EW Corrections in Top-Quark Physics

part II

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OUTLINE

Charge asymmetry at the Tevatron and the LHC

NLO QCD and EW corrections to $t\bar{t}V$, $(V = H, W, Z)$

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

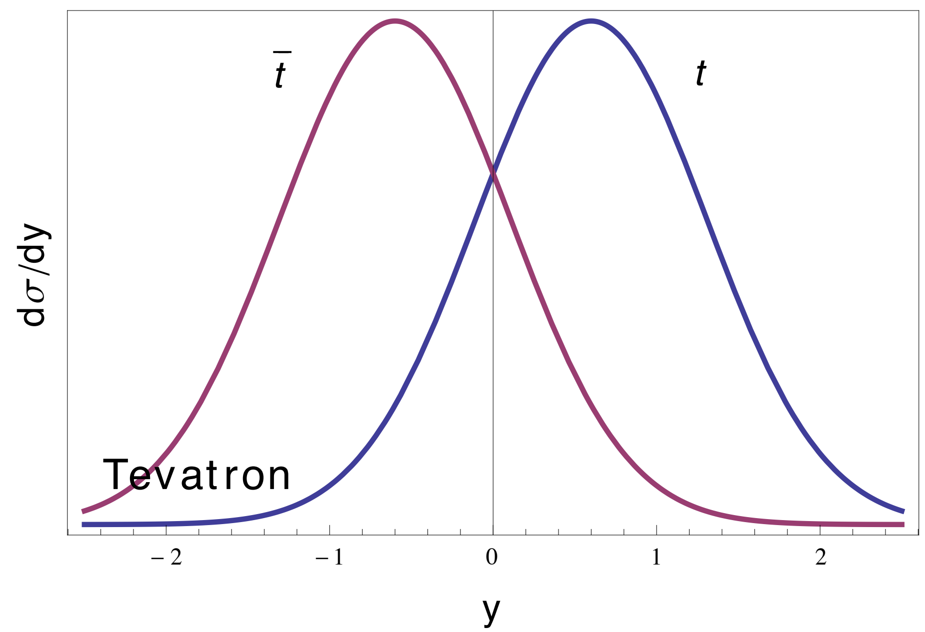
$t\bar{t}V$ **and** $t\bar{t}VV$ **at NLO QCD** (V radiation is EW!)

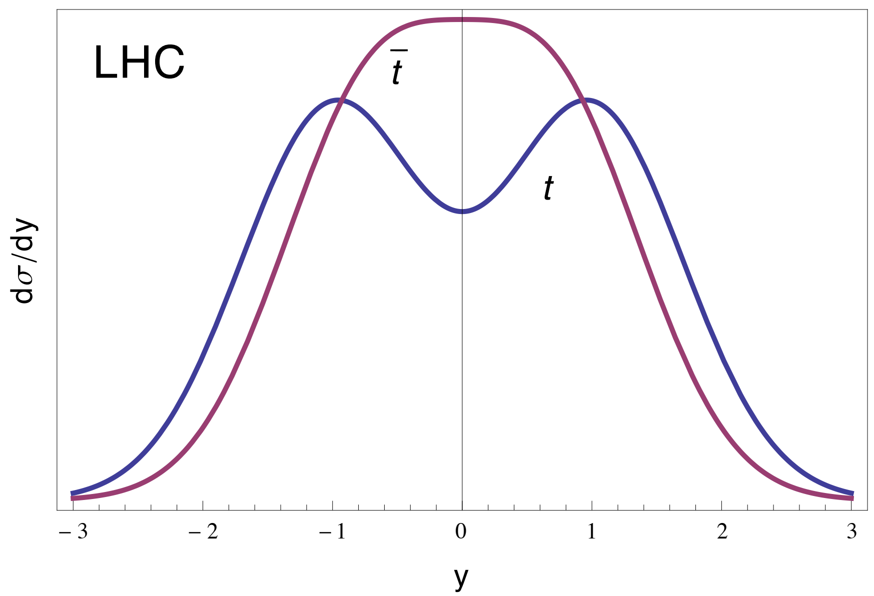
- Completely automated results and total cross section energy dependence
- Asymmetries in $t\bar{t}V$ at NLO in QCD

Single top and its pathologies

Conclusions

Charge asymmetry





forward-backward

$$A_{t\bar{t}} = \frac{N(y_t > y_{\bar{t}}) - N(y_{\bar{t}} > y_t)}{N(y_t > y_{\bar{t}}) + N(y_{\bar{t}} > y_t)}$$

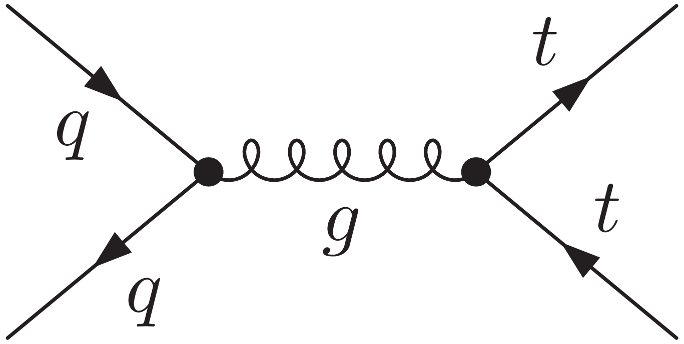
$$A_{\text{lab}} = \frac{N(y_t > 0) - N(y_t < 0)}{N(y_t > 0) + N(y_t < 0)}$$

central

$$A_C^{\eta} = \frac{N(\Delta_\eta > 0) - N(\Delta_\eta < 0)}{N(\Delta_\eta > 0) + N(\Delta_\eta < 0)}$$

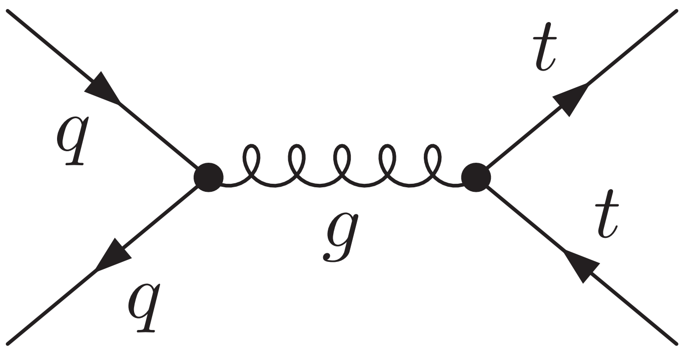
$$A_C^{y} = \frac{N(\Delta_y > 0) - N(\Delta_y < 0)}{N(\Delta_y > 0) + N(\Delta_y < 0)}$$

Same mechanisms at the matrix level for Tevatron and the LHC



At LO partonic processes are not asymmetric.
QCD produces the asymmetry only at NLO!
NLO in the cross-section, LO in A_{FB}

$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$



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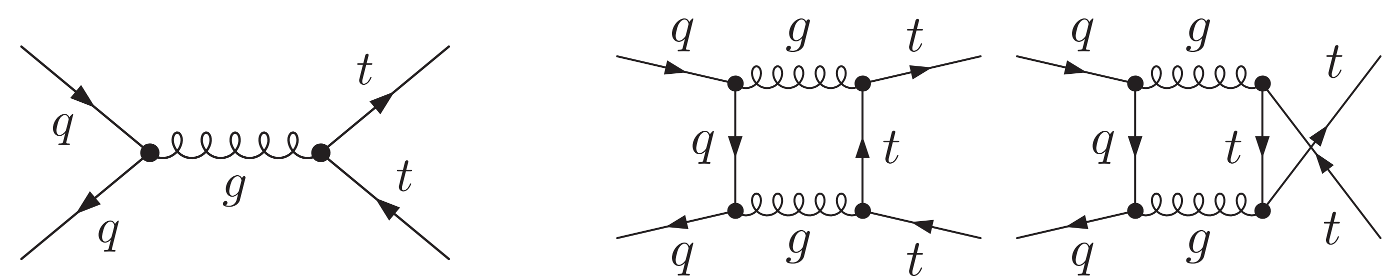
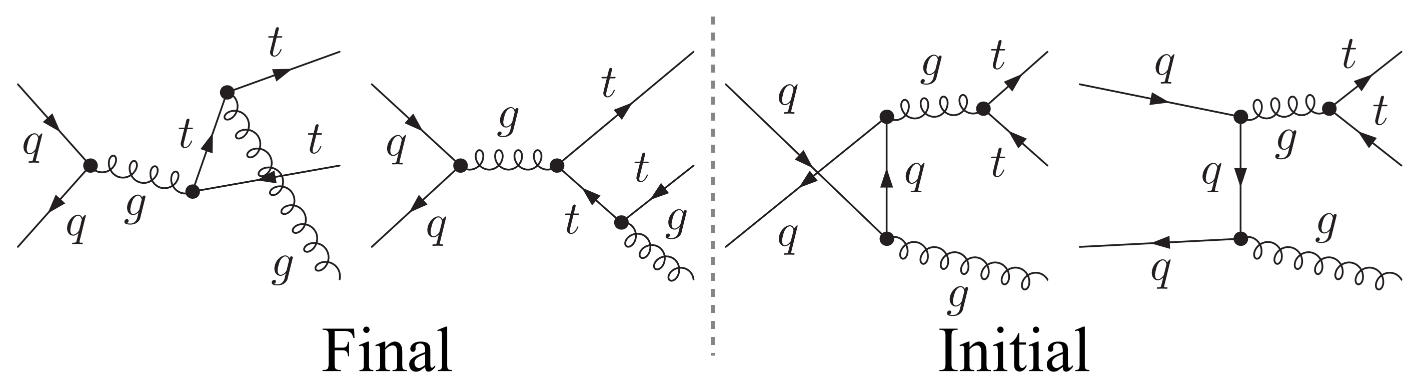
gg initial state does not contribute to Tevatron and LHC asymmetry numerator!
q-qbar QCD contribution only from interactions between initial and final state!

$$\alpha_s \frac{N_1}{D_0}$$

VIRTUAL (Only Boxes)
NO UV, NO Coll. Div.
Only IR



REAL
Only the interference of initial- and final-state gluon emissions is asymmetric.



Kuhn, Rodrigo '99

$$\alpha \frac{\tilde{N}_1}{D_0}$$

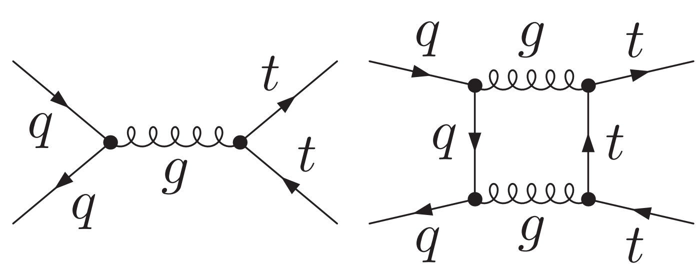
It is useful to divide the electroweak contribution into a QED (photon) and a weak (Z) part.

QED

The QED contribution can be easily obtained from the QCD calculation and the substitution of one gluon into one photon in the squared amplitudes.

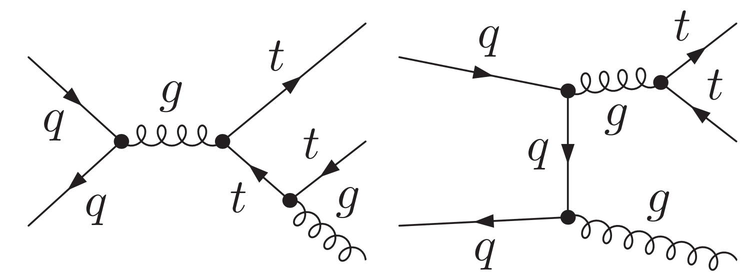
$$q\bar{q} \to t\bar{t}$$

$$\overline{|\mathcal{M}^{t\bar{t}}|}^2_{\mathcal{O}(\alpha_s^3)}$$



$$q\bar{q} \to t\bar{t}g$$

$$\overline{|\mathcal{M}^{t\bar{t}g}|}^2_{\mathcal{O}(\alpha_s^3)}$$



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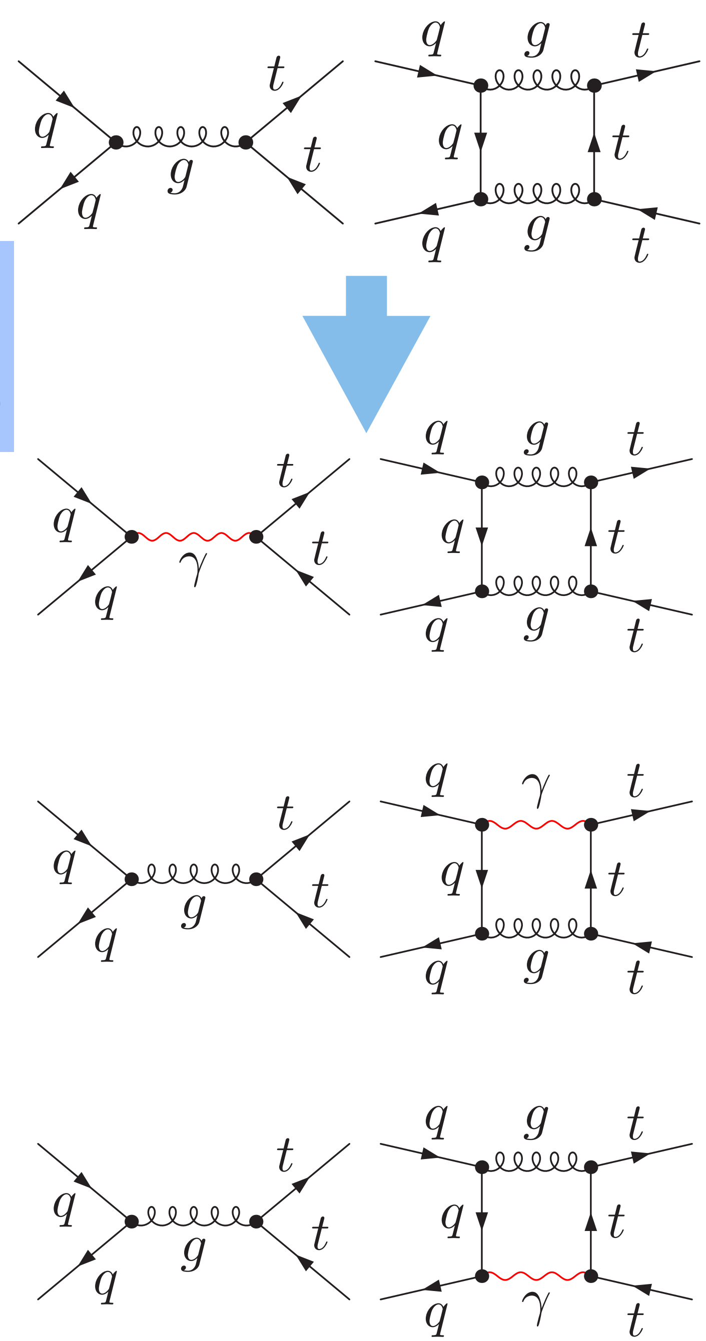
#(QED diagrams) = 3 #(QCD diagrams)

$\overline{|\mathcal{M}^{t\bar{t}}|}^2_{\mathcal{O}(\alpha_s^2\alpha)}$



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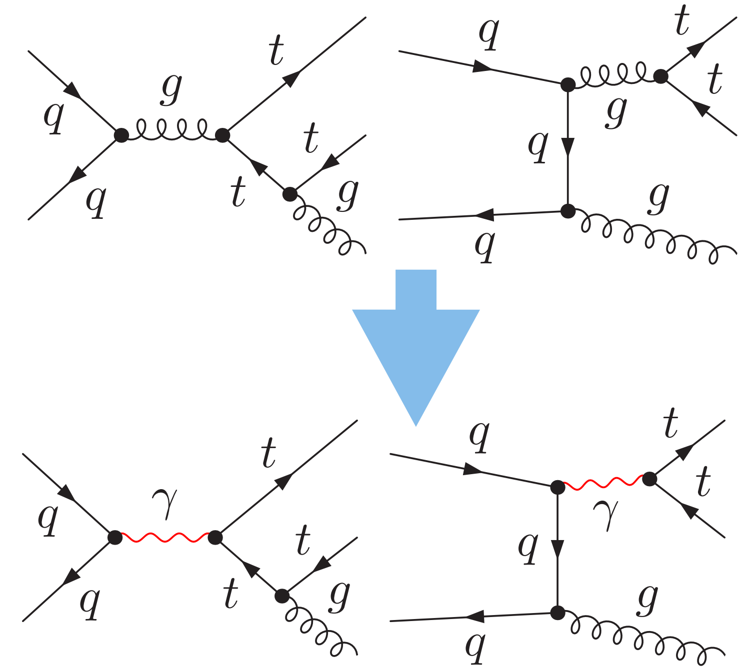
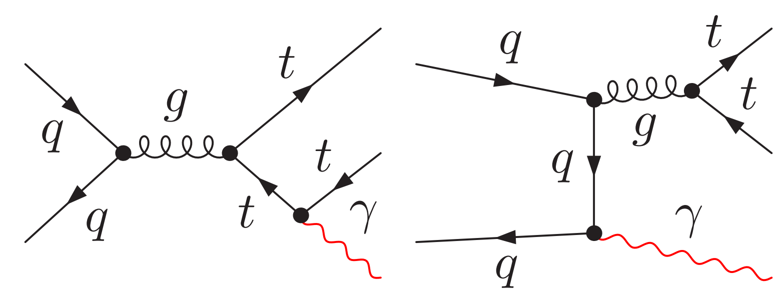


$q\bar{q} \to t\bar{t}\gamma$

$\overline{|\mathcal{M}^{t\bar{t}\gamma}|}^2_{\mathcal{O}(\alpha_s^2\alpha)}$



DIFFERENCES:
Only couplings and color factors!

$$A_{FB} = \frac{N}{D} = \frac{\alpha^2 \tilde{N}_0 + \alpha_s^3 N_1 + \alpha_s^2 \alpha \tilde{N}_1 + \alpha_s^4 N_2 + \cdots}{\alpha^2 \tilde{D}_0 + \alpha_s^2 D_0 + \alpha_s^3 D_1 + \alpha_s^2 \alpha \tilde{D}_1 + \cdots} = \alpha_s \frac{N_1}{D_0} + \alpha \frac{\tilde{N}_1}{D_0} + \frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$

Hollik, D.P. '11

$$R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}$$

QED corrections can be obtained from QCD × R_{QED}

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Weak

The same diagrams as in the QED part, but $\gamma \to Z$.

Z is not massless → If we write Weak=QCD × R_{Weak}:
R_{Weak} does not depend only on couplings and color factors.

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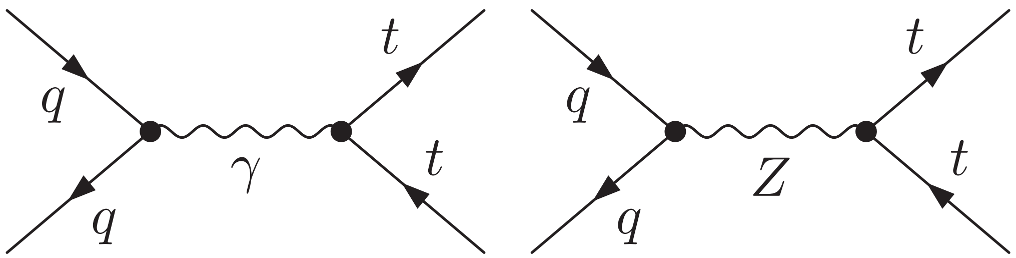
$$\frac{\alpha^2}{\alpha_s^2} \frac{\tilde{N}_0}{D_0}$$



Different couplings for different chiralities produce asymmetric terms in the cross section

$$\frac{d\sigma_{asym}}{d\cos\theta} = 2\pi\alpha^2 \cos\theta \left(1 - \frac{4m_t^2}{s}\right) \left[\kappa \frac{Q_q Q_t A_q A_t}{(s - M_Z^2)} + 2\kappa^2 A_q A_t V_q V_t \frac{s}{(s - M_Z^2)^2}\right]$$

Forward-backward asymmetry

(a) $A_{FB}^{t\bar{t}}$

EW CORRECTIONS

	$A_{FB}^{t\bar{t}}$	$\mu = m_t/2$	$\mu = m_t$	$\mu = 2m_t$
$\mathcal{O}(\alpha_s^3)$	$u\bar{u}$	7.01%	6.29%	5.71%
$\mathcal{O}(\alpha_s^3)$	$d\bar{d}$	1.16%	1.03%	0.92%
$\mathcal{O}(\alpha_s^2\alpha)_{QED}$	$u\bar{u}$	1.35%	1.35%	1.35%
$\mathcal{O}(\alpha_s^2\alpha)_{QED}$	$d\bar{d}$	-0.11%	-0.11%	-0.11%
$\mathcal{O}(\alpha_s^2\alpha)_{weak}$	$u\bar{u}$	0.16%	0.16%	0.16%
$\mathcal{O}(\alpha_s^2\alpha)_{weak}$	$d\bar{d}$	-0.04%	-0.04%	-0.04%
$\mathcal{O}(\alpha^2)$	$u\bar{u}$	0.18%	0.23%	0.28%
$\mathcal{O}(\alpha^2)$	$d\bar{d}$	0.02%	0.03%	0.03%
tot	$p\bar{p}$	9.72%	8.93%	8.31%

$R_{QED}^{u\bar{u}} = (0.192, 0.214, 0.237)$

$R_{QED}^{d\bar{d}} = (-0.096, -0.107, -0.119)$

- R_{QED} depend only on the renormalization scale, not on A_{FB} definitions and cuts.
(with fixed scales)

Hollik, DP '11

$\mathcal{O}(\alpha_s^2\alpha)$ QED is the dominant contribution of the electroweak corrections.
It is stable under factorization and renormalization scale variation.

u and d have different charges: contributions of opposite sign for $\mathcal{O}(\alpha_s^2\alpha)$

Forward-backward asymmetry

$$R^{t\bar{t}}_{EW} = \frac{N^{t\bar{t}}_{\mathcal{O}(\alpha_s^2\alpha)+\mathcal{O}(\alpha^2)}}{N^{t\bar{t}}_{\mathcal{O}(\alpha_s^3)}} = (0.190, 0.220, 0.254)$$

$$R^{p\bar{p}}_{EW} = \frac{N^{p\bar{p}}_{\mathcal{O}(\alpha_s^2\alpha)+\mathcal{O}(\alpha^2)}}{N^{p\bar{p}}_{\mathcal{O}(\alpha_s^3)}} = (0.186, 0.218, 0.243)$$

$$R^{t\bar{t}}_{EW}(M_{t\bar{t}} > 450\ \text{GeV}) = (0.200, 0.232, 0.266)$$

$$R^{t\bar{t}}_{EW}(|\Delta y| > 1) = (0.191, 0.216, 0.246)$$

The complete ratios R_{EW} depend on fac/ren scales, and very slightly on A_{FB} definitions and cuts.

Hollik, DP '11

Forward-backward asymmetry

$$R_{EW}^{t\bar{t}} = \frac{N^{t\bar{t}}_{\mathcal{O}(\alpha_s^2\alpha)+\mathcal{O}(\alpha^2)}}{N^{t\bar{t}}_{\mathcal{O}(\alpha_s^3)}} = (0.190, 0.220, 0.254) \qquad R_{EW}^{t\bar{t}}(M_{t\bar{t}} > 450 \text{ GeV}) = (0.200, 0.232, 0.266)$$

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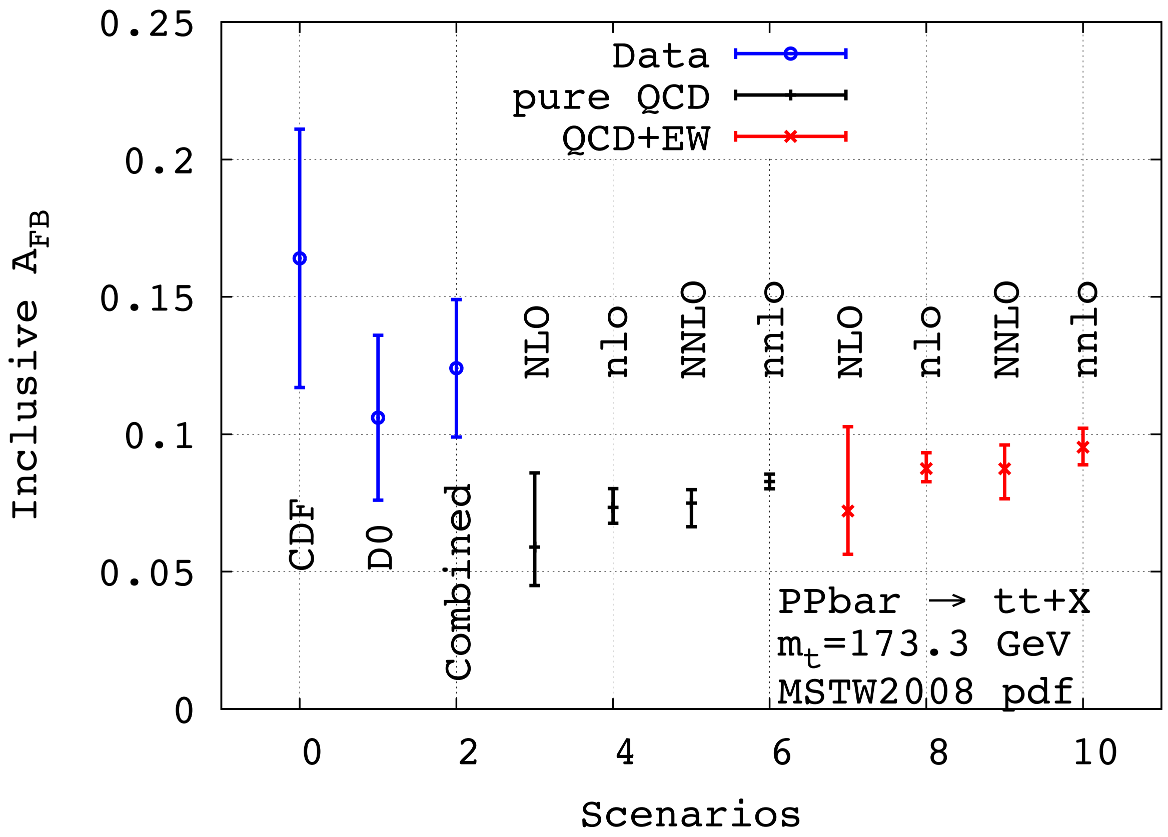
Hollik, DP '11

EW corrections to AFB are not induced by Sudakov logs. However, they are "more important" than EW corrections to cross sections. 2 Reasons:

- LO cross section is $\mathcal{O}(\alpha_s^2)$, LO numerator of A_{FB} is $\mathcal{O}(\alpha_s^3)$

- The dominant EW contribution ($\mathcal{O}(\alpha_s^2\alpha)$ QED) to the A_{FB} originates only from boxes: 3 times the number of diagrams of the QCD case.
The QED contribution to the total cross section originates "from vertex corrections": same number of diagrams of QCD case.

Forward-backward asymmetry



Czakon, Fiedler, Mitov '14

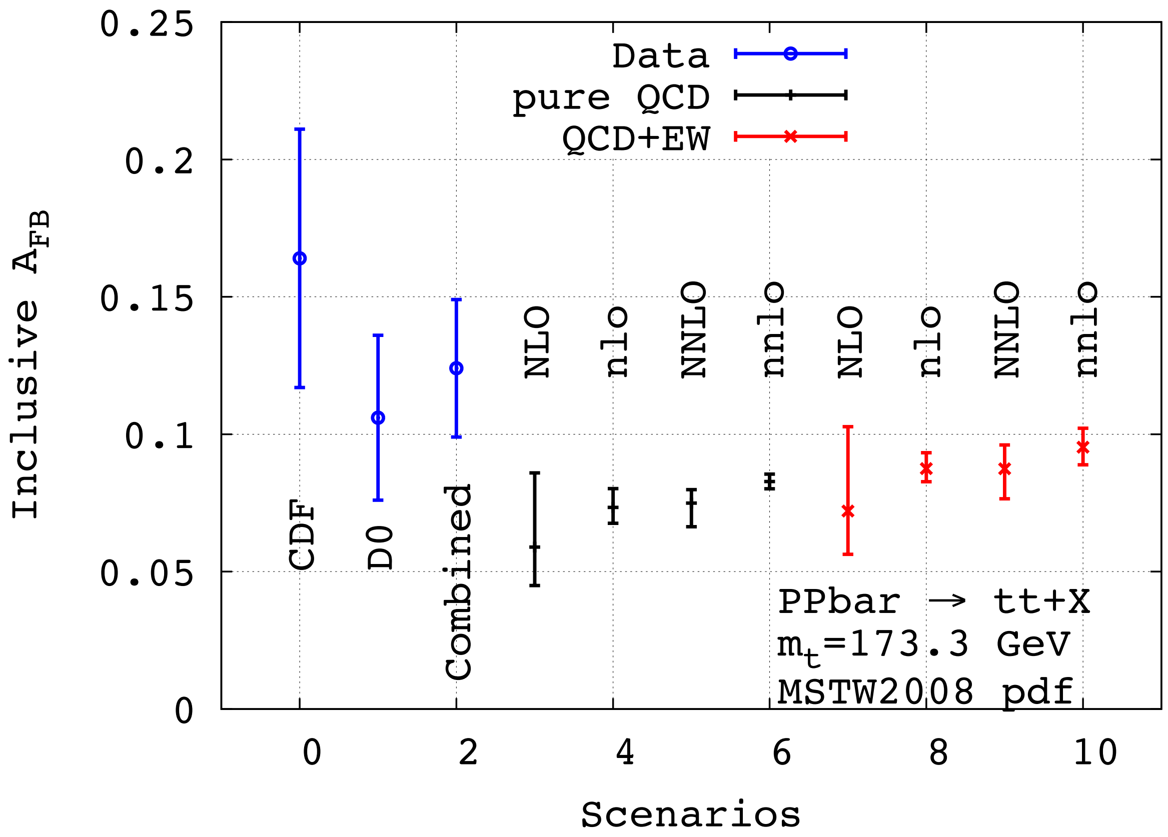
Capital:	unexpanded
Small:	expanded
Red:	QCD+EW
Black:	QCD

No EW corrections in the denominator of:

$$A_{t\bar{t}} = \frac{N(y_t > y_{\bar{t}}) - N(y_{\bar{t}} > y_t)}{N(y_t > y_{\bar{t}}) + N(y_{\bar{t}} > y_t)}$$

- EW contribution is relevant.
- NLO≠NNLO, nlo~nnlo.

Forward-backward asymmetry



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Sudakov logs suppress the total cross section in the denominator (especially for high invariant mass) and increase the asymmetric numerator.

Resummed logs increase A_{FB} by a factor 1.05. (0.5% overlap with NLO EW)

Bin [GeV]	$A_{FB}^{t\bar{t}}(\%)$			$\mathcal{R}_{FB}(t)$	$\mathcal{R}_{FB}^{\alpha_s^2}(t)$	$\mathcal{R}_t$
$[2\,m_{t\bar{t}}, 1960]$	7.7	7.5	1.6	1.02	1.03	0.98
$[2\,m_{t\bar{t}}, 450]$	5.6	5.4	–	1.02	1.03	0.98
$[450, 900]$	11	12	2.3	1.02	1.04	0.97

Manohar, Trott '12

Charge asymmetry

At the LHC same partonic processes, but different partonic luminosities.

The gluon-gluon luminosity is larger, so the asymmetry is smaller.
Gluon-quark initial states start to be "interesting" (per mill).

The ratio of integrated luminosities $u\bar{u}/d\bar{d}$ at the Tevatron(LHC) is 4(2).
The cancellation between QED contributions is bigger. The EW contribution at the LHC is in general smaller (~ 15%, 20% of QCD contribution).

$$R_{QED}(Q_q) = \frac{\alpha \tilde{N}_1^{QED}}{\alpha_s N_1} = Q_q Q_t \frac{36}{5} \frac{\alpha}{\alpha_s}$$

$\sqrt{s}$			$M_c = 2m_t$	0.5 TeV	0.7 TeV	1 TeV
7 TeV	QCD:	$A_C^{\Delta\|y\|}$ (%)	1.07 (4)	1.27 (4)	1.68 (4)	2.06 (5)
	QCD + EW:	$A_C^{\Delta\|y\|}$ (%)	1.23 (5)	1.48 (4)	1.95 (4)	2.40 (6)
8 TeV	QCD:	$A_C^{\Delta\|y\|}$ (%)	0.96 (4)	1.14 (4)	1.48 (4)	1.85 (4)
	QCD + EW:	$A_C^{\Delta\|y\|}$ (%)	1.11 (4)	1.33 (5)	1.73 (5)	2.20 (5)

			$M_c = 2m_t$	0.5 TeV	1 TeV	2 TeV
14 TeV	QCD:	$A_C^{\Delta\|y\|}$ (%)	0.58 (3)	0.74 (3)	1.11 (5)	1.72 (10)
	QCD + EW:	$A_C^{\Delta\|y\|}$ (%)	0.67 (4)	0.86 (5)	1.32 (8)	2.12 (10)

Bernreuther, Si '12

Top-quark pair in association with a heavy boson

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

Weak corrections to **Higgs** hadroproduction in association with a top-quark pair
Frixione, Hirschi, DP, Shao, Zaro arXiv:1407.0823

$t\bar{t}H$

QCD NLO and **EW** NLO corrections to **ttH** production with top quark decays at hadron collider
Yu, Wen-Gan, Ren-You, Chong, Lei arXiv:1407.1110

$t\bar{t}H$

Electroweak and QCD corrections to top-pair hadroproduction in association with **heavy bosons**
Frixione, Hirschi, DP, Shao, Zaro arXiv:1504.03446

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$V = H, W, Z$

QCD corrections included in a consistent framework, with scale uncertainties.
PDF errors for NLO QCD+EW.
Automated results via MadGraph5_aMC@NLO.

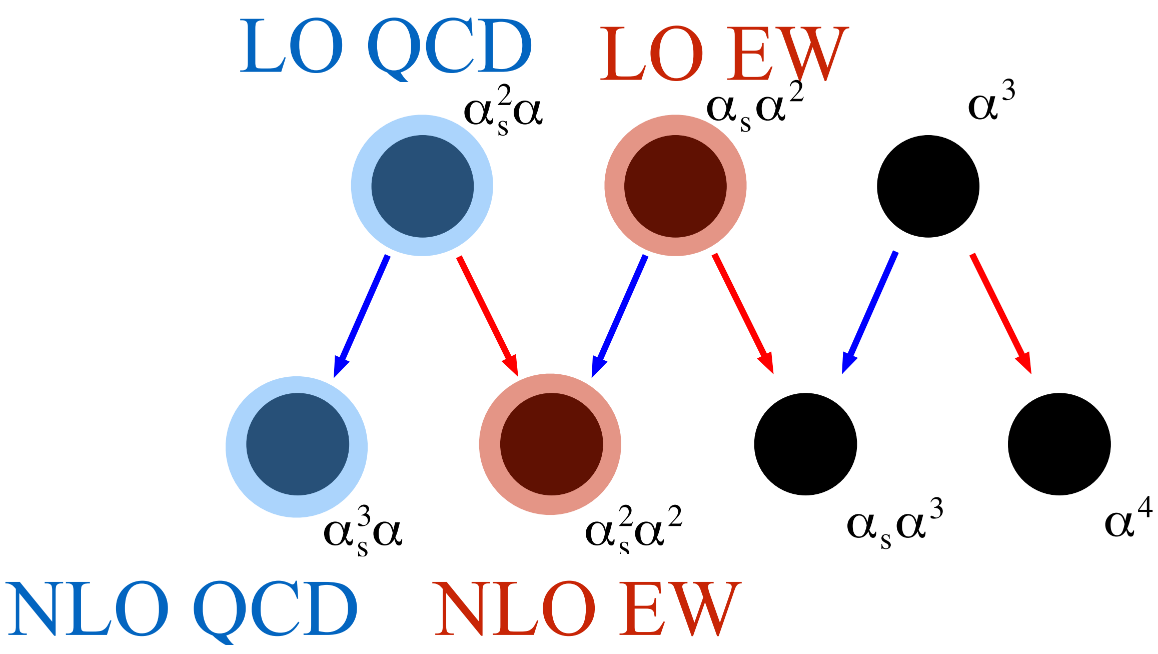
$t\bar{t}V$ production: numerical results

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

Contributions

Heavy Boson radiation HBR ($pp \to t\bar{t}V + V'$) is of the same order of NLO EW. (Does it cancel Sudakov logs?)

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



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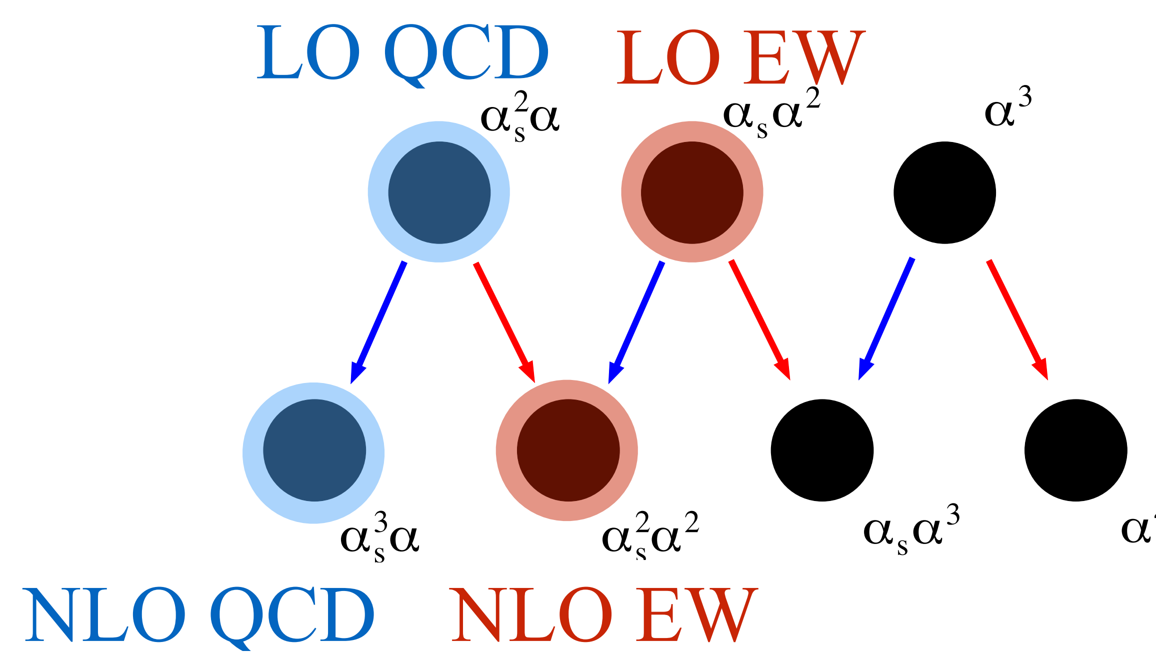


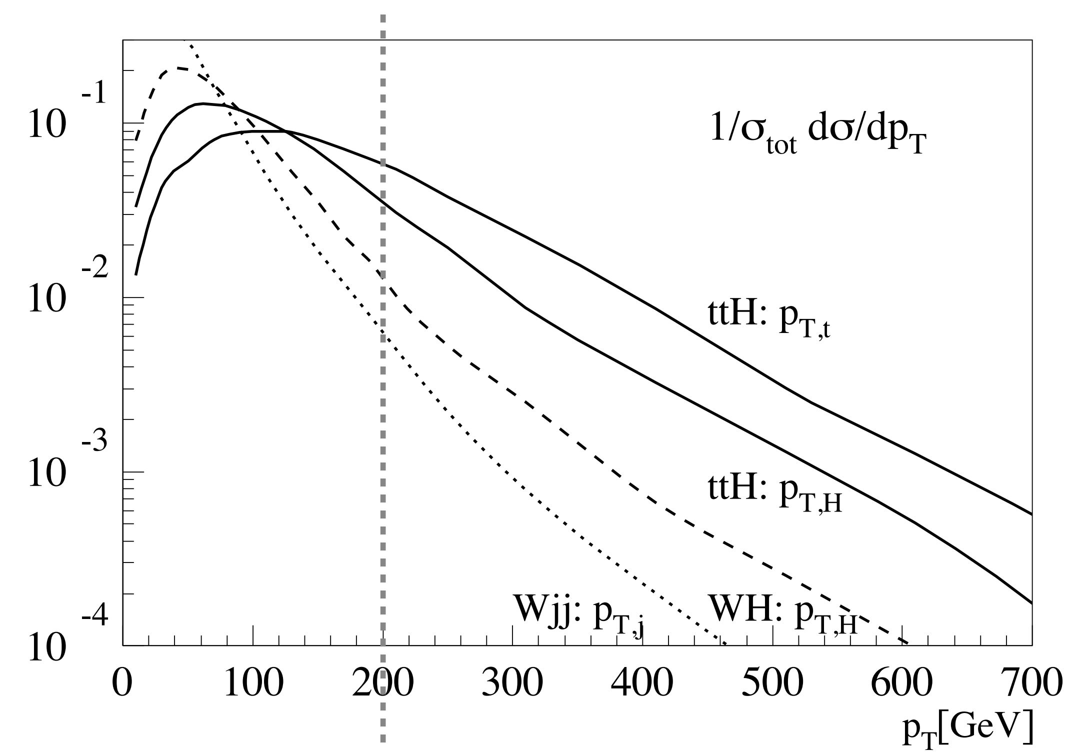
Boosted regime

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

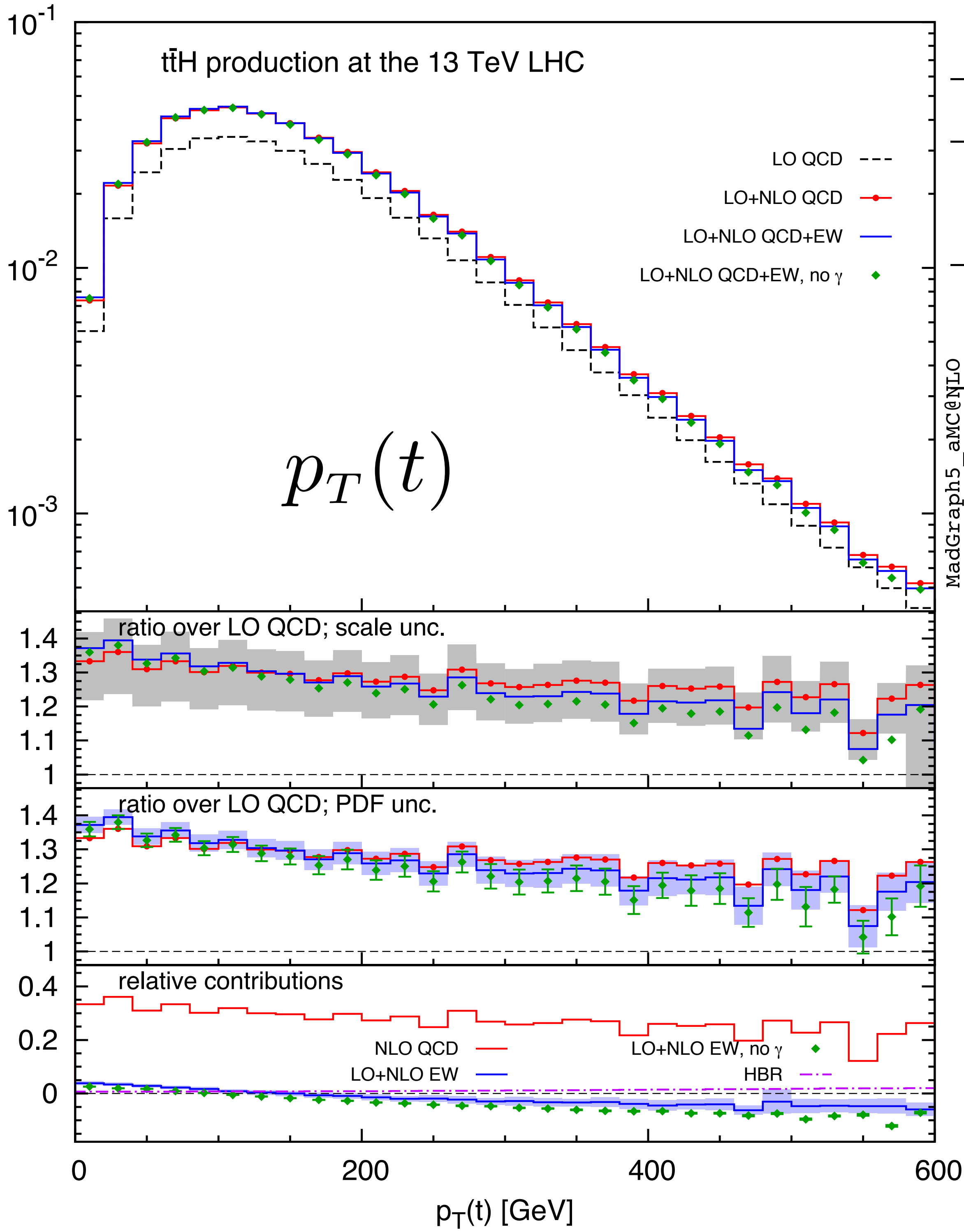
S/B increases for boosted tops and Higgs.

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)

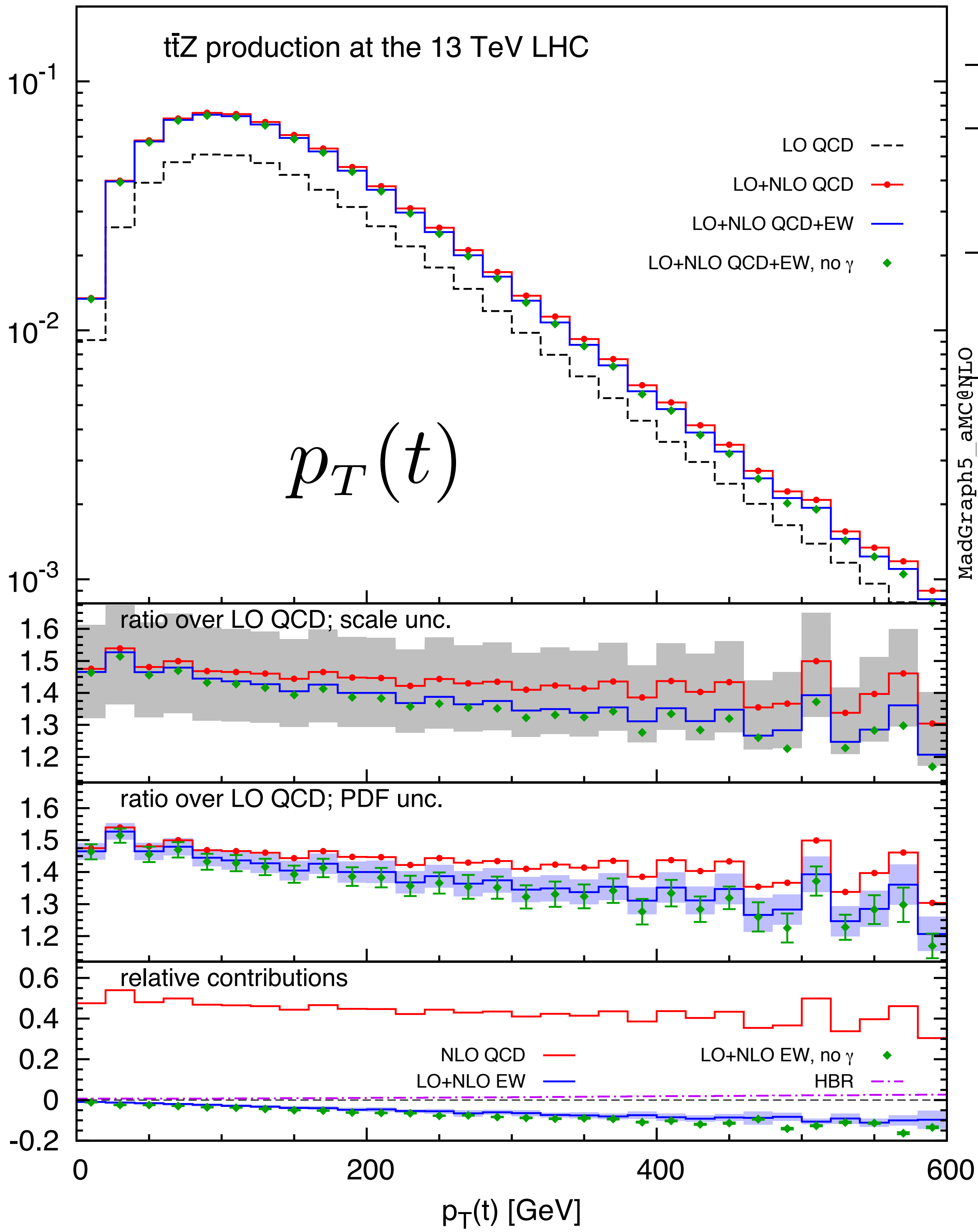
Scale variation

(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)

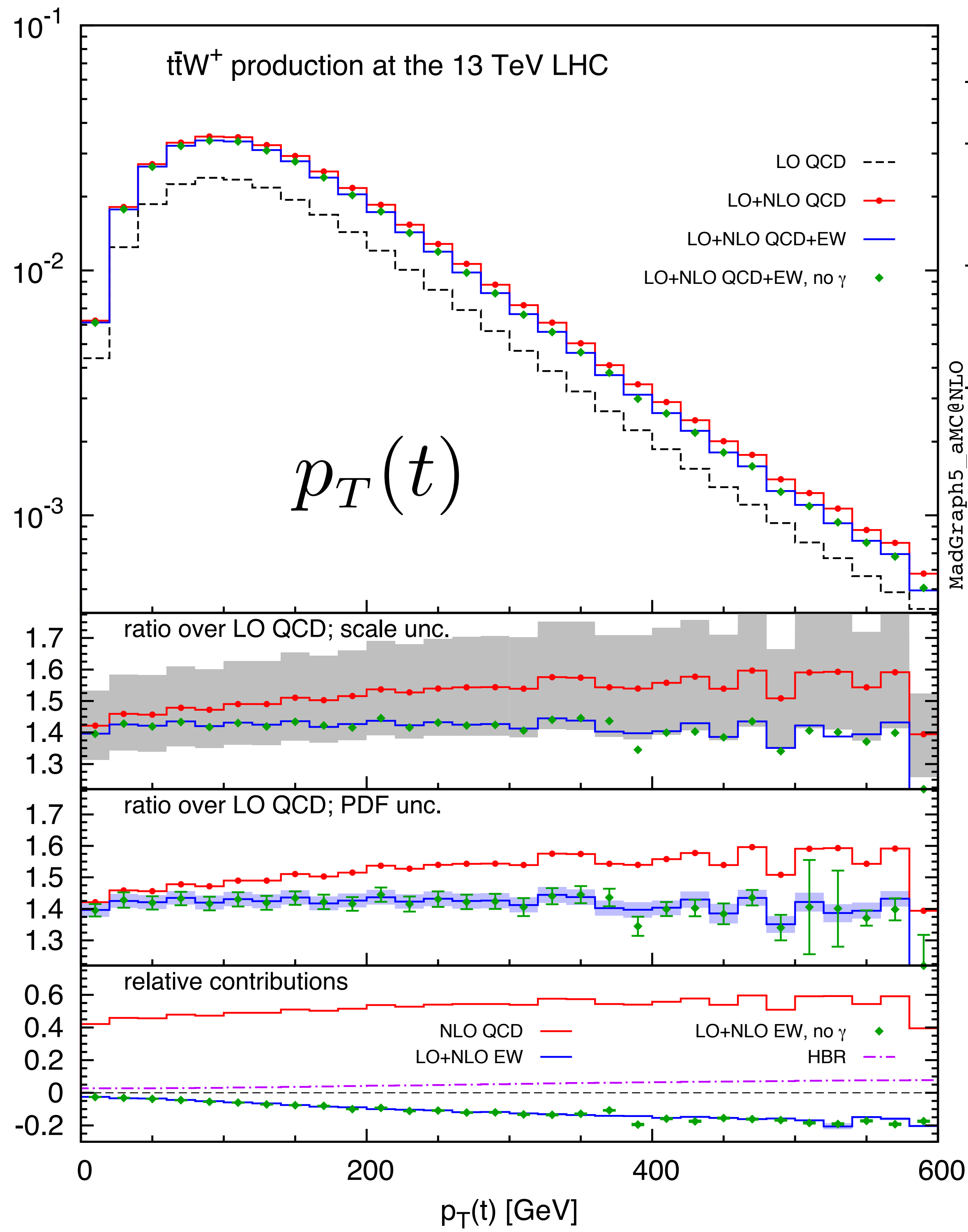
Scale variation

(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)

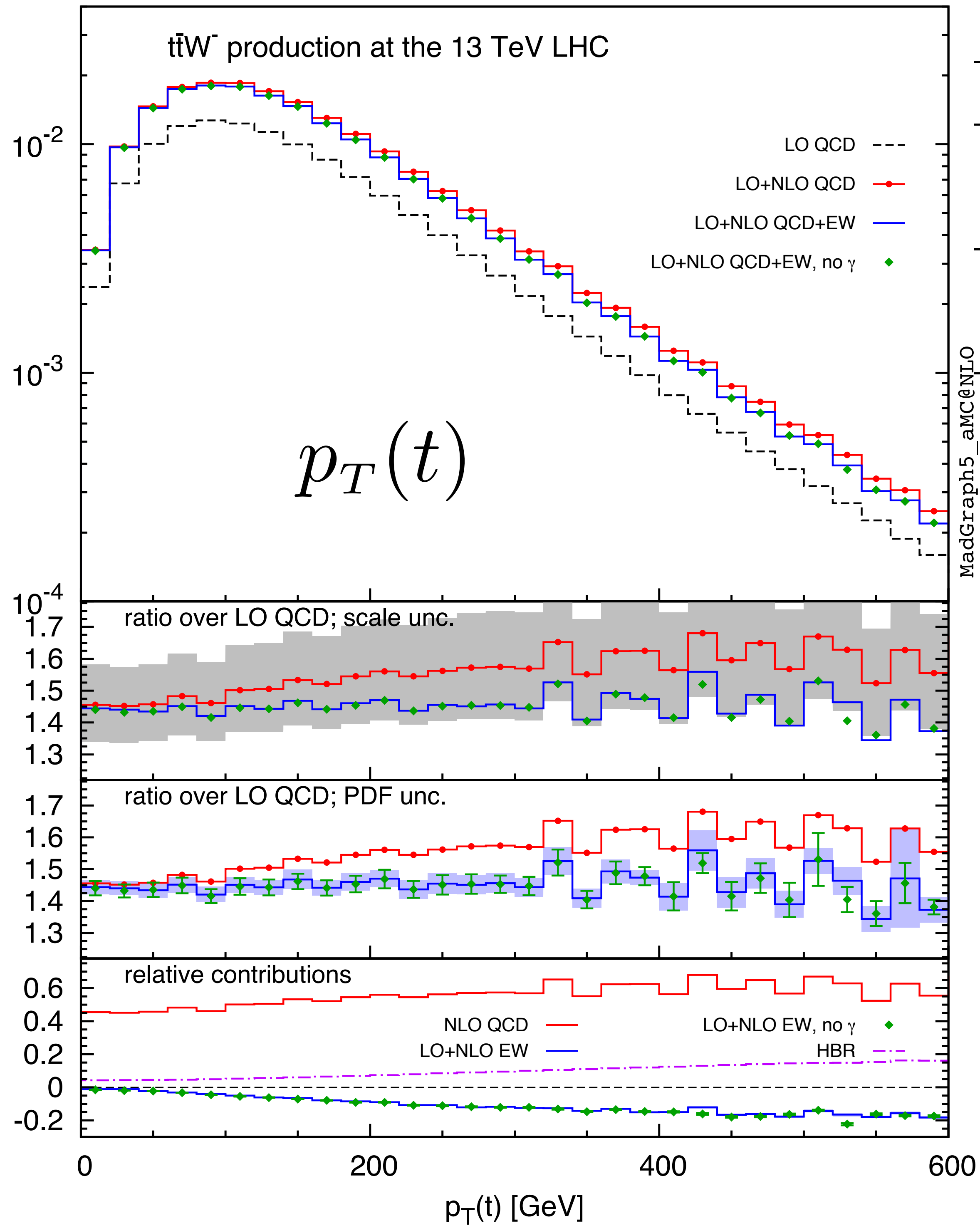
Scale variation

(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

Top-quark pair in association with one or two vector bosons at NLO QCD

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

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

Maltoni, DP, Tsinikos '15

Automated results via MadGraph5_aMC@NLO.
- "Only" NLO QCD corrections.
- Consistent framework for all the processes.
- Study of PDFs and scale uncertainties.
- NLO results for top-quark charge asymmetry

Top-quark pair in association with one or two vector bosons at NLO QCD

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

Maltoni, DP, Tsinikos '15

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

See also:

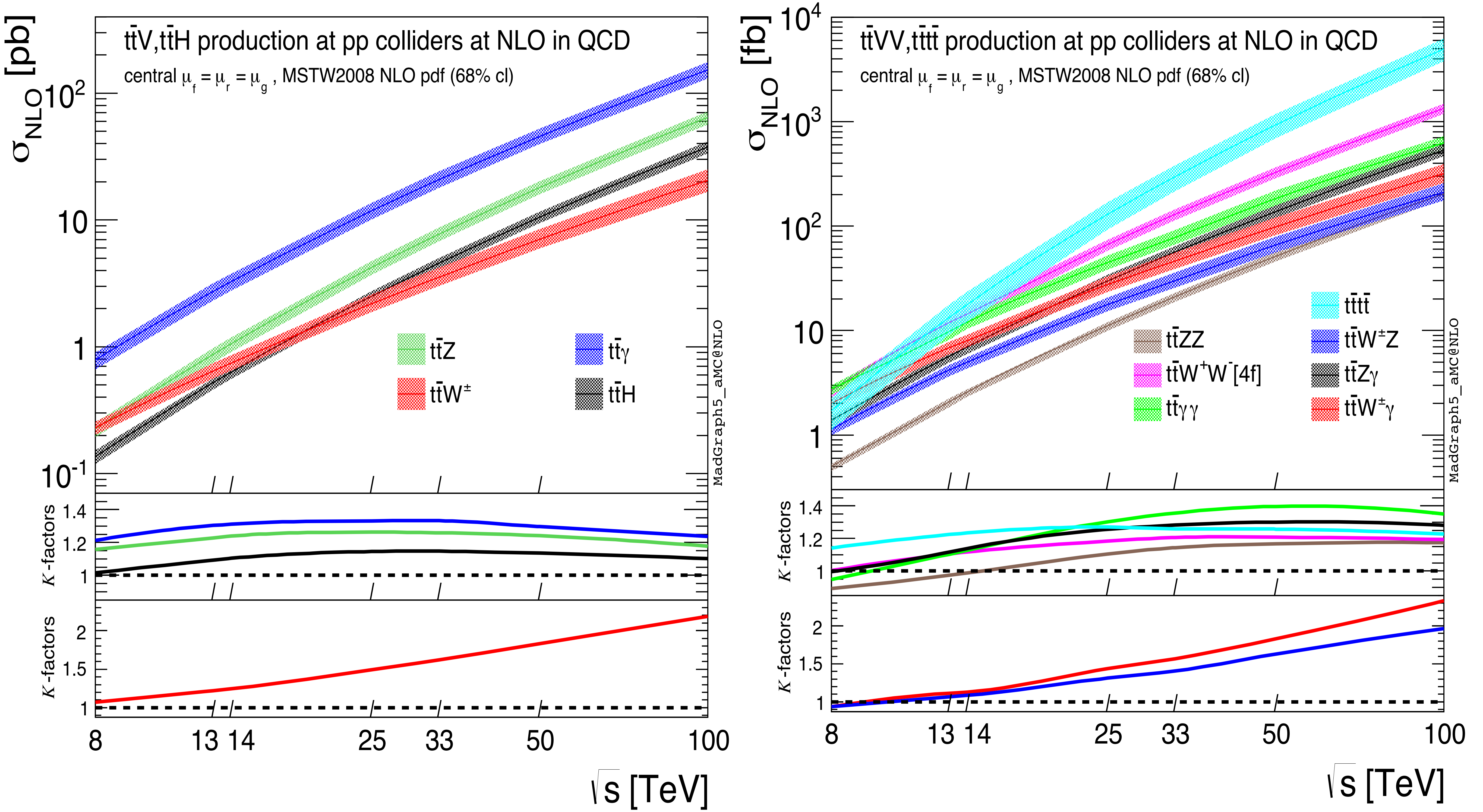
$t\bar{t}W^{\pm}$ *Garzelli et al '12, Campbell Ellis '12, Maltoni et al '14*

$t\bar{t}Z$ *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*

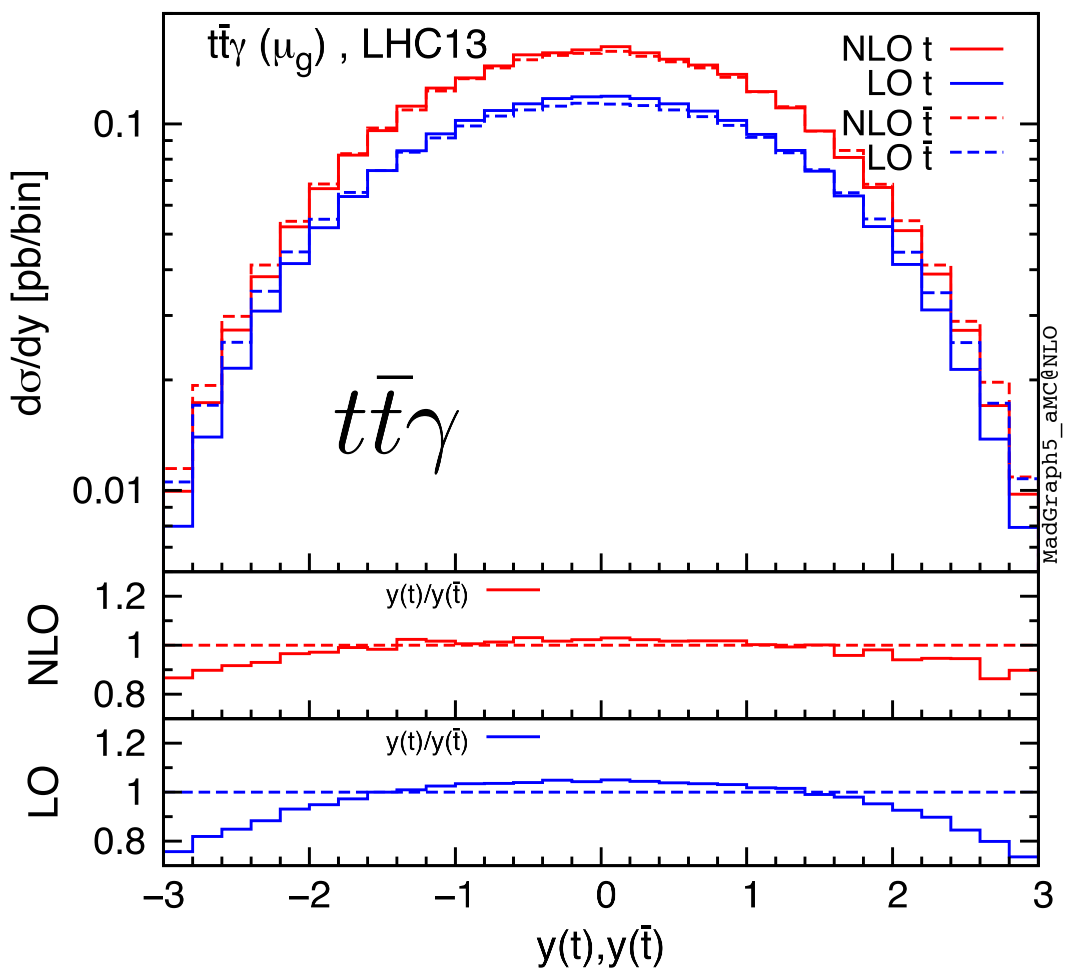
$t\bar{t}\gamma\gamma$ *Kardos Trocsanyi '14, van Deurzen et al '15*

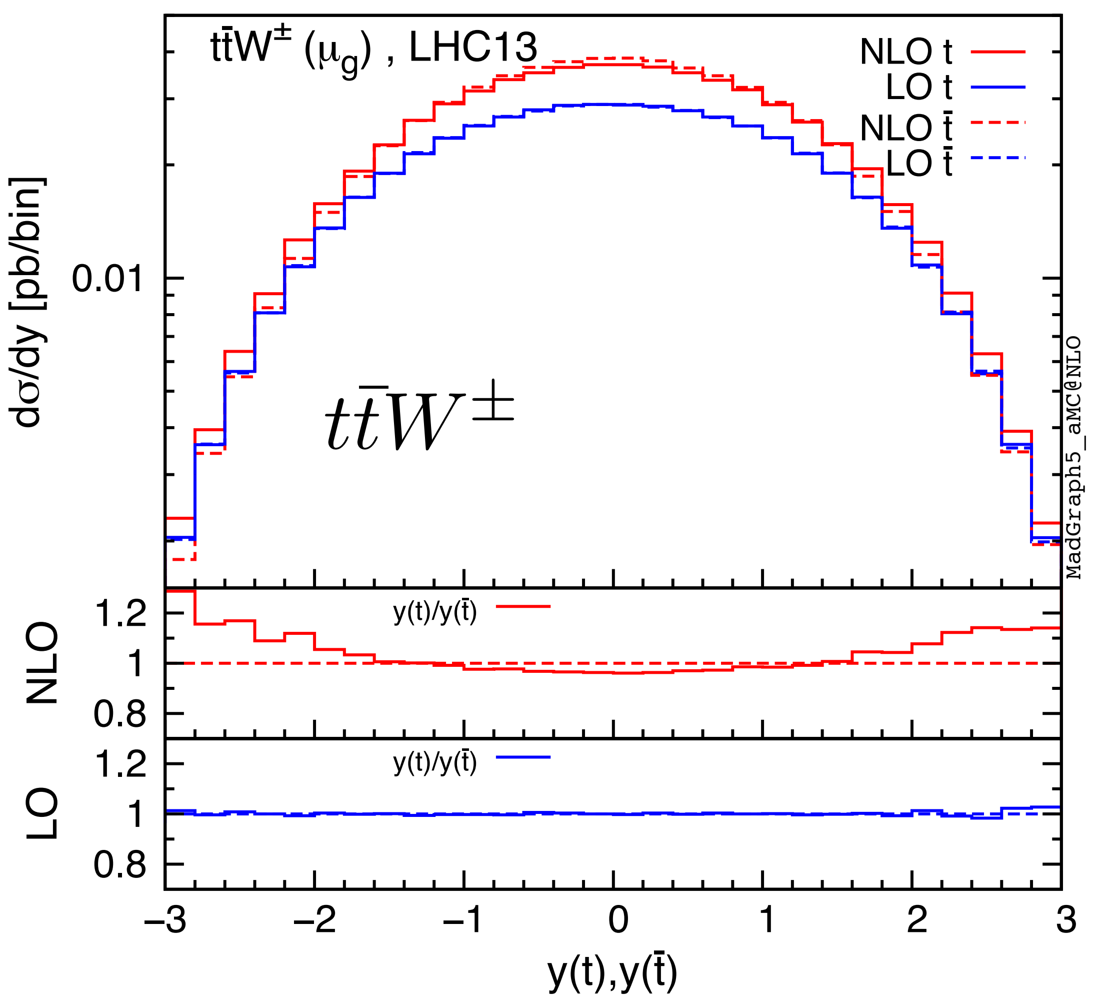
Energy dependence



Maltoni, DP, Tsinikos '15

Distributions: representative results at fixed order





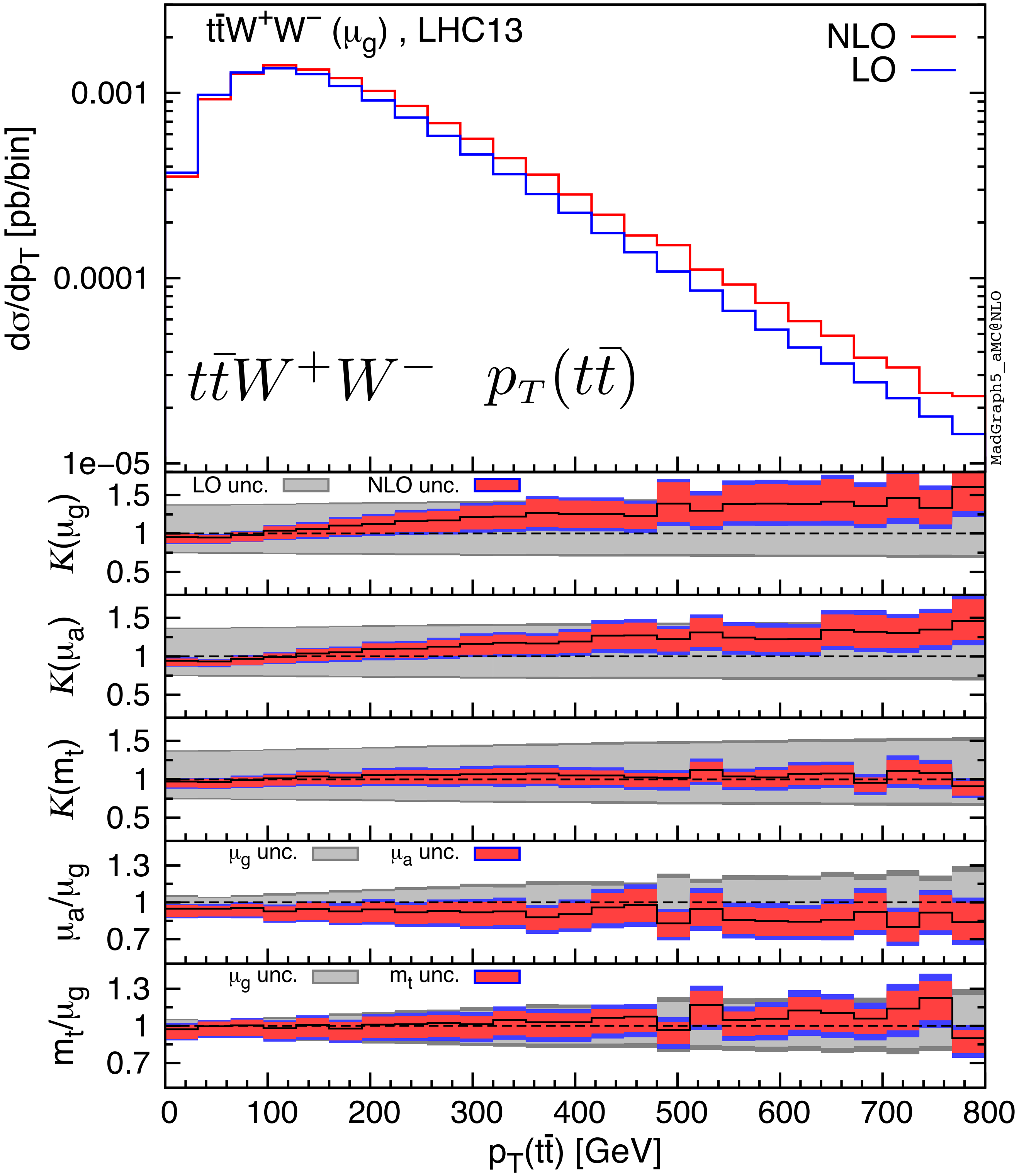
Central Asymmetries

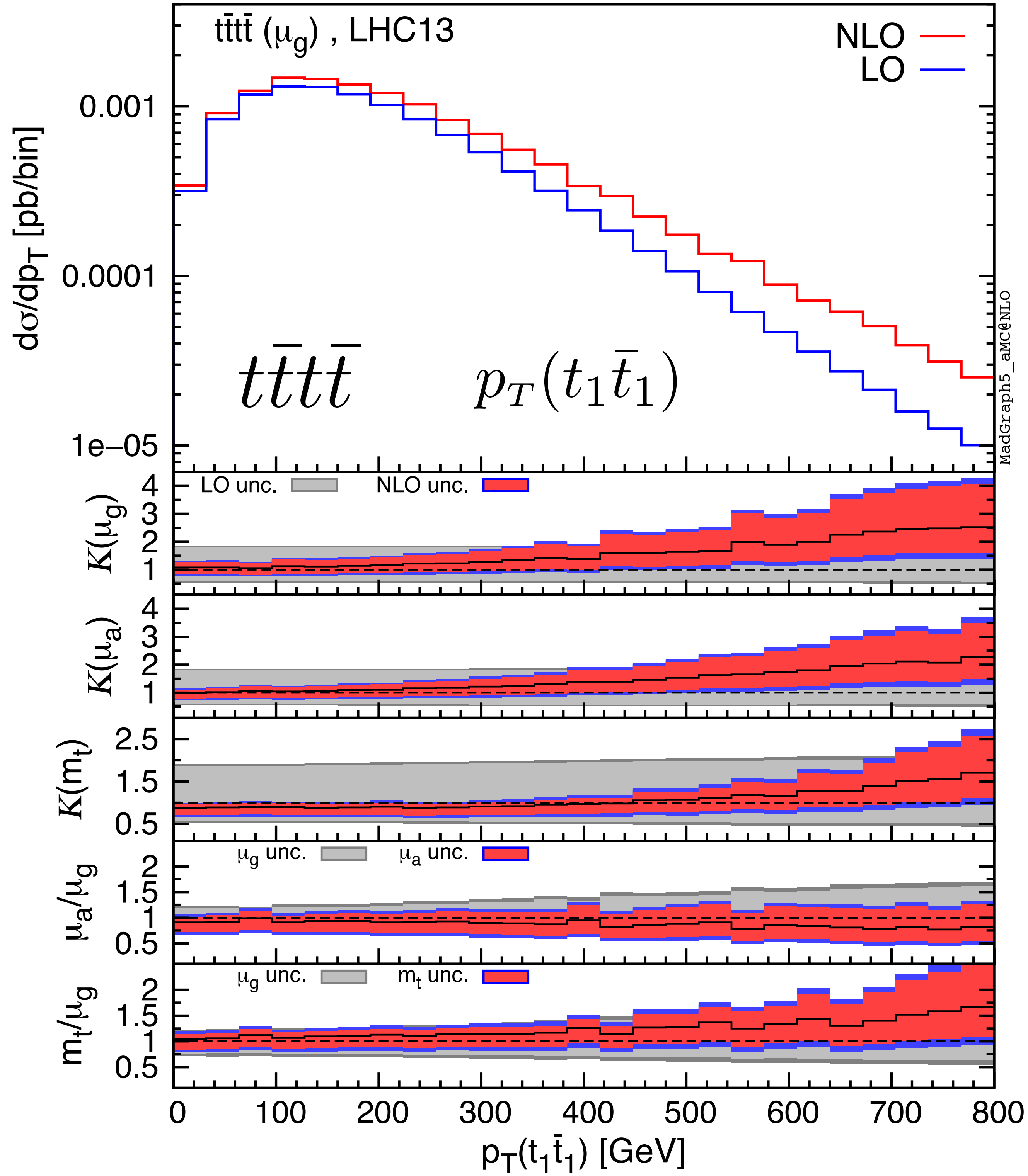
13 TeV A_c [%]	$t\bar{t}H$	$t\bar{t}Z$	$t\bar{t}W^{\pm}$	$t\bar{t}\gamma$
LO	-	$-0.12^{+0.01\ +0.01}_{-0.01\ -0.02} \pm 0.03$	-	$-3.93^{+0.26\ +0.14}_{-0.23\ -0.11} \pm 0.03$
NLO	$1.00^{+0.30\ +0.06}_{-0.20\ -0.04} \pm 0.02$	$0.85^{+0.25\ +0.06}_{-0.17\ -0.05} \pm 0.03$	$2.90^{+0.67\ +0.06}_{-0.47\ -0.07}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

Maltoni, DP, Tsinikos '15.

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

Distributions: representative results at fixed order





Maltoni, DP, Tsinikos '15

Single-top and its pathologies

<u>Associated tW</u> production at LHC: a complete calculation of **electroweak supersymmetric** effects at one loop
Beccaria, Macorini, Renard, Verzegnassi arXiv:hep-ph/0601175

A complete one-loop description of **<u>associated tW</u>** production at LHC and a search for possible genuine **supersymmetric** effects at hadron collider

Beccaria, Carloni Calame, Macorini, Montagna, Piccinini, Renard, Verzegnassi arXiv:0705.3101

Single top production in the **<u>t-channel</u>** at LHC: a realistic **test of electroweak models**

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Electroweak Corrections to **<u>t-channel</u>** single top production at the LHC
Mirabella arXiv:0811.2051

Electroweak Radiative Corrections to Single-top Production **(<u>s- and t-channel</u>)**
Bardin, Bondarenko, Kalinovskaya, Kolesnikov, von Schlippe arXiv:1008.1859

NLO EW and QCD proton-proton cross section calculations with **mcsanc-v1.01 (<u>s- and t-channel</u>)**
Bondarenko, Sapronov arXiv:1301.3687

Real QED only soft *Within MSSM* *IR regularized with Γt*
Only partonic results

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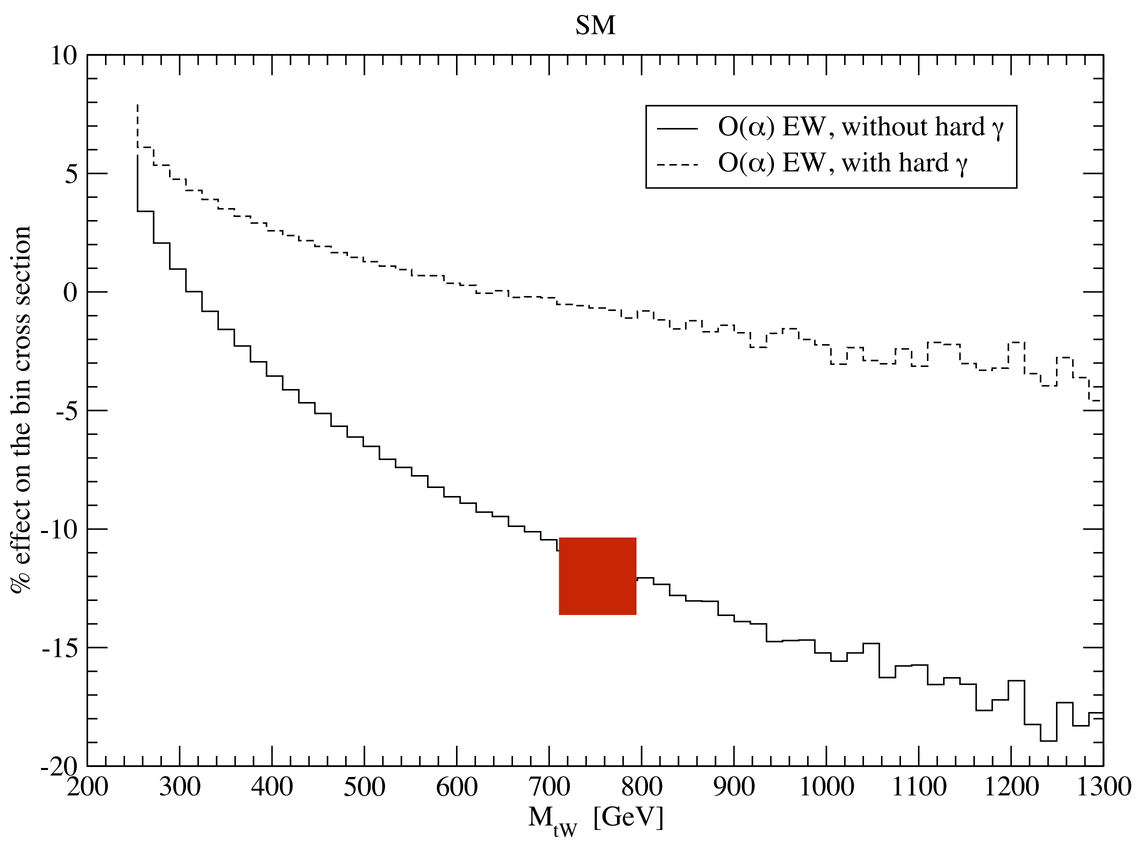
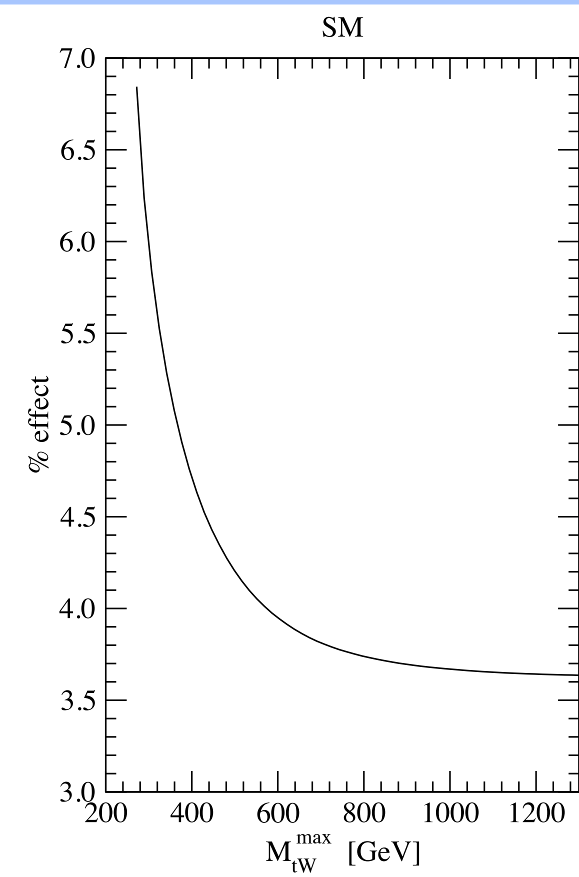
Only partonic results

numerical results at the LHC 14 TeV





Associated tW

arXiv:0705.3101

s- and t-channel

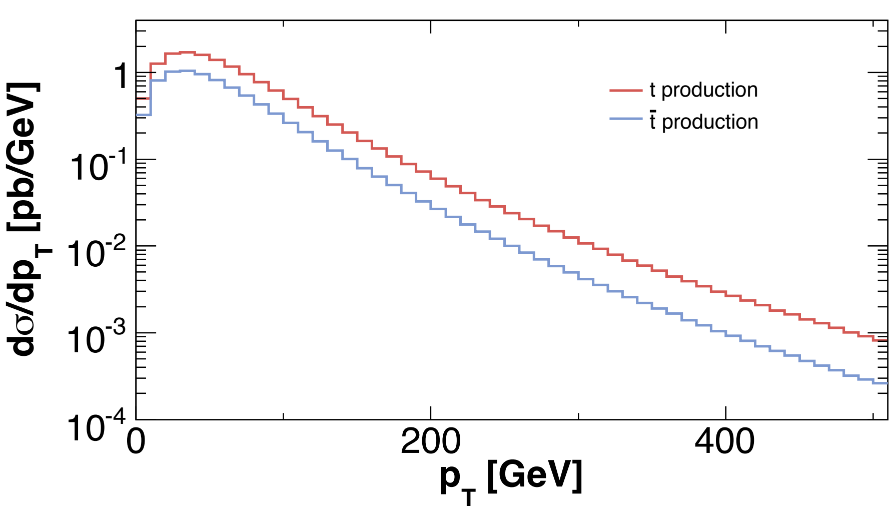
arXiv:1301.3687

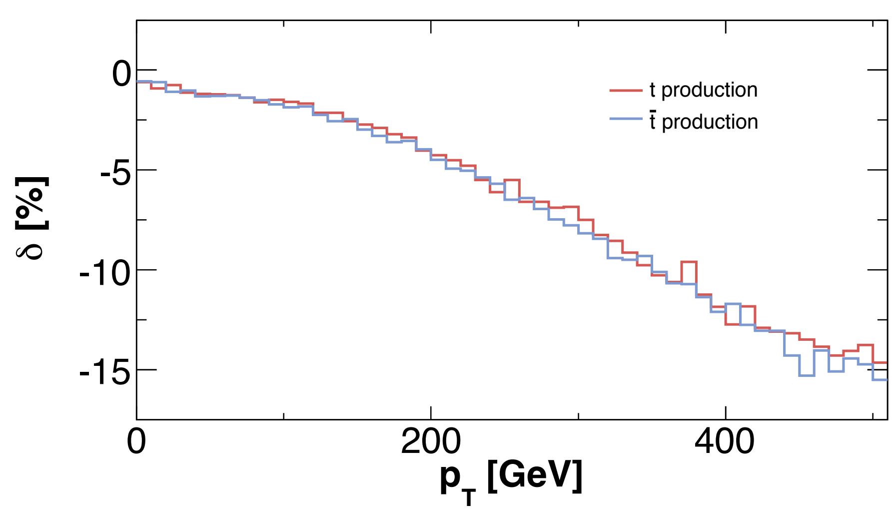
$pp \to$	$t + \bar{b}$ (s-channel)	$\bar{t} + b$ (s-channel)
LO	5.134(1)	3.205(1)
LO MCFM	5.133(1)	3.203(1)
NLO QCD	6.921(2)	4.313(2)
NLO MCFM	6.923(2)	4.309(1)
NLO EW	5.022(1)	3.140(1)
δ_{QCD}, %	34.79(5)	34.56(8)
δ_{EW}, %	-2.18(1)	-2.02(2)

$pp \to$	$t + q$ (t-channel)	$\bar{t} + q$ (t-channel)
LO	158.73(2)	95.18(2)
LO MCFM	158.69(7)	95.27(4)
NLO QCD	152.13(9)	90.44(7)
NLO MCFM	152.07(14)	90.50(8)
NLO EW	164.44(5)	98.65(4)
δ_{QCD}, %	-4.17(6)	-4.08(8)
δ_{EW}, %	3.59(3)	3.66(5)

t-channel

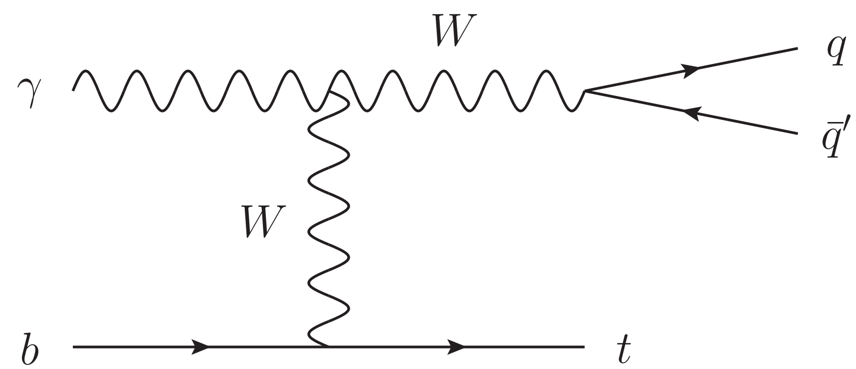
arXiv:0811.2051



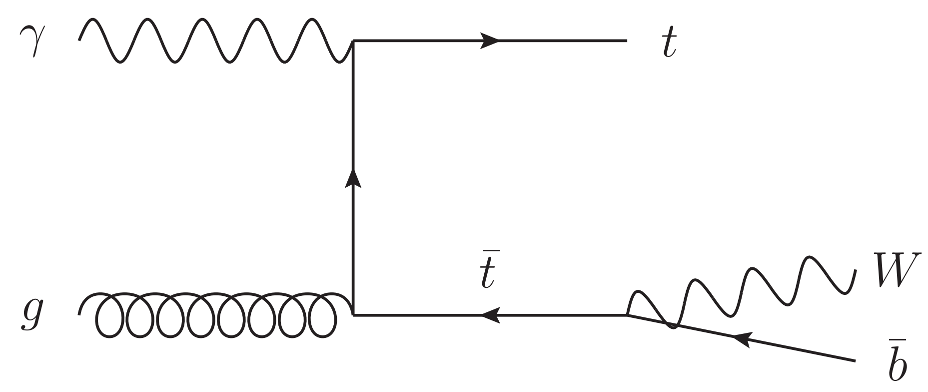


Pathologies

All the previous calculations included **only** real photon radiation.
Real quark radiation and initial-state photons have **NOT** been taken into account.
What if we include them?



NLO EW quark radiation to tj or tW with W decay?



NLO EW quark radiation to tW or ttbar with t decay?

NLO QCD pathologies are present also at the NLO EW.
With 4FS (and HBR) pathologies become even worse.

Is it necessary to move to stable final-state particles?

CONCLUSION

EW corrections to the asymmetries are huge and necessary for a realistic description. They are not Sudakov enhanced.

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

$t\bar{t}V$ and $t\bar{t}VV$ have been studied at NLO QCD accuracy, K-factors for charged final states strongly depend on energy of pp collision. Top-quark asymmetries are present also for $t\bar{t}V$ and NLO QCD corrections reduce the value for $t\bar{t}\gamma$.

Single top: EW corrections are large for tW production. For t-channel, they are of the same size of NLO QCD corrections, with opposite sign.
Updated results involving quark radiation and photons in the initial states are desirable, but technically not straightforward.

EXTRA SLIDES

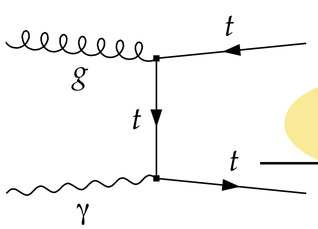
Why do we care about photons in the proton?

2 representative examples:

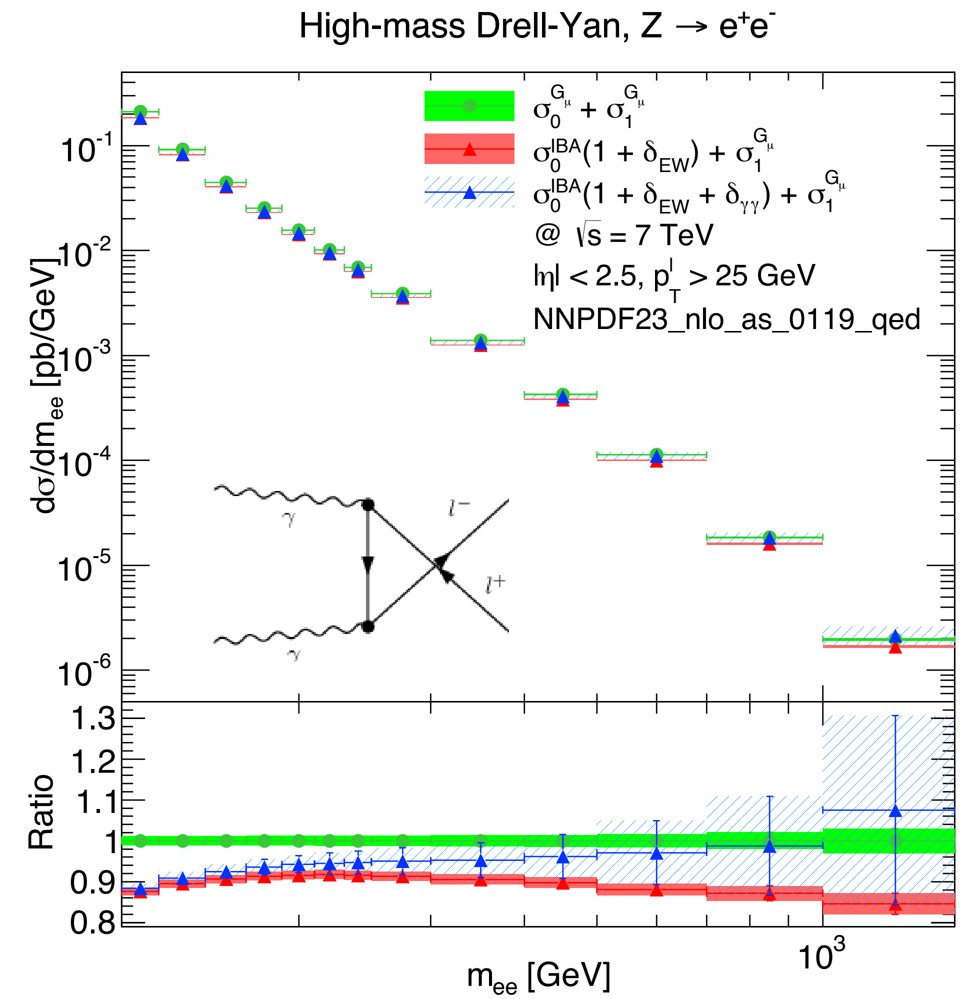
$t\bar{t}$

Process	$\sigma_{\rm tot}$ 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

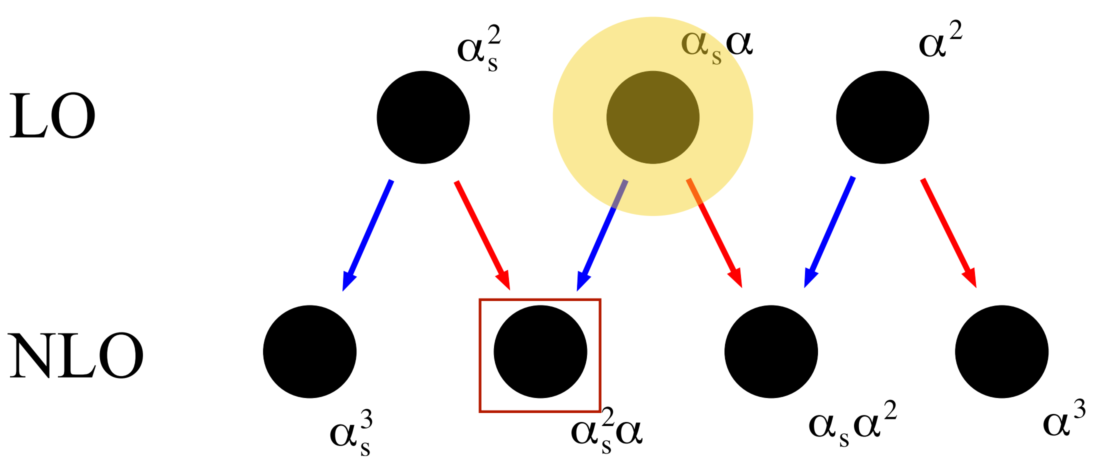


Integrated hadronic cross section for $t\bar{t}$ production at the LHC, at NLO QED

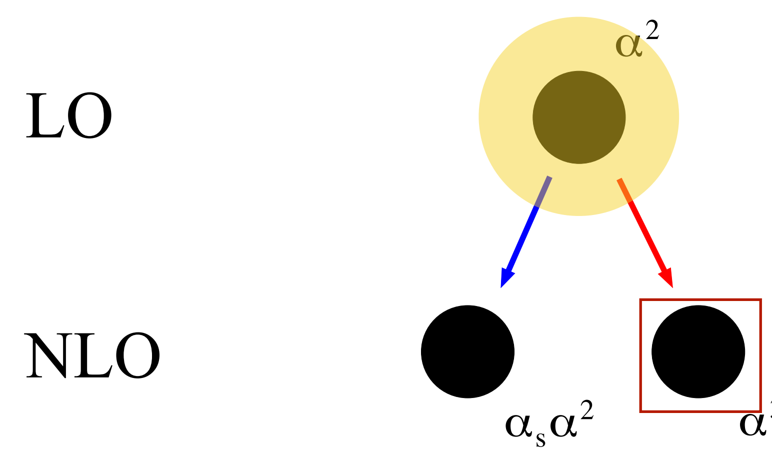


Hollik, Kollar '07 MRST2004QED

Carrazza '14 NNPDF2.3QED

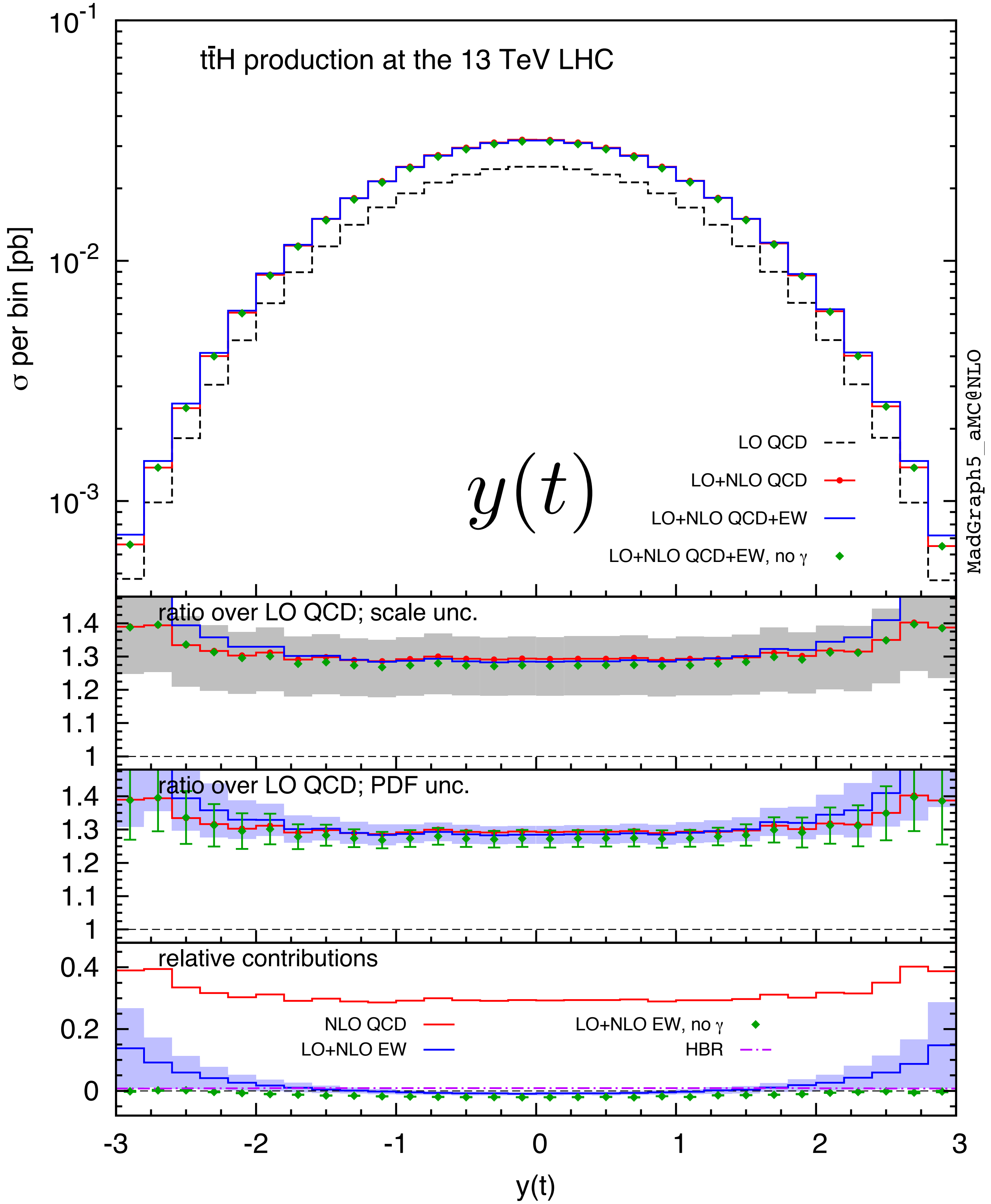


NLO EW

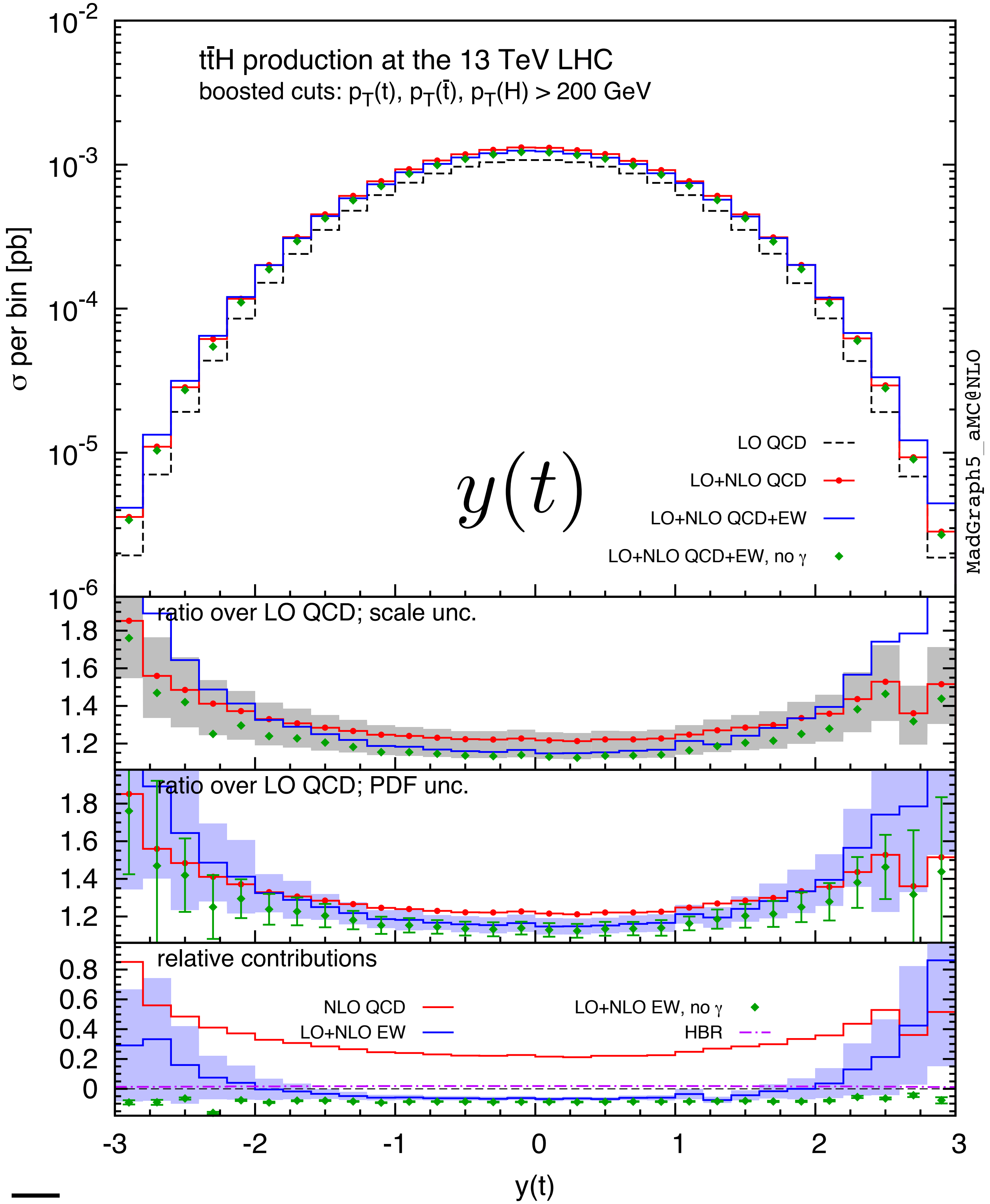


NLO EW

Rapidity distributions: unboosted vs. boosted



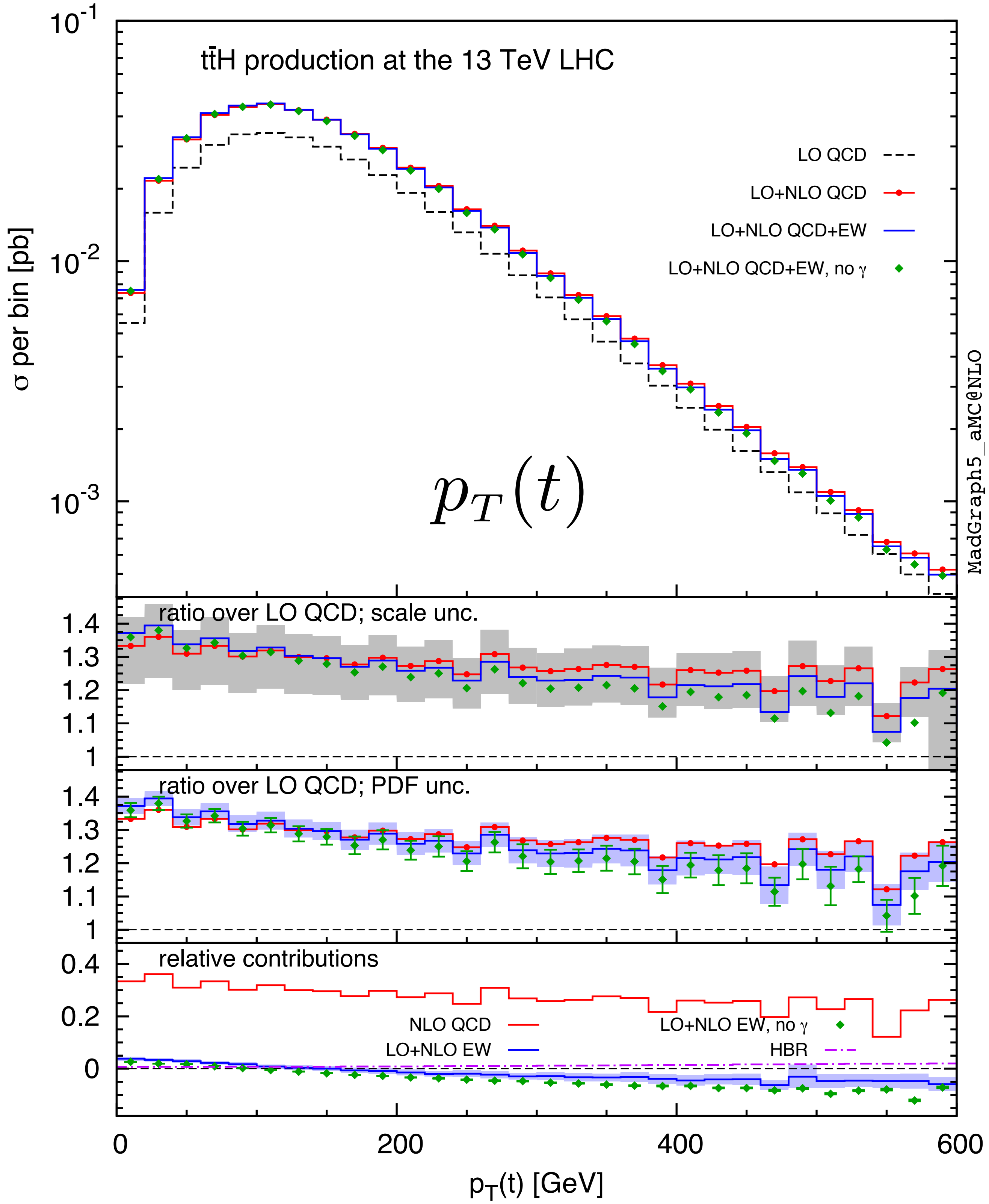
13 TeV

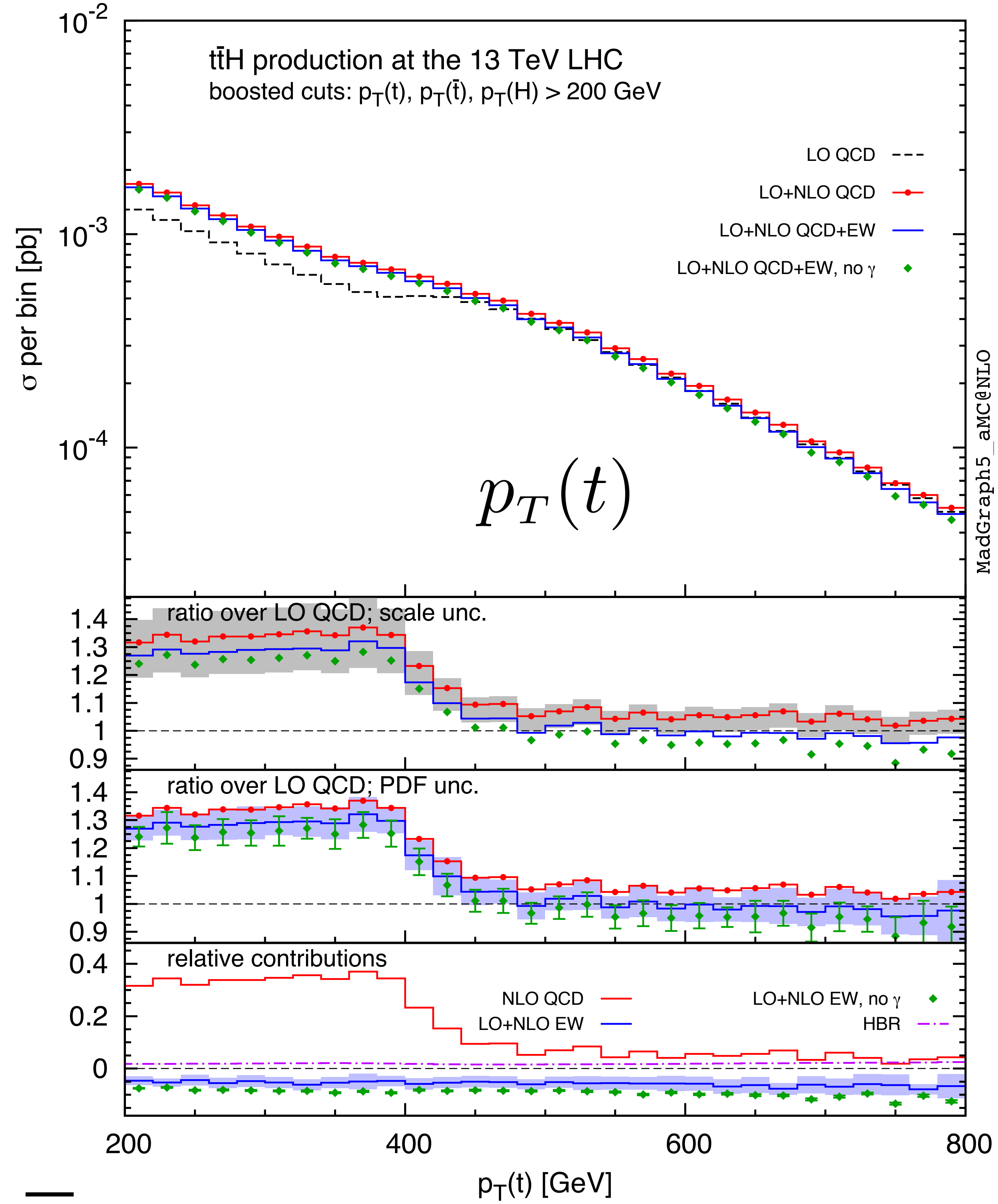


13 TeV

$t\bar{t}H$

Transverse momentum distributions: unboosted vs. boosted



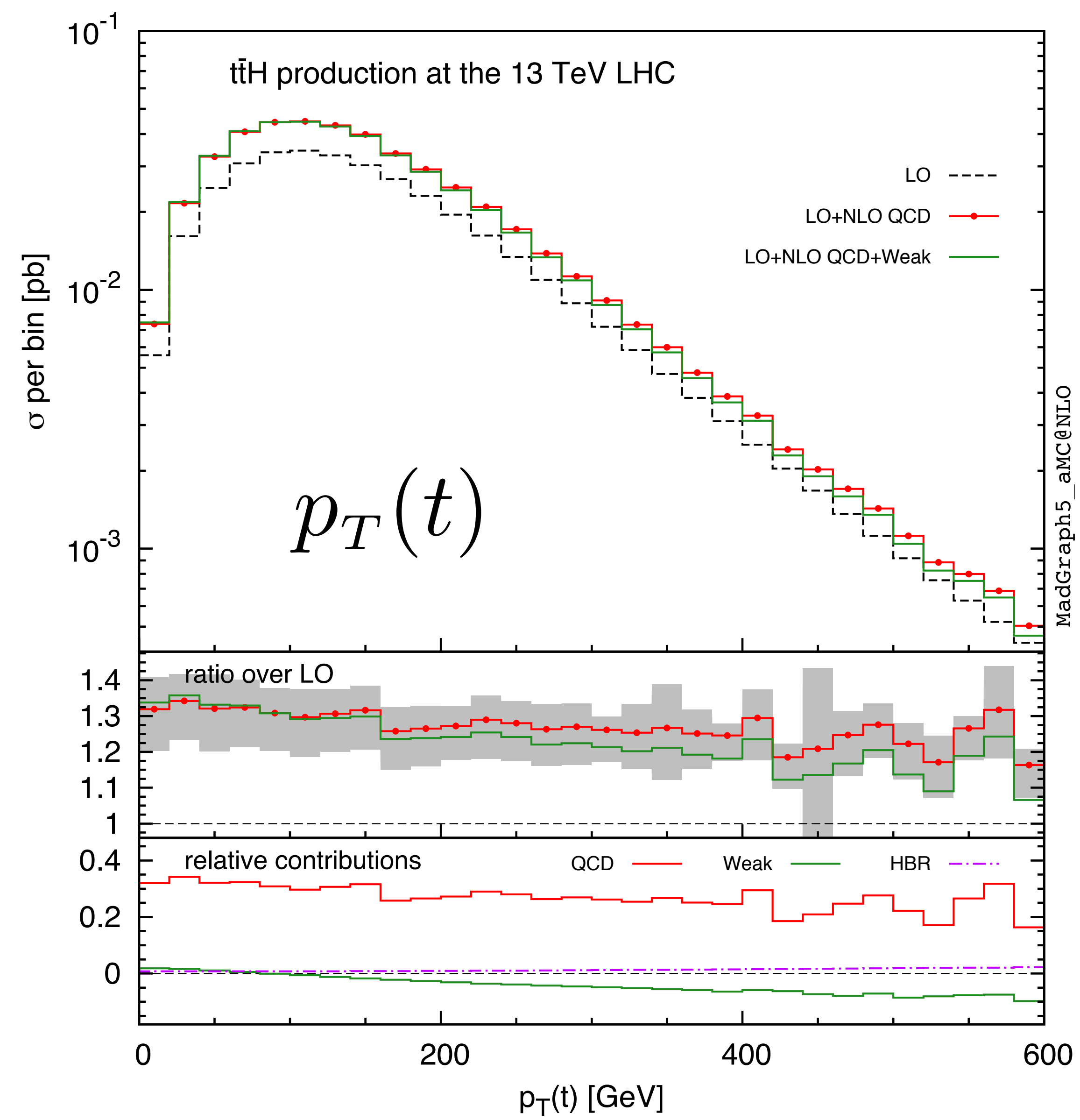


13 TeV $t\bar{t}H$ 13 TeV

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
```

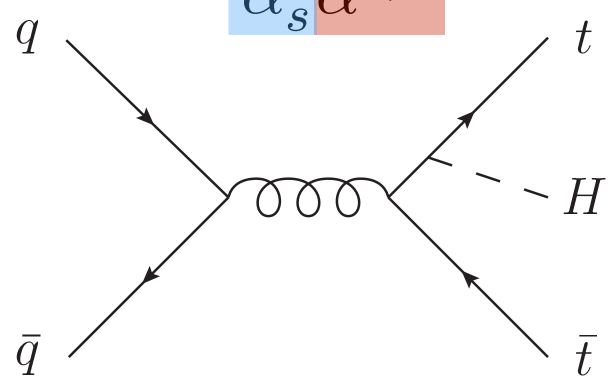
In this talk I will present results for NLO QCD and EW corrections to

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

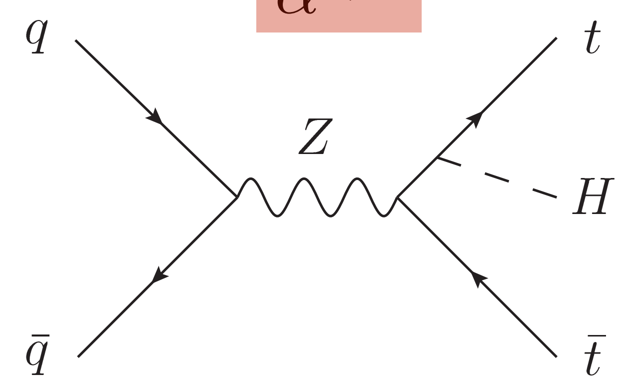
Frixione, Hirschi, DP, Shao, Zaro '15

Structure of NLO EW-QCD corrections

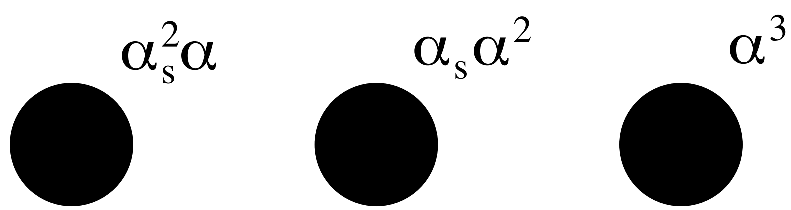
$\alpha_s^1 \alpha^{1/2}$



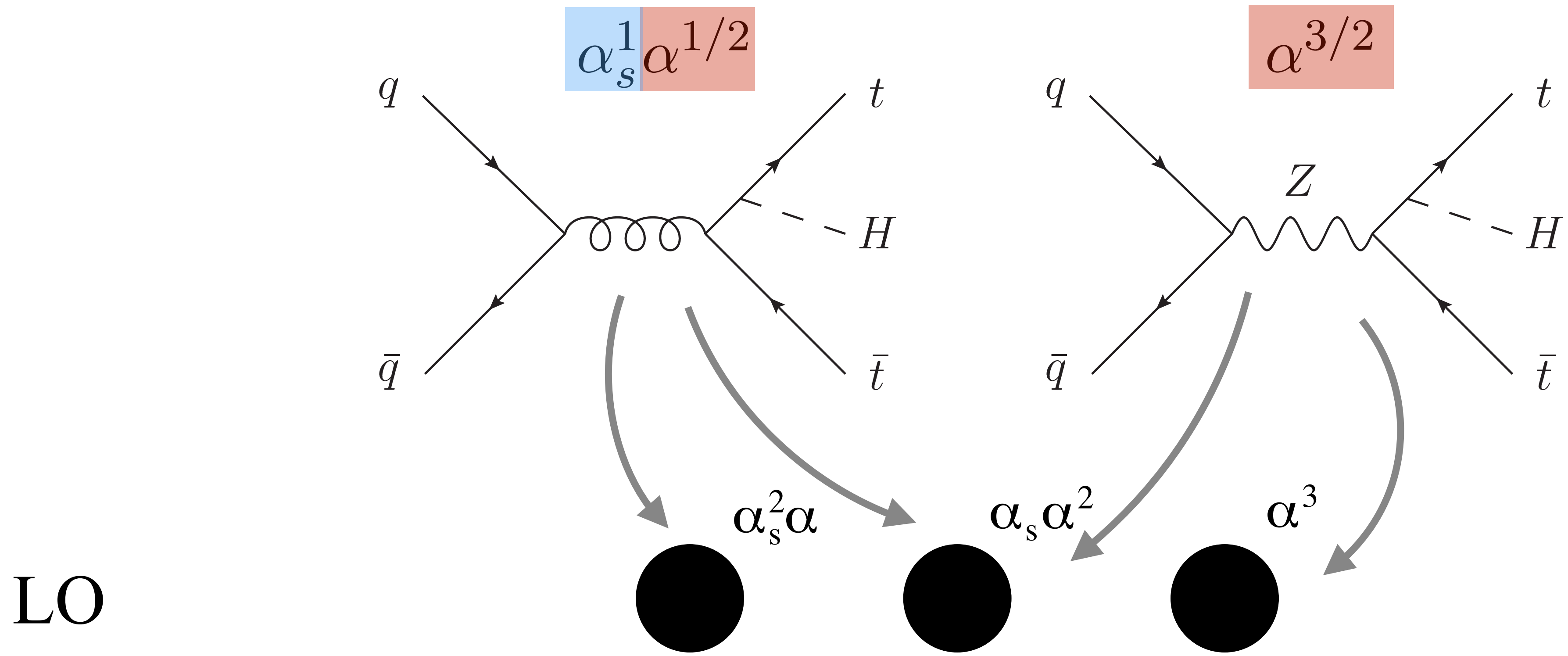
$\alpha^{3/2}$



LO



Structure of NLO EW-QCD corrections



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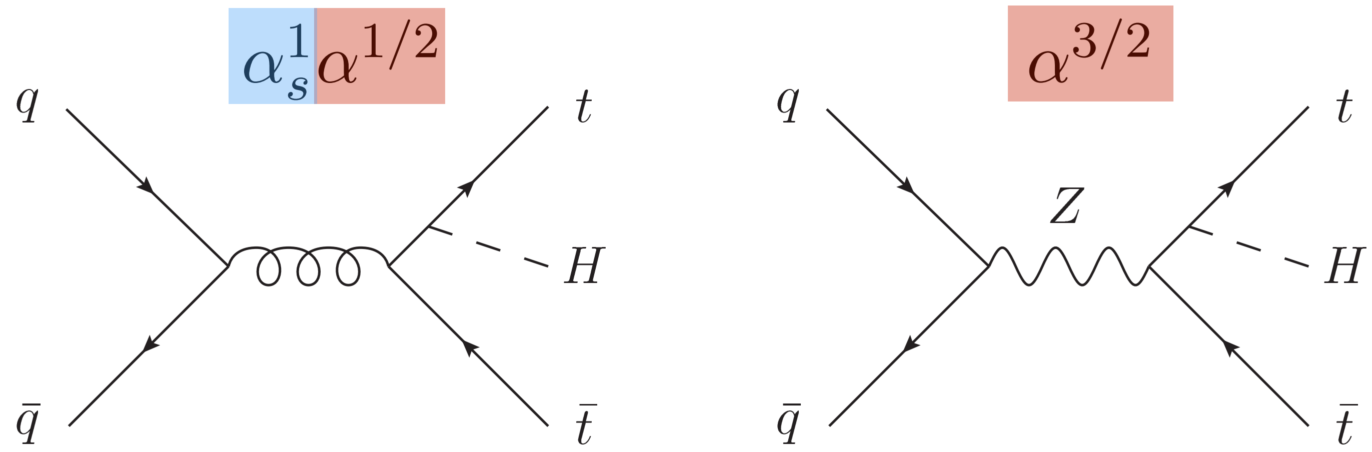
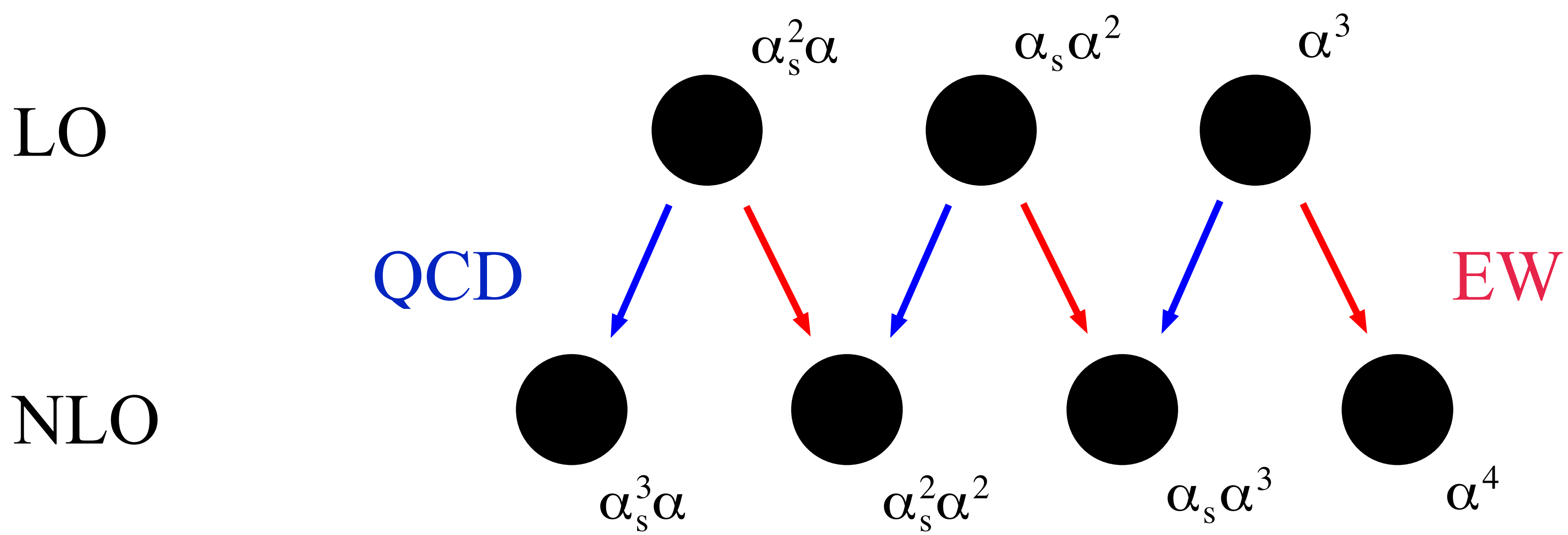
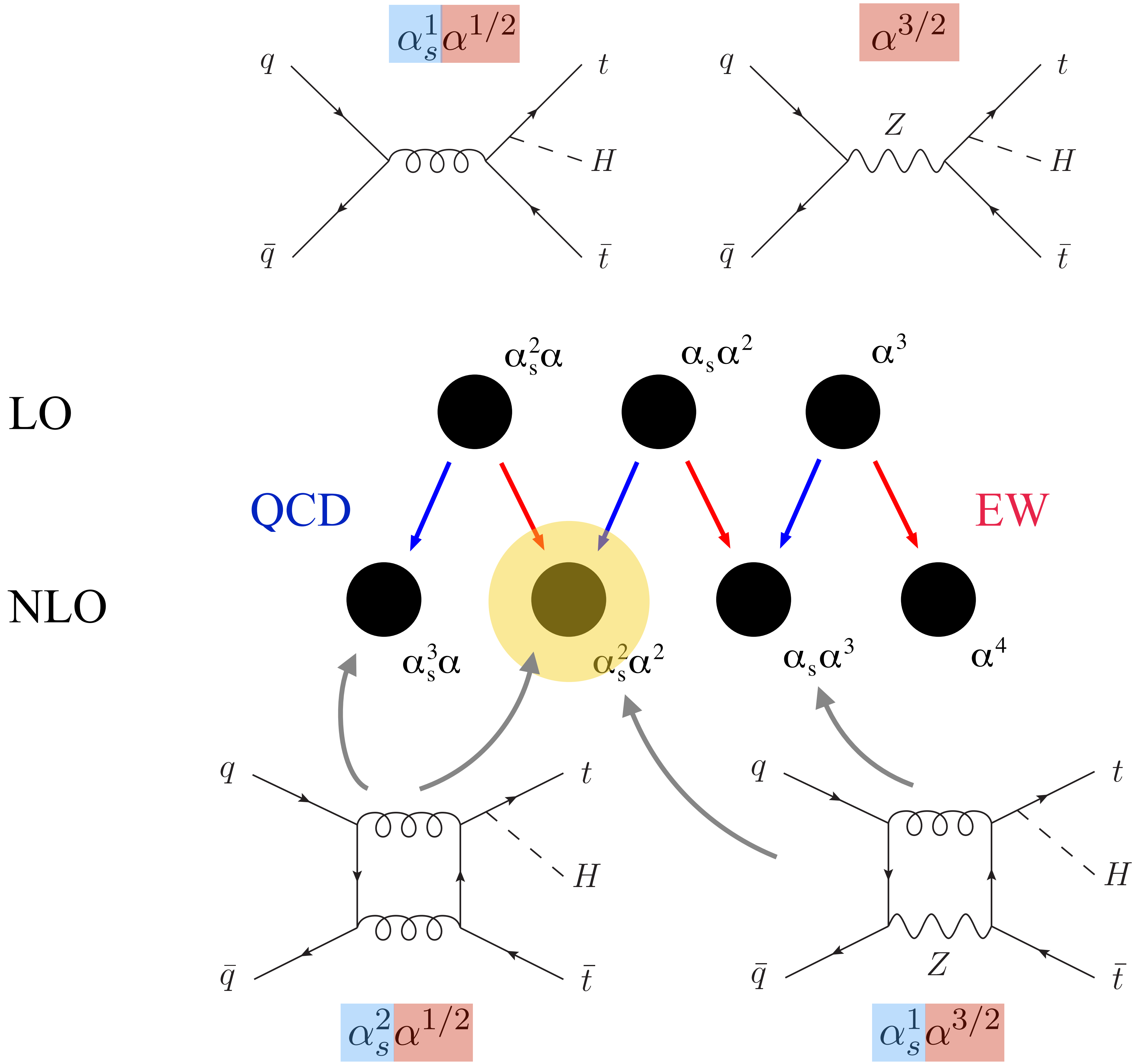
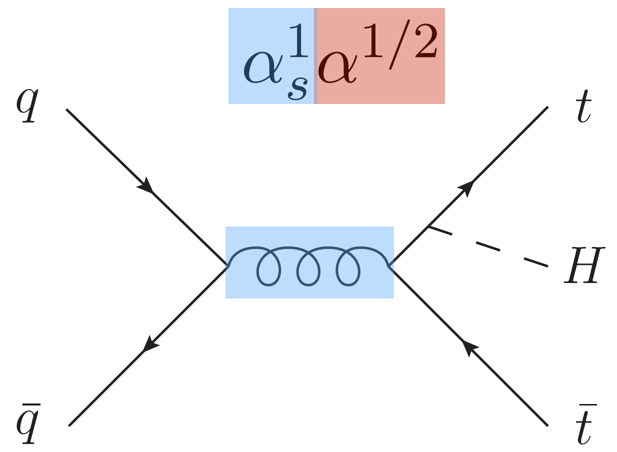


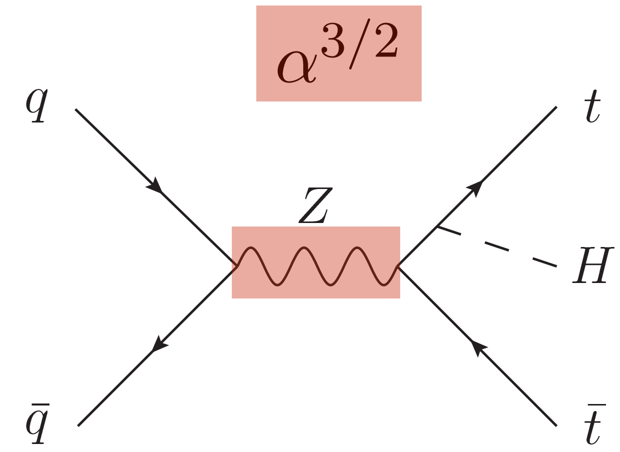


Structure of NLO EW-QCD corrections



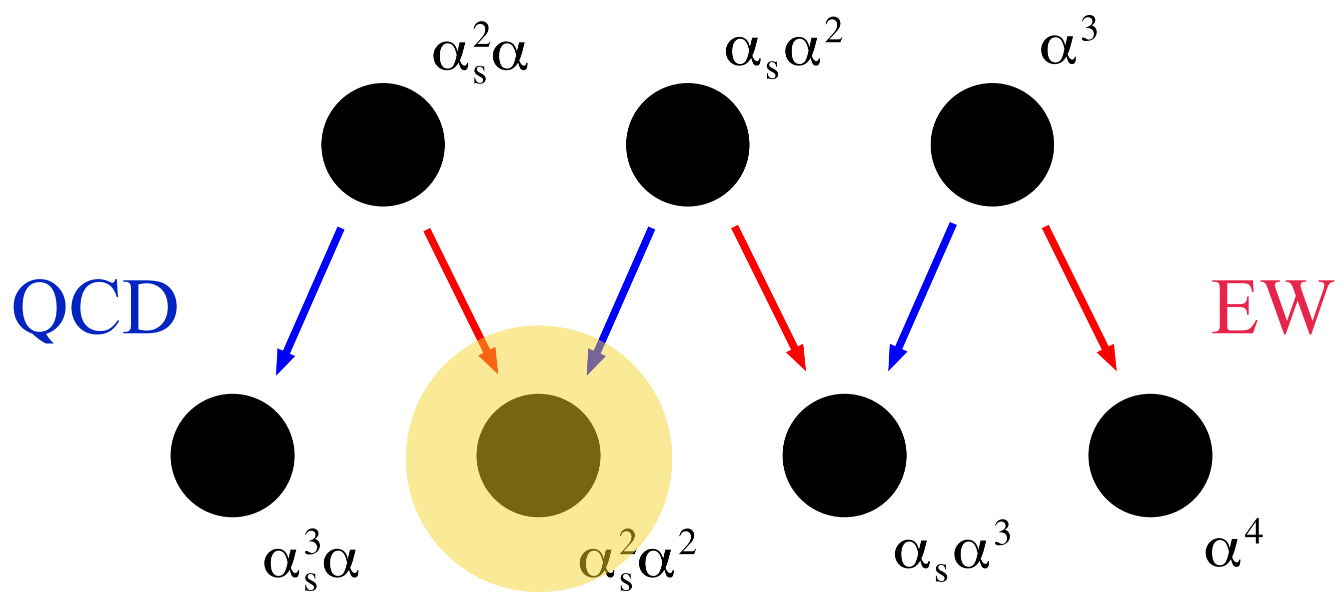
Structure of NLO EW-QCD corrections

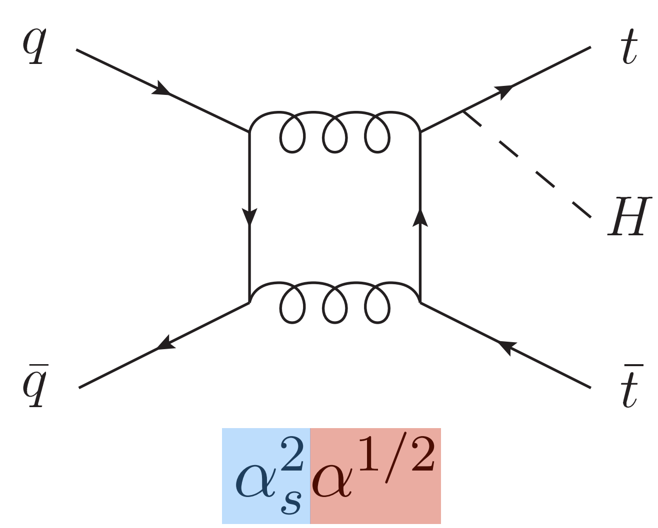


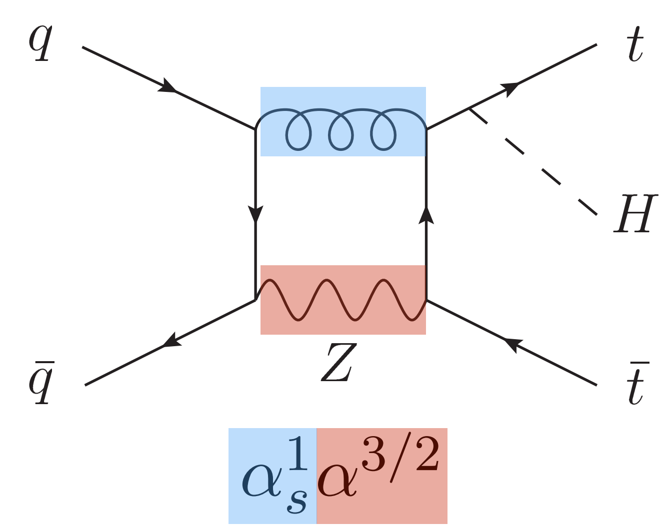


LO

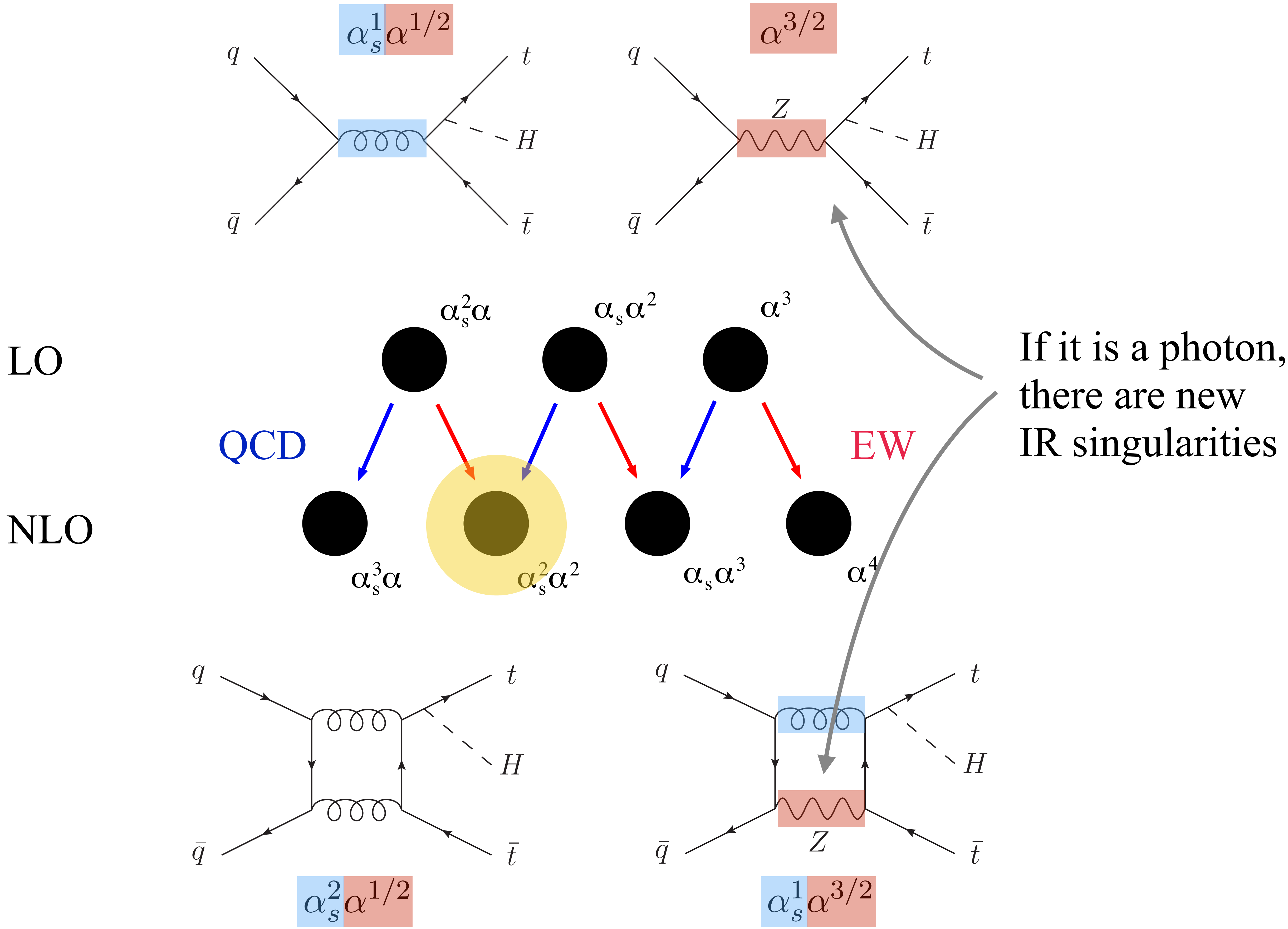
NLO







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)

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

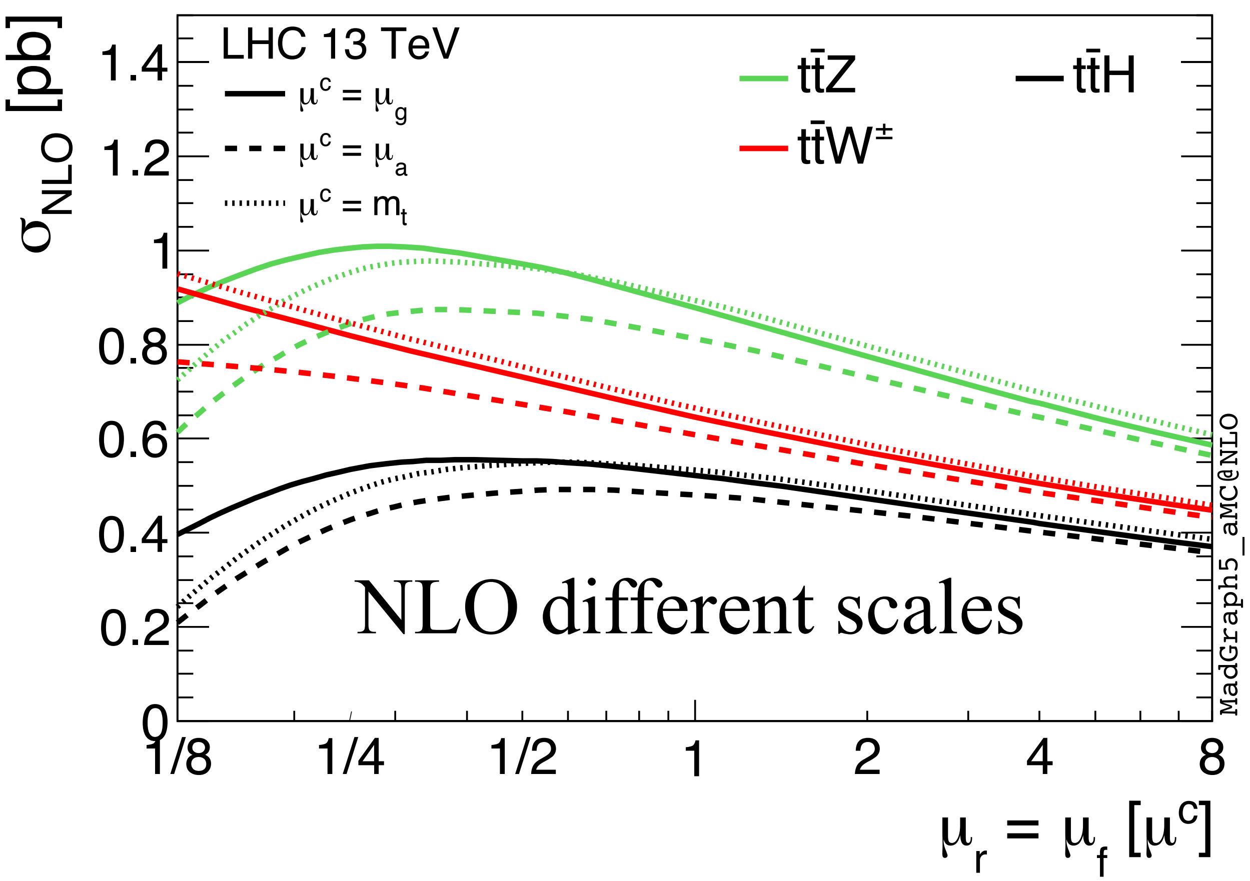
We compare the scale dependencies for the fixed scale and for two (common) definitions of dynamical scales: the **a**rithmetic and **g**eometric mean of final-state transverse masses.

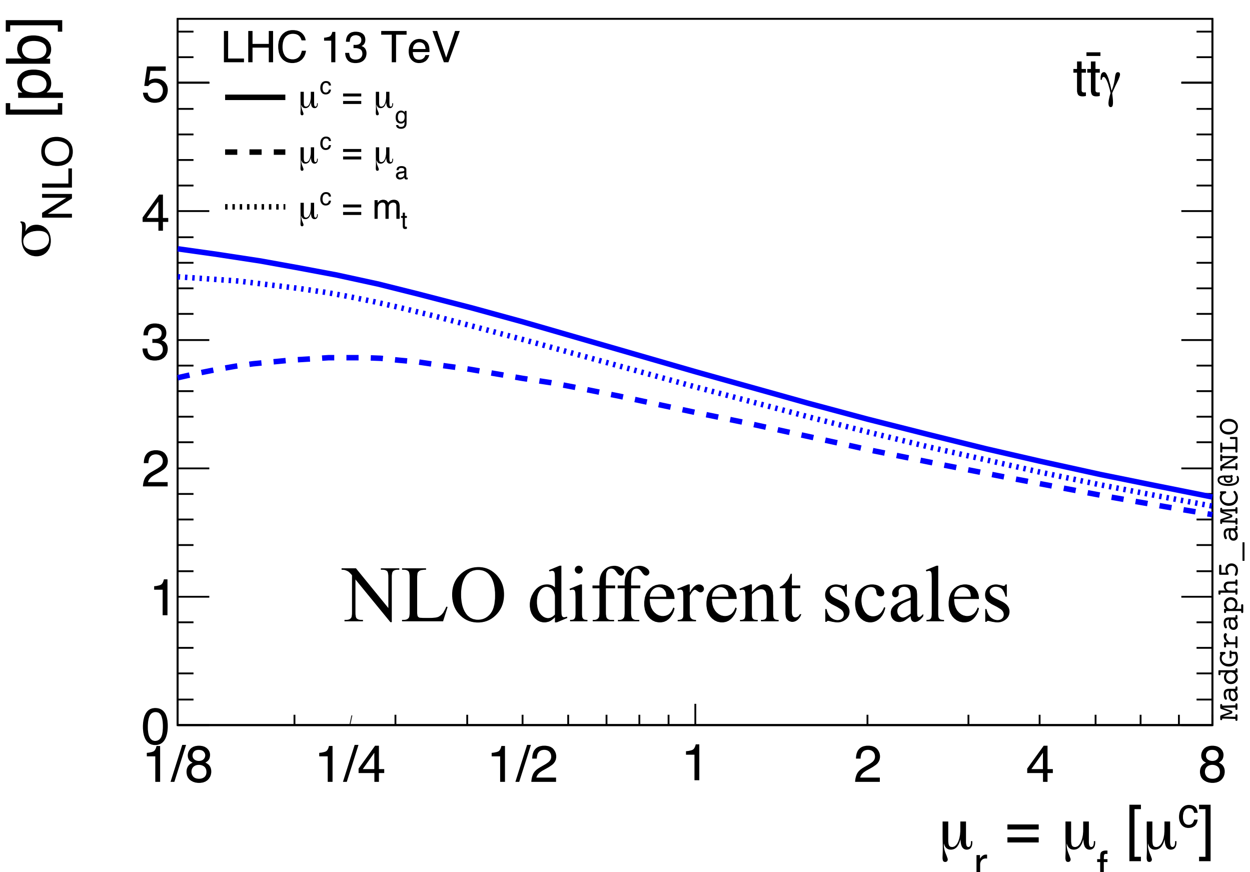
$$\mu_a = \frac{H_T}{N} := \frac{1}{N} \sum_{i=1,N(+1)} m_{T,i}$$

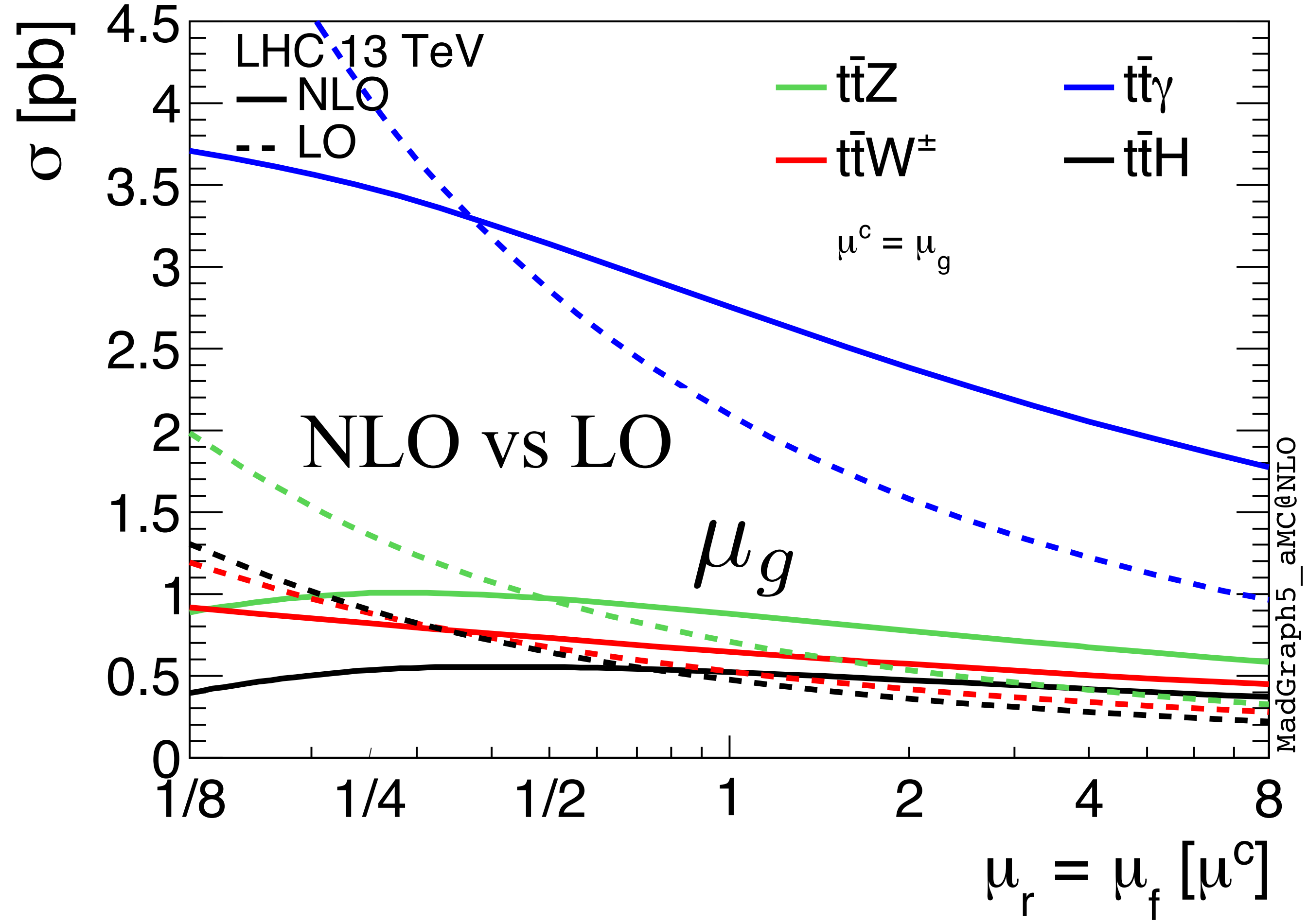
$$\mu_g := \left(\prod_{i=1,N} m_{T,i} \right)^{1/N}$$

WE DO NOT SEARCH FOR THE BEST SCALE!

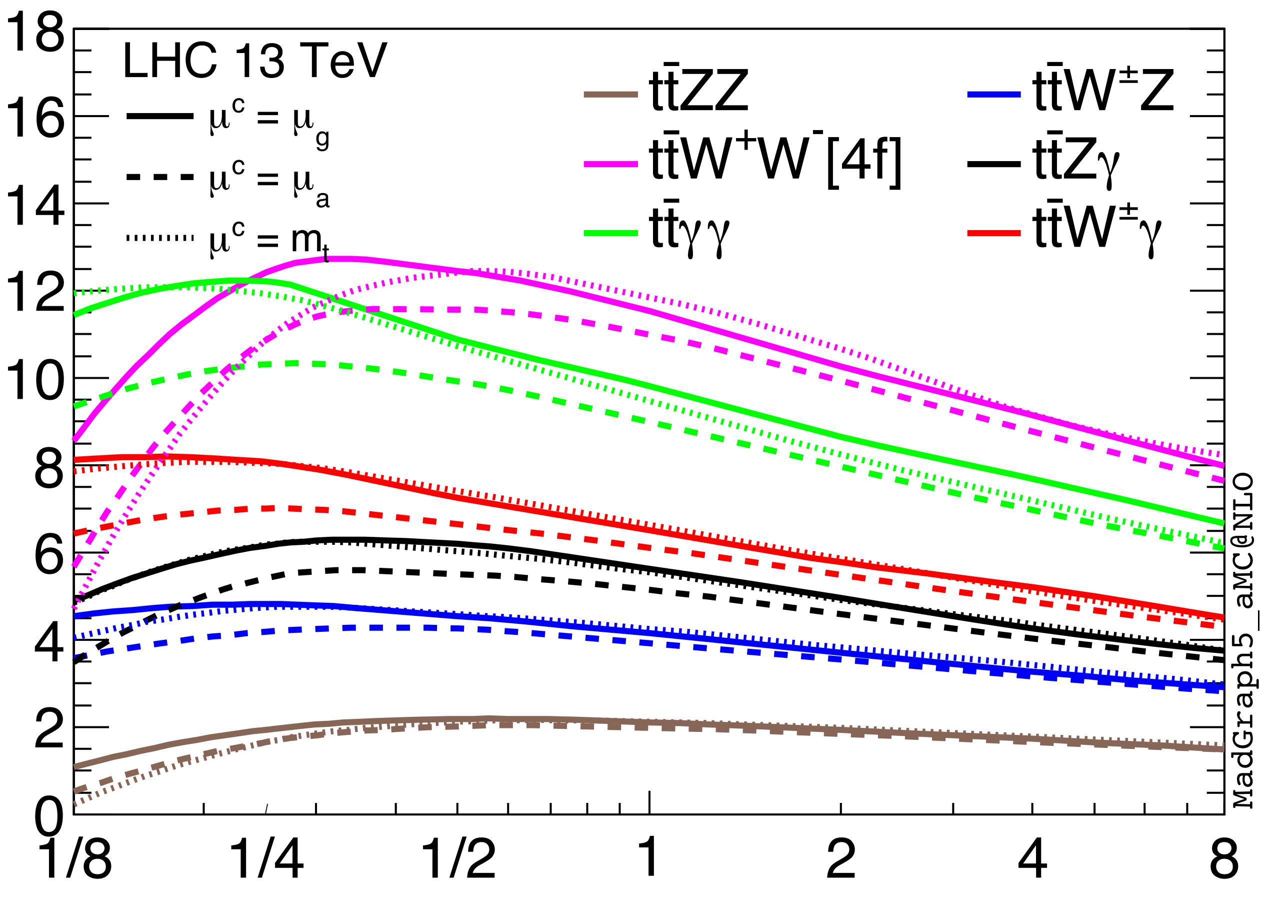
Scale dependence: $t\bar{t}V$ processes



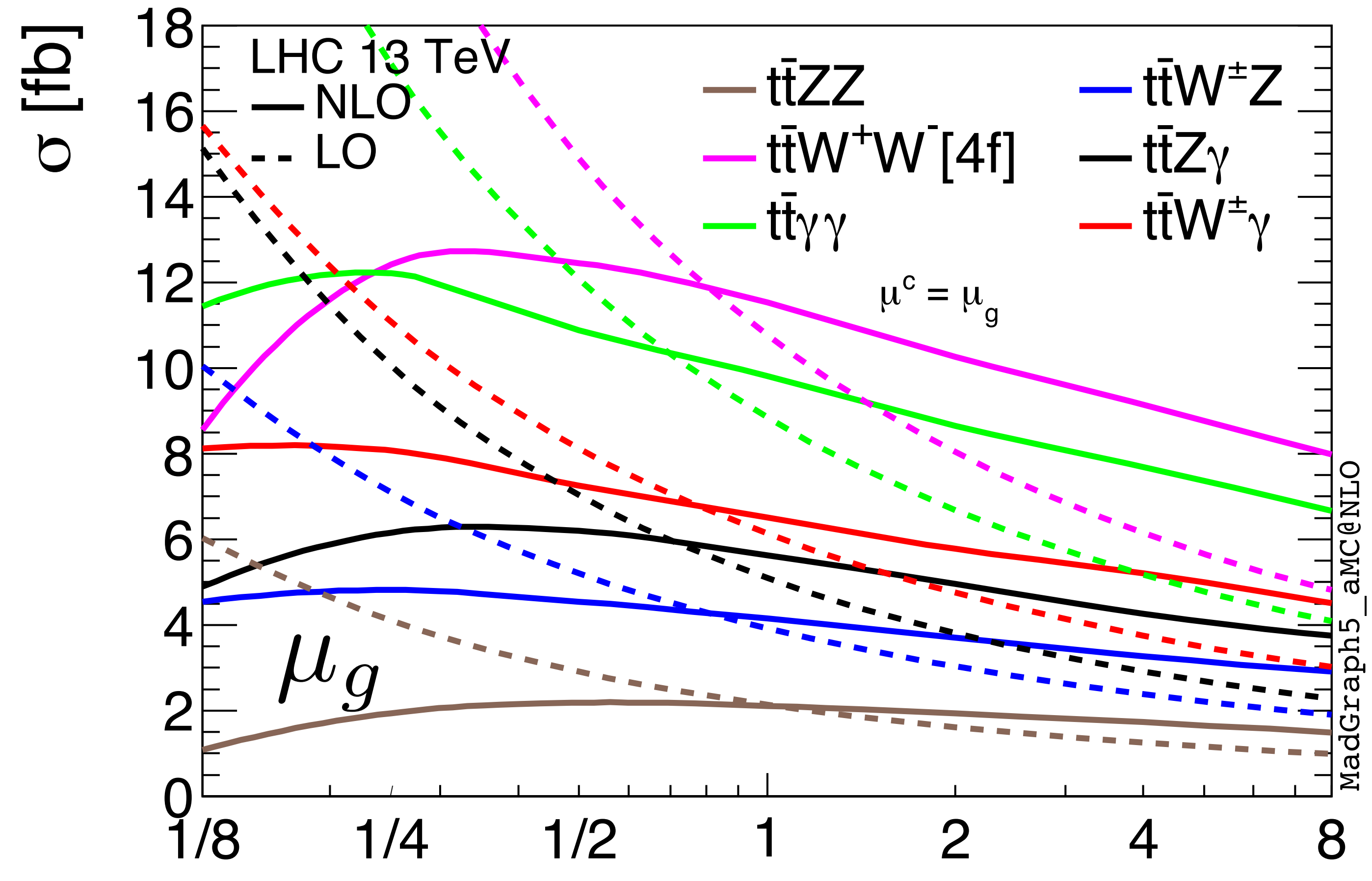




Scale dependence: $t\bar{t}VV$ processes



NLO different scales

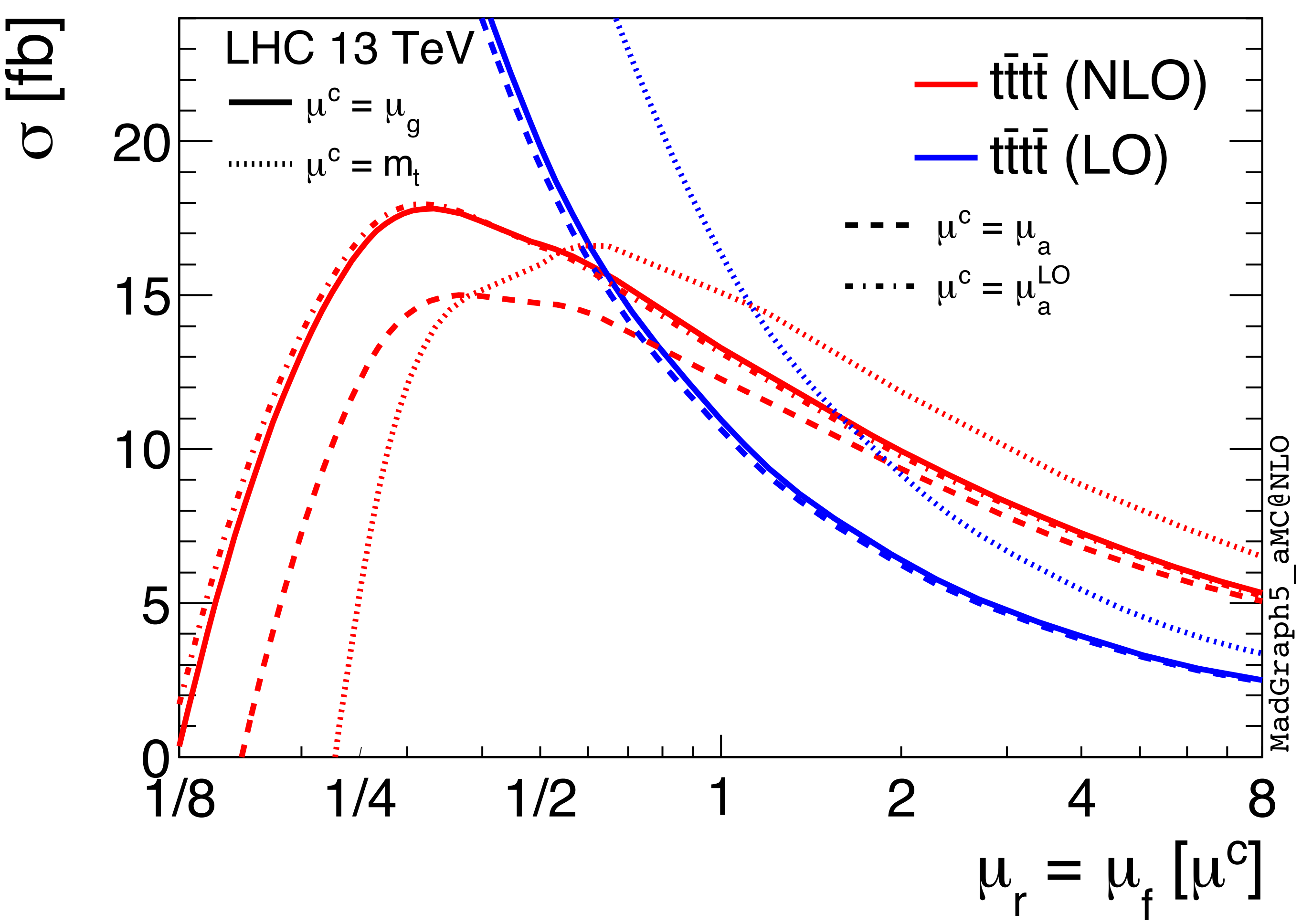


NLO vs LO

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

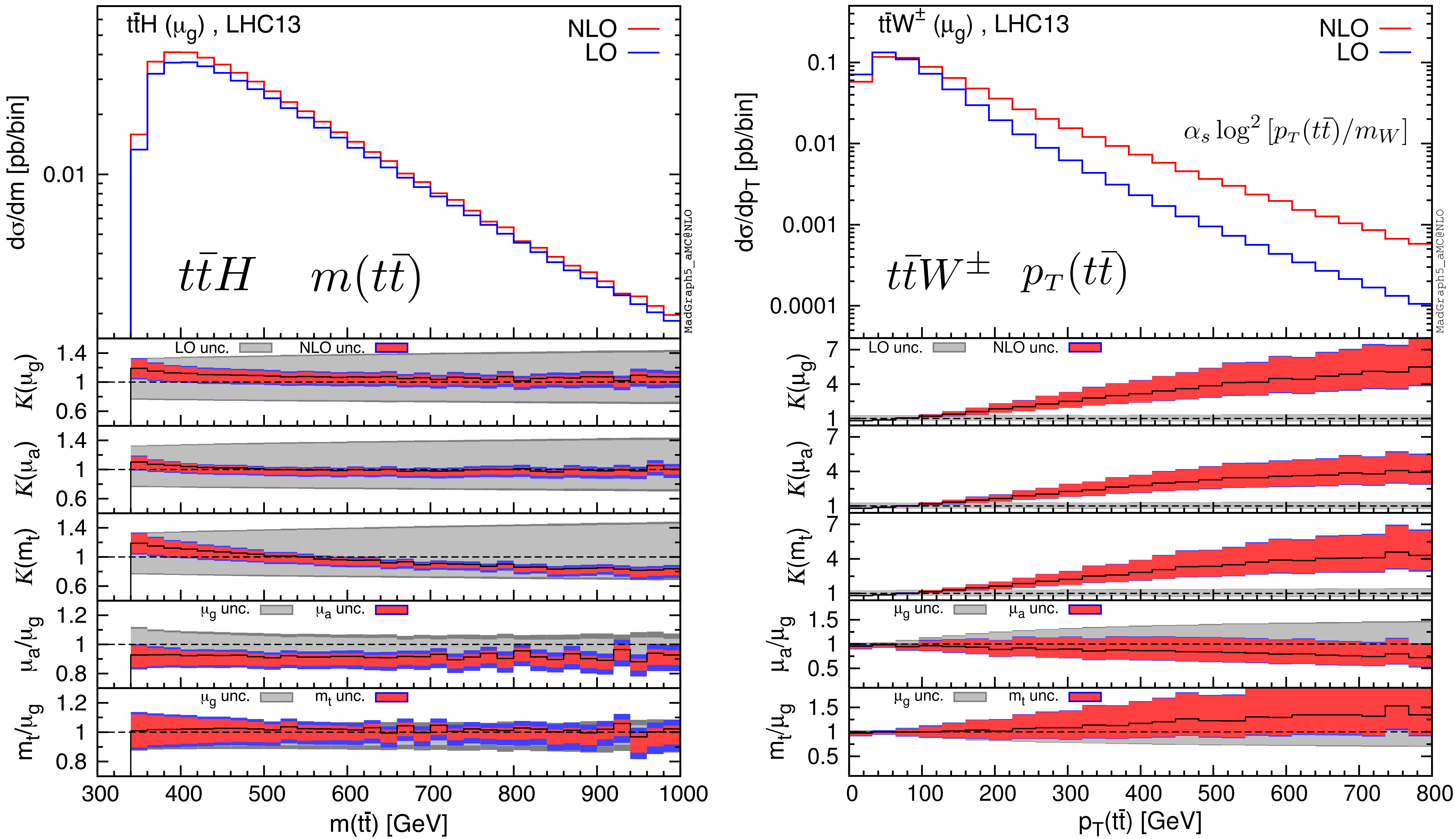
Bevilacqua and Worek '12

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

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

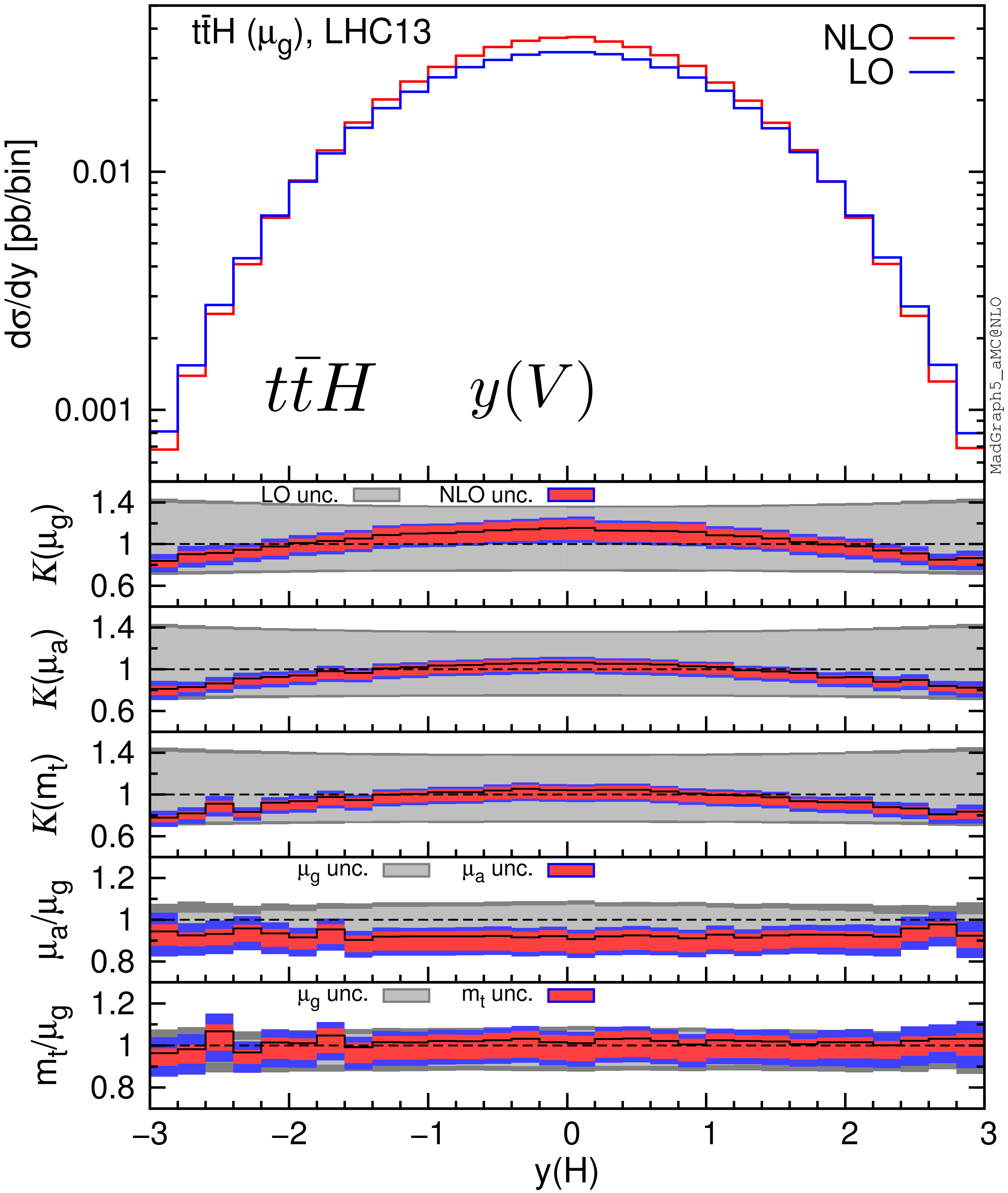
$$K\text{−factor} = 1.22$$

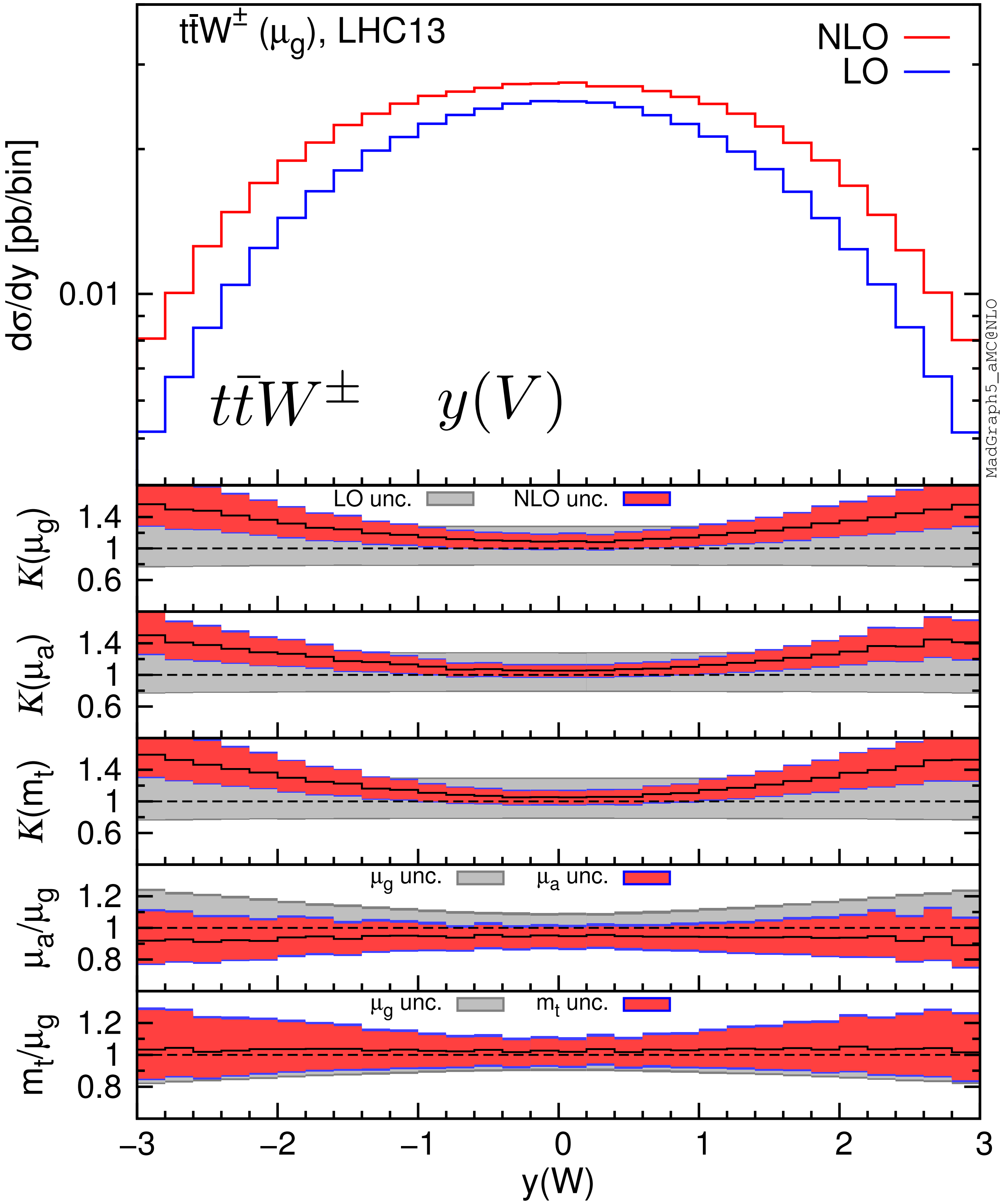
Distributions: representative results at fixed order



Maltoni, DP, Tsinikos '15

Distributions: representative results at fixed order





Maltoni, DP, Tsinikos '15