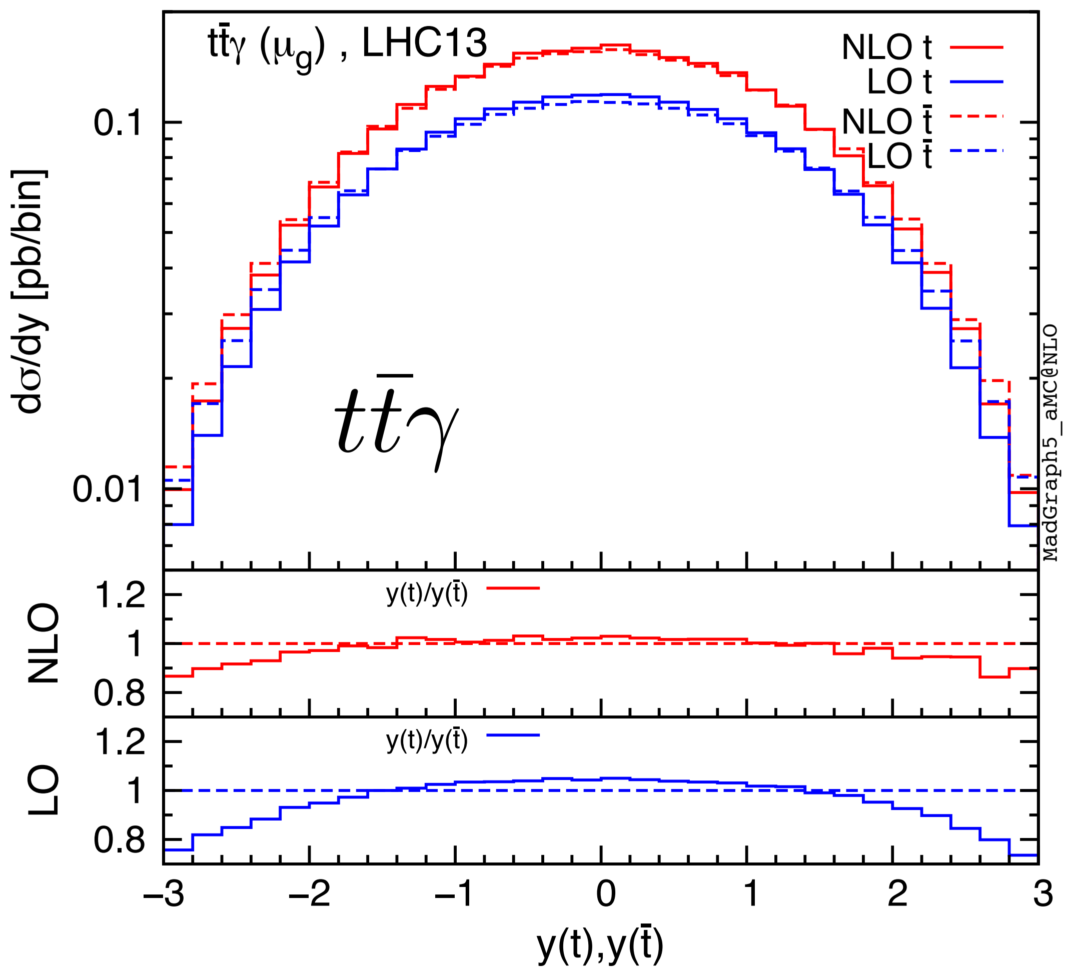
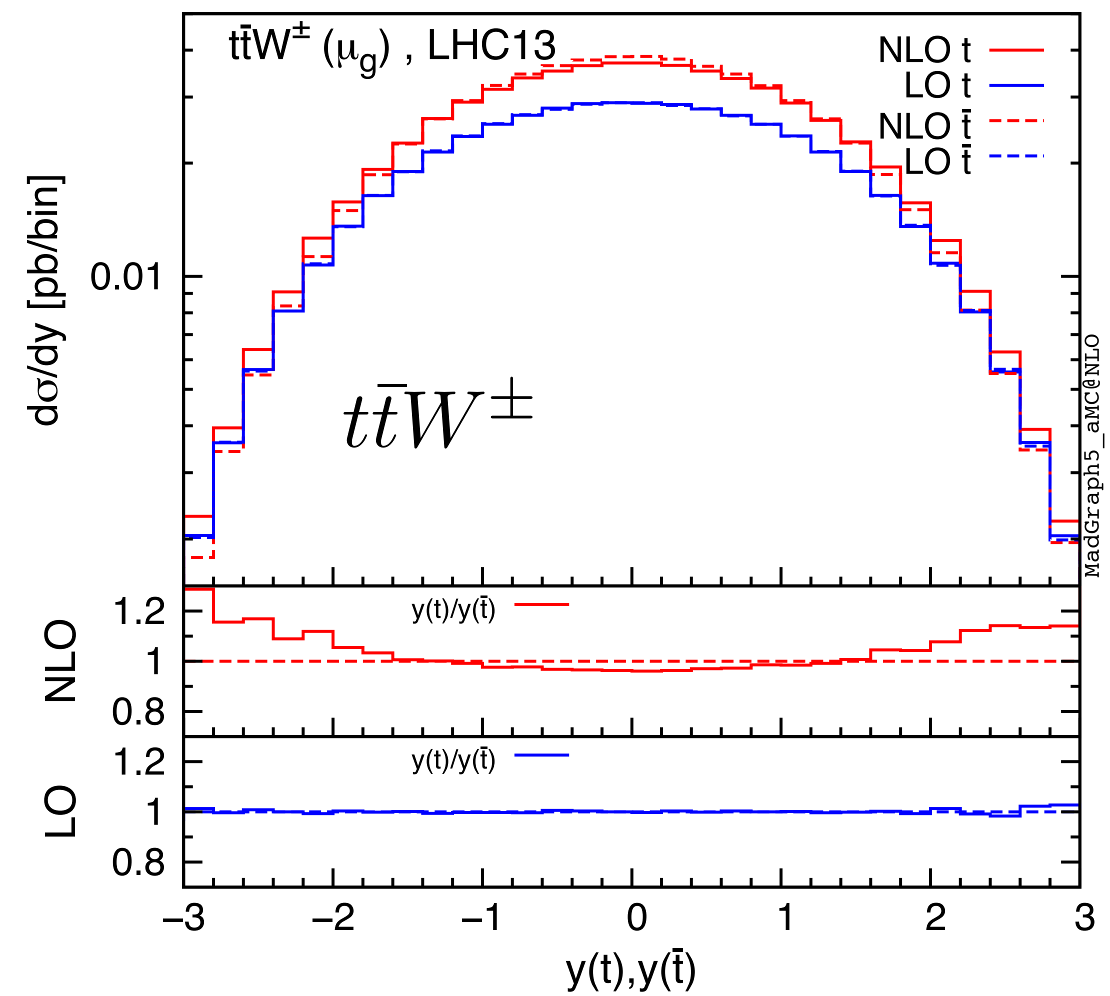
Distributions: representative results at fixed order





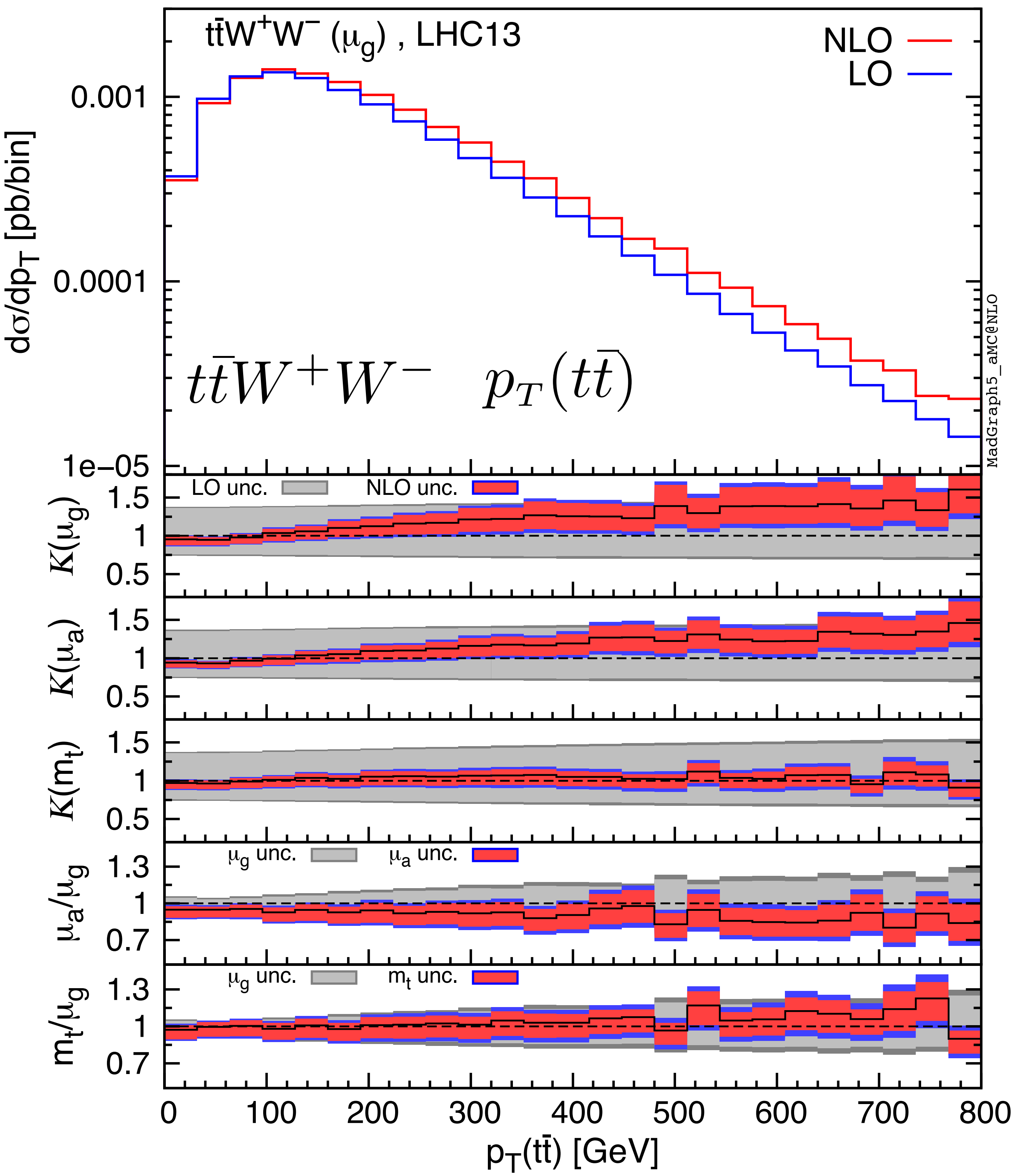
Central Asymmetries

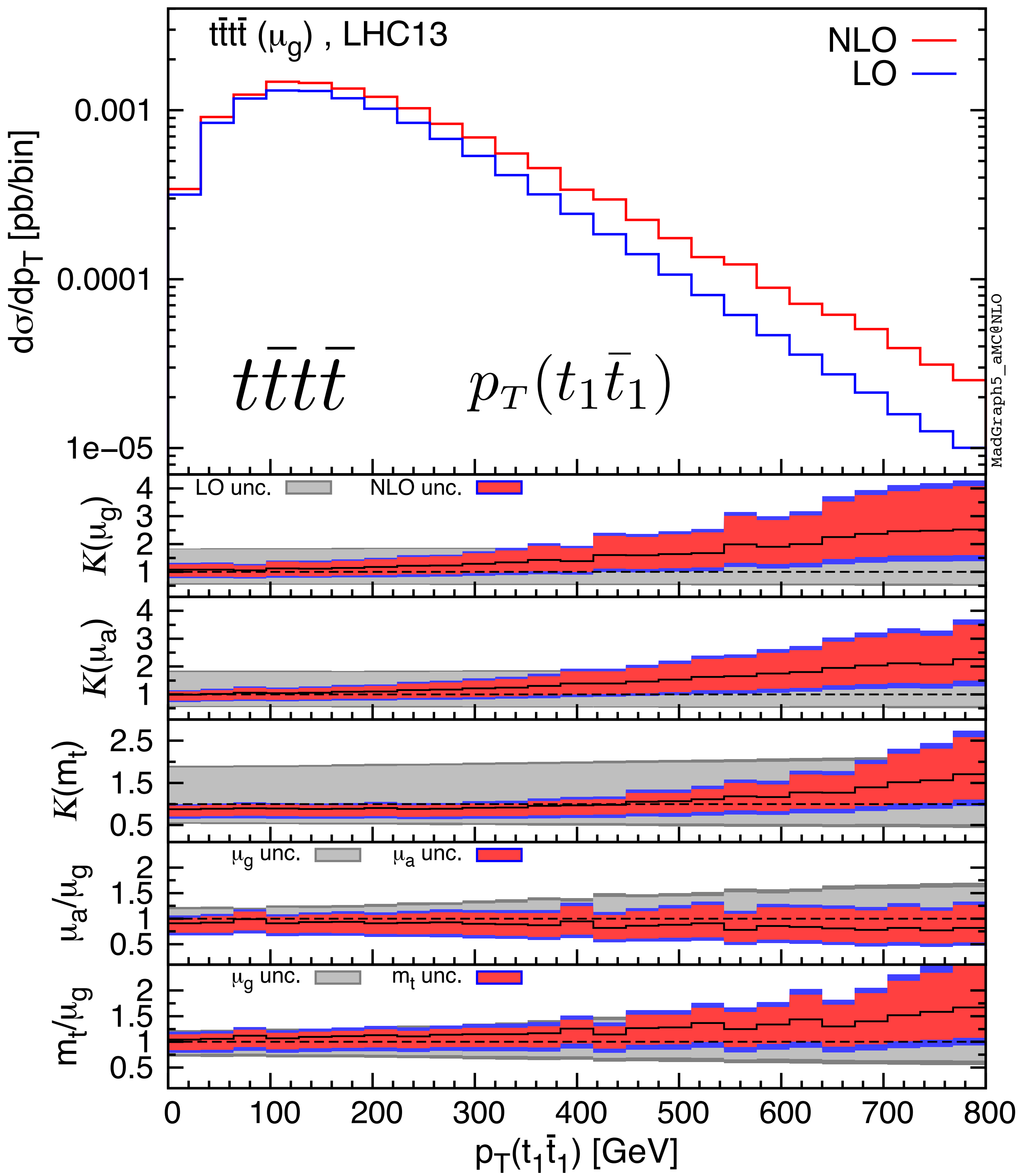
13 TeV A_c [%]	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}W^{\pm}$	$t\bar{t}\gamma$
LO	-	$-0.12^{+0.01}_{-0.01}\ ^{+0.01}_{-0.02} \pm 0.03$	-	$-3.93^{+0.26}_{-0.23}\ ^{+0.14}_{-0.11} \pm 0.03$
NLO	$1.00^{+0.30}_{-0.20}\ ^{+0.06}_{-0.04} \pm 0.02$	$0.85^{+0.25}_{-0.17}\ ^{+0.06}_{-0.05} \pm 0.03$	$2.90^{+0.67}_{-0.47}\ ^{+0.06}_{-0.07} \pm 0.07$	$-1.79^{+0.50}_{-0.39}\ ^{+0.06}_{-0.09} \pm 0.06$

Maltoni, DP, Tsinikos ‘15

See also: *Mangano, Maltoni, Tsinikos, Zaro ’14* for $t\bar{t}W^{\pm}$

Distributions: representative results at fixed order





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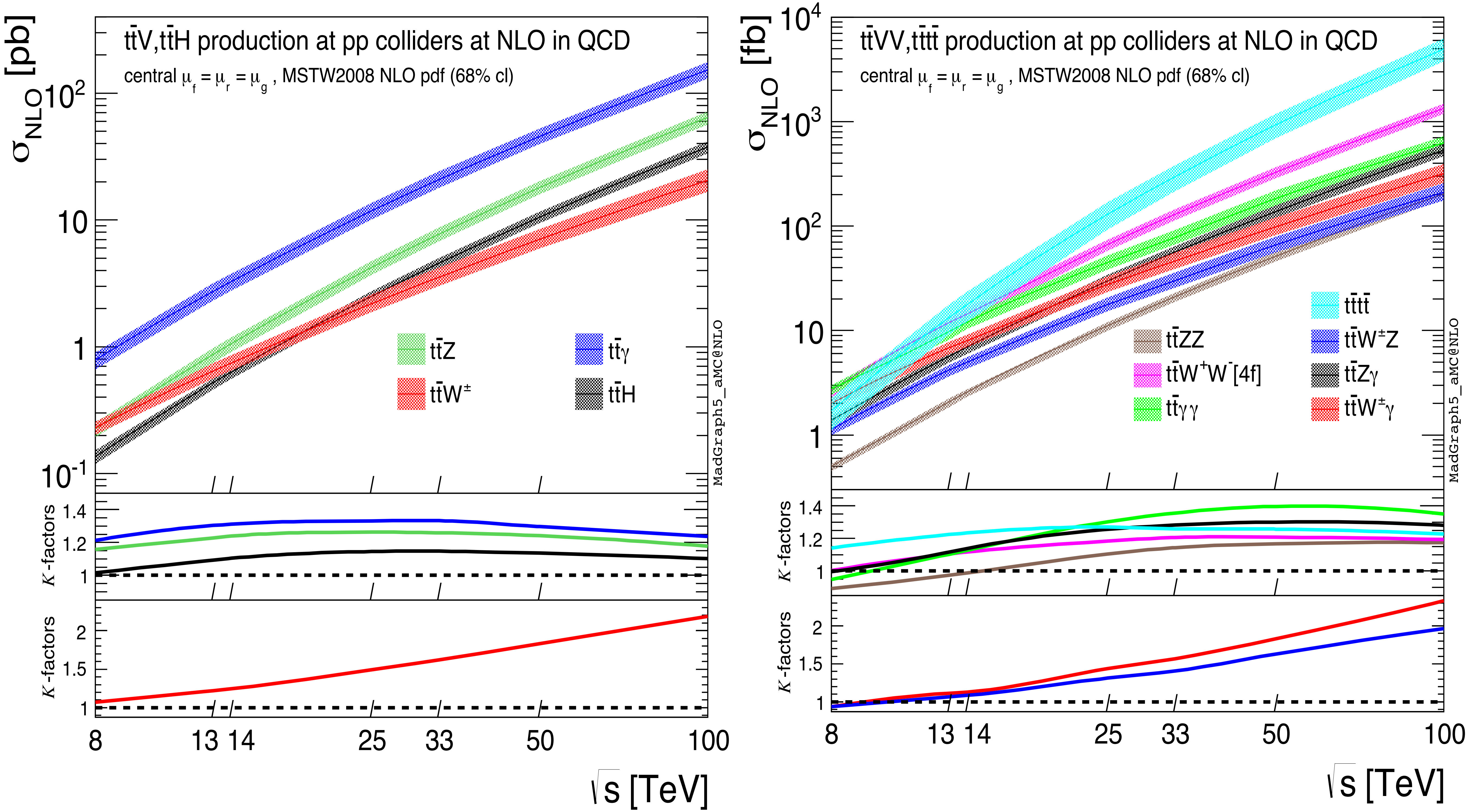
Energy dependence



Maltoni, DP, Tsinikos ‘15

$t\bar{t}H$, leptonic signatures

Analyses based on: *CMS, Search for the associated production of the Higgs boson with a top-quark pair, arXiv:1408.1682*

Three different signal regions:

- SR1: two same-sign leptons
- SR2: three leptons
- SR4: four leptons

Non-trivial leptonic and hadronic decays combinatoric from:
$t\bar{t}W^{\pm}$, $t\bar{t}Z/\gamma^*$, $t\bar{t}W^+W^-$, $t\bar{t}ZZ$, $t\bar{t}W^{\pm}Z$ and $t\bar{t}t\bar{t}$ production

K and $K^{\rm PS}$ are very similar for all SR and processes, besides in

13 TeV σ[fb]		SR1	SR2	SR3
	$\rm NLO^{PS}$	$1.62^{+7.3\%}_{-10.4\%}\,^{+2.1\%}_{-2.4\%} \pm 0.02$	$2.85^{+10.0\%}_{-11.6\%}\,^{+2.0\%}_{-2.5\%} \pm 0.03$	$0.303^{+10.5}_{-11.5}\,^{+1.9}_{-2.3} \pm 0.003$
$t\bar{t}Z/\gamma^*$	$\rm LO^{PS}$	$1.467^{+36.7\%}_{-24.9\%}\,^{+2.2\%}_{-2.3\%} \pm 0.008$	$2.31^{+36.4\%}_{-24.7\%}\,^{+2.1\%}_{-2.2\%} \pm 0.01$	$0.240^{+35.8}_{-24.4}\,^{+2.0}_{-2.2} \pm 0.001$
$K = 1.23$	$K^{\rm PS}$	1.11 ± 0.02	1.24 ± 0.01	1.26 ± 0.01

Signals and backgrounds: SR1,SR2 and SR3

13 TeV σ[fb]		SR1	SR2	SR3
	$\mathrm{NLO^{PS}}$	$1.56^{+5.8}_{-9.2}{}^{+2.1}_{-2.7} \pm 0.02$	$1.63^{+6.3\%}_{-9.6\%}{}^{+2.0\%}_{-2.6\%} \pm 0.02$	$0.108^{+7.1}_{-9.6}{}^{+2.0}_{-2.4} \pm 0.002$
$t\bar{t}H(H \to W^+W^-)$	$\mathrm{LO^{PS}}$	$1.395^{+35.7\%}_{-24.4\%}{}^{+2.1\%}_{-2.3\%} \pm 0.008$	$1.469^{+35.2\%}_{-24.2\%}{}^{+2.0\%}_{-2.2\%} \pm 0.009$	$0.0976^{+34.9}_{-24.0}{}^{+2.0}_{-2.2} \pm 0.0007$
$K = 1.10$	K^{PS}	1.12 ± 0.02	1.11 ± 0.02	1.11 ± 0.02
	$\mathrm{NLO^{PS}}$	$0.0449^{+5.6}_{-9.4}{}^{+2.3}_{-2.8} \pm 0.0004$	$0.134^{+6.2\%}_{-9.5\%}{}^{+2.1\%}_{-2.5\%} \pm 0.002$	$0.0190^{+6.4}_{-9.4}{}^{+2.0}_{-2.4} \pm 0.0003$
$t\bar{t}H(H \to ZZ)$	$\mathrm{LO^{PS}}$	$0.0416^{+36.0}_{-24.5}{}^{+2.2}_{-2.3} \pm 0.0002$	$0.1212^{+35.3\%}_{-24.1\%}{}^{+2.1\%}_{-2.1\%} \pm 0.0008$	$0.0171^{+34.8}_{-23.9}{}^{+1.9}_{-2.1} \pm 0.0001$
$K = 1.10$	K^{PS}	1.08 ± 0.01	1.09 ± 0.02	1.11 ± 0.02
	$\mathrm{NLO^{PS}}$	$0.555^{+5.2\%}_{-9.1\%}{}^{+2.3\%}_{-2.8\%} \pm 0.007$	$0.696^{+6.4\%}_{-9.6\%}{}^{+2.1\%}_{-2.6\%} \pm 0.008$	$0.0529^{+7.1}_{-9.9}{}^{+2.1}_{-2.5} \pm 0.0007$
$t\bar{t}H(H \to \tau^+\tau^-)$	$\mathrm{LO^{PS}}$	$0.515^{+35.9\%}_{-24.5\%}{}^{+2.2\%}_{-2.3\%} \pm 0.003$	$0.635^{+35.3\%}_{-24.2\%}{}^{+2.0\%}_{-2.2\%} \pm 0.003$	$0.0470^{+35.1}_{-24.1}{}^{+2.0}_{-2.2} \pm 0.0003$
$K = 1.10$	K^{PS}	1.08 ± 0.02	1.10 ± 0.01	1.13 ± 0.02
	$\mathrm{NLO^{PS}}$	$5.89^{+15.5\%}_{-12.9\%}{}^{+1.6\%}_{-1.2\%} \pm 0.07$	$2.73^{+13.1}_{-11.6}{}^{+1.7}_{-1.4} \pm 0.02$	-
$t\bar{t}W^\pm$	$\mathrm{LO^{PS}}$	$4.59^{+27.7\%}_{-20.2\%}{}^{+1.8\%}_{-1.9\%} \pm 0.03$	$2.212^{+27.4}_{-20.0}{}^{+1.8}_{-1.9} \pm 0.008$	-
$K = 1.22$	K^{PS}	1.28 ± 0.02	1.23 ± 0.01	-
	$\mathrm{NLO^{PS}}$	$1.62^{+7.3\%}_{-10.4\%}{}^{+2.1\%}_{-2.4\%} \pm 0.02$	$2.85^{+10.0\%}_{-11.6\%}{}^{+2.0\%}_{-2.5\%} \pm 0.03$	$0.303^{+10.5}_{-11.5}{}^{+1.9}_{-2.3} \pm 0.003$
$t\bar{t}Z/\gamma^*$	$\mathrm{LO^{PS}}$	$1.467^{+36.7\%}_{-24.9\%}{}^{+2.2\%}_{-2.3\%} \pm 0.008$	$2.31^{+36.4\%}_{-24.7\%}{}^{+2.1\%}_{-2.2\%} \pm 0.01$	$0.240^{+35.8}_{-24.4}{}^{+2.0}_{-2.2} \pm 0.001$
$K = 1.23$	K^{PS}	1.11 ± 0.02	1.24 ± 0.01	1.26 ± 0.01
	$\mathrm{NLO^{PS}}$	$0.28^{+7.5}_{-10.9}{}^{+2.2}_{-2.5} \pm 0.003$	$0.214^{+7.3}_{-10.7}{}^{+2.3}_{-2.5} \pm 0.003$	$0.0137^{+8.5}_{-11.2}{}^{+2.2}_{-2.5} \pm 0.0002$
$t\bar{t}W^+W^-$	$\mathrm{LO^{PS}}$	$0.26^{+38.3}_{-25.5}{}^{+2.3}_{-2.4} \pm 0.001$	$0.194^{+37.9}_{-25.3}{}^{+2.2}_{-2.2} \pm 0.001$	$0.01207^{+37.7}_{-25.2}{}^{+2.2}_{-2.2} \pm 0.00008$
$K = 1.10$	K^{PS}	1.11 ± 0.01	1.09 ± 0.03	1.13 ± 0.02
	$\mathrm{NLO^{PS}}$	$(9.62^{+3.3}_{-8.3}{}^{+1.8}_{-1.8} \pm 0.06) \times 10^{-3}$	$(5.82^{+3.7}_{-8.3}{}^{+1.8}_{-1.7} \pm 0.04) \times 10^{-3}$	$(0.280^{+6.5}_{-9.4}{}^{+1.9}_{-1.9} \pm 0.009) \times 10^{-3}$
$t\bar{t}ZZ$	$\mathrm{LO^{PS}}$	$(9.77^{+36.3}_{-24.5}{}^{+1.9}_{-1.9} \pm 0.02) \times 10^{-3}$	$(5.84^{+35.8}_{-24.3}{}^{+1.9}_{-1.9} \pm 0.02) \times 10^{-3}$	$(0.289^{+35.5}_{-24.1}{}^{+1.9}_{-1.9} \pm 0.004) \times 10^{-3}$
$K = 0.99$	K^{PS}	0.99 ± 0.01	1.00 ± 0.01	0.97 ± 0.03
	$\mathrm{NLO^{PS}}$	$0.0632^{+8.5\%}_{-10.0\%}{}^{+2.2\%}_{-1.7\%} \pm 0.0007$	$0.0307^{+8.3\%}_{-9.9\%}{}^{+2.3\%}_{-1.7\%} \pm 0.0005$	$(1.09^{+7.1}_{-9.1}{}^{+2.3}_{-1.7} \pm 0.02) \times 10^{-3}$
$t\bar{t}W^\pm Z$	$\mathrm{LO^{PS}}$	$0.0599^{+32.2\%}_{-22.6\%}{}^{+2.4\%}_{-2.2\%} \pm 0.0003$	$0.0291^{+31.9\%}_{-22.4\%}{}^{+2.3\%}_{-2.3\%} \pm 0.0002$	$(1.08^{+31.8}_{-22.4}{}^{+2.4}_{-2.2} \pm 0.01) \times 10^{-3}$
$K = 1.06$	K^{PS}	1.06 ± 0.01	1.06 ± 0.02	1.01 ± 0.02
	$\mathrm{NLO^{PS}}$	$0.335^{+28.6}_{-26.2}{}^{+5.7}_{-6.5} \pm 0.004$	$0.221^{+27.1}_{-25.6}{}^{+5.2}_{-6.1} \pm 0.003$	$0.0126^{+27.3}_{-25.6}{}^{+5.0}_{-5.9} \pm 0.0003$
$t\bar{t}t\bar{t}$	$\mathrm{LO^{PS}}$	$0.267^{+80.9}_{-41.6}{}^{+4.7}_{-4.6} \pm 0.001$	$0.178^{+80.3\%}_{-41.4\%}{}^{+4.4\%}_{-4.4\%} \pm 0.001$	$0.00988^{+79.8}_{-41.3}{}^{+4.2}_{-4.2} \pm 0.00007$
$K = 1.22$	K^{PS}	1.26 ± 0.02	1.24 ± 0.02	1.27 ± 0.03

Maltoni, DP, Tsinikos ‘15

OUTLINE

NLO QCD + PS to $t\bar{t}V$, $t\bar{t}VV$ and $t\bar{t}t\bar{t}$

- Study of scale and PDF uncertainties and energy dependence
- Simulations of searches for $t\bar{t}H$ in leptonic signatures

NLO QCD and EW corrections to $t\bar{t}V$

- Completely automated results at 8, 13, 100 TeV and in a boosted regime

Conclusions and Outlook

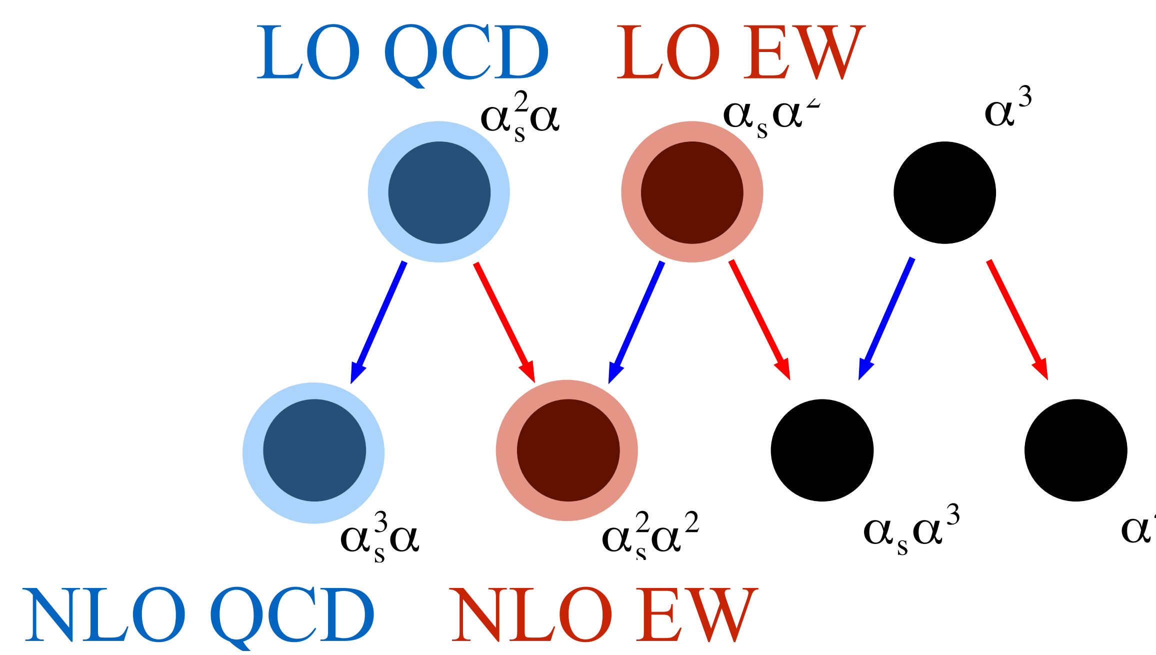
NLO QCD +EW for $t\bar{t}V$ production ($V = H, W, Z$)

Alpha(mZ)-scheme, NNPDF2.3_QED, $\mu = \frac{H_T}{2}$, $\frac{1}{2}\mu \leq \mu_R, \mu_F \leq 2\mu$

Contributions

HBR ($pp \to t\bar{t}V + V'$) is of the same order of NLO EW.

The Photon PDF (with large uncertainties) enters in LO EW and NLO EW.



The generation of EW-QCD loops, real emission of gluons, quarks and photons is completely automated.

```
define p = p b b~ a
generate p p > t t~ h [QCD QED]
output ttbarh_QCD_QED
```

FKS IR counterterms completely automated.

NLO QCD +EW for $t\bar{t}V$ production $(V = H, W, Z)$

Alpha(mZ)-scheme, NNPDF2.3_QED, $\mu = \frac{H_T}{2}$, $\frac{1}{2}\mu \leq \mu_R, \mu_F \leq 2\mu$

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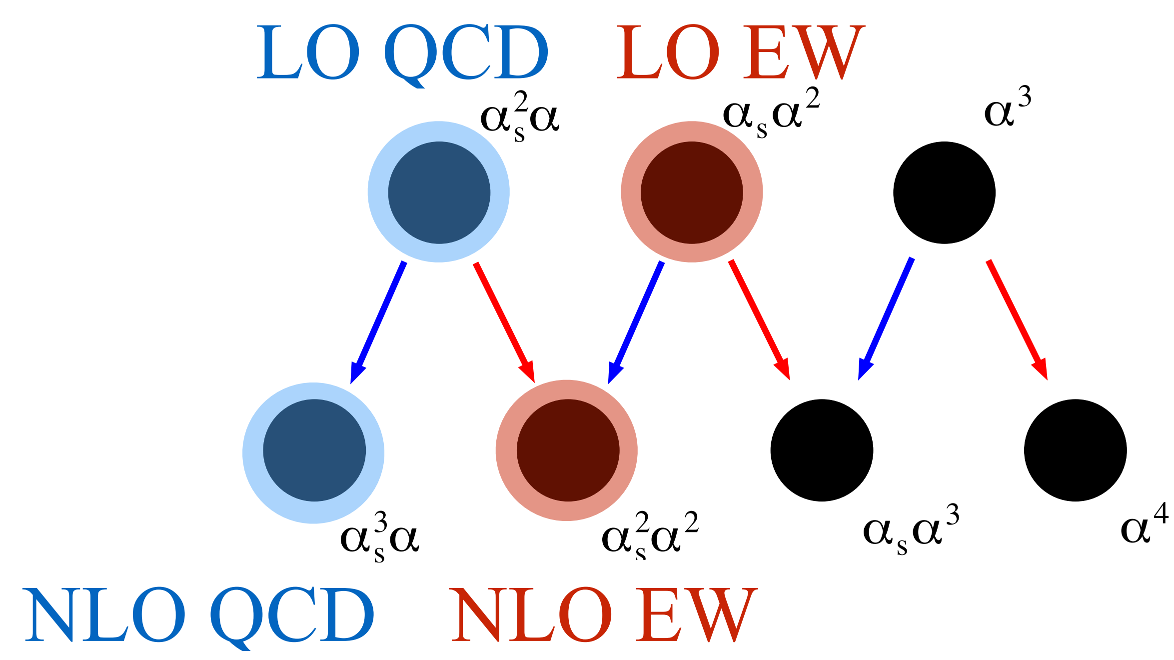


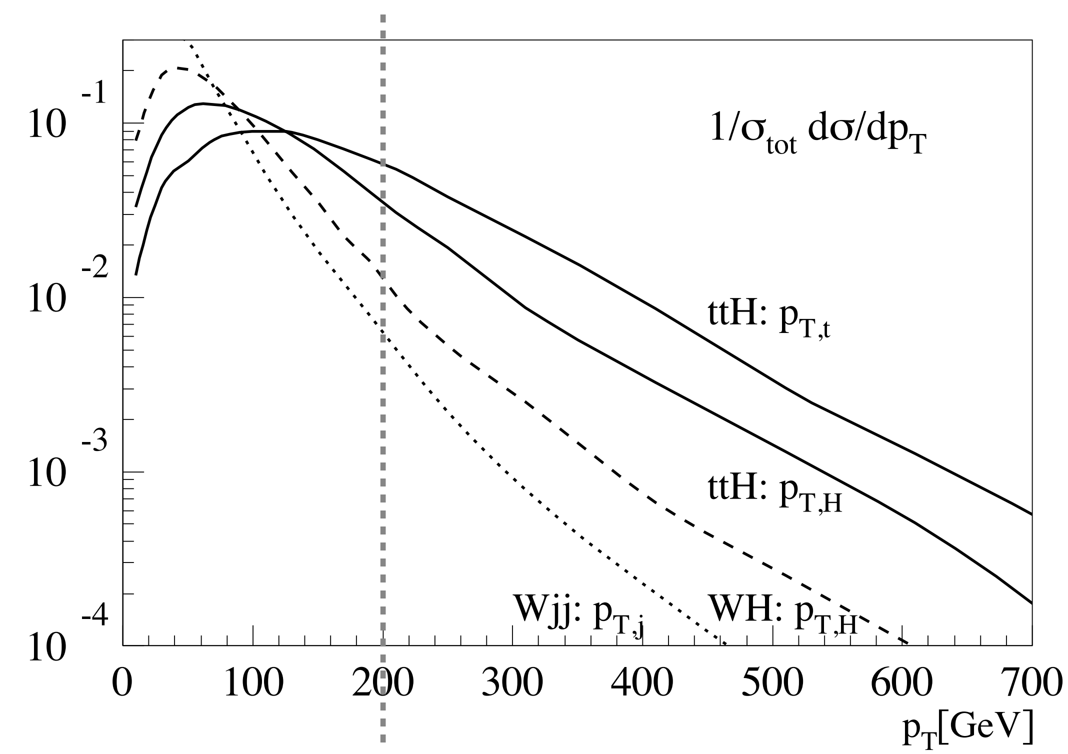
Boosted regime

$p_T(t) \geq 200$ GeV, $p_T(\bar{t}) \geq 200$ GeV, $p_T(H) \geq 200$ GeV

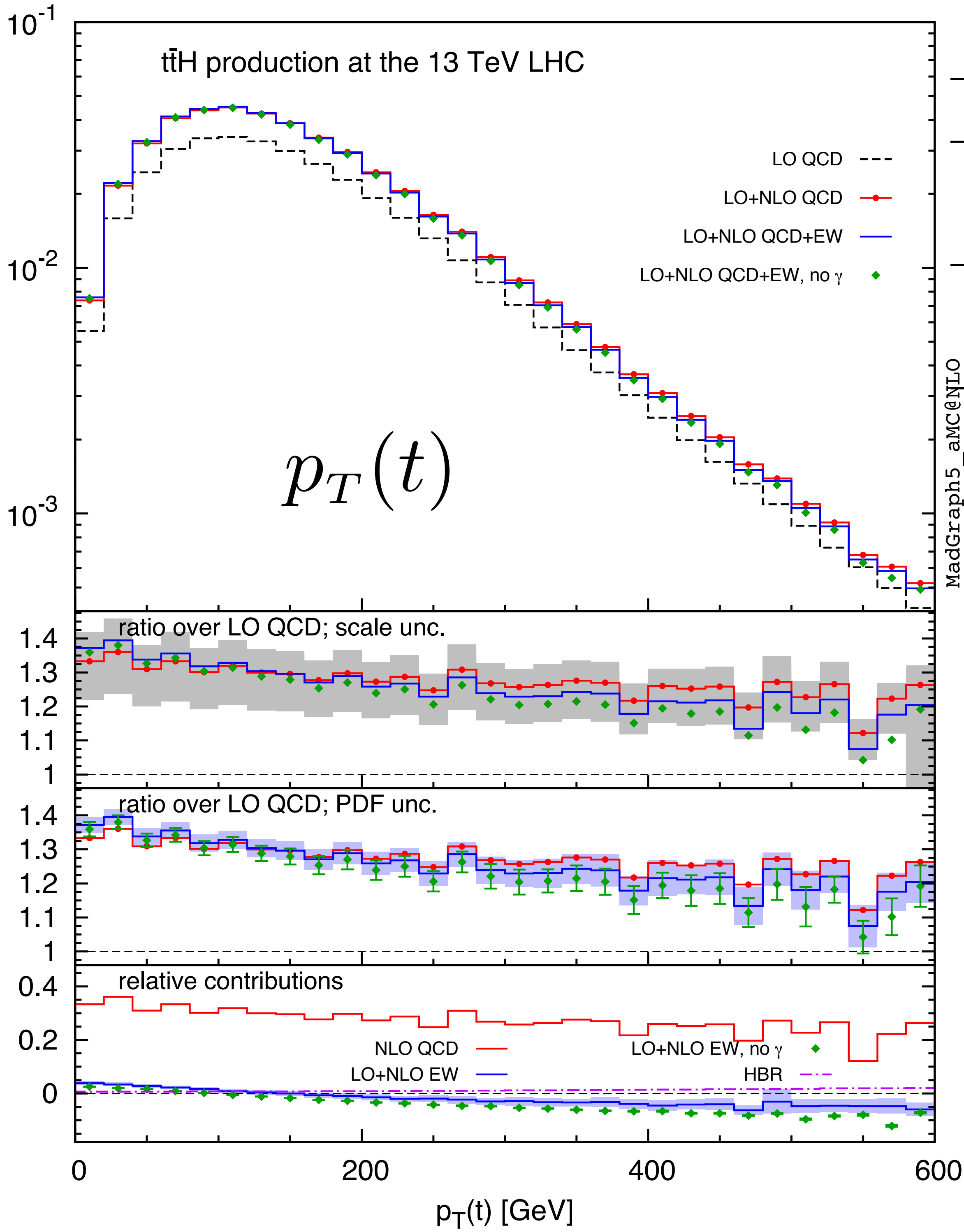
S/B increases for boosted tops and Higgs.

Plehn, Salam, Spannowsky '10

Sudakov logs are relevant in these regions!



Numerical results



$t\bar{t}H$: $\delta(\%)$	8 TeV	13 TeV	100 TeV
NLO QCD	$25.9^{+5.4}_{-11.1}$	$29.7^{+6.8}_{-11.1}$ $(24.2^{+4.8}_{-10.6})$	$40.8^{+9.3}_{-9.1}$
LO EW	1.8 ± 1.3	1.2 ± 0.9 (2.8 ± 2.0)	0.0 ± 0.2
LO EW no γ	-0.3 ± 0.0	-0.4 ± 0.0 (-0.2 ± 0.0)	-0.6 ± 0.0
NLO EW	-0.6 ± 0.1	-1.2 ± 0.1 (-8.2 ± 0.3)	-2.7 ± 0.0
NLO EW no γ	-0.7 ± 0.0	-1.4 ± 0.0 (-8.5 ± 0.2)	-2.7 ± 0.0
HBR	0.88	0.89 (1.87)	0.91

(Boosted regime in brackets)

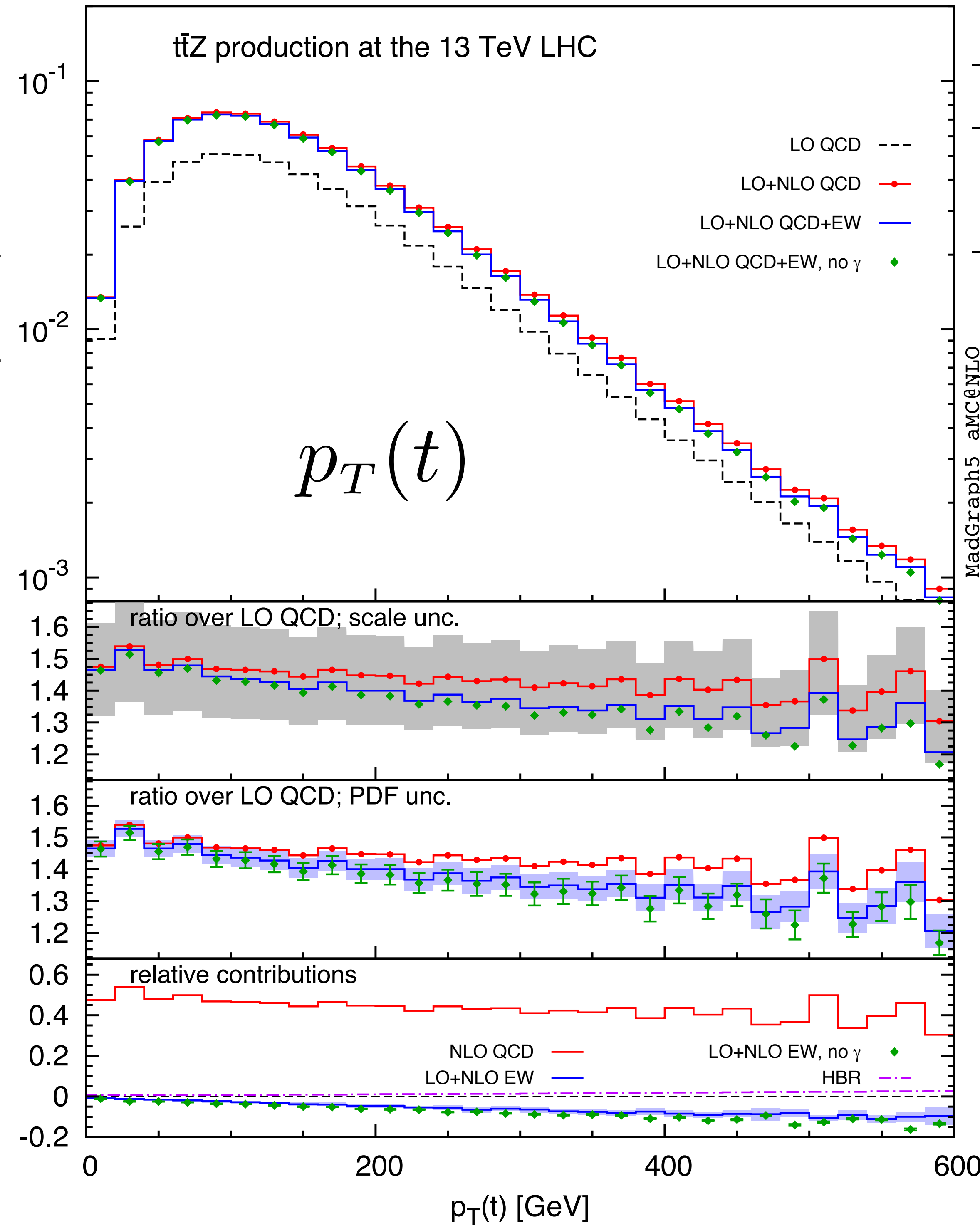
Scale variation

(NLO QCD+EW) PDF var.

$$t\bar{t}H$$

Frixione, Hirschi, DP, Shao, Zaro ‘15

Numerical results



$t\bar{t}Z$: $\delta(\%)$	8 TeV	13 TeV	100 TeV
NLO QCD	$43.2^{+12.8}_{-15.9}$	$45.9^{+13.2}_{-15.5}$ $(40.2^{+11.1}_{-15.0})$	$50.4^{+11.4}_{-10.9}$
LO EW	0.5 ± 0.9	0.0 ± 0.7 (2.1 ± 1.6)	-1.1 ± 0.2
LO EW no γ	-0.8 ± 0.1	-1.1 ± 0.0 (-0.3 ± 0.0)	-1.6 ± 0.0
NLO EW	-3.3 ± 0.3	-3.8 ± 0.2 (-11.1 ± 0.5)	-5.2 ± 0.1
NLO EW no γ	-3.7 ± 0.1	-4.1 ± 0.1 (-11.5 ± 0.3)	-5.4 ± 0.0
HBR	0.95	0.96 (2.13)	0.85

(Boosted regime in brackets)

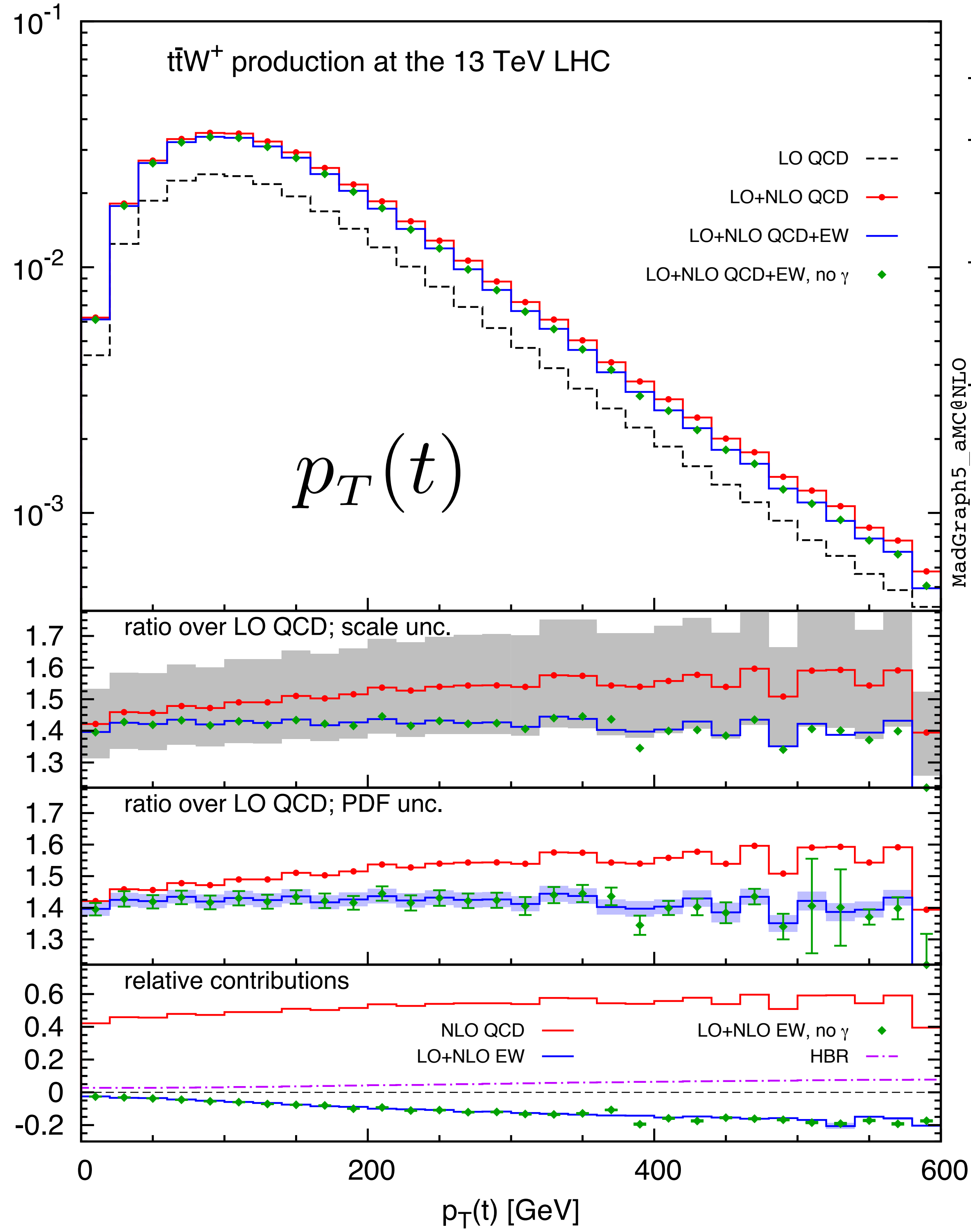
Scale variation

(NLO QCD+EW) PDF var.

$$t\bar{t}Z$$

Frixione, Hirschi, DP, Shao, Zaro ‘15

Numerical results



$t\bar{t}W^+ : \delta(\%)$	8 TeV	13 TeV	100 TeV
NLO QCD	$40.8^{+11.2}_{-12.3}$	$50.1^{+14.2}_{-13.5}$ $(59.7^{+18.9}_{-17.7})$	$156.4^{+38.3}_{-35.0}$
LO EW	0	0	0
LO EW no γ	0	0	0
NLO EW	-6.9 ± 0.2	-7.7 ± 0.2 (-19.2 ± 0.7)	-9.3 ± 0.2
NLO EW no γ	-7.1 ± 0.2	-8.0 ± 0.2 (-20.0 ± 0.5)	-9.6 ± 0.1
HBR	2.41	3.88 (7.41)	21.52

(Boosted regime in brackets)

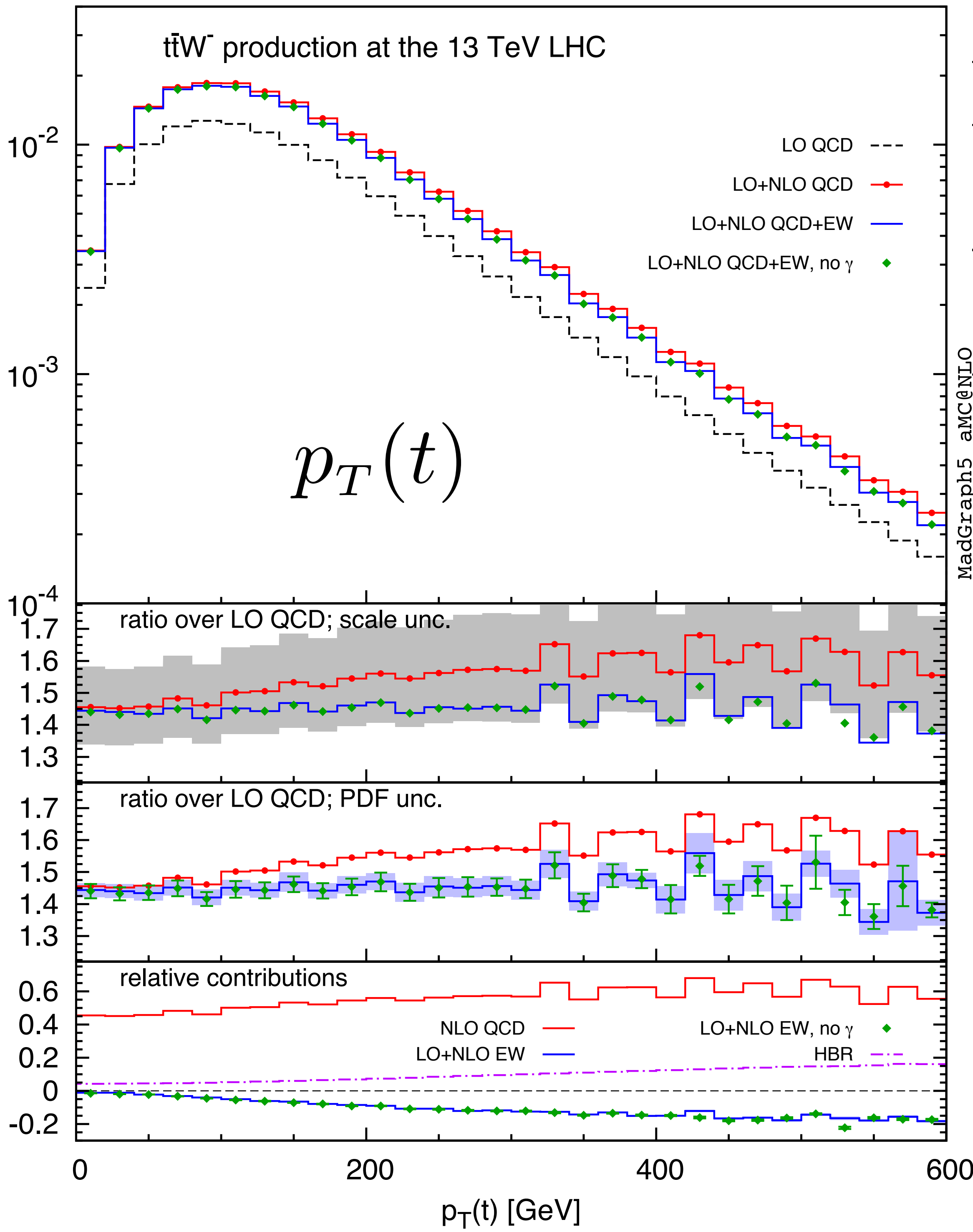
Scale variation

(NLO QCD+EW) PDF var.

$t\bar{t}W^+$

Frixione, Hirschi, DP, Shao, Zaro ‘15

Numerical results



$t\bar{t}W^-$: $\delta(\%)$	8 TeV	13 TeV	100 TeV
NLO QCD	$42.2^{+11.9}_{-12.7}$	$51.5^{+14.8}_{-13.8}$ $(66.3^{+21.7}_{-19.6})$	$153.6^{+37.7}_{-34.9}$
LO EW	0	0	0
LO EW no γ	0	0	0
NLO EW	-6.0 ± 0.3	-6.7 ± 0.2 (-18.3 ± 0.8)	-8.5 ± 0.2
NLO EW no γ	-6.2 ± 0.2	-7.0 ± 0.2 (-19.1 ± 0.6)	-8.8 ± 0.1
HBR	4.35	6.50 (15.01)	28.91

(Boosted regime in brackets)

Scale variation

(NLO QCD+EW) PDF var.

$t\bar{t}W^-$

Frixione, Hirschi, DP, Shao, Zaro '15

CONCLUSION

We performed a thorough analysis of PDF and scale uncertainties at NLO QCD for $t\bar{t}V$ and $t\bar{t}VV$ processes with the public version of **MadGraph5_ aMC@NLO.** We provided also NLO+PS results, in a realistic experimental set-up, for all the signal and background processes involved in the searches of $t\bar{t}H$ with leptonic and diphoton signatures at the LHC.

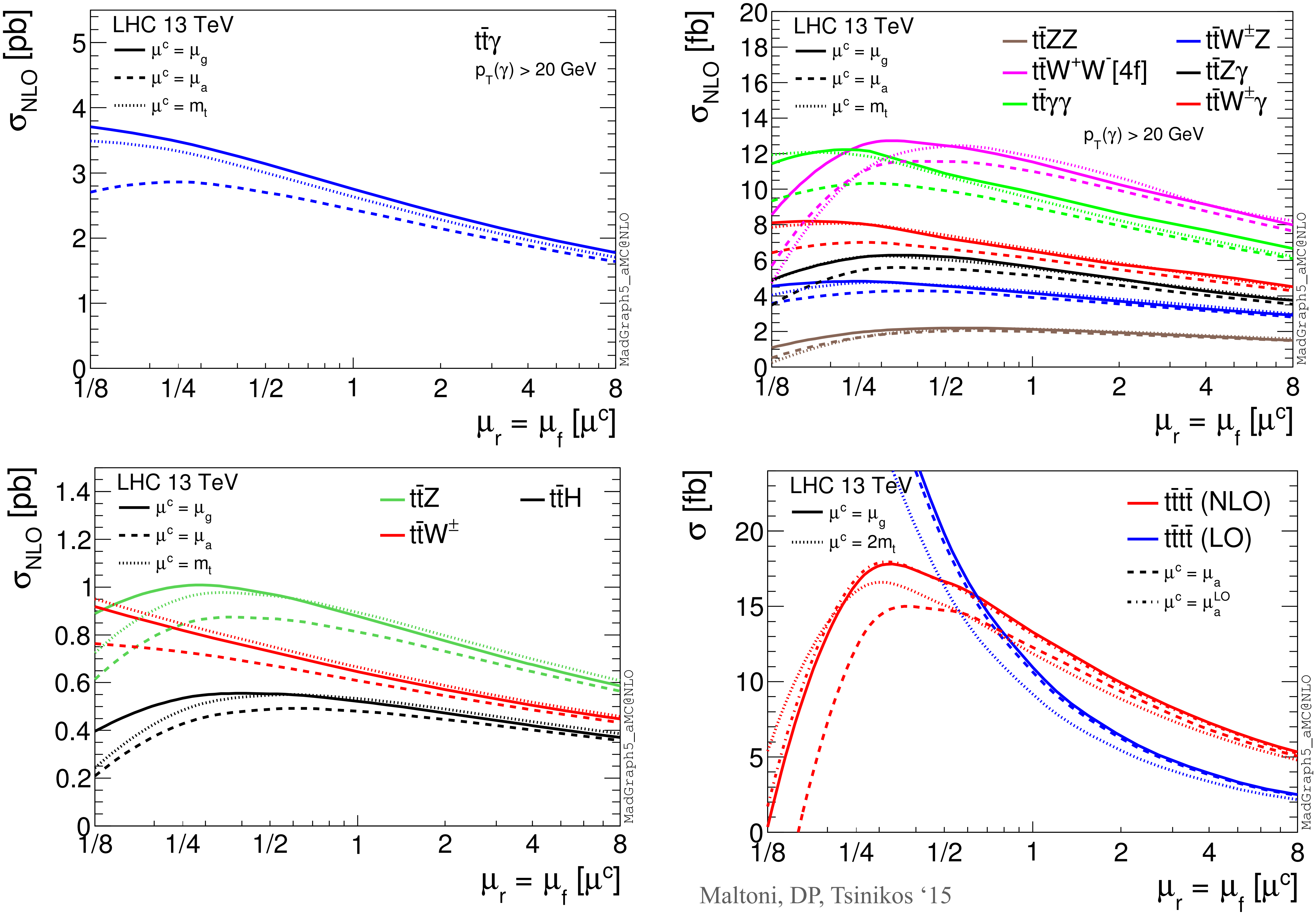
The scale dependence in $t\bar{t}V$ and $t\bar{t}VV$ processes changes for different scale definitions, with no clear sign of a general "best-scale choice".
K-factors of charged final-states strongly depend on the total energy of the pp collision and on specific kinematic variables.
NLO QCD corrections reduce the value of the top-quark asymmetry in $t\bar{t}\gamma$.

The automation in **MadGraph5_aMC@NLO** of NLO EW and QCD corrections is in progress. NLO QCD and EW corrections to $t\bar{t}V$ have been calculated in a completely automated approach.

The $t\bar{t}V$ ($V = H, W, Z$) processes show non-negligible corrections for large pt and in a boosted regime, due to Sudakov logs.
NLO EW corrections are particularly large for $t\bar{t}W^+$ and $t\bar{t}W^-$.

EXTRA SLIDES

Scale dependence: NLO, different scales



Maltoni, DP, Tsinikos '15

Automation of NLO corrections in Madgraph5_aMC@NLO

What do we mean with automation of EW corrections?

The possibility of calculating QCD and EW corrections for SM processes (matched to shower effects) with a process-independent approach.

```
generate process [QCD]
output process_QCD
```

→

```
generate process [QCD EW]
output process_QCD_EW
```

The automation of NLO QCD has been achieved, but we need higher precision to match the experimental accuracy at the LHC and future colliders.

- NNLO QCD automation is out of our theoretical capabilities at the moment.
- NLO EW corrections are of the same order ($\alpha_s^2 \sim \alpha$), the Sudakov logarithms can enhance their size. NLO QCD and EW corrections **can be automated.**

Amplitudes and matrix elements

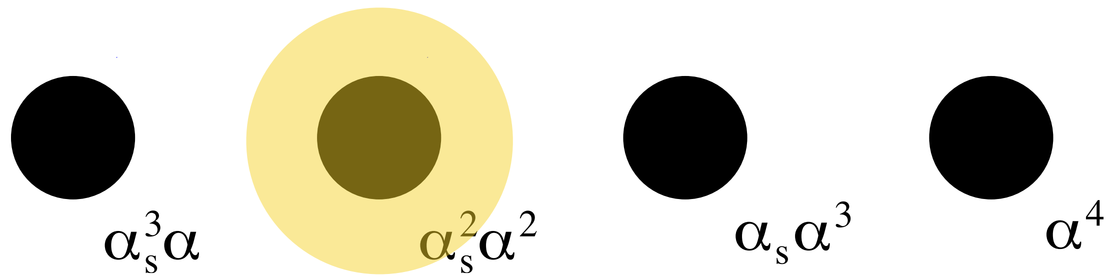
NLO UFO models: (UV CT, R2)

- SM-alpha(mZ) (EW+QCD, Weak+QCD)
- SM-Gμ (EW+QCD, Weak+QCD)

Weak = EW without photonics corrections (to be used when gauge invariant).

The matrix element calculation is completely automated. Example: $t\bar{t}V$

NLO orders of $t\bar{t}V$



Processes with only final-state massive particles

The generation of EW-QCD loops, real emission of gluons, quarks and photons is completely automated.

FKS IR counterterms completely automated. Also for photons in the initial state.

Heavy Boson Radiation (HBR)

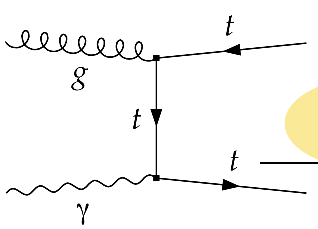
$$pp \to t\bar{t}H + V$$
$$V = H, W, Z$$

Formally of order $\alpha_S^2\alpha^2$

Why do we care about photons in the proton?

2 representative examples:

$t\bar{t}$

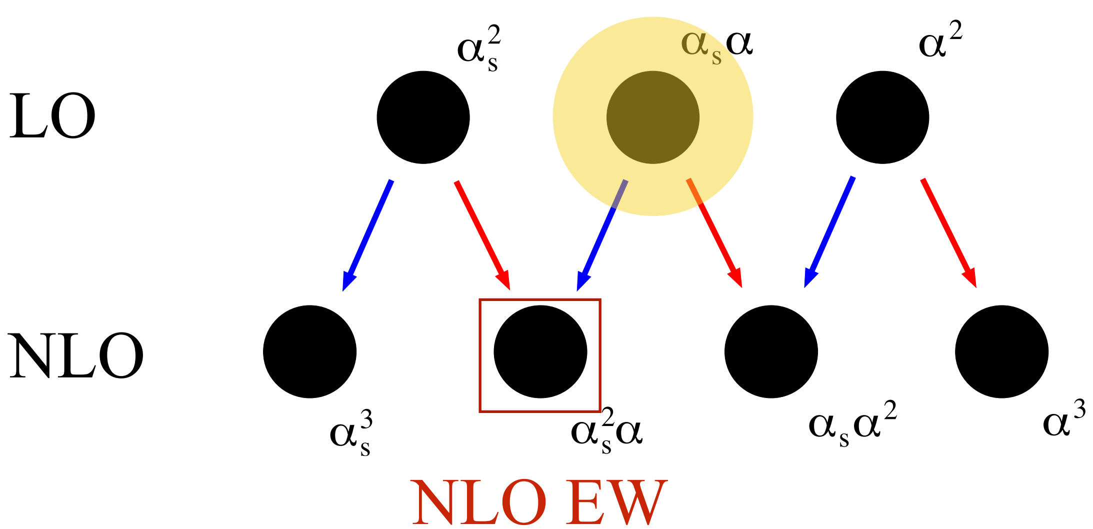


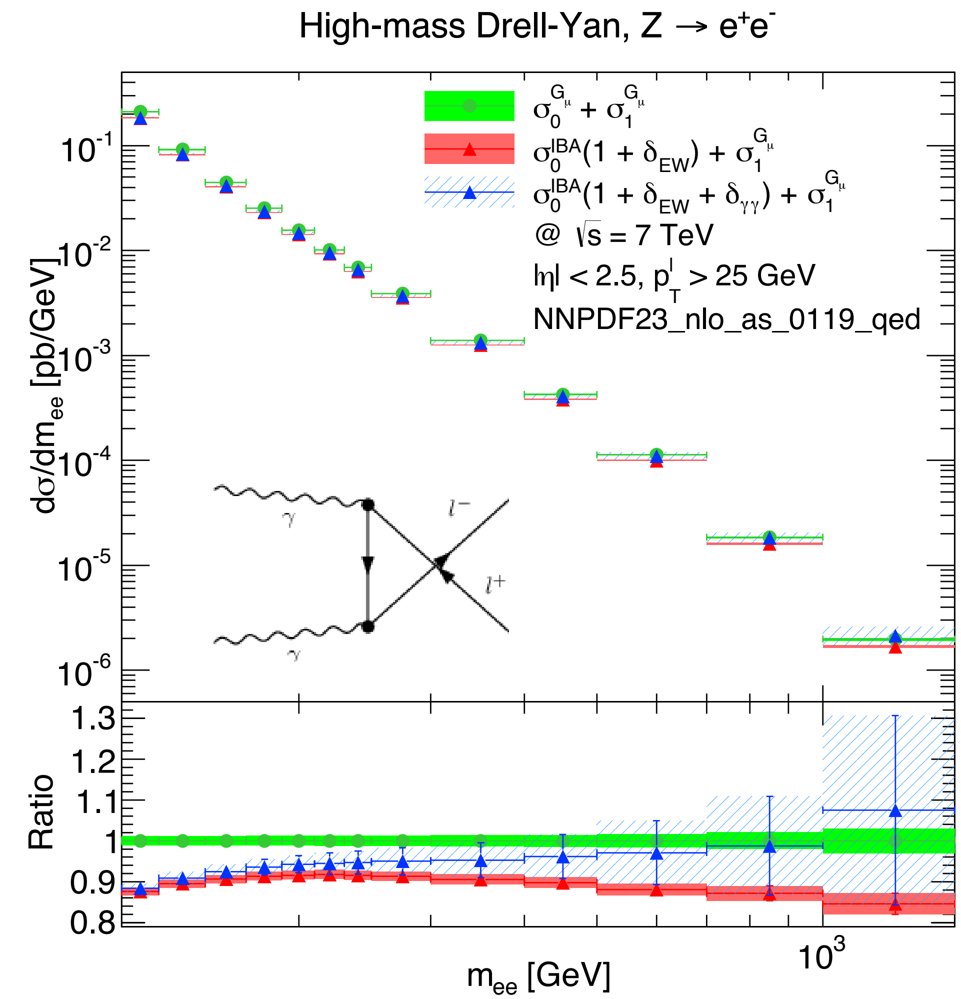
Process	σ_{tot} without cuts [pb]	
	Born	correction
$u\bar{u}$	34.25	-1.41
$d\bar{d}$	21.61	-0.228
$s\bar{s}$	4.682	-0.0410
$c\bar{c}$	2.075	-0.0762
gg	407.8	2.08
$g\gamma$		4.45
pp	470.4	4.78

NLO QED

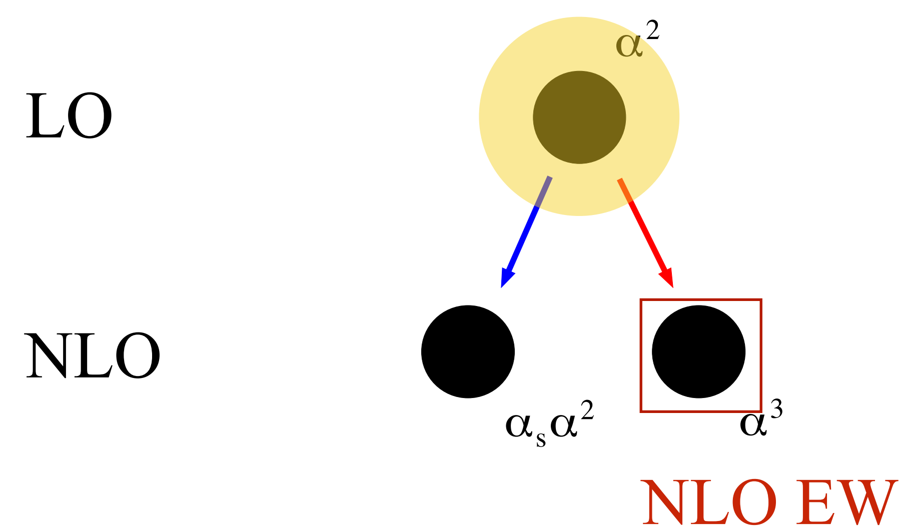
Integrated hadronic cross section for $t\bar{t}$ production at the LHC, at NLO QED

Hollik, Kollar '07 MRST2004QED

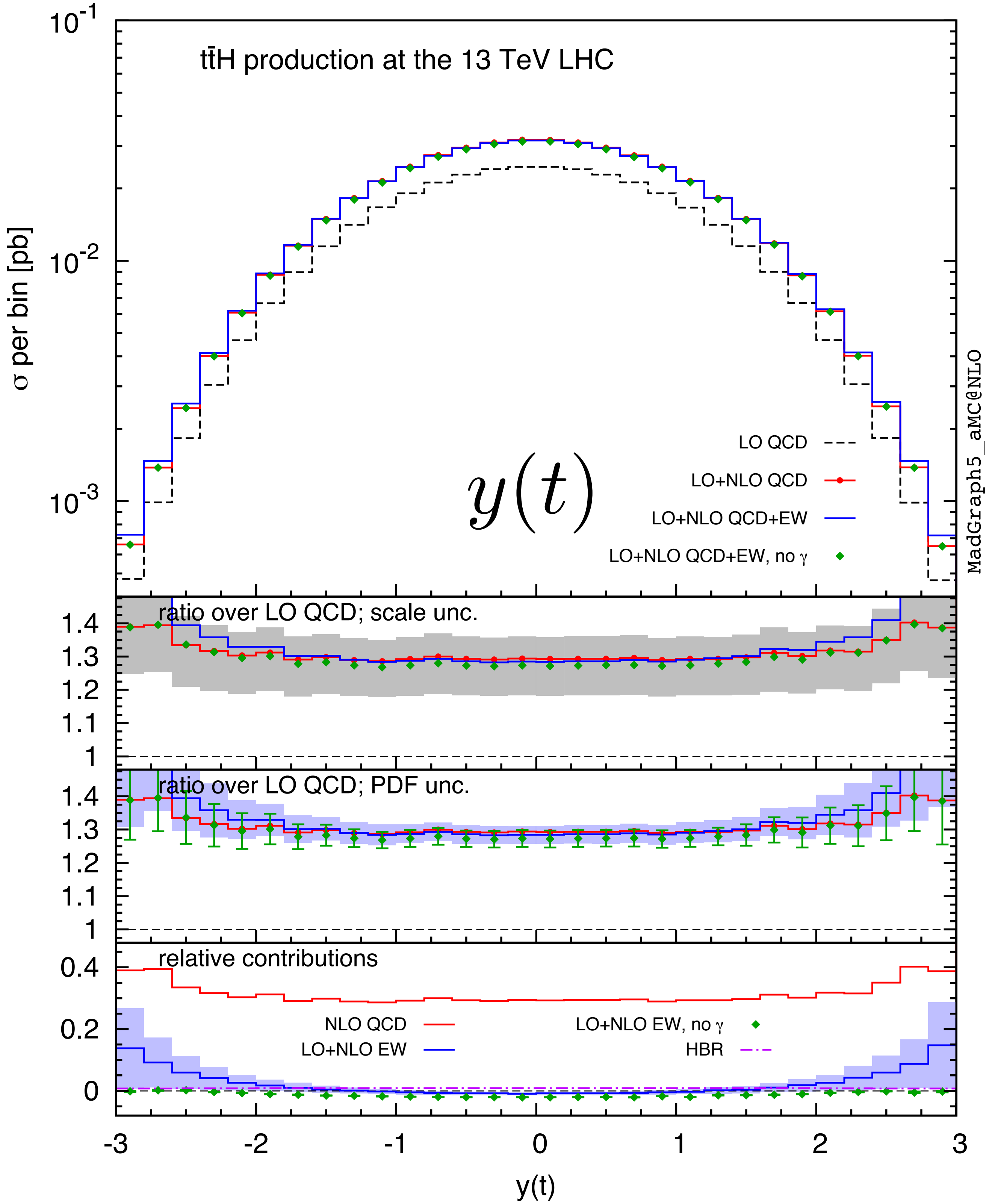




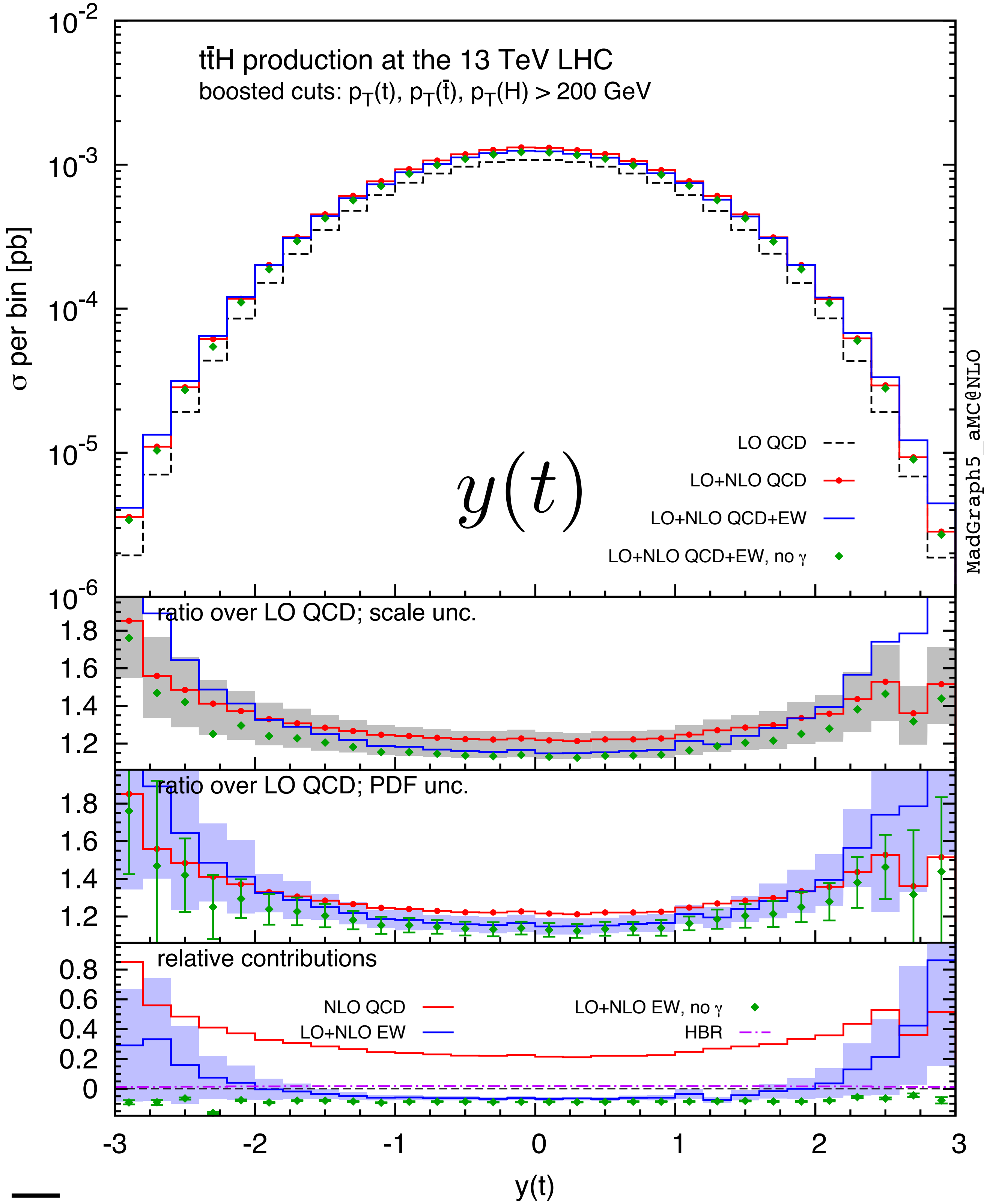
Carrazza '14 NNPDF2.3QED



Rapidity distributions: unboosted vs. boosted



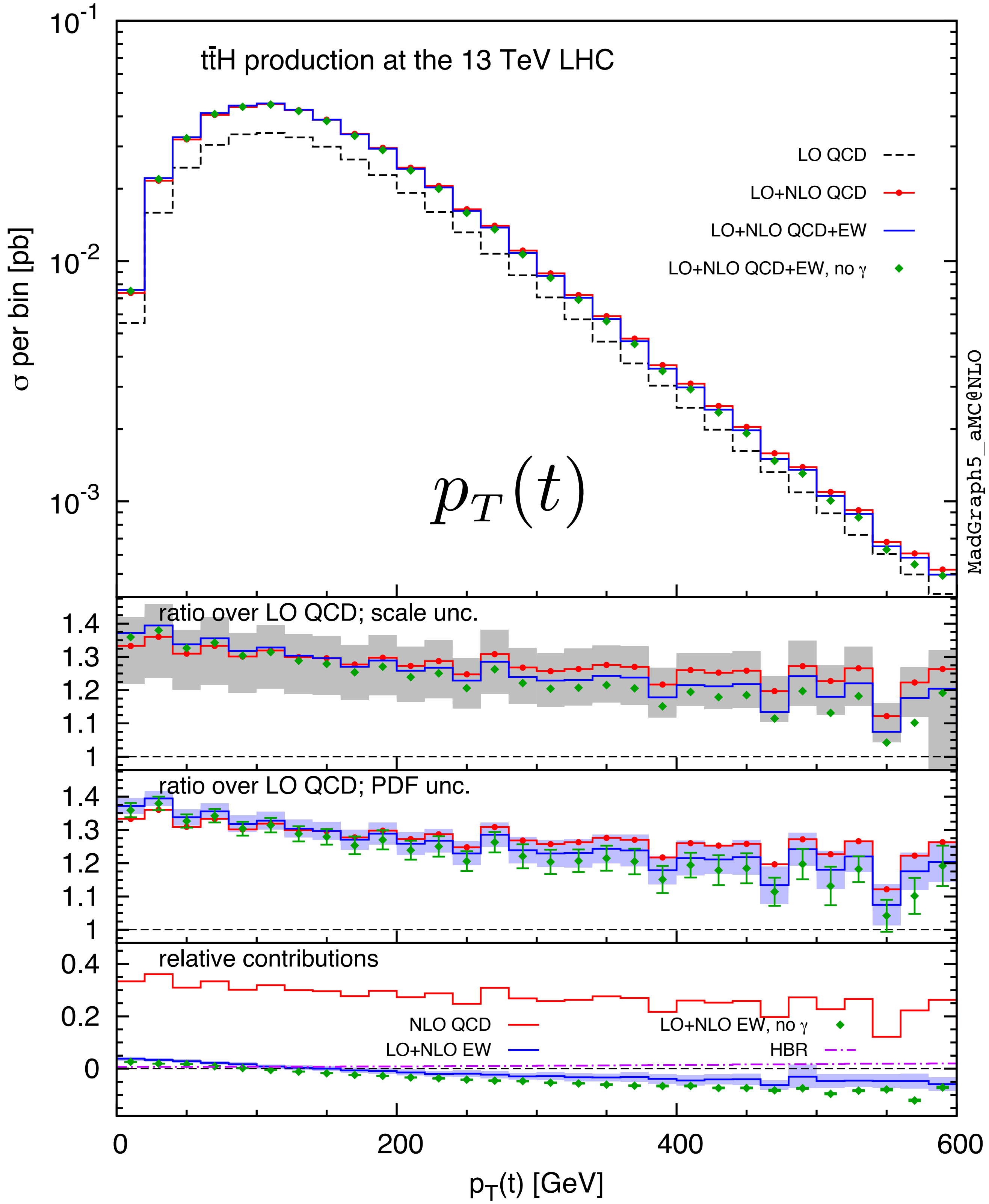
13 TeV



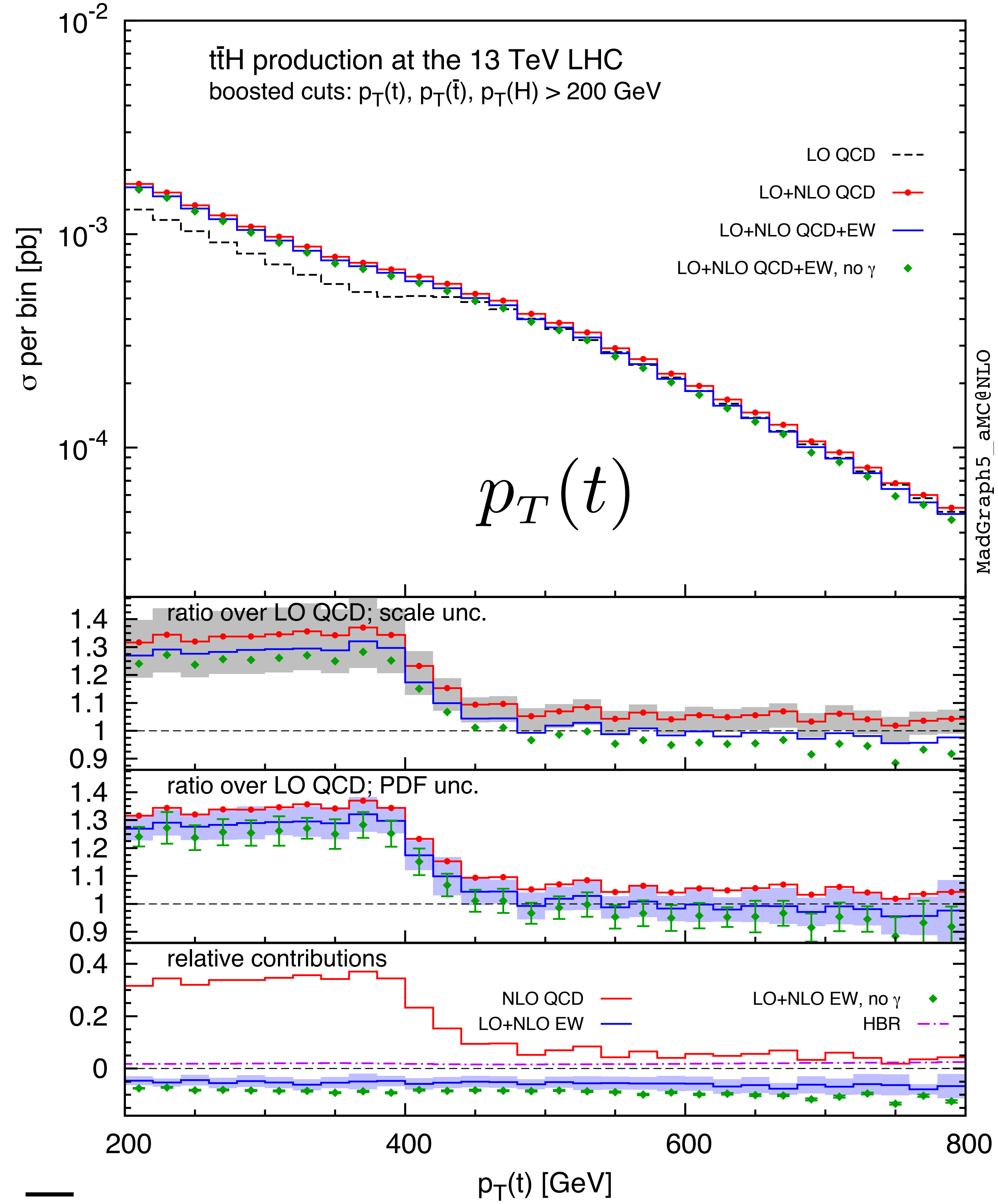
13 TeV

$t\bar{t}H$

Transverse momentum distributions: unboosted vs. boosted



13 TeV



13 TeV

$t\bar{t}H$

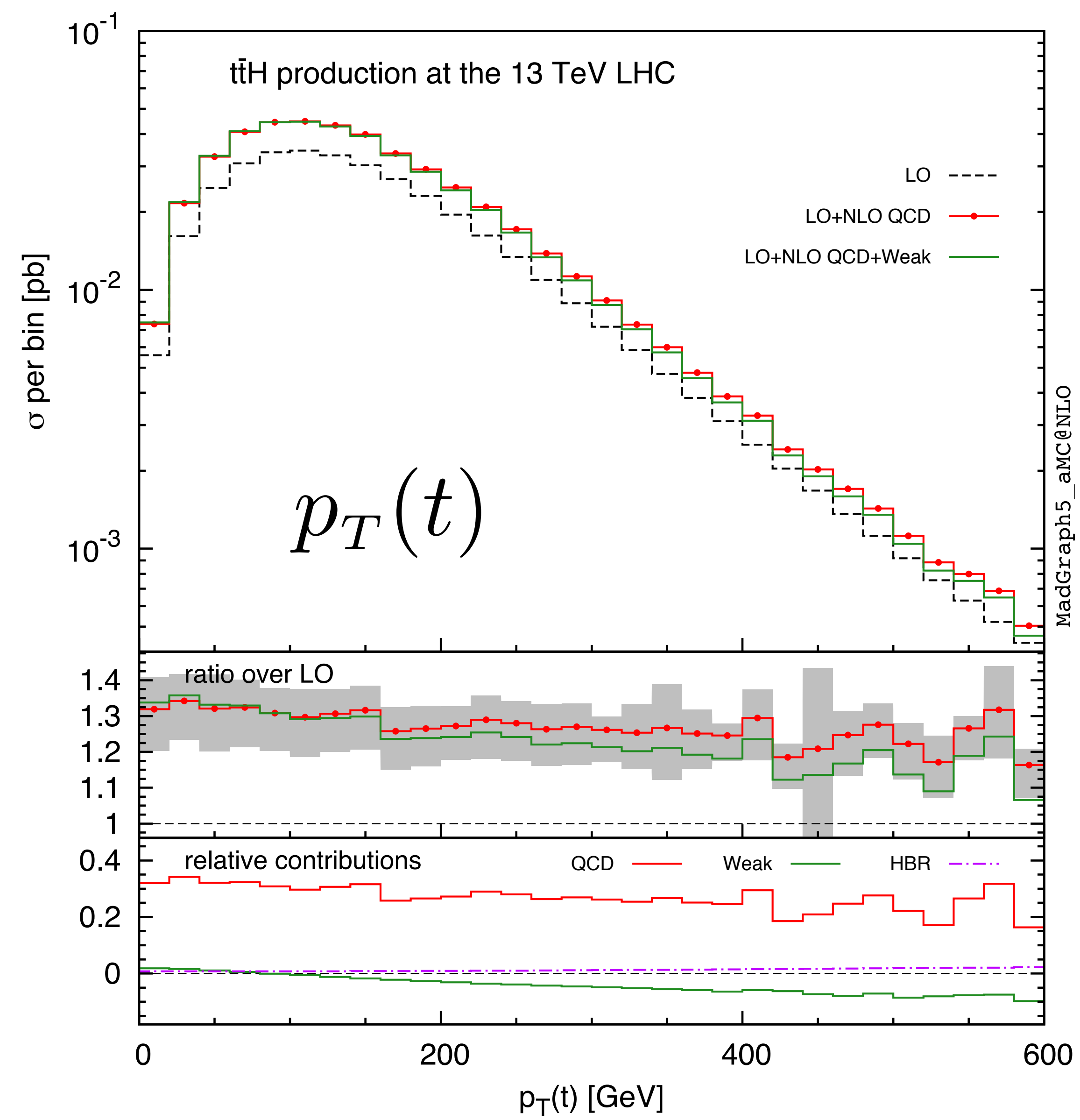
Pheno studies

NLO purely Weak and QCD corrections to $t\bar{t}H$ production have been produced "assembling by hand" the FKS counterterms.

Frixione, Hirschi, DP, Shao, Zaro '14

Now, for the complete NLO QCD and EW corrections, with photons in the initial state, we need to type:

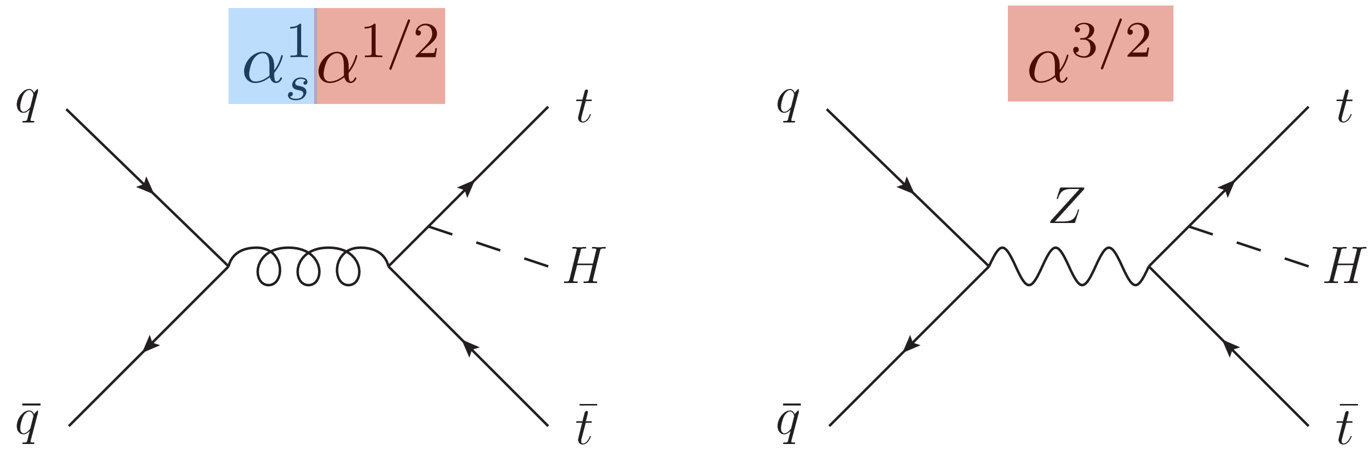
```
define p = p b b~ a
generate p p > t t~ h [QCD QED]
output ttbarh_QCD_QED
```



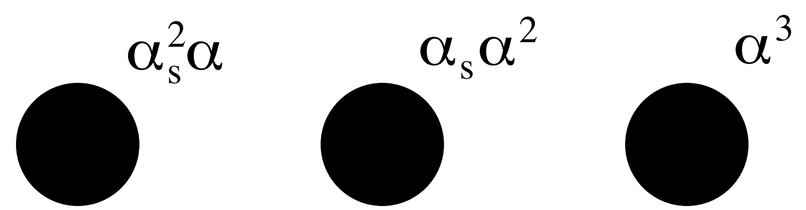
In this talk I presented results for NLO QCD and EW corrections to $t\bar{t}V$ $\quad V = H, W, Z$

Frixione, Hirschi, DP, Shao, Zaro '15

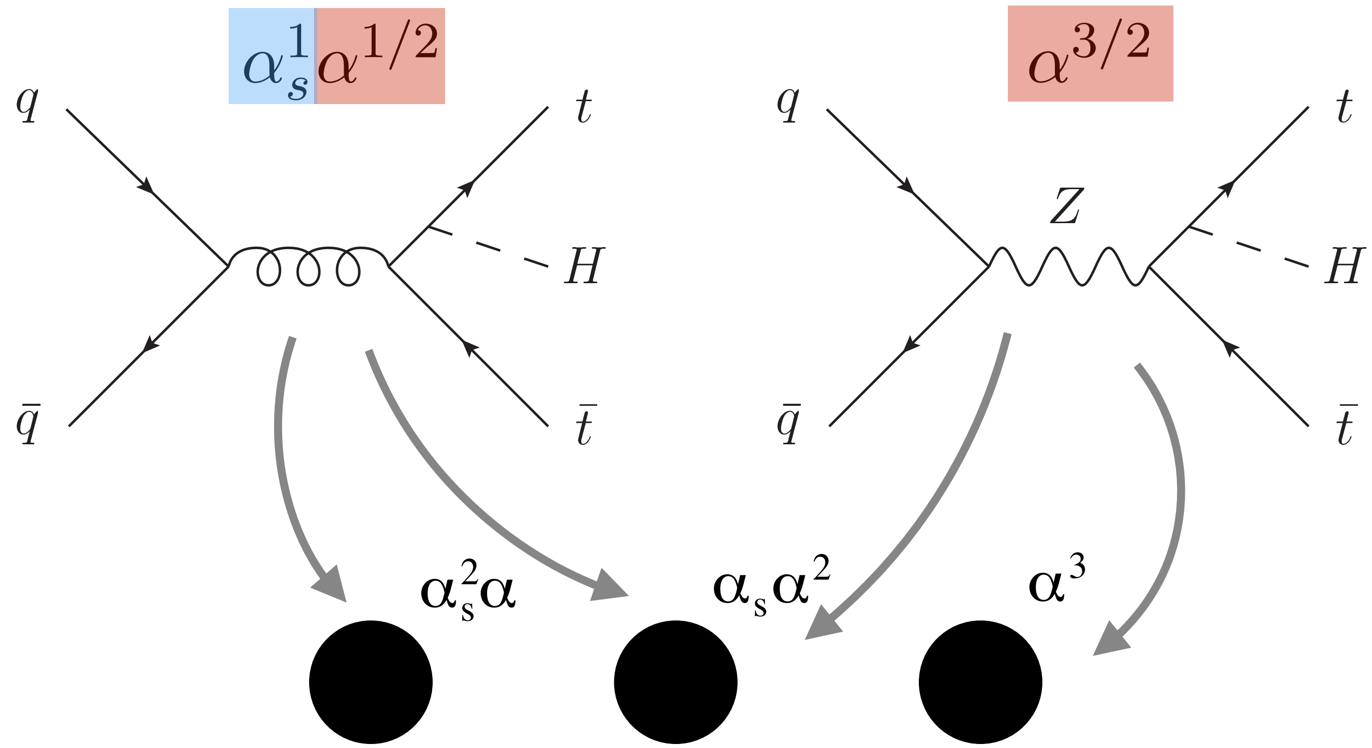
Structure of NLO EW-QCD corrections



LO

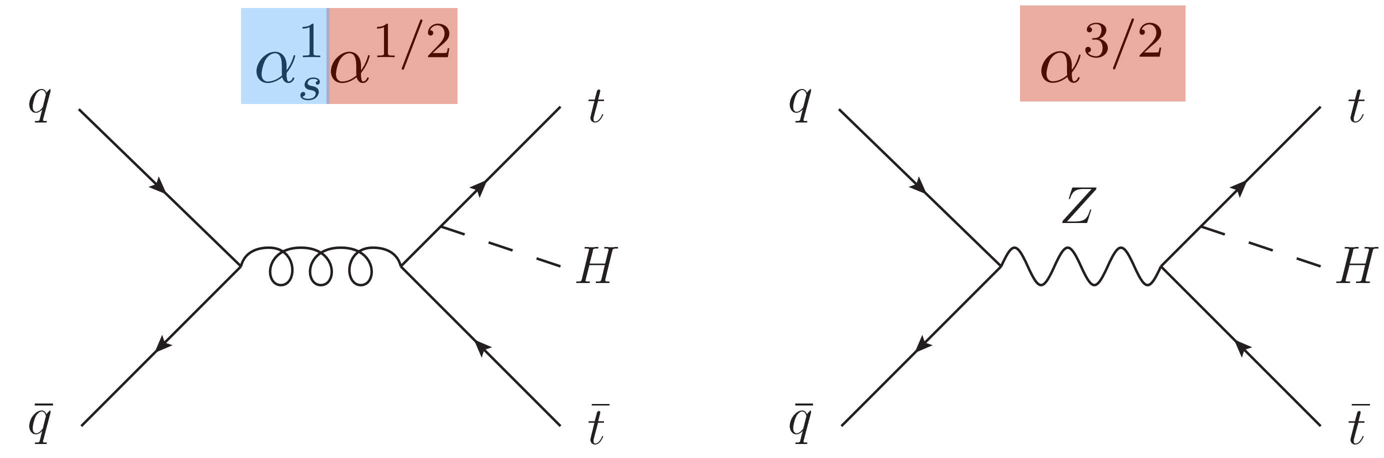


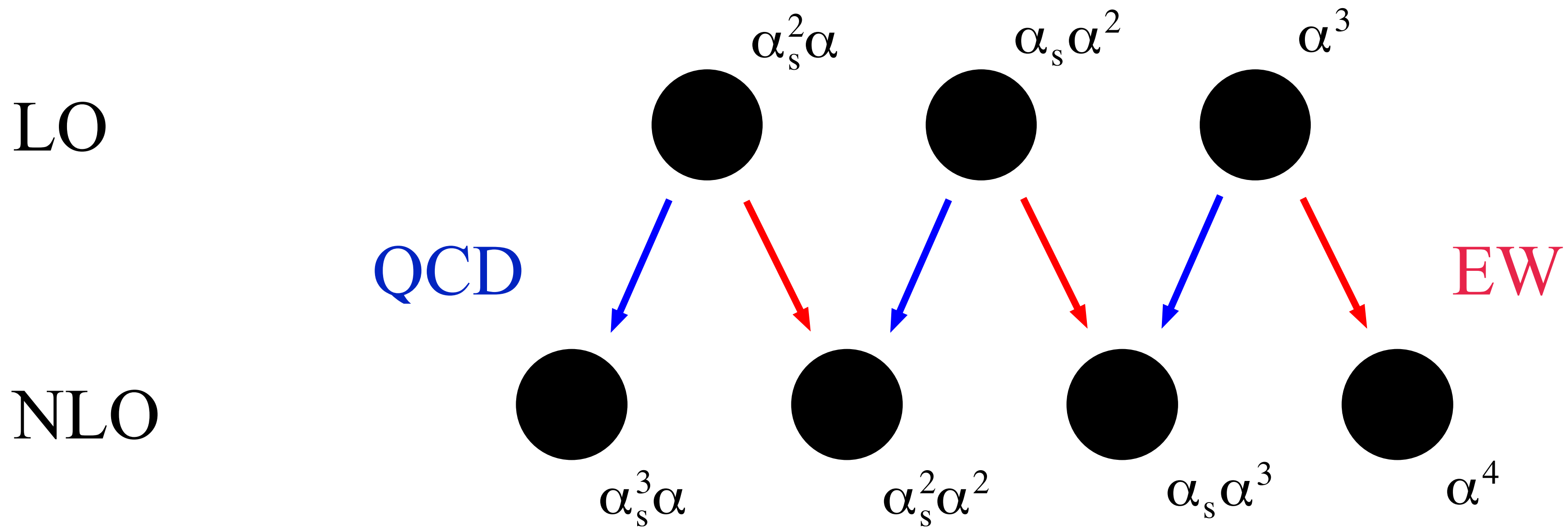
Structure of NLO EW-QCD corrections



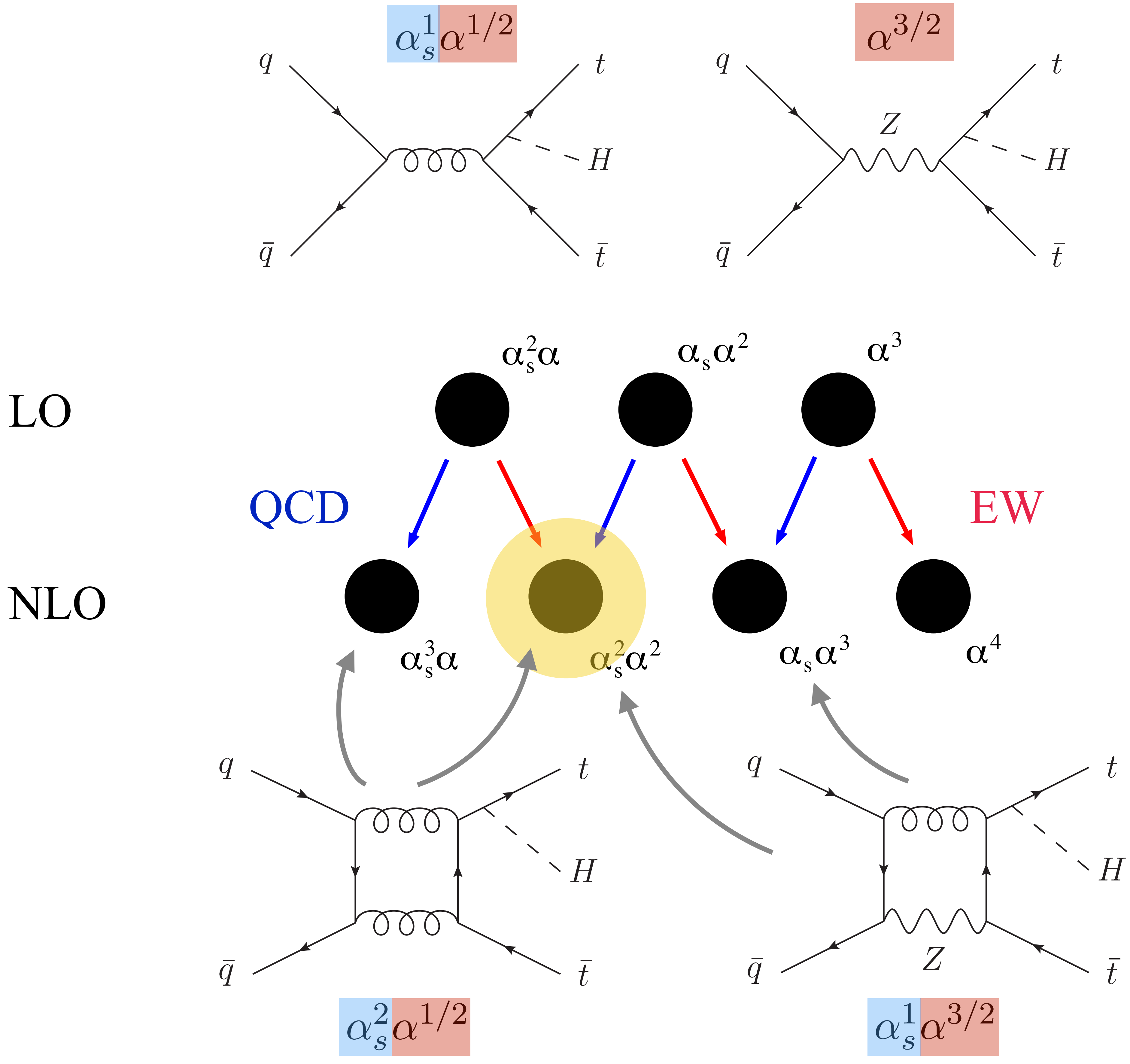
LO

Structure of NLO EW-QCD corrections

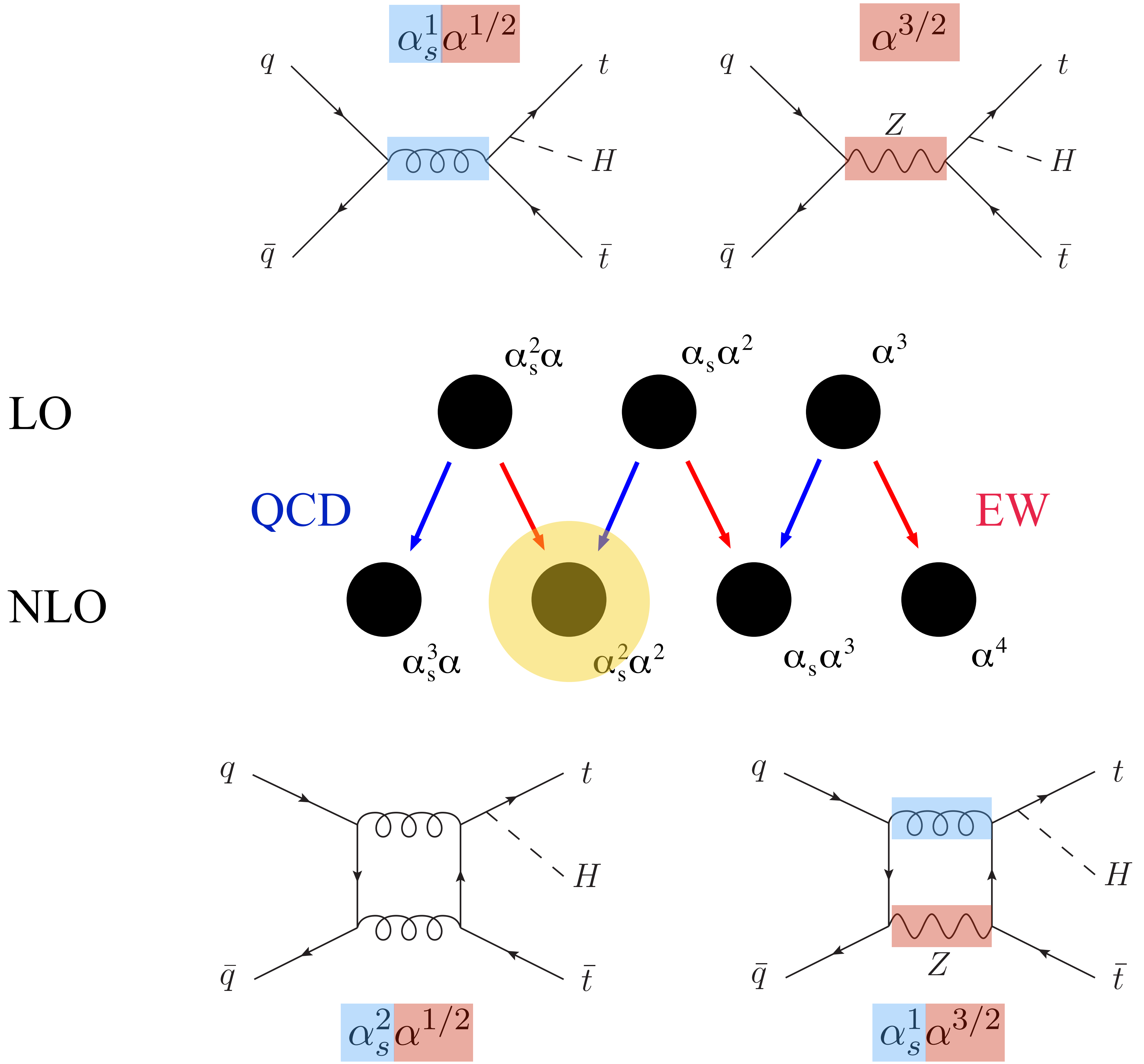




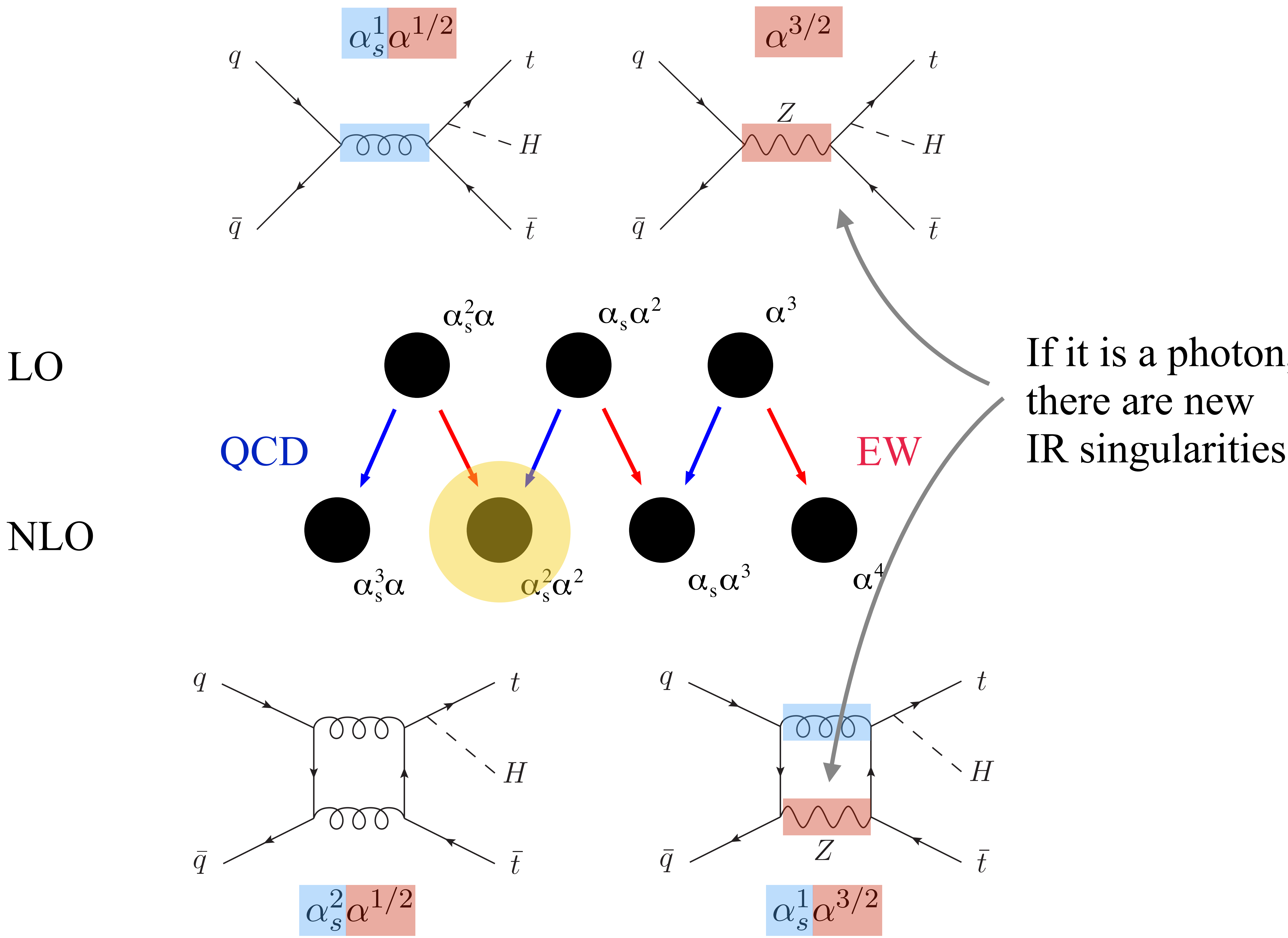
Structure of NLO EW-QCD corrections



Structure of NLO EW-QCD corrections



Structure of NLO EW-QCD corrections



Comparison between different schemes

$$m_W = 80.385 \ \text{GeV}\,, \qquad m_Z = 91.188 \ \text{GeV}$$

$\alpha(m_Z)$ scheme → $\frac{1}{\alpha(m_Z)} = 128.93$

G_μ scheme → $G_\mu = 1.16639 \cdot 10^{-5} \longrightarrow \frac{1}{\alpha} = 132.23$

	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}W^+$	$t\bar{t}W^-$
$\sigma_{\text{LO QCD}}(\text{pb})$	$3.617 \cdot 10^{-1}$	$5.282 \cdot 10^{-1}$	$2.496 \cdot 10^{-1}$	$1.265 \cdot 10^{-1}$
$\sigma^{G_\mu}_{\text{LO QCD}}(\text{pb})$	$3.527 \cdot 10^{-1}$	$5.152 \cdot 10^{-1}$	$2.433 \cdot 10^{-1}$	$1.234 \cdot 10^{-1}$
$\Delta^{G_\mu}_{\text{LO QCD}}(\%)$	2.5	2.5	2.5	2.5
$\delta_{\text{LO EW}}(\%)$	1.2	0.0	0	0
$\delta^{G_\mu}_{\text{LO EW}}(\%)$	1.2	0.0	0	0
$\Delta^{G_\mu}_{\text{LO EW}}(\%)$	2.5	2.5	2.5	2.5
$\delta_{\text{NLO EW}}(\%)$	−1.2	−3.8	−7.7	−6.7
$\delta^{G_\mu}_{\text{NLO EW}}(\%)$	1.8	−0.7	−4.5	−3.5
$\Delta^{G_\mu}_{\text{NLO EW}}(\%)$	−0.5	−0.7	−0.9	−0.9

Table 11: Comparison between results in the $\alpha(m_Z)$ and G_μ scheme, at 13 TeV.

$$\Delta^{G_\mu}_{\text{LO QCD}} = \frac{\sigma_{\text{LO QCD}} - \sigma^{G_\mu}_{\text{LO QCD}}}{\sigma_{\text{LO QCD}}}$$

$$\delta_{\text{X}} = \frac{\sigma_{\text{X}}}{\sigma_{\text{LO QCD}}}$$

Why Weak corrections to $t\bar{t}H$ production?

We calculated NLO corrections of mixed QCD-Weak origin, ignoring QED effects. We compared them to NLO QCD corrections.

Phenomenology motivations

Electroweak corrections are in general small. However, the Sudakov logarithms $\alpha_W \ln^2 s/M_W^2$ can enhance their size. They originate only from Weak corrections

The cross section of $t\bar{t}H$ depends directly on $\lambda^2_{t\bar{t}H}$. At NLO, only Weak corrections introduce a dependence on other Higgs couplings.

Automation of NLO corrections

Without QED (photons), the structure of IR singularities is simpler
$t\bar{t}H$ was the first pheno study of EW corrections in the **MG5_aMC@NLO** framework.

Numerical results weak corrections

Inclusive rates

(Boosted regime in brackets)

NLO corrections

$\delta_{\rm NLO}(\%)$	8 TeV	13 TeV	100 TeV
QCD	$+25.6^{+6.2}_{-11.8}$ $(+19.6^{+3.7}_{-11.0})$	$+29.3^{+7.4}_{-11.6}$ $(+23.9^{+5.4}_{-11.2})$	$+40.4^{+9.9}_{-11.6}$ $(+39.1^{+9.7}_{-10.4})$
weak	-1.2 (-8.3)	-1.8 (-8.2)	-3.0 (-7.8)

Heavy Boson Radiation

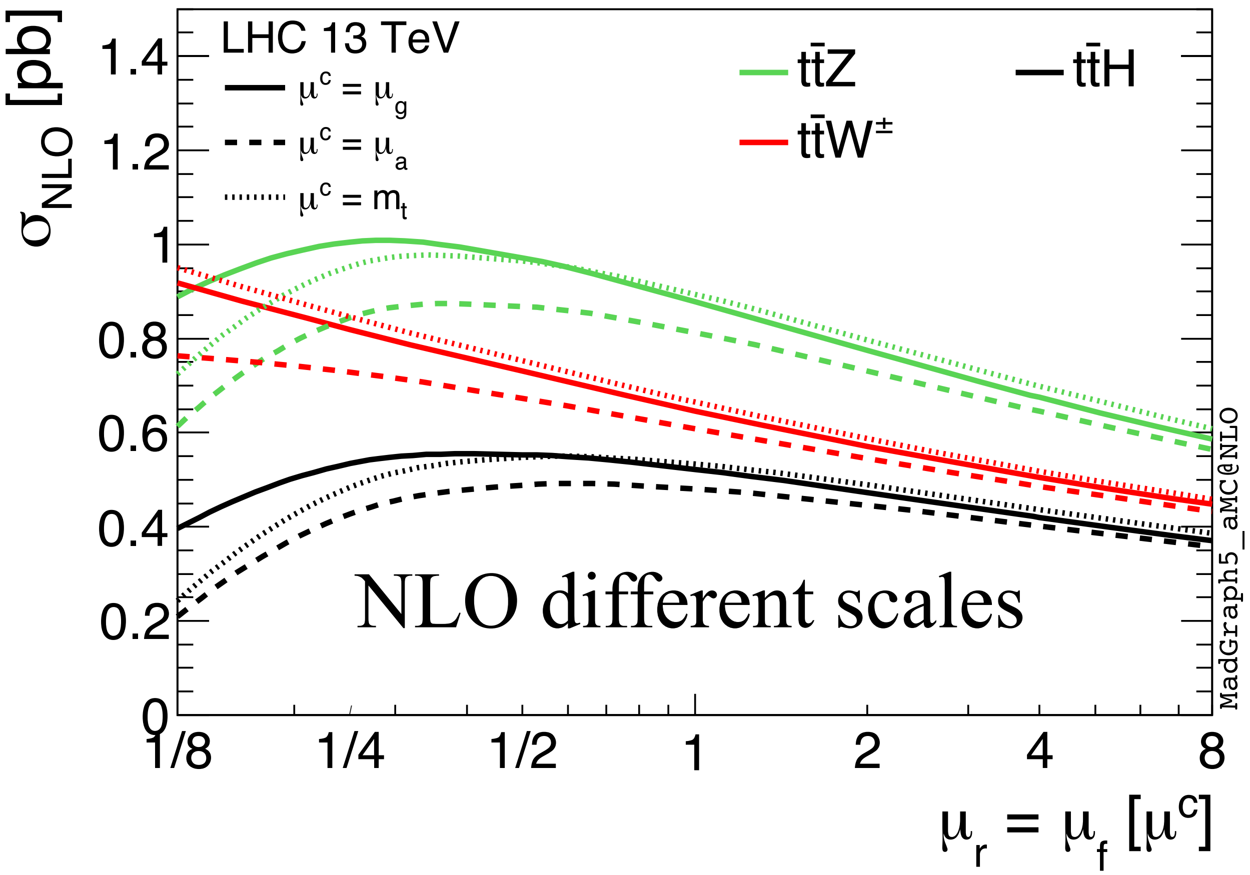
$\delta_{\rm HBR}(\%)$	8 TeV	13 TeV	100 TeV
W	$+0.42(+0.74)$	$+0.37(+0.70)$	$+0.14(+0.22)$
Z	$+0.29(+0.56)$	$+0.34(+0.68)$	$+0.51(+0.95)$
H	$+0.17(+0.43)$	$+0.19(+0.48)$	$+0.25(+0.53)$
sum	$+0.88(+1.73)$	$+0.90(+1.86)$	$+0.90(+1.70)$

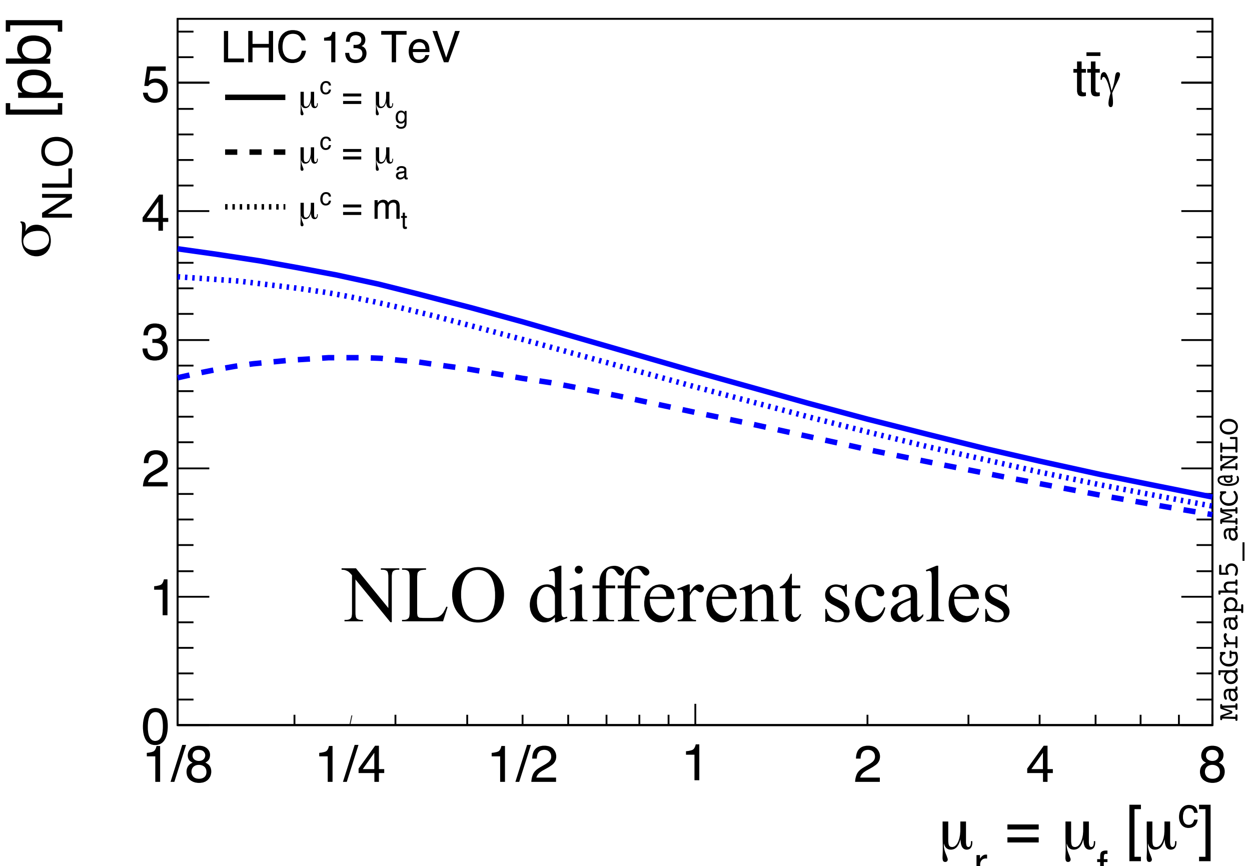
Partial compensation of Sudakov logs

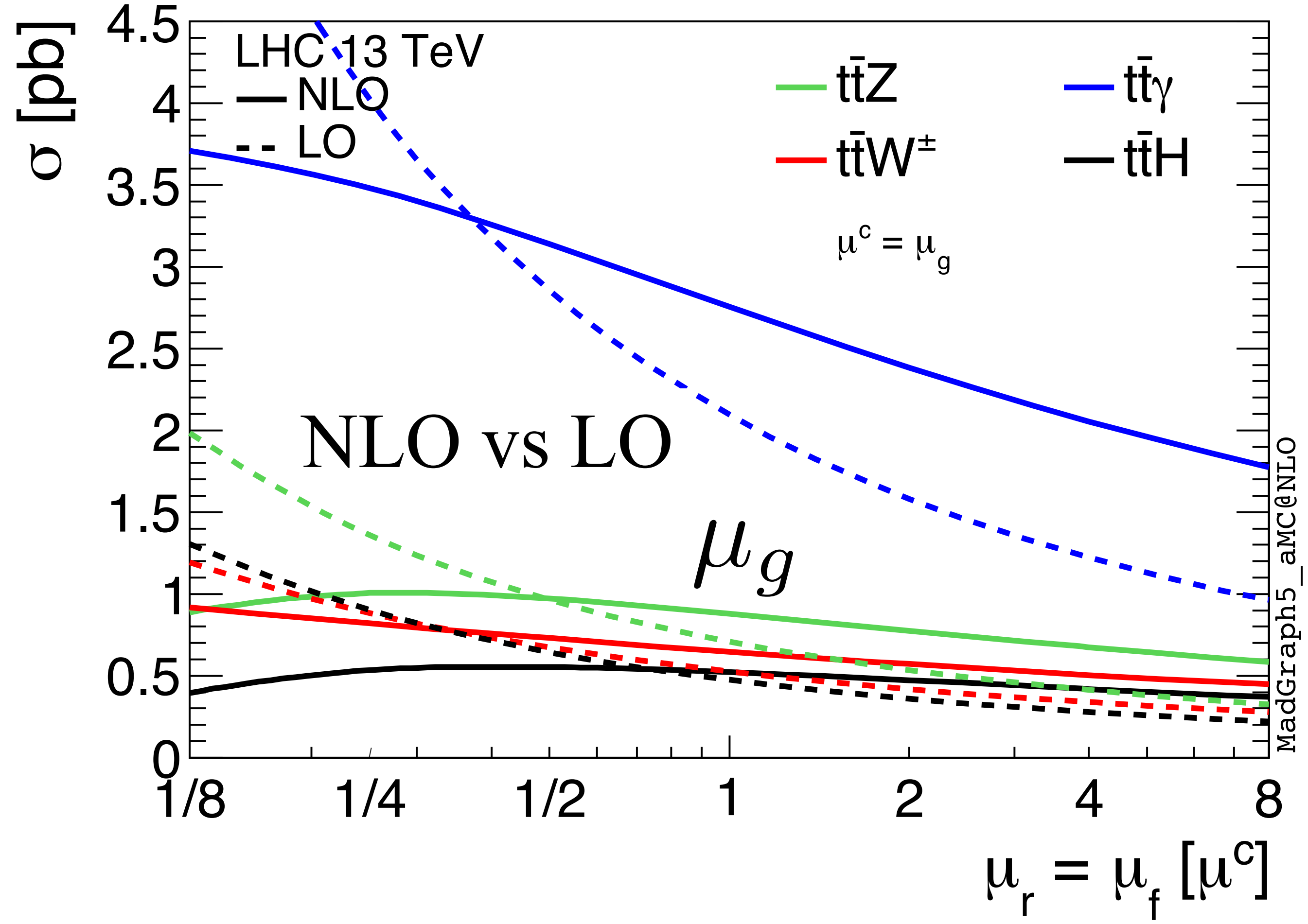
NLO weak subchannels

$\delta_{\rm NLO}(\%)$	8 TeV	13 TeV	100 TeV
gg	-0.67 (-2.9)	-1.12 (-4.0)	-2.64 (-6.8)
$u\bar{u}$	-0.01 (-3.2)	-0.15 (-2.3)	-0.10 (-0.5)
$d\bar{d}$	-0.55 (-2.2)	-0.52 (-1.9)	-0.23 (-0.5)

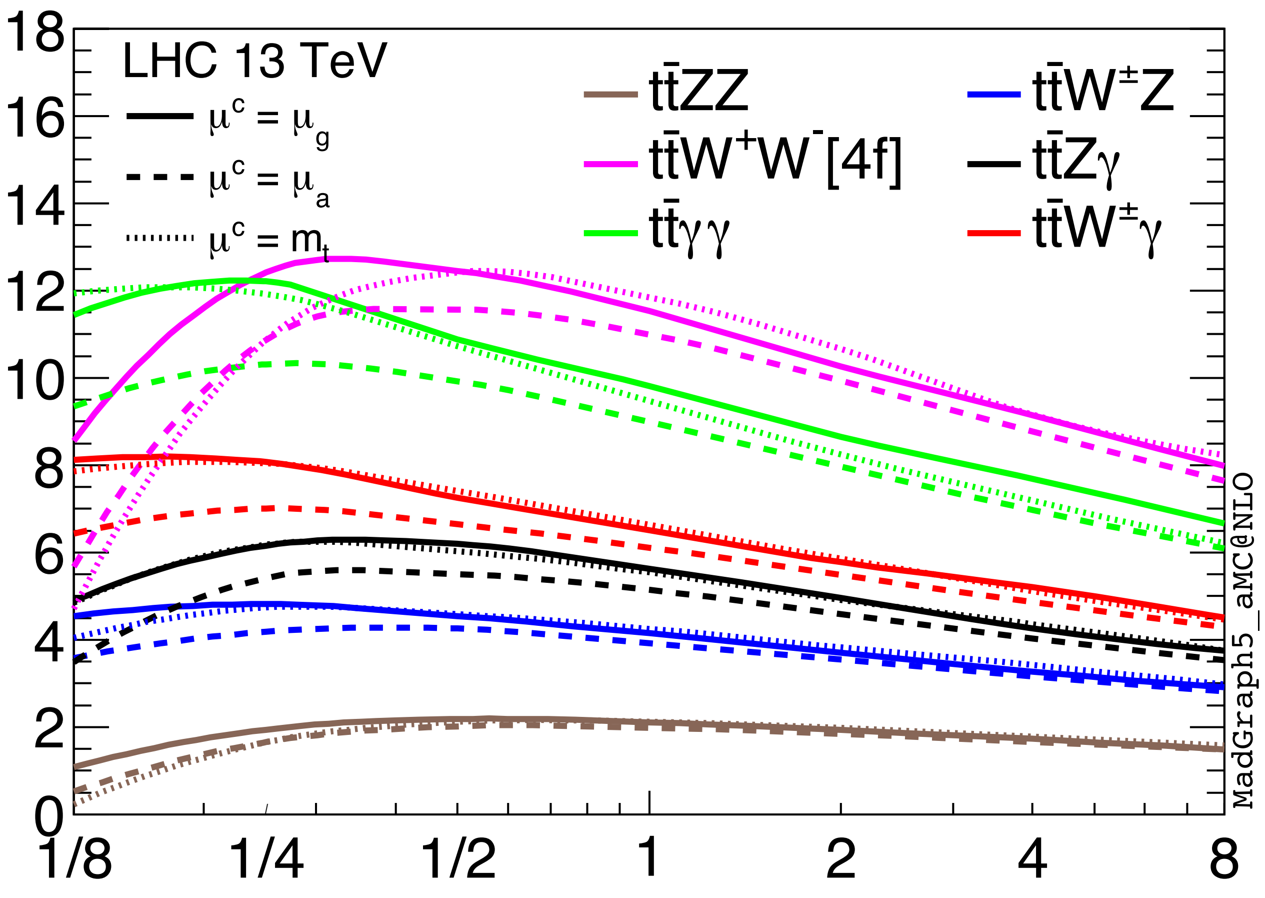
Scale dependence: $t\bar{t}V$ processes

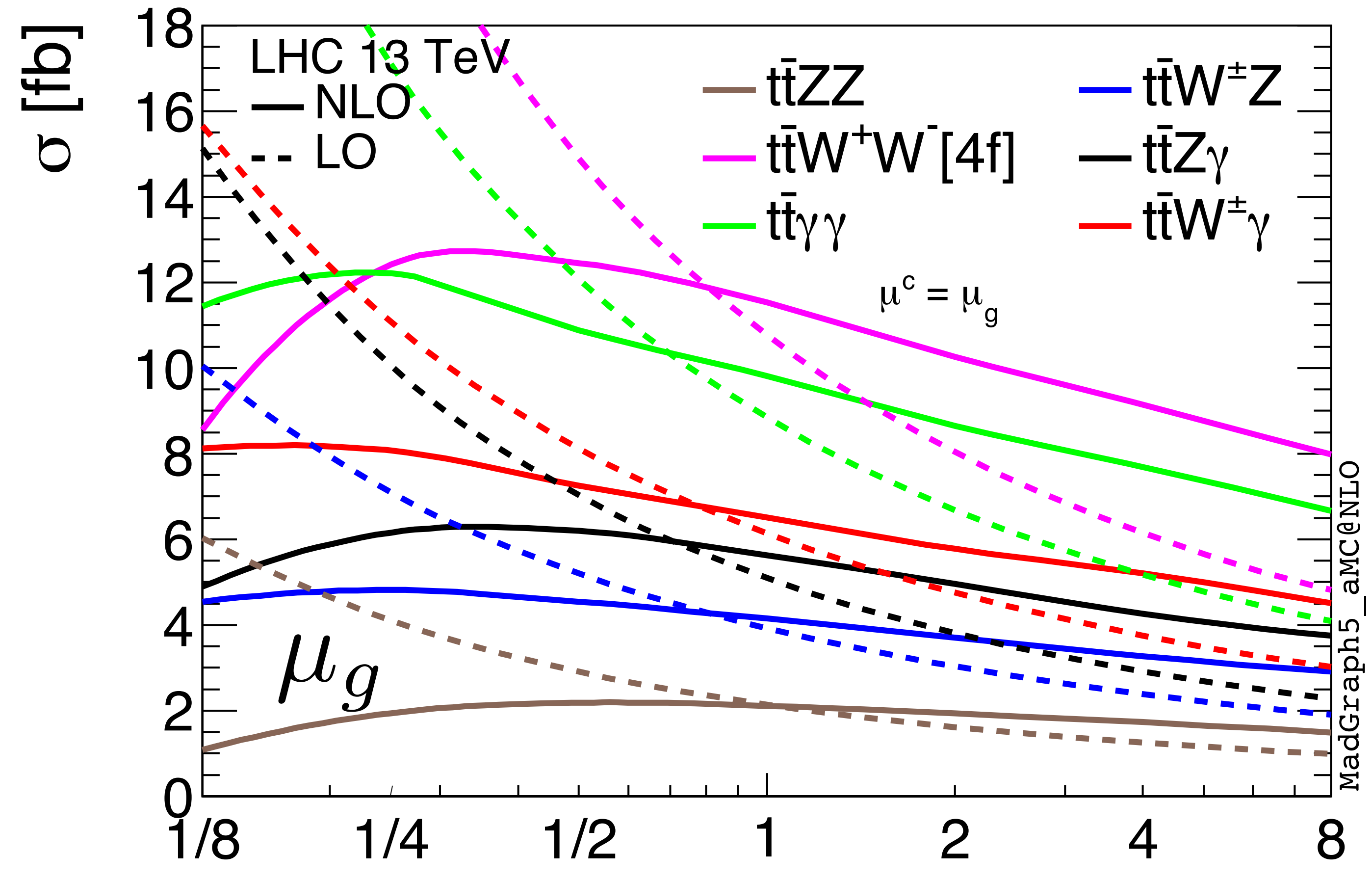






Scale dependence: $t\bar{t}VV$ processes

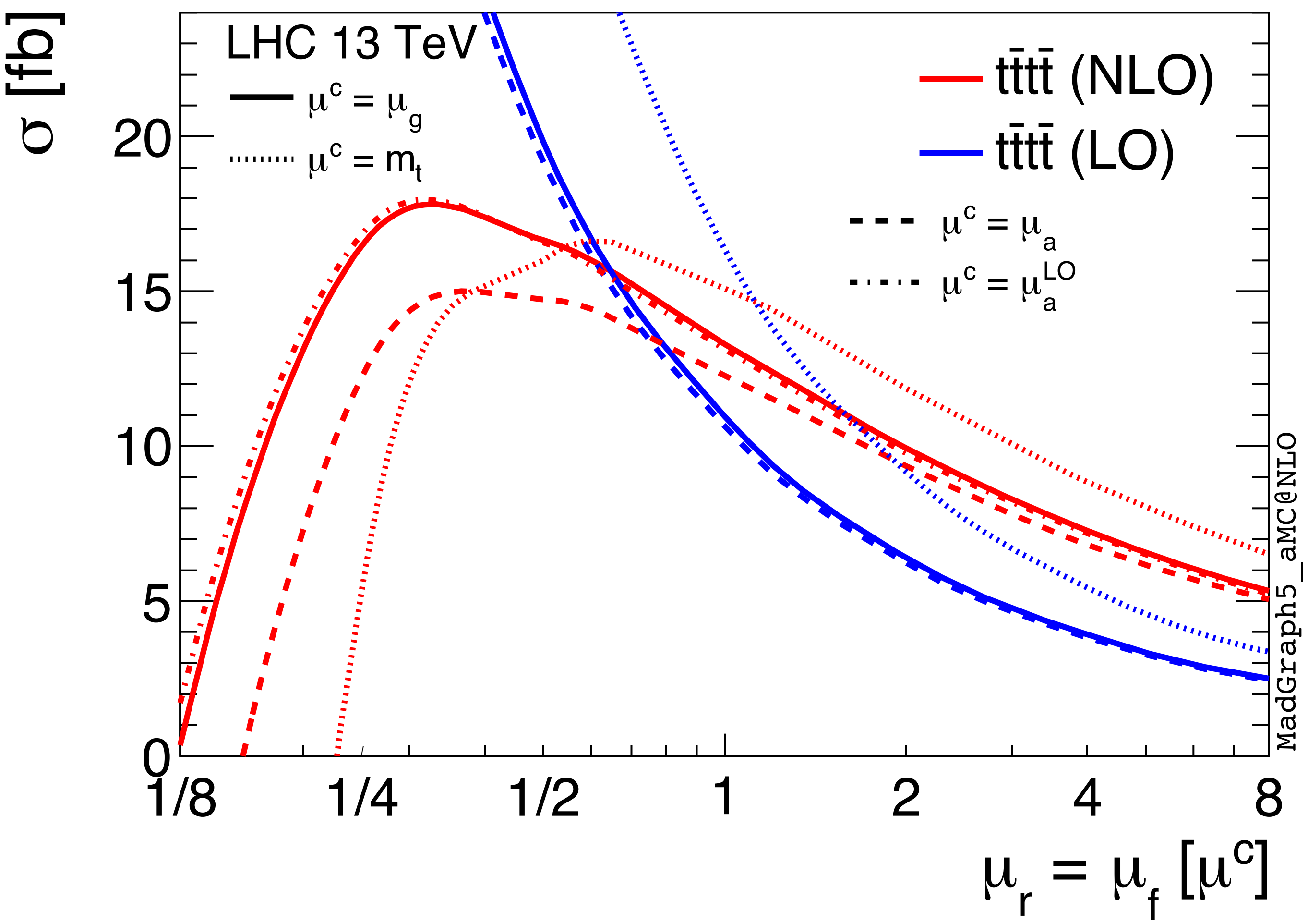




13 TeV σ[fb]	$t\bar{t}ZZ$	$t\bar{t}W^+W^-$[4f]	$t\bar{t}\gamma\gamma$
NLO	$2.117^{+3.8\%}_{-8.6\%}\ ^{+1.9\%}_{-1.8\%}$	$11.84^{+8.3\%}_{-11.2\%}\ ^{+2.3\%}_{-2.4\%}$	$10.26^{+13.9\%}_{-13.3\%}\ ^{+1.3\%}_{-1.3\%}$
LO	$2.137^{+36.1\%}_{-24.4\%}\ ^{+1.9\%}_{-1.9\%}$	$10.78^{+38.3\%}_{-25.4\%}\ ^{+2.2\%}_{-2.2\%}$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

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

Scale dependence: $t\bar{t}t\bar{t}$



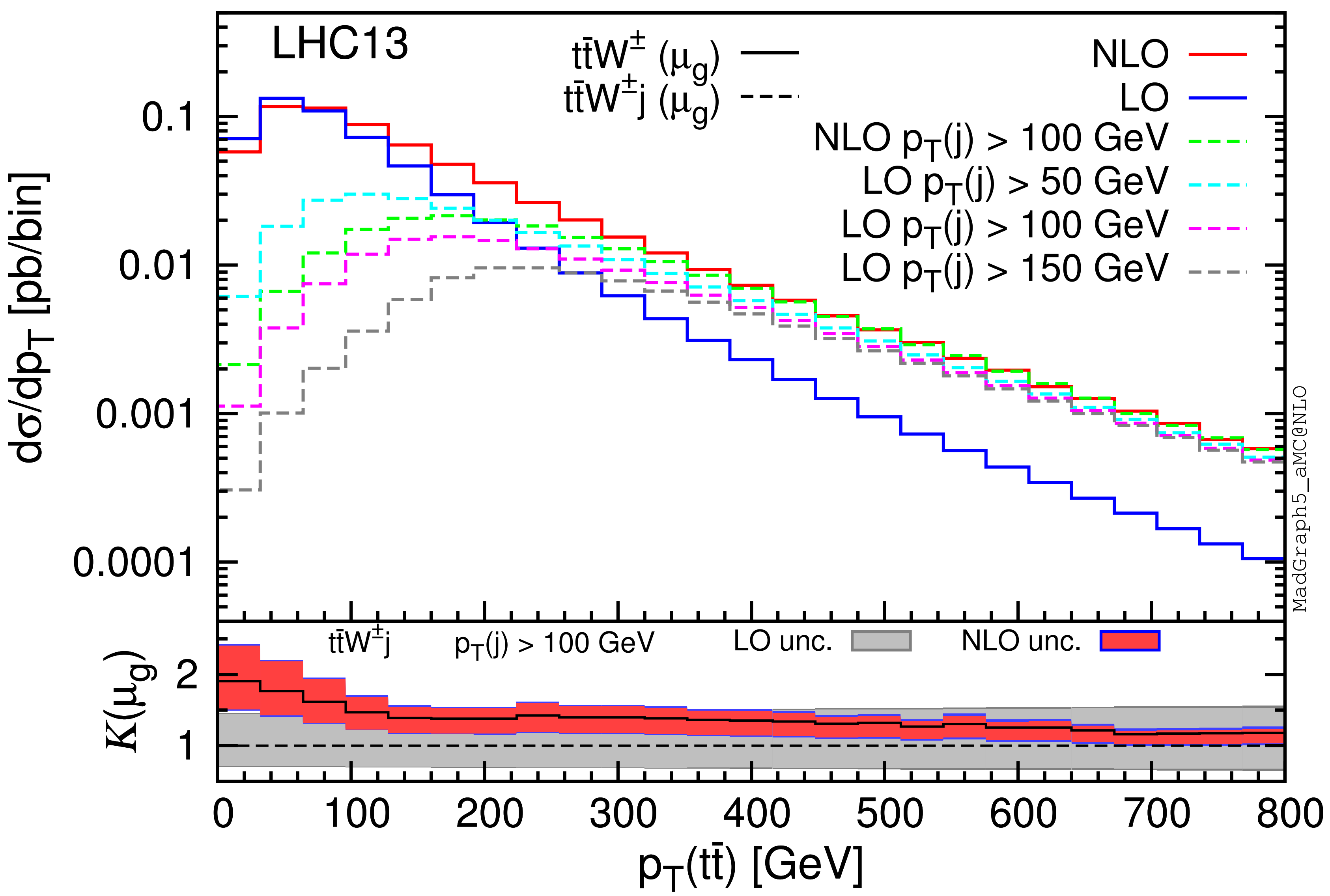
NLO vs LO, different scales.
Studies performed also in
Bevilacqua and Worek '12

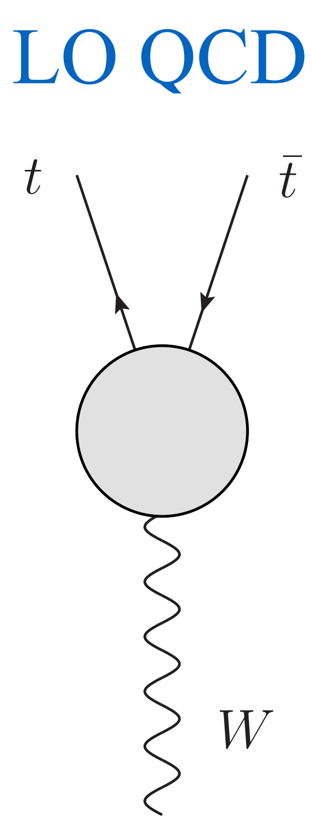
$$\sigma_{\rm NLO} = 13.31^{+25.8\%}_{-25.3\%}\,{}^{+5.8\%}_{-6.6\%}\ \text{fb}$$

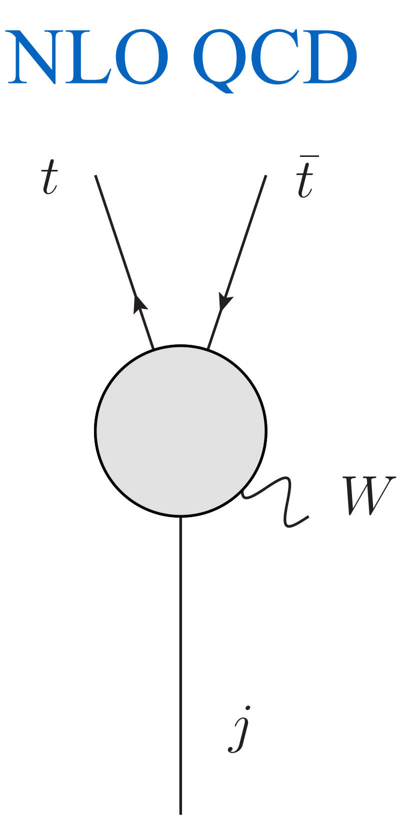
$$\sigma_{\rm LO} = 10.94^{+81.1\%}_{-41.6\%}\,{}^{+4.8\%}_{-4.7\%}\ \text{fb}$$

$$K\text{−factor} = 1.22$$

Additional study for pt of ttbar in ttbarW







σ [fb]	8 TeV	13 TeV	14 TeV	25 TeV	33 TeV	50 TeV	100 TeV
$t\bar{t}ZZ$	$0.502^{+2.9\%}_{-8.6\%}{}^{+2.7\%}_{-2.2\%}$	$2.12^{+3.8\%}_{-8.6\%}{}^{+1.9\%}_{-1.8\%}$	$2.59^{+4.3\%}_{-8.7\%}{}^{+1.8\%}_{-1.8\%}$	$11.1^{+6.9\%}_{-9.1\%}{}^{+1.2\%}_{-1.4\%}$	$21.1^{+8.1\%}_{-9.4\%}{}^{+1.1\%}_{-1.3\%}$	$51.6^{+9.9\%}_{-9.8\%}{}^{+0.9\%}_{-1.1\%}$	$204^{+11.3\%}_{-9.9\%}{}^{+0.8\%}_{-1.0\%}$
$t\bar{t}W^+W^-$[4f]	$2.67^{+6.2\%}_{-11.1\%}{}^{+2.9\%}_{-2.7\%}$	$11.8^{+8.3\%}_{-11.2\%}{}^{+2.3\%}_{-2.4\%}$	$14.4^{+12.2\%}_{-12.8\%}{}^{+2.6\%}_{-2.9\%}$	$66.6^{+9.5\%}_{-10.8\%}{}^{+1.6\%}_{-2.0\%}$	$130^{+10.2\%}_{-10.8\%}{}^{+1.5\%}_{-1.8\%}$	$327^{+10.9\%}_{-10.6\%}{}^{+1.3\%}_{-1.6\%}$	$1336^{+10.3\%}_{-9.9\%}{}^{+1.0\%}_{-1.3\%}$
$t\bar{t}\gamma\gamma$	$2.77^{+6.4\%}_{-10.5\%}{}^{+1.9\%}_{-1.5\%}$	$10.3^{+13.9\%}_{-13.3\%}{}^{+1.3\%}_{-1.3\%}$	$12^{+12.5\%}_{-12.6\%}{}^{+1.2\%}_{-1.2\%}$	$44.8^{+15.7\%}_{-13.5\%}{}^{+0.9\%}_{-0.9\%}$	$78.2^{+16.4\%}_{-13.6\%}{}^{+0.8\%}_{-0.9\%}$	$184^{+19.2\%}_{-14.7\%}{}^{+0.8\%}_{-0.9\%}$	$624^{+15.5\%}_{-13.4\%}{}^{+0.7\%}_{-1.0\%}$
$t\bar{t}W^\pm Z$	$1.13^{+5.8\%}_{-9.8\%}{}^{+3.1\%}_{-2.1\%}$	$4.16^{+9.8\%}_{-10.7\%}{}^{+2.2\%}_{-1.6\%}$	$4.96^{+10.4\%}_{-10.8\%}{}^{+2.1\%}_{-1.6\%}$	$17.8^{+15.1\%}_{-12.6\%}{}^{+1.5\%}_{-1.1\%}$	$30.2^{+18.3\%}_{-14.1\%}{}^{+1.2\%}_{-0.9\%}$	$66^{+18.9\%}_{-14.3\%}{}^{+1.1\%}_{-0.8\%}$	$210^{+21.6\%}_{-15.8\%}{}^{+1.0\%}_{-0.8\%}$
$t\bar{t}Z\gamma$	$1.39^{+6.9\%}_{-11.2\%}{}^{+2.5\%}_{-2.2\%}$	$5.77^{+10.5\%}_{-12.1\%}{}^{+1.8\%}_{-1.9\%}$	$6.95^{+10.7\%}_{-12.1\%}{}^{+1.8\%}_{-1.9\%}$	$29.9^{+12.9\%}_{-12.4\%}{}^{+1.3\%}_{-1.5\%}$	$56.5^{+13.2\%}_{-12.2\%}{}^{+1.2\%}_{-1.4\%}$	$138^{+13.7\%}_{-12.0\%}{}^{+1.0\%}_{-1.1\%}$	$533^{+13.3\%}_{-11.1\%}{}^{+0.8\%}_{-1.0\%}$
$t\bar{t}W^\pm\gamma$	$2.01^{+7.9\%}_{-10.5\%}{}^{+2.6\%}_{-1.8\%}$	$6.73^{+12.0\%}_{-11.6\%}{}^{+1.8\%}_{-1.4\%}$	$7.99^{+12.8\%}_{-11.9\%}{}^{+1.7\%}_{-1.3\%}$	$27.6^{+18.7\%}_{-14.4\%}{}^{+1.2\%}_{-0.9\%}$	$46.3^{+20.2\%}_{-15.1\%}{}^{+1.1\%}_{-0.8\%}$	$98.4^{+21.9\%}_{-15.9\%}{}^{+1.0\%}_{-0.7\%}$	$318^{+22.5\%}_{-17.7\%}{}^{+1.0\%}_{-0.7\%}$
$t\bar{t}t\bar{t}$	$1.71^{+24.9\%}_{-26.2\%}{}^{+7.9\%}_{-8.4\%}$	$13.3^{+25.8\%}_{-25.3\%}{}^{+5.8\%}_{-6.6\%}$	$17.8^{+26.6\%}_{-25.4\%}{}^{+5.5\%}_{-6.4\%}$	$130^{+26.7\%}_{-24.3\%}{}^{+3.8\%}_{-4.6\%}$	$297^{+25.5\%}_{-23.3\%}{}^{+3.1\%}_{-3.9\%}$	$929^{+24.9\%}_{-22.4\%}{}^{+2.4\%}_{-3.0\%}$	$4934^{+25.0\%}_{-21.3\%}{}^{+1.7\%}_{-2.1\%}$

σ [pb]	8 TeV	13 TeV	14 TeV	25 TeV	33 TeV	50 TeV	100 TeV
$t\bar{t}Z$	$0.226^{+9.0\%}_{-11.9\%}{}^{+2.6\%}_{-3.0\%}$	$0.874^{+10.3\%}_{-11.7\%}{}^{+2.0\%}_{-2.5\%}$	$1.057^{+10.4\%}_{-11.7\%}{}^{+1.9\%}_{-2.4\%}$	$4.224^{+11.0\%}_{-11.0\%}{}^{+1.5\%}_{-1.8\%}$	$7.735^{+11.2\%}_{-10.8\%}{}^{+1.3\%}_{-1.5\%}$	$18^{+11.1\%}_{-10.2\%}{}^{+1.1\%}_{-1.3\%}$	$64.17^{+11.1\%}_{-11.0\%}{}^{+0.9\%}_{-1.2\%}$
$t\bar{t}W^\pm$	$0.23^{+9.6\%}_{-10.6\%}{}^{+2.3\%}_{-1.7\%}$	$0.645^{+13.0\%}_{-11.6\%}{}^{+1.7\%}_{-1.3\%}$	$0.745^{+13.5\%}_{-11.8\%}{}^{+1.6\%}_{-1.3\%}$	$2.188^{+17.0\%}_{-13.2\%}{}^{+1.3\%}_{-0.9\%}$	$3.534^{+18.1\%}_{-13.7\%}{}^{+1.2\%}_{-0.8\%}$	$7.03^{+19.2\%}_{-14.3\%}{}^{+1.1\%}_{-0.8\%}$	$20.55^{+21.5\%}_{-18.1\%}{}^{+1.1\%}_{-0.8\%}$
$t\bar{t}\gamma$	$0.788^{+12.7\%}_{-13.5\%}{}^{+2.1\%}_{-2.4\%}$	$2.746^{+14.2\%}_{-13.5\%}{}^{+1.6\%}_{-1.9\%}$	$3.26^{+14.2\%}_{-13.4\%}{}^{+1.6\%}_{-1.9\%}$	$11.77^{+14.5\%}_{-12.7\%}{}^{+1.2\%}_{-1.4\%}$	$20.84^{+14.9\%}_{-12.5\%}{}^{+1.1\%}_{-1.3\%}$	$45.68^{+14.2\%}_{-11.7\%}{}^{+1.0\%}_{-1.2\%}$	$152.6^{+14.3\%}_{-13.7\%}{}^{+0.9\%}_{-1.2\%}$
$t\bar{t}H$	$0.136^{+3.3\%}_{-9.1\%}{}^{+2.8\%}_{-3.2\%}$	$0.522^{+6.0\%}_{-9.4\%}{}^{+2.1\%}_{-2.6\%}$	$0.631^{+6.3\%}_{-9.4\%}{}^{+2.0\%}_{-2.5\%}$	$2.505^{+8.3\%}_{-9.4\%}{}^{+1.6\%}_{-1.9\%}$	$4.567^{+8.8\%}_{-9.2\%}{}^{+1.4\%}_{-1.7\%}$	$10.55^{+9.5\%}_{-9.0\%}{}^{+1.2\%}_{-1.4\%}$	$37.65^{+10.0\%}_{-9.8\%}{}^{+1.0\%}_{-1.3\%}$

$t\bar{t}H$ with $(H \to \gamma\gamma)$ decay

Analyses based on: *CMS, Search for the associated production of the Higgs boson with a top-quark pair, arXiv:1408.1682*

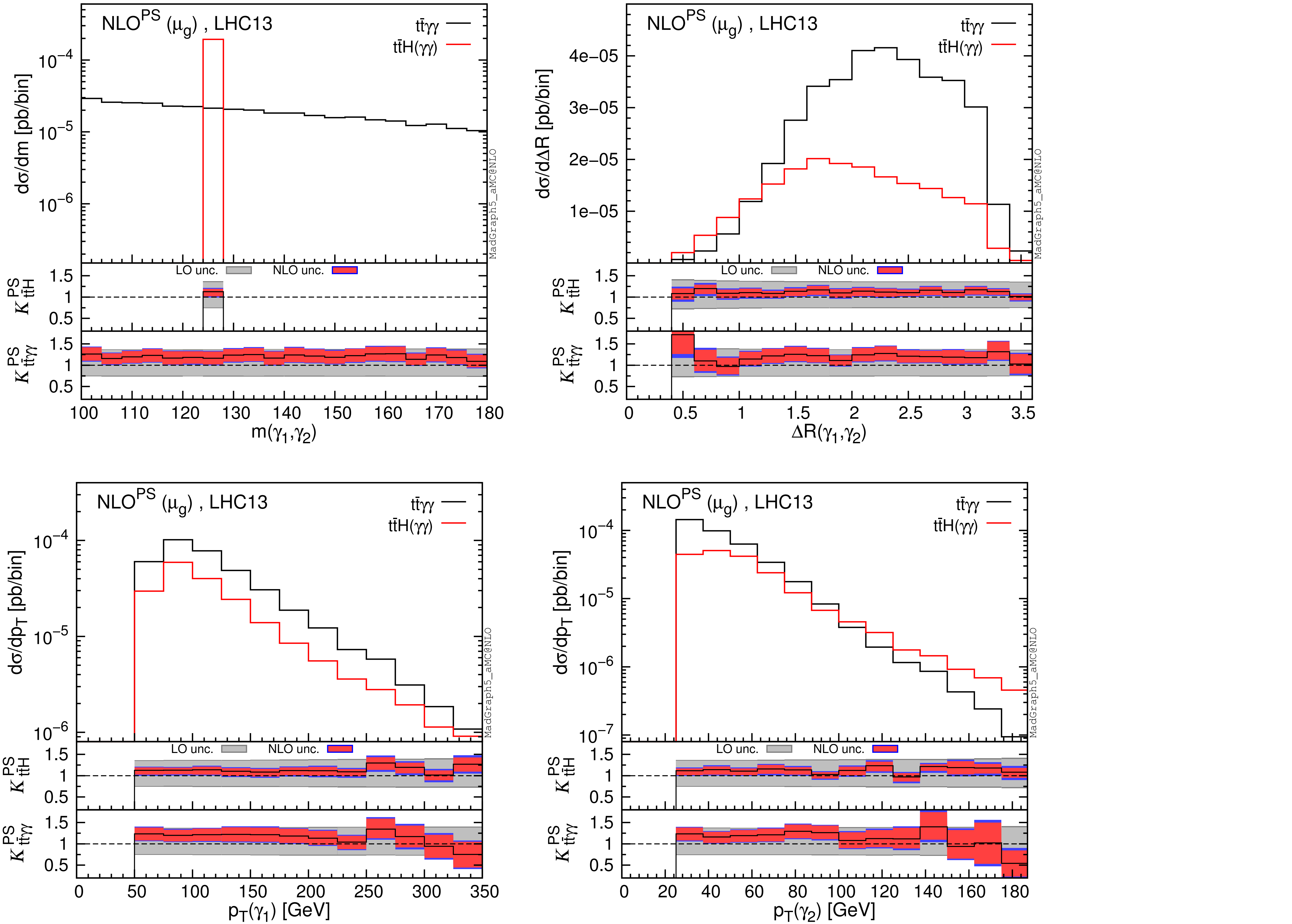
$$p_T(e) > 7\,\text{GeV}\,, \quad |\eta(e) < 2.5|\,, \quad p_T(\mu) > 5\,\text{GeV}\,, \quad |\eta(\mu) < 2.4|\,,$$
$$|\eta(\gamma)| < 2.5\,, \quad p_T(j) > 25\,\text{GeV}\,, \quad |\eta(j) < 2.4|\,,$$

preselection cuts

$$100\,\text{GeV} < m(\gamma_1\gamma_2) < 180\,\text{GeV}\,, \quad p_T(\gamma_1) > \frac{m(\gamma_1\gamma_2)}{2}\,, \quad p_T(\gamma_2) > 25\,\text{GeV}\,,$$
$$\Delta R(\gamma_1,\gamma_2),\, \Delta R(\gamma_{1,2}, j) > 0.4\,, \quad \Delta R(\gamma_{1,2},\ell) > 0.4\,, \quad p_T(\ell_1) > 20\,\text{GeV}\,,$$
$$\text{and} \quad \Delta R(l_i, l_j) > 0.4\,, \quad \text{if leptons are more than one.}$$

Analysis cuts

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



NLO^{PS} (μ_g) , LHC13
$t\bar{t}\gamma\gamma$
$t\bar{t}H(\gamma\gamma)$
dσ/dm [pb/bin]
LO unc.
NLO unc.
$K^{PS}_{t\bar{t}H}$
$K^{PS}_{t\bar{t}\gamma\gamma}$
m(γ1,γ2)
dσ/dΔR [pb/bin]
ΔR(γ1,γ2)
dσ/dp_T [pb/bin]
p_T(γ1) [GeV]
p_T(γ2) [GeV]
MadGraph5_aMC@NLO

- **Signal region one (SR1): two same-sign leptons**

Exactly two same-sign leptons with with $p_T(\ell) > 20$ GeV are requested. The event is selected if it includes at least four jets with one or more of them that are b-tagged. Furthermore it is required that $p_T(\ell_1) + p_T(\ell_2) + E_T^{\text{miss}} > 100\,\text{GeV}$ and, for the dielectron events, $|m(e^{\pm}e^{\pm}) - m_Z| > 10$ GeV and $E_T^{\text{miss}} > 30$ GeV, in order to suppress background from electron sign misidentification in Z boson decays.

- **Signal region two (SR2): three leptons**

Exactly three leptons with $p_T(\ell_1) > 20$ GeV, $p_T(\ell_2) > 10$ GeV, $p_T(\ell_3 = e(\mu)) > 7(5)$ GeV are requested. The event is selected if it includes at least two jets with one or more of them that are b-tagged. For a Z boson background suppression, events with an opposite-sign same-flavor lepton pair are required to have $|m(\ell^+\ell^-) - m_Z| > 10$ GeV. Also, for this kind of events if the number of jets is equal or less than three, the cut $E_T^{\text{miss}} > 80$ GeV is applied.

- **Signal region three (SR3): four leptons**

Exactly four leptons with $p_T(\ell_1) > 20$ GeV, $p_T(\ell_2) > 10$ GeV, $p_T(\ell_{3,4} = e(\mu)) > 7(5)$ GeV are requested. The event is selected if it includes at least two jets with one or more of them that are b-tagged. Also here, for a Z boson background suppression, events with an opposite-sign same-flavor lepton pair are required to have $|m(\ell^+\ell^-) - m_Z| > 10$ GeV.