EW corrections with and without the photon PDF at 100 TeV: some examples

slides realized in collaboration with
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CERN

QCD EW and tools at 100 TeV
8-10-2015

Purpose of the talk:

Estimate the typical size of EW corrections at 100 TeV by looking at similar distributions in different "simple processes":

transverse momenta and invariant masses in: VV, HV, $t\bar{t}$

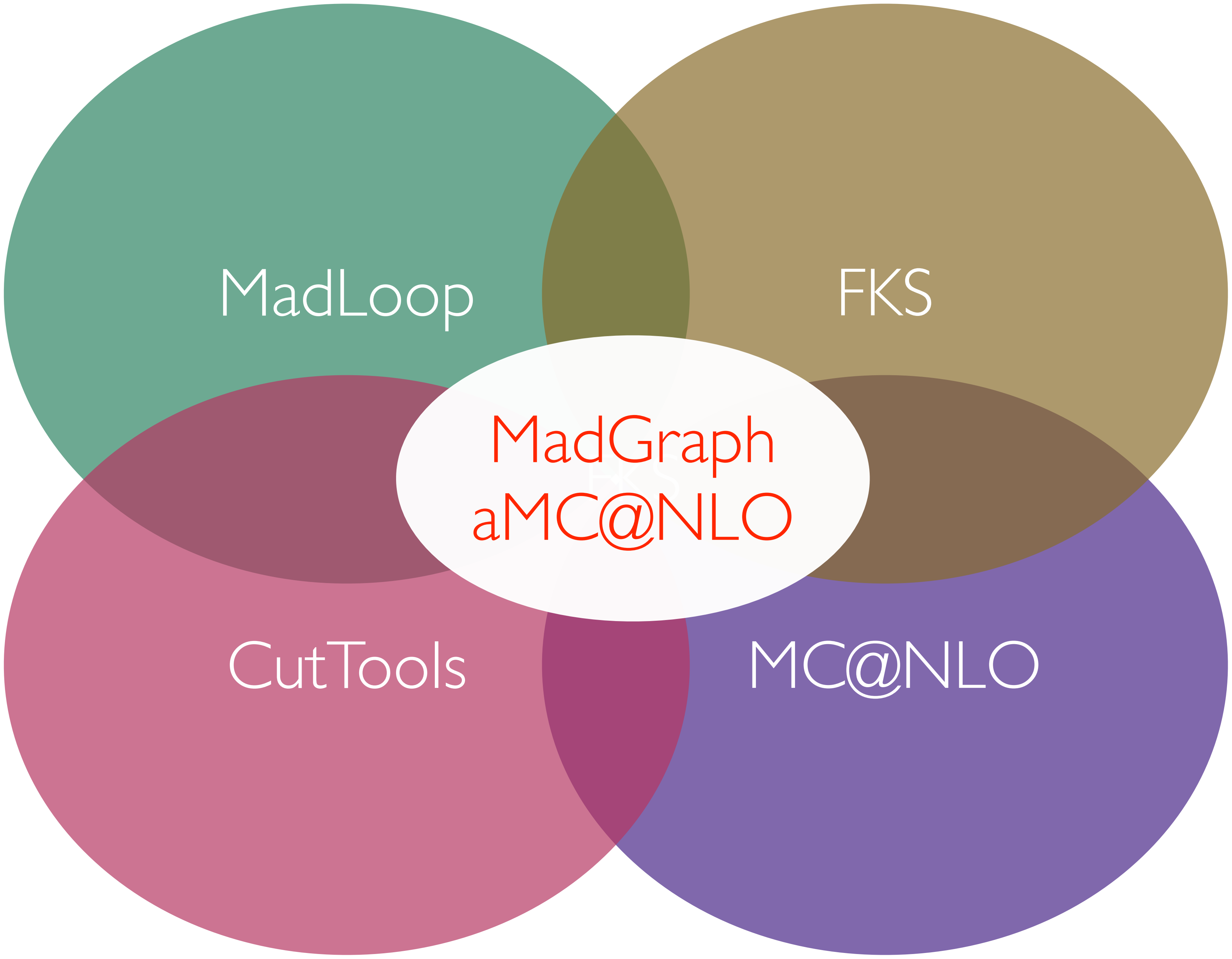
At the same time, we want to estimate the impact of the photon PDF (central value and errors) at 100 TeV.

Disclaimer

We want to raise possible issues related to NLO EW corrections at 100 TeV. No final answers or definitive statements will be given!

Automation of NLO corrections in Madgraph5_aMC@NLO

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

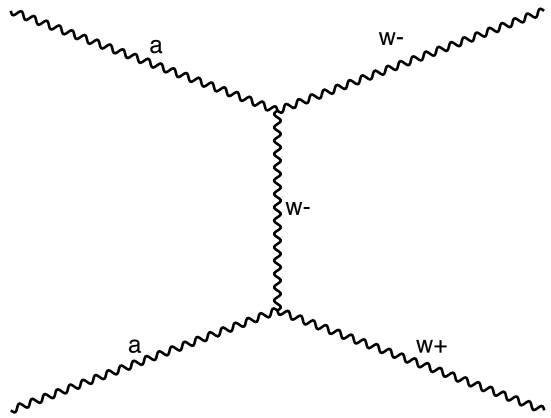


The **automation** for **NLO QCD+EW** is in progress!.

Set-up and photon-PDF perturbative orders

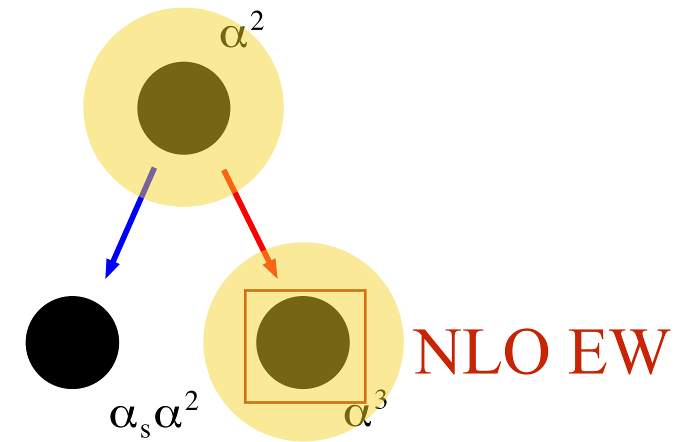
G_μ scheme, NNPDF2.3_QED, $\mu = \frac{H_T}{2}$, $\frac{1}{2}\mu \leq \mu_R, \mu_F \leq 2\mu$

WW

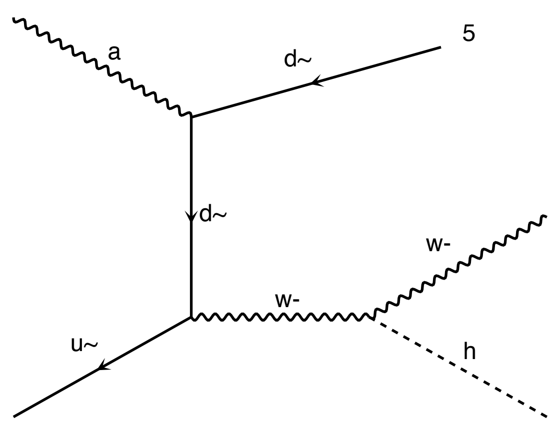


LO

NLO

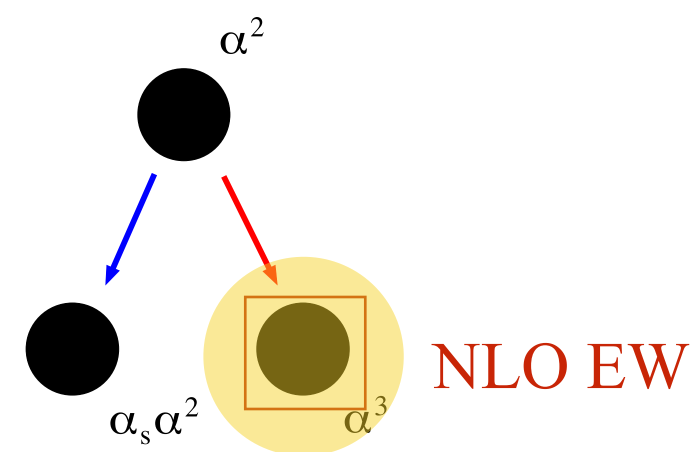


ZZ, ZW, HZ, HW

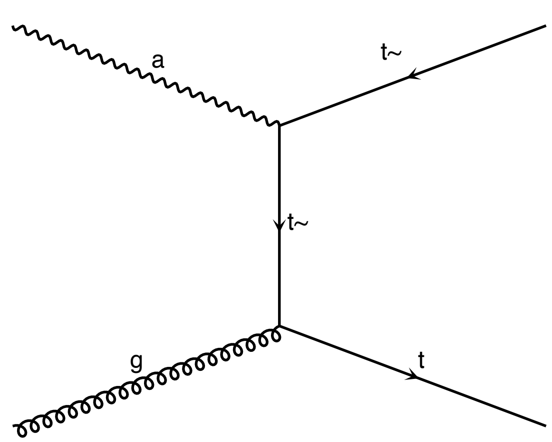


LO

NLO

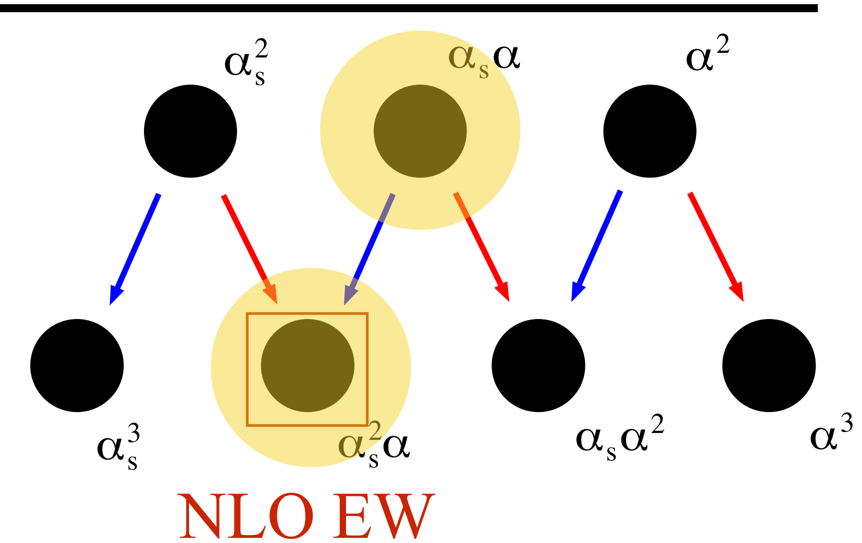


$t\bar{t}$



LO

NLO



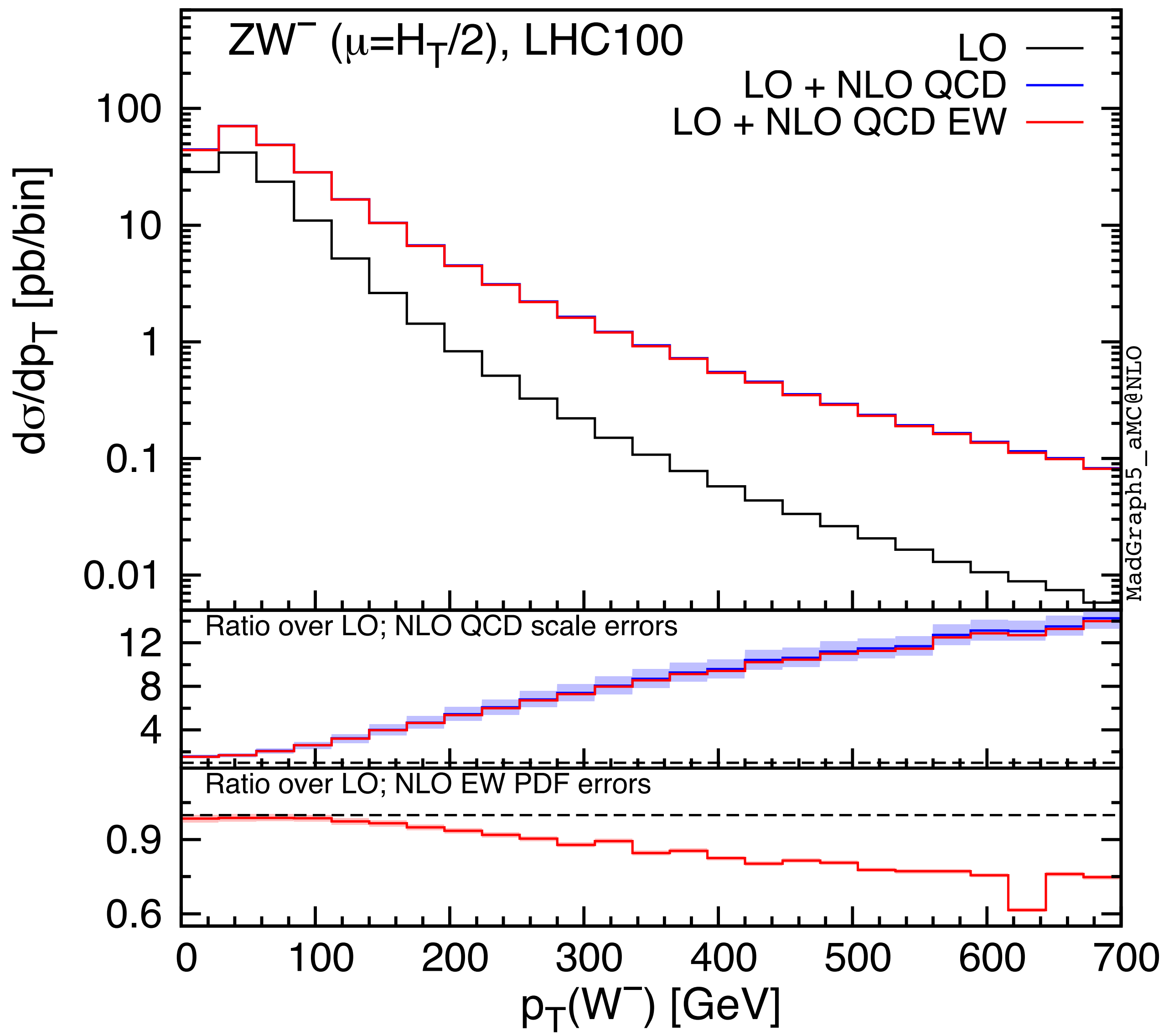
two vector bosons

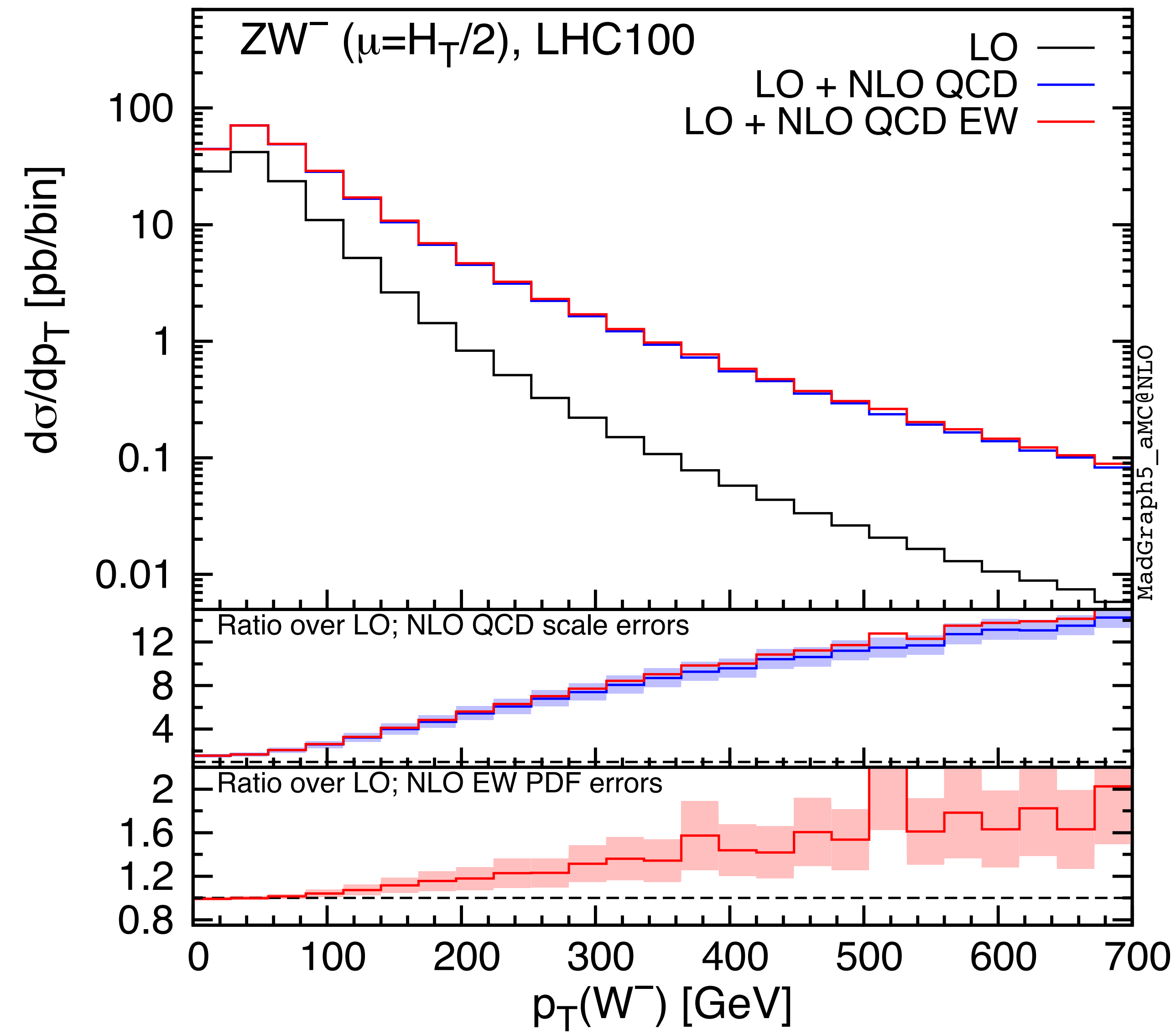
VV

four-flavour scheme

WZ

differential plots



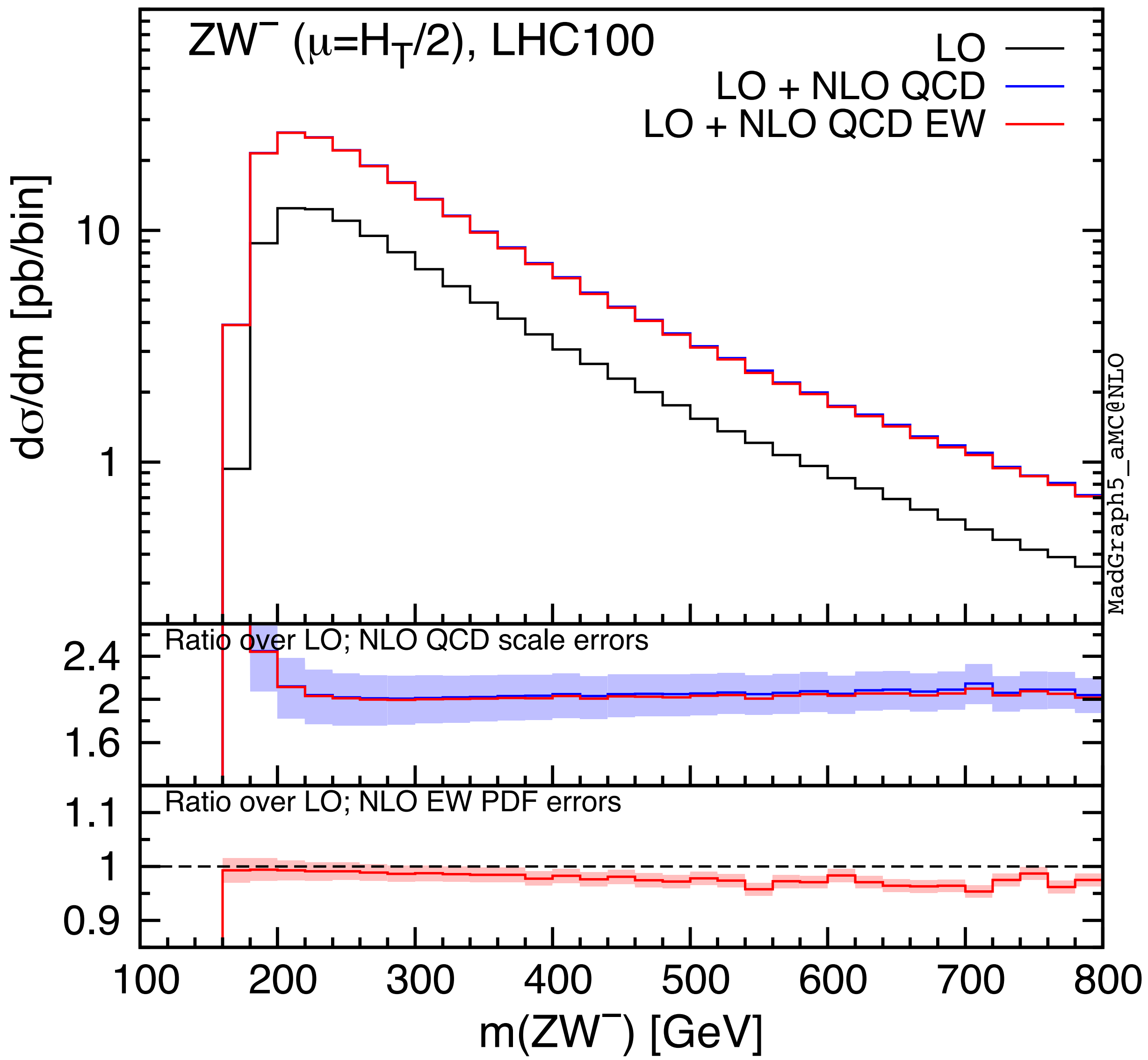


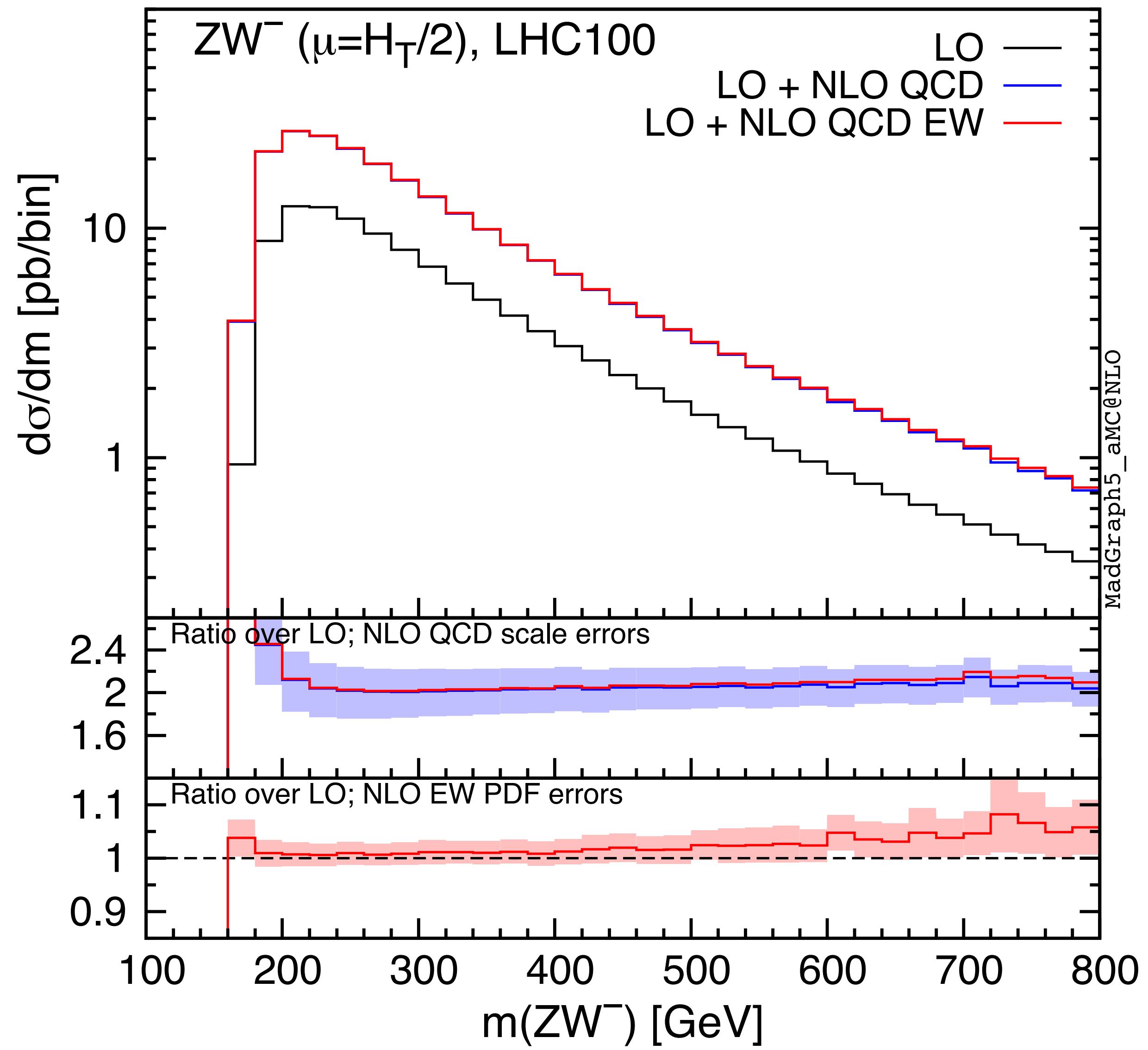
photon PDF **NO**

photon PDF **YES**

WZ

differential plots



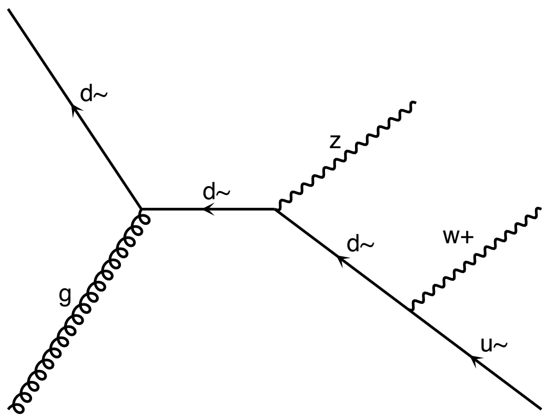


photon PDF **NO**

photon PDF **YES**

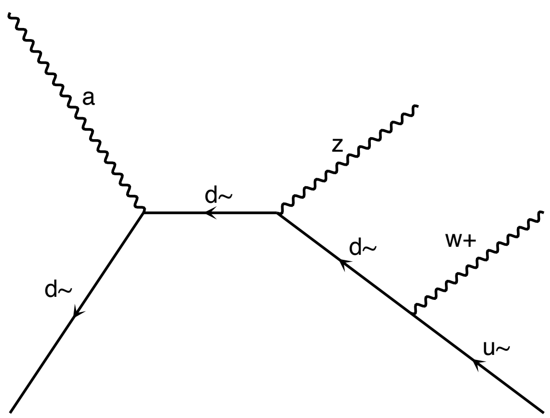
WZ

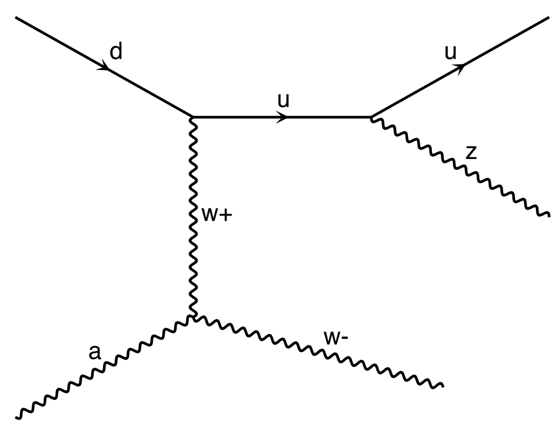
what’s going on?



$$d\sigma^{dg \to W^- Z u} = c^d_{WZ} d\sigma_L^{dg \to Z d} \frac{\alpha}{2\pi} \log^2 \left[\frac{(p_T^Z)^2}{M_W^2} \right]$$

Zj +
soft and collinear W





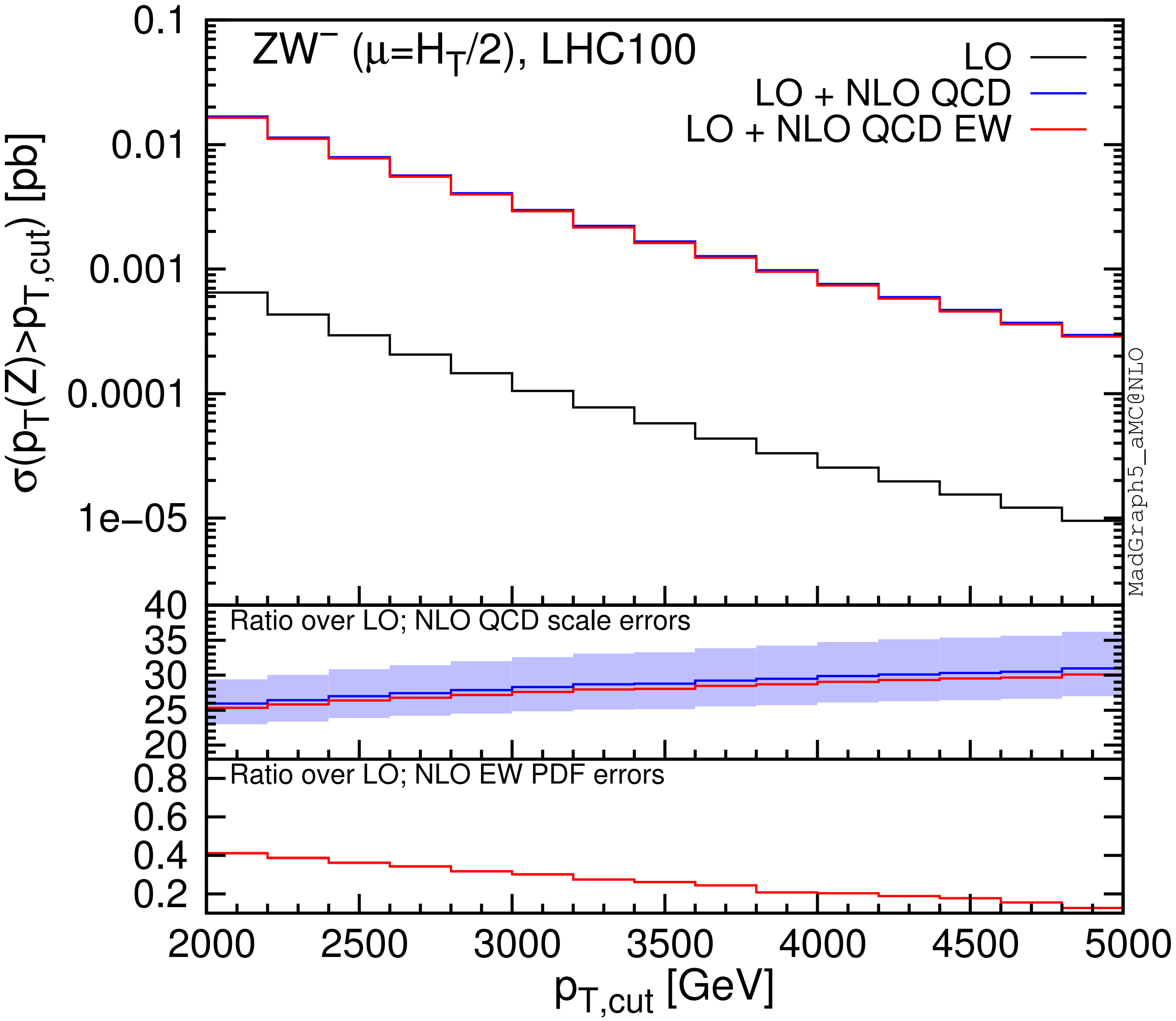
$$d\sigma^{d\gamma \to W^- Z u} = \frac{c^2_{L,d} c^d_{WZ}}{a_W^2} d\sigma_L^{d\gamma \to W^- u} \frac{\alpha}{2\pi} \log^2 \left[\frac{(p_T^{W^-})^2}{M_Z^2} \right]$$

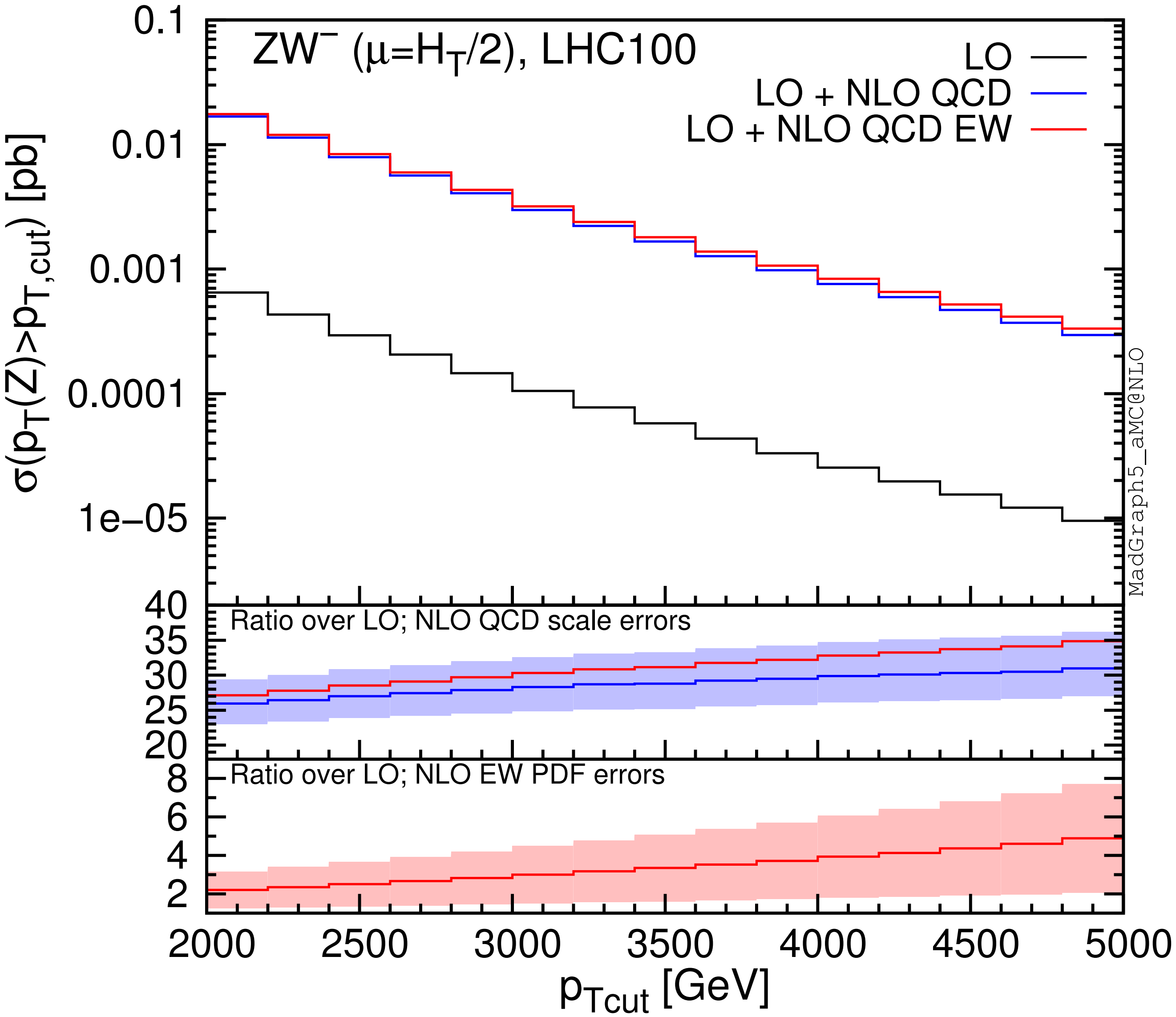
See also Baglio, Ninh,Weber ‘13

- The large growth for high pt in NLO QCD corrections and photon-quark in NLO EW have similar origins: the same cuts may suppress both effects.

- The photon couples to the W, originating new t-channel configurations that enhance the relative size of photon-quark contributions in NLO EW. NLO QCD corrections do not exhibit similar features.

WZ
cumulative plots



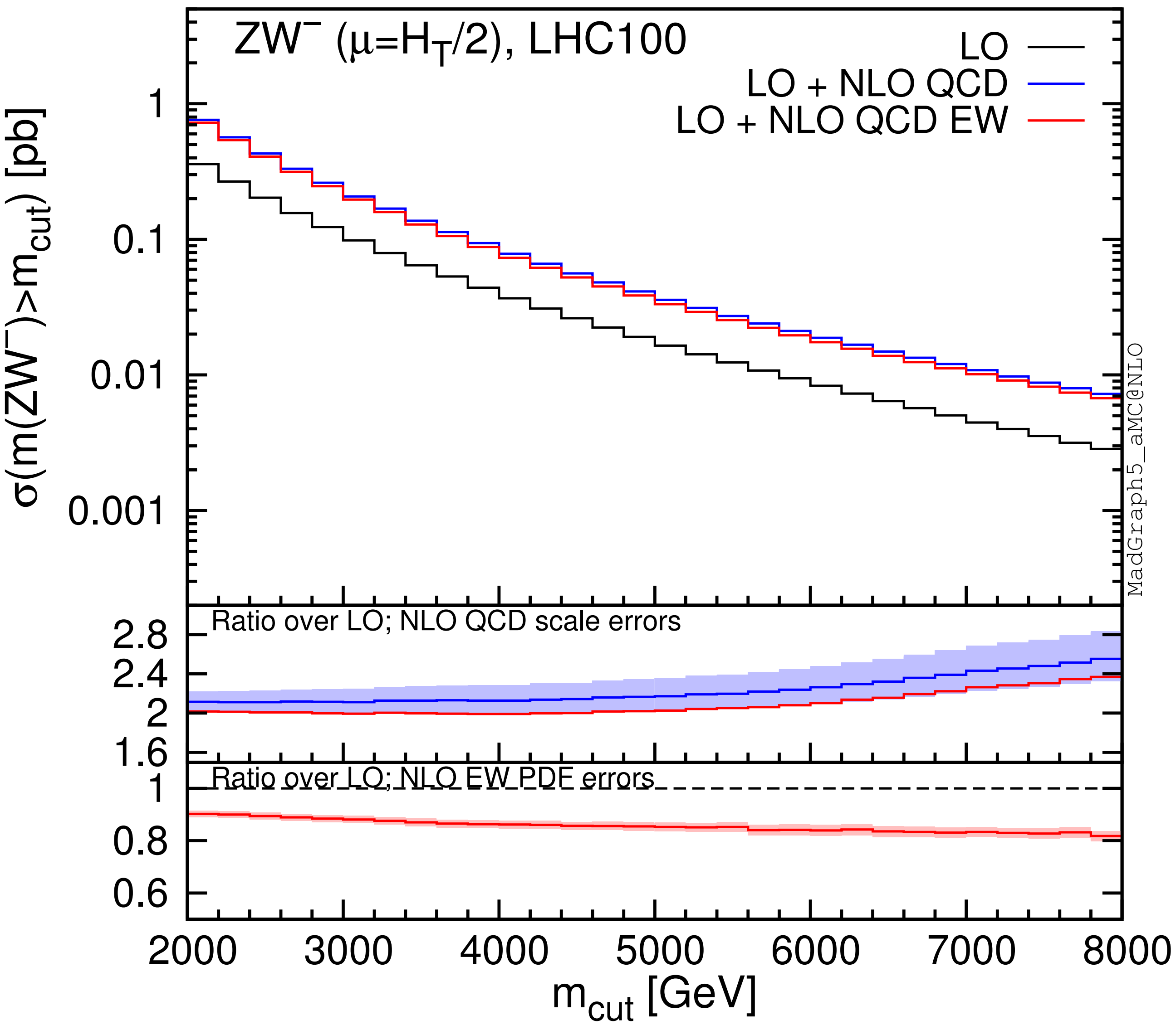


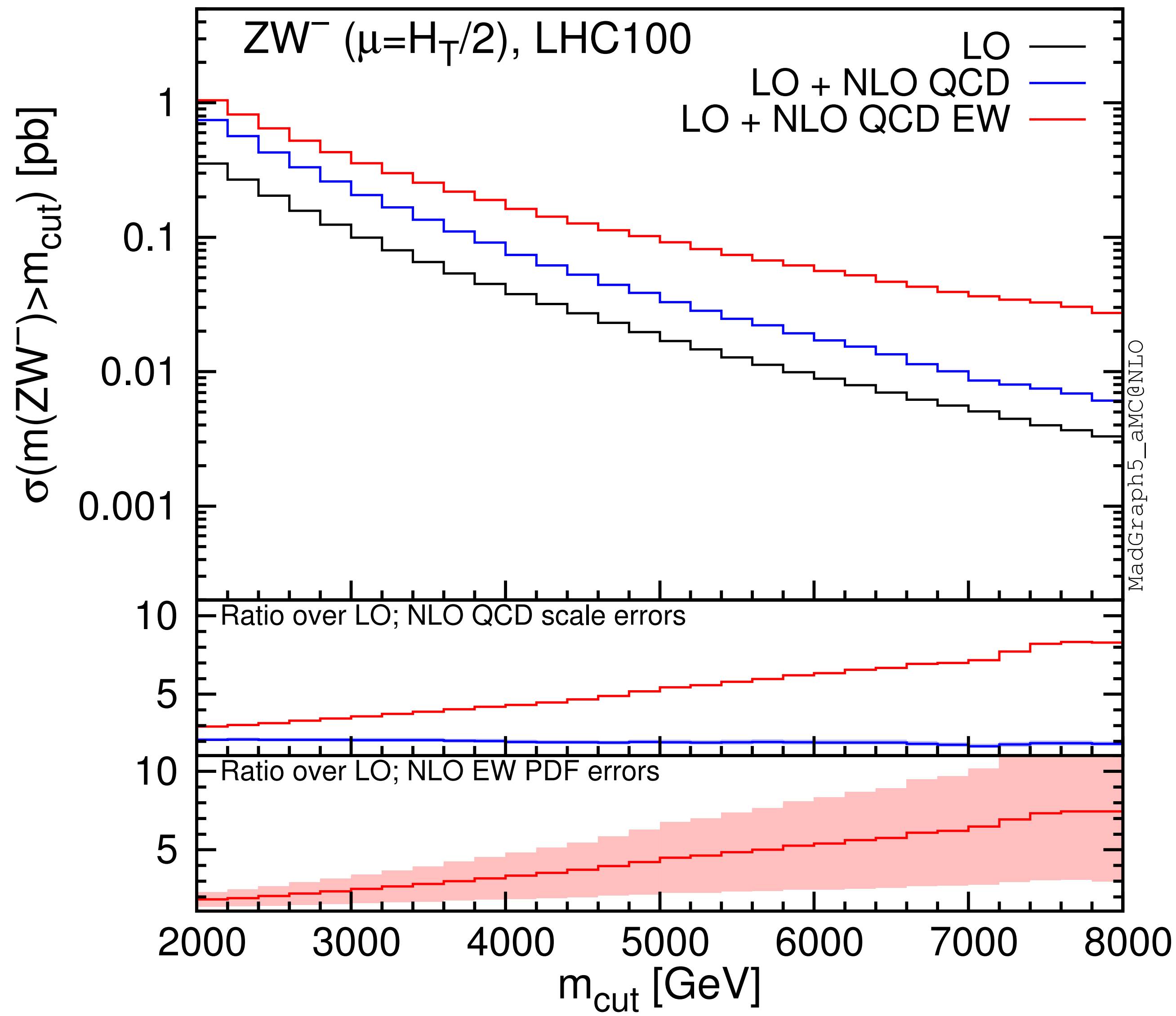
photon PDF **NO**

photon PDF **YES**

WZ

cumulative plots

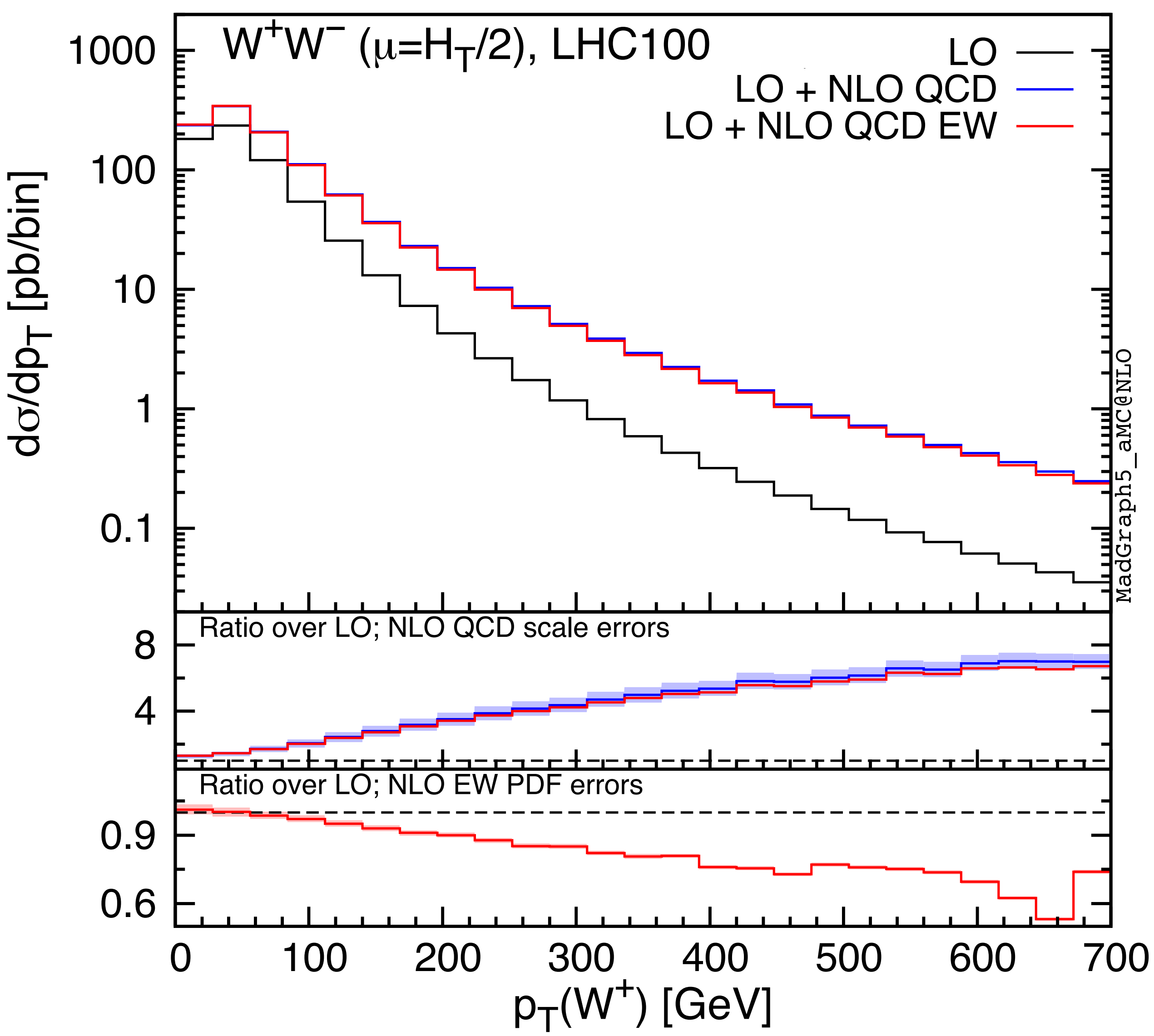




photon PDF **NO**

photon PDF **YES**

WW
differential plots



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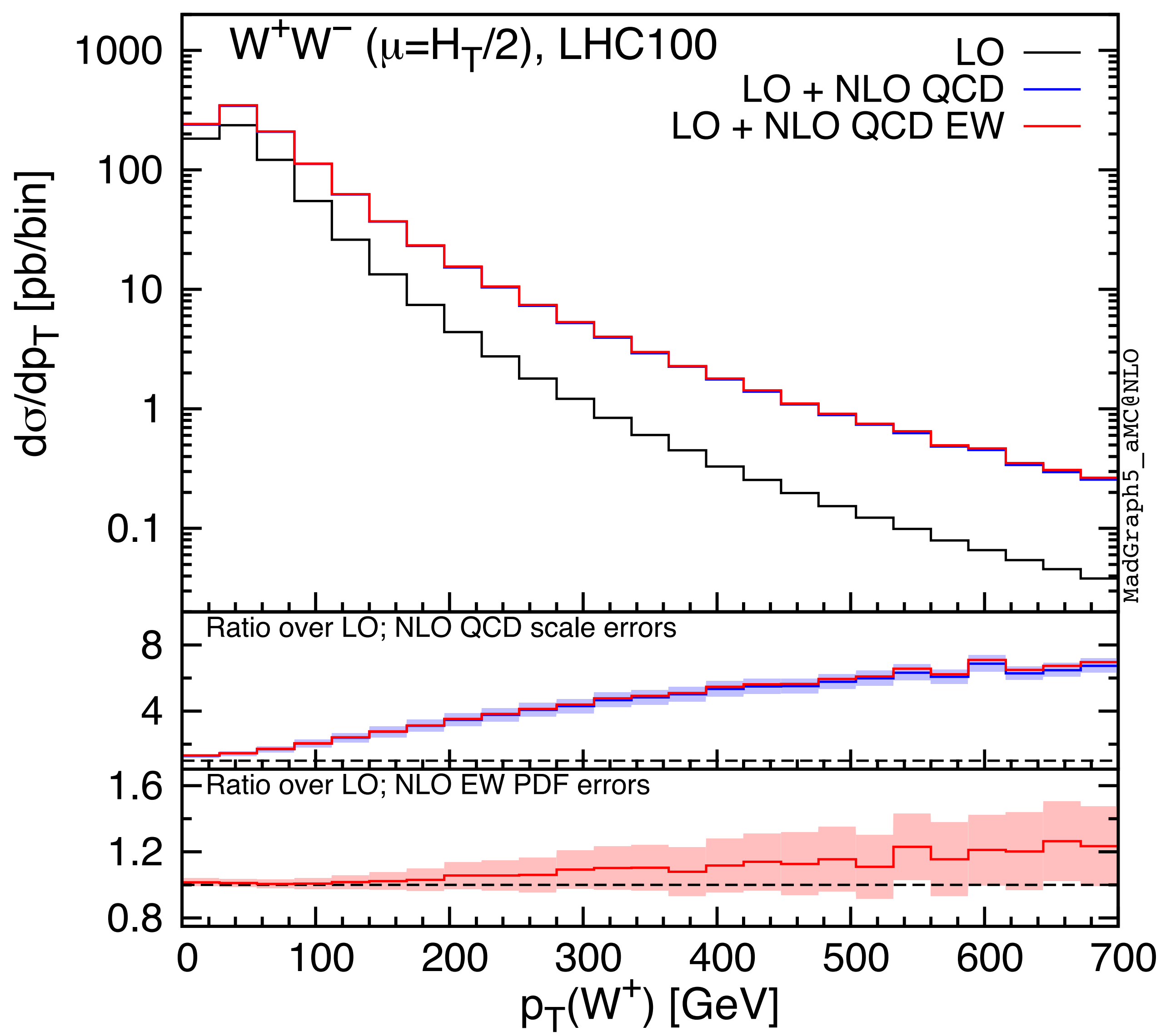
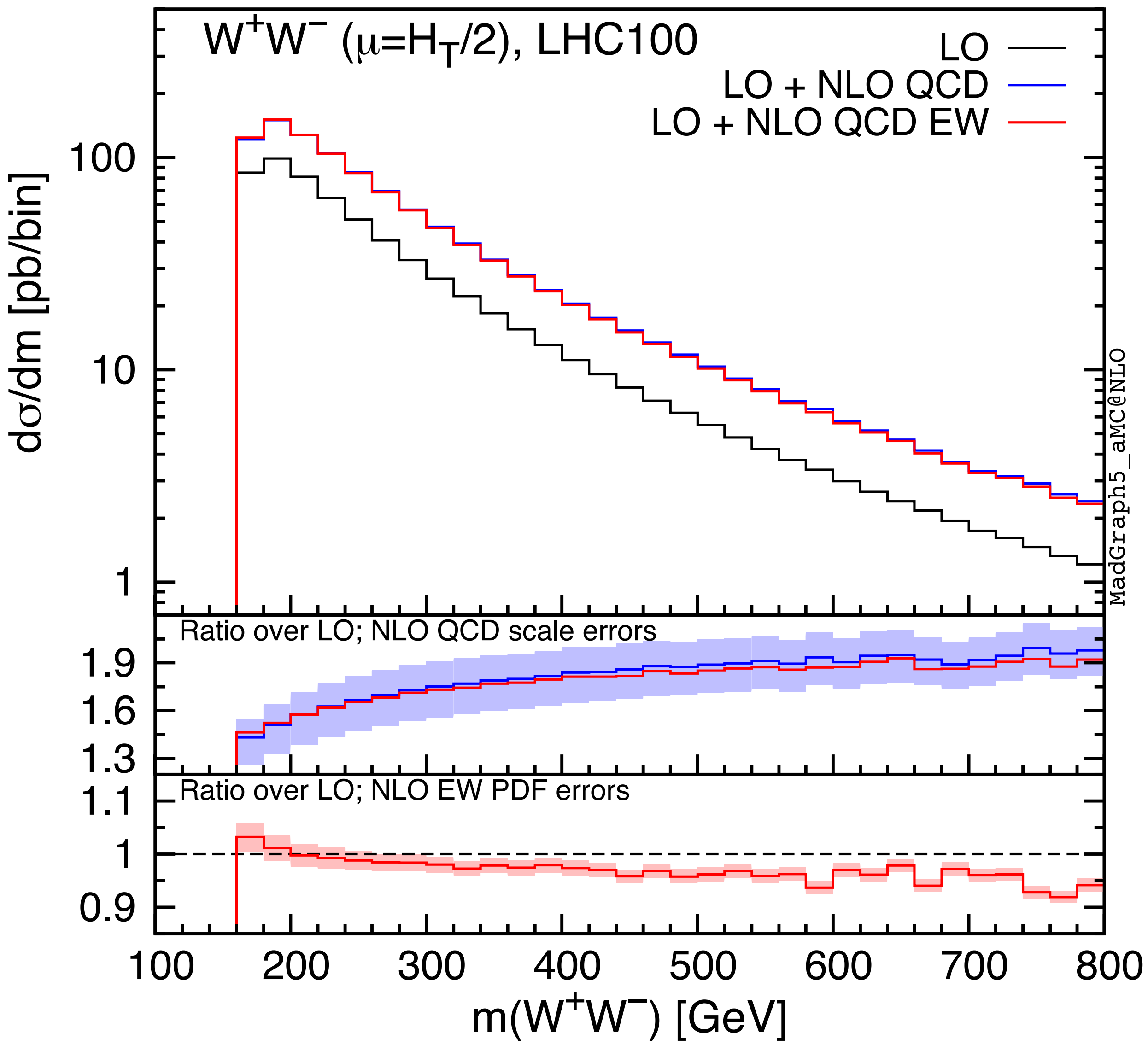
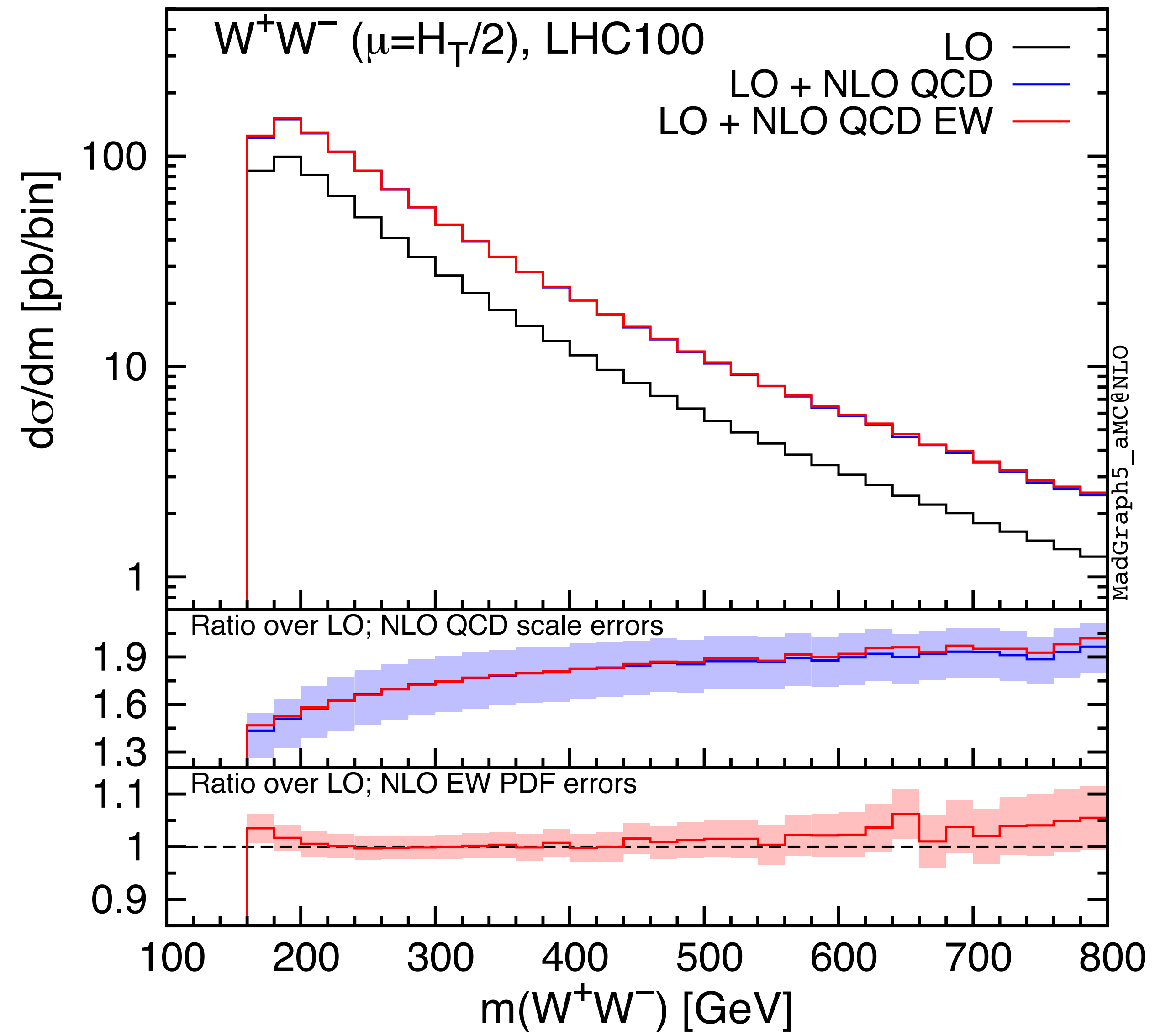


photon PDF **YES**

WW

differential plots



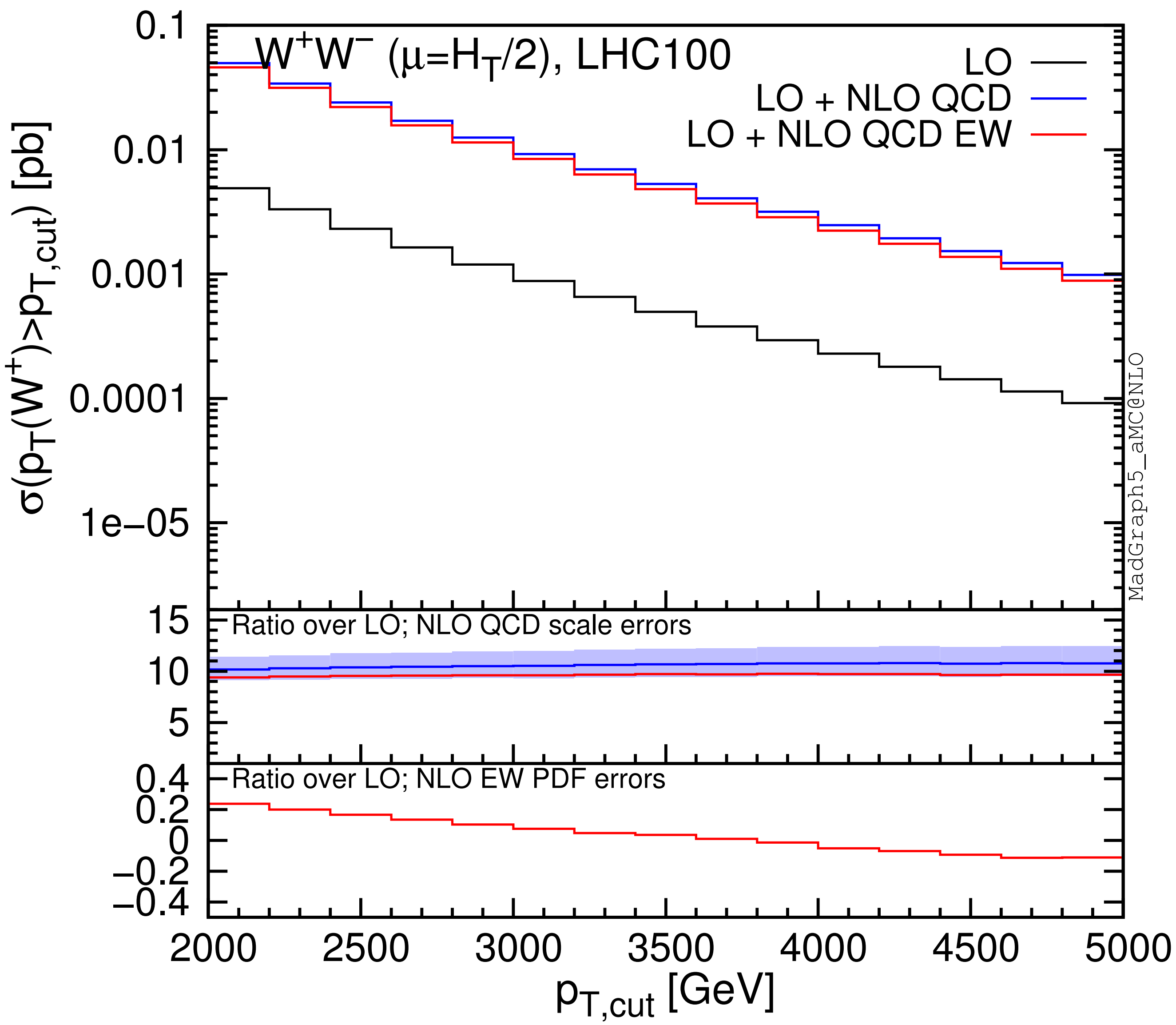


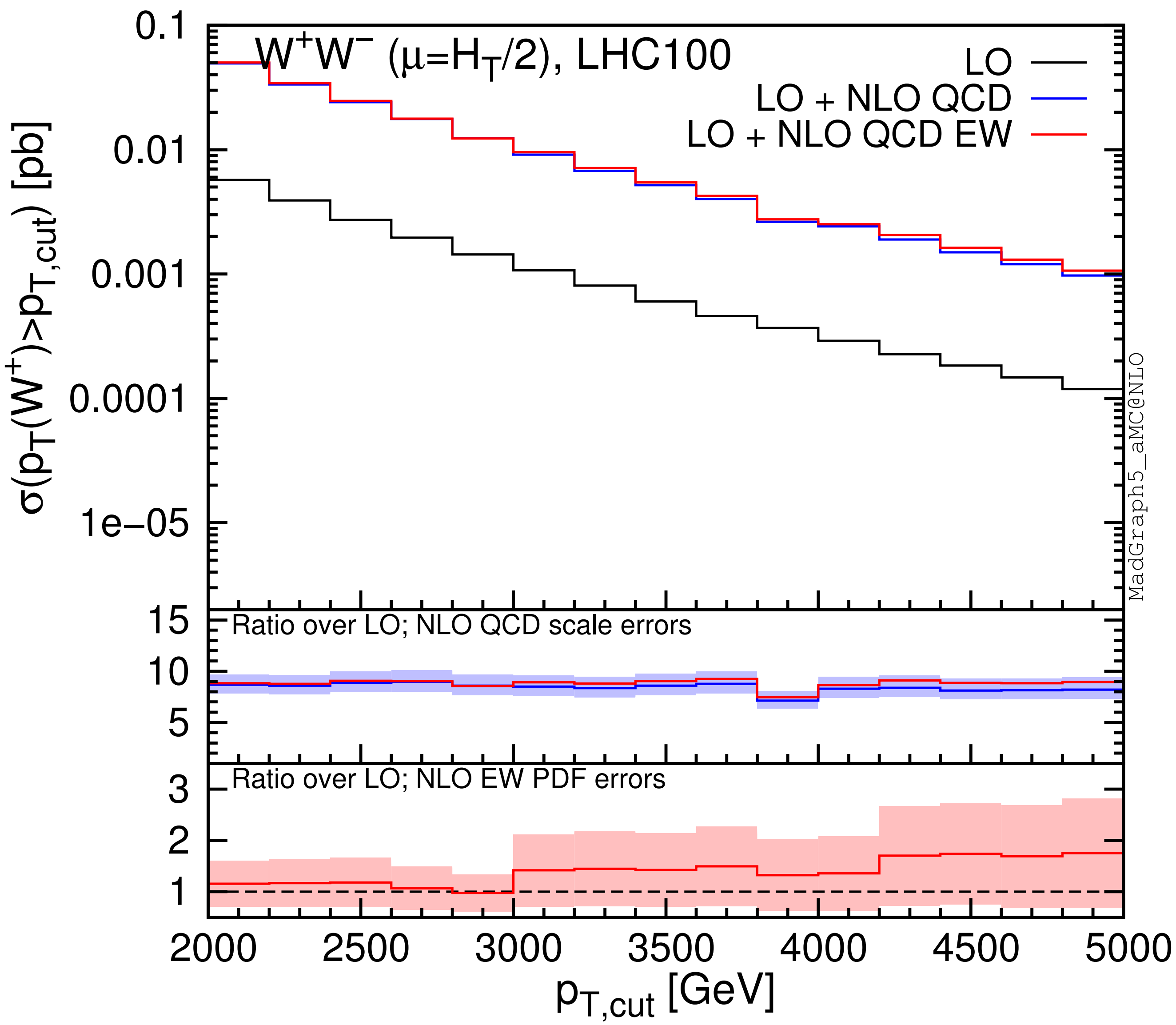
photon PDF **NO**

photon PDF **YES**

WW

cumulative plots



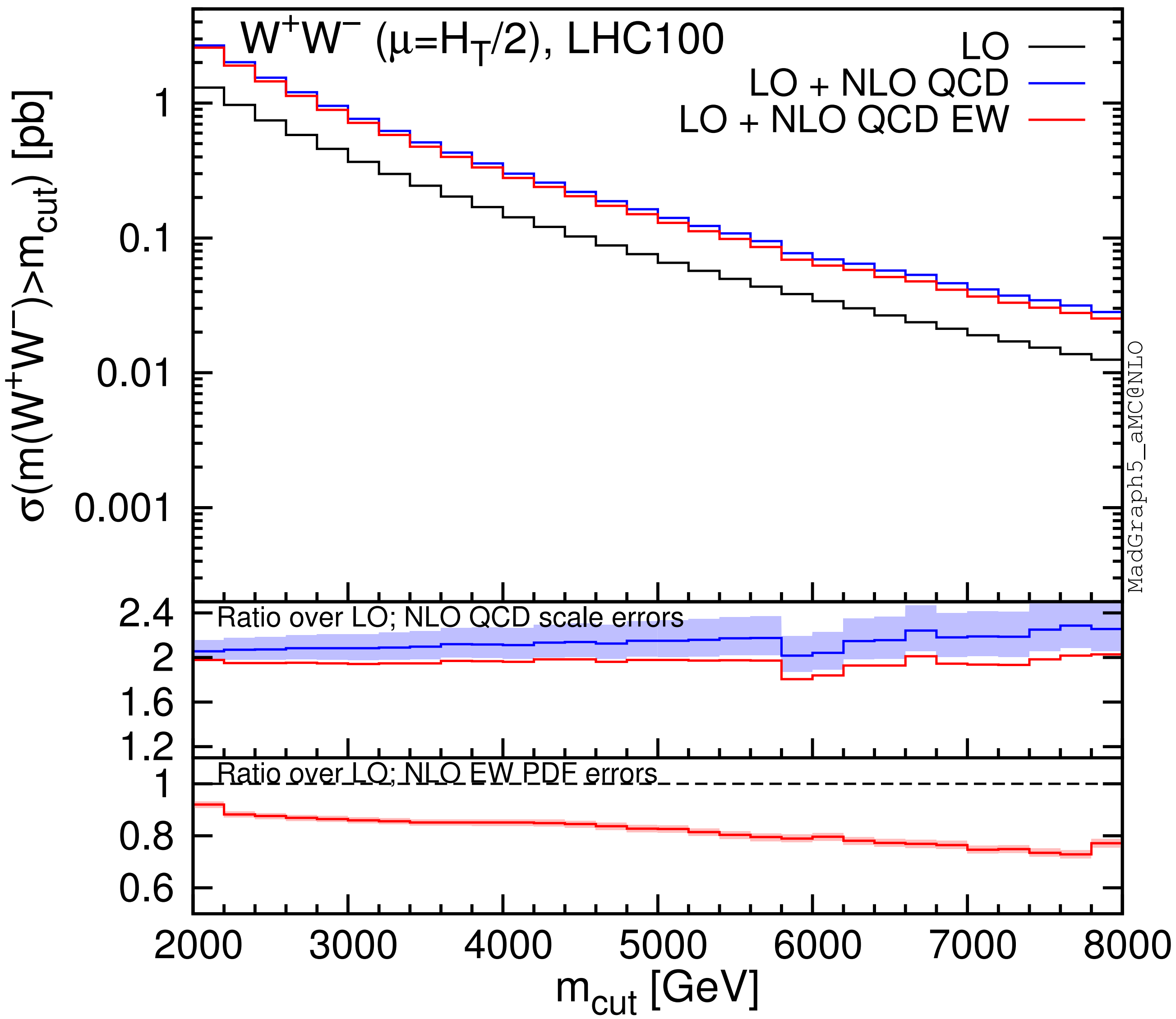


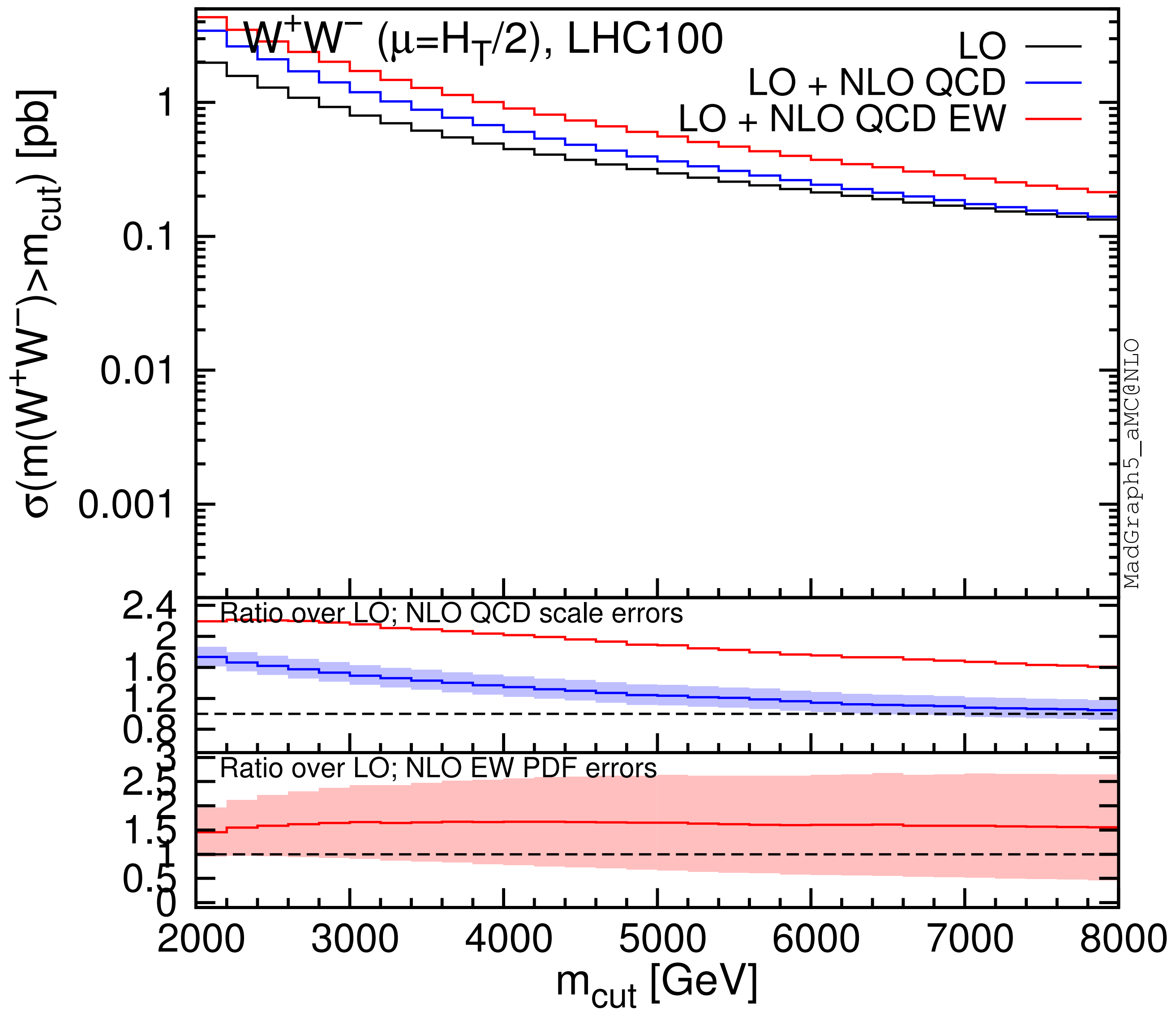
photon PDF **NO**

photon PDF **YES**

WW

cumulative plots

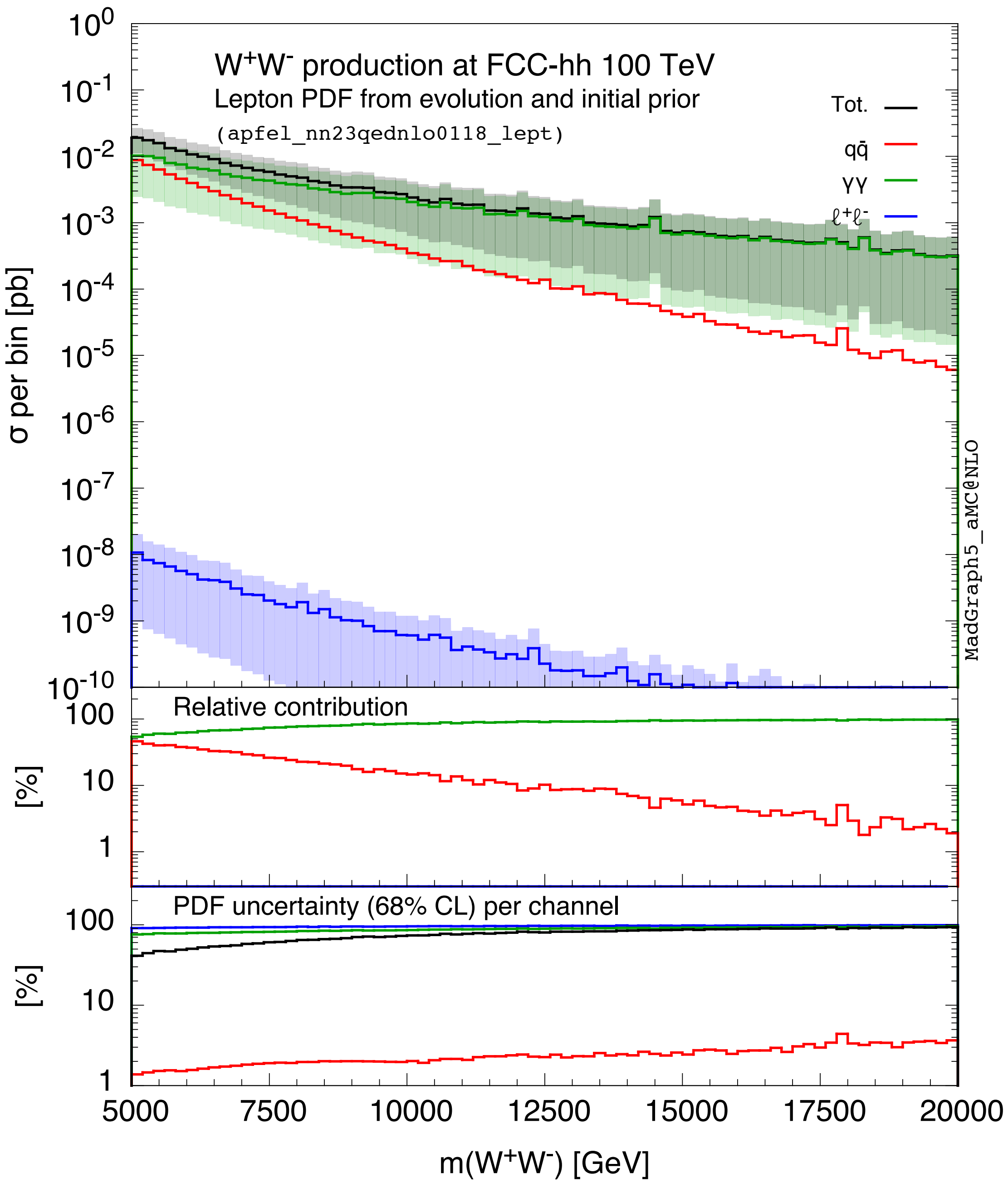




photon PDF **NO** photon PDF **YES**

WW

what's going on?



Bertone, Carrazza, DP, Zaro '15

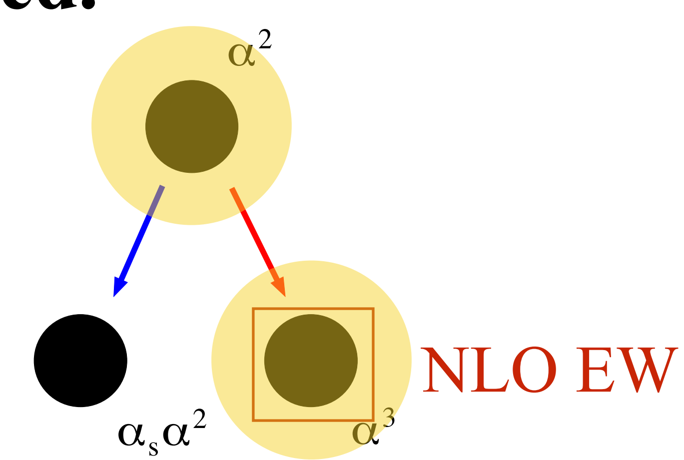
For m(WW) < 5 TeV everything is very similar to WZ. For high energies, the photon-photon initial state from LO becomes dominant.

At high m(WW), NLO QCD K-factor —> 1, since photon-photon —> WW has no NLO QCD corrections.

Similarly to the WZ case, Sudakov logs are not under control in pt distributions and have to be resummed.

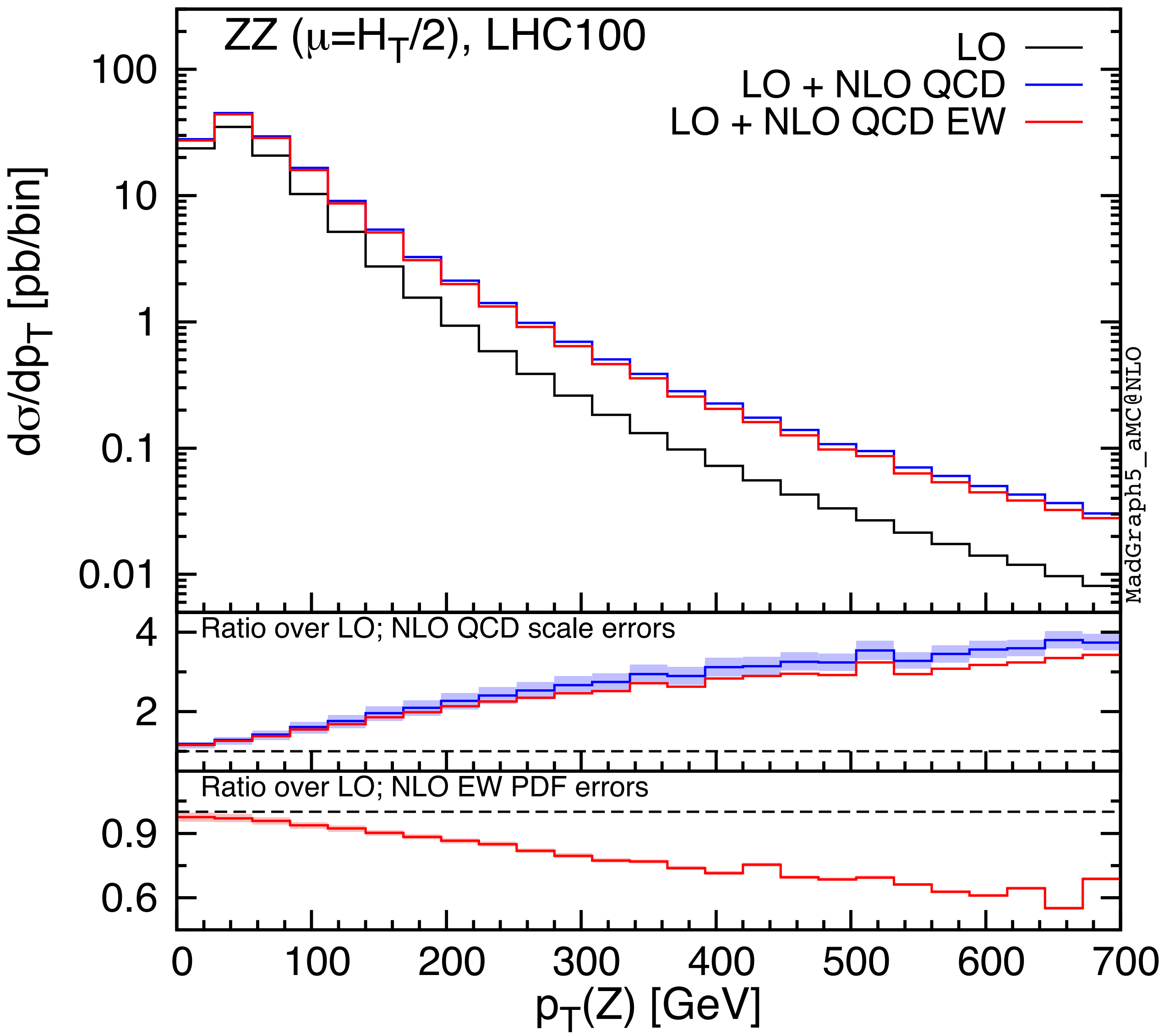
LO

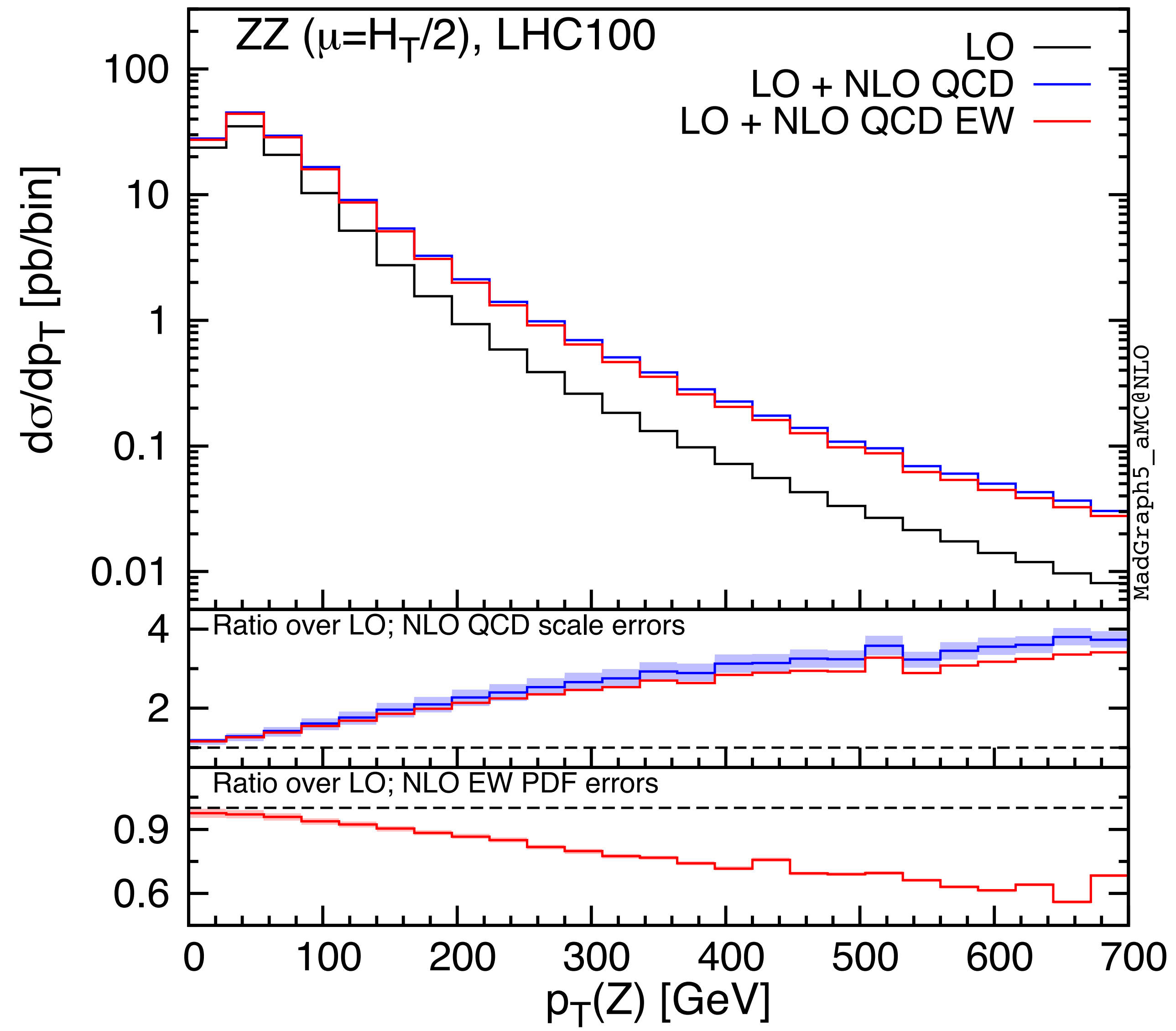
NLO



ZZ

differential plots

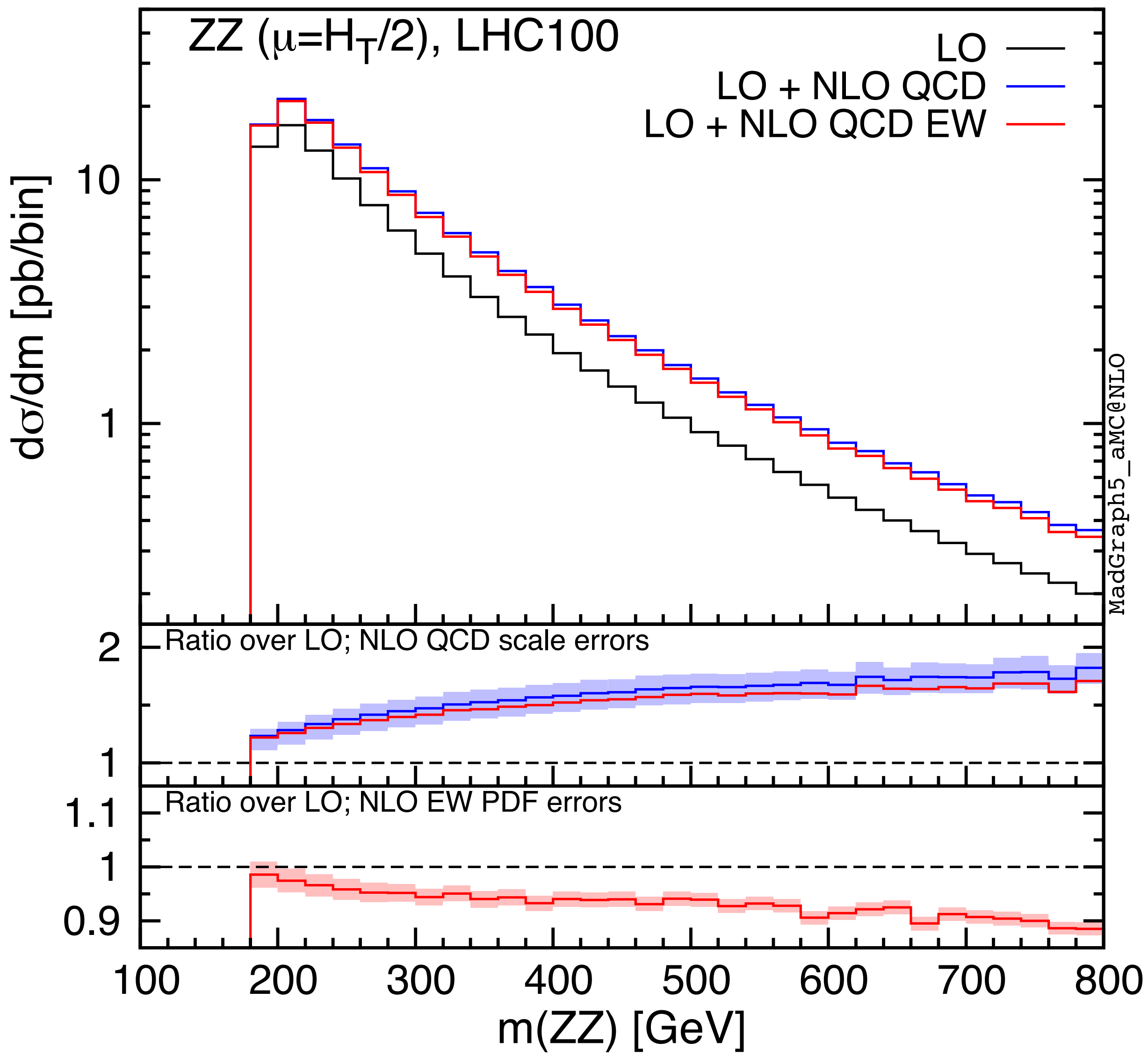


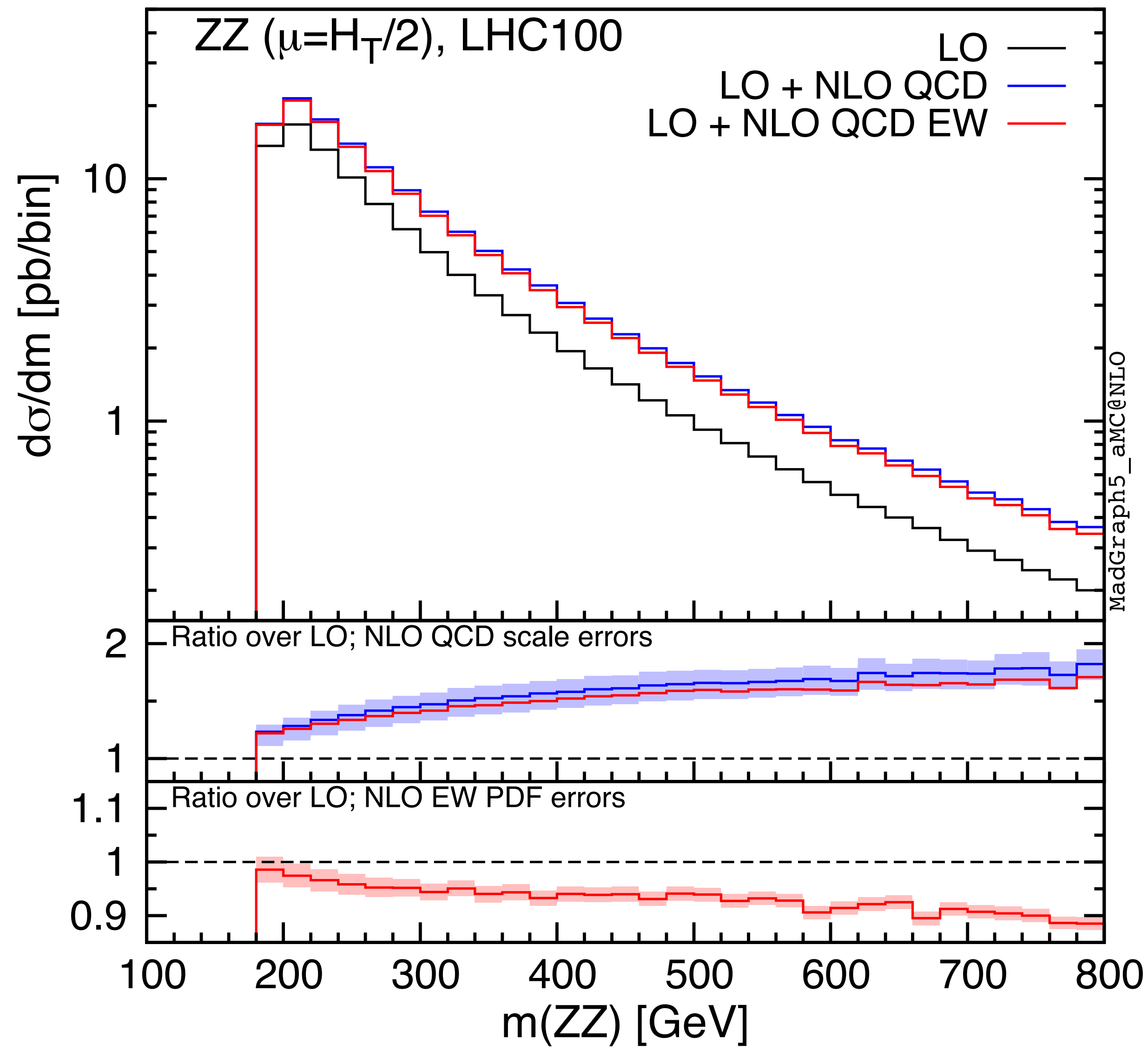


photon PDF **NO**

photon PDF **YES**

ZZ
differential plots





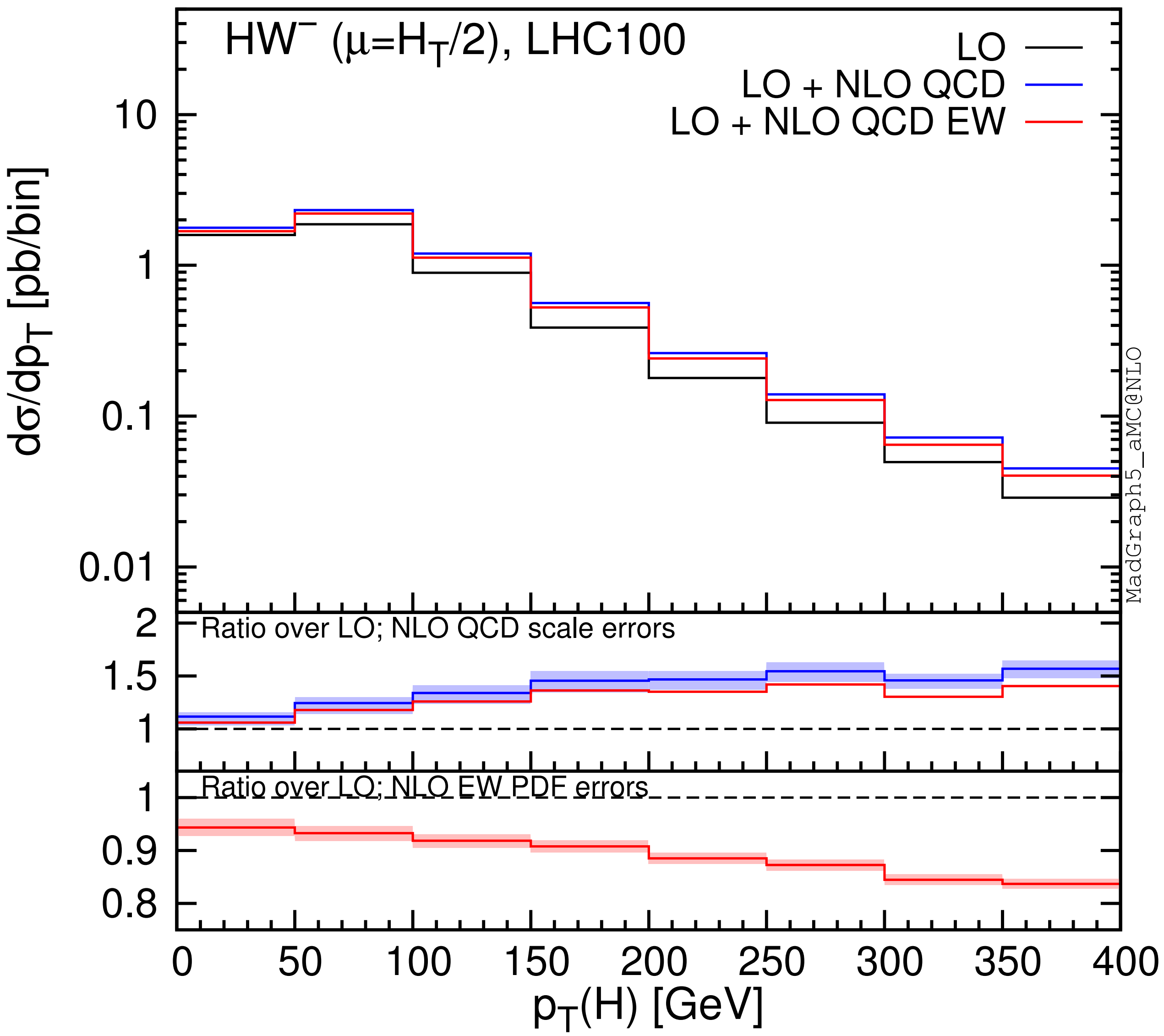
photon PDF **NO**

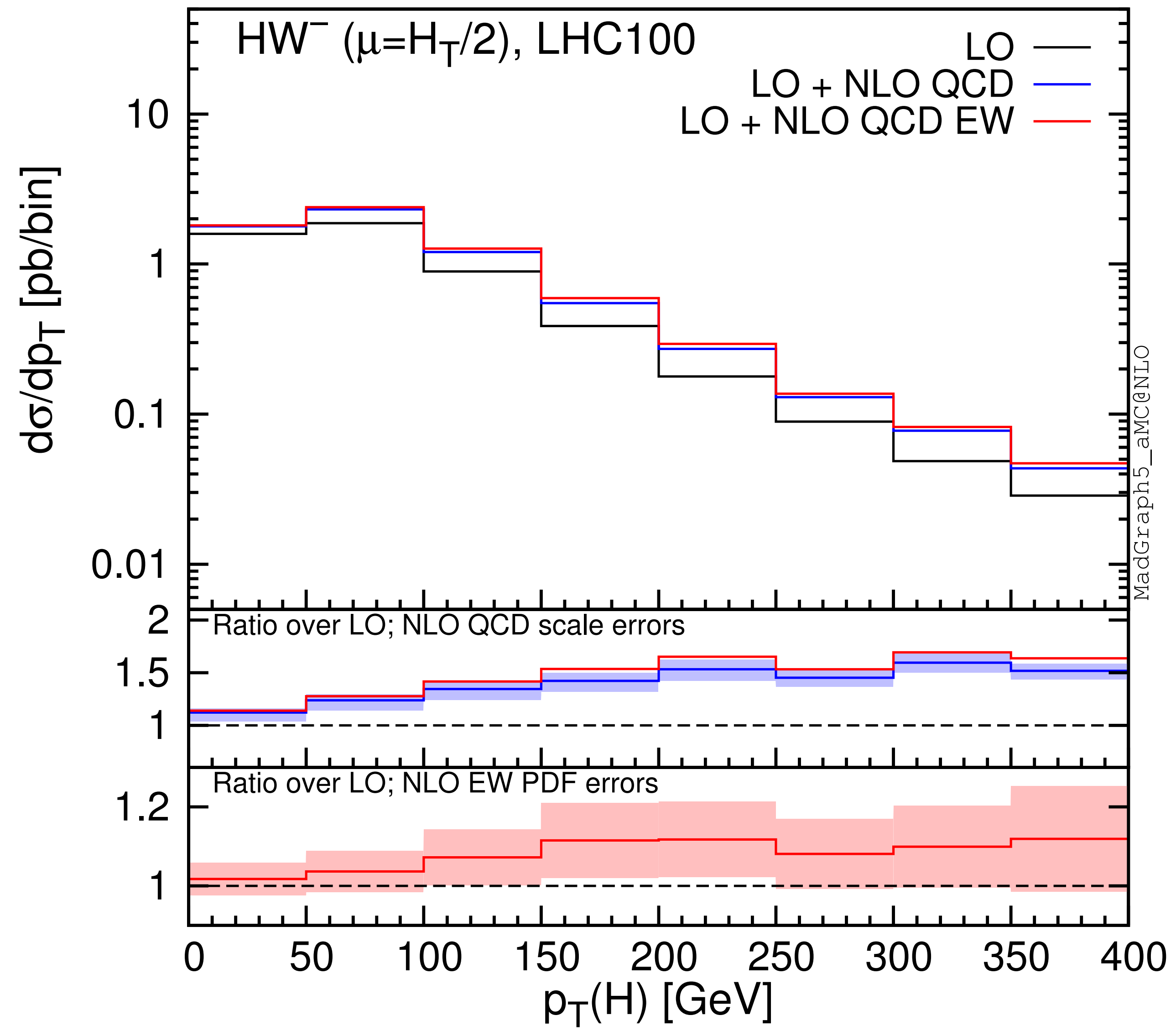
photon PDF **YES**

Higgsstrahlung
HV

HW

differential plots



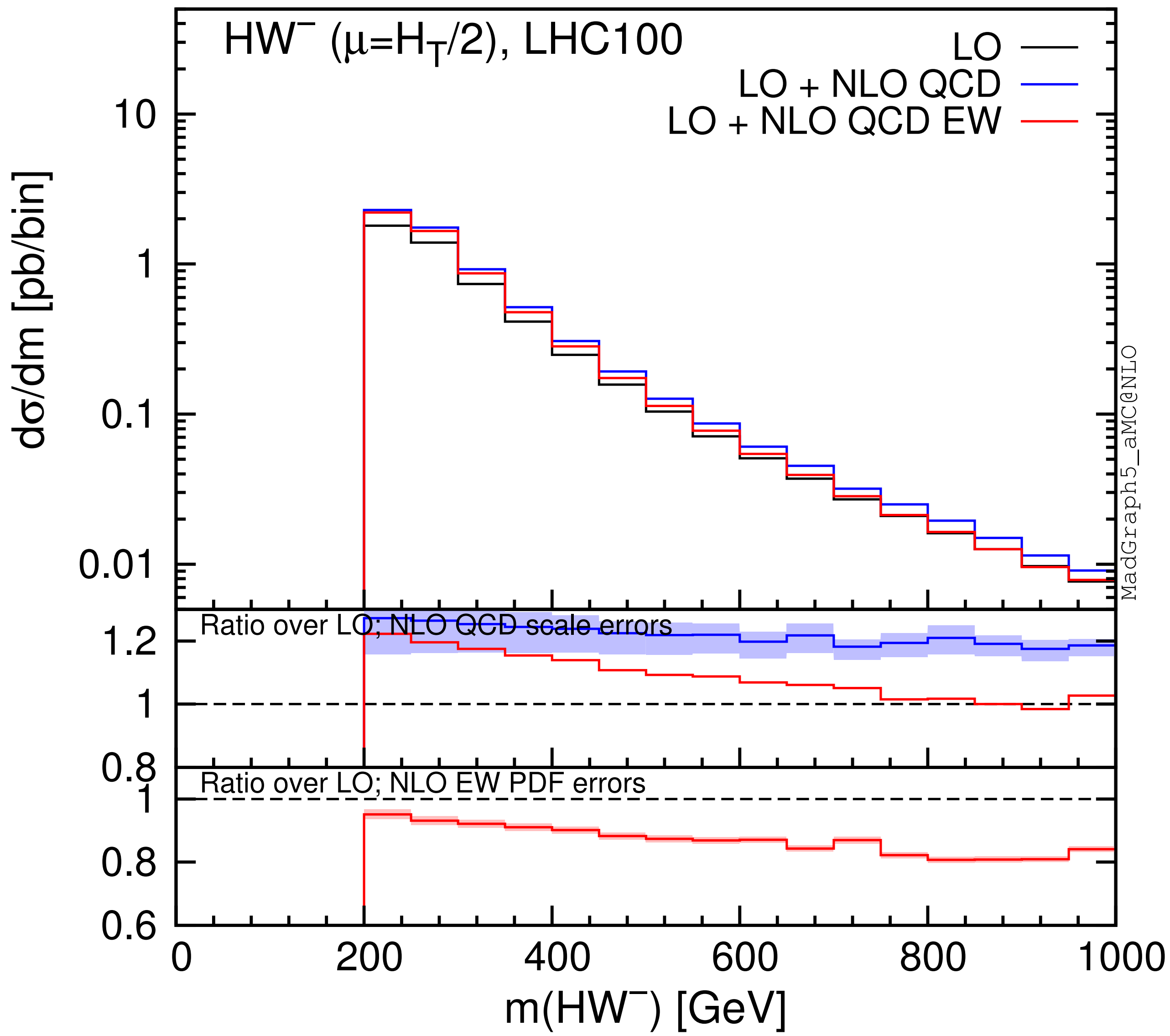


photon PDF **NO**

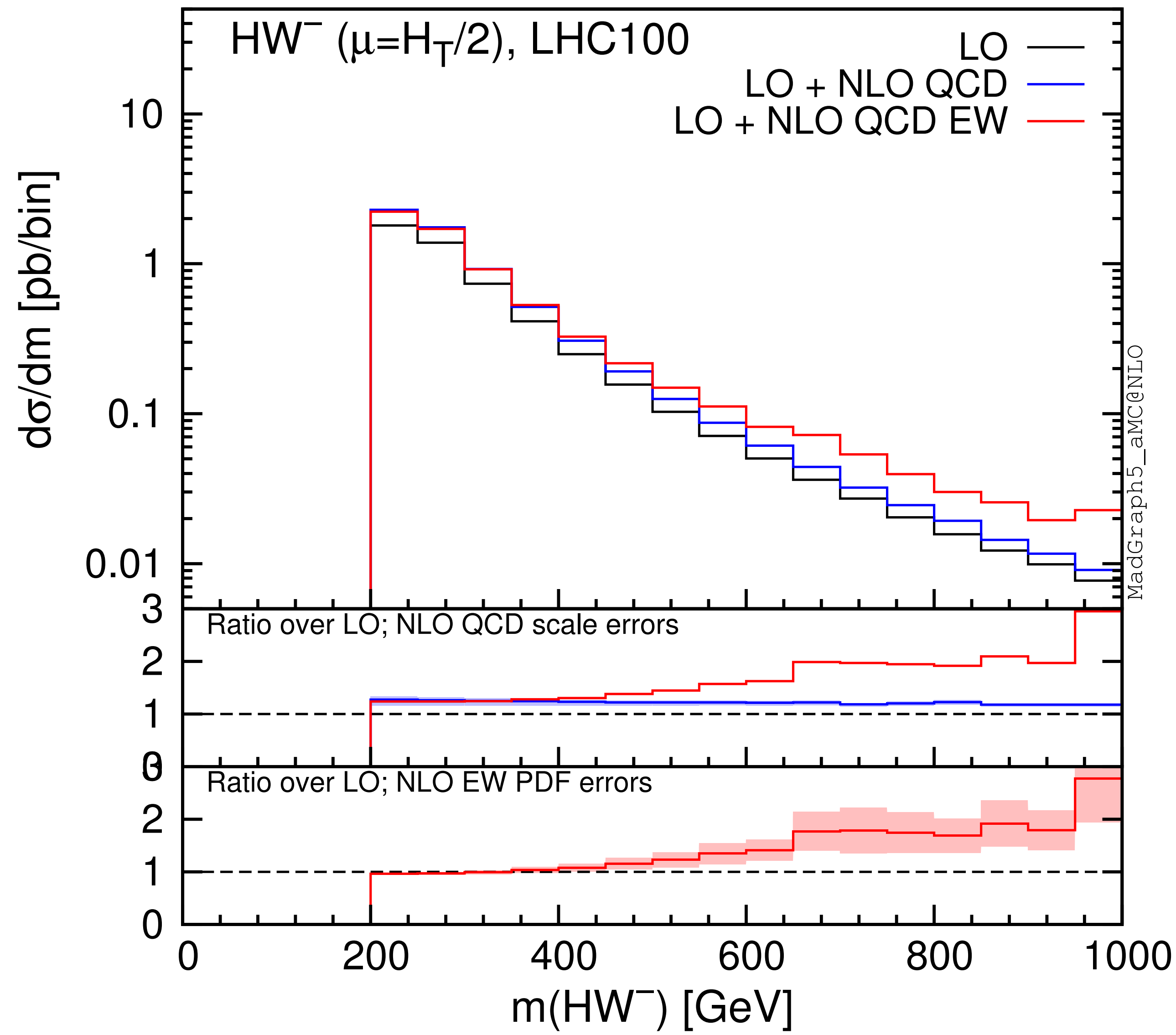
photon PDF **YES**

HW

differential plots



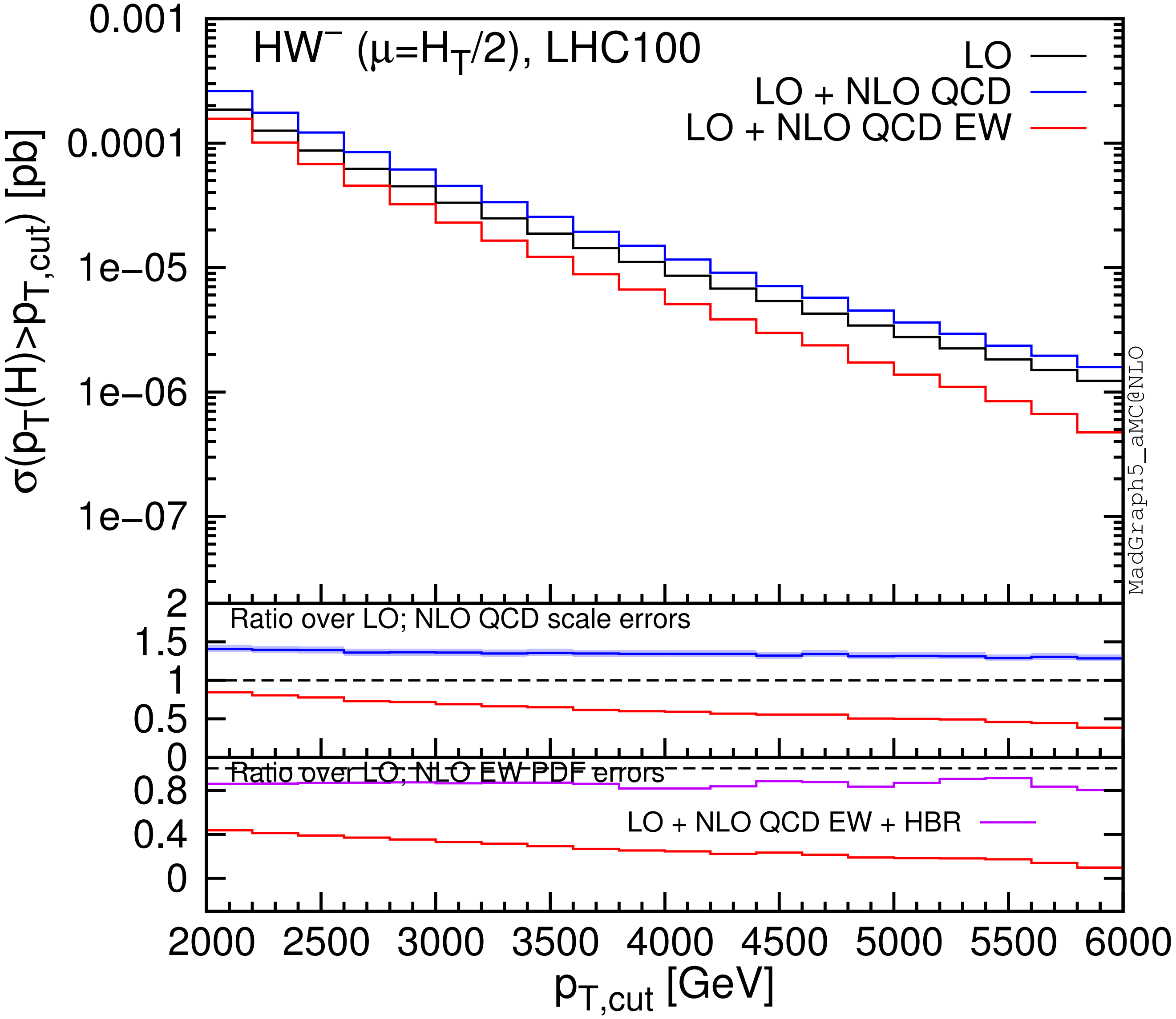
photon PDF **NO**

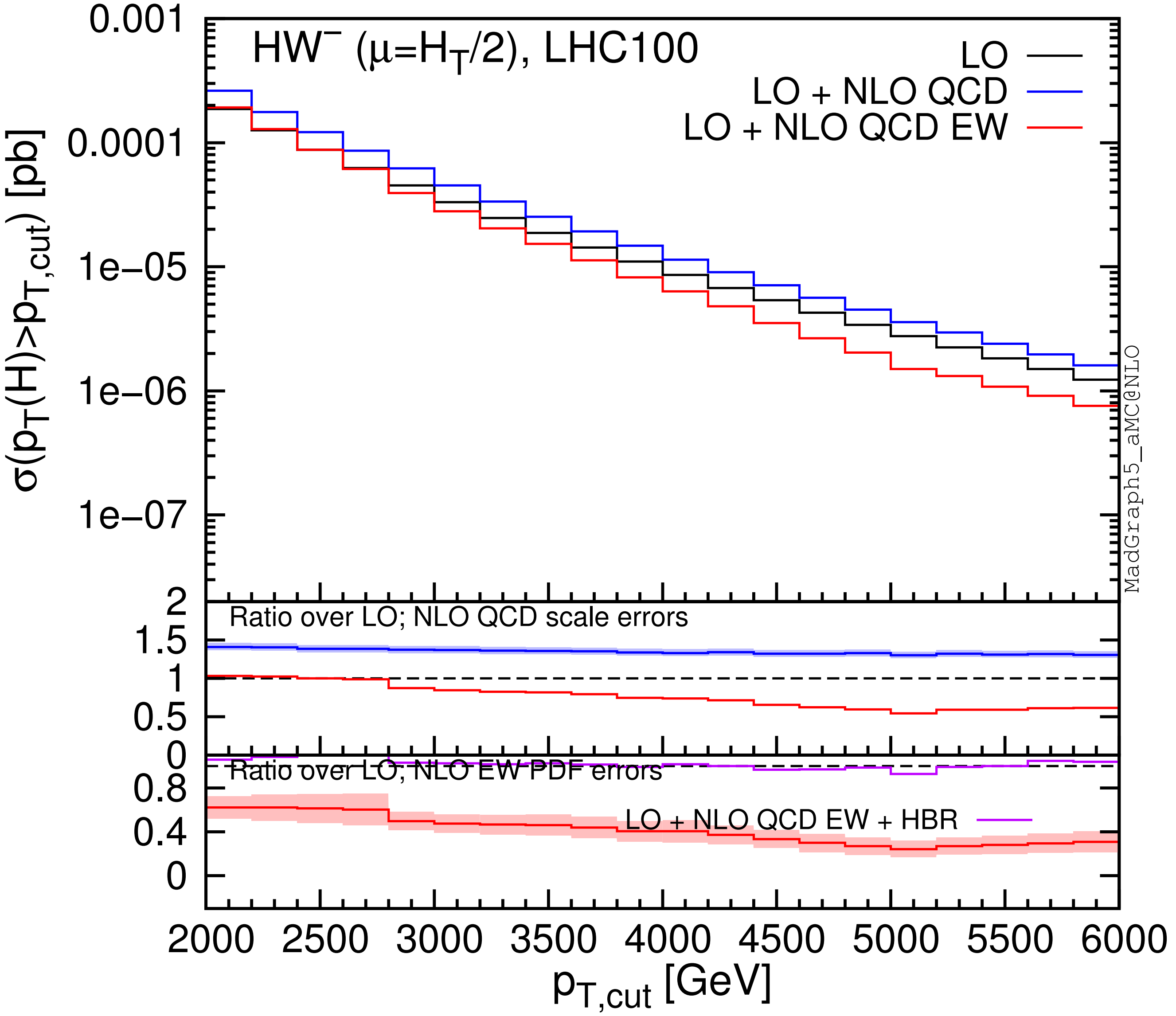


photon PDF **YES**

HW

cumulative plots



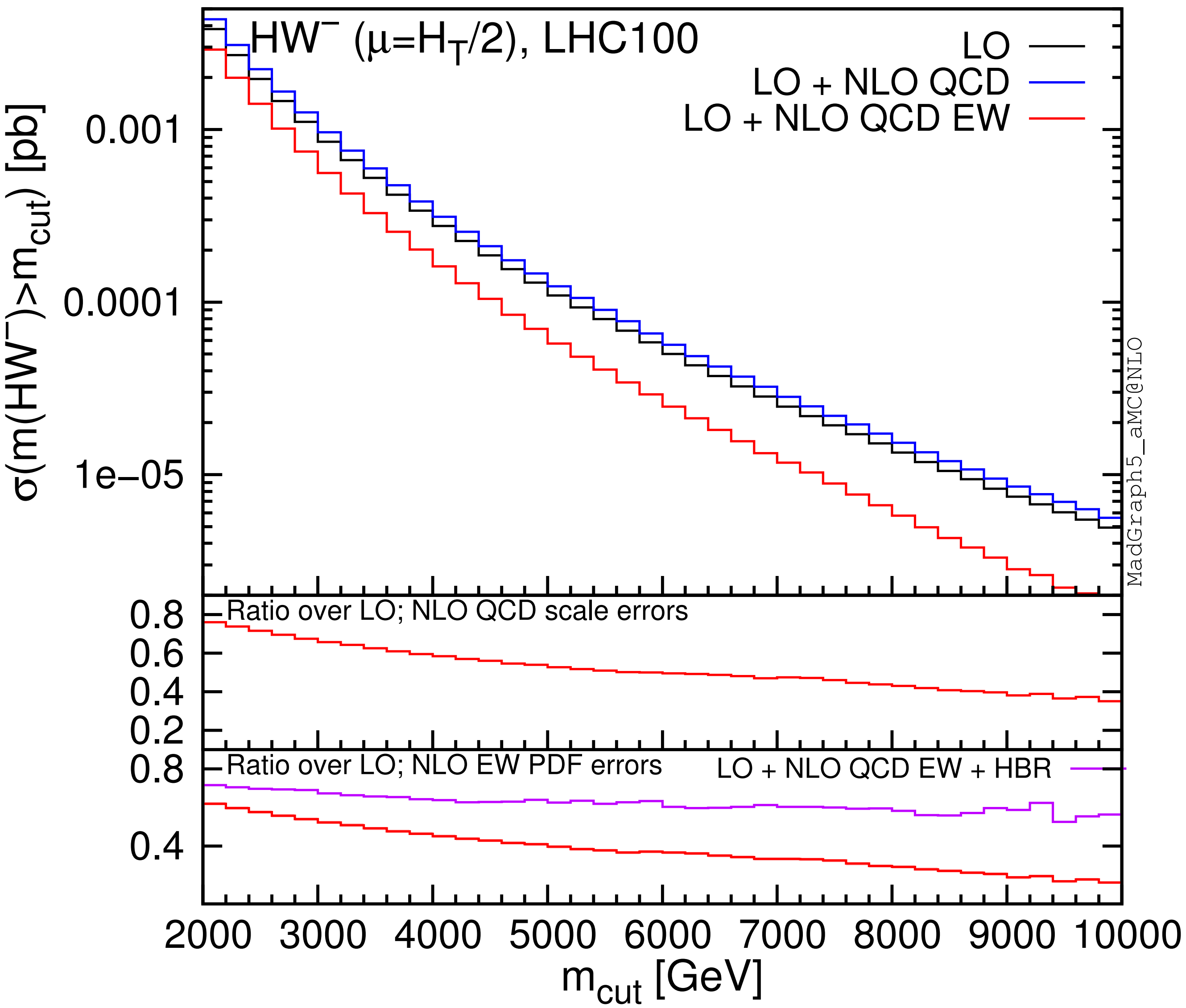


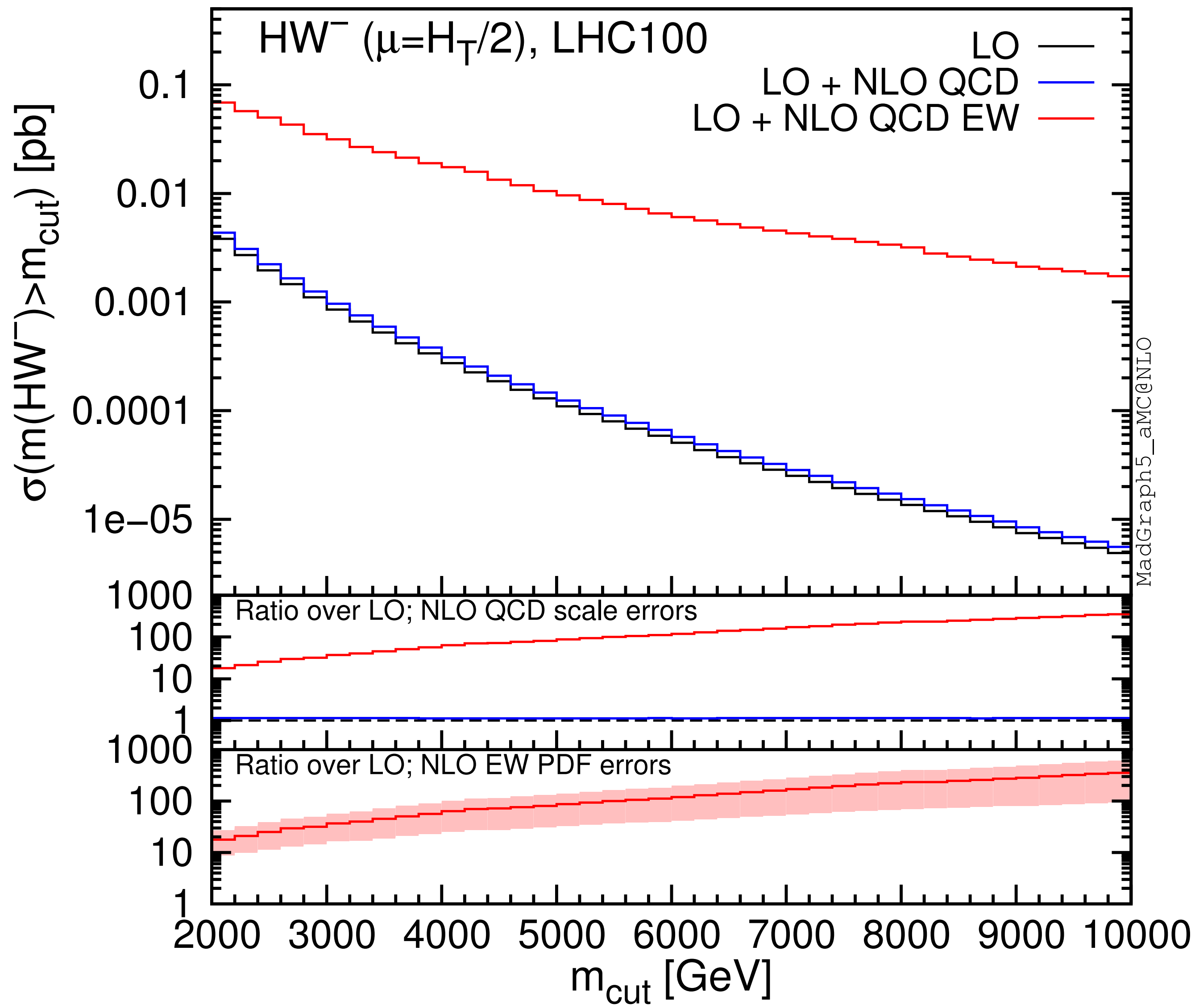
photon PDF **NO**

photon PDF **YES**

HW

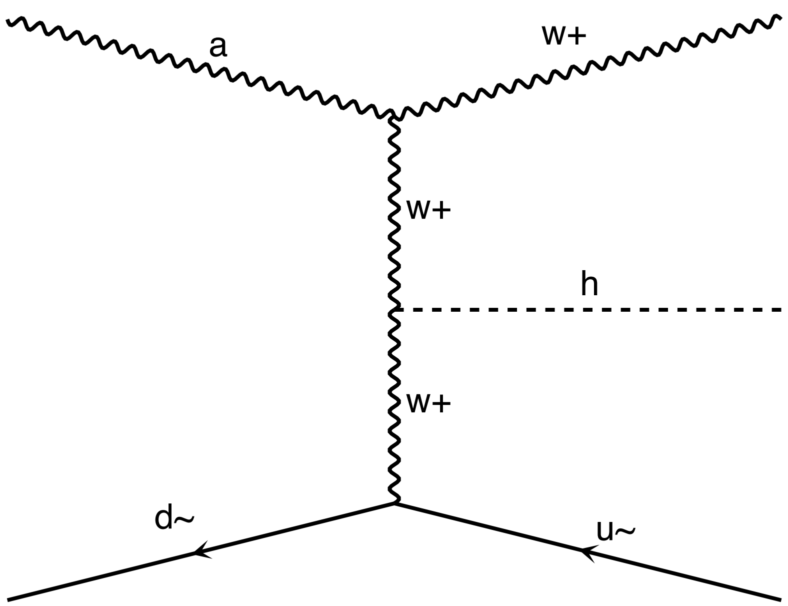
cumulative plots





photon PDF **NO** photon PDF **YES**

HW
what's going on?



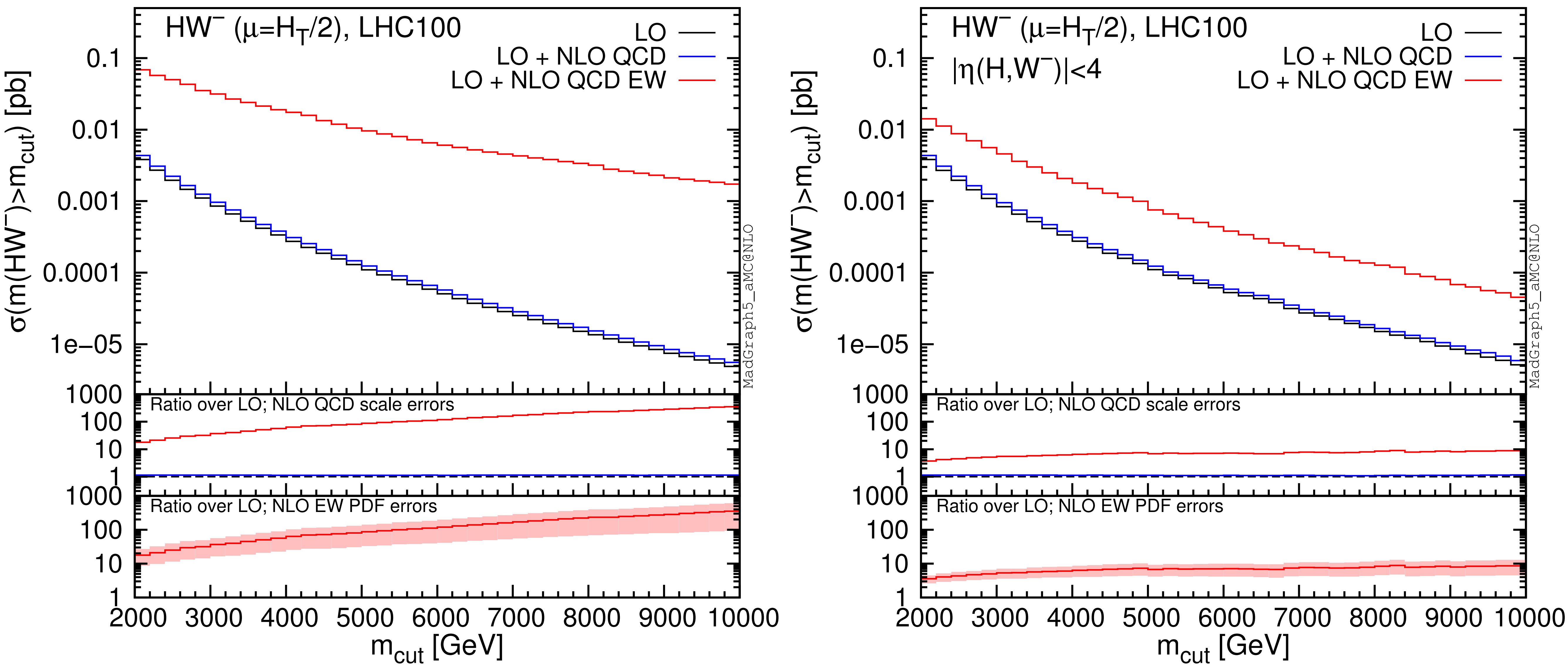
At variance with VV processes, Log^2 enhancements in pt distributions are not present at NLO QCD or EW; there is not photon-quark or gluon-quark to Higgs + jet at tree level that can factorize W or Z soft and collinear emission.

However, HW is produced only via s-channel at LO, while the photon-quark initial state introduces t-channels via W and photon interaction, which are much less suppressed for high m(HW) and lead to huge (100-600) K-factors.

Heavy Boson Radiation (HBR) is of the same perturbative order and the same numerical size of "genuine" NLO EW corrections.

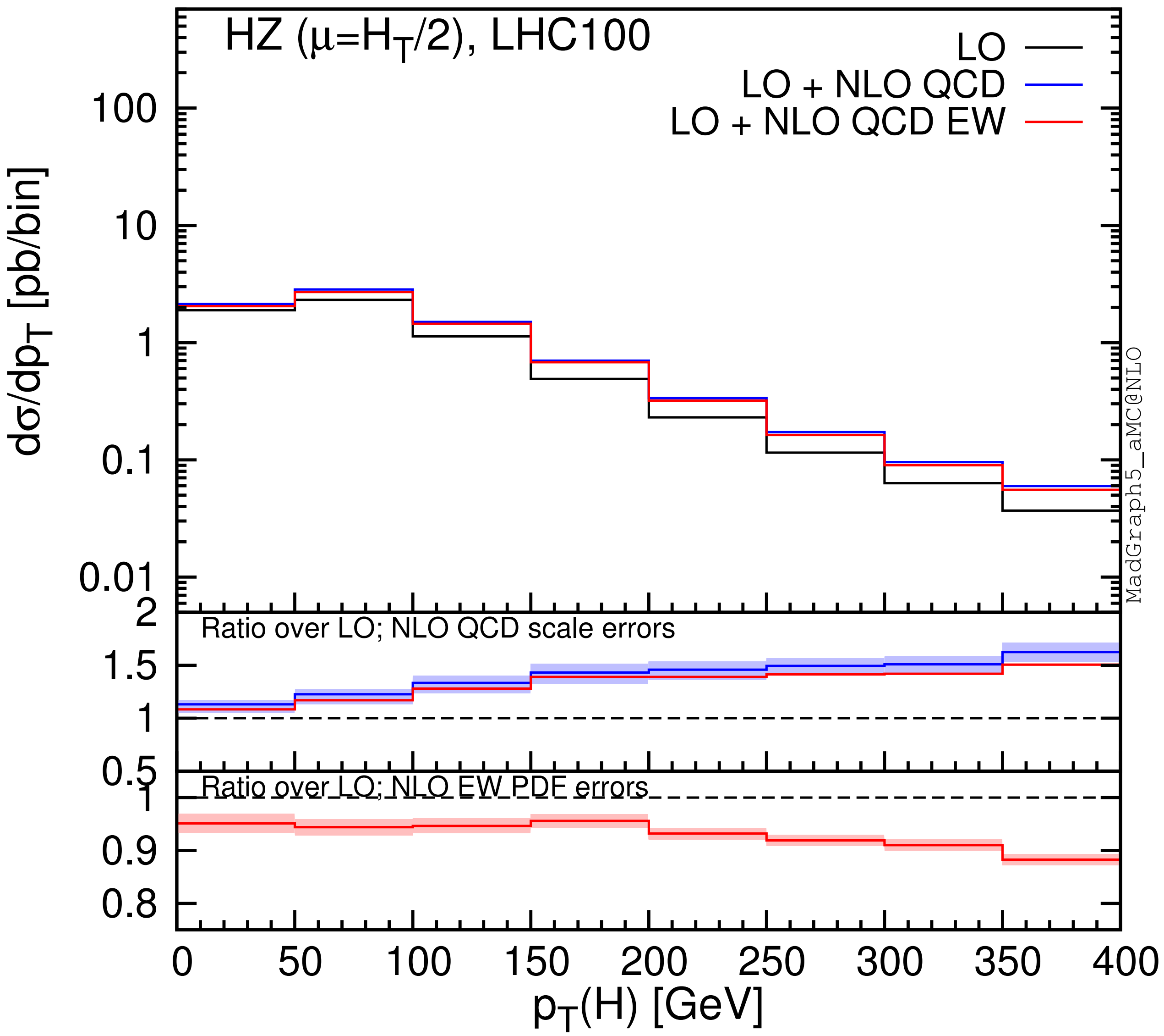
HW

what if additional cuts are applied?

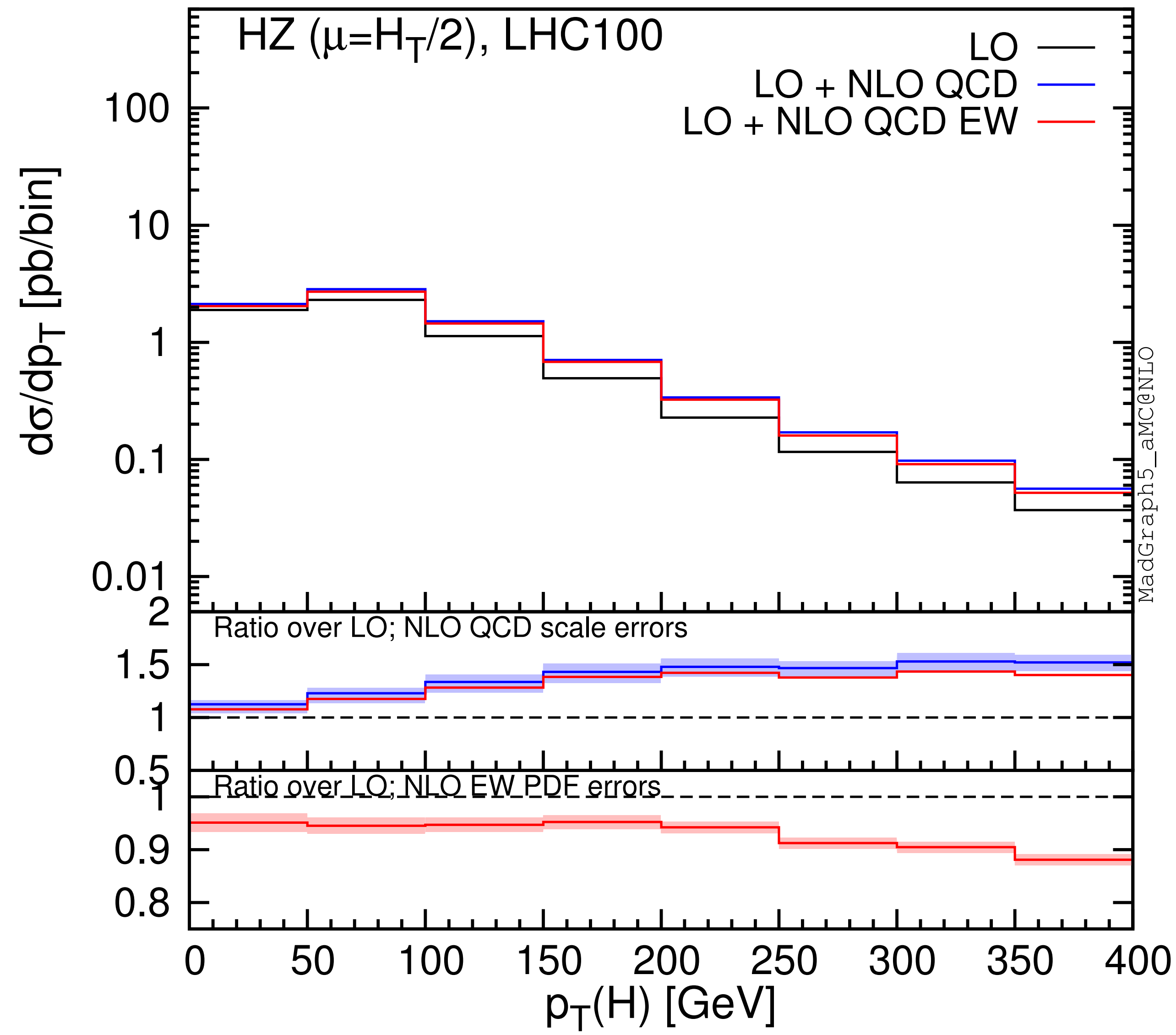


Cuts on H and W pseudo rapidities strongly reduce the photon-quark contribution at high m(HW), without affecting LO and NLO QCD results. Besides HW, **cuts can in general strongly affect size of radiative corrections: Which cuts and on which particles at 100 TeV?**

HZ
differential plots



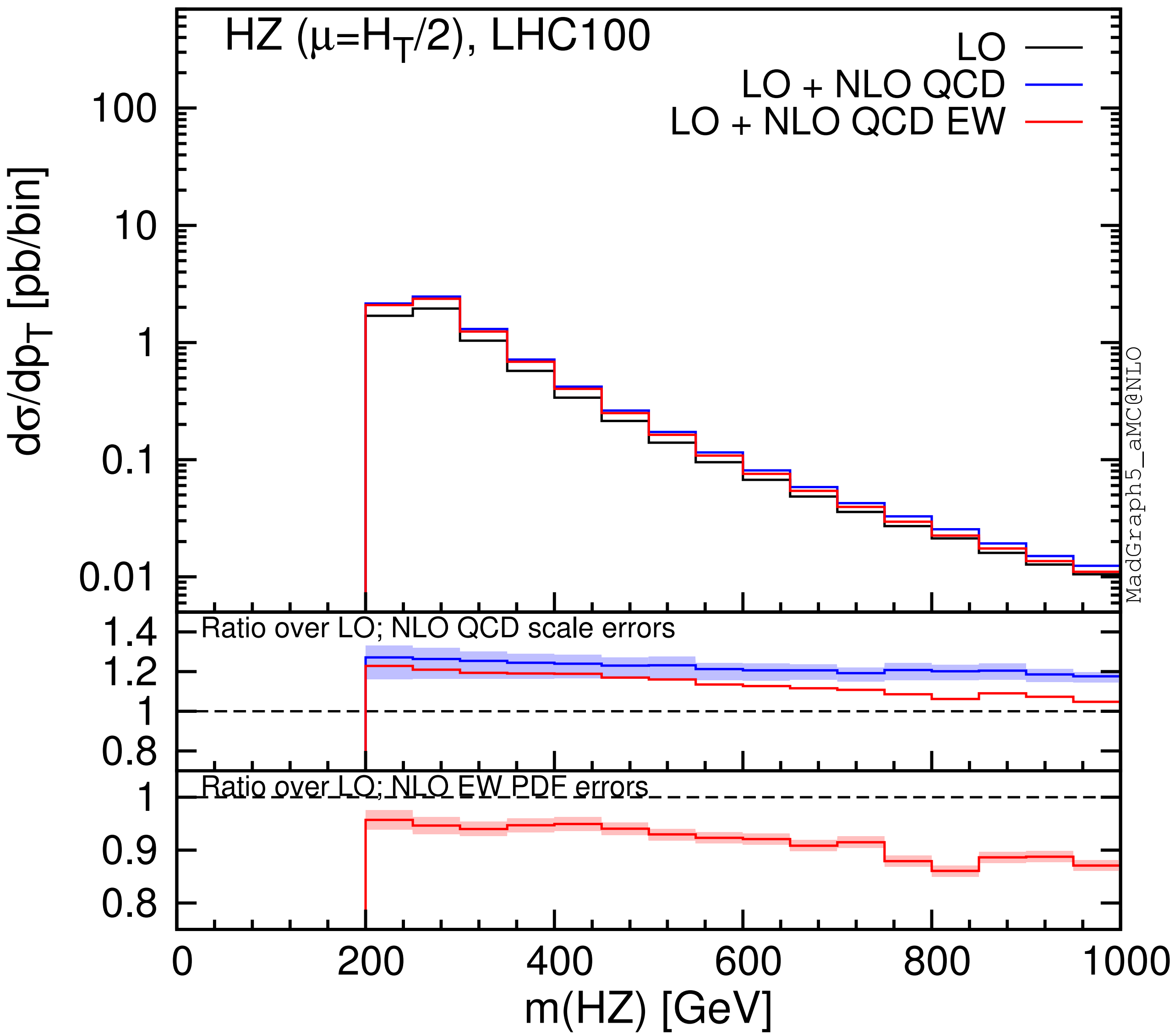
photon PDF **NO**

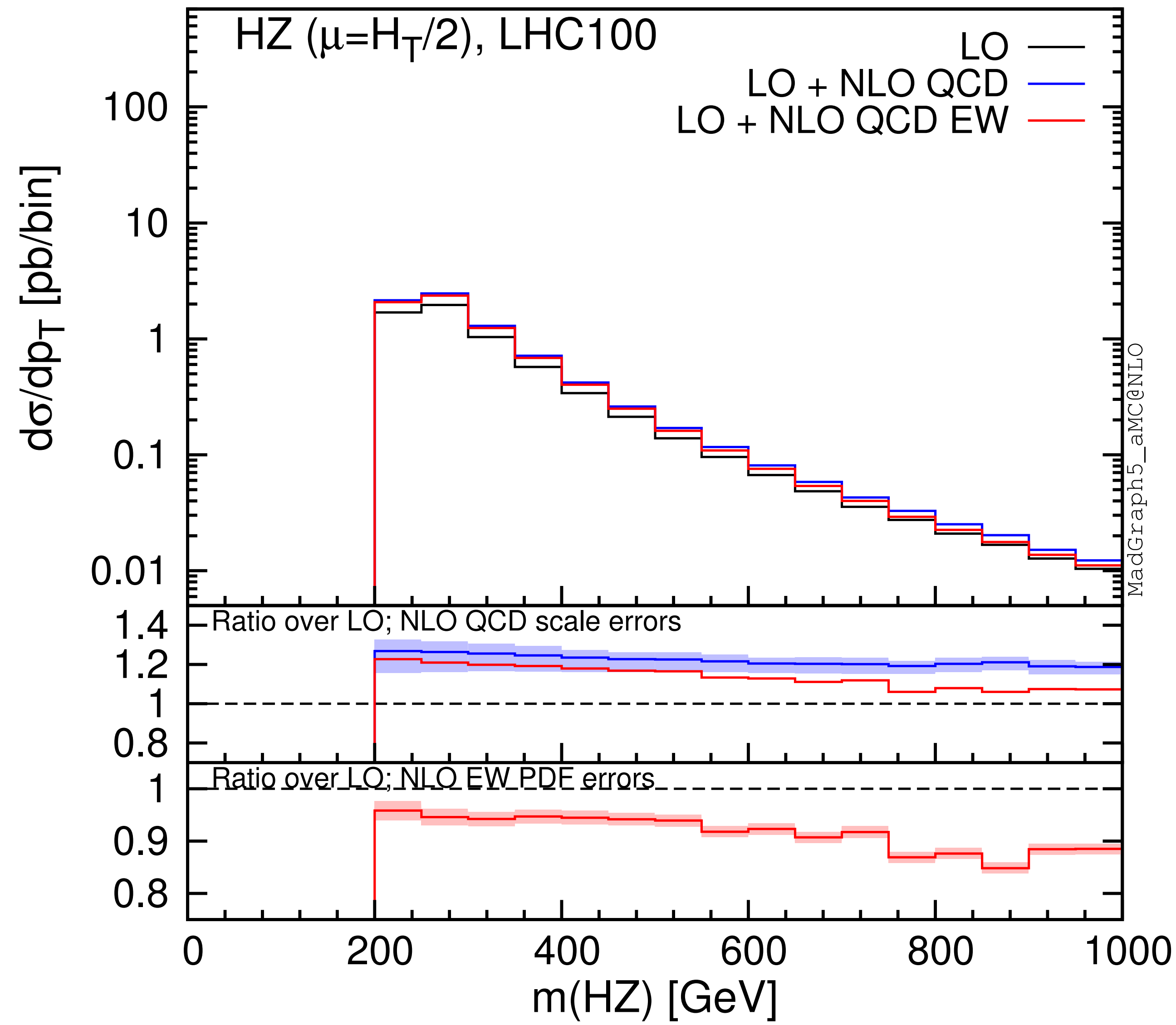


photon PDF **YES**

HZ

differential plots



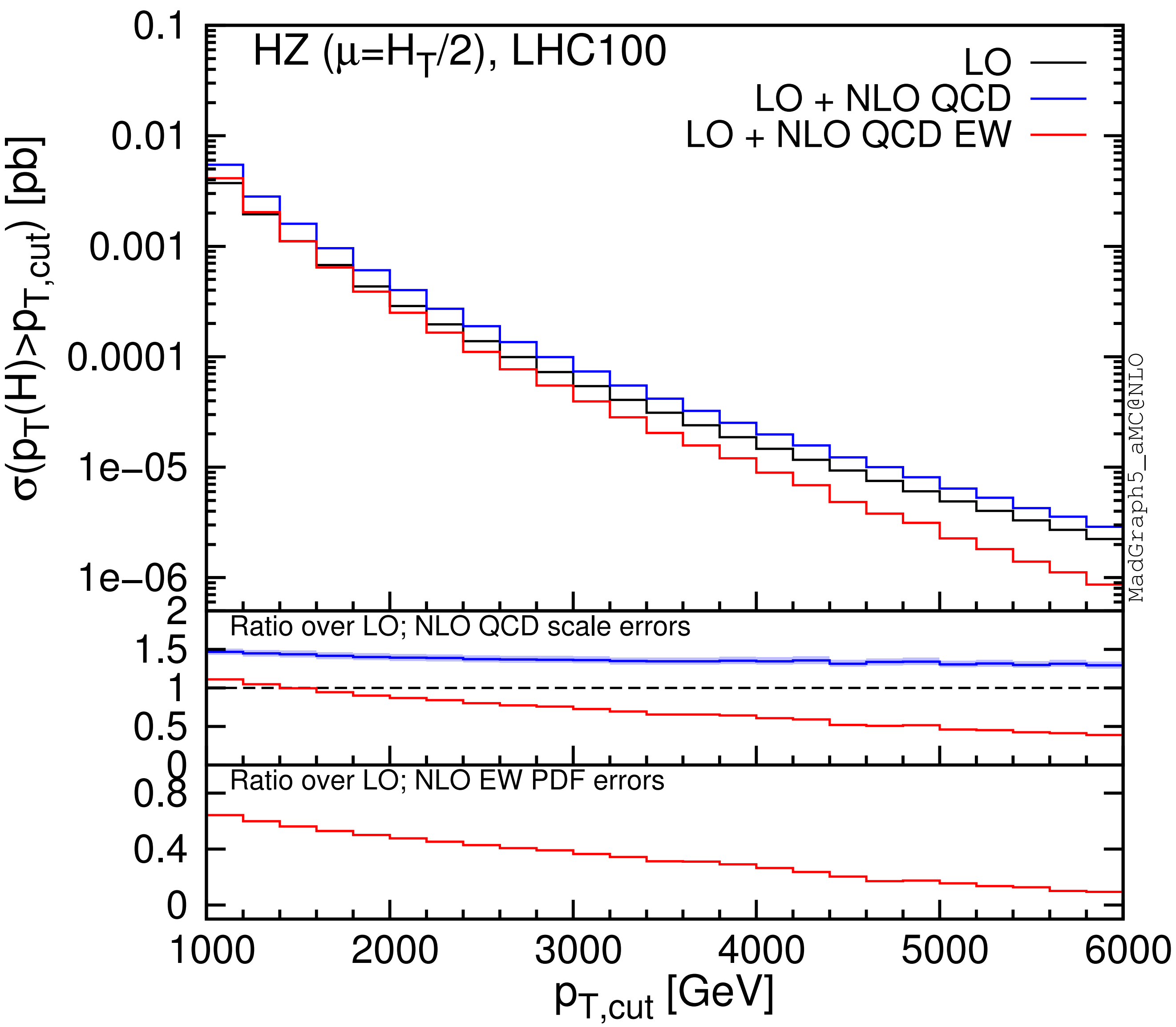


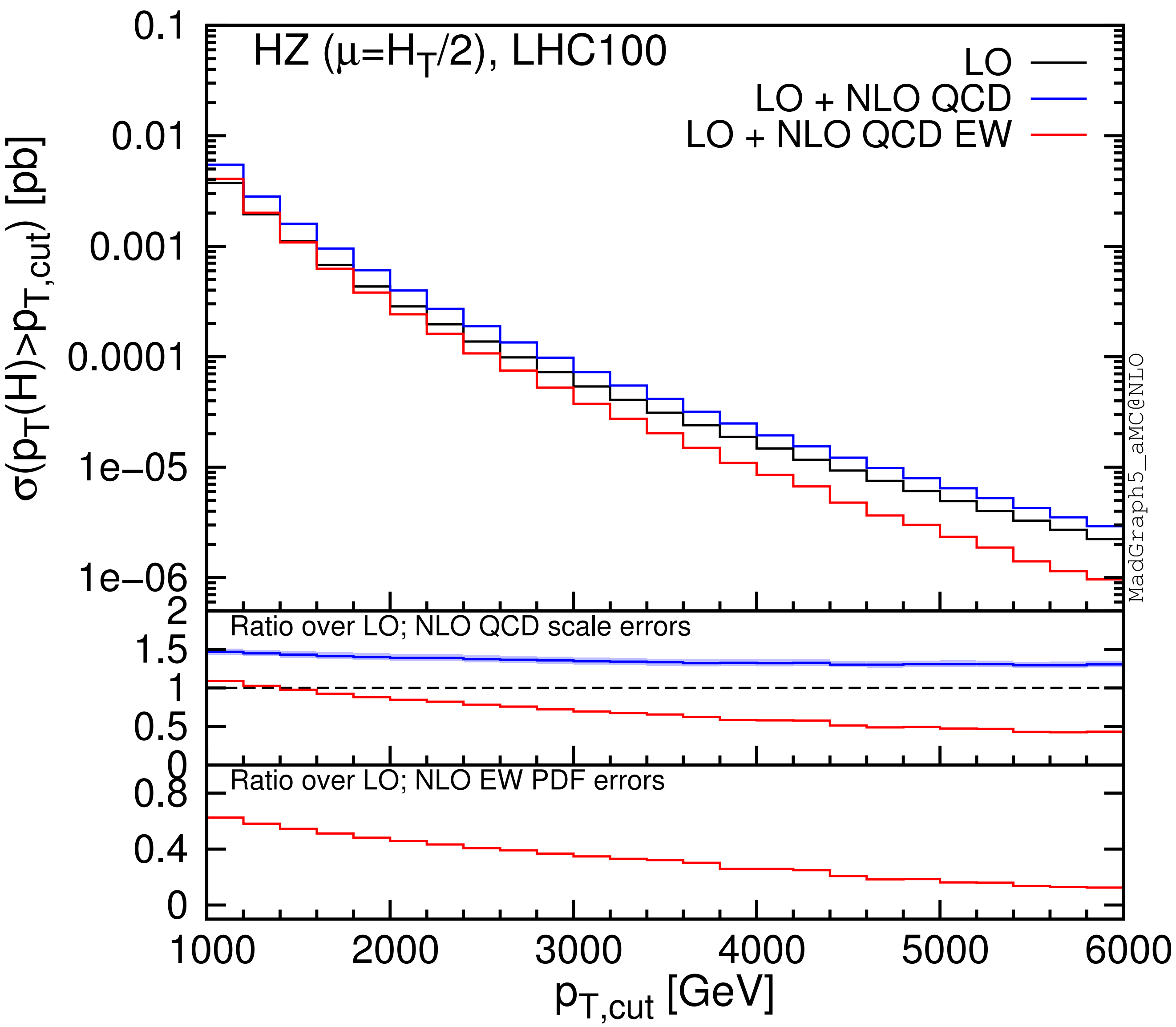
photon PDF **NO**

photon PDF **YES**

HZ

cumulative plots



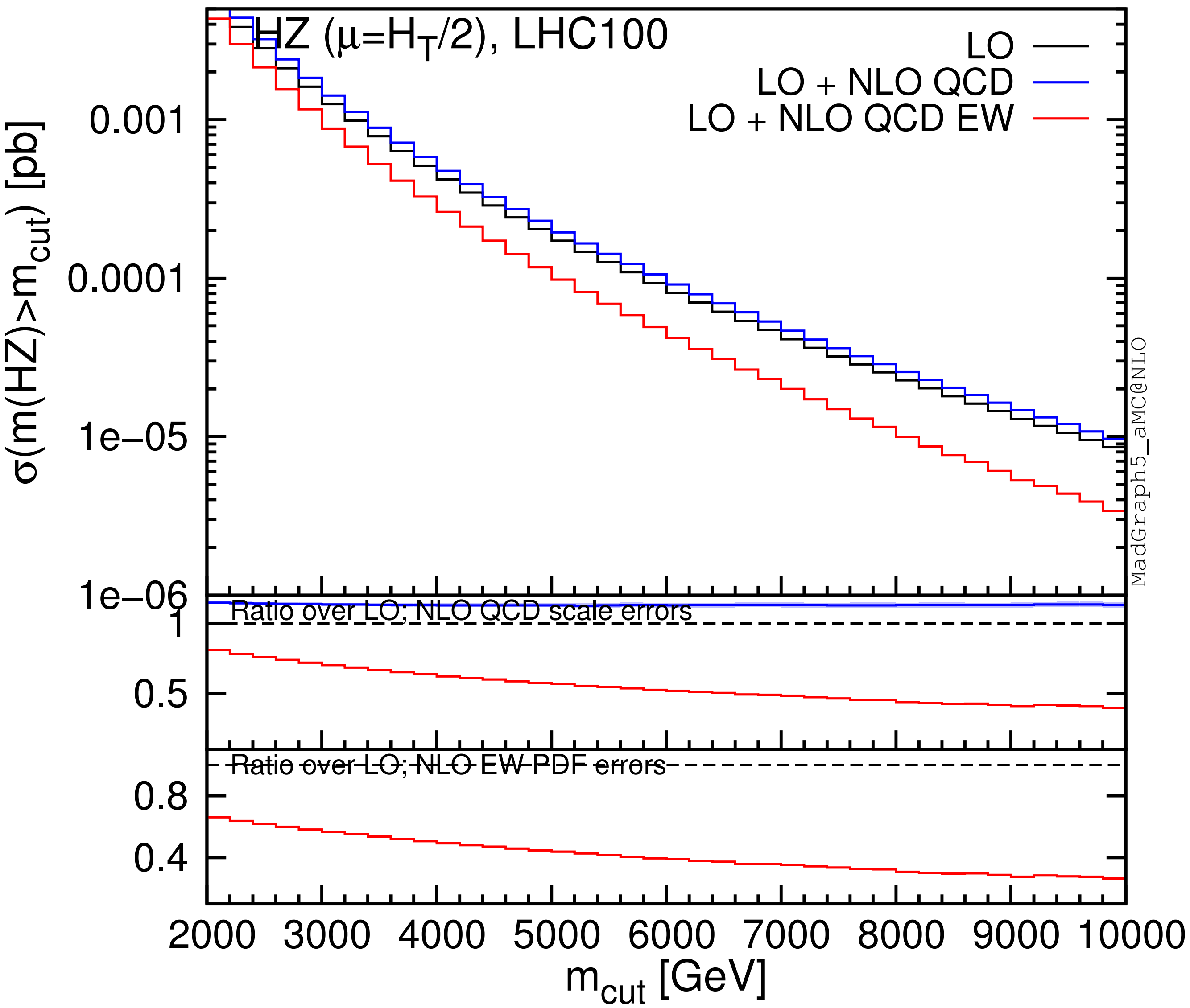


photon PDF **NO**

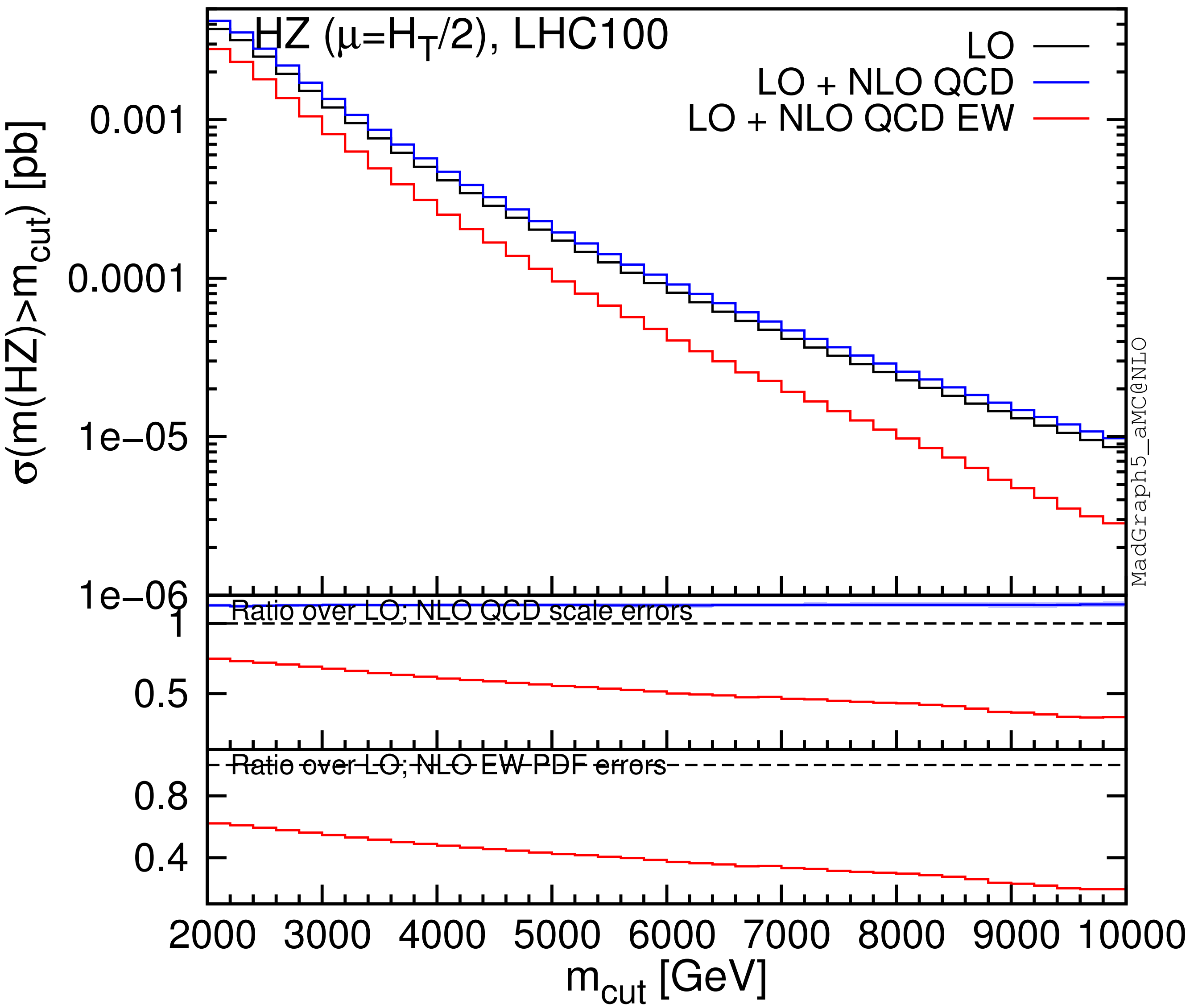
photon PDF **YES**

HZ

cumulative plots

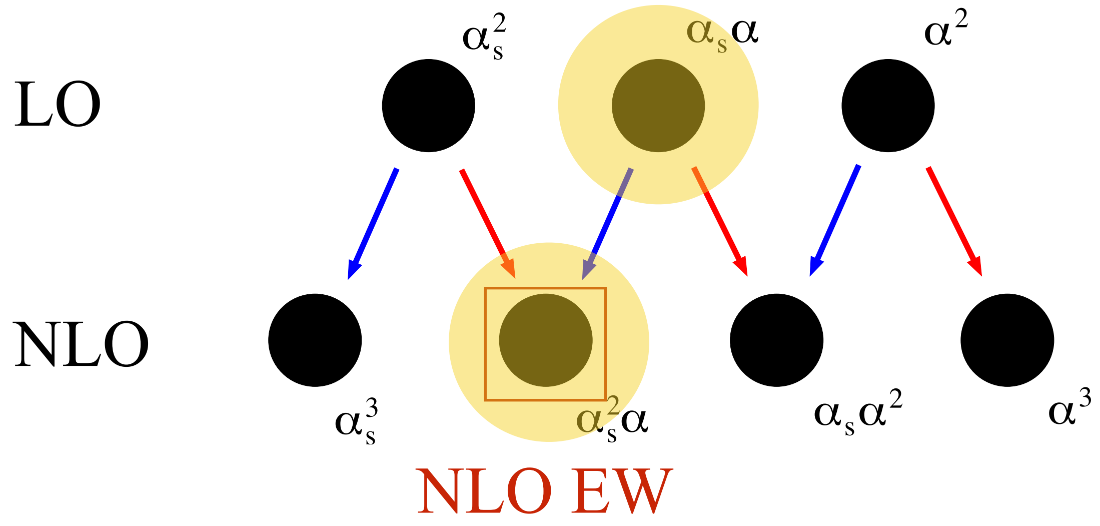


photon PDF **NO**



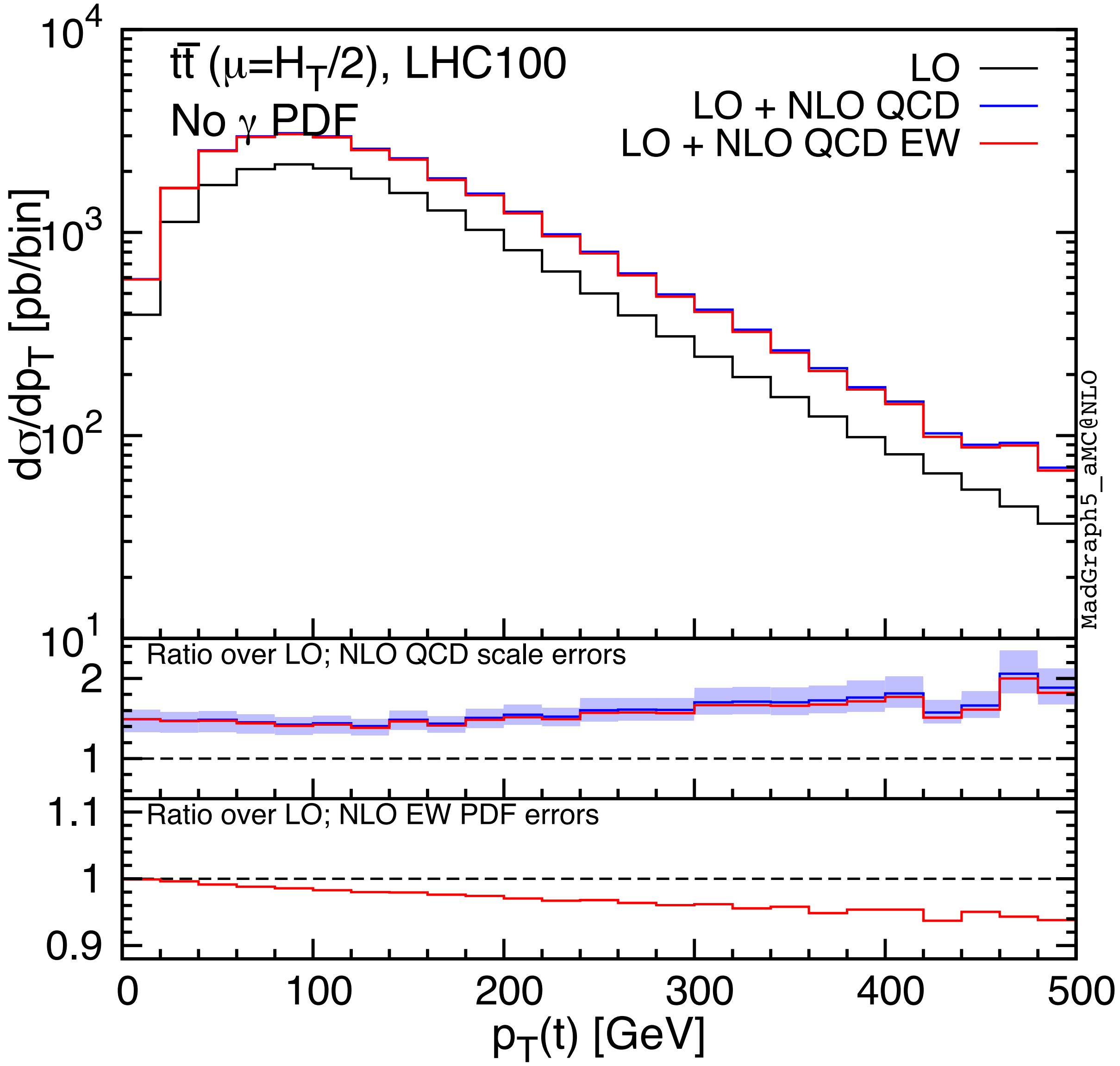
photon PDF **YES**

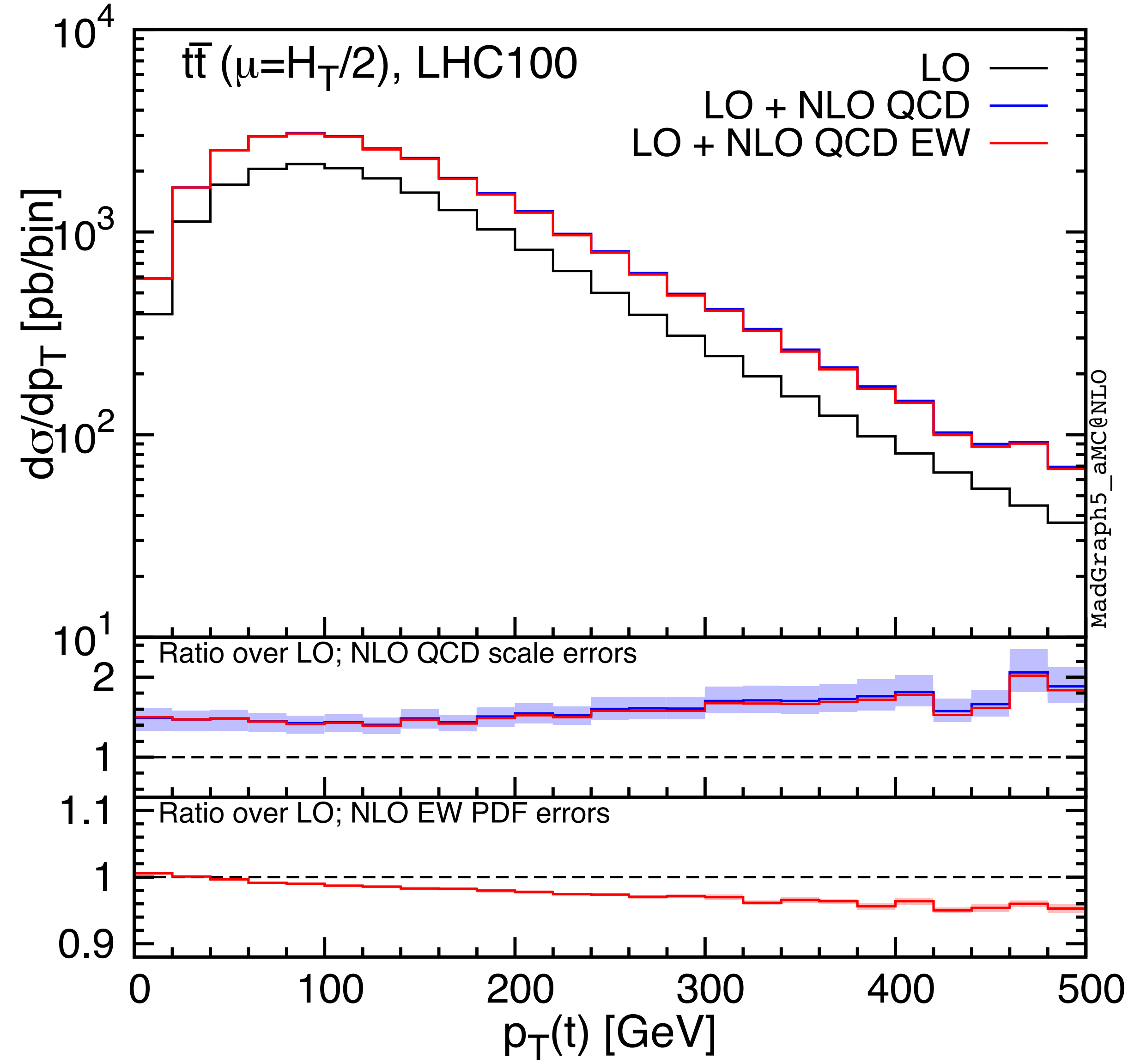
top-quark pair production



$t\bar{t}$

differential plots

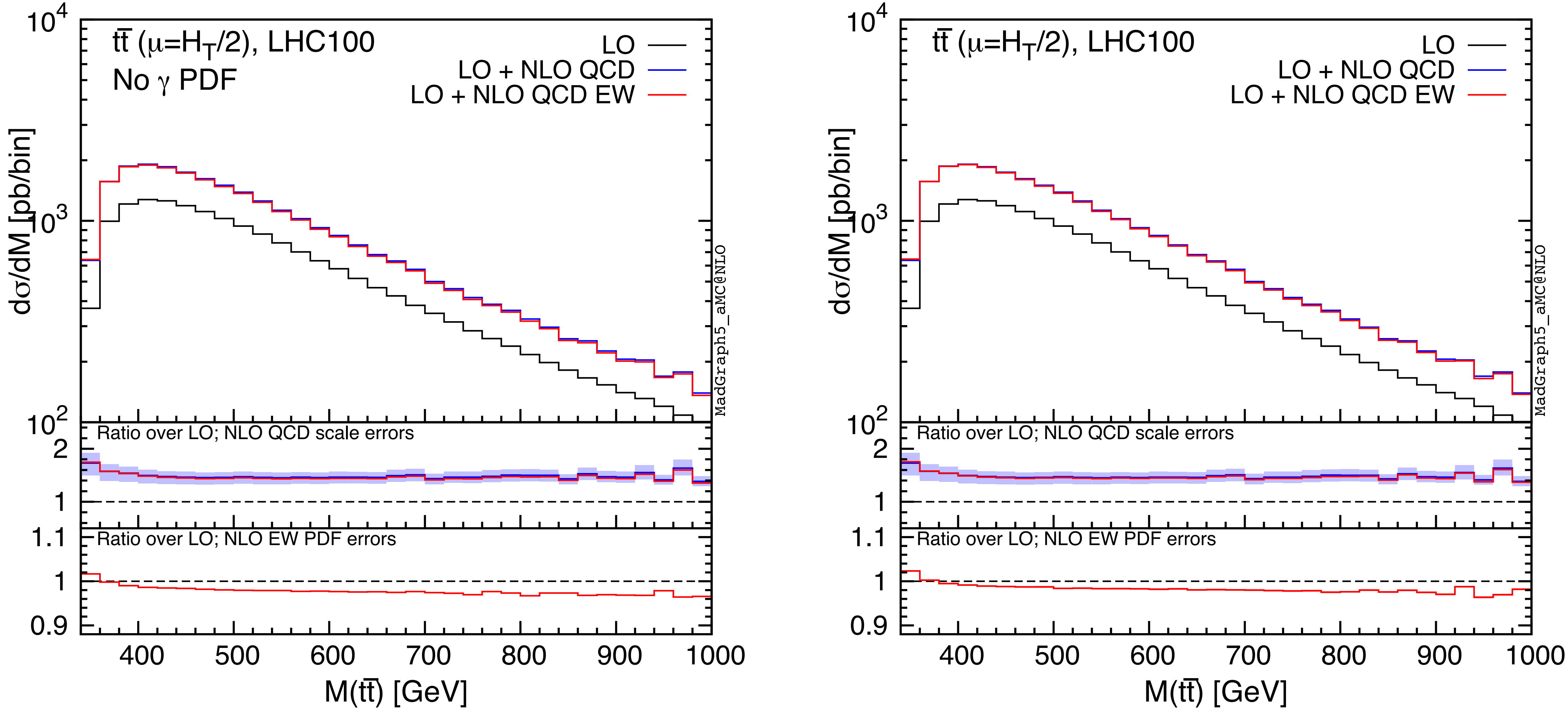




photon PDF **NO** photon PDF **YES**

$t\bar{t}$

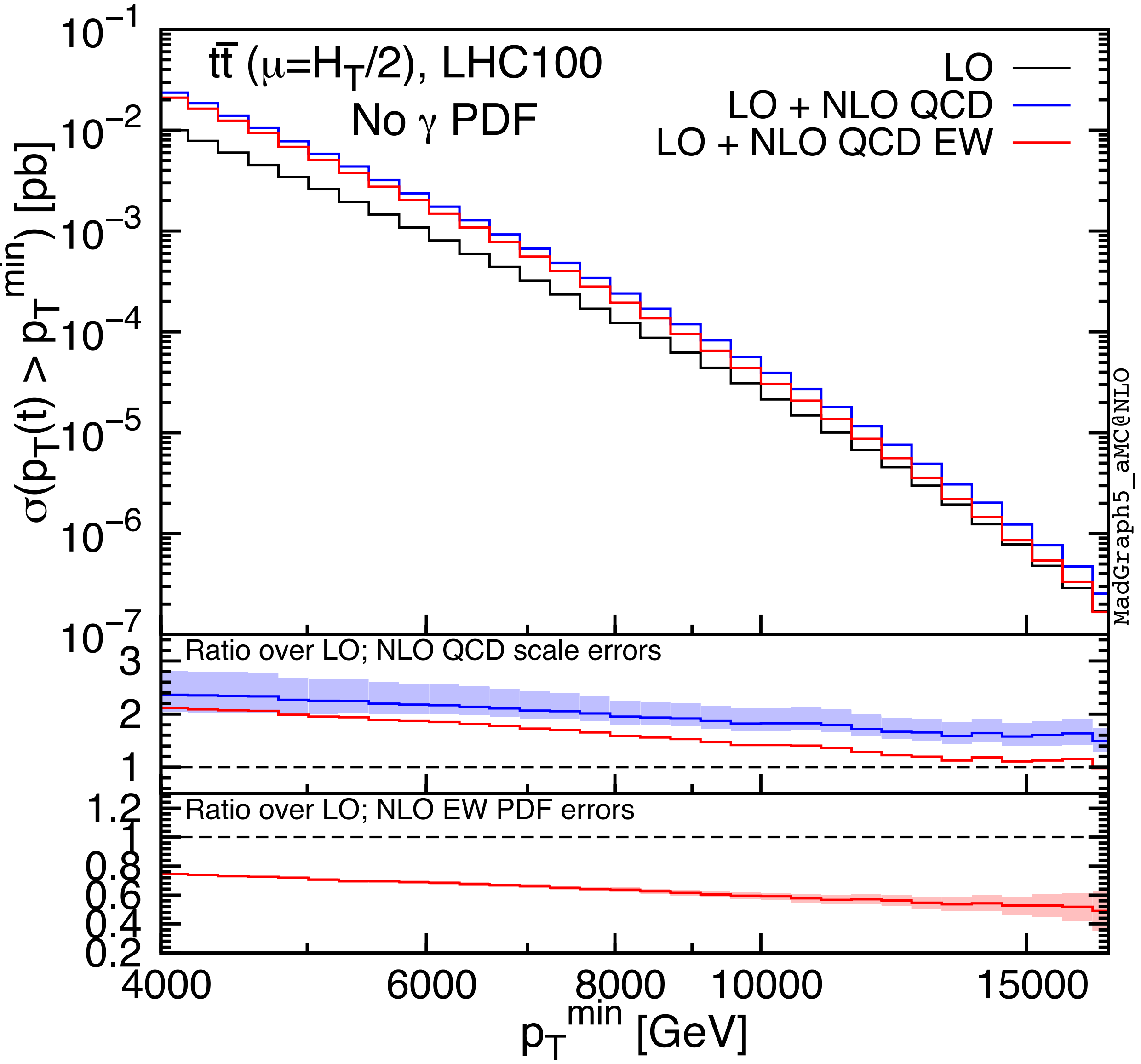
differential plots

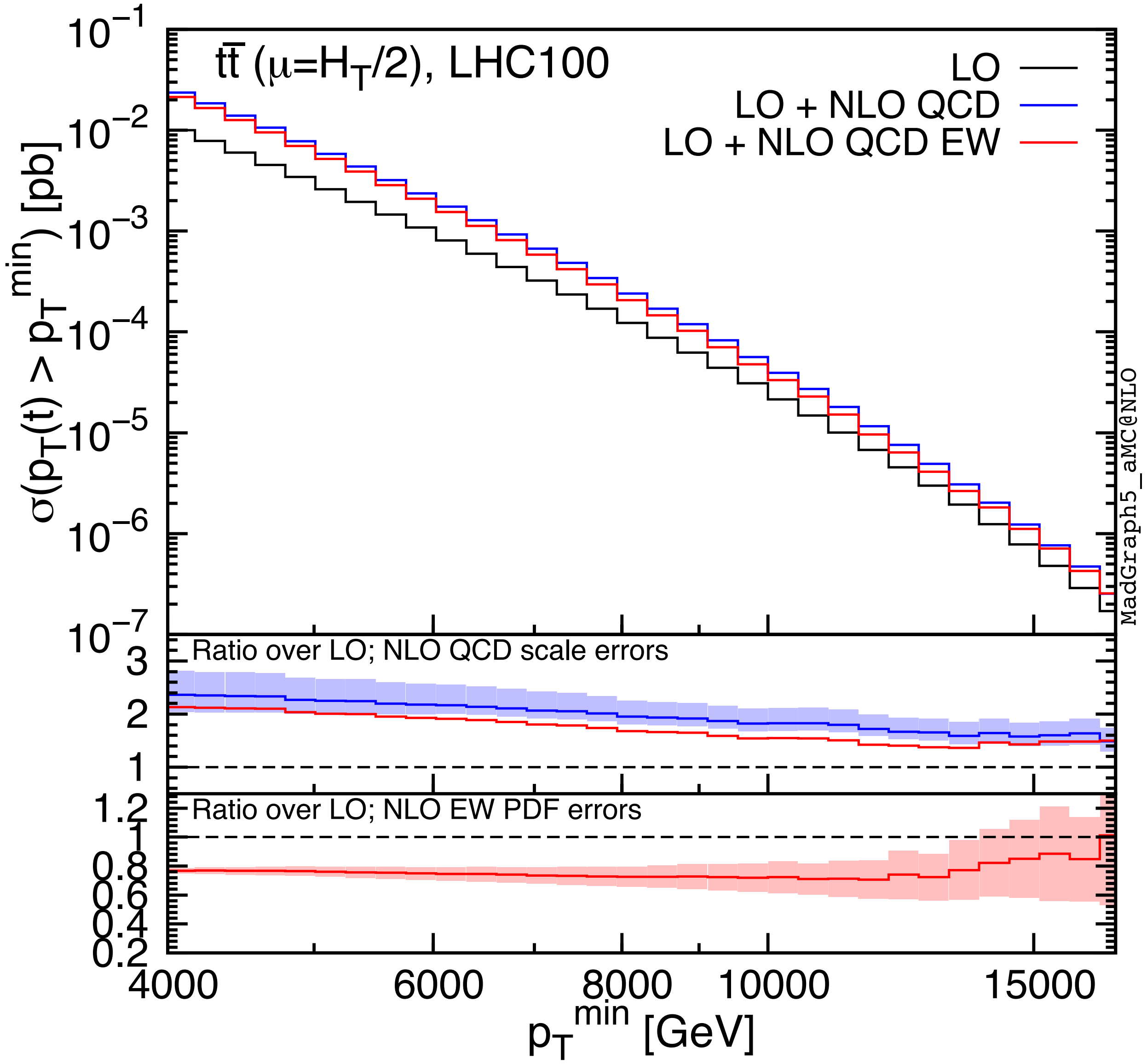


photon PDF **NO** photon PDF **YES**

$t\bar{t}$

cumulative plots



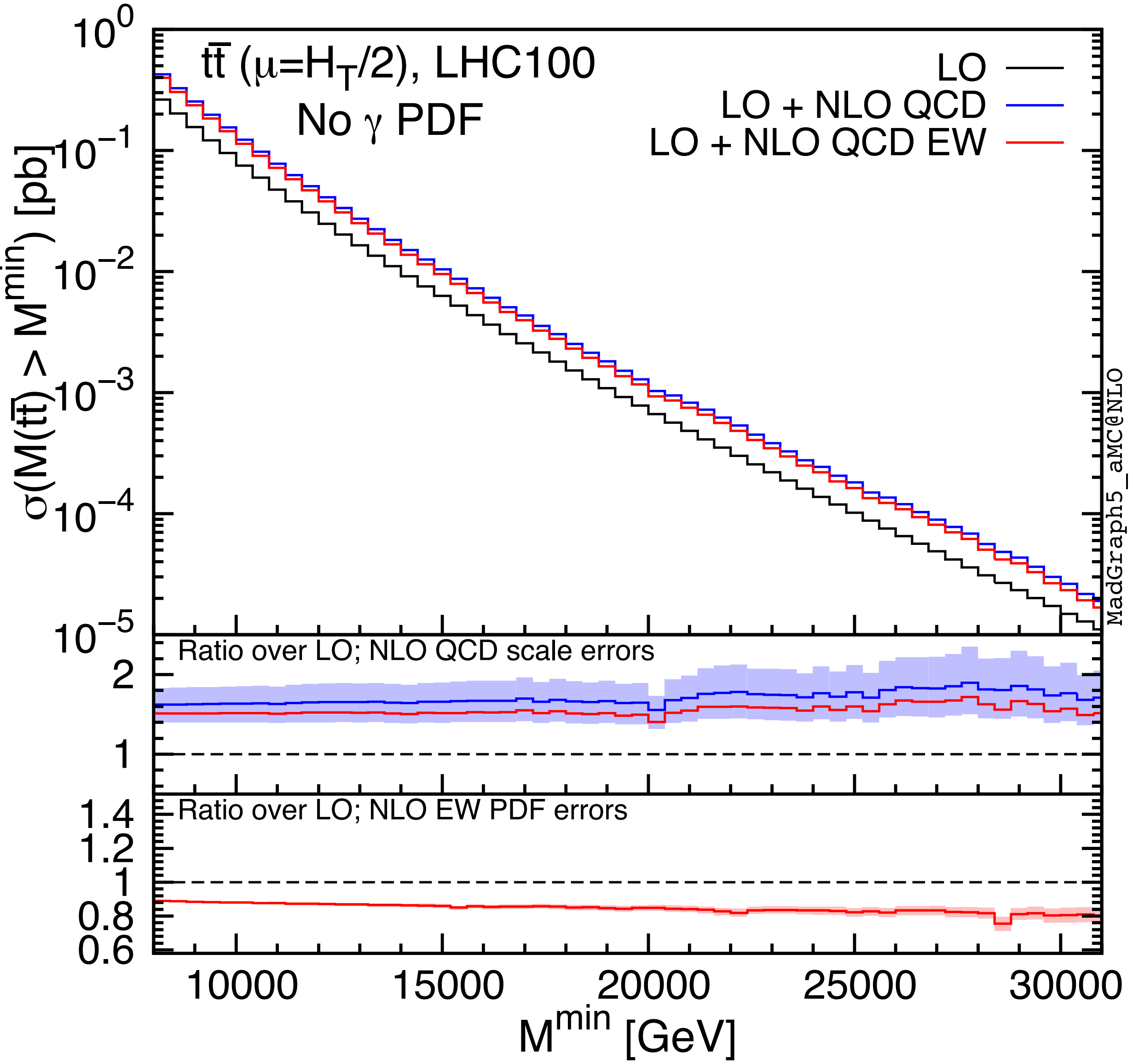


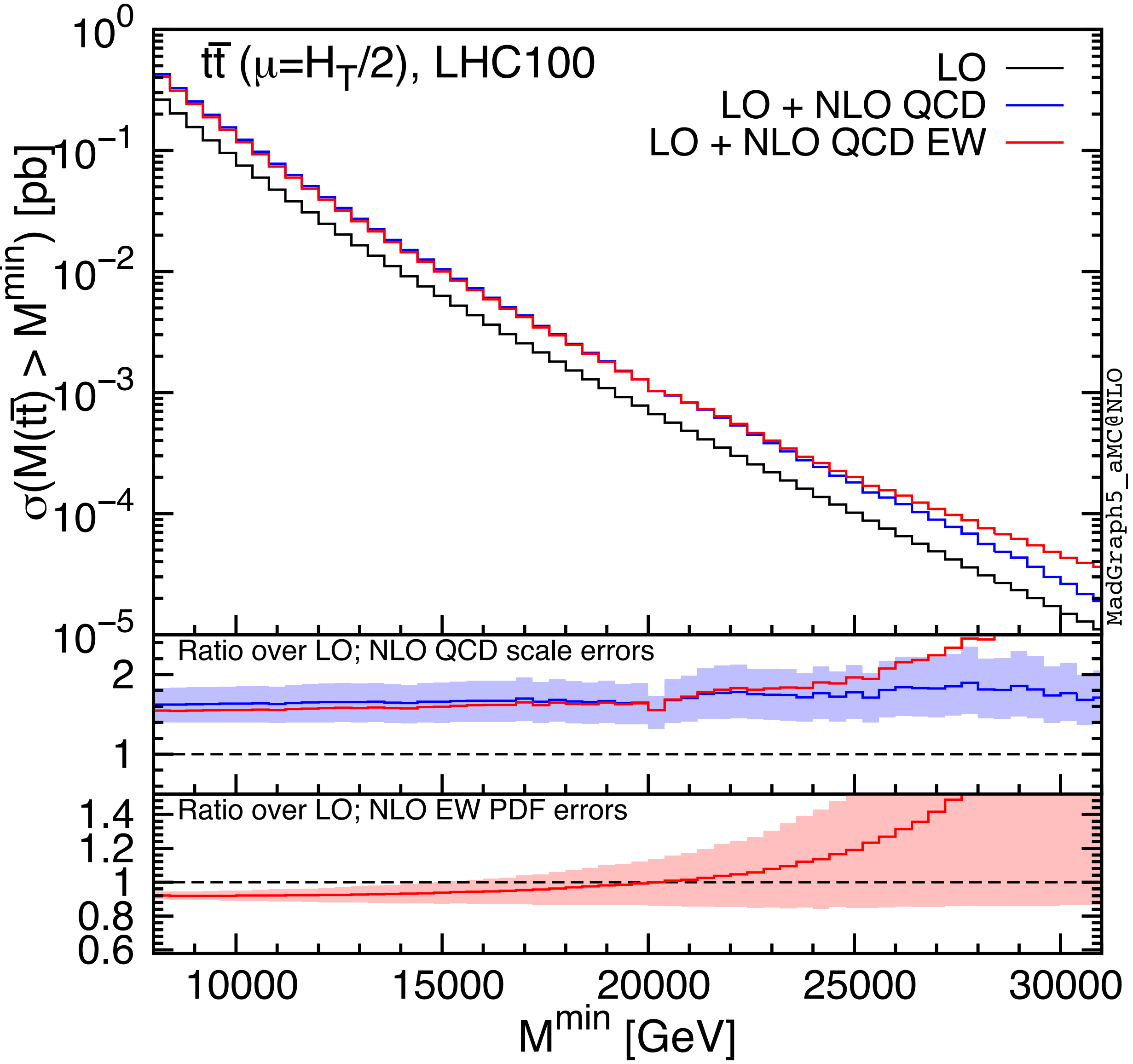
photon PDF **NO**

photon PDF **YES**

$t\bar{t}$

cumulative plots

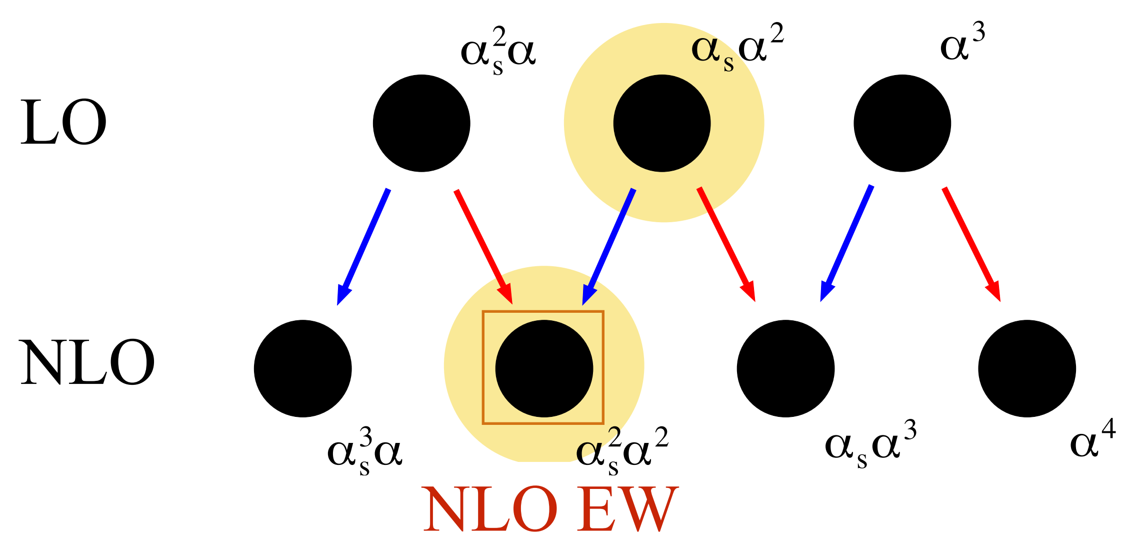




photon PDF **NO** photon PDF **YES**

some additional results for

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



NLO EW corrections and HBR

$t\bar{t}H$

$t\bar{t}H$: $\delta(\%)$	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

$t\bar{t}Z$

$t\bar{t}Z$: $\delta(\%)$	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

$t\bar{t}W^-$

$t\bar{t}W^-$: $\delta(\%)$	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

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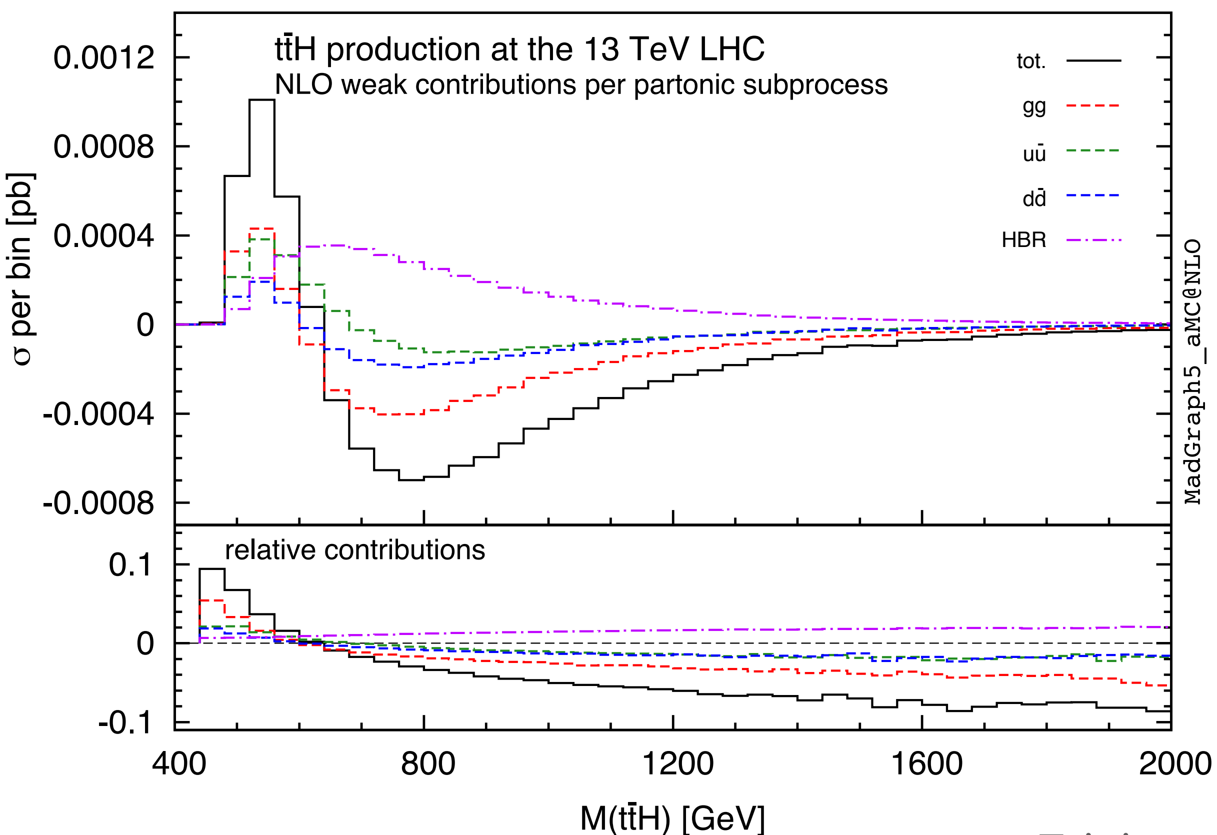
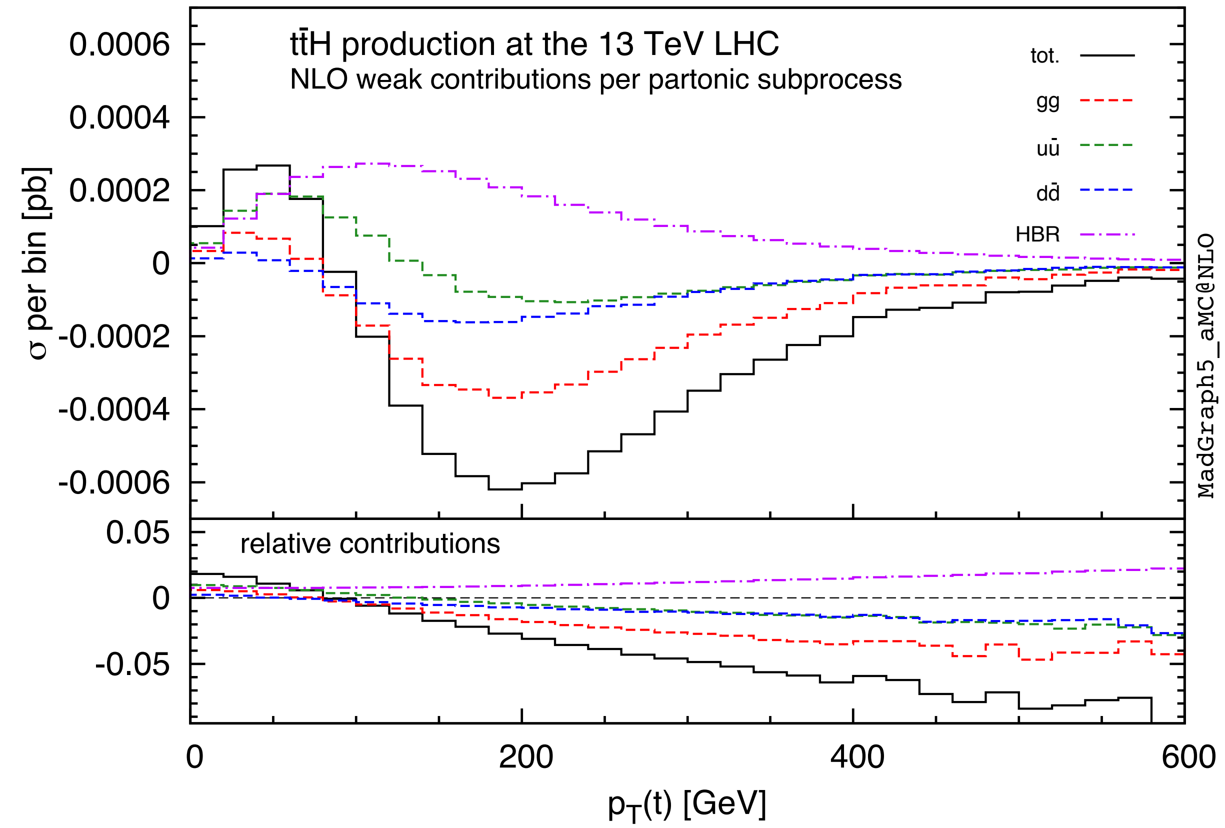
NLO Weak corrections for $t\bar{t}H$





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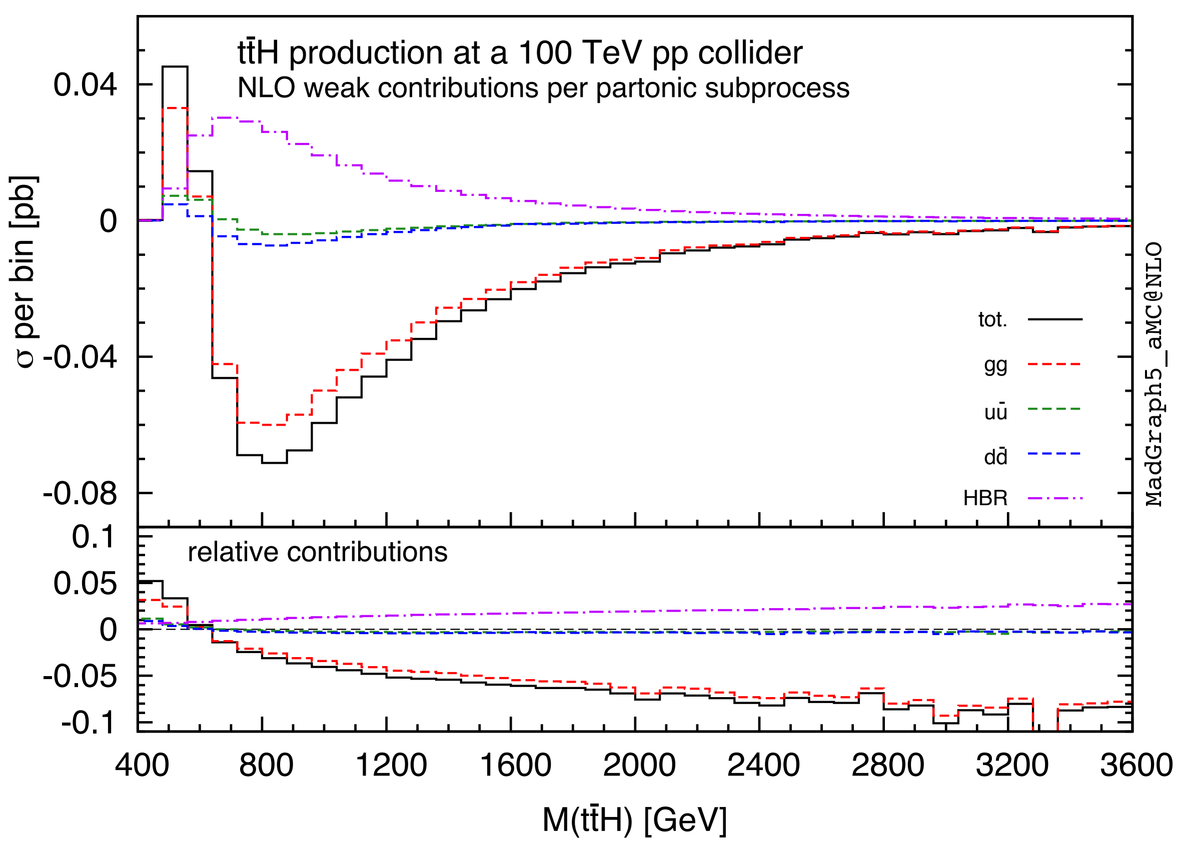
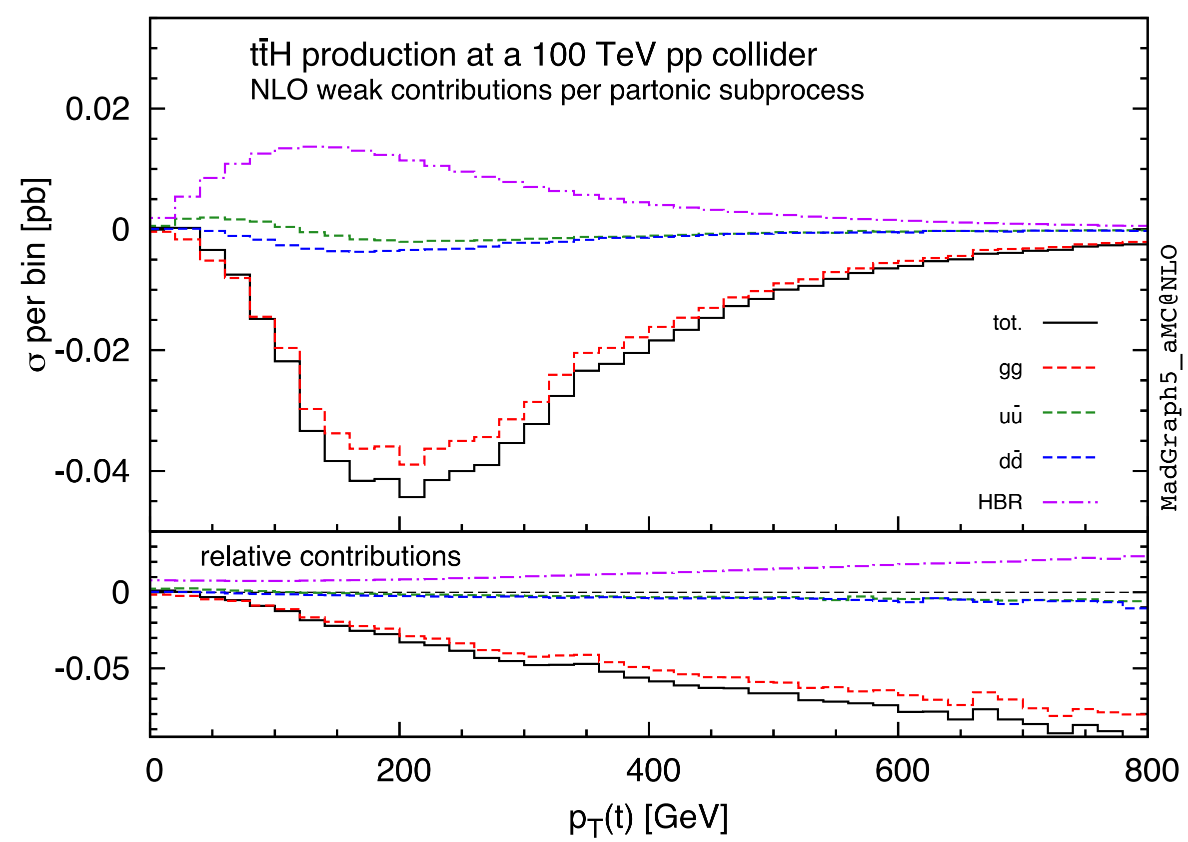
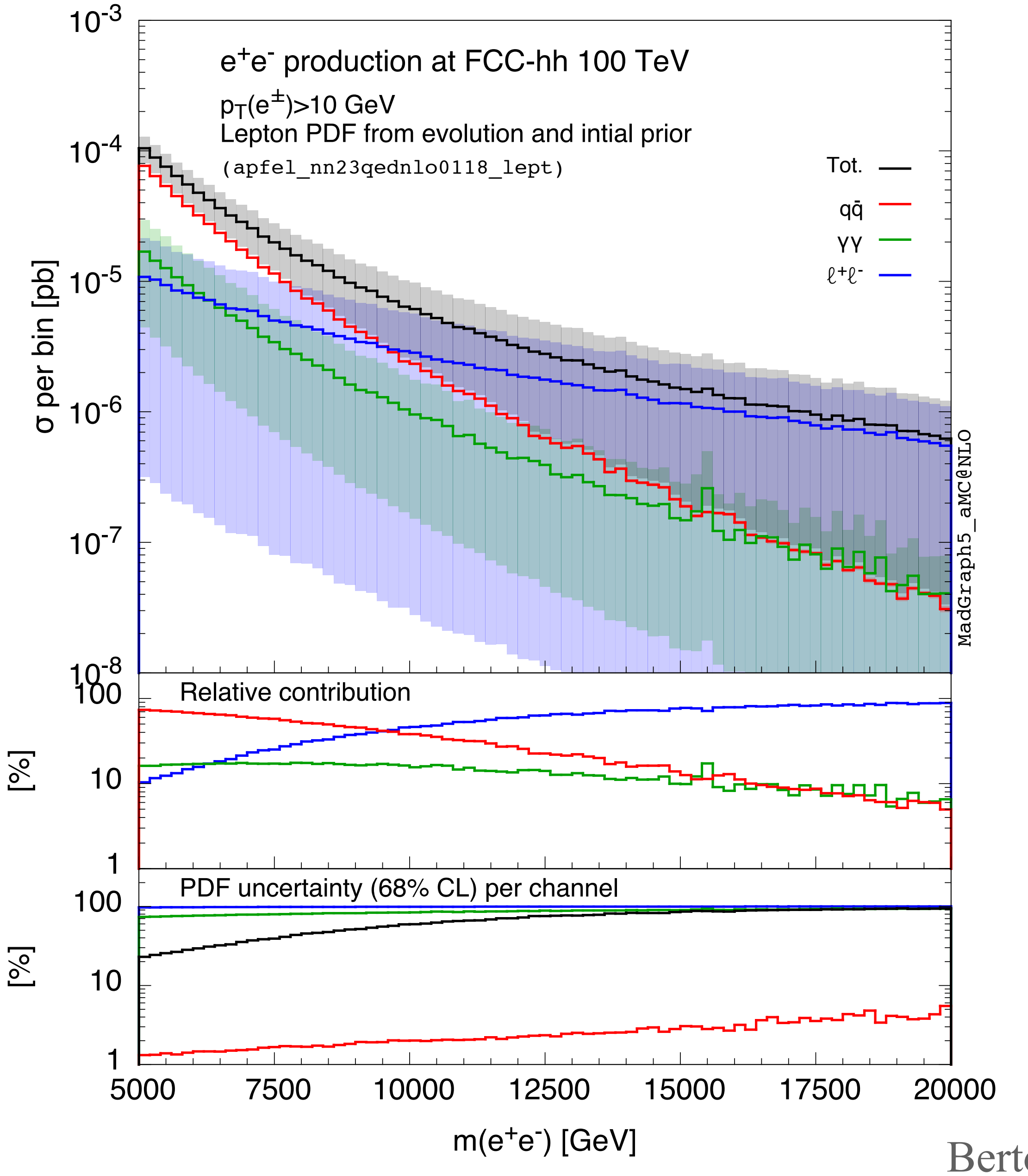
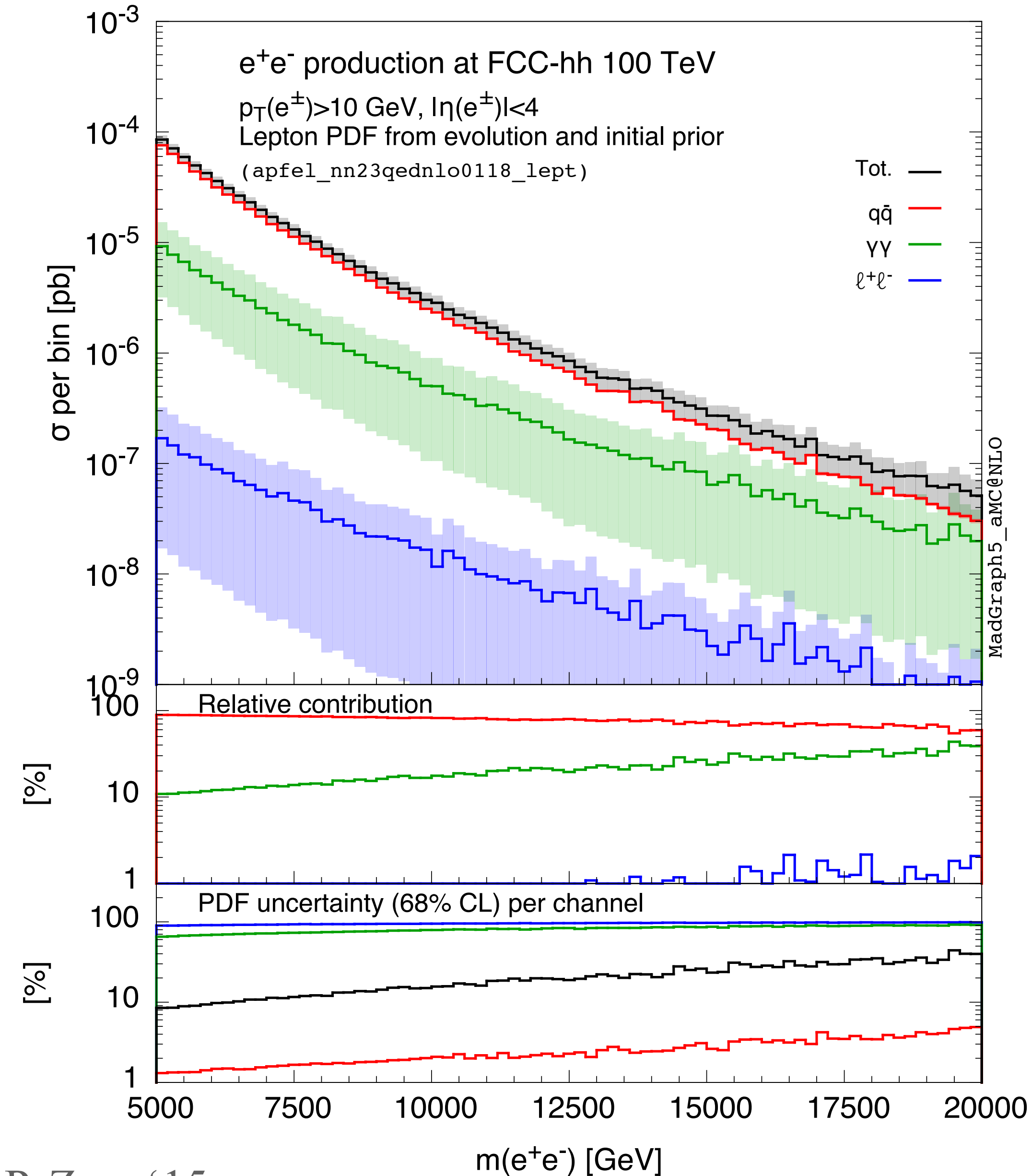




lepton PDFs





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The impact of lepton PDFs is expected to be small also at 100 TeV when “reasonable” cuts are applied. Leptons PDF are naturally involved when EW corrections to photon-induced processes are considered.

Listen to Stefano’s talk!

CONCLUSION

We analysed pt and invariant-mass distributions of VV, HV and $t\bar{t}$ production at NLO QCD and NLO EW accuracy, with **MadGraph5_aMC@NLO**.

NLO EW corrections at high energies can involve large negative contributions from Sudakov logs, which point to the necessity of going beyond NLO and resumming the logs.

The contribution from photon-induced processes can be huge and with very large uncertainties. However, this does not necessarily apply to all processes and distributions. Cuts may be essential for a realistic prediction. Which cuts on which particles? Other PDFs sets, as CT14QED, have to be considered.

Heavy-Boson Radiation (HBR) is of the same perturbative order of NLO EW corrections and can be numerically equivalent or even larger, but with opposite sign. Should we consider it as an additional contribution ?

We presented also results for $t\bar{t}V,$ ($V = H, W, Z$). We have shown that the hierarchy of PDF luminosities is more severe at 100 TeV, enhancing contributions from gluon-gluon initial states also in NLO EW corrections.

EXTRA SLIDES

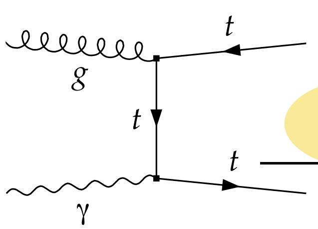
Why do we care about photons in the proton?

2 representative examples:

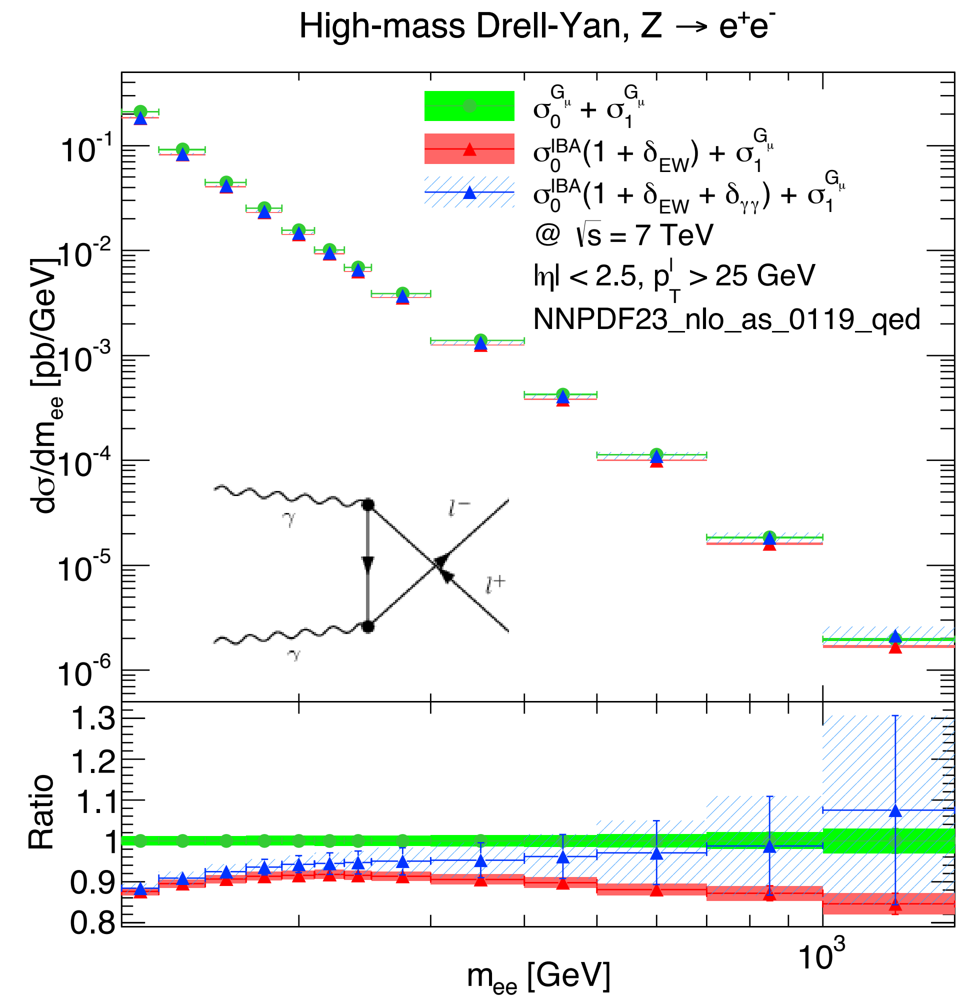
$t\bar{t}$

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

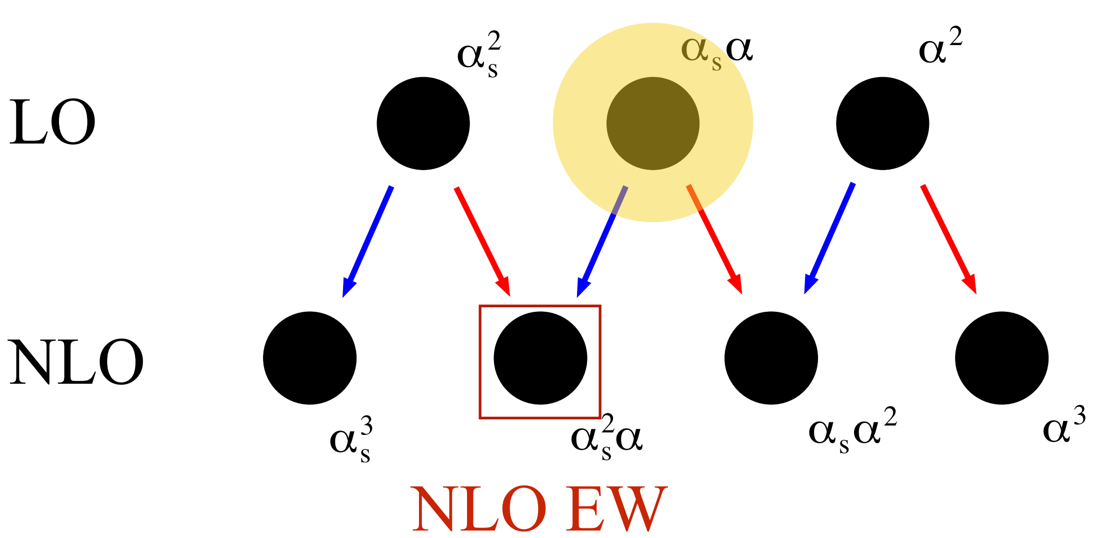
NLO QED



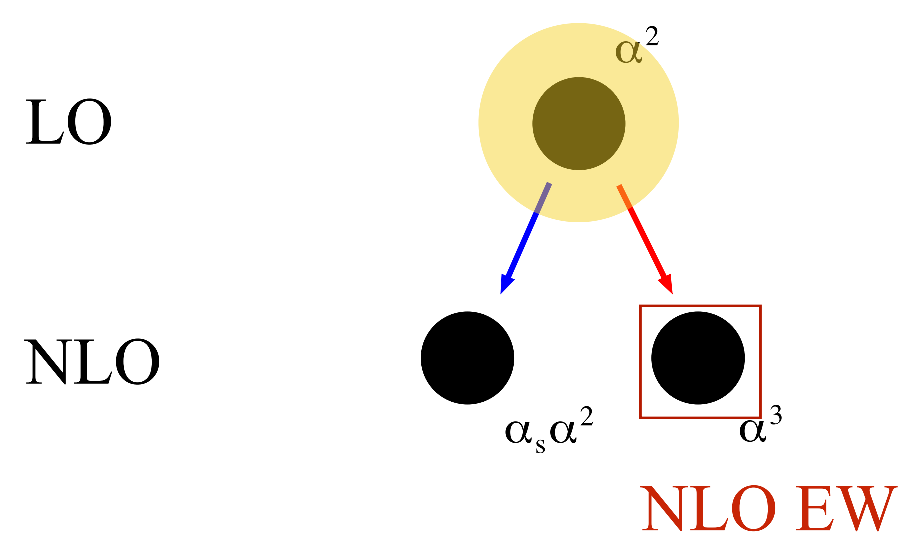
Integrated hadronic cross section for $t\bar{t}$ production at the LHC, at NLO QED



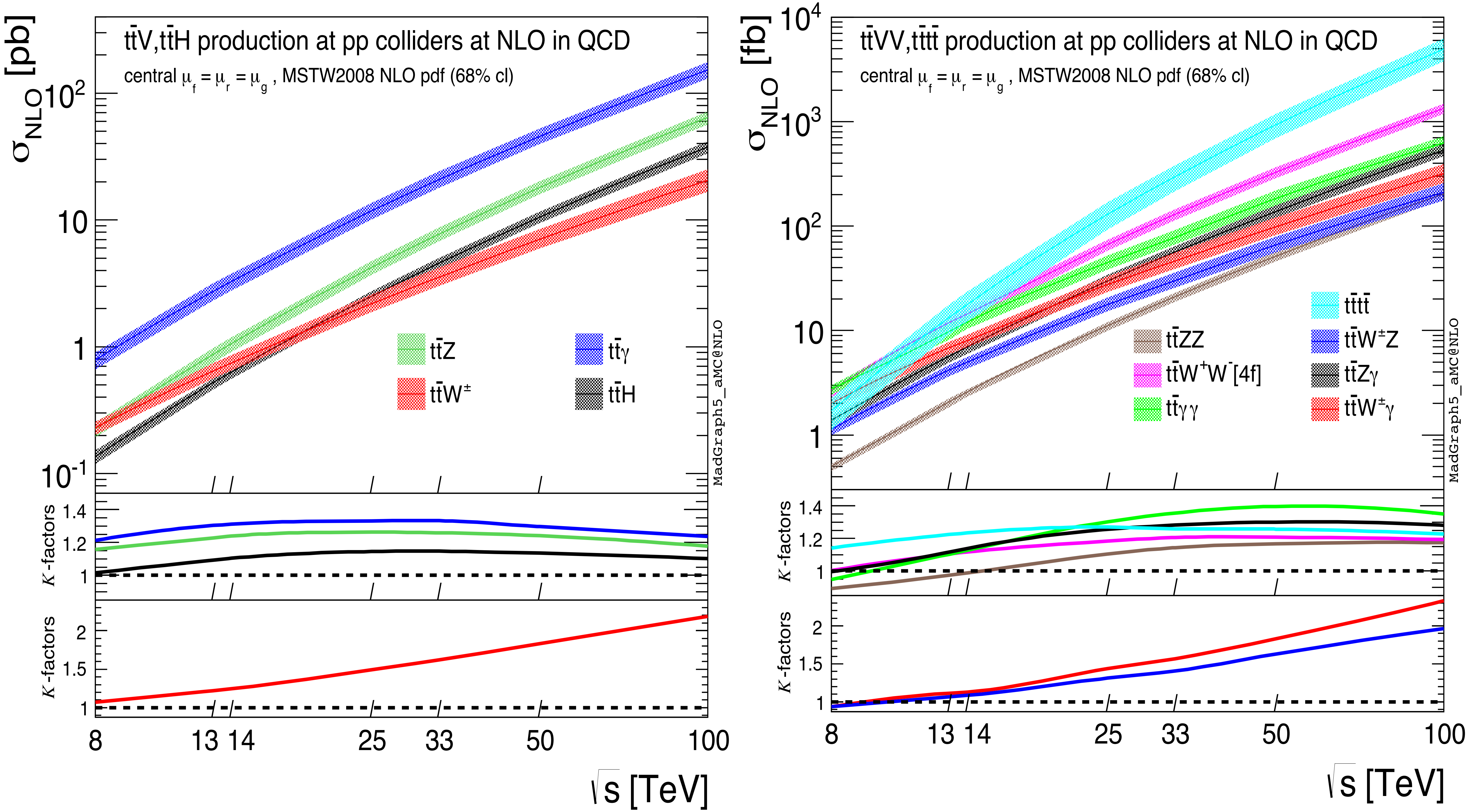
Hollik, Kollar '07 MRST2004QED



Carrazza '14 NNPDF2.3QED



Energy dependence



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.**

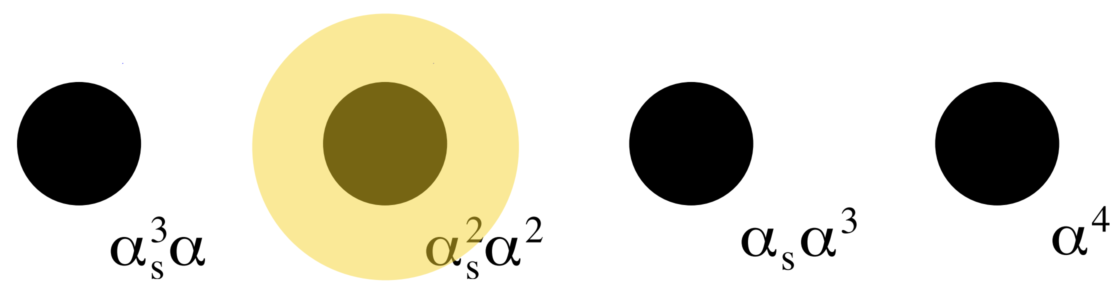
Amplitudes and matrix elements

NLO UFO models:	- 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. 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 $\alpha_S^2\alpha^2$

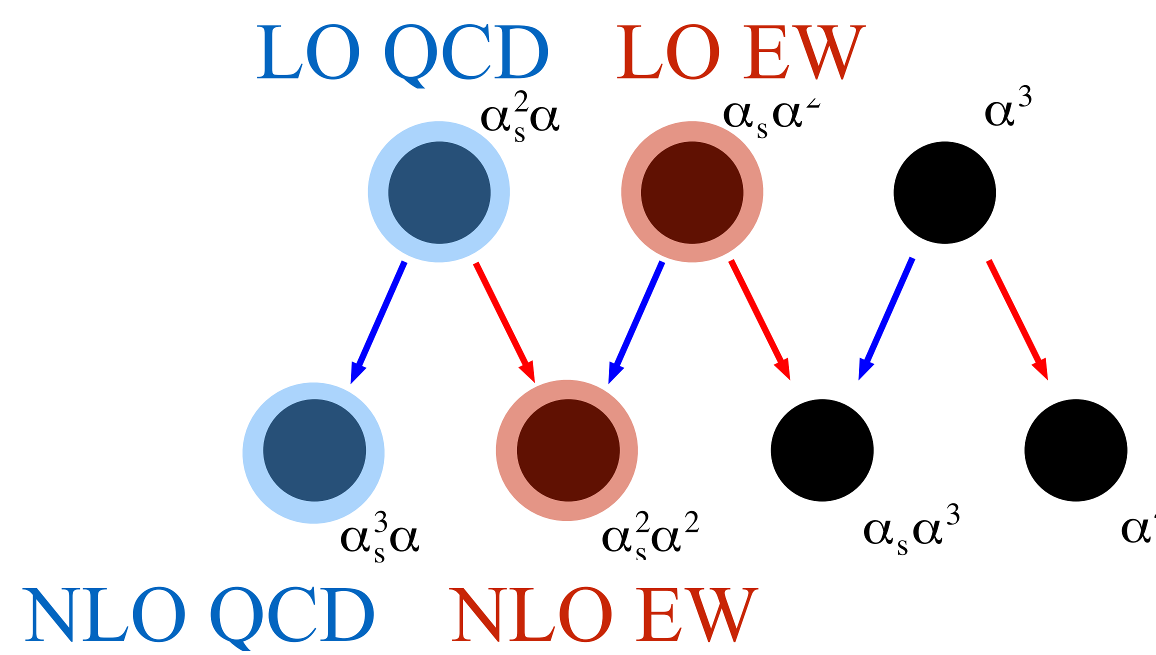
NLO QCD +EW for $t\bar{t}V$ production ($V = H, W, Z$)

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

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.

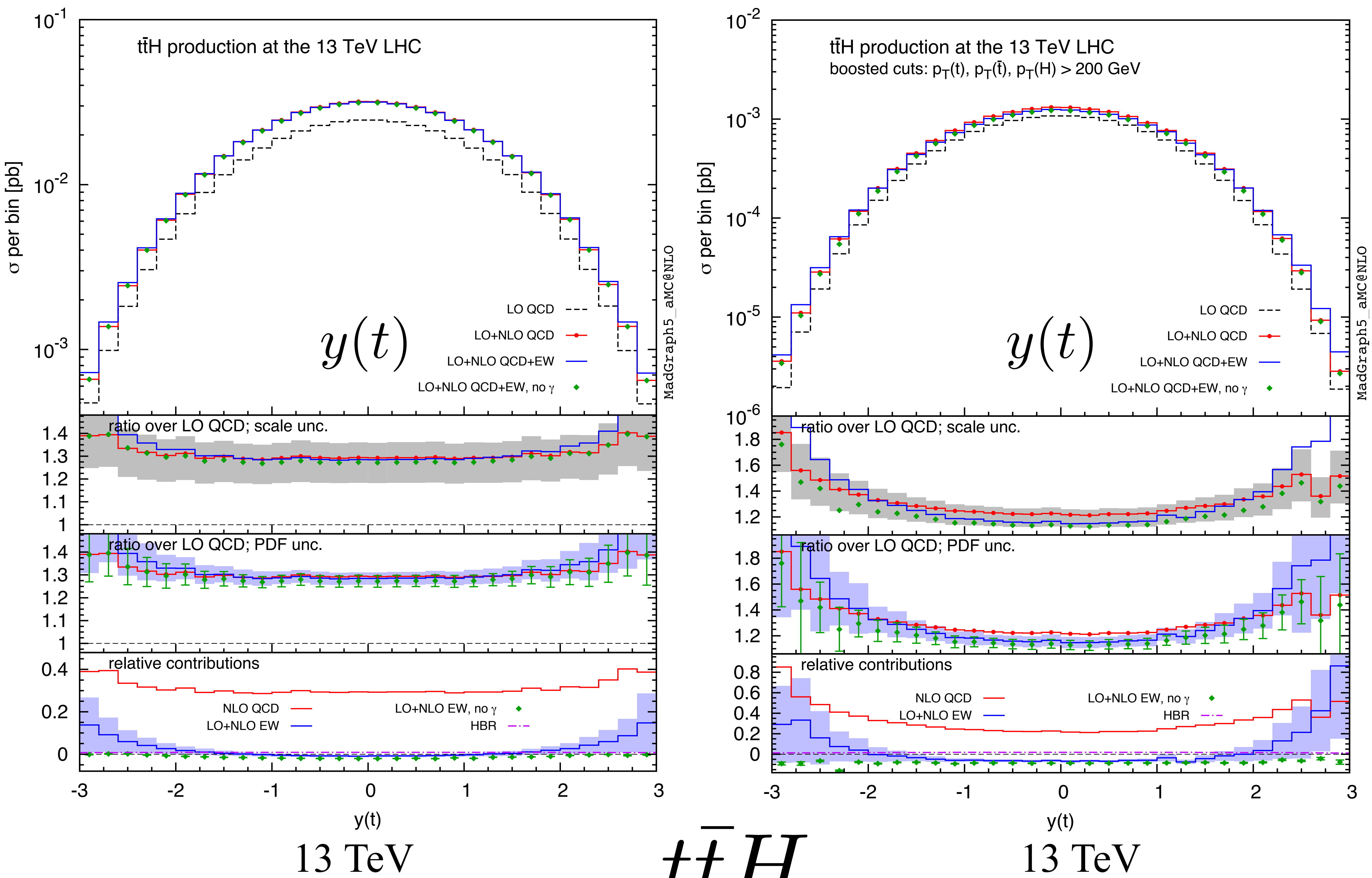


The generation of EW-QCD loops, real emission of gluons, quarks and photons is completely automated.

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

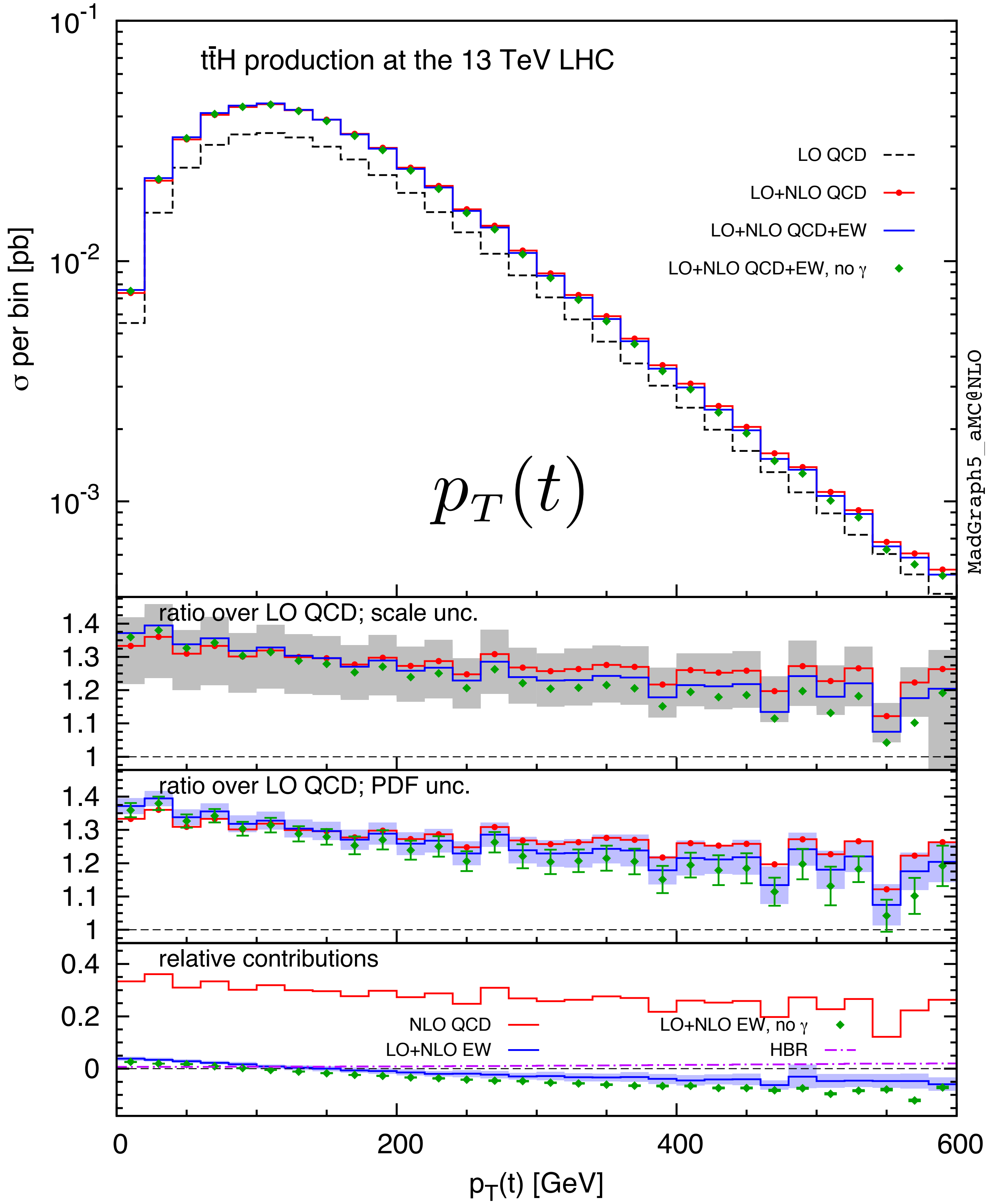
FKS IR counterterms completely automated.

Rapidity distributions: unboosted vs. boosted

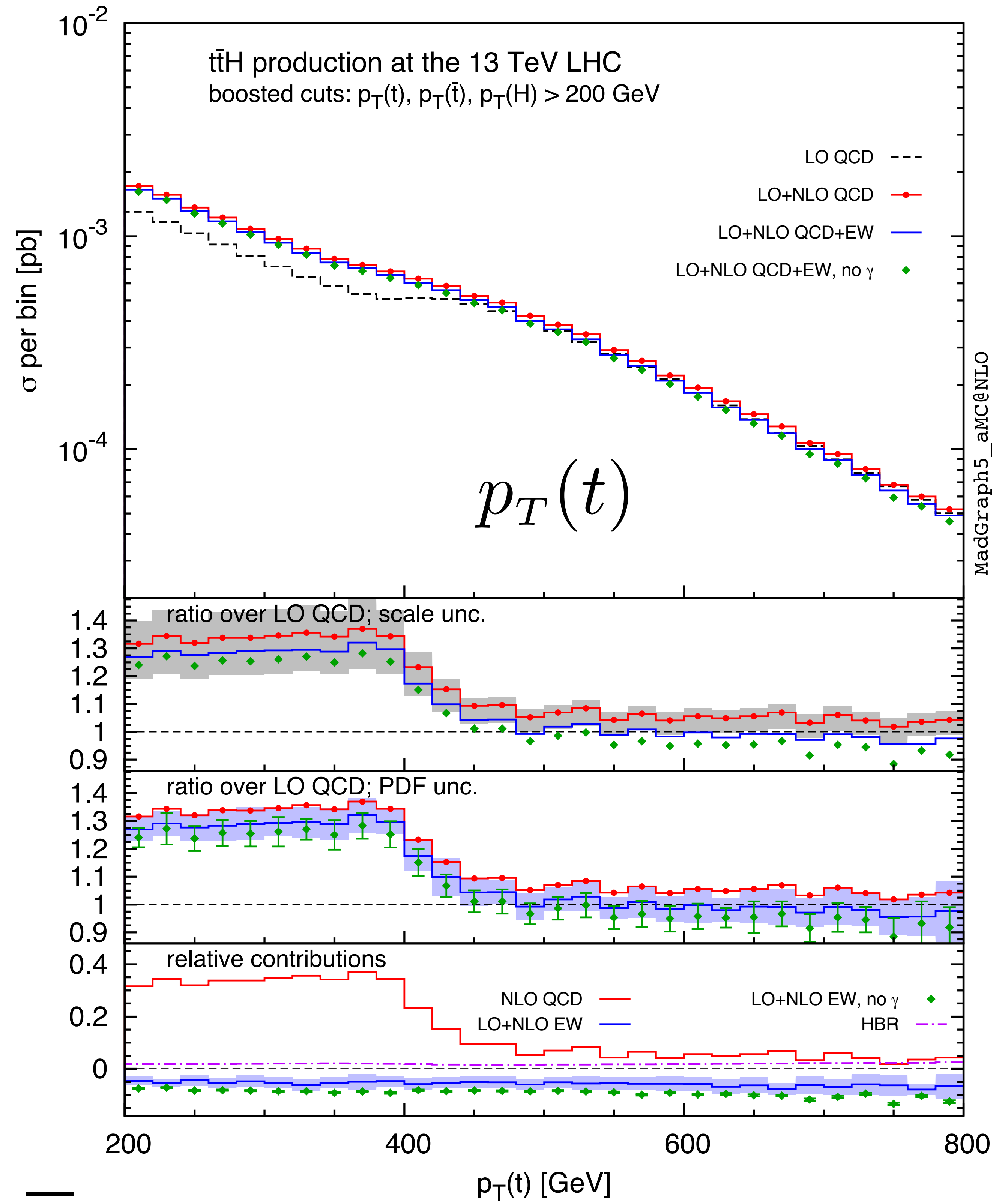


$t\bar{t}H$

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.

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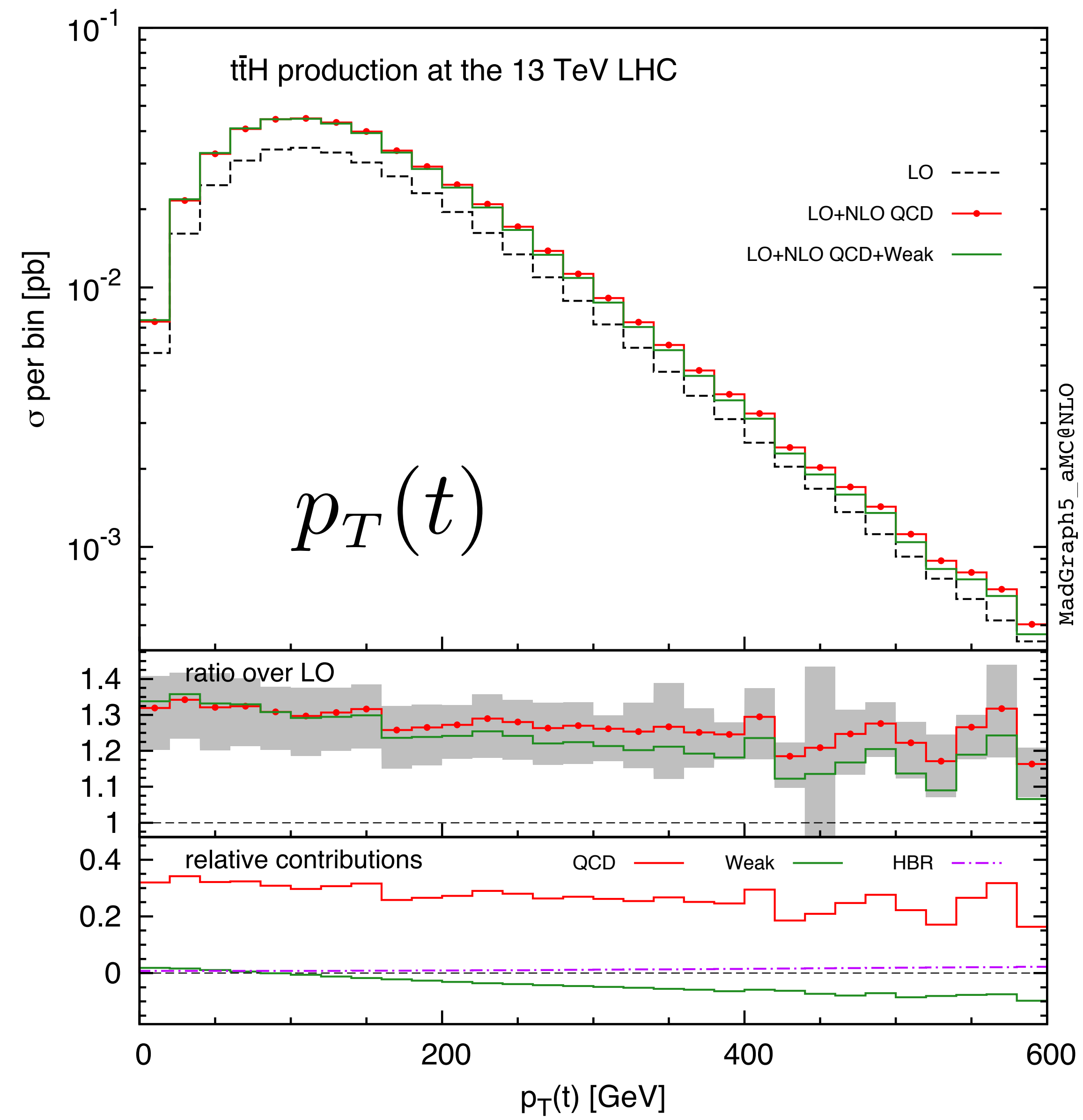
Now, for the complete NLO QCD and EW corrections, with photons in the initial state, we need to type:

```
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

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

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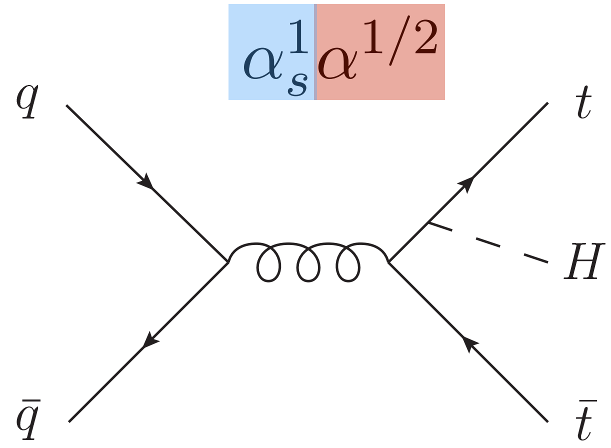
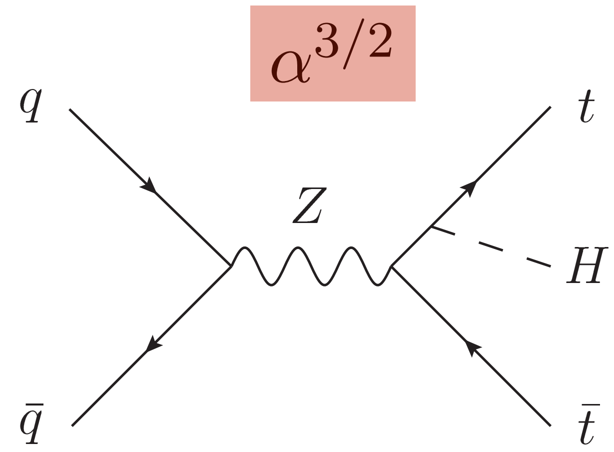
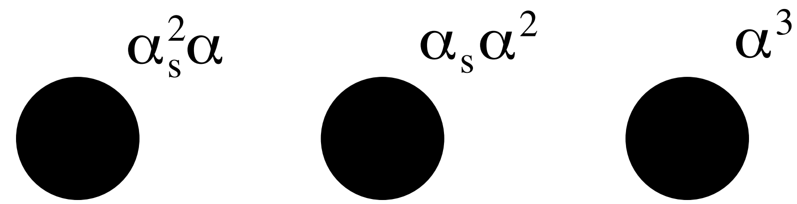
Structure of NLO EW-QCD corrections

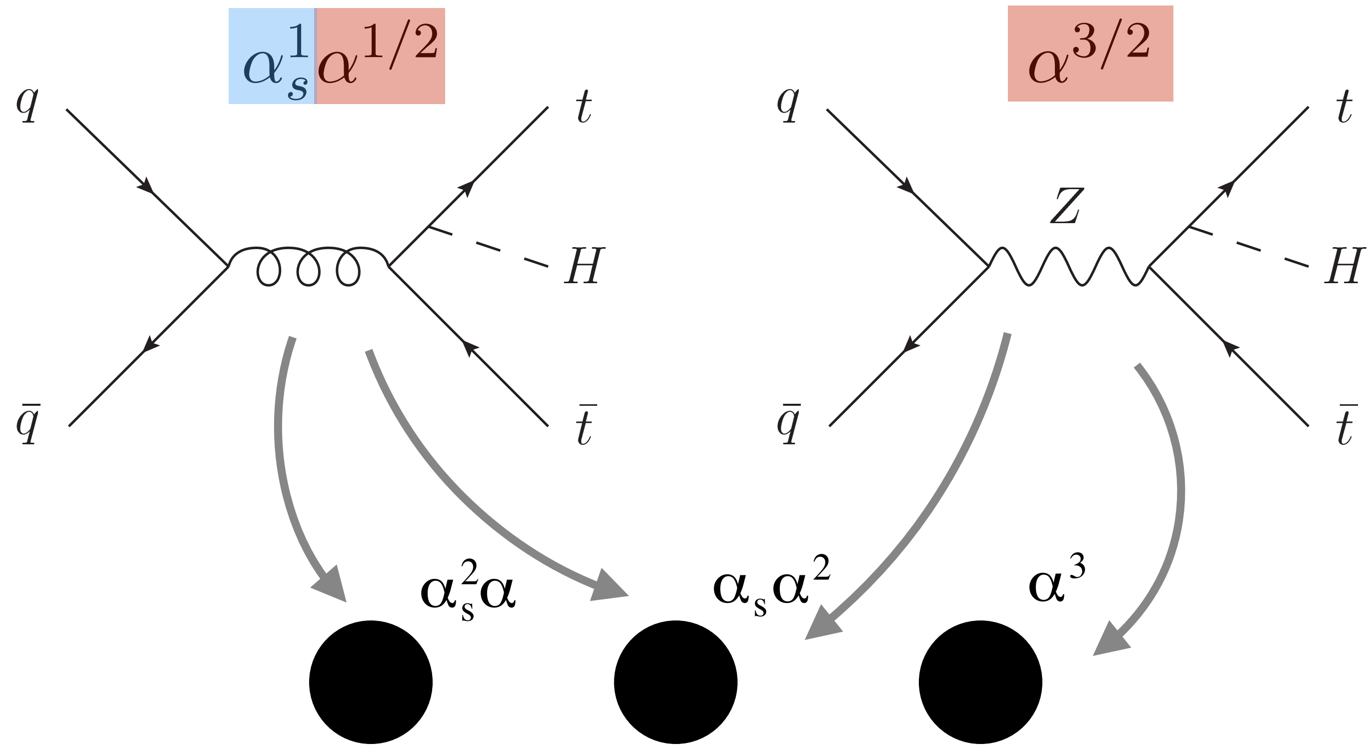




LO

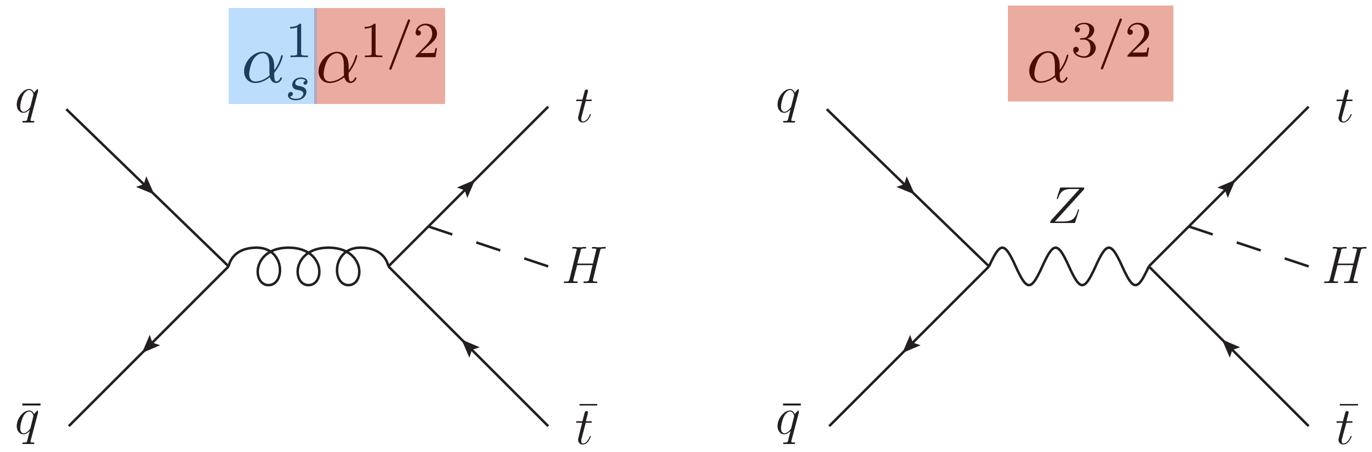


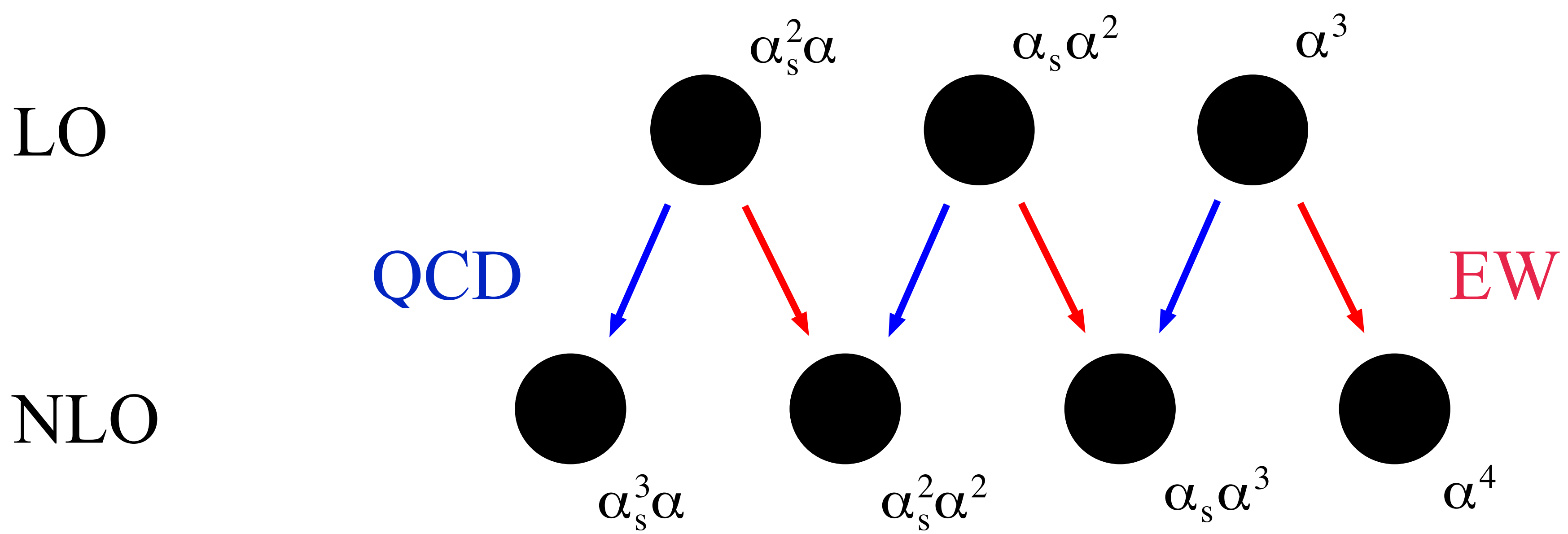
Structure of NLO EW-QCD corrections



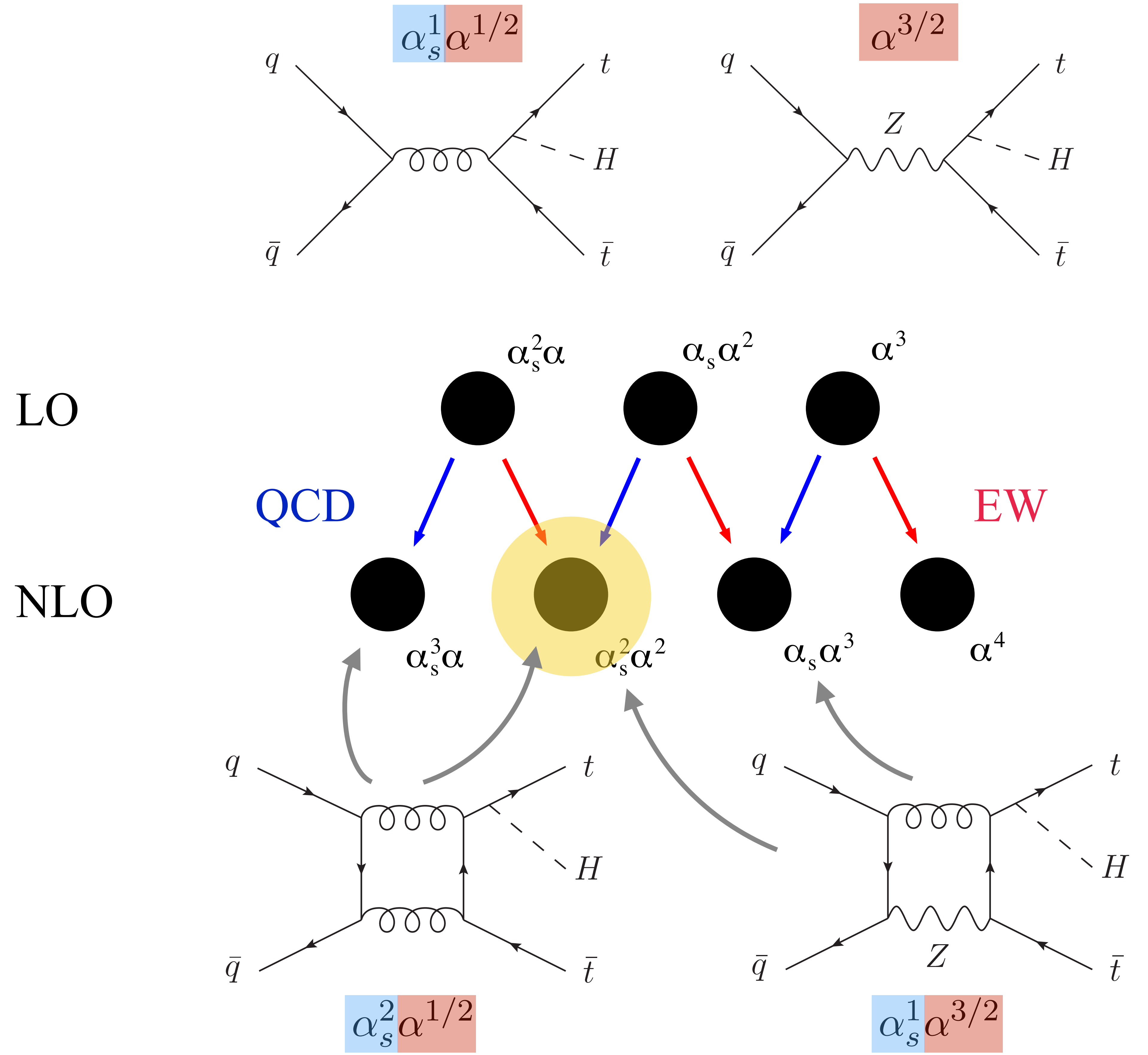
LO

Structure of NLO EW-QCD corrections

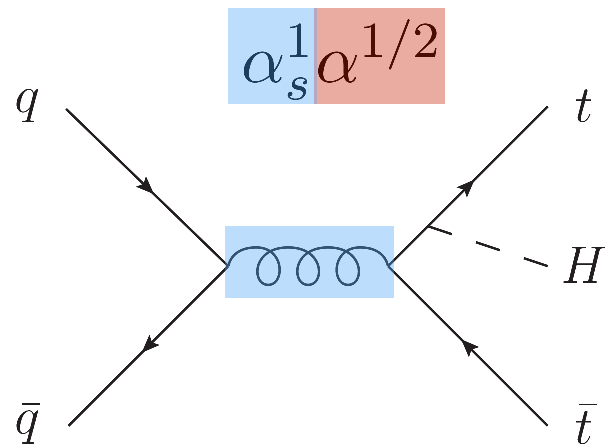


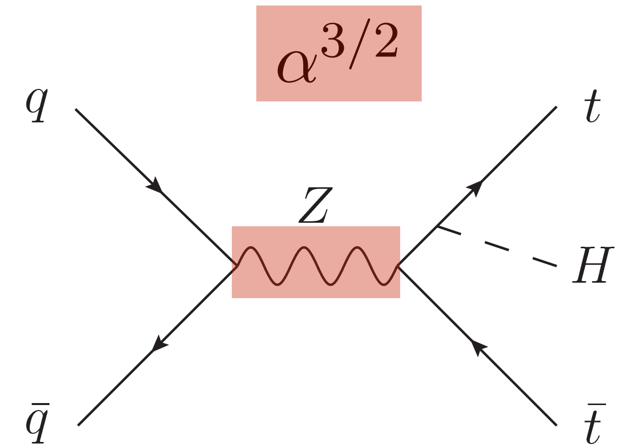


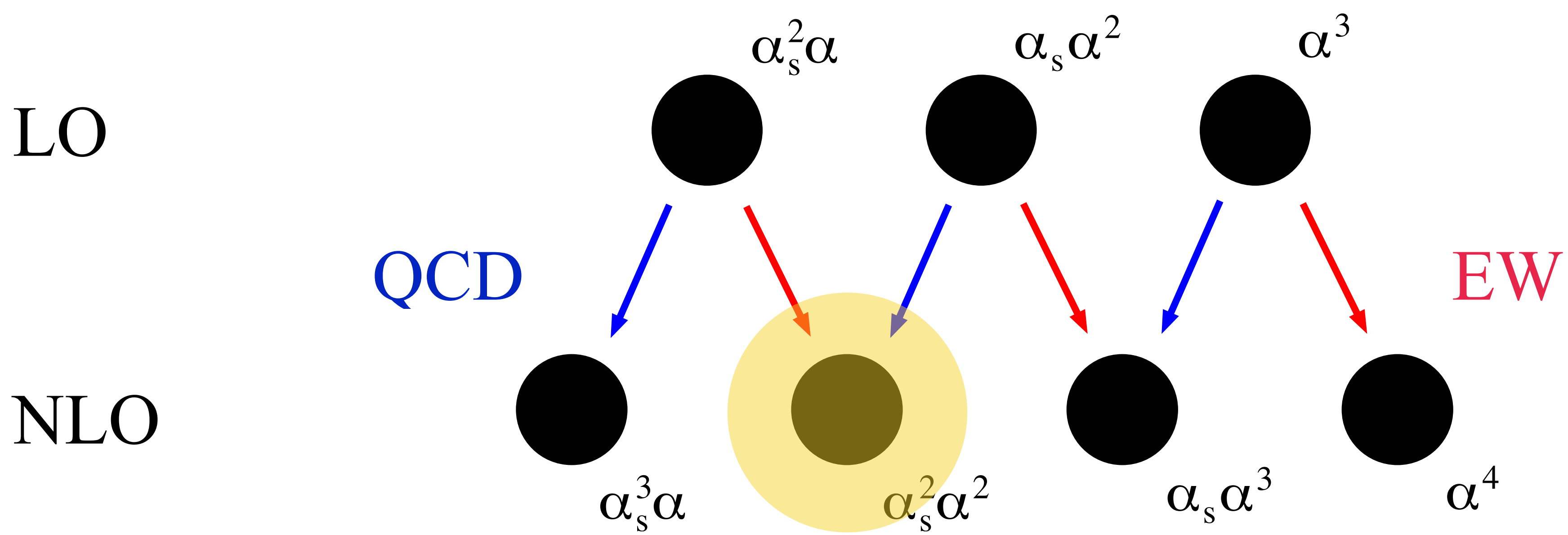
Structure of NLO EW-QCD corrections

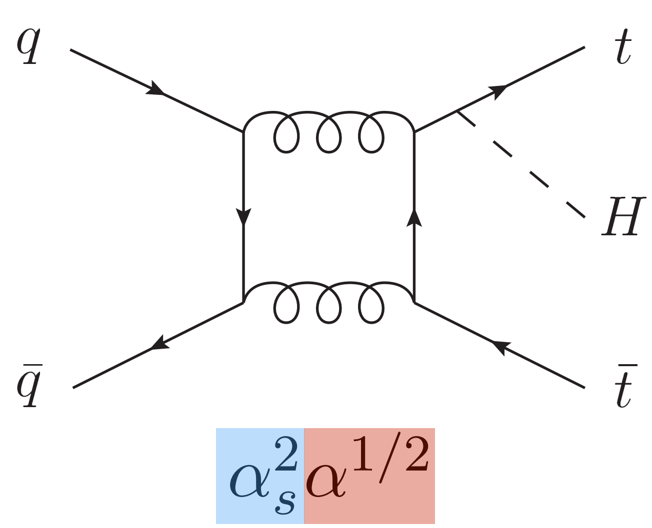


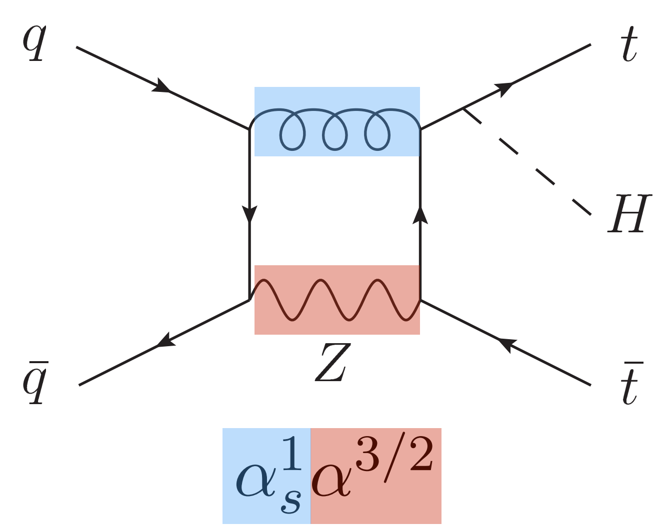
Structure of NLO EW-QCD corrections



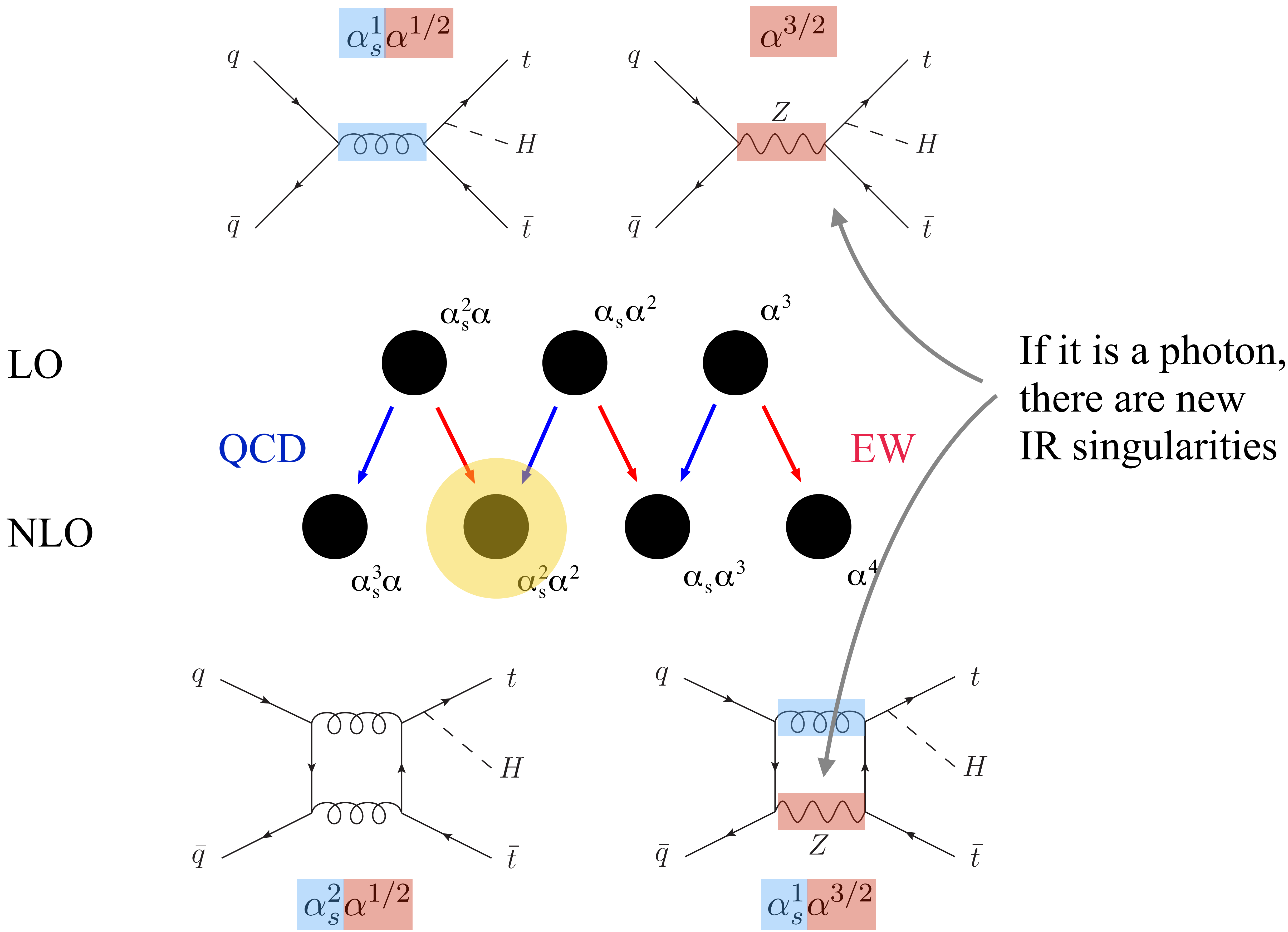








Structure of NLO EW-QCD corrections



Comparison between different schemes

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

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

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

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

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

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

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 $\lambda_{t\bar{t}H}^2$. 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

$\delta_{\mathrm{NLO}}(\%)$	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

$\delta_{\mathrm{HBR}}(\%)$	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

$\delta_{\mathrm{NLO}}(\%)$	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)