Large **NLO** contributions in **ttW** and **four-top** production from **supposedly subleading EW** contributions

based on arXiv:1711.02116
in collaboration with R. Frederix and M. Zaro

Davide Pagani

Milan Xmas Meeting
Milano
20-12-2017

What are Complete-NLO predictions?

Complete-NLO predictions

We are used to speak about **NLO QCD** and **NLO EW** corrections.

Is there any other fixed-order SM contribution before going to NNLO?

YES! Already with 2->2 processes (dijet, ttbar), there are other contributions.

Complete-NLO predictions

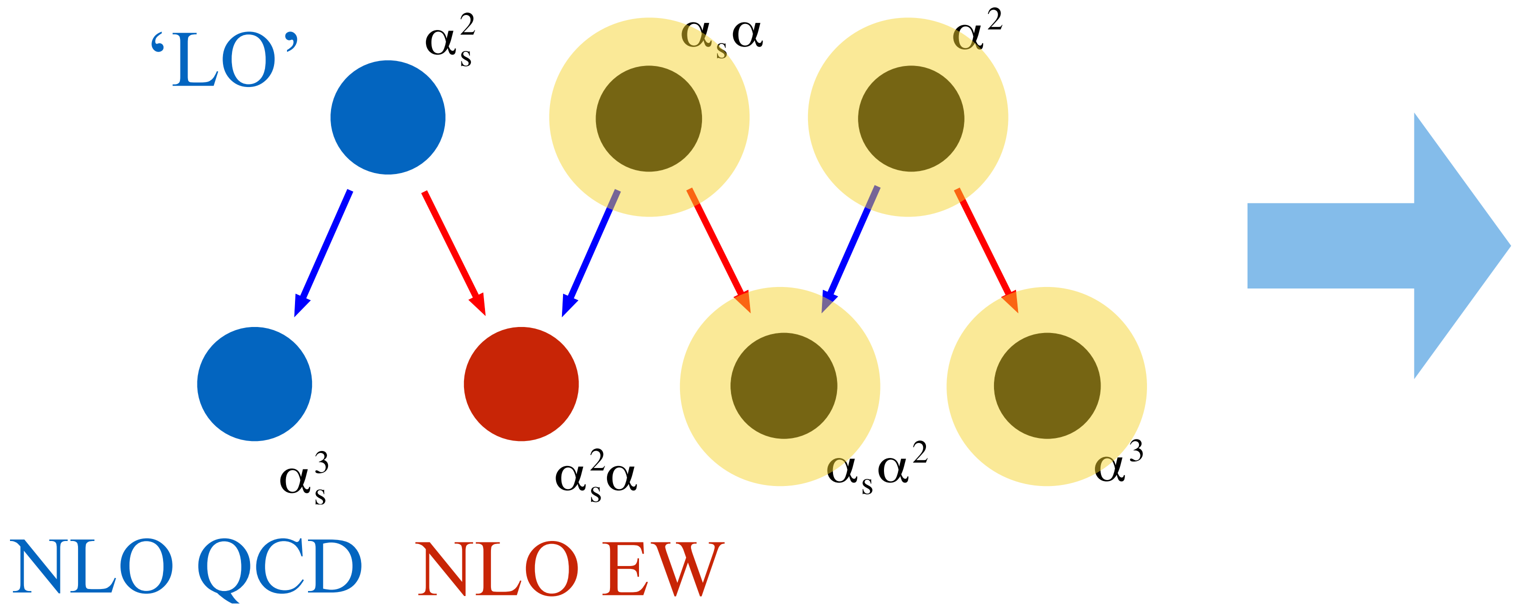
We are used to speak about **NLO QCD** and **NLO EW** corrections.

Is there any other fixed-order SM contribution before going to NNLO?

YES! Already with 2->2 processes (dijet, ttbar), there are other contributions.

LO

NLO



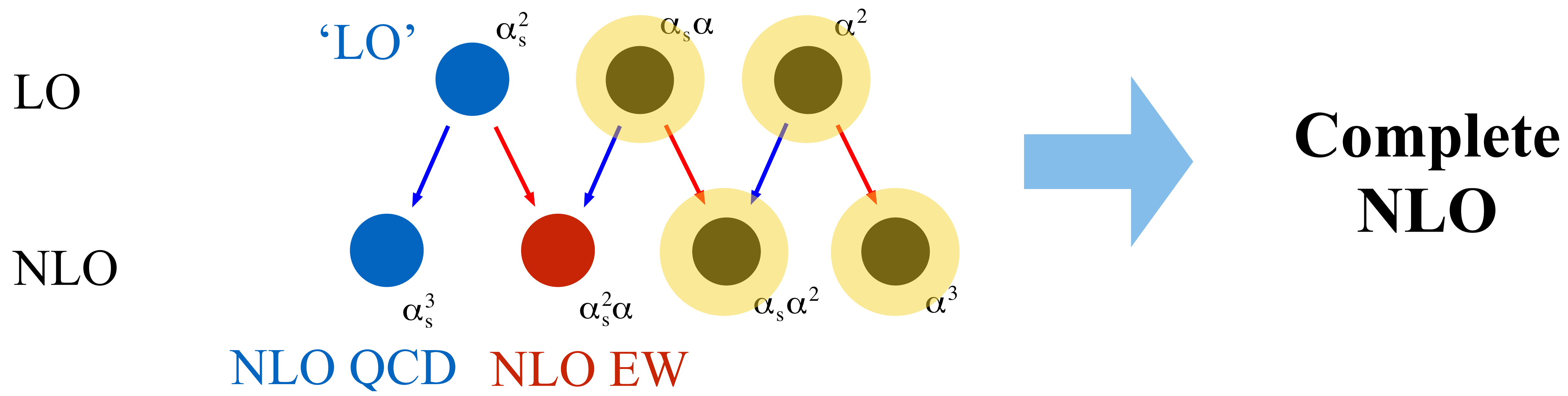
Complete NLO

Complete-NLO predictions

We are used to speak about **NLO QCD** and **NLO EW** corrections.

Is there any other fixed-order SM contribution before going to NNLO?

YES! Already with 2->2 processes (dijet, ttbar), there are other contributions.



Why does nobody calculate the other orders inside the Complete-NLO?

Because they are expected to be small due to the $\mathcal{O}(\alpha/\alpha_s)$ suppression!

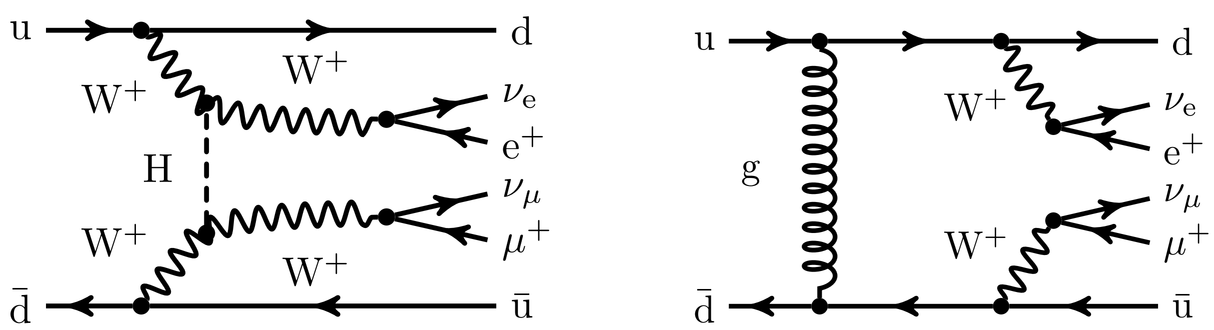
Before the recent automations, nobody wanted to calculate terms that are expected to be small. First complete-NLO calculations:

Dijet: *Frederix, Frixione, Hirschi, DP, Shao, Zaro '16*

ttbar: *Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '16*

… but Complete-NLO can be large

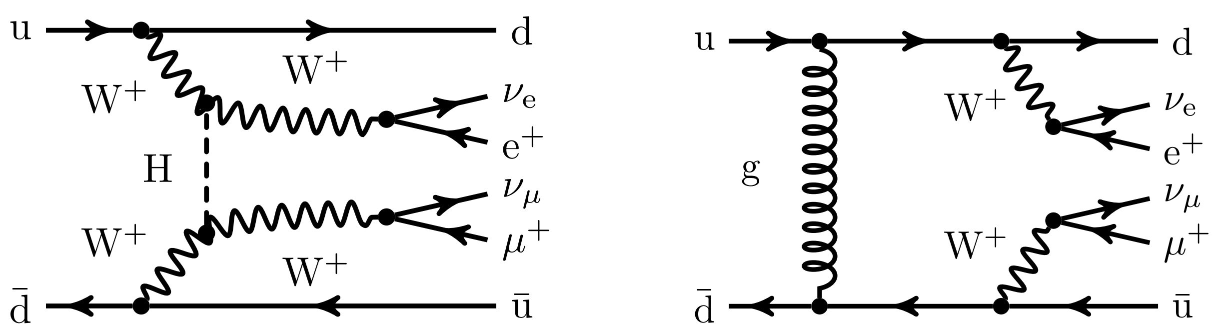
$\mathrm{pp} \to \mu^+\nu_\mu \mathrm{e}^+\nu_\mathrm{e}\mathrm{jj}$ same-sign WW scattering



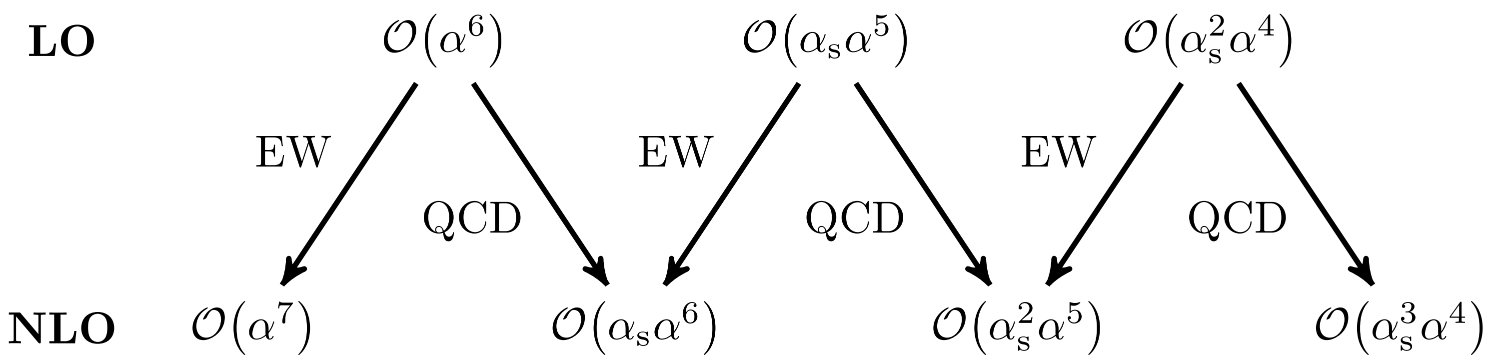
Biedermann, Denner, Pellen ’17

… but Complete-NLO can be large

$pp \to \mu^+\nu_\mu e^+\nu_e jj$ same-sign WW scattering



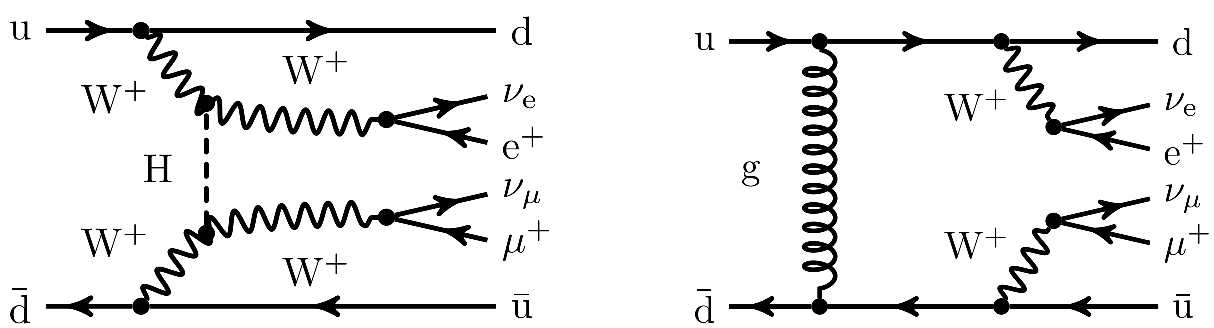
Biedermann, Denner, Pellen '17



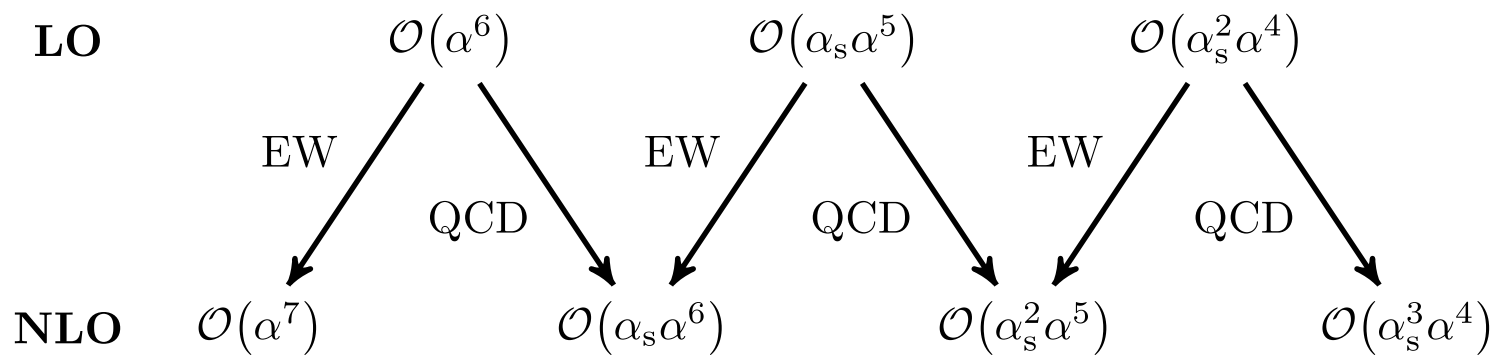
Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_s\alpha^6)$	$\mathcal{O}(\alpha_s^2\alpha^5)$	$\mathcal{O}(\alpha_s^3\alpha^4)$	Sum
$\delta\sigma_{NLO}$ [fb]	$-0.2169(3)$	$-0.0568(5)$	$-0.00032(13)$	$-0.0063(4)$	$-0.2804(7)$
$\delta\sigma_{NLO}/\sigma_{LO}$ [%]	-13.2	-3.5	0.0	-0.4	-17.1

… but Complete-NLO can be large

$\mathrm{pp} \to \mu^+ \nu_\mu \mathrm{e}^+ \nu_\mathrm{e} \mathrm{jj}$ same-sign WW scattering



Biedermann, Denner, Pellen '17

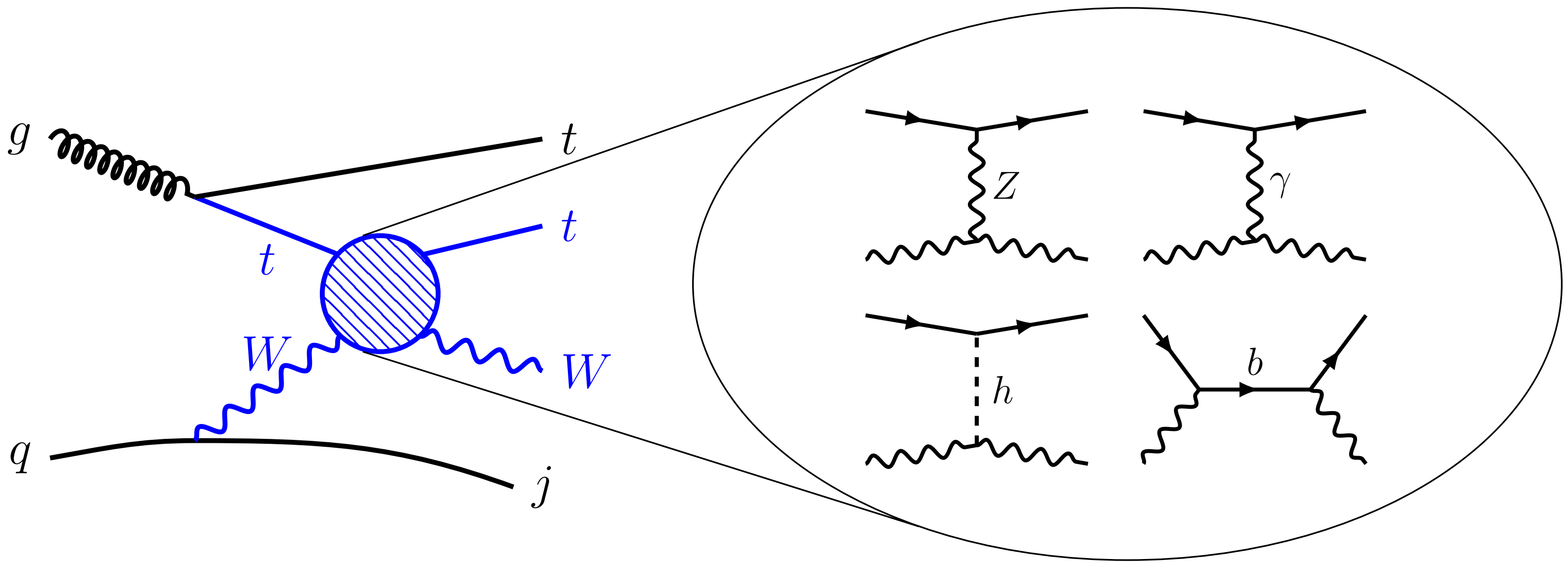


Order	$\mathcal{O}(\alpha^7)$	$\mathcal{O}(\alpha_\mathrm{s}\alpha^6)$	$\mathcal{O}(\alpha_\mathrm{s}^2\alpha^5)$	$\mathcal{O}(\alpha_\mathrm{s}^3\alpha^4)$	Sum
$\delta\sigma_\mathrm{NLO}$ [fb]	−0.2169(3)	−0.0568(5)	−0.00032(13)	−0.0063(4)	−0.2804(7)
$\delta\sigma_\mathrm{NLO}/\sigma_\mathrm{LO}$ [%]	−13.2	−3.5	0.0	−0.4	−17.1

Is same-sign WW scattering special? Do we have other processes with **supposedly subleading** contributions that are **large**?
We demonstrate that also ttW and four-top have this feature.

Why ttW and four-top?

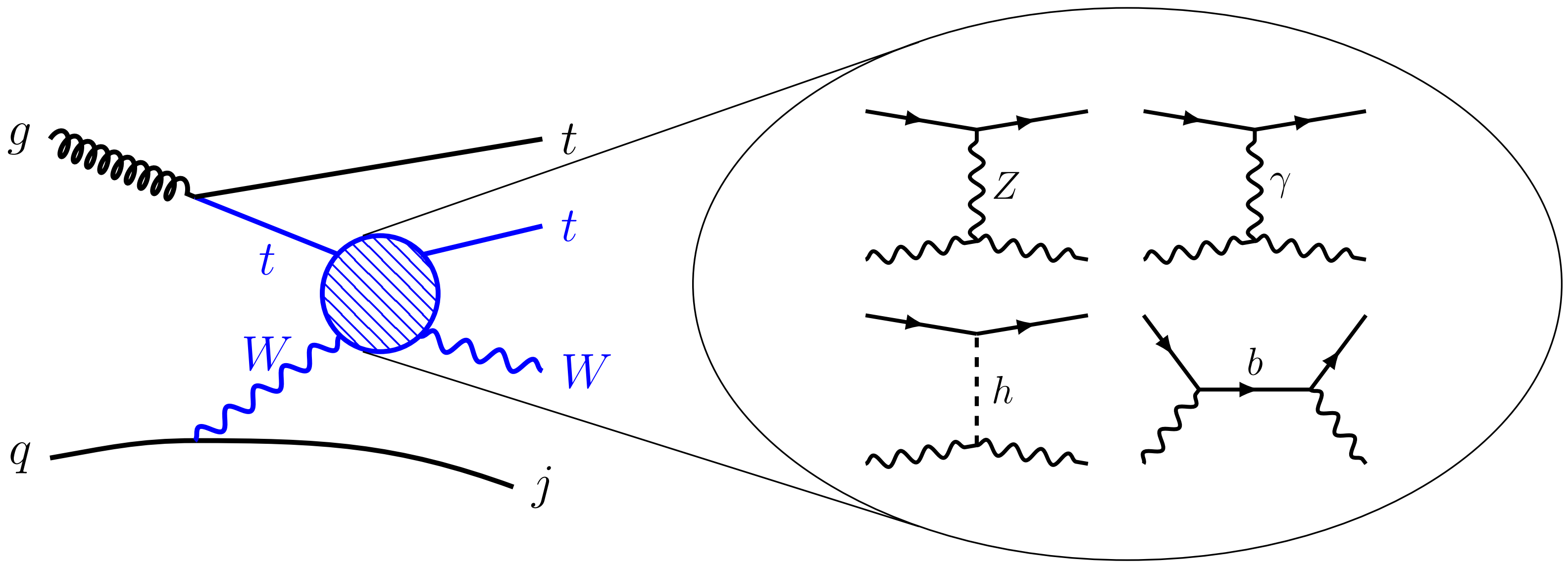
ttWj as a probe of tW —> tW scattering



Dror, Farina, Salvioni, Serra '15

$$\frac{i\bar{c}_R}{v^2} H^\dagger \overleftrightarrow{D_\mu} H \bar{t}_R \gamma^\mu t_R$$

ttWj as a probe of tW —> tW scattering

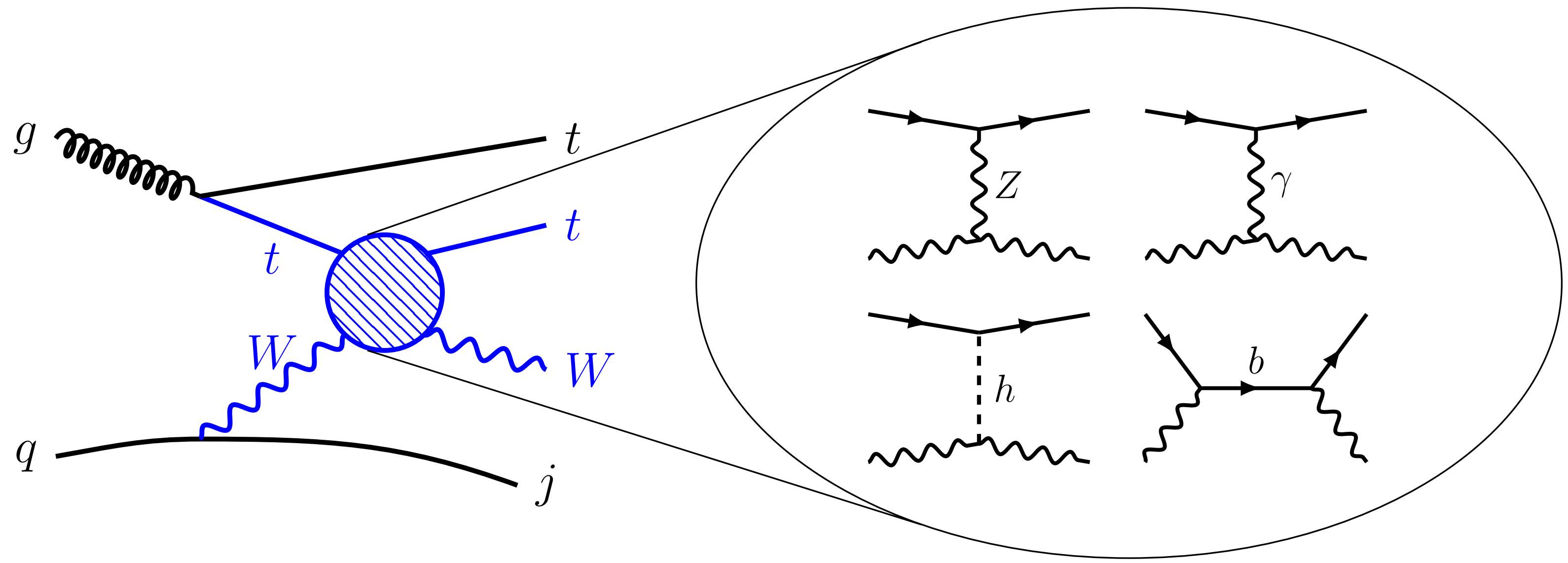


Dror, Farina, Salvioni, Serra '15

$$\frac{i\bar{c}_R}{v^2} H^\dagger \overleftrightarrow{D_\mu} H \bar{t}_R \gamma^\mu t_R$$

$p_T^j > 20$		$(t\bar{t}W)_{\text{QCD}}$	$(t\bar{t}W)_{\text{EW}}$	$(t\bar{t}Wj)_{\text{QCD}}$	$(t\bar{t}Wj)_{\text{EW}}$	$(t\bar{t}Wj)_{\text{full}}$
13 TeV	SM	347.9	2.85	341.3	56.0	386.1
	$\Delta_R = 1$	347.9	2.71	341.3	94.6	423.9

ttWj as a probe of tW —> tW scattering



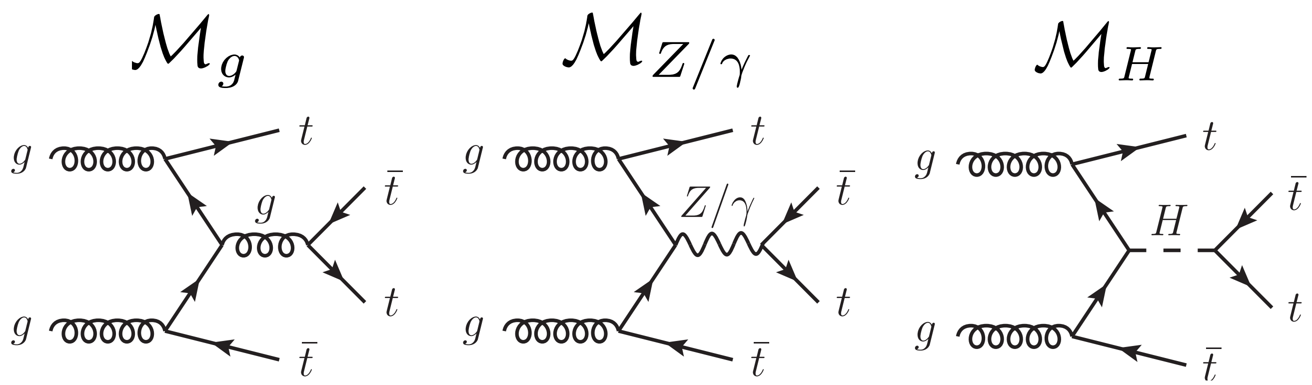
Dror, Farina, Salvioni, Serra '15

$$\frac{i\bar{c}_R}{v^2} H^\dagger \overleftrightarrow{D}_\mu H \bar{t}_R \gamma^\mu t_R$$

$p_T^j > 20$		$(t\bar{t}W)_{\text{QCD}}$	$(t\bar{t}W)_{\text{EW}}$	$(t\bar{t}Wj)_{\text{QCD}}$	$(t\bar{t}Wj)_{\text{EW}}$	$(t\bar{t}Wj)_{\text{full}}$
13 TeV	SM	347.9	2.85	341.3	56.0	386.1
	$\Delta_R = 1$	347.9	2.71	341.3	94.6	423.9

ttWj is part of inclusive ttW production, but the tW-scattering component does not appear neither at NLO QCD nor (squared) at NLO EW.
It appears beyond NLO EW, in an EW subleading contribution, which anyway induces large NLO corrections.

y_t and Γ_H determination via $t\bar{t}t\bar{t}$



$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} \propto \left|\mathcal{M}_g + \mathcal{M}_{Z/\gamma}\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_H \propto \left|\mathcal{M}_H\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int} \propto \mathcal{M}_{g+Z/\gamma}\mathcal{M}_H^\dagger + \mathcal{M}_{g+Z/\gamma}^\dagger\mathcal{M}_H$$

The cross section depends on y_t to the fourth power.
It does not depend on Γ_H, since the Higgs is off-shell.

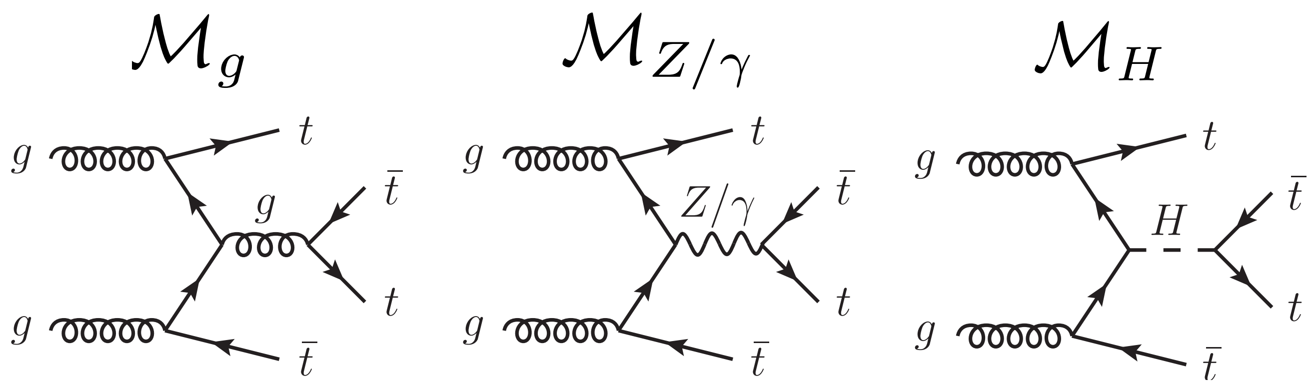
$$\kappa_t \equiv y_{Htt}/y_{Htt}^{\rm SM}$$

$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \boxed{\kappa_t^2}\sigma_{\rm int}^{\rm SM} + \boxed{\kappa_t^4}\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$

In combination with the measurement of $t\bar{t}H$, both y_t and Γ_H can be determined.

Cao, Chen, Liu '16

y_t and Γ_H determination via $t\bar{t}t\bar{t}$



$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} \propto \left|\mathcal{M}_g + \mathcal{M}_{Z/\gamma}\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{H} \propto \left|\mathcal{M}_H\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int} \propto \mathcal{M}_{g+Z/\gamma}\mathcal{M}_H^\dagger + \mathcal{M}_{g+Z/\gamma}^\dagger\mathcal{M}_H$$

The cross section depends on y_t to the fourth power.
It does not depend on Γ_H, since the Higgs is off-shell.

$$\kappa_t \equiv y_{Htt}/y_{Htt}^{\rm SM}$$

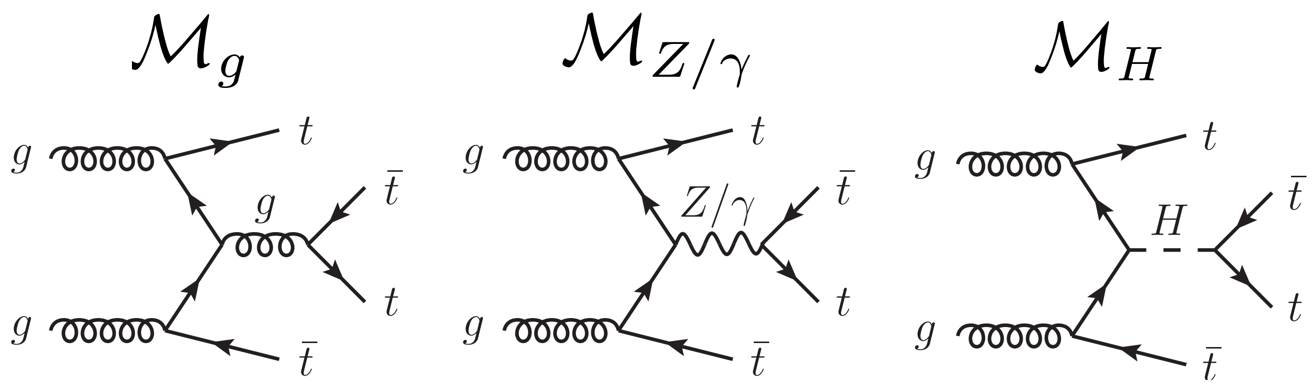
$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \boxed{\kappa_t^2}\sigma_{\rm int}^{\rm SM} + \boxed{\kappa_t^4}\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$

In combination with the measurement of $t\bar{t}H$, both y_t and Γ_H can be determined.

	14 TeV	100 TeV
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	12.390 fb,	3276 fb
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{H}$:	1.477 fb,	271.3 fb
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$:	−2.060 fb.	−356.9 fb

Cao, Chen, Liu ‘16

y_t and Γ_H determination via $t\bar{t}t\bar{t}$



$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} \propto \left|\mathcal{M}_g + \mathcal{M}_{Z/\gamma}\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{H} \propto \left|\mathcal{M}_H\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int} \propto \mathcal{M}_{g+Z/\gamma}\mathcal{M}_H^\dagger + \mathcal{M}_{g+Z/\gamma}^\dagger \mathcal{M}_H$$

The cross section depends on y_t to the fourth power.
It does not depend on Γ_H, since the Higgs is off-shell.

$$\kappa_t \equiv y_{Htt}/y_{Htt}^{\rm SM}$$

$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \boxed{\kappa_t^2}\sigma_{\rm int}^{\rm SM} + \boxed{\kappa_t^4}\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$$

In combination with the measurement of $t\bar{t}H$, both y_t and Γ_H can be determined.

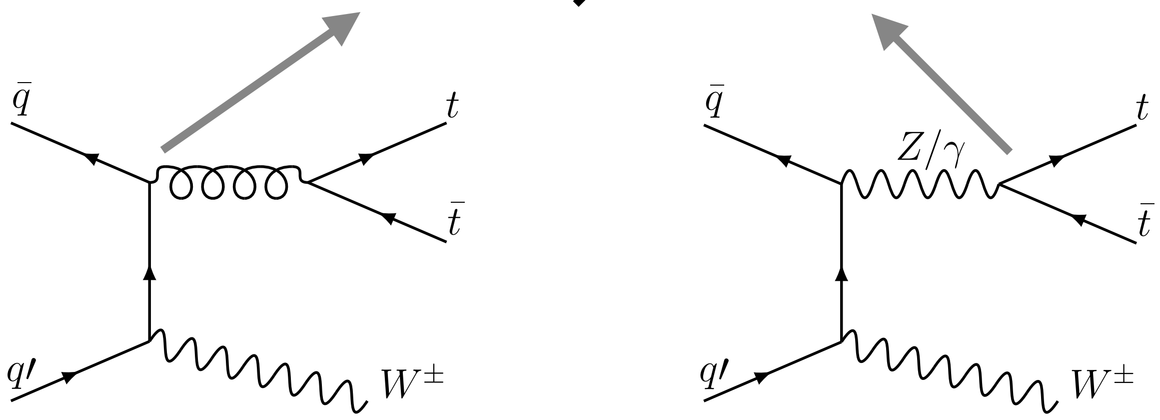
	14 TeV	100 TeV
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	12.390 fb,	3276 fb
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{H}$:	1.477 fb,	271.3 fb
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$:	−2.060 fb.	−356.9 fb

Cao, Chen, Liu '16

There are large contributions at LO, with large cancellations.
What happens with NLO corrections? How is tt —> tt scattering affected?
Relevant issue for precise y_t measurement.

$t\bar{t}W^{\pm}$ and $t\bar{t}t\bar{t}$ at LO

$$\Sigma_{\mathrm{LO}}^{t\bar{t}W^{\pm}}(\alpha_s,\alpha) = \alpha_s^2\alpha\Sigma_{3,0}^{t\bar{t}W^{\pm}} + \alpha_s\alpha\Sigma_{3,1}^{t\bar{t}W^{\pm}} + \alpha^2\Sigma_{3,2}^{t\bar{t}W^{\pm}}$$
$$\equiv \Sigma_{\mathrm{LO}_1} + \Sigma_{\mathrm{LO}_2} + \Sigma_{\mathrm{LO}_3},$$

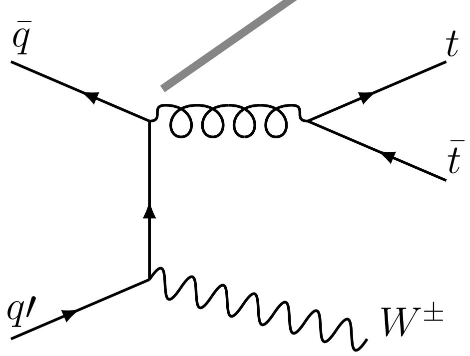


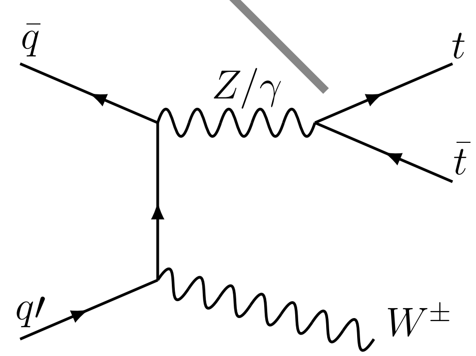
Only initial states without gluons are present.

Σ_{LO_1} ➡ $\mathrm{LO}_{\mathrm{QCD}}$

$t\bar{t}W^{\pm}$ and $t\bar{t}t\bar{t}$ at LO

$$\Sigma_{\rm LO}^{t\bar{t}W^{\pm}}(\alpha_s,\alpha) = \alpha_s^2\alpha\Sigma_{3,0}^{t\bar{t}W^{\pm}} + \alpha_s\alpha\Sigma_{3,1}^{t\bar{t}W^{\pm}} + \alpha^2\Sigma_{3,2}^{t\bar{t}W^{\pm}}$$
$$\equiv \Sigma_{\rm LO_1} + \Sigma_{\rm LO_2} + \Sigma_{\rm LO_3}\,,$$

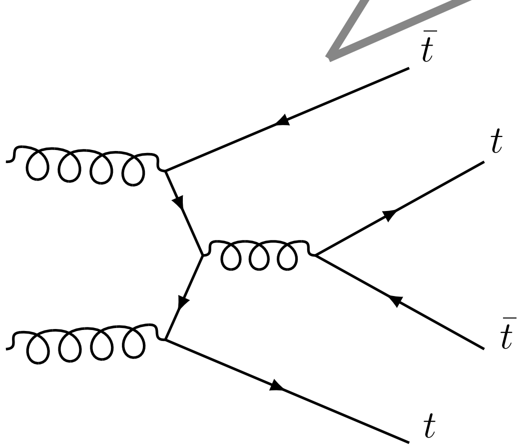


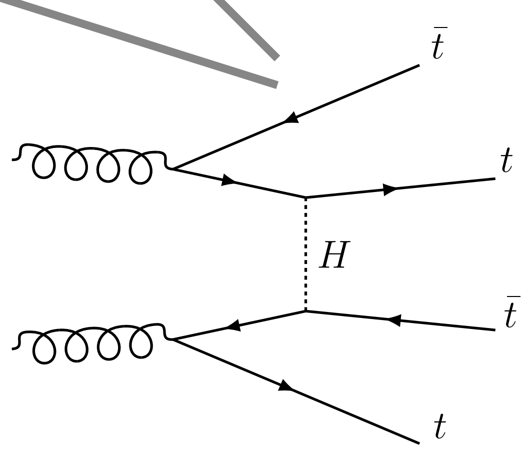


Only initial states without gluons are present.

$\Sigma_{\rm LO_1} \rightarrow {\rm LO_{QCD}}$

$$\Sigma_{\rm LO}^{t\bar{t}t\bar{t}}(\alpha_s,\alpha) = \alpha_s^4\Sigma_{4,0}^{t\bar{t}t\bar{t}} + \alpha_s^3\alpha\Sigma_{4,1}^{t\bar{t}t\bar{t}} + \alpha_s^2\alpha^2\Sigma_{4,2}^{t\bar{t}t\bar{t}} + \alpha_s^3\alpha\Sigma_{4,3}^{t\bar{t}t\bar{t}} + \alpha^4\Sigma_{4,4}^{t\bar{t}t\bar{t}}$$
$$\equiv \Sigma_{\rm LO_1} + \Sigma_{\rm LO_2} + \Sigma_{\rm LO_3} + \Sigma_{\rm LO_4} + \Sigma_{\rm LO_5}\,.$$



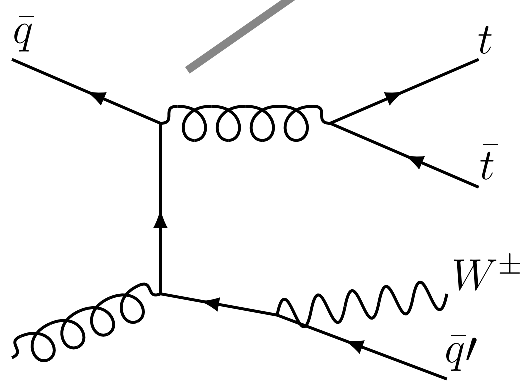


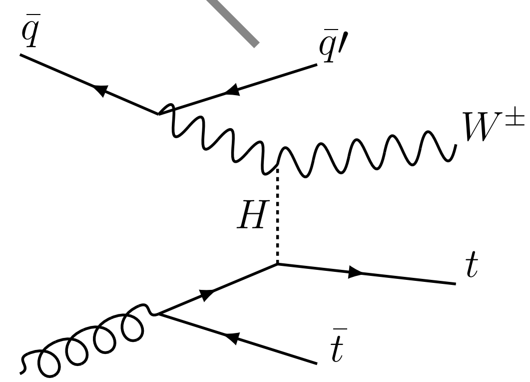
The gg initial-state is giving ~90% of LO cross section at 13 TeV and almost all the cross section at 100 TeV.

There is no gg contribution at LO4 and LO5.

$t\bar{t}W^{\pm}$ and $t\bar{t}t\bar{t}$ at NLO

$$\Sigma^{t\bar{t}W^{\pm}}_{\rm NLO}(\alpha_s,\alpha) = \alpha_s^3\alpha\Sigma^{t\bar{t}W^{\pm}}_{4,0} + \alpha_s^2\alpha^2\Sigma^{t\bar{t}W^{\pm}}_{4,1} + \alpha_s\alpha^3\Sigma^{t\bar{t}W^{\pm}}_{4,2} + \alpha^4\Sigma^{t\bar{t}W^{\pm}}_{4,3}$$
$$\equiv \Sigma_{\rm NLO_1} + \Sigma_{\rm NLO_2} + \Sigma_{\rm NLO_3} + \Sigma_{\rm NLO_4}\,,$$



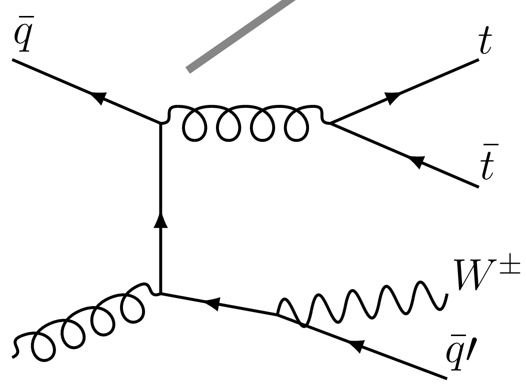


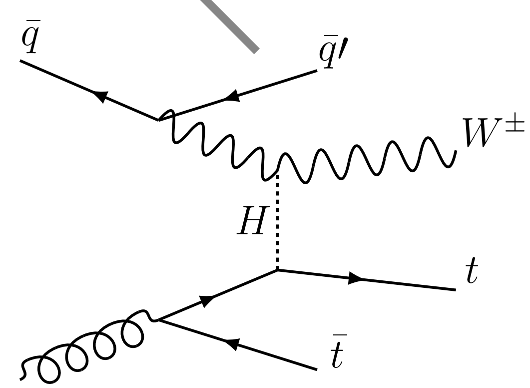
$\Sigma_{\rm NLO_1} \longrightarrow {\rm NLO_{QCD}}$

$\Sigma_{\rm NLO_2} \longrightarrow {\rm NLO_{EW}}$

$t\bar{t}W^{\pm}$ and $t\bar{t}t\bar{t}$ at NLO

$$\Sigma_{\rm NLO}^{t\bar{t}W^{\pm}}(\alpha_s,\alpha) = \alpha_s^3\alpha\Sigma_{4,0}^{t\bar{t}W^{\pm}} + \alpha_s^2\alpha^2\Sigma_{4,1}^{t\bar{t}W^{\pm}} + \alpha_s\alpha^3\Sigma_{4,2}^{t\bar{t}W^{\pm}} + \alpha^4\Sigma_{4,3}^{t\bar{t}W^{\pm}}$$
$$\equiv \Sigma_{\rm NLO_1} + \Sigma_{\rm NLO_2} + \Sigma_{\rm NLO_3} + \Sigma_{\rm NLO_4}\,,$$

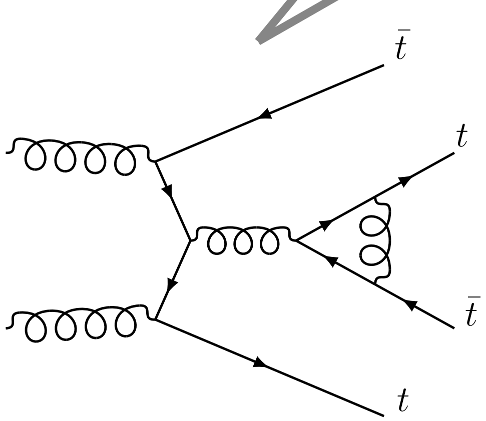


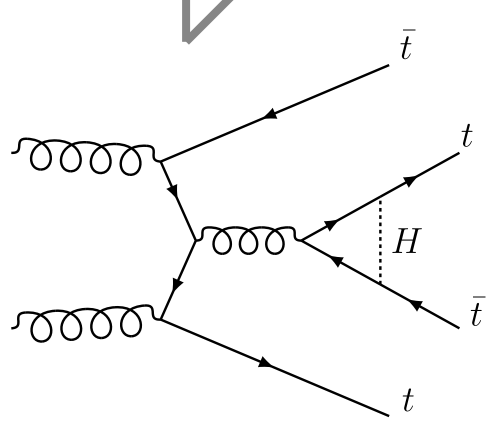


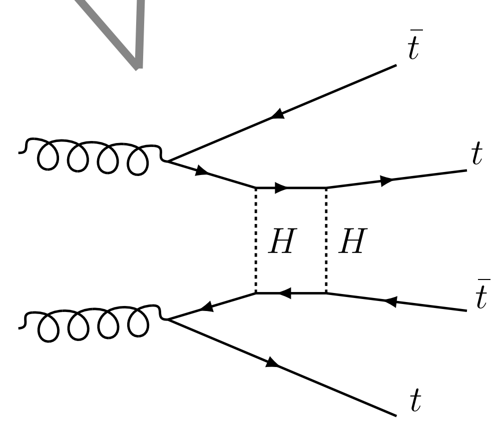
$\Sigma_{\rm NLO_1}$ ➞ $\rm NLO_{QCD}$

$\Sigma_{\rm NLO_2}$ ➞ $\rm NLO_{EW}$

$$\Sigma_{\rm NLO}^{t\bar{t}t\bar{t}}(\alpha_s,\alpha) = \alpha_s^5\Sigma_{5,0}^{t\bar{t}t\bar{t}} + \alpha_s^4\alpha^1\Sigma_{5,1}^{t\bar{t}t\bar{t}} + \alpha_s^3\alpha^2\Sigma_{5,2}^{t\bar{t}t\bar{t}} + \alpha_s^2\alpha^3\Sigma_{5,3}^{t\bar{t}t\bar{t}} + \alpha_s^1\alpha^4\Sigma_{5,4}^{t\bar{t}t\bar{t}} + \alpha^5\Sigma_{5,5}^{t\bar{t}t\bar{t}}$$
$$\equiv \Sigma_{\rm NLO_1} + \Sigma_{\rm NLO_2} + \Sigma_{\rm NLO_3} + \Sigma_{\rm NLO_4} + \Sigma_{\rm NLO_5} + \Sigma_{\rm NLO_6}\,. \qquad ($$







There is no gg contribution at NLO4 and NLO5.

Calculation Framework

The calculation has been performed in a completely automated way via the MadGraph5_aMC@NLO framework, without any customisation for the two processes considered. *(see talk of Marco)*

$$m_t = 173.34 \text{ GeV}\,, \quad m_H = 125 \text{ GeV}\,, \quad m_W = 80.385 \text{ GeV}\,, \quad m_Z = 91.1876 \text{ GeV}$$

$$G_\mu = 1.16639 \cdot 10^{-5} \text{ GeV}^{-2}$$

EW renormalisation in the G_mu-scheme

$$\mu_c = \frac{H_T}{2} \quad \text{for} \quad t\bar{t}W^\pm\,,$$

$$\mu_c = \frac{H_T}{4} \quad \text{for} \quad t\bar{t}t\bar{t}\,,$$

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

`LUXqed_plus_PDF4LHC15_nnlo_100`

the contribution of photon PDF is small for both the processes.

ttW

Cross sections

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO+NLO}}{\mathrm{LO_{QCD}+NLO_{QCD}}}$
$\mu = H_T/2$	$363^{+24\%}_{-18\%}$	$544^{+11\%}_{-11\%}\,(456^{+5\%}_{-7\%})$	$366^{+23\%}_{-18\%}$	$577^{+11\%}_{-11\%}\,(476^{+5\%}_{-7\%})$	1.06 (1.04)

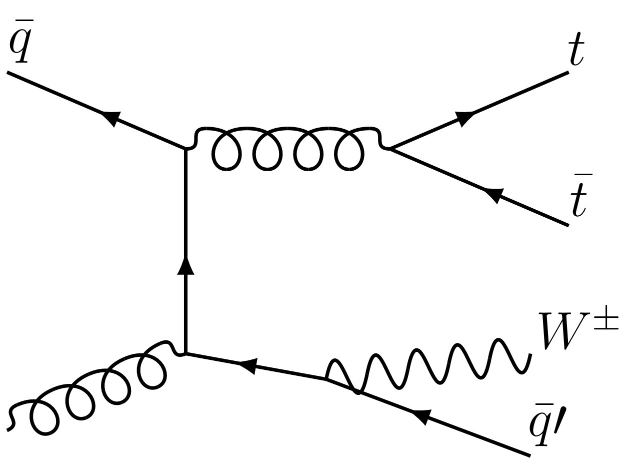
13 TeV

σ[pb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO+NLO}}{\mathrm{LO_{QCD}+NLO_{QCD}}}$
$\mu = H_T/2$	$6.64^{+28\%}_{-21\%}$	$16.58^{+17\%}_{-15\%}\,(11.37^{+11\%}_{-12\%})$	$6.72^{+27\%}_{-21\%}$	$20.86^{+15\%}_{-14\%}\,(14.80^{+11\%}_{-11\%})$	1.26 (1.30)

100 TeV

Number in parentheses refer to the case of a jet veto applied

$p_T(j) > 100$ GeV and $|y(j)| < 2.5$



At LO top-quark pairs recoil always against the W.
At NLO QCD, at large pt, they mainly recoil against a jet, which can emit a W and thus a correction of order $\alpha_s \log^2 [p_T(t\bar{t})/m_W]$.
The effect is further enhanced since $qg \to t\bar{t}W^\pm q'$ has a gluon in the initial state.

Cross sections: order by order

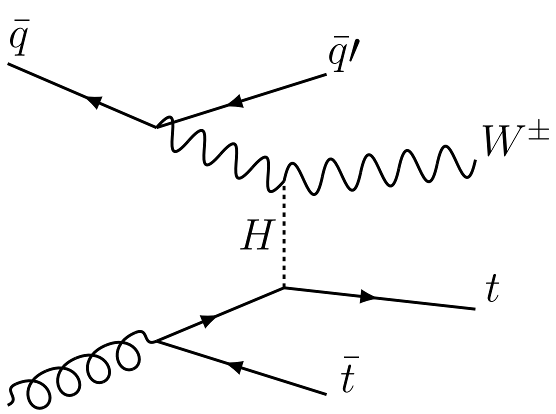
$$\delta_{(\mathrm{N})\mathrm{LO}_i}(\mu) = \frac{\Sigma_{(\mathrm{N})\mathrm{LO}_i}(\mu)}{\Sigma_{\mathrm{LO_{QCD}}}(\mu)} \qquad \mathrm{LO}_1 \equiv \mathrm{LO_{QCD}}$$

13 TeV

$\delta[\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$	Naive estimate
LO_2	-	-	-	10
LO_3	0.8	0.9	1.1	1
NLO_1	34.8 (7.0)	50.0 (25.7)	63.4 (42.0)	10
NLO_2	−4.4 (−4.8)	−4.2 (−4.6)	−4.0 (−4.4)	1
NLO_3	11.9 (8.9)	12.2 (9.1)	12.5 (9.3)	0.1
NLO_4	0.02 (−0.02)	0.04 (−0.02)	0.05 (−0.01)	0.01

100 TeV

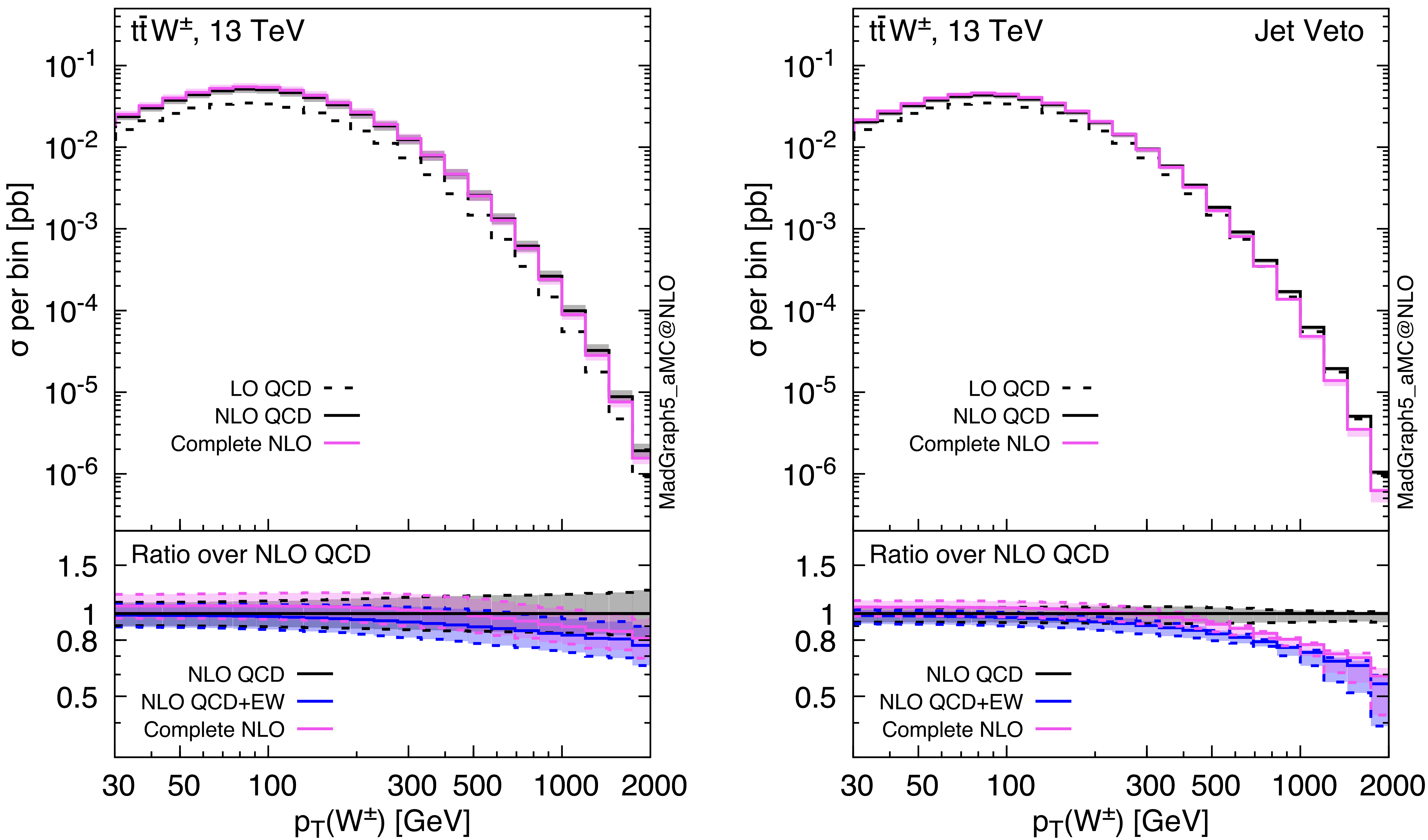
$\delta[\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$
LO_2	-	-	-
LO_3	0.9	1.1	1.3
NLO_1	159.5 (69.8)	149.5 (71.1)	142.7 (73.4)
NLO_2	−5.8 (−6.4)	−5.6 (−6.2)	−5.4 (−6.1)
NLO_3	67.5 (55.6)	68.8 (56.6)	70.0 (57.6)
NLO_4	0.2 (0.1)	0.2 (0.2)	0.3 (0.2)



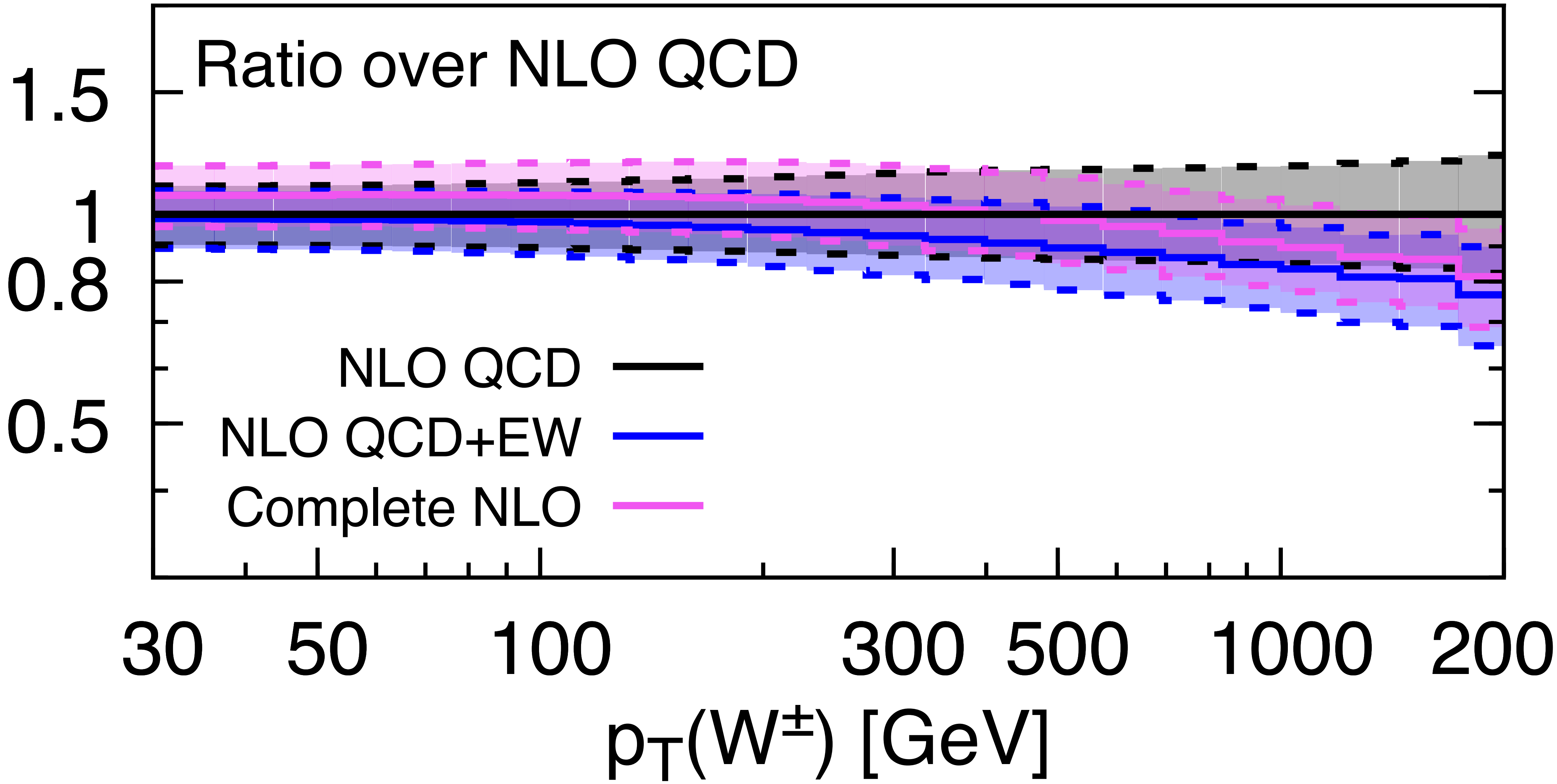
NLO_3 is large and it is not suppressed by the jet veto (number in parentheses) as much as NLO QCD corrections.
NLO QCD corrections depend on the scale, while NLO EW and NLO_3 do not.

Distributions

13 TeV



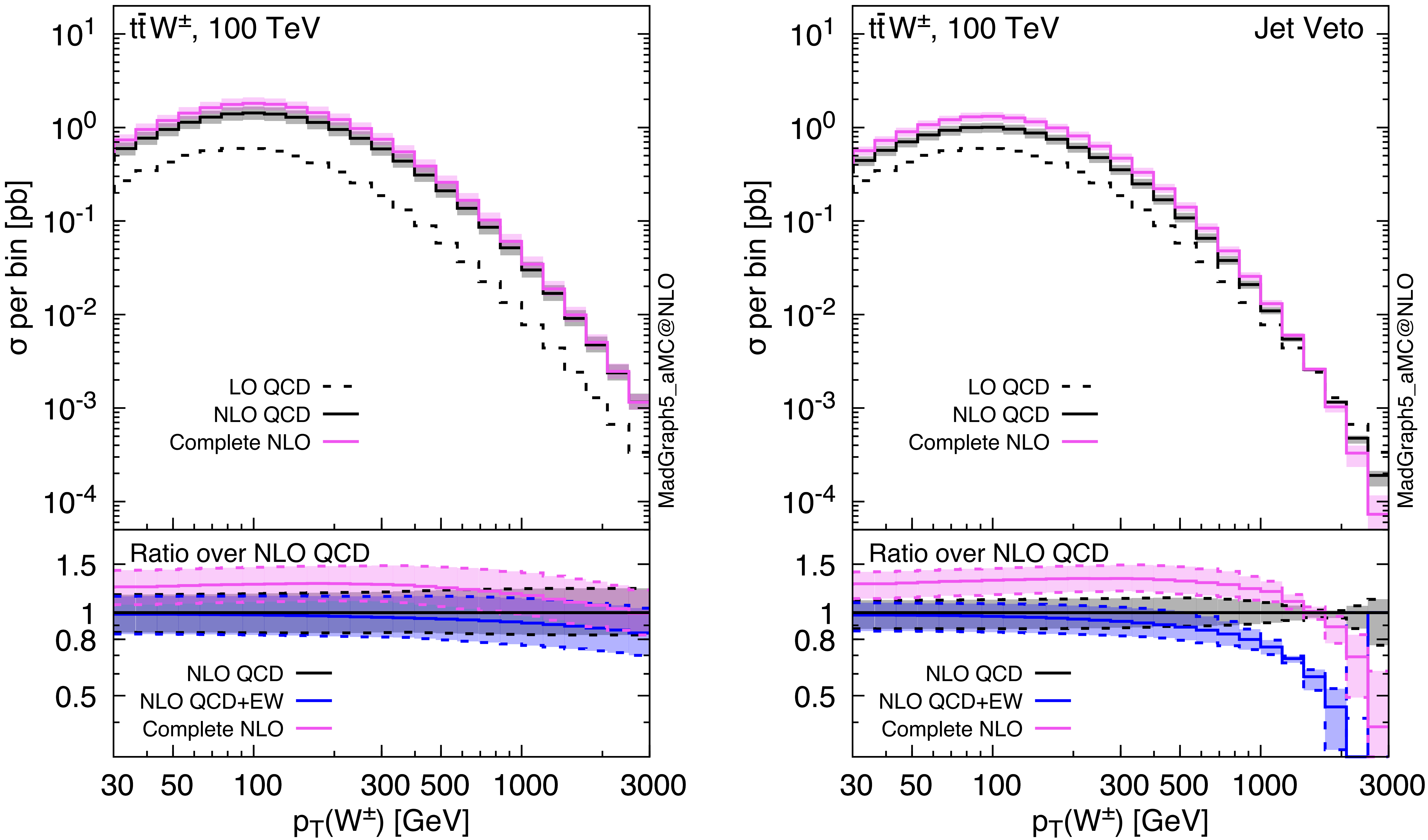
Distributions



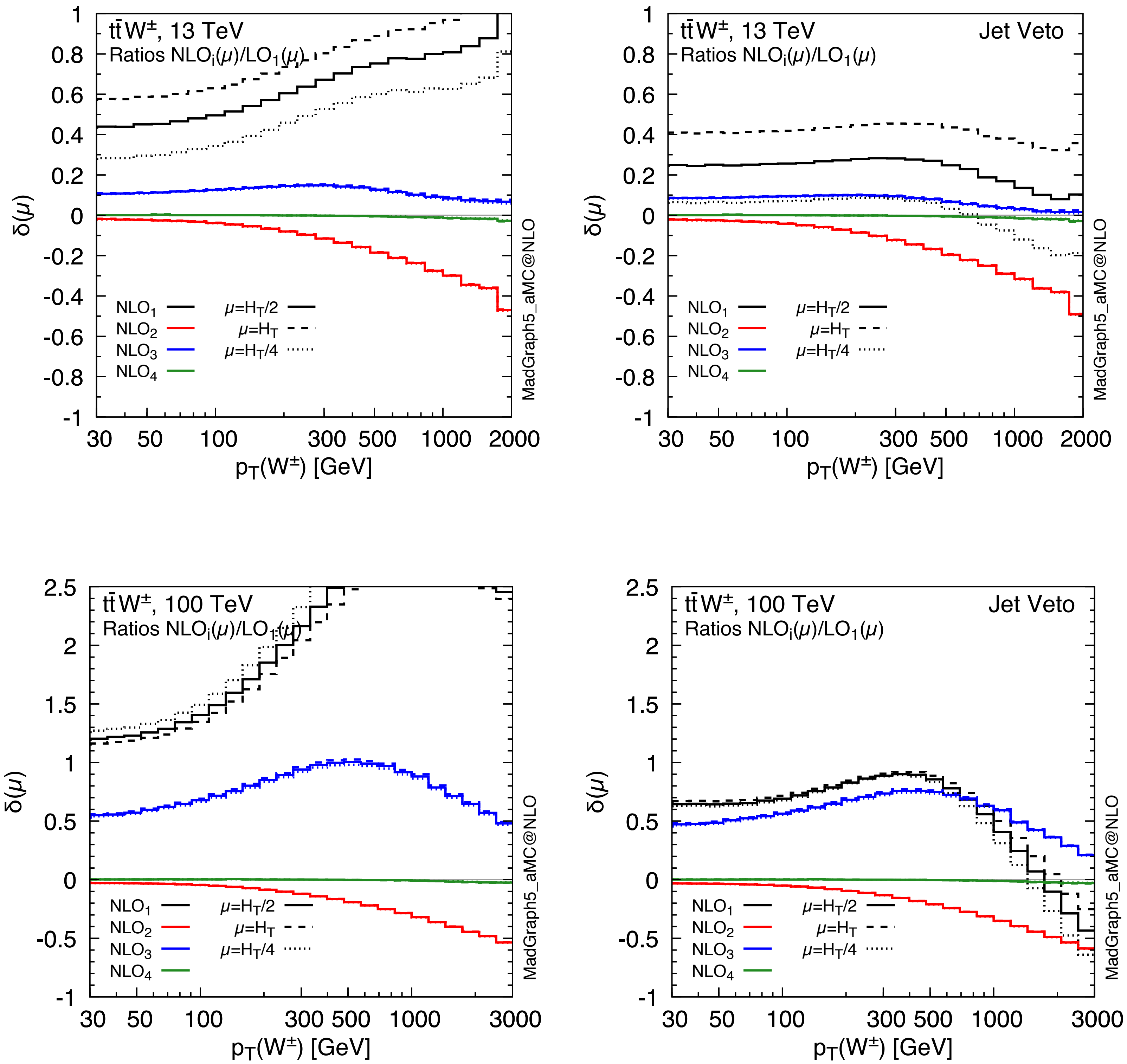
Zoom left plot

Distributions

100 TeV



Distributions



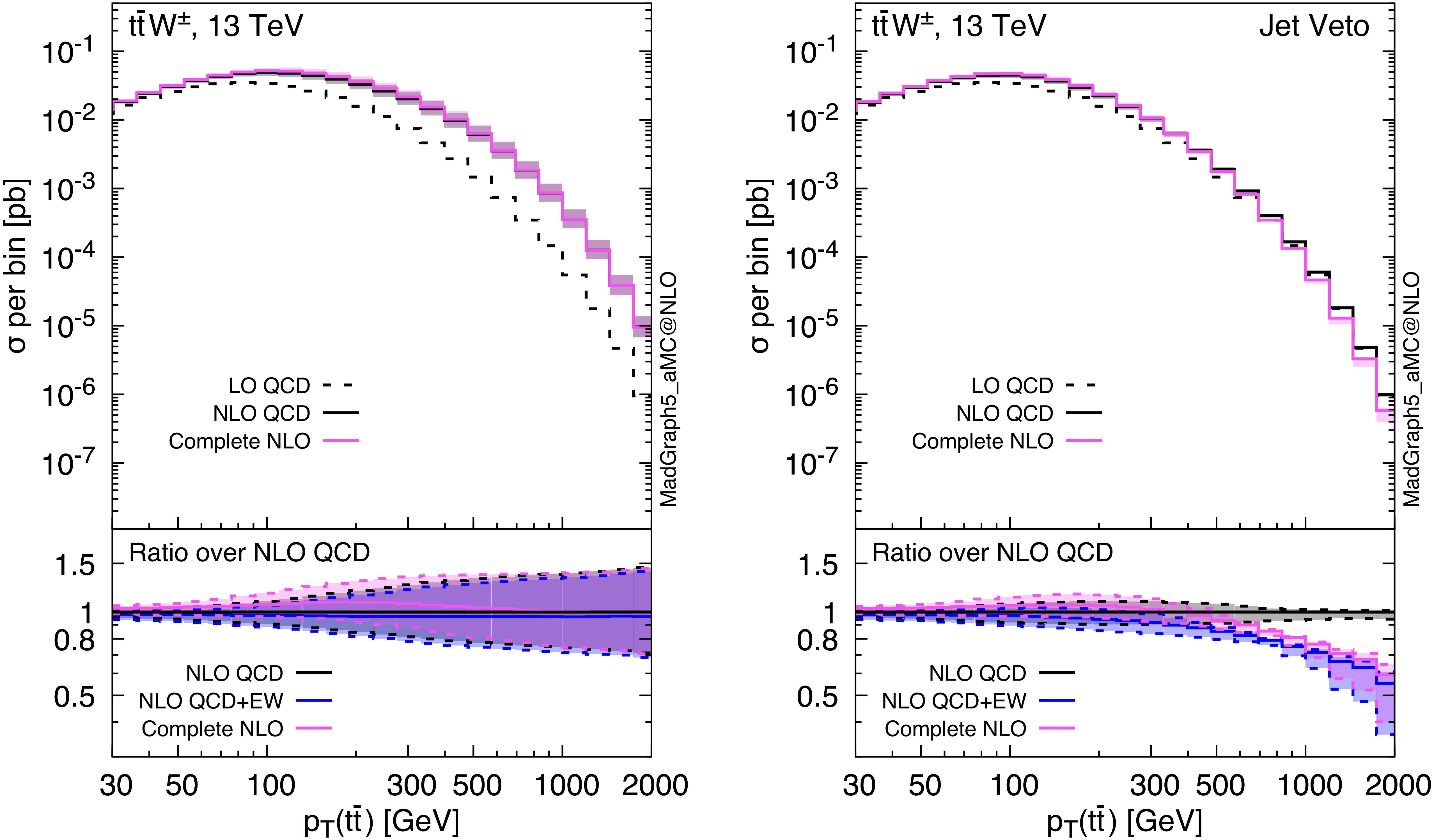
13 TeV

$$\delta_{(\mathrm{N})\mathrm{LO}_i}(\mu) = \frac{\Sigma_{(\mathrm{N})\mathrm{LO}_i}(\mu)}{\Sigma_{\mathrm{LO_{QCD}}}(\mu)}$$

100 TeV

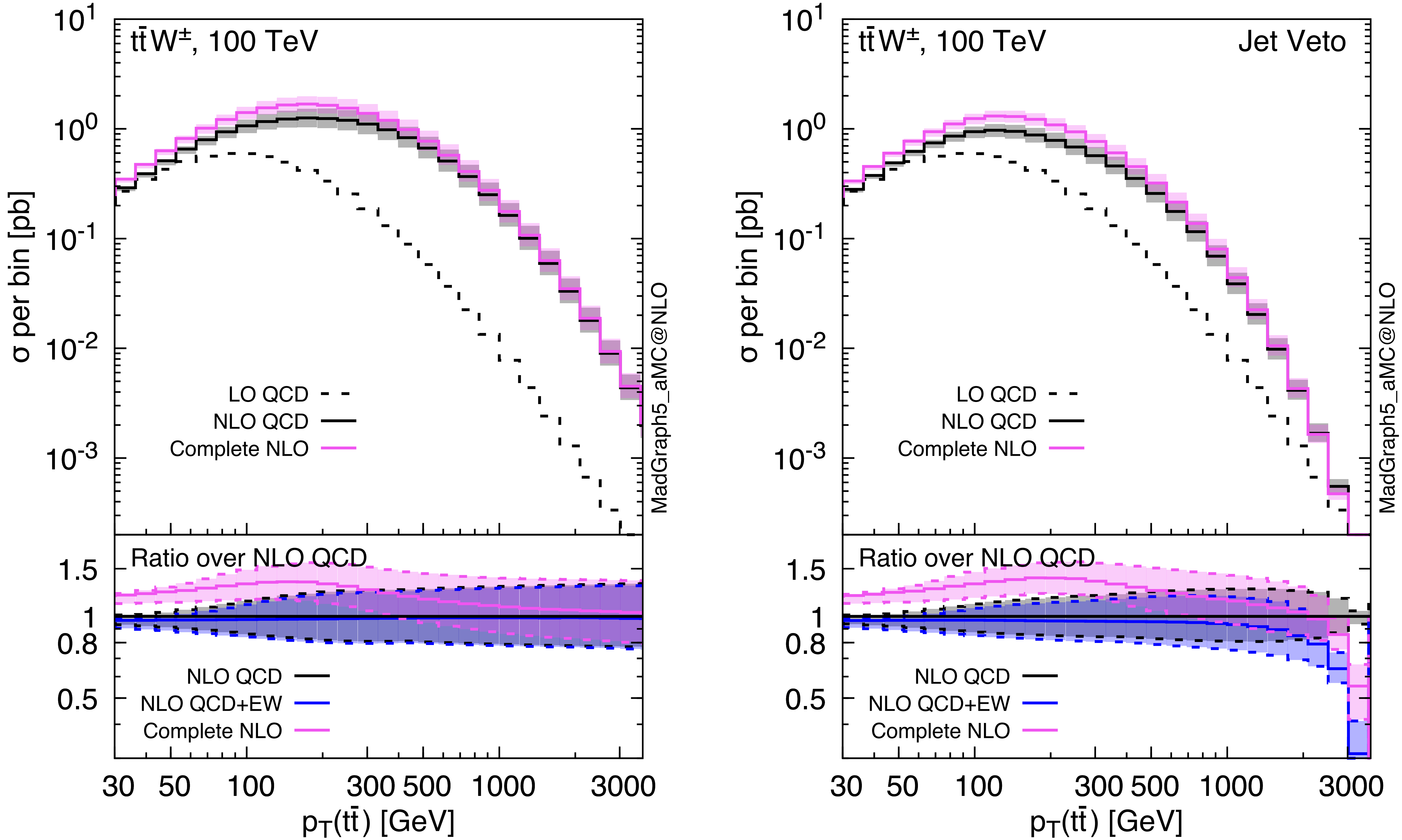
Distributions

13 TeV



Distributions

100 TeV



13 TeV

σ[fb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$6.83^{+70\%}_{-38\%}$	$11.12^{+19\%}_{-23\%}$	$7.59^{+64\%}_{-36\%}$	$11.97^{+18\%}_{-21\%}$	1.11 (1.08)

four-top

σ[pb]	$\mathrm{LO_{QCD}}$	$\mathrm{LO_{QCD}+NLO_{QCD}}$	LO	LO + NLO	$\frac{\mathrm{LO(+NLO)}}{\mathrm{LO_{QCD}(+NLO_{QCD})}}$
$\mu = H_T/4$	$2.37^{+49\%}_{-31\%}$	$3.98^{+18\%}_{-19\%}$	$2.63^{+44\%}_{-28\%}$	$4.18^{+17\%}_{-17\%}$	1.11 (1.05)

100 TeV

Cross sections

13 TeV

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-26.0	-28.3	-30.5
LO_3	32.6	39.0	45.9
LO_4	0.2	0.3	0.4
LO_5	0.02	0.03	0.05
NLO_1	14.0	62.7	103.5
NLO_2	8.6	-3.3	-15.1
NLO_3	-10.3	1.8	16.1
NLO_4	2.3	2.8	3.6
NLO_5	0.12	0.16	0.19
NLO_6	< 0.01	< 0.01	< 0.01
$NLO_2 + NLO_3$	-1.7	-1.6	0.9

Naive estimate

	Naive estimate
LO_2	10
LO_3	1
LO_4	0.1
LO_5	0.01
NLO_1	10
NLO_2	1
NLO_3	0.1
NLO_4	0.01
NLO_5	0.001
NLO_6	0.0001

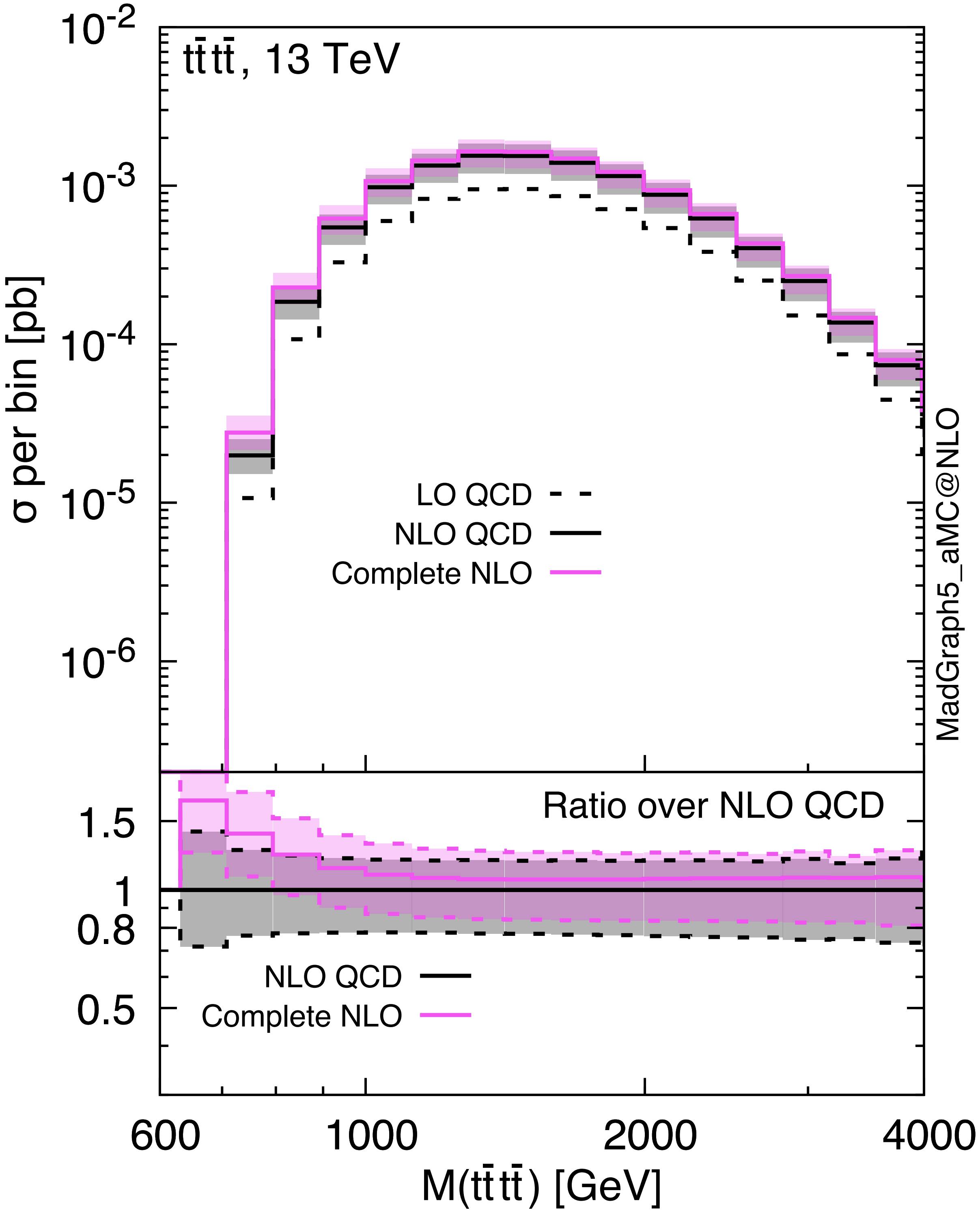
100 TeV

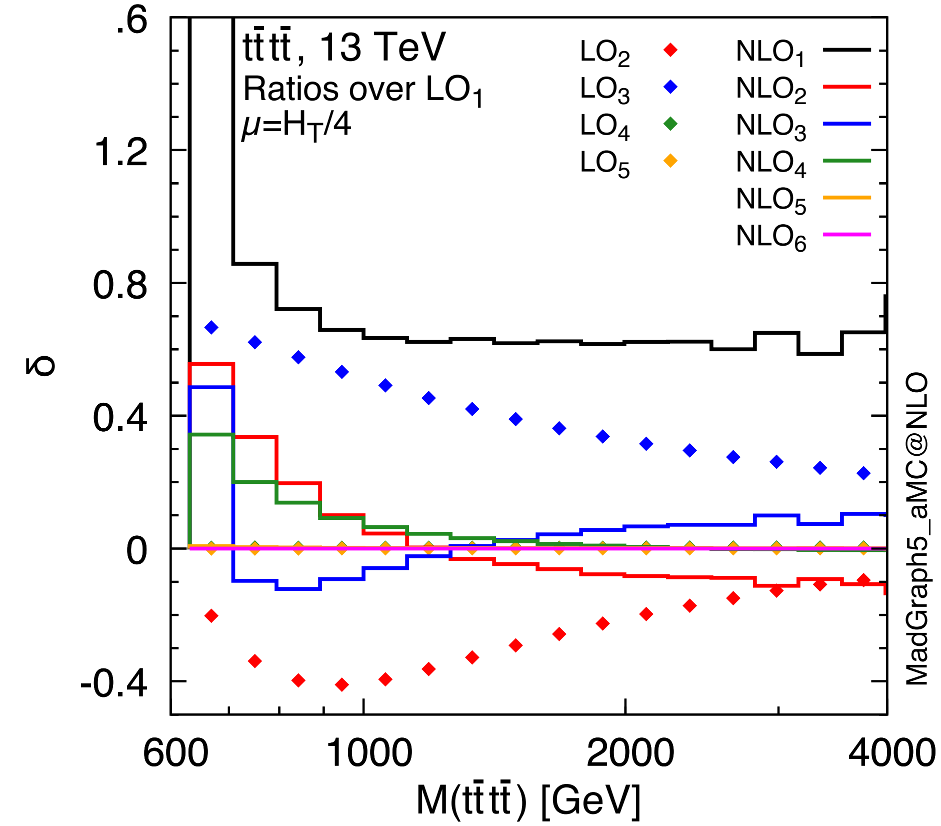
$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-18.7	-20.7	-22.8
LO_3	26.3	31.8	37.8
LO_4	0.05	0.07	0.09
LO_5	0.03	0.05	0.08
NLO_1	33.9	68.2	98.0
NLO_2	-0.3	-5.7	-11.6
NLO_3	-3.9	1.7	8.9
NLO_4	0.7	0.9	1.2
NLO_5	0.12	0.14	0.16
NLO_6	< 0.01	< 0.01	< 0.01
$NLO_2 + NLO_3$	-4.2	-4.0	2.7

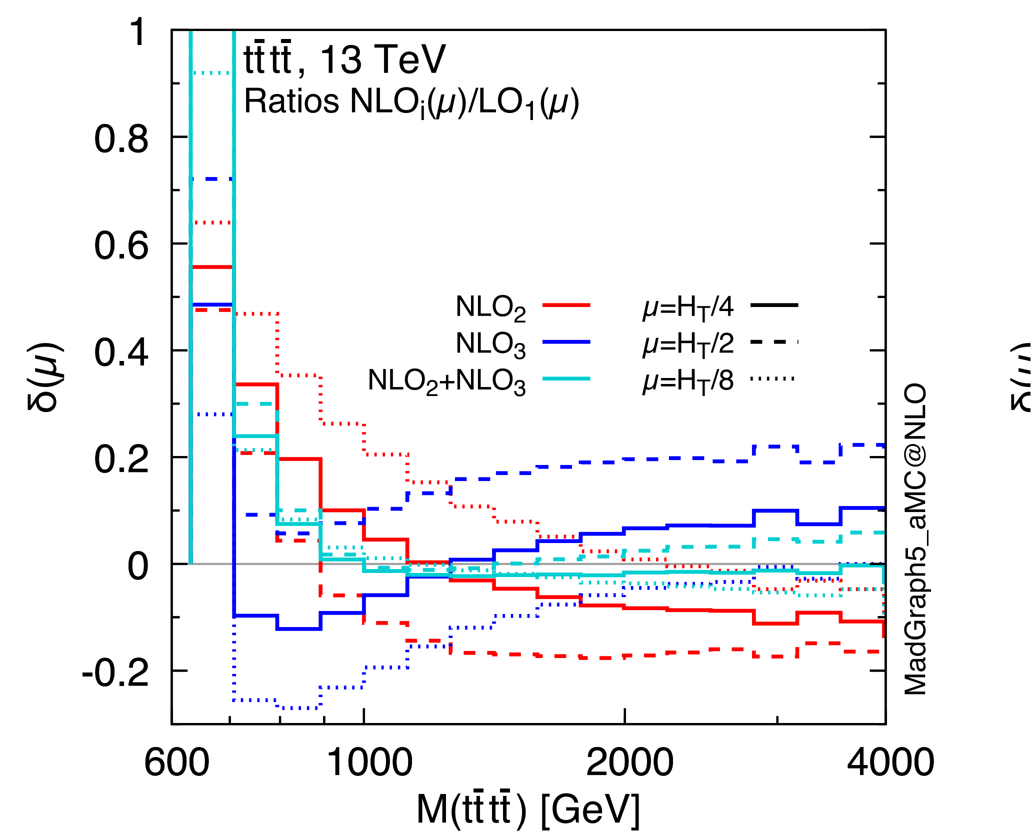
LO_2 and LO_3 are large and have also large cancellations.
NLO_2 and NLO_3 are mainly given by 'QCD corrections' on top of them, so they are large and strongly depend on the scale choice, at variance with standard EW corrections.
Accidentally, relatively to LO_1 , NLO_2+NLO_3 scale dependence almost disappear.

Distributions

13 TeV

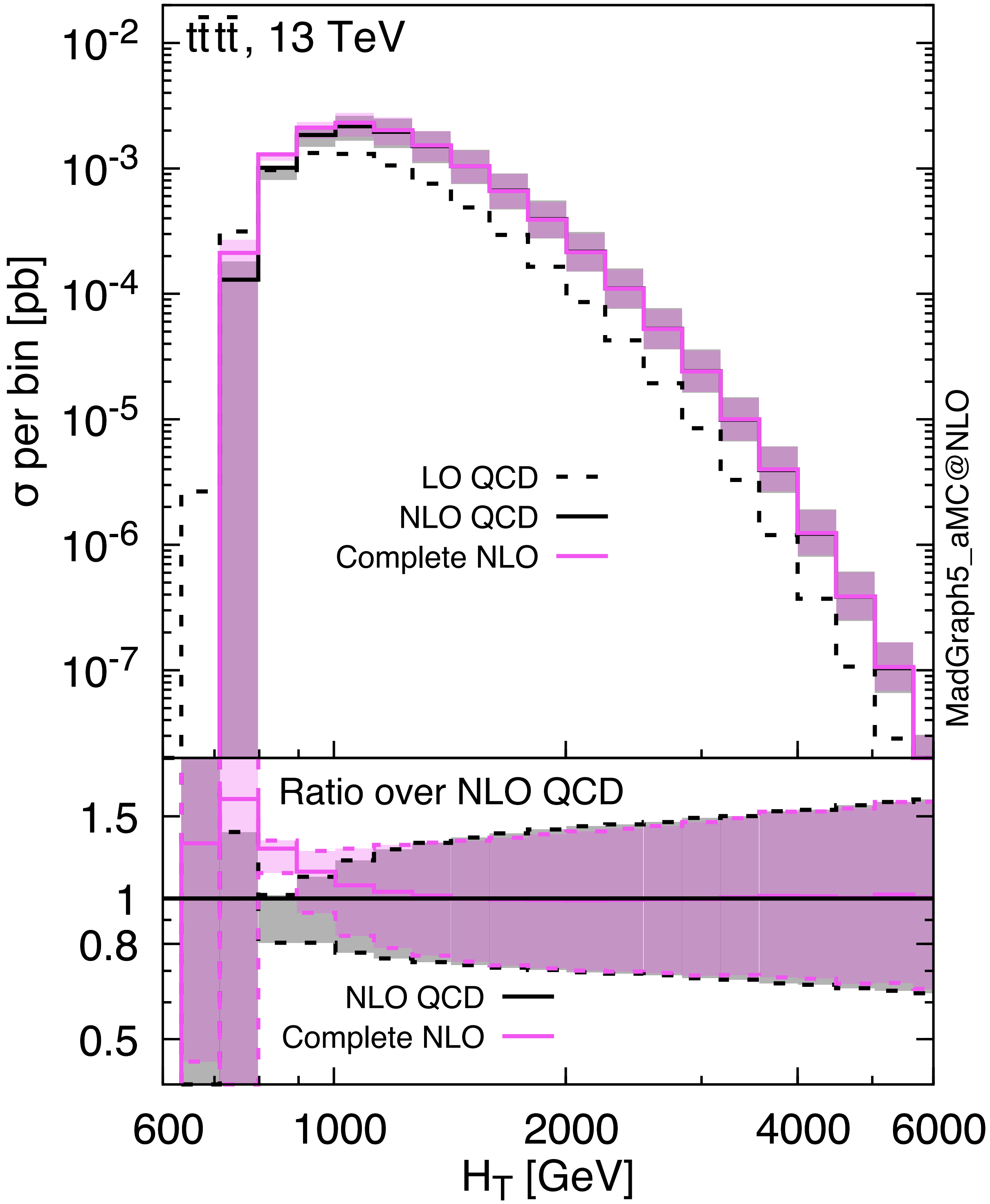


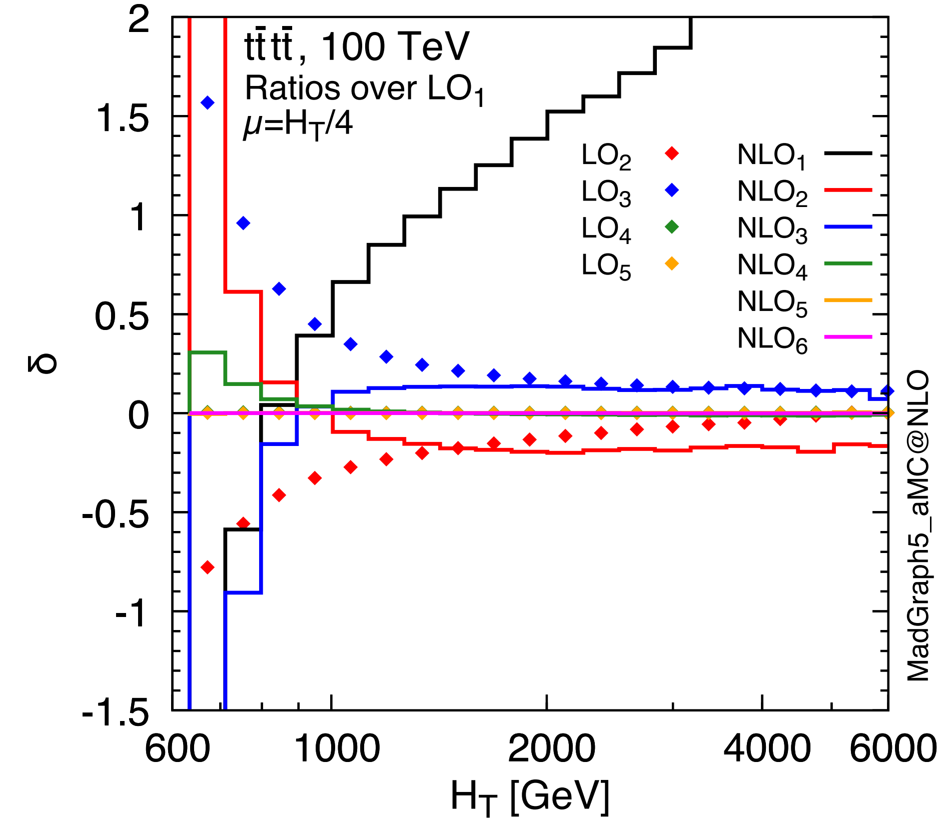


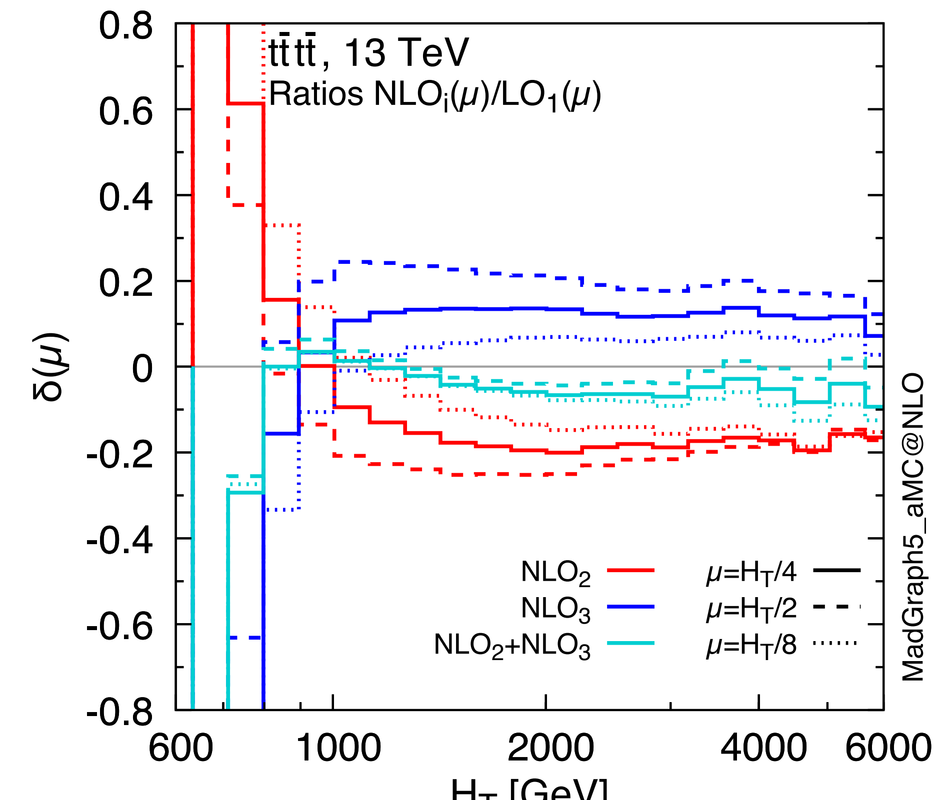


Distributions

13 TeV

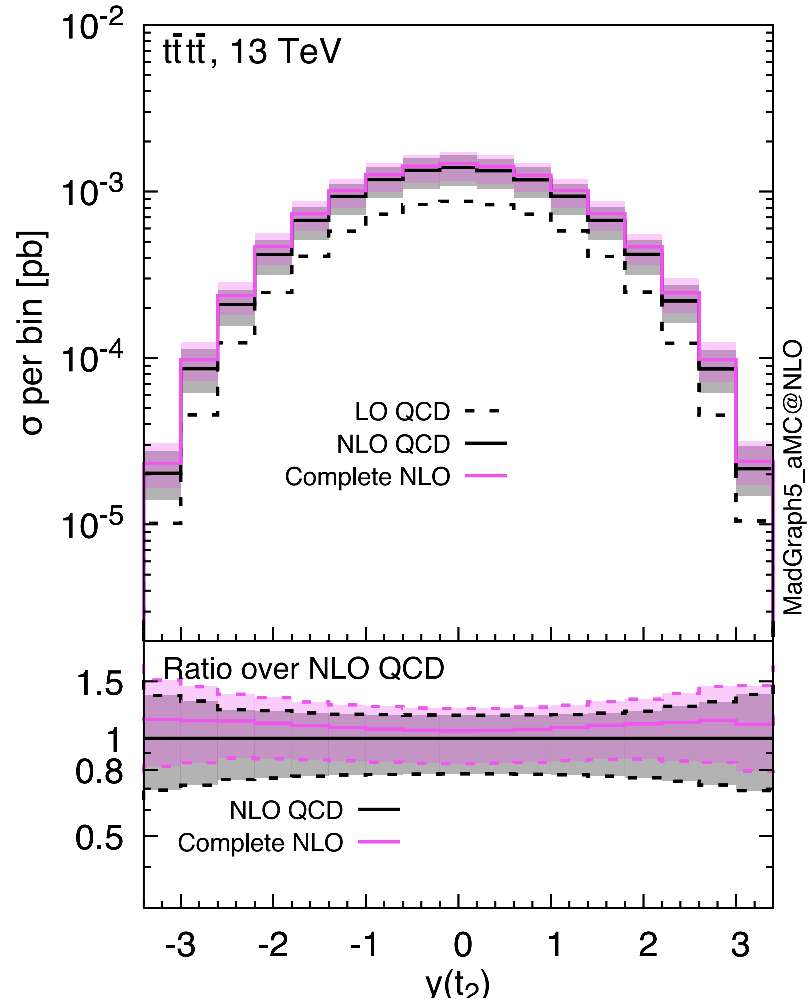


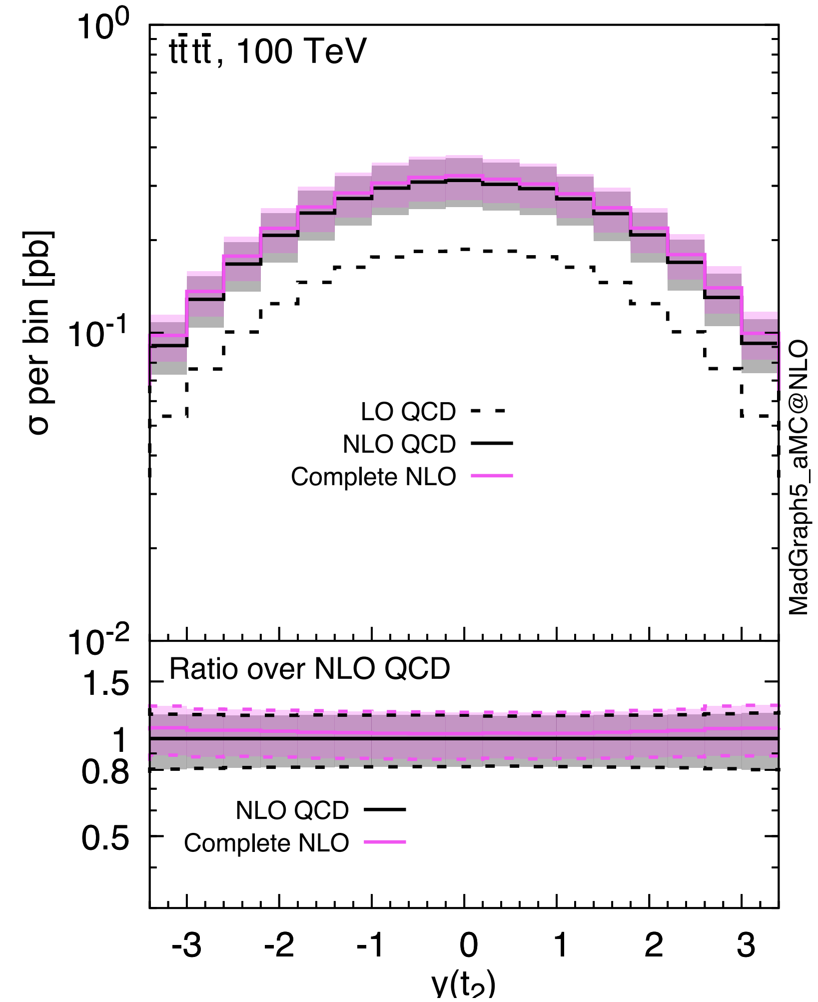




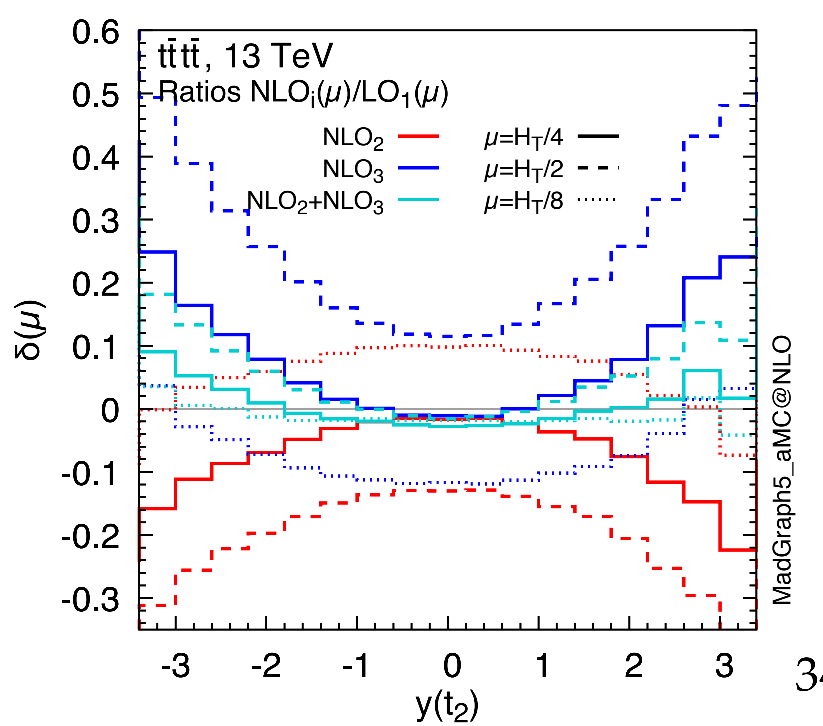
Distributions

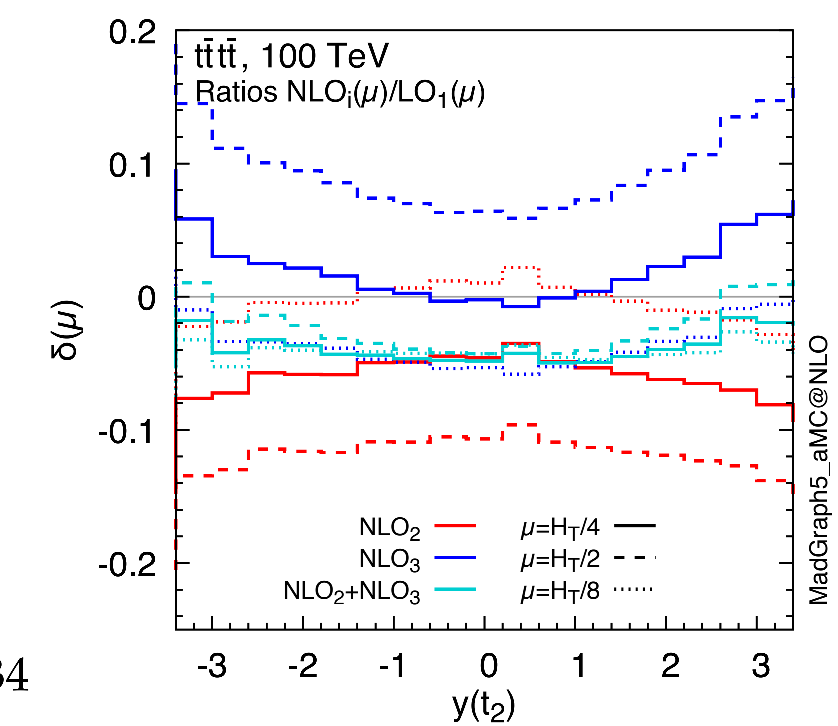
13 TeV





100 TeV





Conclusion

NLO corrections are not only NLO QCD and NLO EW.
The complete-NLO includes further supposedly subleading terms that can actually be large.

ttW production is dominated at h.e. by ttWj configurations, arising both in NLO QCD and NLO_3 corrections. A central-hard jet veto can kill NLO QCD corrections, while preserving NLO_3 ones, increasing the sensitivity to new physics.

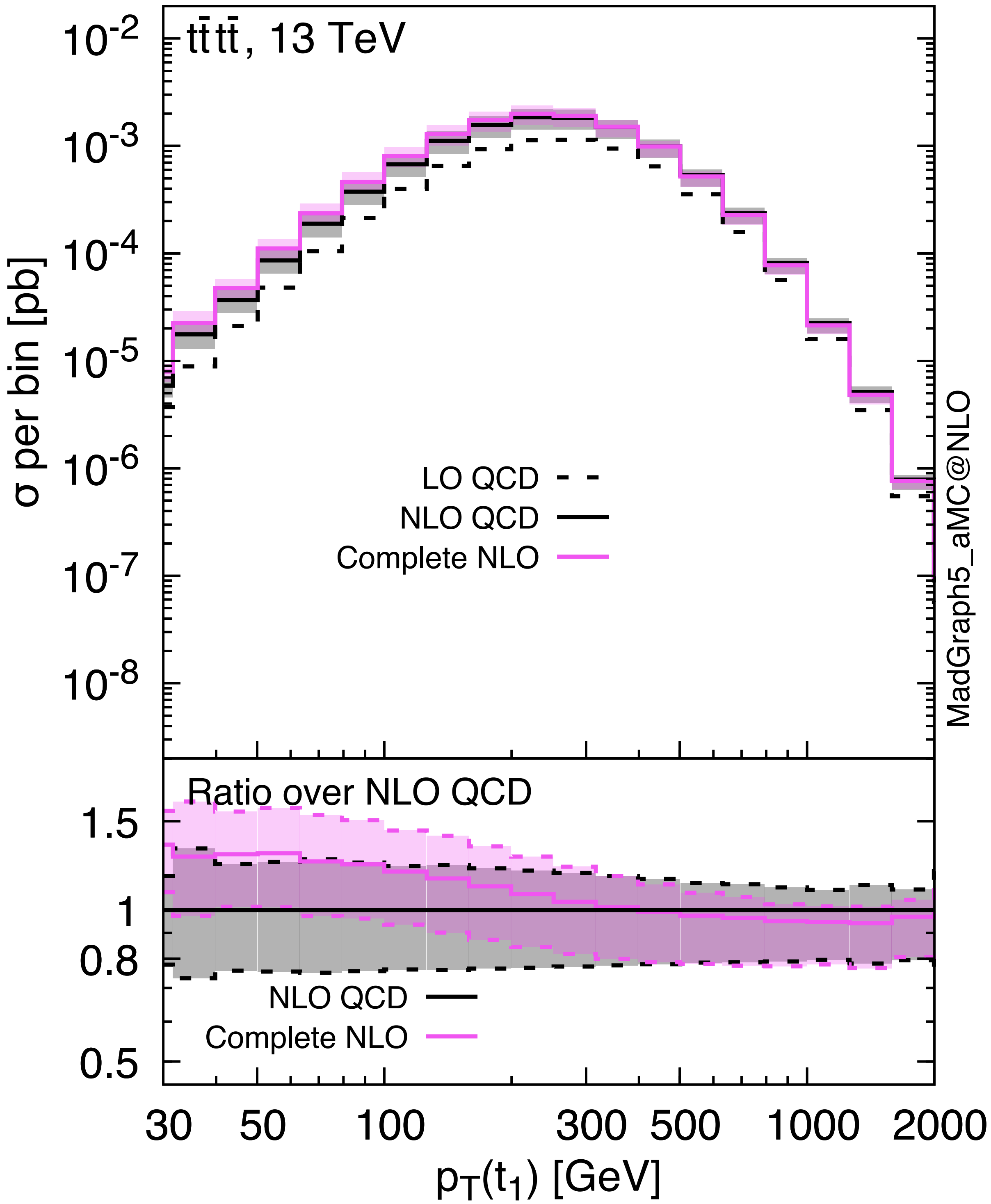
In four-top, complete-NLO ~ NLO QCD, but large cancellations are present within the complete-NLO. LO_2 and LO_3 are large and have also large cancellations. NLO_2 and NLO_3 are mainly given by 'QCD corrections' on top of them; they strongly depend on scale. Relevant for y_t determination.

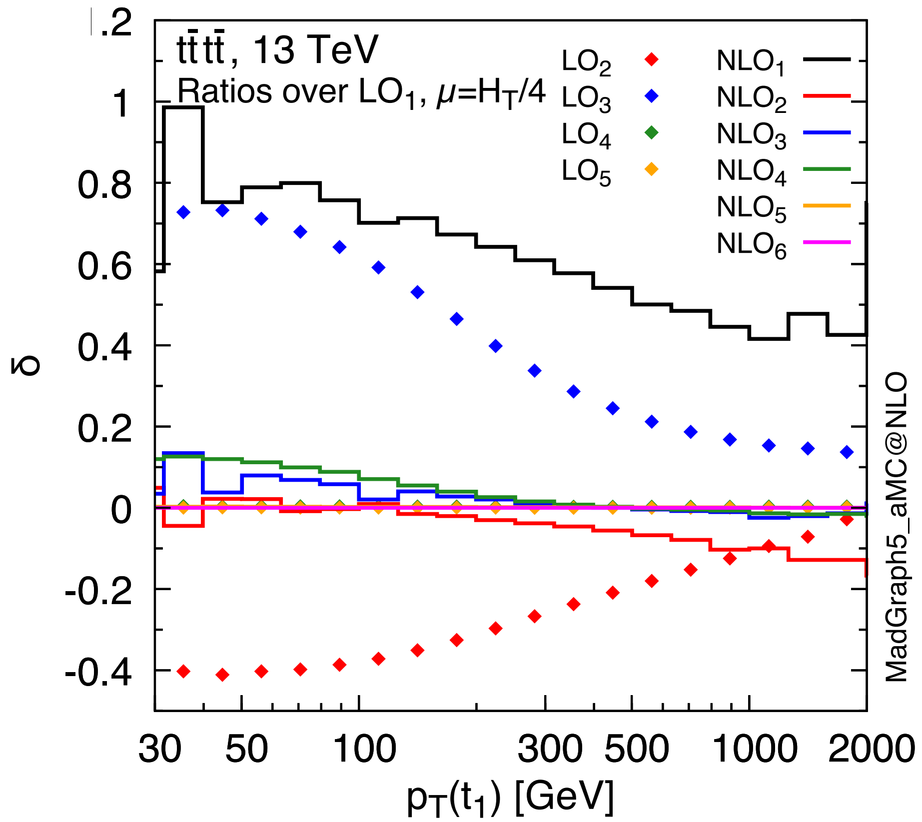
At inclusive level NLO_2+NLO_3 is stable, at differential level cancellations disappear and even NLO_4 is large at the threshold.

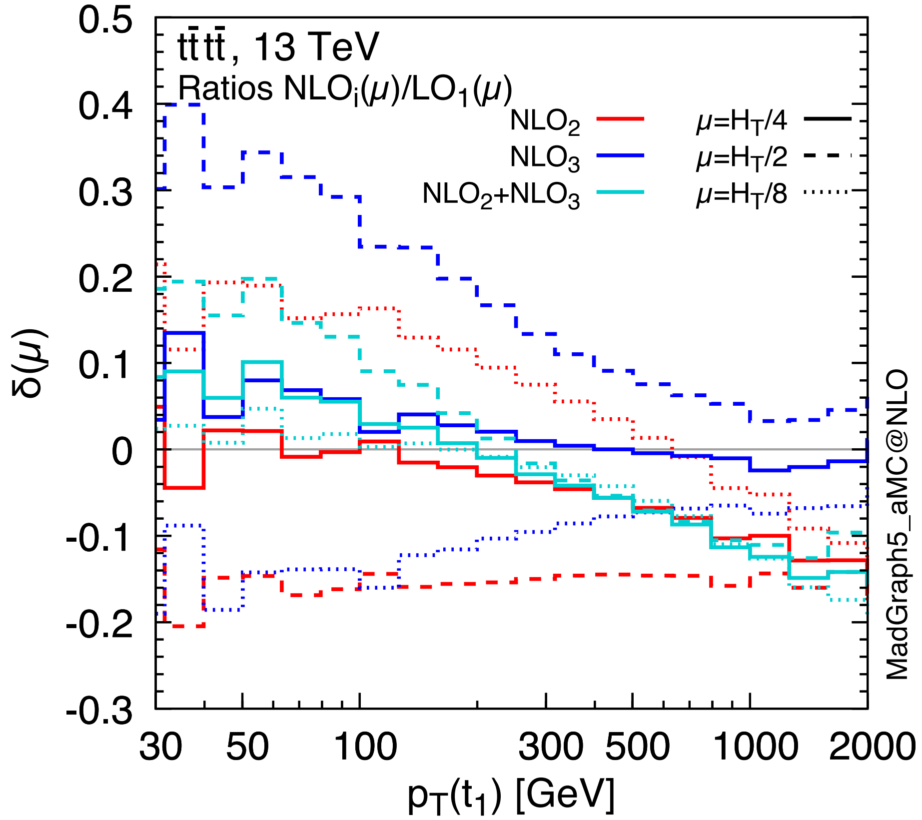
EXTRA SLIDES

Distributions

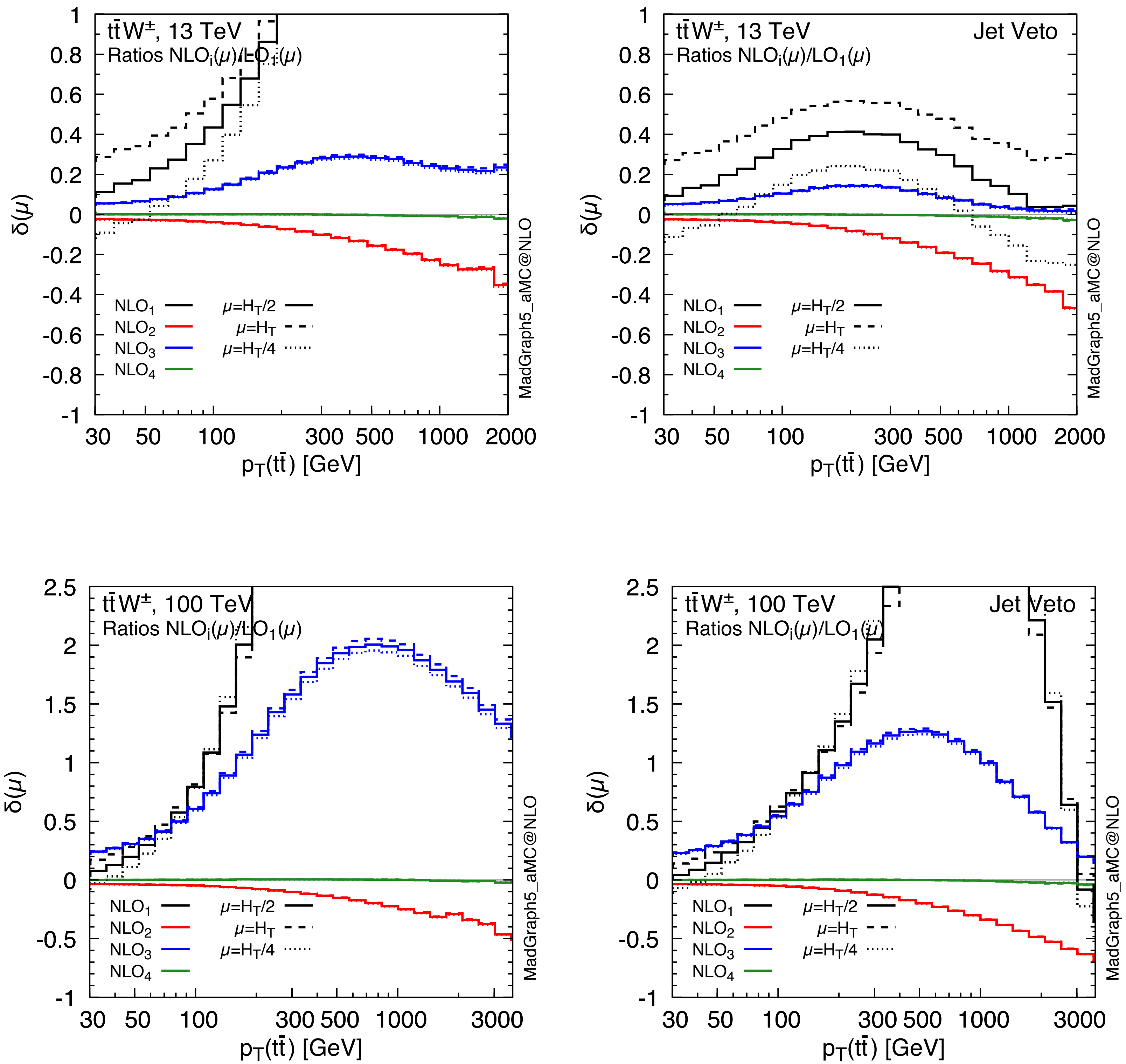
13 TeV







Distributions

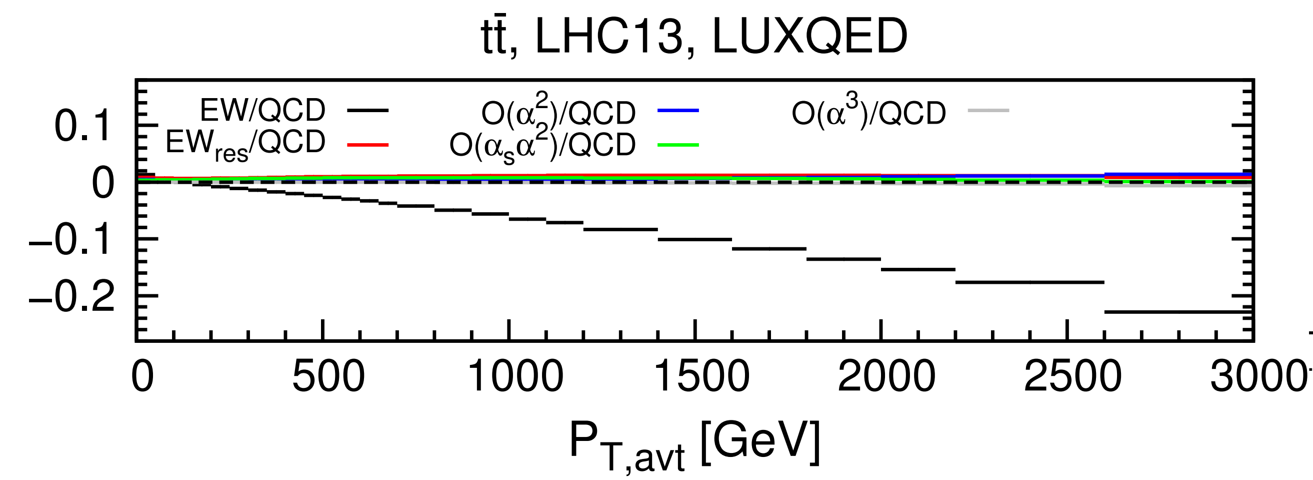


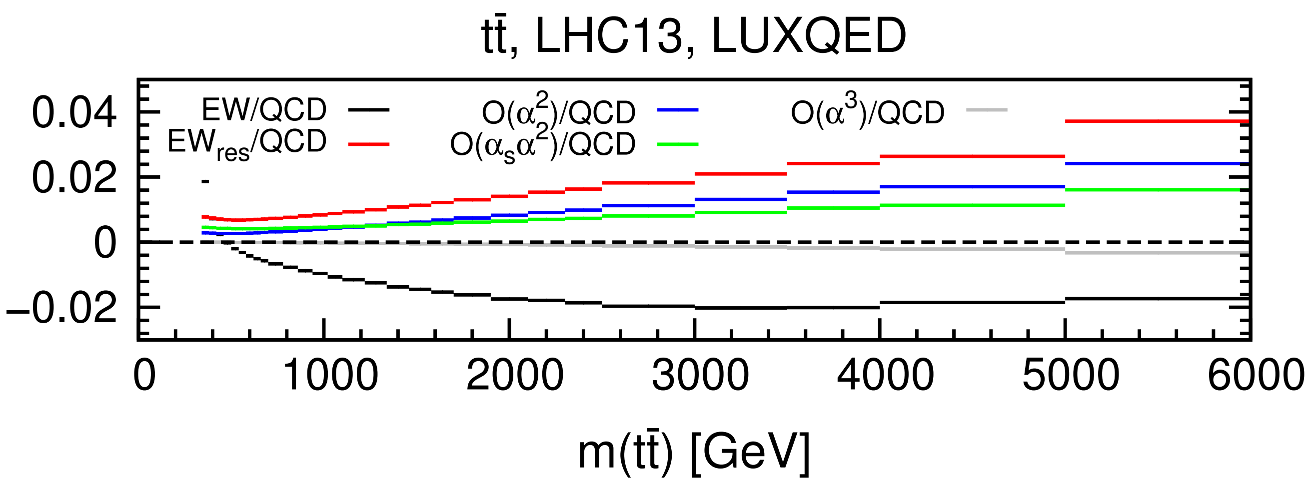
13 TeV

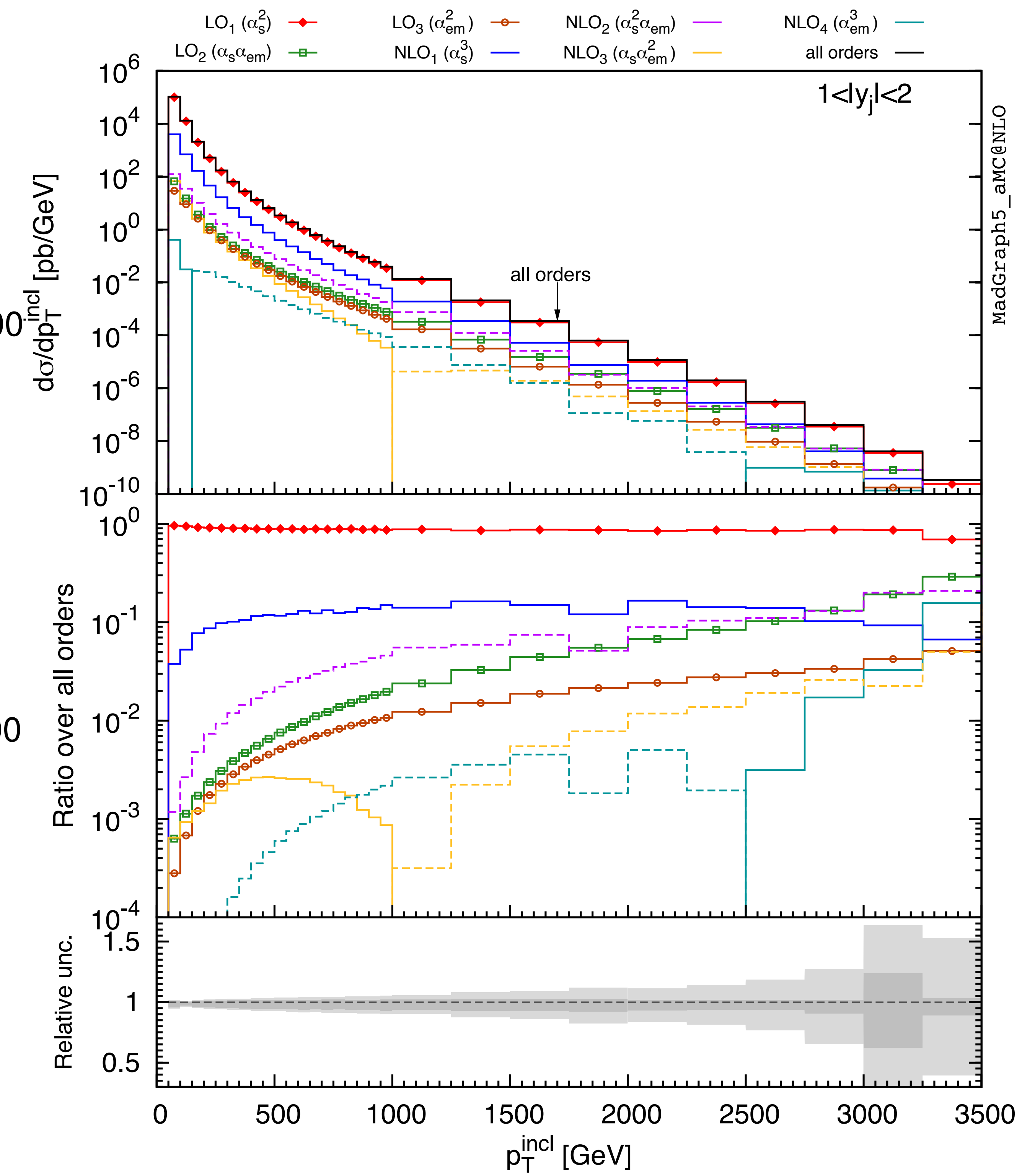
$$\delta_{(\mathrm{N})\mathrm{LO}_i}(\mu) = \frac{\Sigma_{(\mathrm{N})\mathrm{LO}_i}(\mu)}{\Sigma_{\mathrm{LO_{QCD}}}(\mu)}$$

100 TeV

dijet and ttbar production



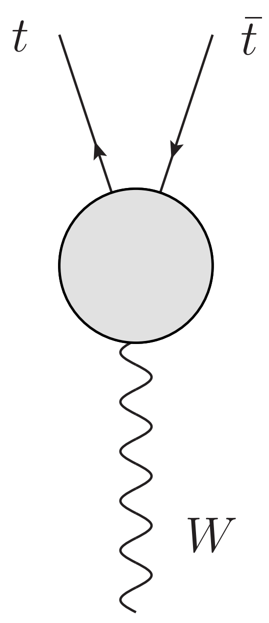




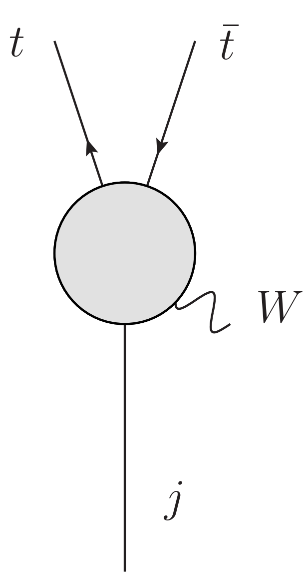
$p_T(t\bar{t})$ distribution in $t\bar{t}V$

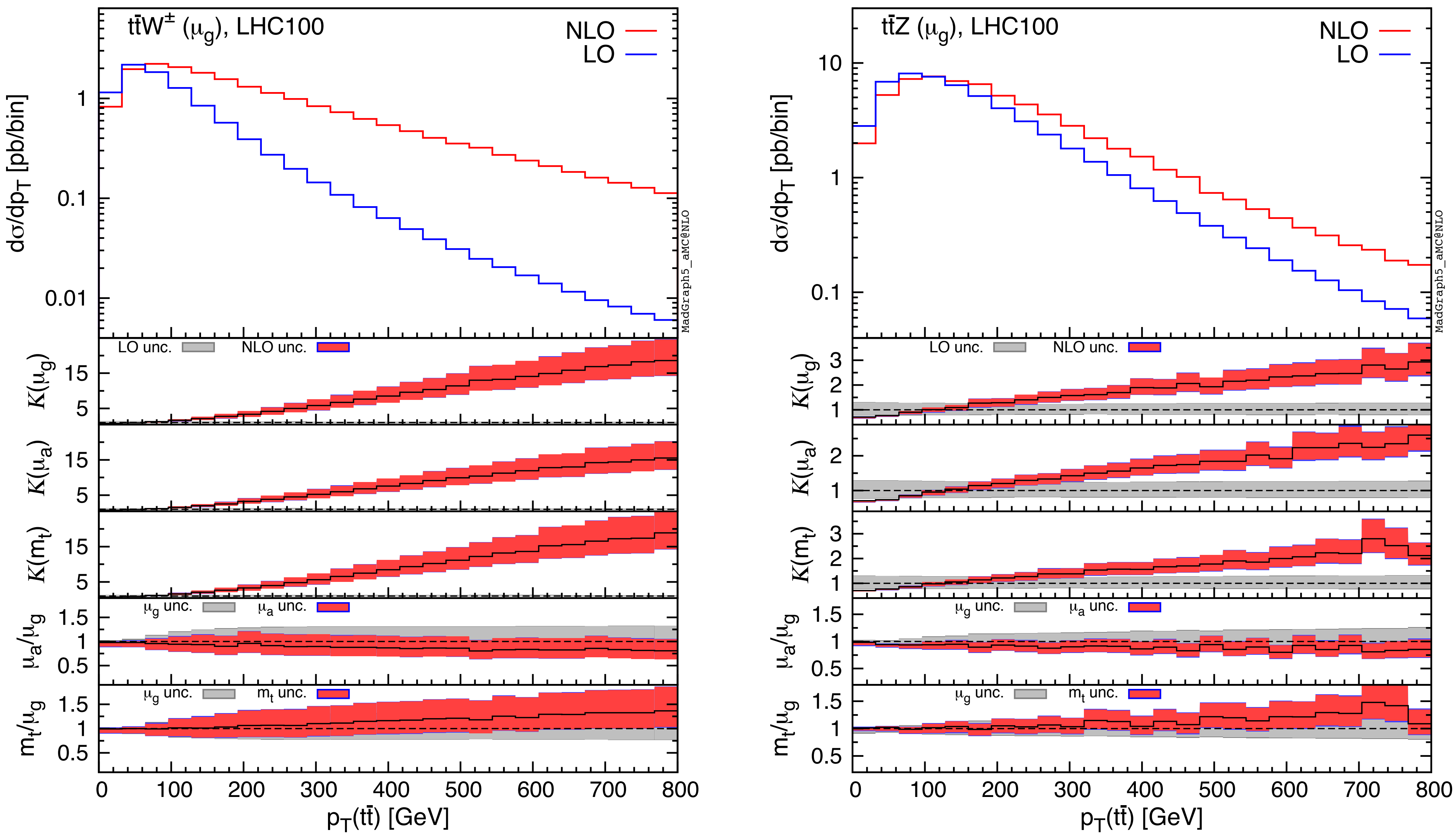
based on Maltoni, DP, Tsinikos, arXiv:1507.05640

LO



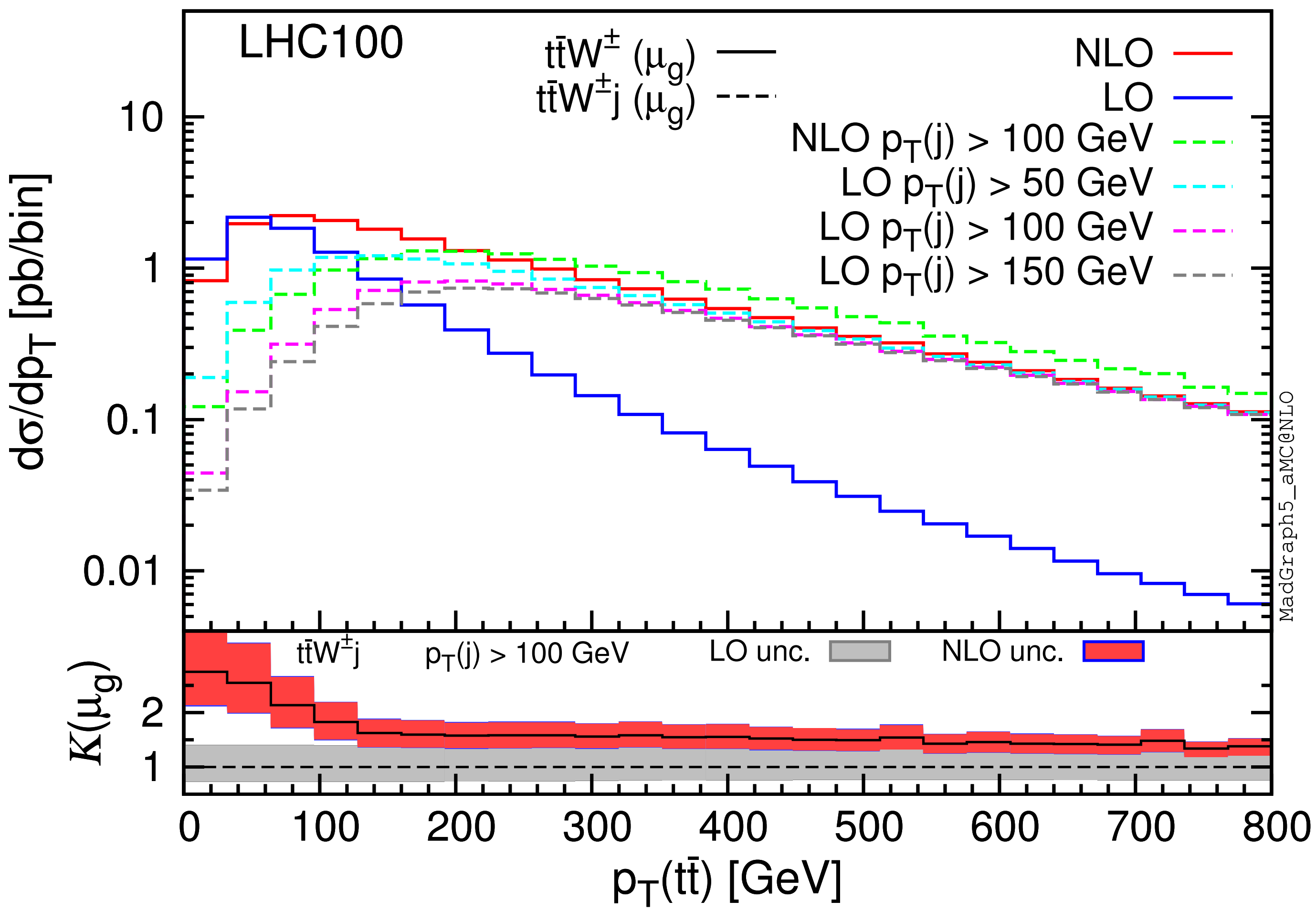
NLO





At LO top-quark pairs recoil always against V. At NLO, at large pt, they mainly recoil against a jet, which can emits the V, leading to a correction of order $\alpha_s \log^2 [p_T(t\bar{t})/m_W]$. The effects is further enhanced in $t\bar{t}W^{\pm}$, where $qg \to t\bar{t}W^{\pm}q'$ has a gluon in the initial state, while the LO has not it. **1500 % corrections at 800 GeV!**

$p_T(t\bar{t})$ distribution in $t\bar{t}V$



If NLO is 1500 % should we worry about NNLO or even h.o. corrections? **NO!**

In this regime we can limit the analysis to $t\bar{t}W^{\pm}j$, which does not exhibits this pathological behavior. The same applies for $t\bar{t}Hj$ and $t\bar{t}Zj$.

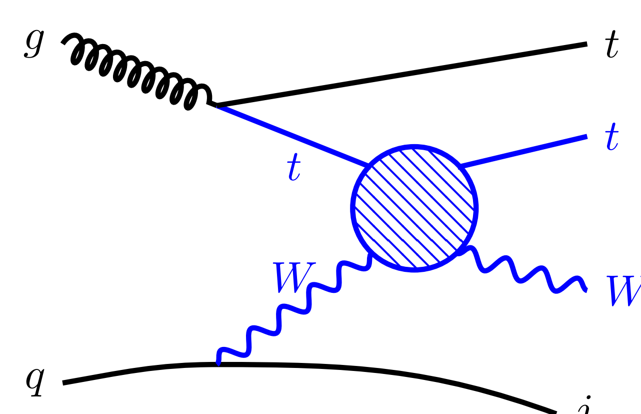
100 TeV σ[pb]	$t\bar{t}Hj$	$t\bar{t}Zj$	$t\bar{t}W^{\pm}j$
NLO	$19.42^{+0.7\%}_{-4.9\%}{}^{+1.0\%}_{-1.2\%}$	$32.38^{+2.4\%}_{-7.4\%}{}^{+0.9\%}_{-1.1\%}$	$17.16^{+14.9\%}_{-13.7\%}{}^{+0.7\%}_{-0.6\%}$
LO	$27.02^{+39.3\%}_{-26.4\%}{}^{+1.1\%}_{-1.6\%}$	$39.81^{+39.8\%}_{-26.7\%}{}^{+1.1\%}_{-1.6\%}$	$15.67^{+37.7\%}_{-25.5\%}{}^{+0.5\%}_{-1.1\%}$
K-factor	0.72	0.81	1.10

Cross sections with $p_T(j) > 100$ GeV

based on Maltoni, DP, Tsinikos, arXiv:1507.05640

BSM

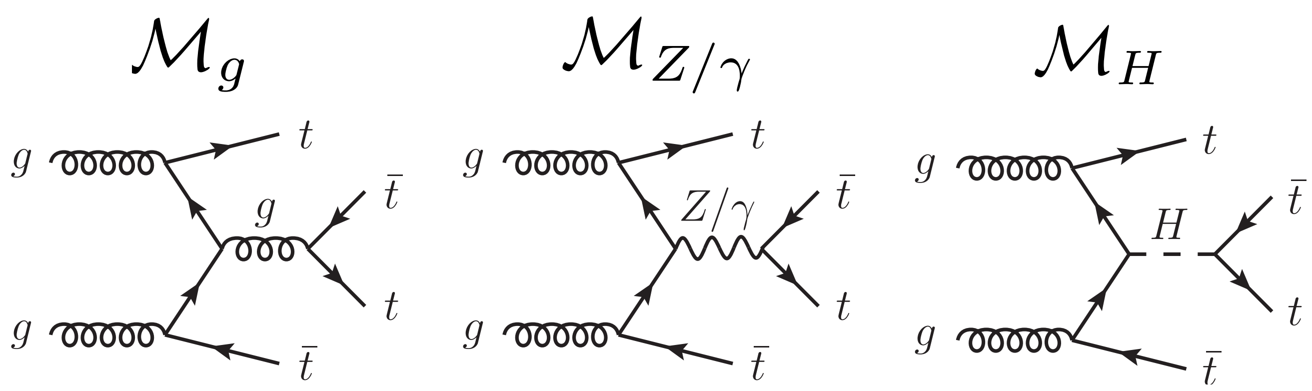
$t\bar{t}W^{\pm}j$ can be used for studying top and W scattering. Limits on $\bar{c}_R$ are expected at the percent/permill level.



$$\frac{i\bar{c}_R}{v^2} H^{\dagger}\overleftrightarrow{D}_{\mu}H\bar{t}_R\gamma^{\mu}t_R$$

Dror, Farina, Salvioni, Serra arXiv:1511.03674

y_t and Γ_H determination via $t\bar{t}t\bar{t}$



$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} \propto \left|\mathcal{M}_g + \mathcal{M}_{Z/\gamma}\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{H} \propto \left|\mathcal{M}_H\right|^2,$$
$$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int} \propto \mathcal{M}_{g+Z/\gamma}\mathcal{M}_H^\dagger + \mathcal{M}_{g+Z/\gamma}^\dagger\mathcal{M}_H$$

The cross section depends on y_t to the fourth power.
It does not depend on Γ_H, since the Higgs is off-shell.

$$\sigma(t\bar{t}t\bar{t}) = \sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma} + \boxed{\kappa_t^2}\sigma^{\rm SM}_{\rm int} + \boxed{\kappa_t^4}\sigma^{\rm SM}(t\bar{t}t\bar{t})_H \qquad \kappa_t \equiv y_{Htt}/y_{Htt}^{\rm SM}$$

In combination with the measurement of $t\bar{t}H$

based on Cao, Chen, Liu
arXiv:1602.01934

$$\sigma(pp \to t\bar{t}H \to t\bar{t}xx) \Rightarrow \mu^{xx}_{t\bar{t}H} \equiv \frac{\sigma}{\sigma^{\rm SM}} = \frac{\kappa_t^2\kappa_x^2}{R_\Gamma} \qquad R_\Gamma \equiv \frac{\Gamma_H}{\Gamma_H^{\rm SM}}$$

both y_t and Γ_H can be determined.

100 TeV

$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{g+Z/\gamma}$:	3276 fb
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_H$:	271.3 fb
$\sigma^{\rm SM}(t\bar{t}t\bar{t})_{\rm int}$:	−356.9 fb

$\Rightarrow$

$$0.962 \le \kappa_t \le 1.031$$
$$0.91\,\Gamma_{\rm H}^{\rm SM} \le \Gamma_{\rm H} \le 1.08\,\Gamma_{\rm H}^{\rm SM}$$
$$\text{for } \mathcal{L} = 30\ {\rm ab}^{-1}$$