Electroweak and QCD corrections to Higgs hadroproduction in association with a top-quark pair

based on arXiv:1407.0823, arXiv:1504.03446

in collaboration with S. Frixione, V. Hirschi, H. -S. Shao, and M. Zaro,

Davide Pagani

LHC Higgs XS ttH (Theory Update)

9-06-2015

OUTLINE

Status of the automation of QCD and EW corrections in aMC@NLO_Madgraph5.

EW and QCD corrections to $t\bar{t}H$ production.

EW and QCD corrections to $t\bar{t}W^{\pm}$ and $t\bar{t}Z$ production, which are irreducible backgrounds for $t\bar{t}H$ leptonic signatures.

CONCLUSION AND OUTLOOK

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
```

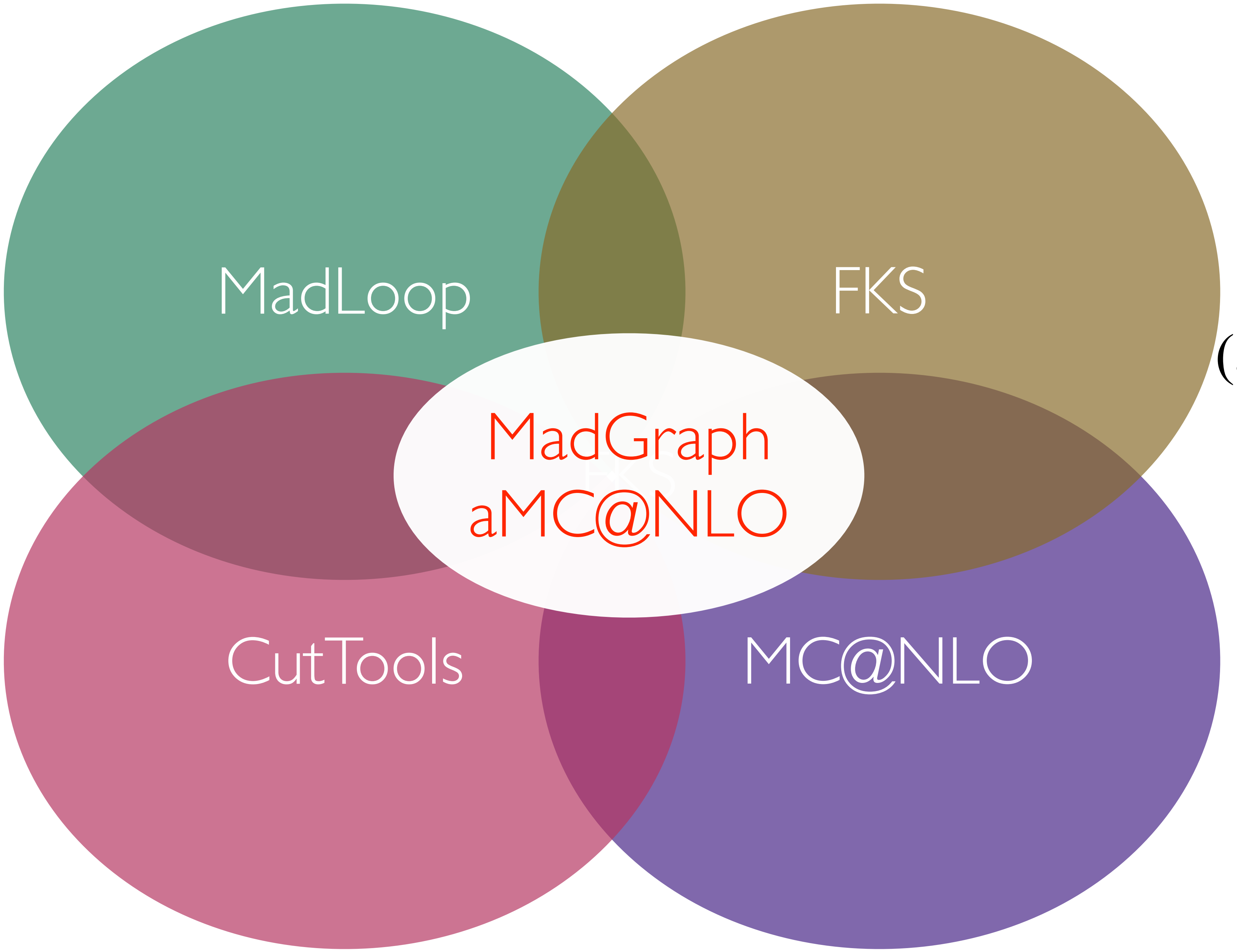
The automation of NLO QCD is a solved problem, but we need higher precision to match the experimental accuracy at the LHC and future colliders.

- 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.**

Automation of NLO corrections in Madgraph5_aMC@NLO

The **complete automation** for **QCD+EW** is in progress.

DONE!



in progress
(almost DONE)

DONE!

in progress

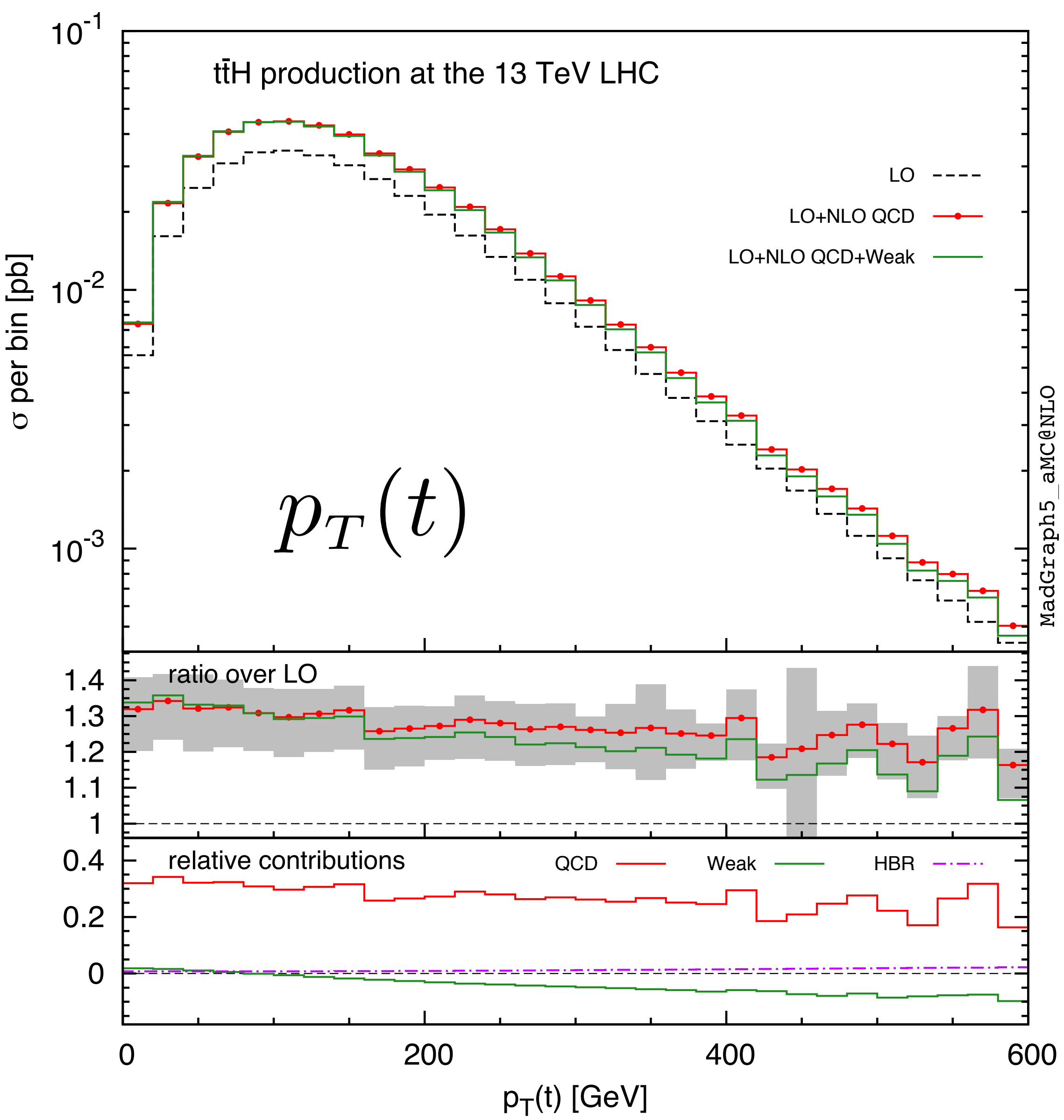
The first pheno study: $t\bar{t}H$

NLO purely Weak and QCD corrections to $t\bar{t}H$ production have been produced "assembling by hand" the FKS counterterms. NO QED effects.

Frixione, Hirschi, DP, Shao, Zaro
arXiv:1407.0823

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 will present results for NLO QCD and EW corrections to

$t\bar{t}V \qquad V = \boxed{H}, W, Z$

Frixione, Hirschi, DP, Shao, Zaro
arXiv:1504.03446

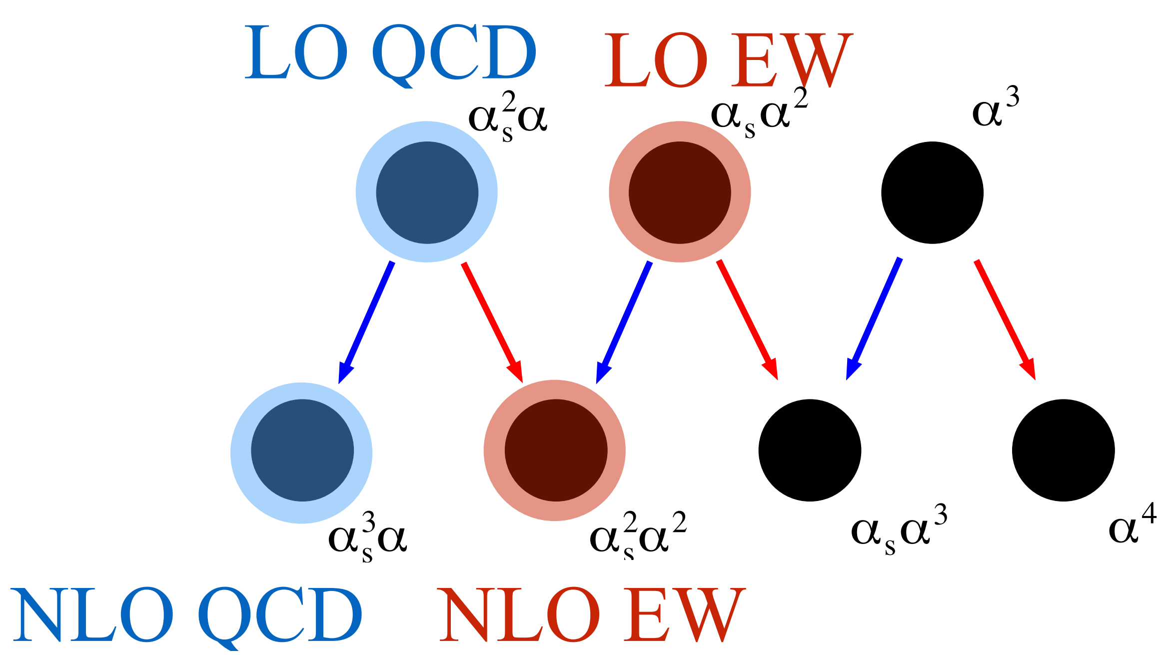
$t\bar{t}V$ production: numerical results

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.

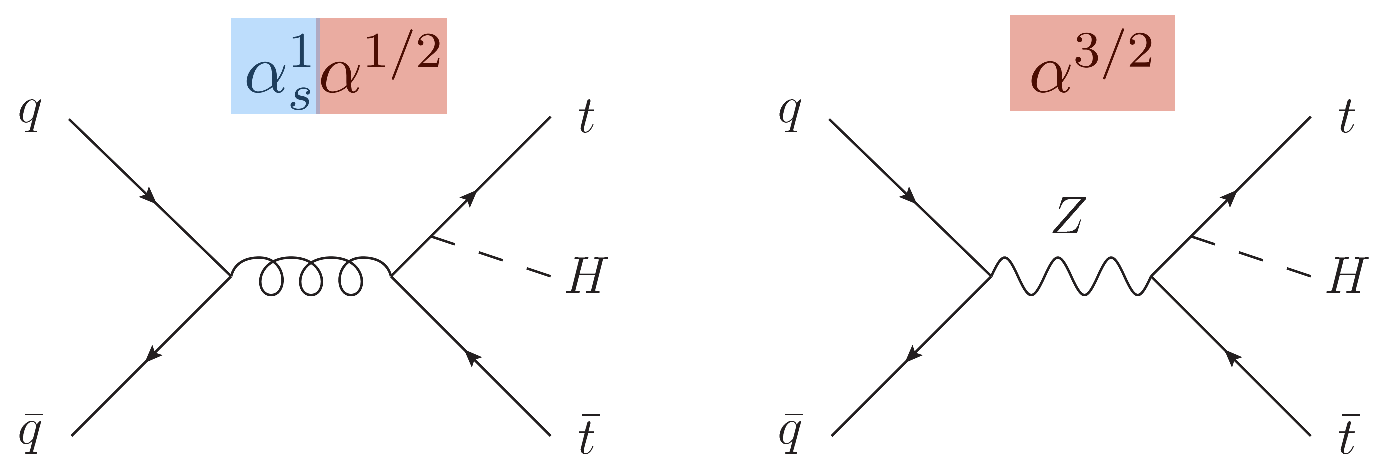


Heavy Boson Radiation (HBR)

$pp \to t\bar{t}H + V$

$V = H, W, Z$

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



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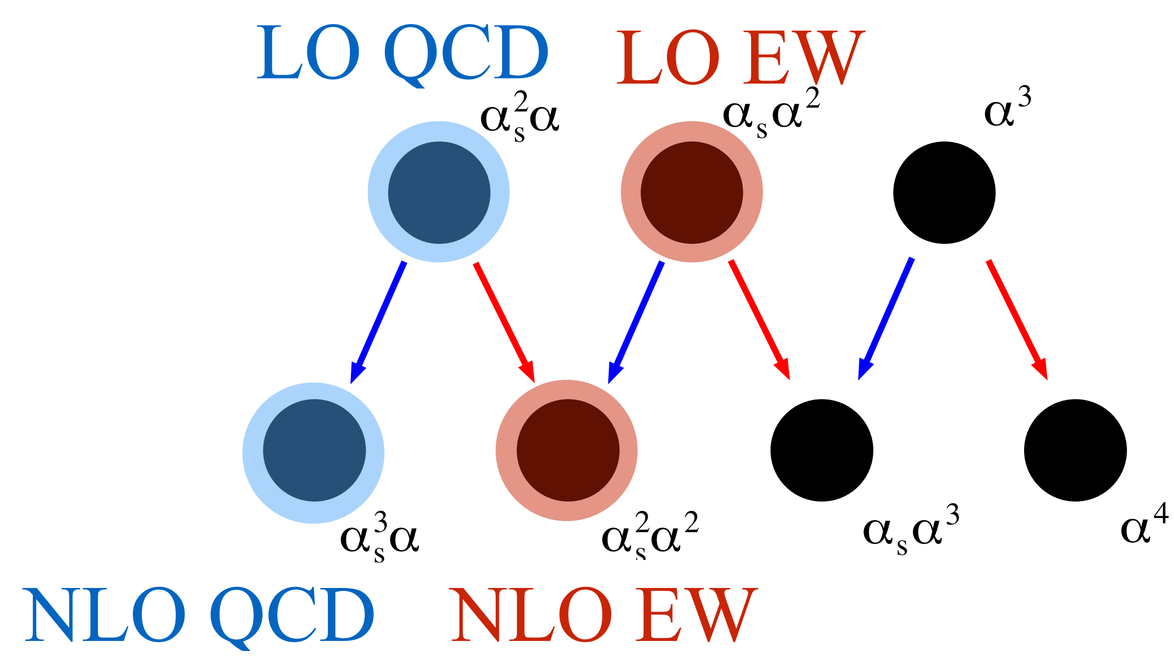


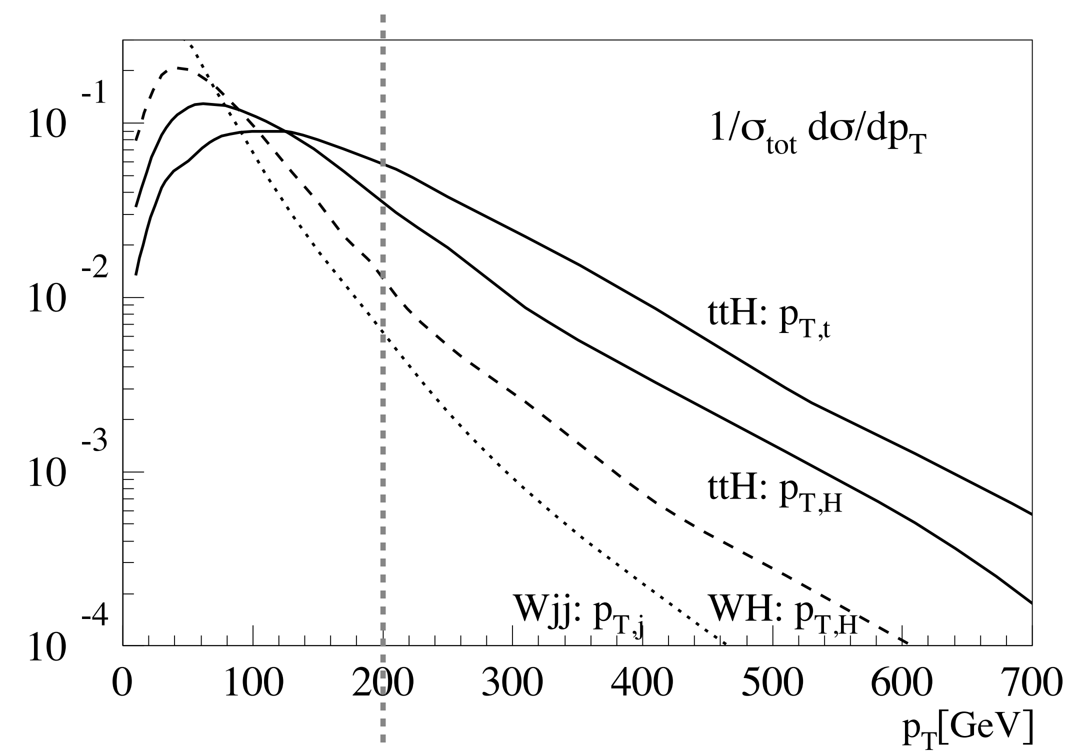
Boosted regime

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

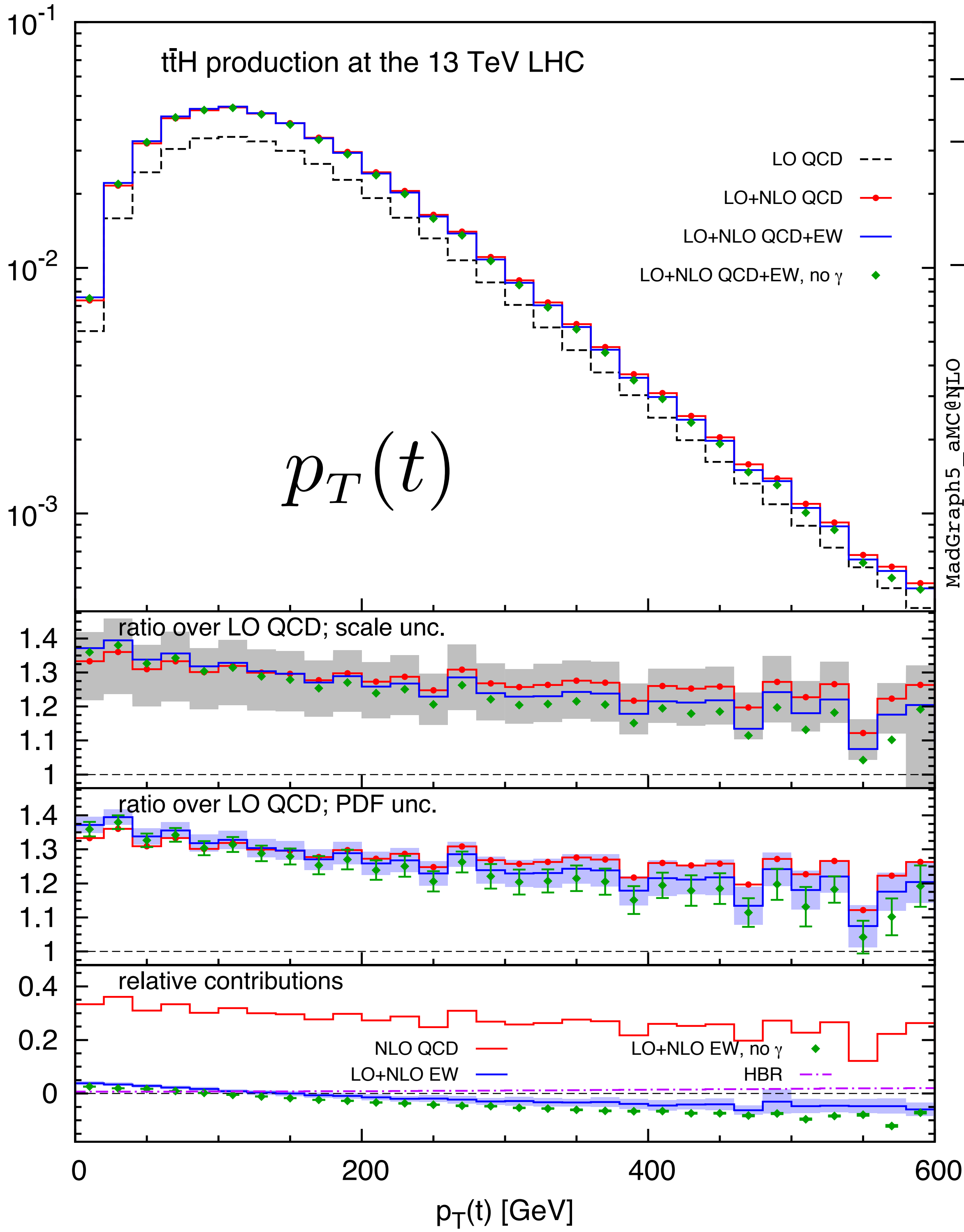
S/B increases for boosted tops and Higgs.

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

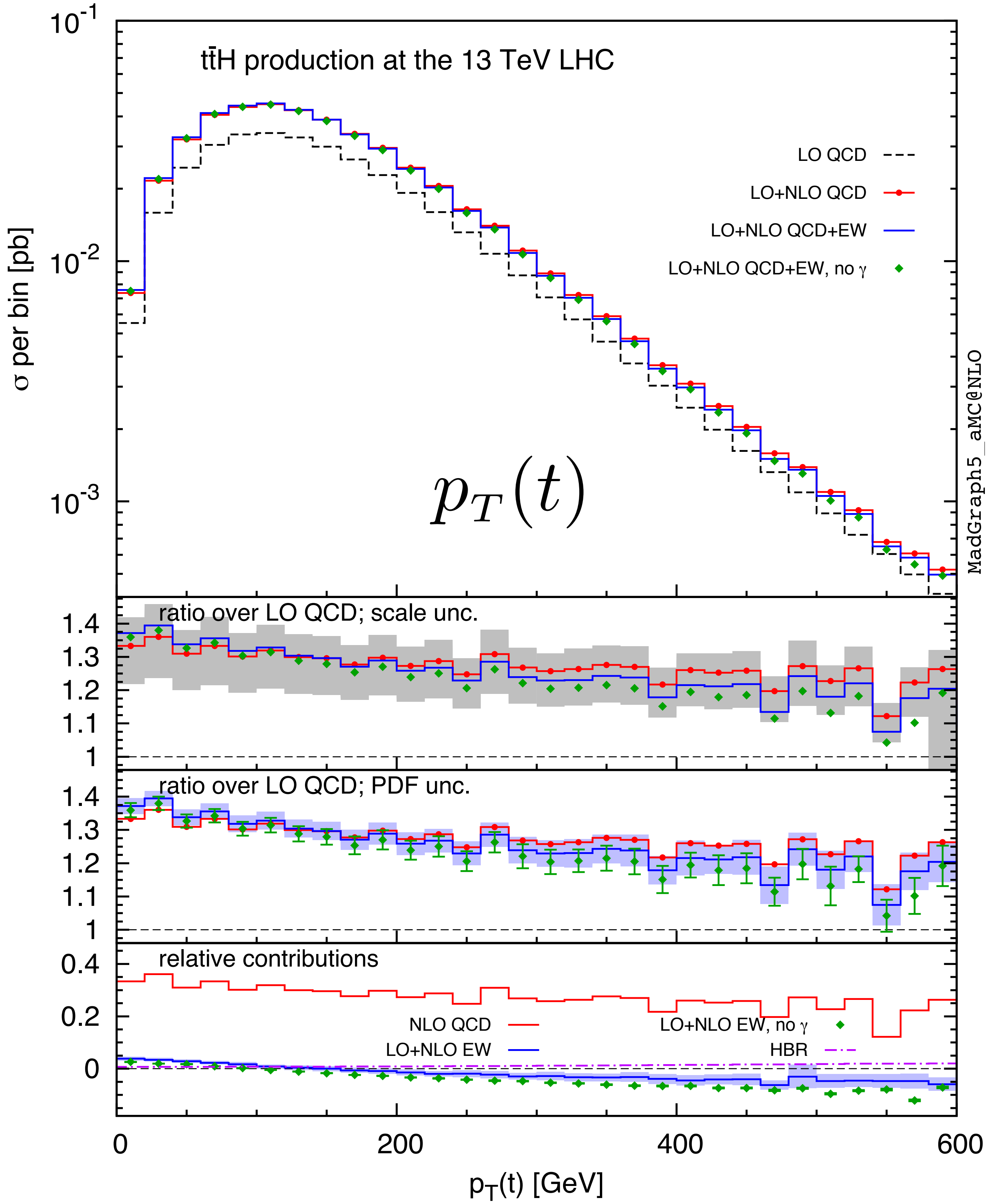
(Boosted regime in brackets)

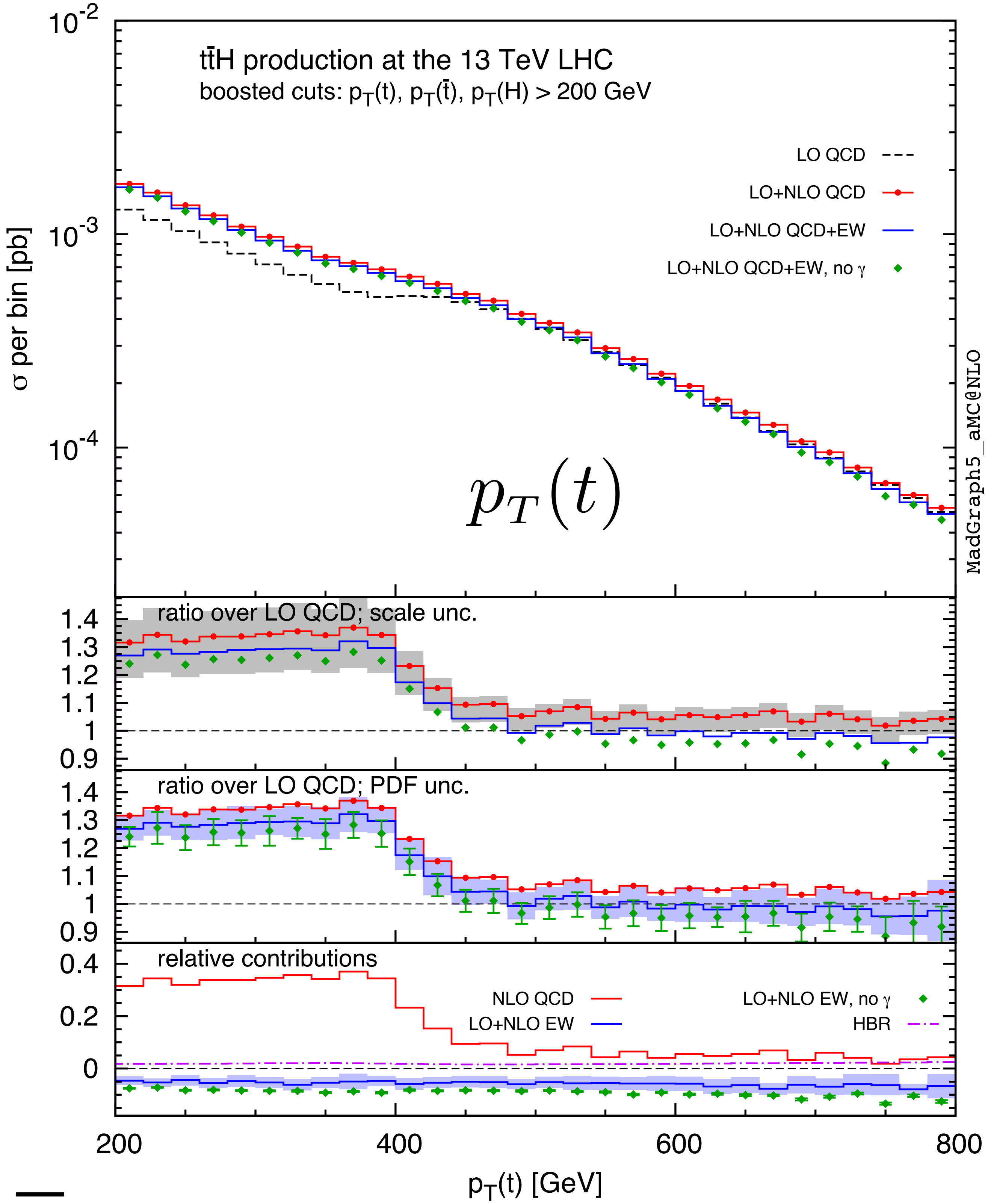
Scale variation

(NLO QCD+EW) PDF var.

$t\bar{t}H$

Transverse momentum distributions: unboosted vs. boosted



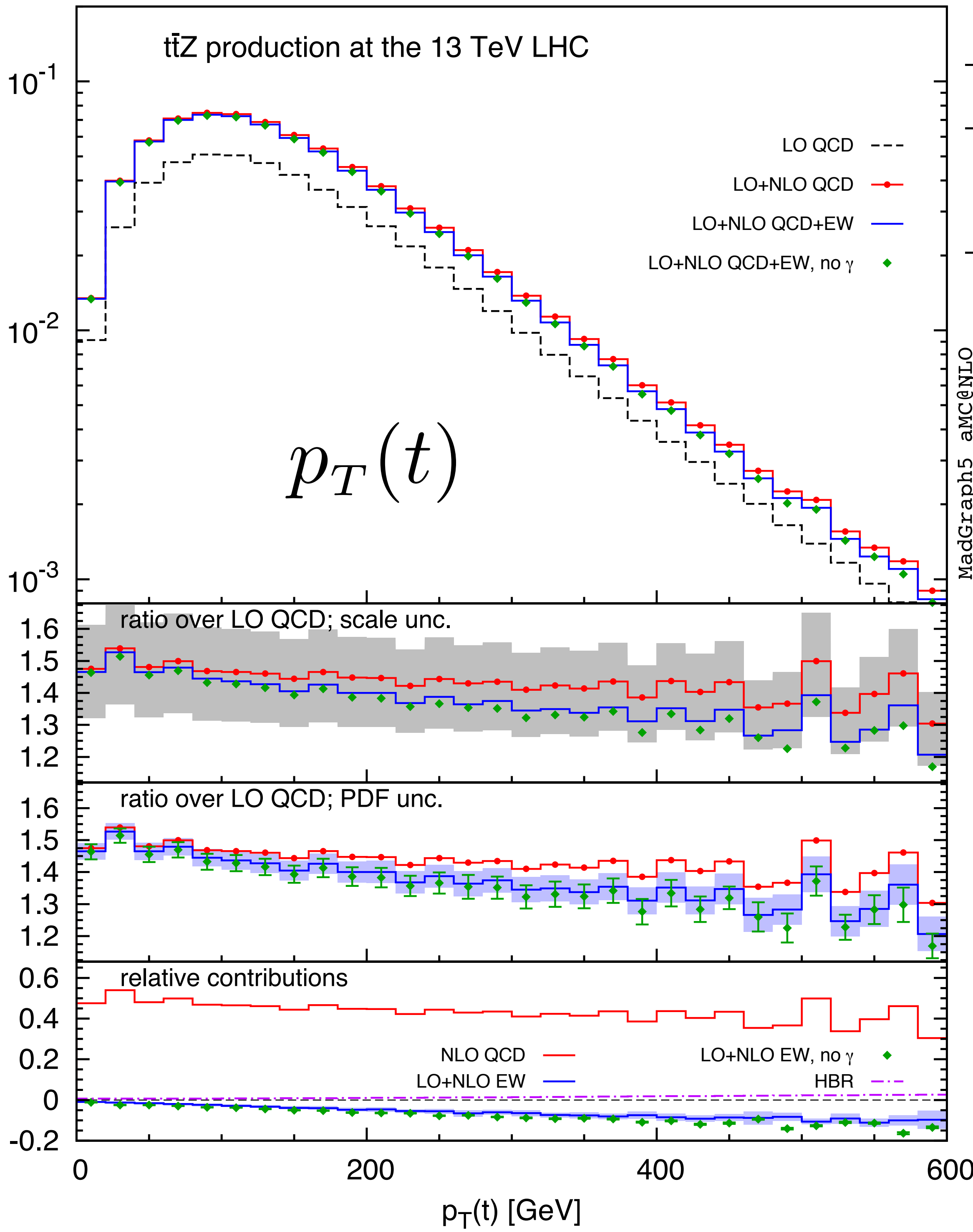


13 TeV

$t\bar{t}H$

13 TeV

Numerical results



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

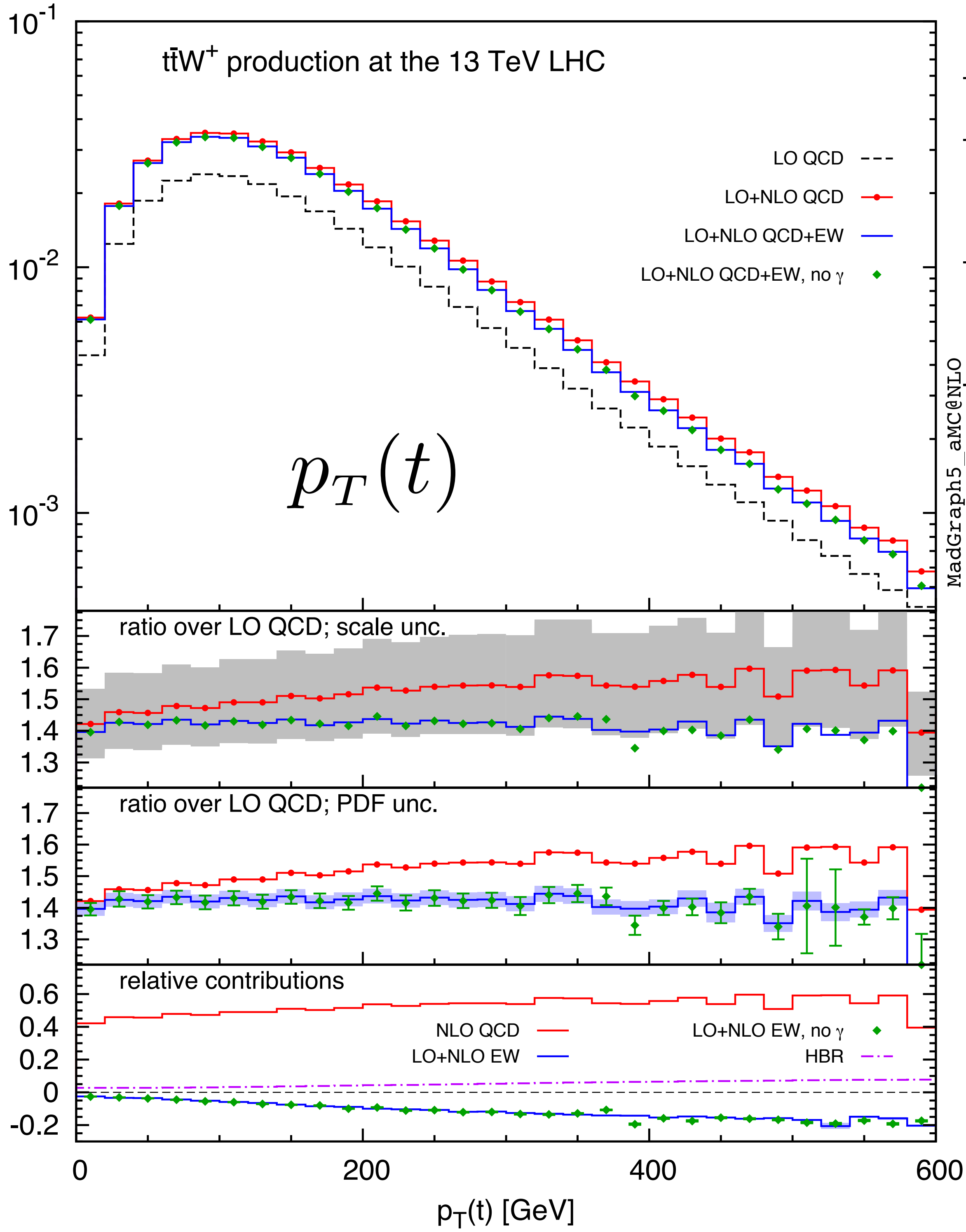
(Boosted regime in brackets)

Scale variation

(NLO QCD+EW) PDF var.

$t\bar{t}Z$

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.

$t\bar{t}W^+$

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

	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}W^+$	$t\bar{t}W^-$
$\sigma_{\text{LO QCD}}(\text{pb})$	$3.617 \cdot 10^{-1}$	$5.282 \cdot 10^{-1}$	$2.496 \cdot 10^{-1}$	$1.265 \cdot 10^{-1}$
$\sigma^{G_\mu}_{\text{LO QCD}}(\text{pb})$	$3.527 \cdot 10^{-1}$	$5.152 \cdot 10^{-1}$	$2.433 \cdot 10^{-1}$	$1.234 \cdot 10^{-1}$
$\Delta^{G_\mu}_{\text{LO QCD}}(\%)$	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.

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

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

CONCLUSION

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

NLO EW corrections to $t\bar{t}V$ are not negligible, especially in the tails of pt distributions and in the total cross sections with boosted cuts.

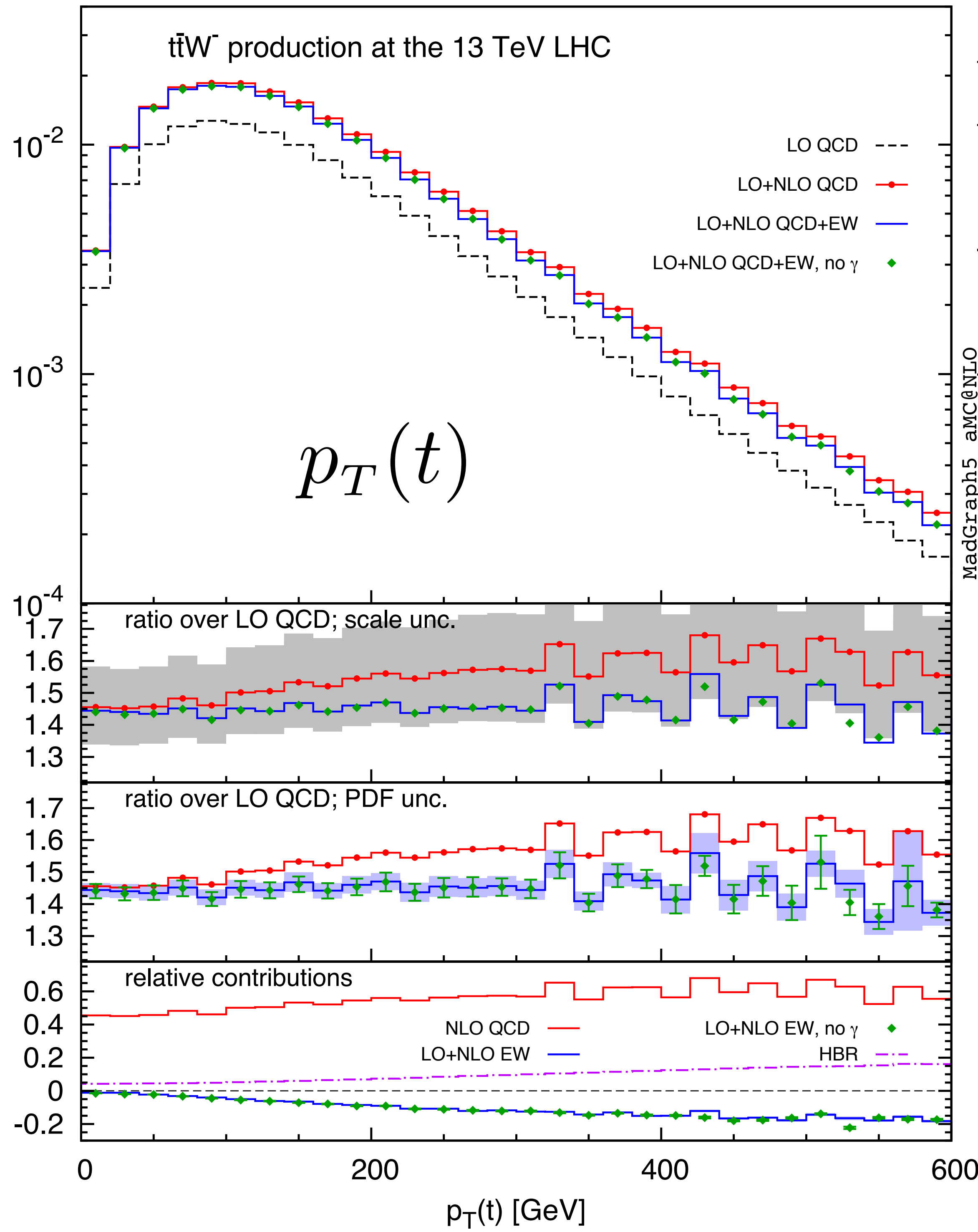
In the case of inclusive $t\bar{t}H$ production EW corrections are within QCD scale uncertainties. The PDF uncertainties associated to the EW corrections are mainly induced by the photon PDF.

OUTLOOK

- Complete the automation of EW+QCD corrections for all processes
- Match NLO EW corrections to shower effects

EXTRA SLIDES

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

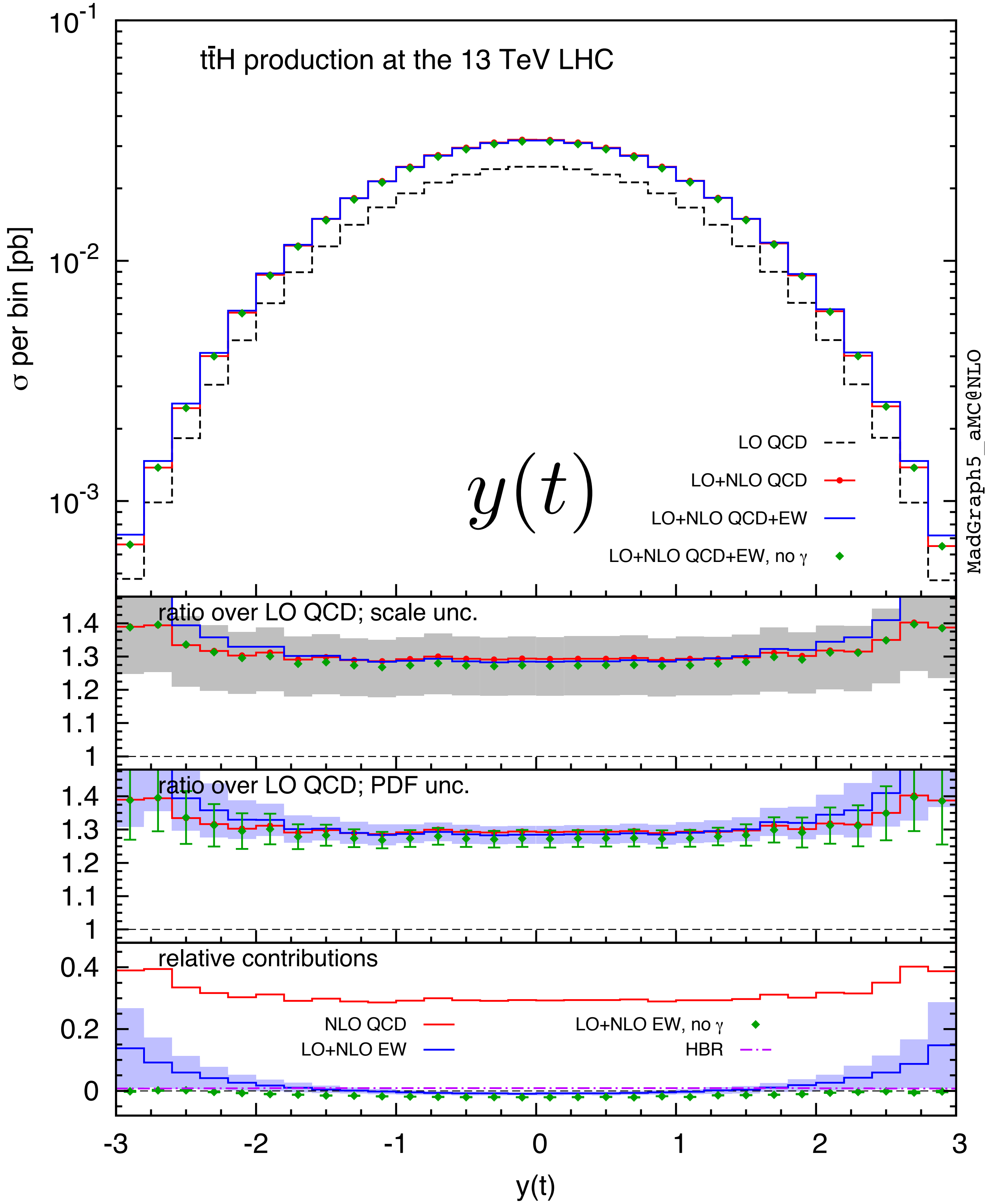
(Boosted regime in brackets)

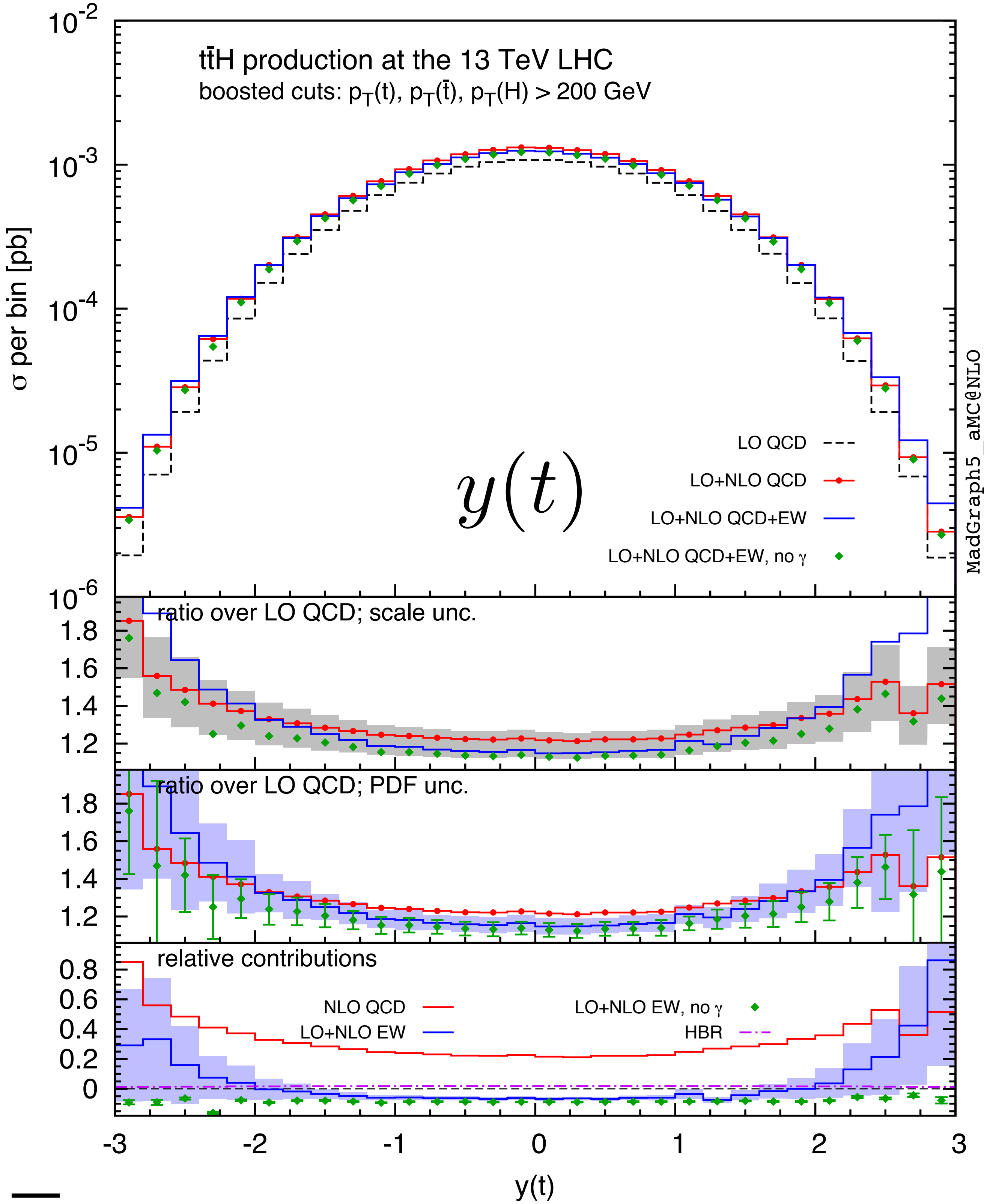
Scale variation

(NLO QCD+EW) PDF var.

$$t\bar{t}W^-$$

Rapidity distributions: unboosted vs. boosted

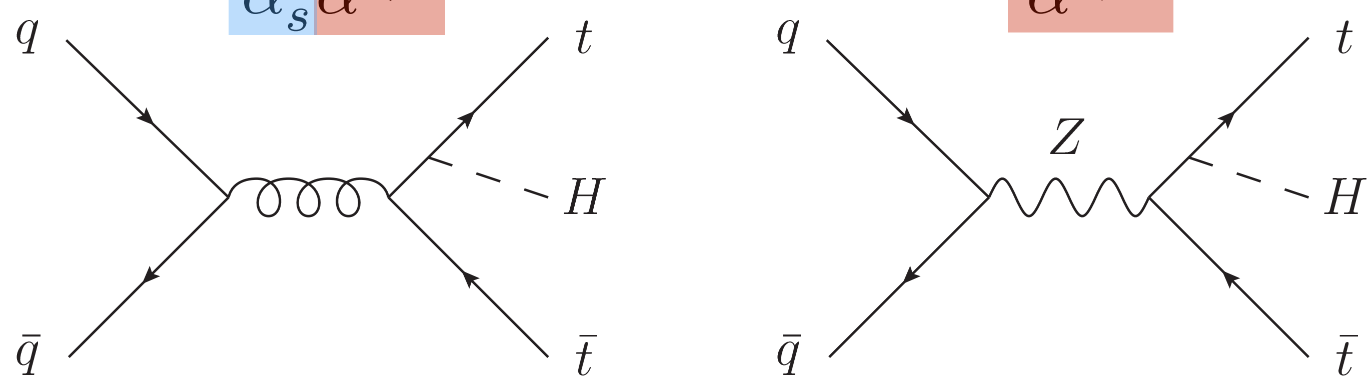




13 TeV $t\bar{t}H$ 13 TeV

Structure of NLO EW-QCD corrections

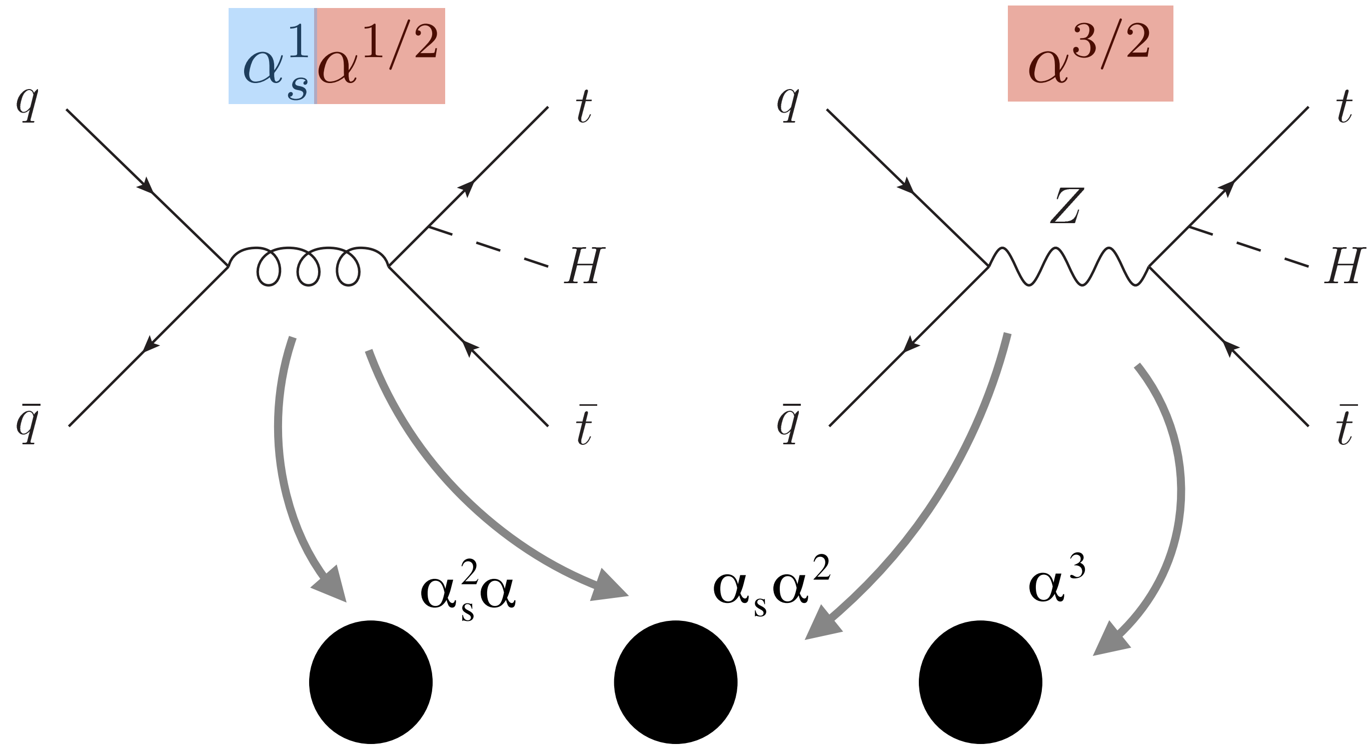
$\alpha_s^1 \alpha^{1/2}$ $\alpha^{3/2}$



$\alpha_s^2\alpha$ $\alpha_s\alpha^2$ α^3

LO

Structure of NLO EW-QCD corrections



LO

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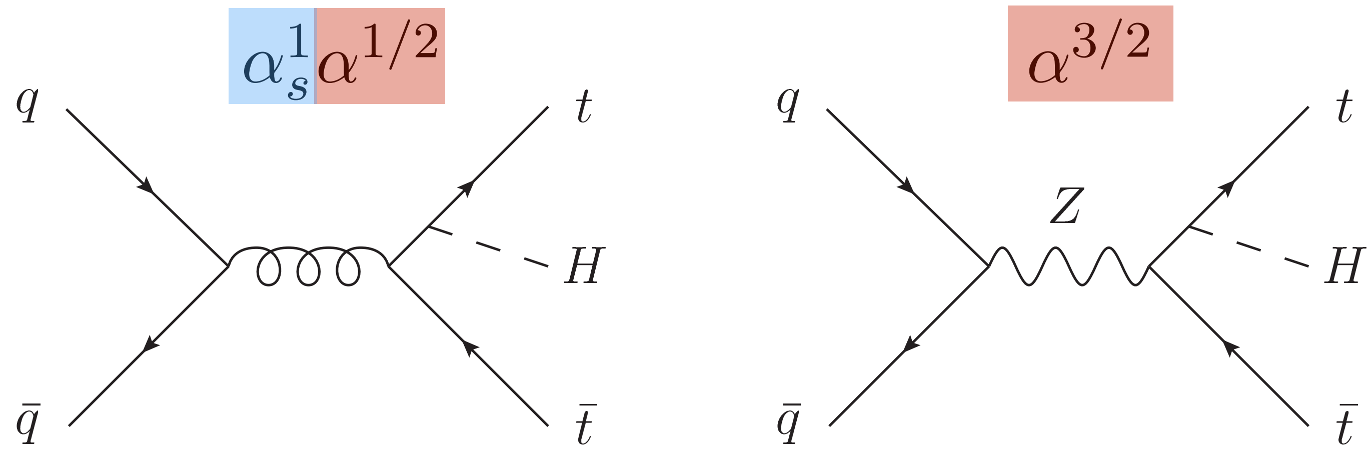
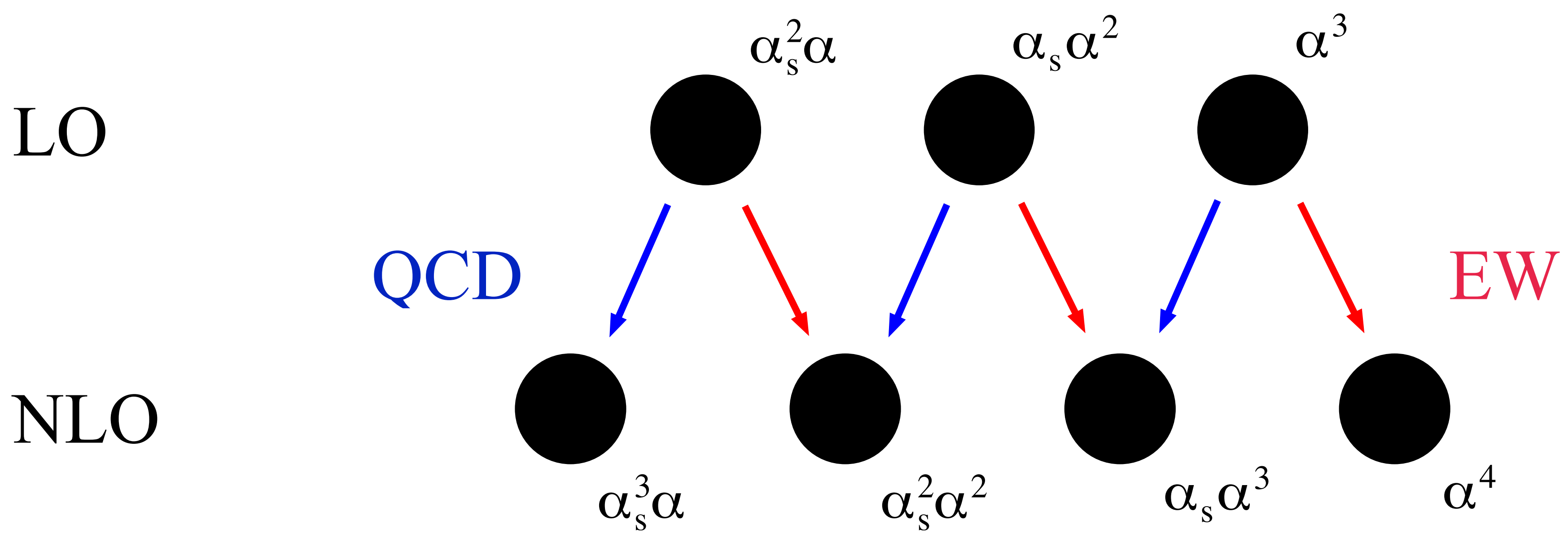
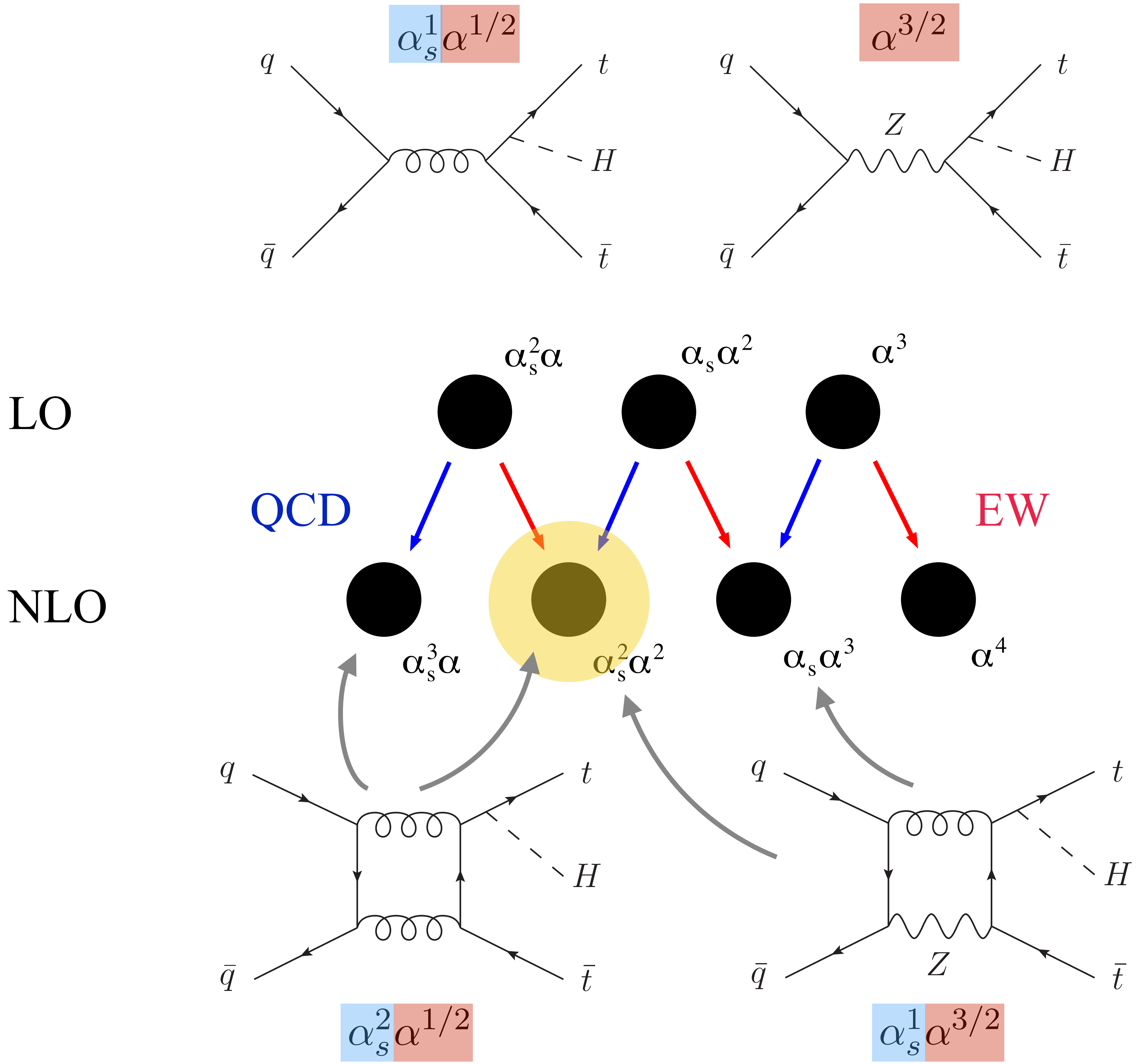




Structure of NLO EW-QCD corrections



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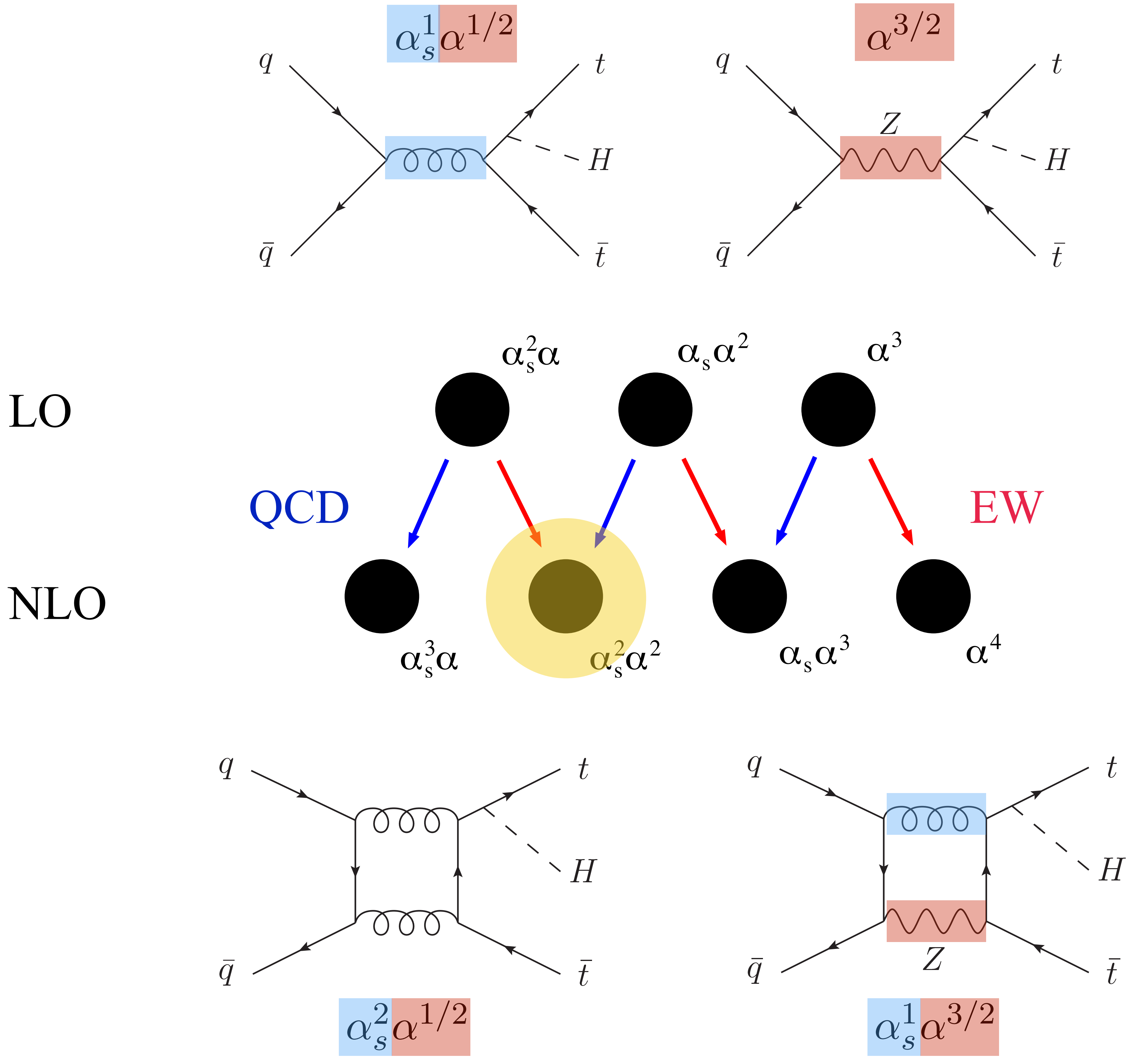

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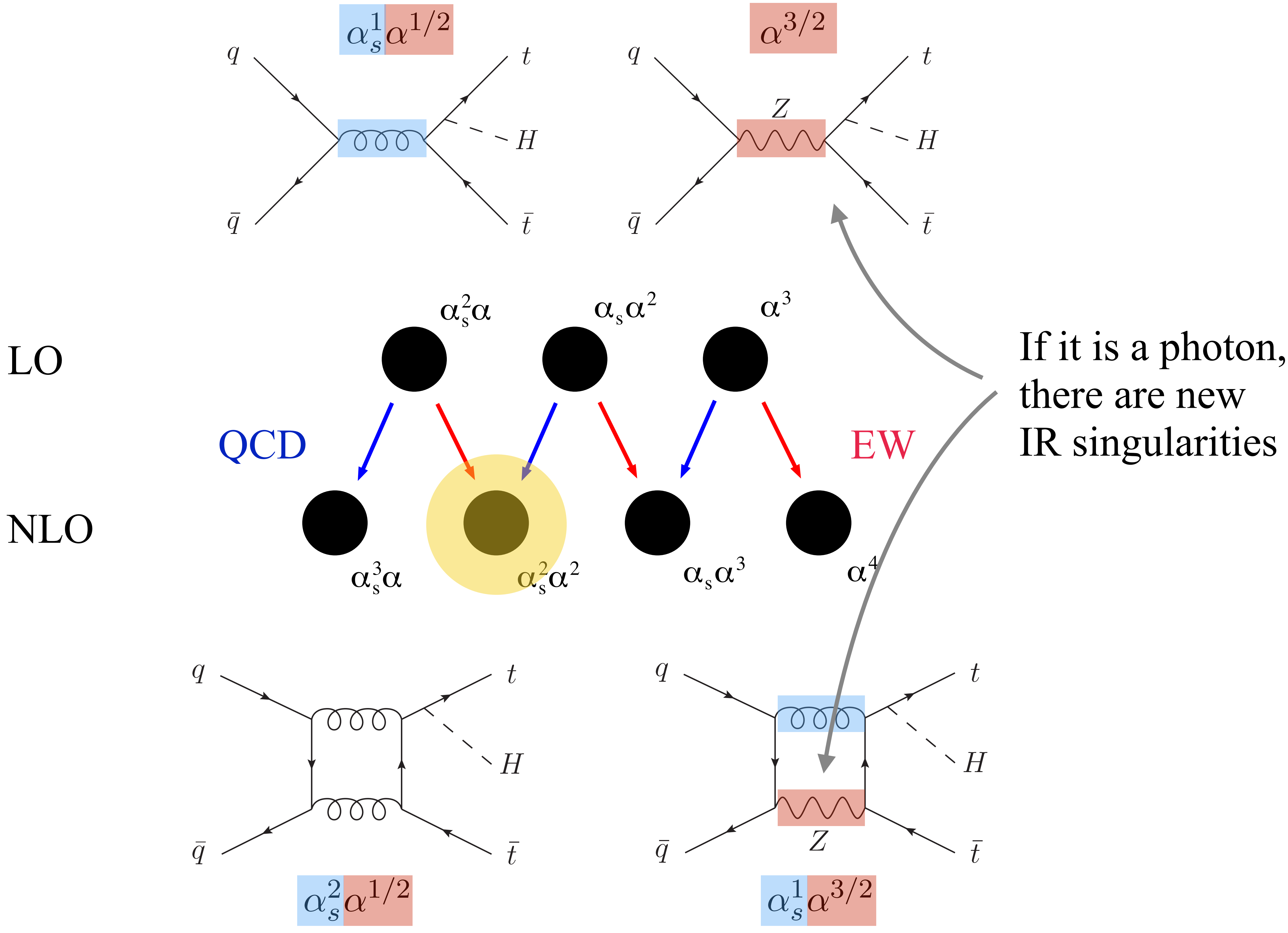


Numerical results weak corrections

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	$-0.67\ (-2.9)$	$-1.12\ (-4.0)$	$-2.64\ (-6.8)$
$u\bar{u}$	$-0.01\ (-3.2)$	$-0.15\ (-2.3)$	$-0.10\ (-0.5)$
$d\bar{d}$	$-0.55\ (-2.2)$	$-0.52\ (-1.9)$	$-0.23\ (-0.5)$

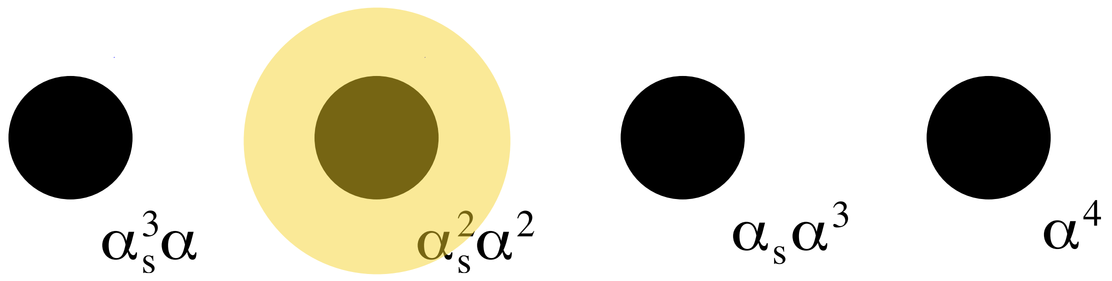
Amplitudes and matrix elements

NLO UFO models: - SM-alpha(mZ) (EW+QCD, Weak+QCD)
(UV CT, R2) - SM-Gμ (EW+QCD, Weak+QCD)

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

The matrix element calculation is completely automated.

NLO



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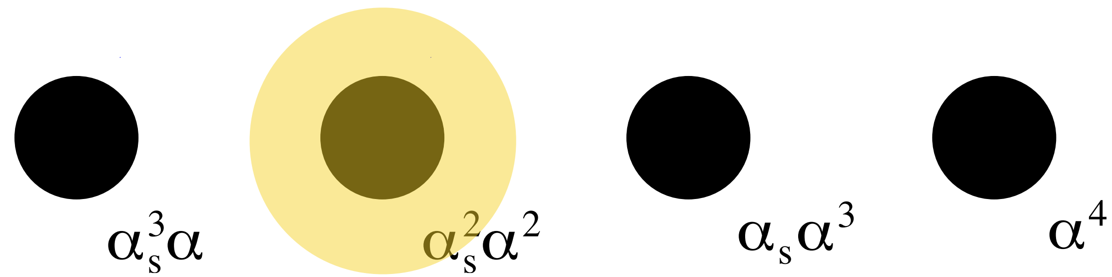


Subprocesses

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)

$$pp \to t\bar{t}H + V$$

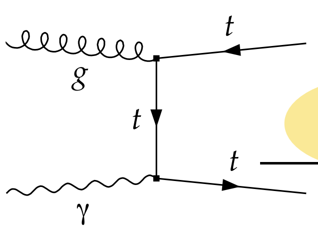
$$V = H, W, Z$$

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

Why do we care about photons in the proton?

2 representative examples:

$t\bar{t}$

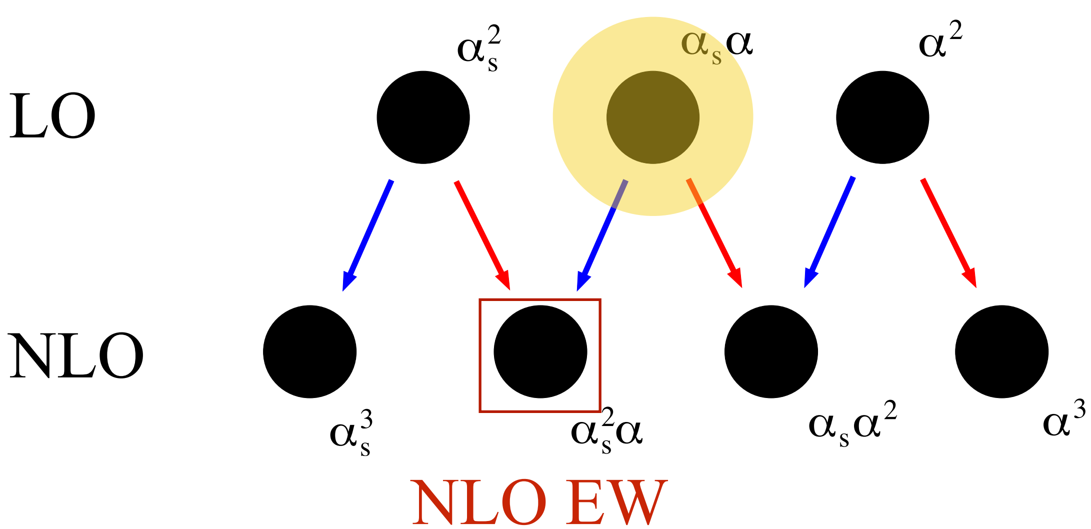


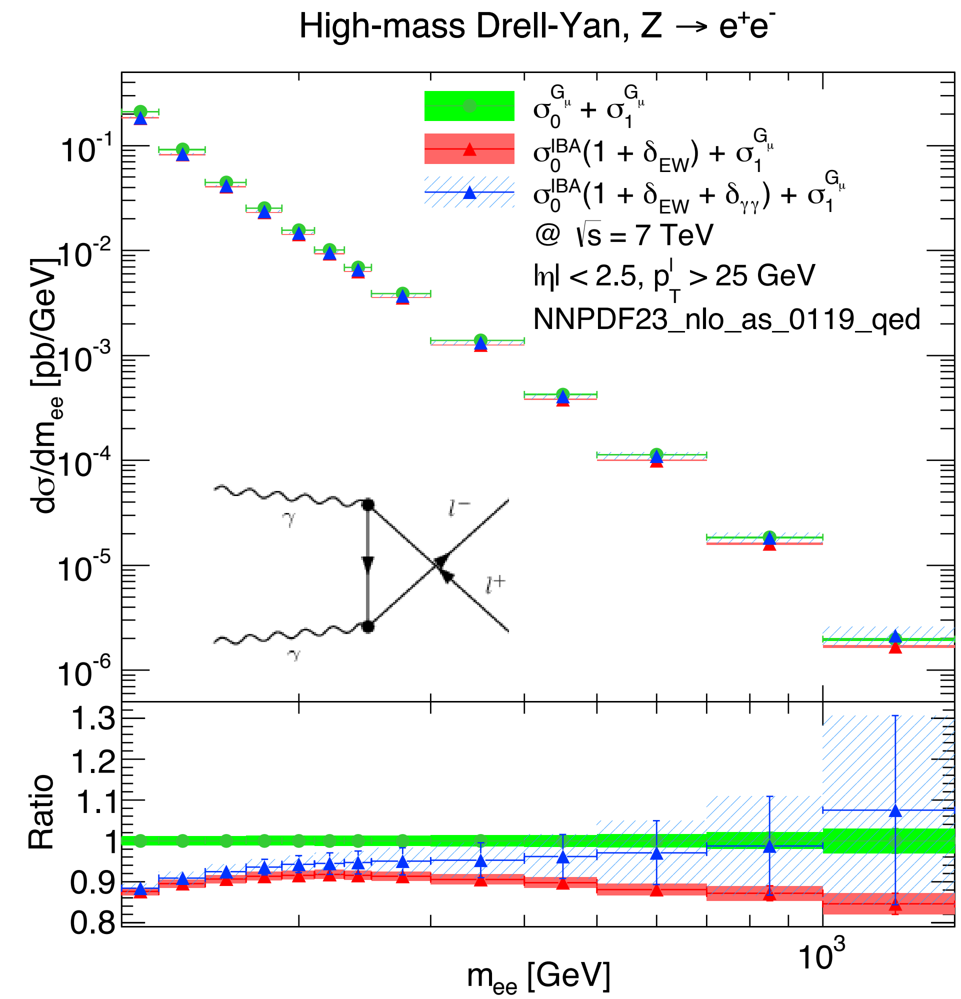
Process	σ_{tot} without cuts [pb]	
	Born	correction
$u\bar{u}$	34.25	-1.41
$d\bar{d}$	21.61	-0.228
$s\bar{s}$	4.682	-0.0410
$c\bar{c}$	2.075	-0.0762
gg	407.8	2.08
$g\gamma$		4.45
pp	470.4	4.78

NLO QED

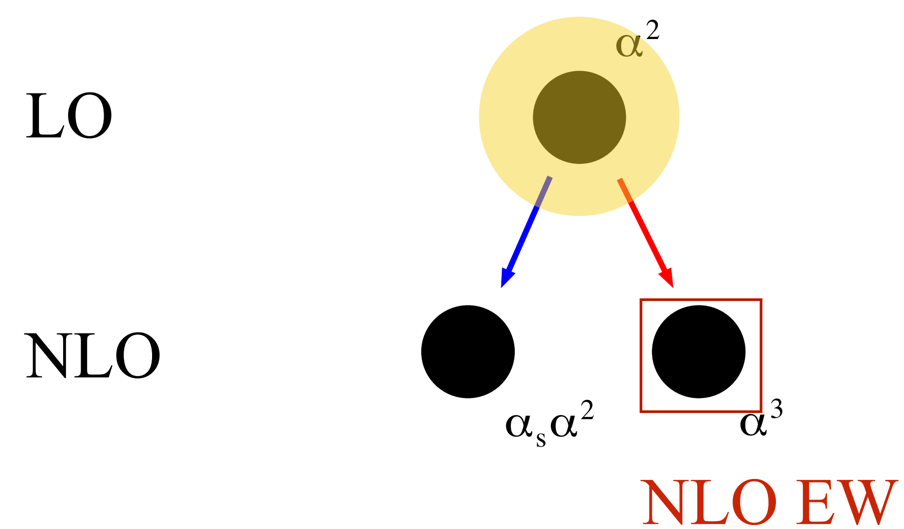
Integrated hadronic cross section for $t\bar{t}$ production at the LHC, at NLO QED

Hollik, Kollar '07 MRST2004QED





Carrazza '14 NNPDF2.3QED



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.