Top pair production in association with a W or a Z boson

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Higgs Toppings Workshop@Benasque

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Nikhef

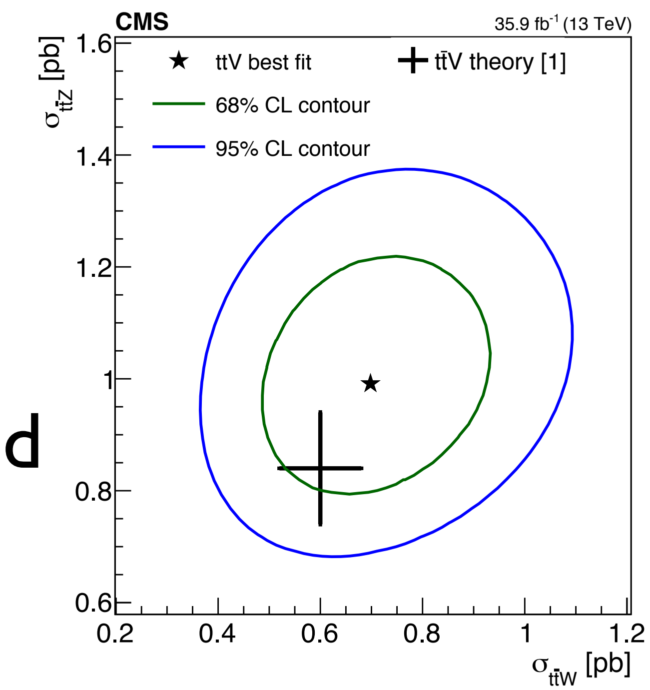
NWO
Netherlands Organisation for Scientific Research

Outline:

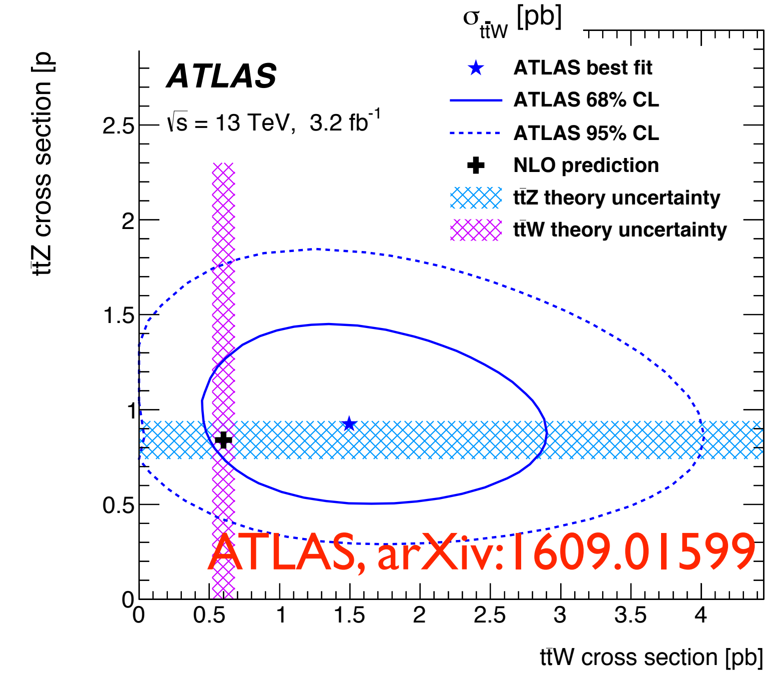
- Motivation
- State-of-the art predictions for $t\bar{t}V$: where do we stand?
- What can $t\bar{t}V$ tell us about new physics?

Motivation - I

- $t\bar{t}W$ and $t\bar{t}Z$ production has already been measured by the LHC experiments!
  ($\sigma_{\text{NLO QCD}}$=540/730 fb @13 TeV)
- They feature a multilepton + (b)-jet final state, possibly with same-sign leptons
- Because of this, they enter as background to many searches, for BSM physics and for the Higgs

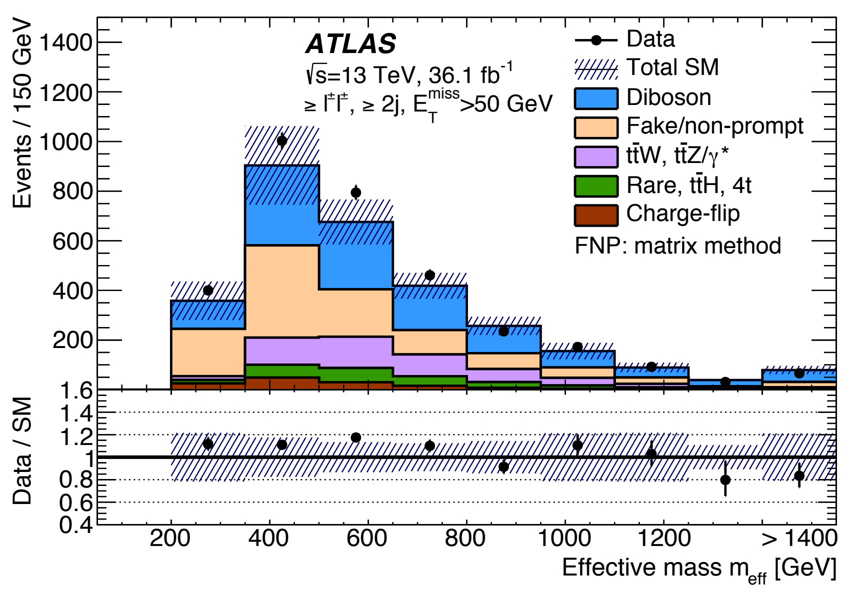


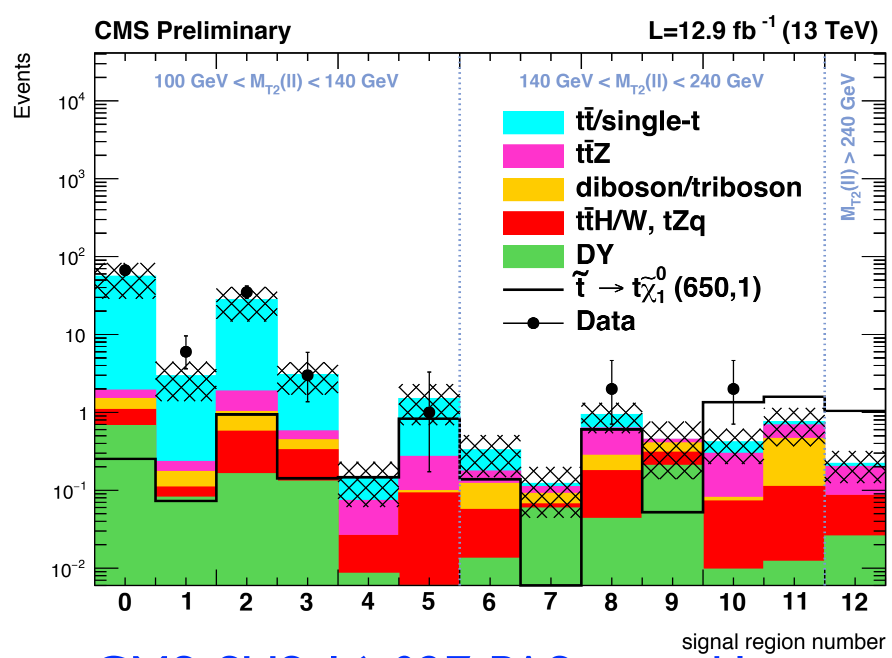
CMS, arXiv:1711.02547



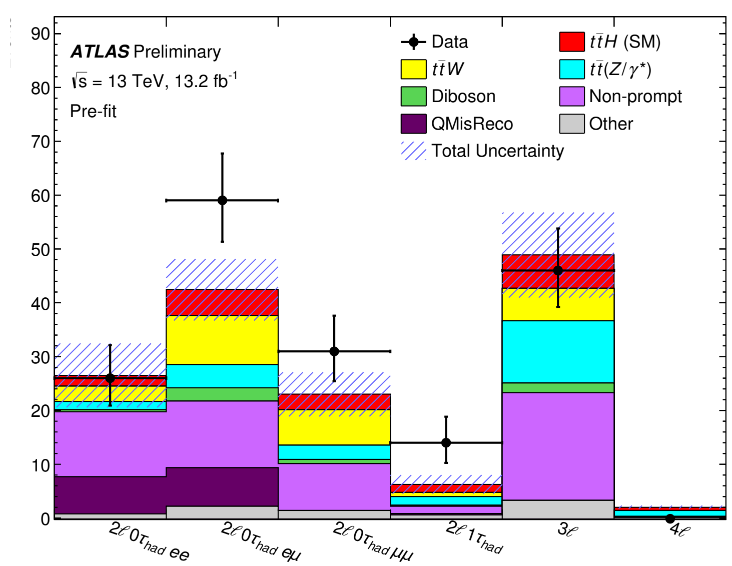
ATLAS, arXiv:1609.01599

ATLAS, 1706.03731 SUSY multilep+jets





CMS, SUS-16-027-PAS stop dilep

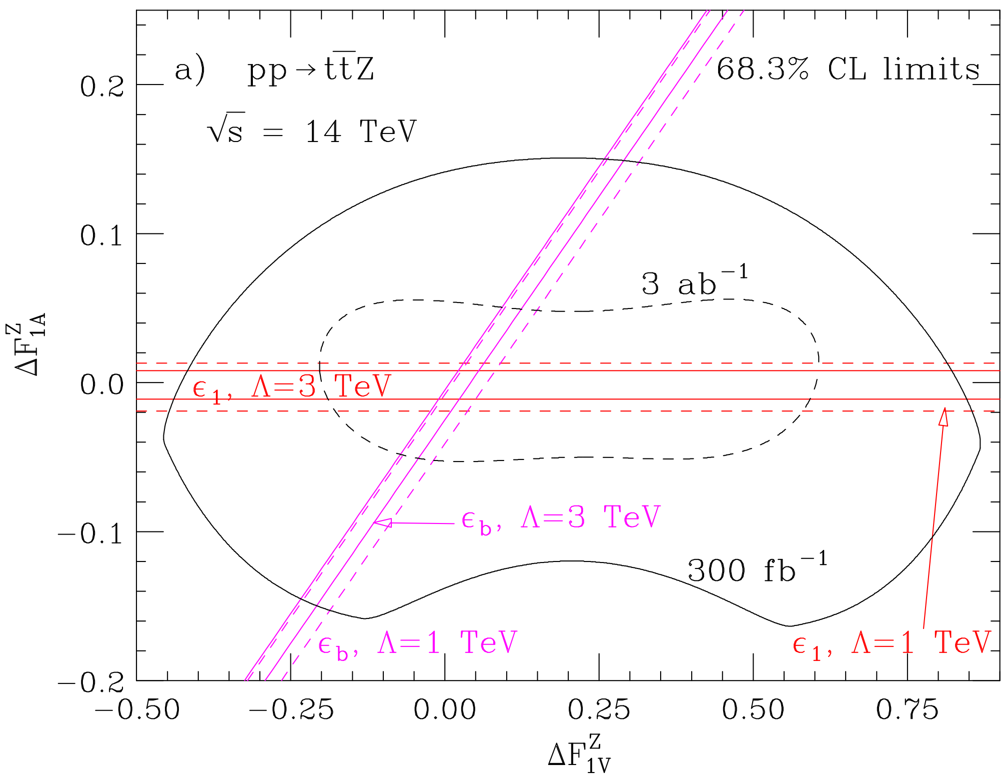


ATLAS-CONF-2016-058 ttH multilep

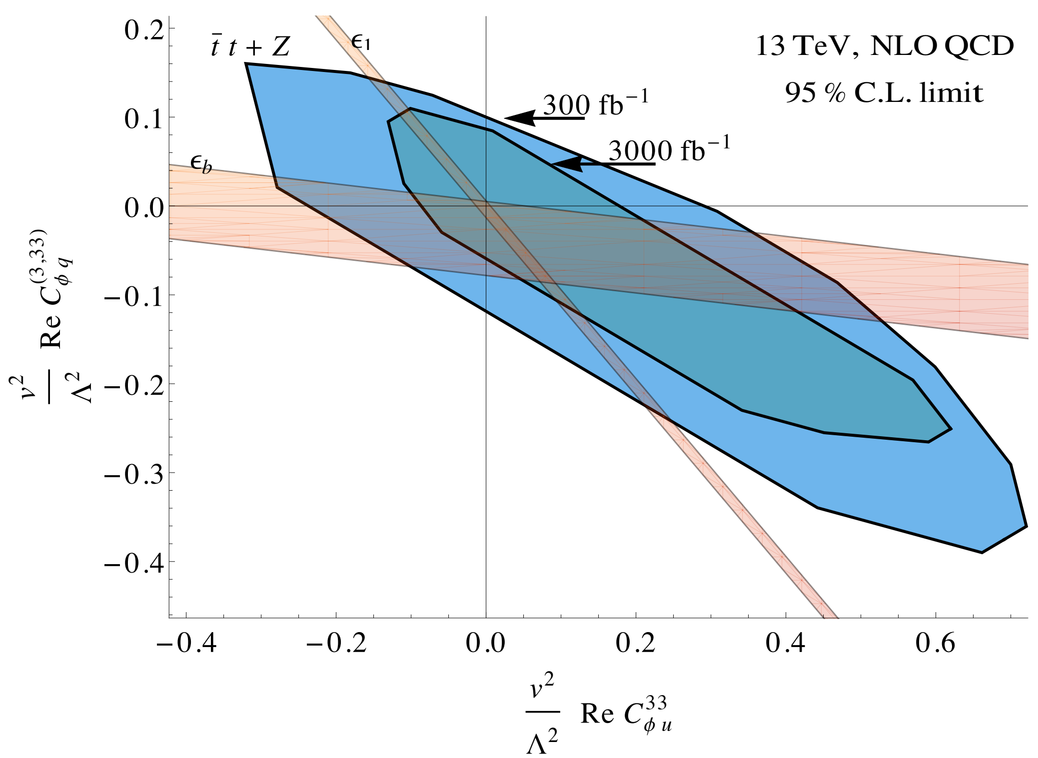
Motivation - II

- These processes are also interesting by themselves: they give direct access to the top weak couplings, otherwise only indirectly bound by EW precision data

Baur, Juste, Orr, Rainwater hep-ph/0412021



Rontsch, Schultze hep-ph/1404.1005



Higher-order corrections for $t\bar{t}V$

Precision for $t\bar{t}W$ and $t\bar{t}Z$

- $t\bar{t}V$(V=W,Z): simulation-wise, well within reach of NLO+PS generators
  - NLO QCD corrections are moderate-to-large (~60%) at 13 TeV. Beware, for ttW they are huge (150%) at 100 TeV

    $t\bar{t}\gamma$ Melnikov et al. arXiv:1102.1967; $t\bar{t}W$,$t\bar{t}\gamma^*$/Z, $t\bar{t}\gamma$ Hirschi et al. arXiv:1103.0621; $t\bar{t}Z$ Lazopoulos et al. arXiv:0804.2220; $t\bar{t}Z$ Kardos et al. arXiv:1111.0610; $t\bar{t}W$ Campbell et al. arXiv:1204.5678; …
  - +1j can be included with NLO merging
  - Beyond NLO QCD, resumed predictions (NNLL) and EW corrections are available for $t\bar{t}V$

    Frixione, Hirschi, Pagani, Shao, MZ, arXiv:1504.03446
    Broggio, Ferroglia, Ossola, Pecjak, arXiv:1607.05303 & 1702.00800
  - Both effects are found to be moderate; EW corrections enhanced in the tails

EW corrections, $\alpha^2\alpha_s^2$ (boosted kin.)

$t\bar{t}W^+$: $\delta(\%)$	13 TeV	$t\bar{t}Z$ 13 TeV
NLO QCD	$50.1^{+14.2}_{-13.5} \pm 2.4$ $(59.7^{+18.9}_{-17.7} \pm 3.1)$	$45.9^{+13.2}_{-15.5} \pm 2.9$ $(40.2^{+11.1}_{-15.0} \pm 4.7)$
LO EW	0	0.0 ± 0.7 (2.1 ± 1.6)
LO EW no γ	0	-1.1 ± 0.0 (-0.3 ± 0.0)
NLO EW	-7.7 ± 0.2 (-19.2 ± 0.7)	-3.8 ± 0.2 (-11.1 ± 0.5)
NLO EW no γ	-8.0 ± 0.2 (-20.0 ± 0.5)	-4.1 ± 0.1 (-11.5 ± 0.3)
HBR	3.88 (7.41)	0.96 (2.13)

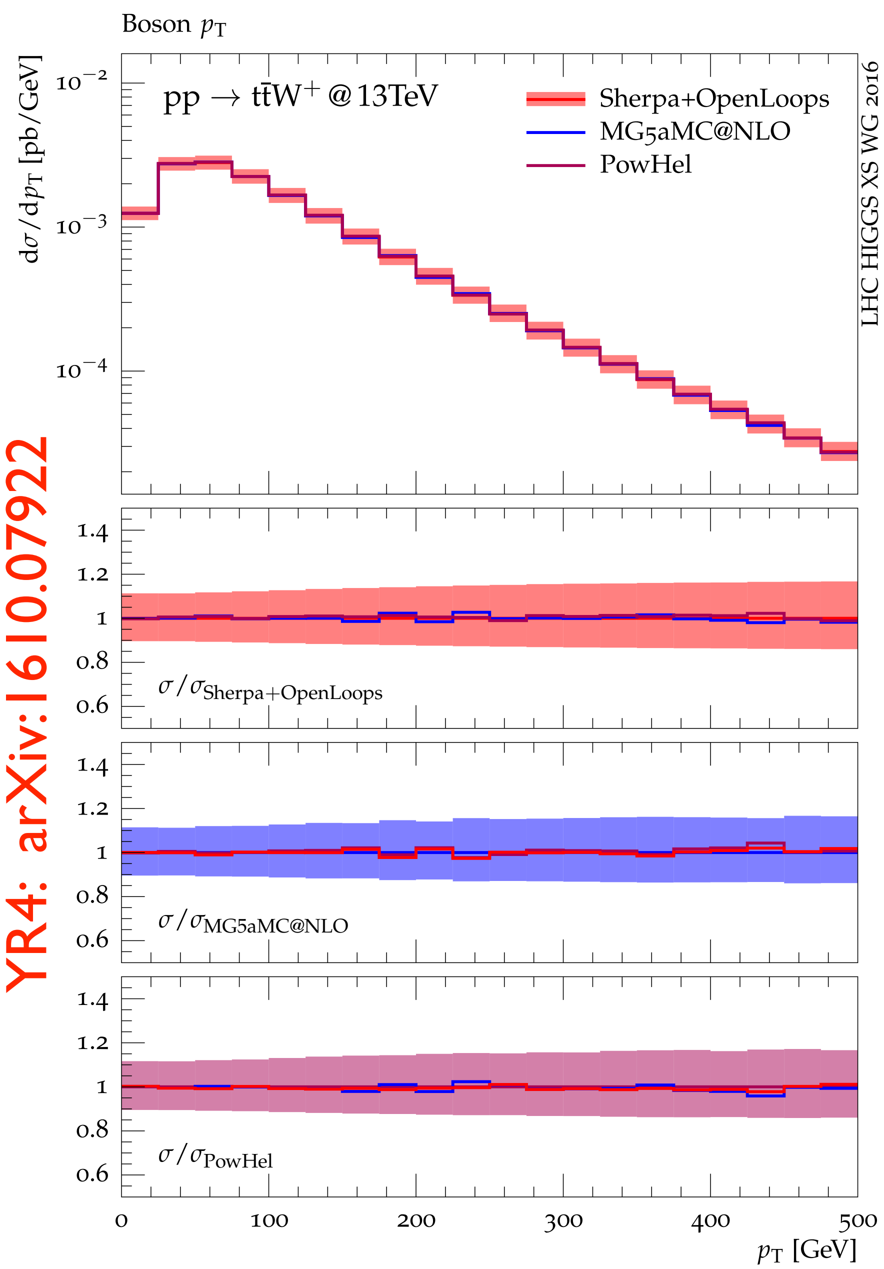
NNLL resummation

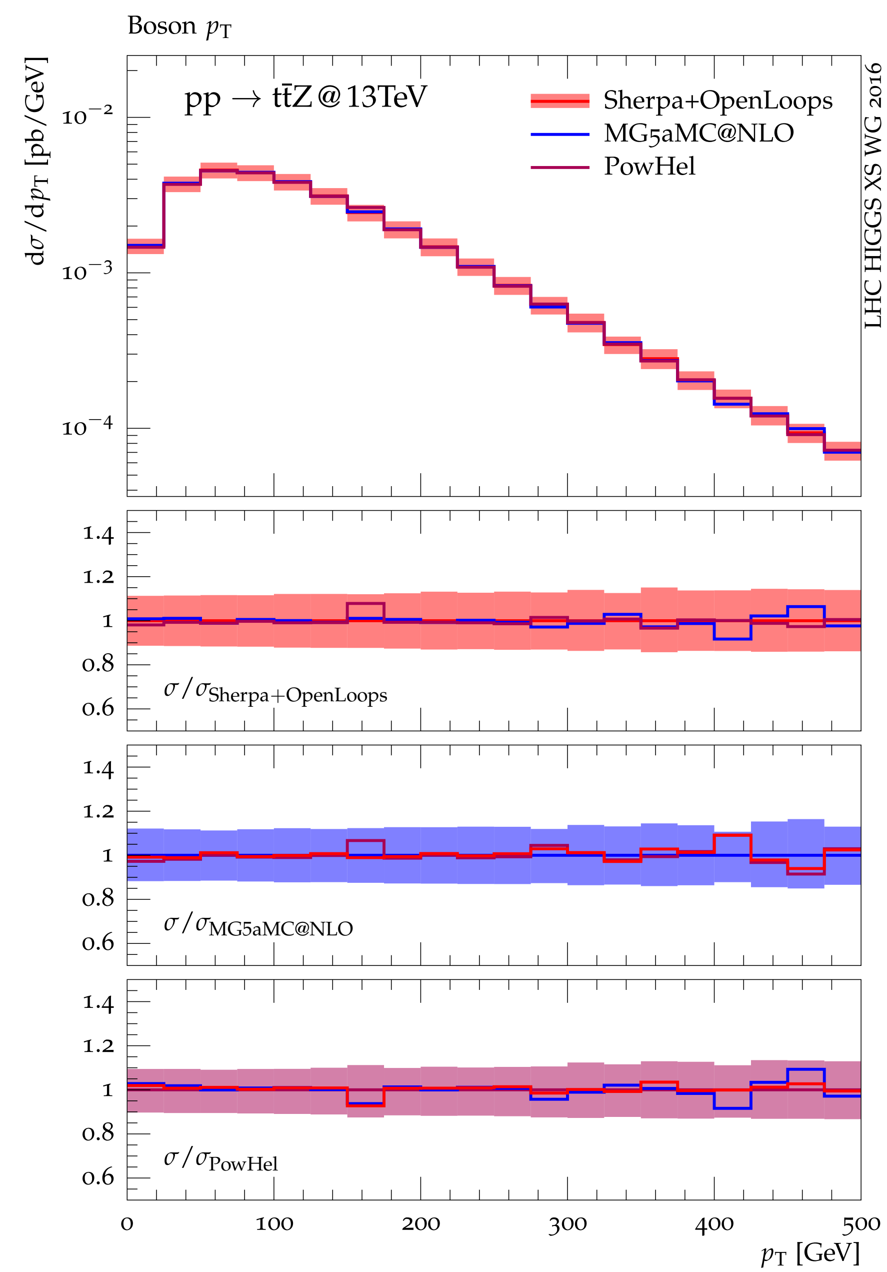
13 TeV NLO	$t\bar{t}W^+$	$356.3^{+43.7}_{-39.5}$
13 TeV NLO	$t\bar{t}W^-$	$182.2^{+23.1}_{-20.4}$
13 TeV NLO	$t\bar{t}Z$	$728.3^{+93.8}_{-90.3}$
13 TeV NLO+NNLL	$t\bar{t}W^+$	$341.0^{+23.1}_{-13.6}$
13 TeV NLO+NNLL	$t\bar{t}W^-$	$177.1^{+12.0}_{-6.9}$
13 TeV NLO+NNLL	$t\bar{t}Z$	$777.8^{+61.3}_{-65.2}$

$t\bar{t}V$ tool comparison

- Very good agreement among various tools and O(10%) Th. Unc.

YR4: arXiv:1610.07922





Complete-NLO corrections for $t\bar{t}W$

Frederix, Pagani, MZ, arXiv:1711.02116

13 TeV

$\delta[\%]$	$\mu = H_T/2$
LO_2	-
LO_3	0.9
NLO_1	50.0 (25.7)
NLO_2	−4.2 (−4.6)
NLO_3	12.2 (9.1)
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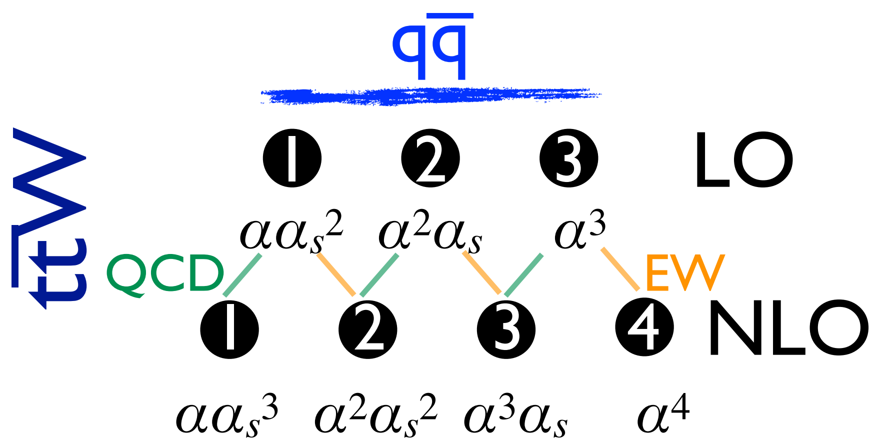

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- Subleading contributions to $t\bar{t}W$ (and $t\bar{t}Z$) exist beyond NLO QCD and EW. An estimate based on coupling-constants suggest them to be negligible.
- This is not the case:

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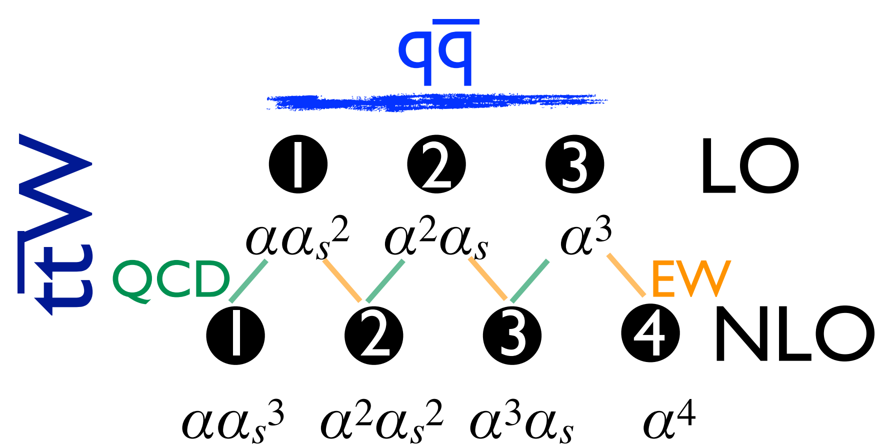

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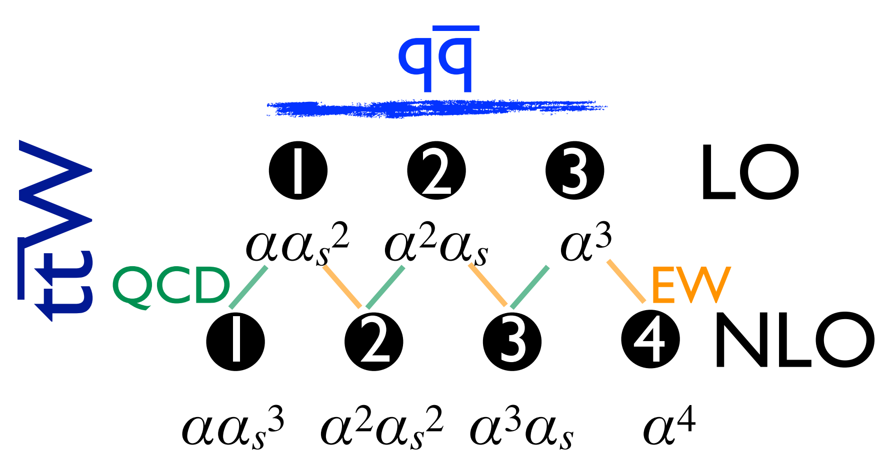

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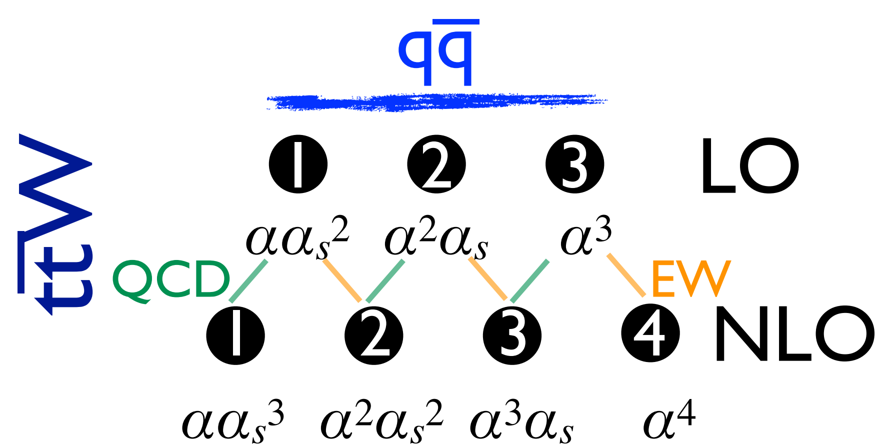

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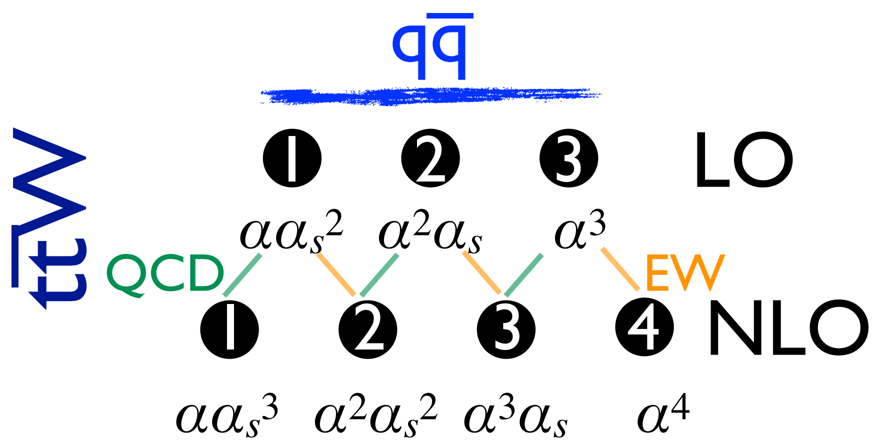

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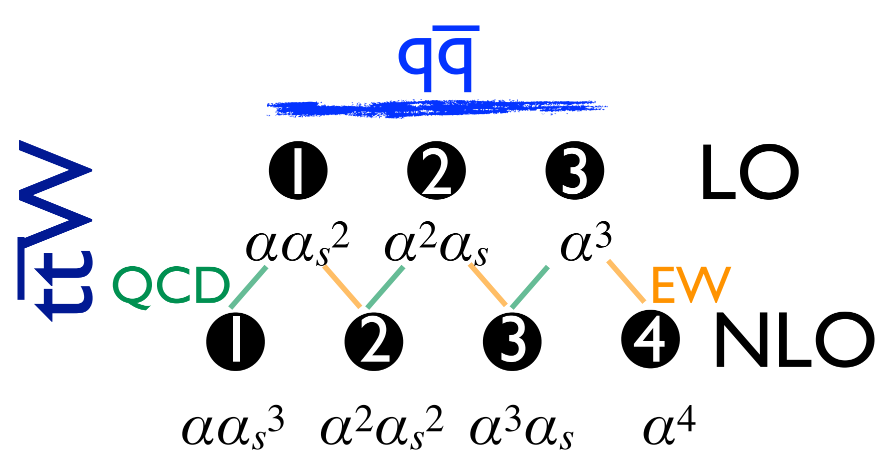

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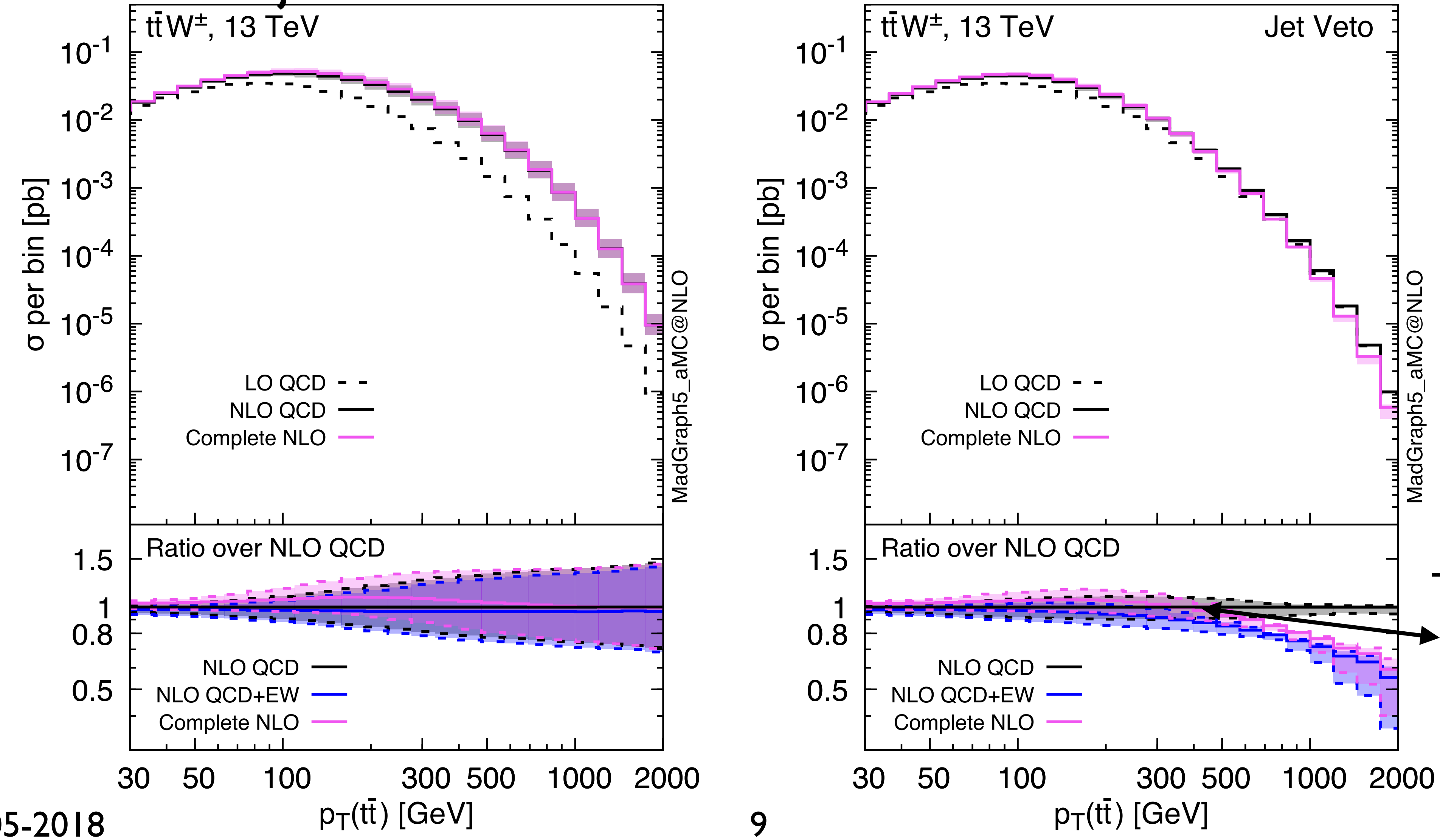
- The jet veto greatly reduces the NLO_1 (QCD corrections), which is dominated by hard radiation, and only mildly affects the other contributions
- At 100 TeV, $\mathrm{NLO}_3/\mathrm{LO}_1$~60% → almost as large as NLO_1 with the jet veto

$p_T(t\bar{t})$ and the effect of the jet veto

- QCD corrections to $t\bar{t}W$ are dominated by real emissions recoiling against the $t\bar{t}$ pair, with the W collinear to the emission or soft
- This leads to giant K-factors for the $p_T(t\bar{t})$ distribution, which are greatly reduced with a jet veto



The NLO QCD+EW and complete NLO uncertainty band barely overlap

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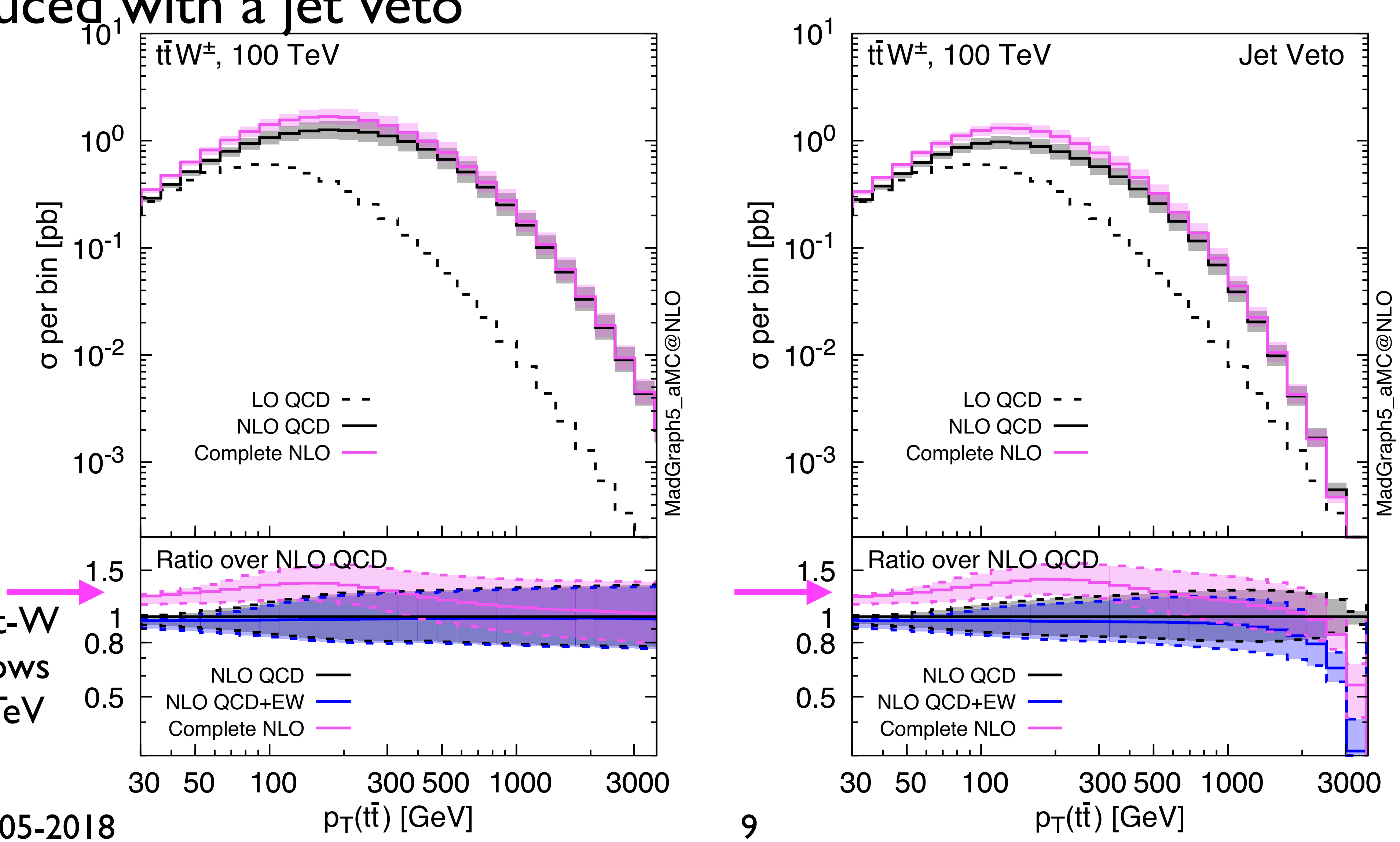

The effect of t-W scattering grows huge at 100 TeV

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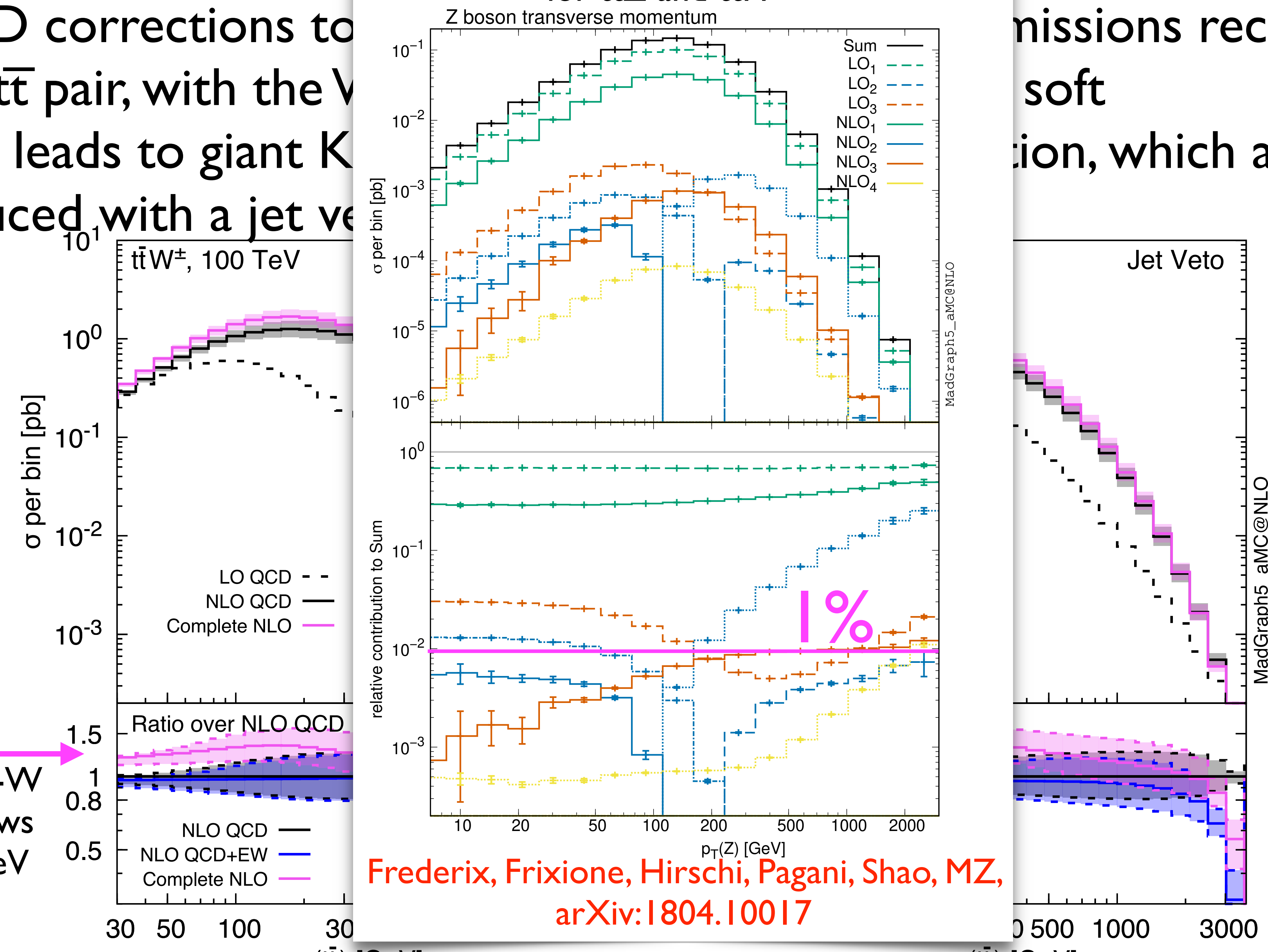
Subleading contributions negligible for ttZ and ttH

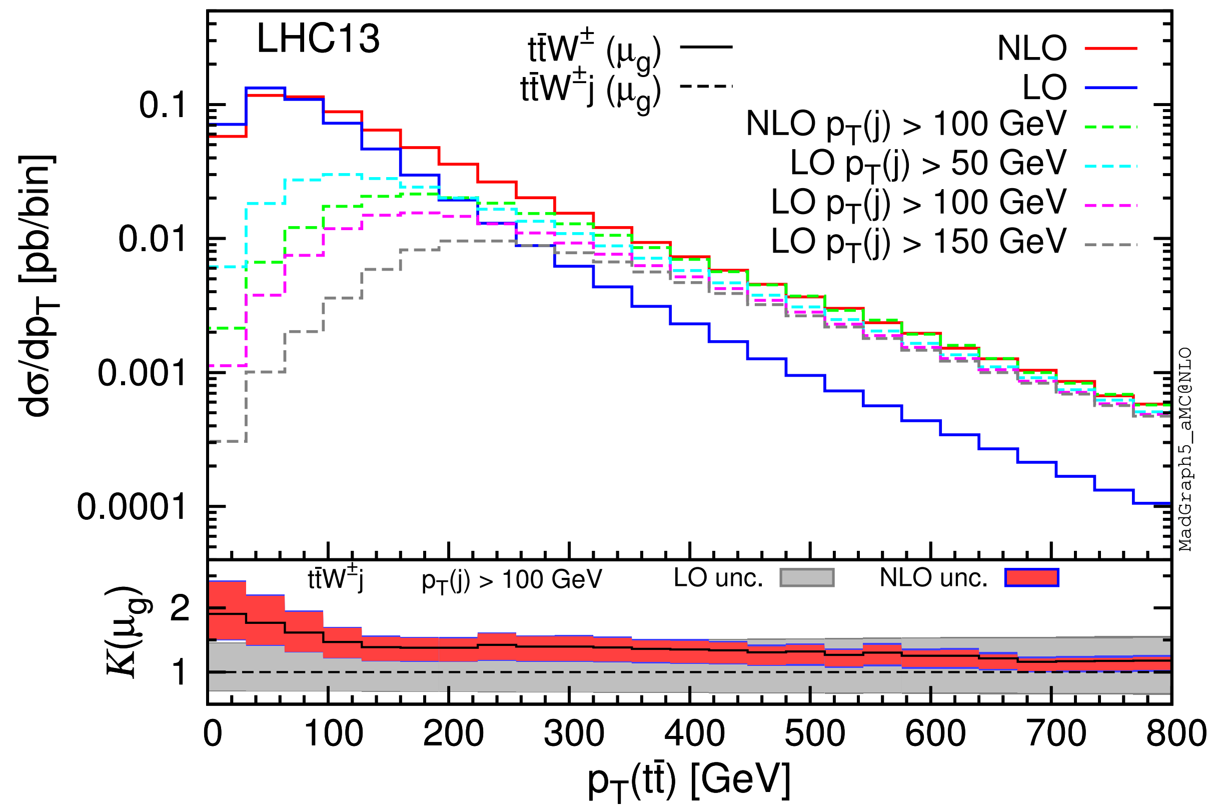


Frederix, Frixione, Hirschi, Pagani, Shao, MZ, arXiv:1804.10017

The effect of t-W scattering grows huge at 100 TeV

More on $p_T(t\bar{t})$ and other $t\bar{t}V(V)$ processes

Maltoni Pagani, Tsinikos, arXiv:1507.05640

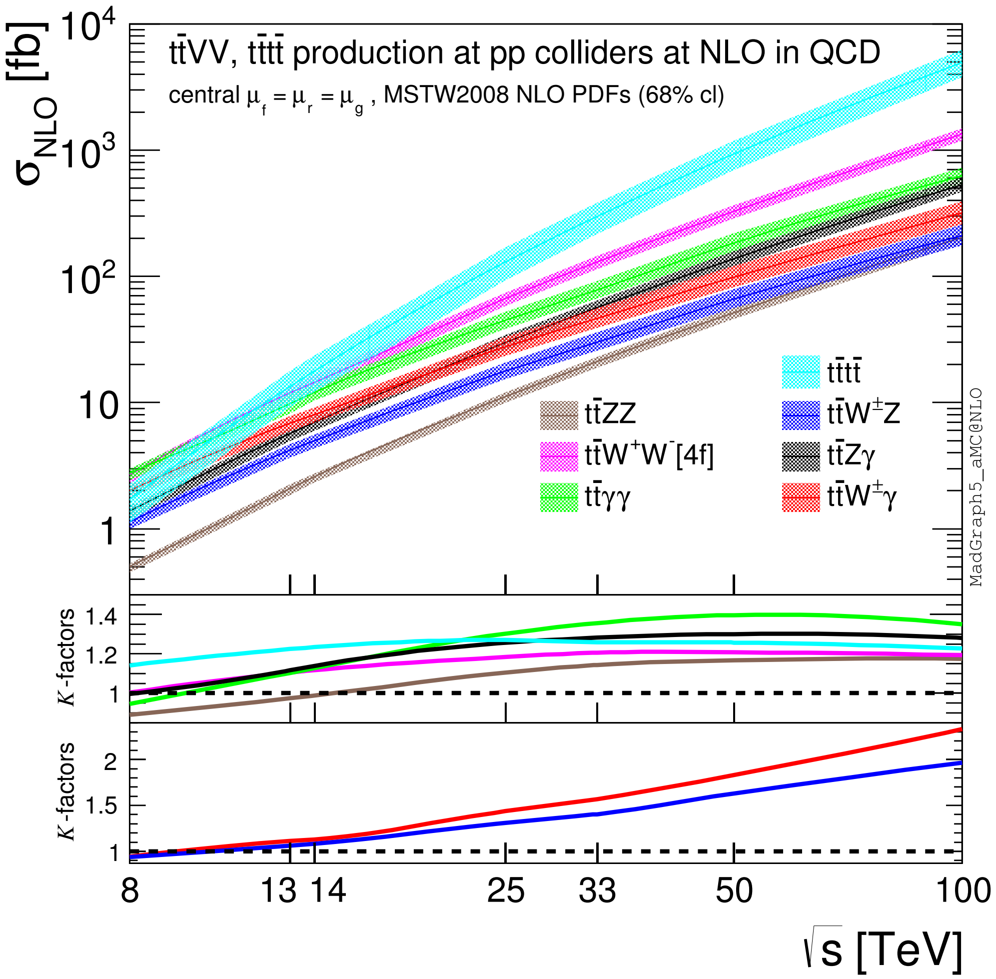


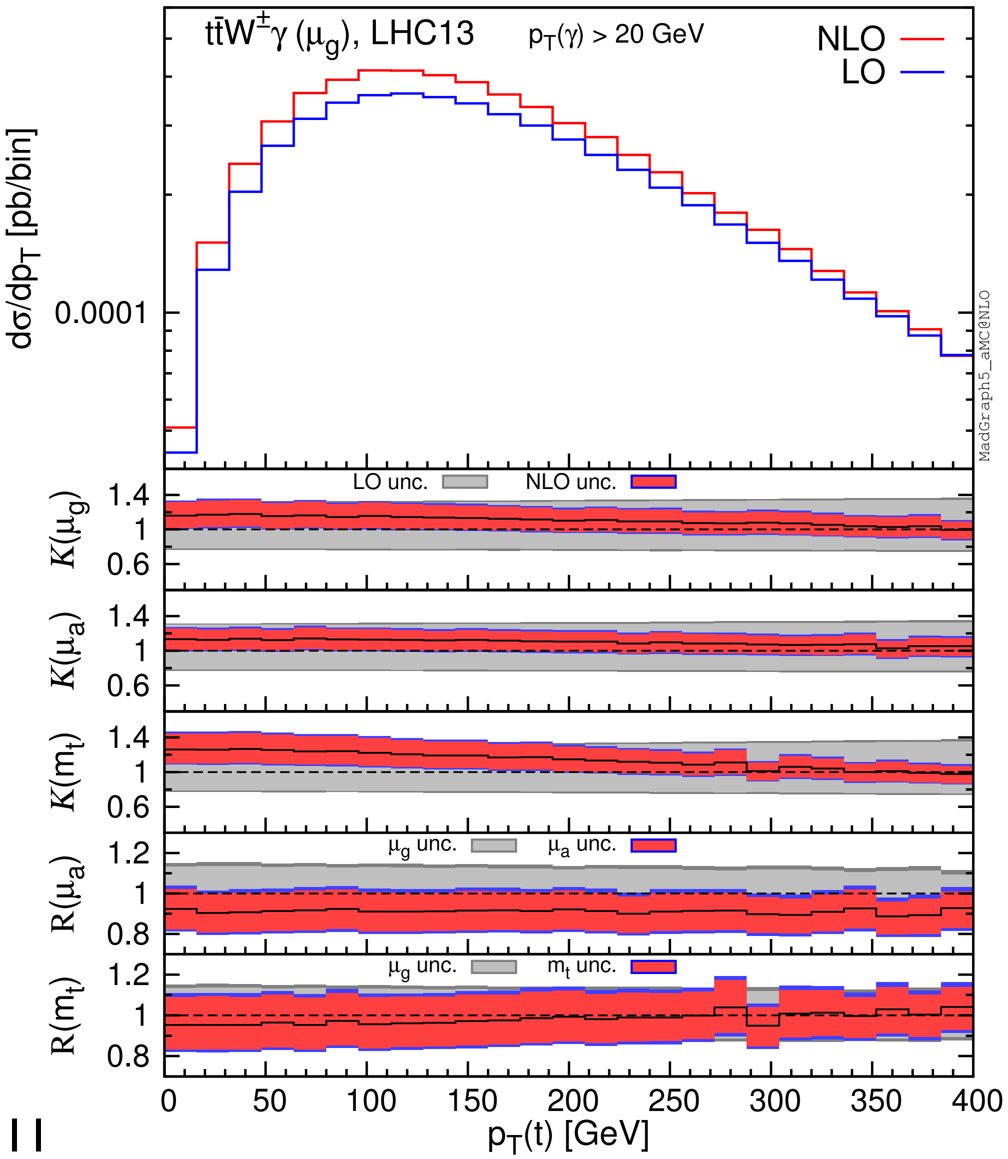
- $p_T(t\bar{t})$ receives huge NLO corrections, due to configurations where the $t\bar{t}$ pair recoils against a hard jet (and a soft V)
- Do we expect large corrections also at NNLO?
  Probably not: $t\bar{t}Wj$ receives smaller corrections at NLO
- The same happens for $t\bar{t}VV$
- In 1507.05640 a very detailed study of all $t\bar{t}V$, $t\bar{t}VV$ processes is present

Complex backgrounds for $t\bar{t}H$: $t\bar{t}VV$

Maltoni et al, arXiv:1507.05640

- All $t\bar{t}$+VV processes studied at NLO+PS accuracy
- NLO corrections essential for realistic phenomenology
- Detailed study in the context of $t\bar{t}H$ searches

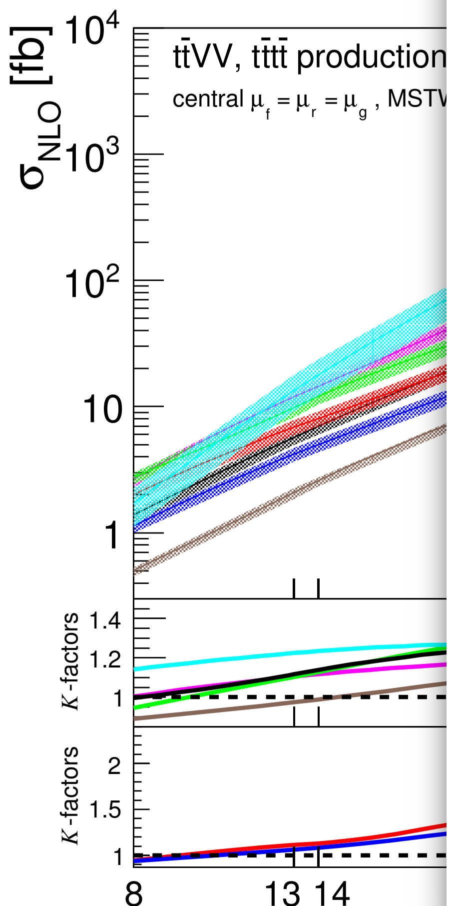


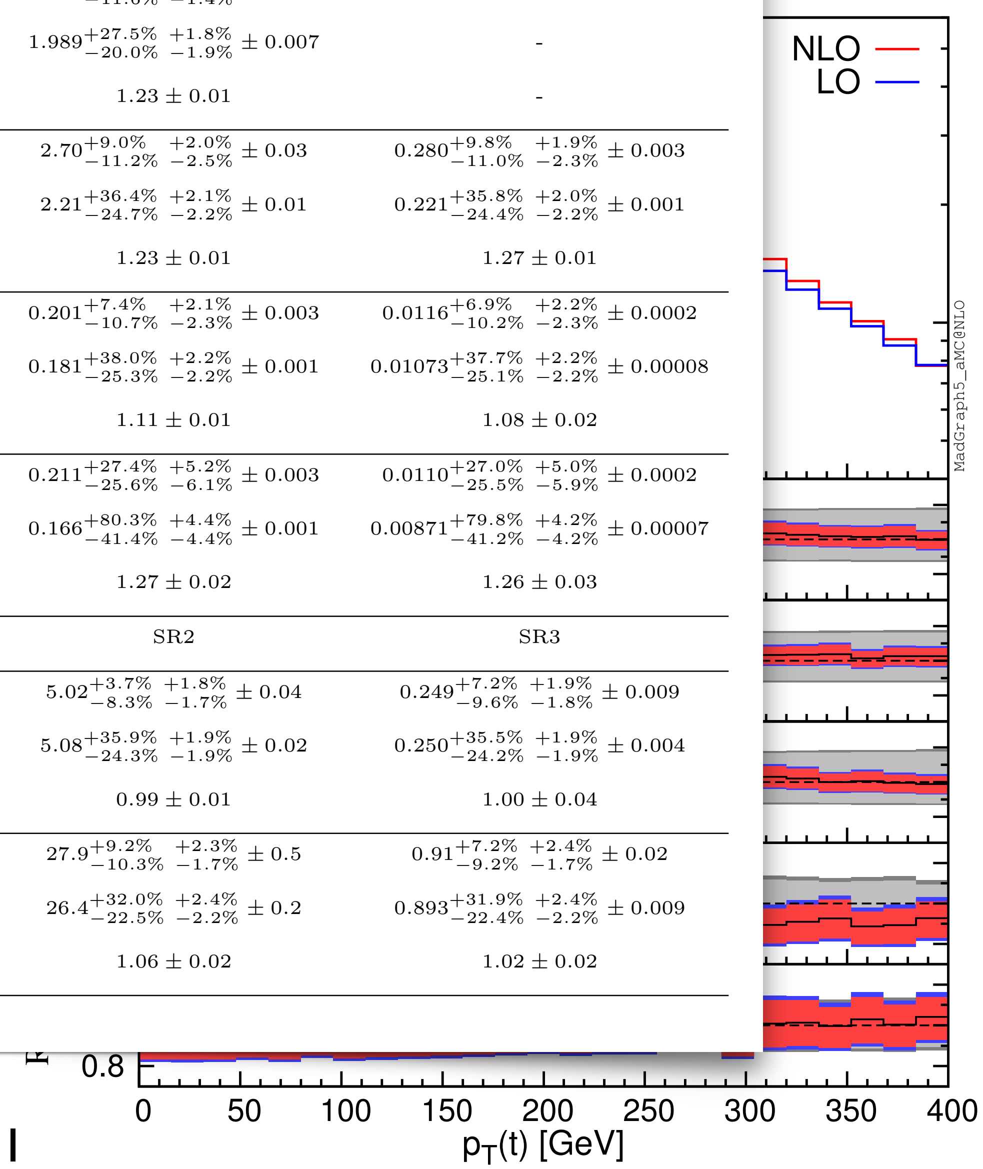


Complex backgrounds for $t\bar{t}$H:

- All $t\bar{t}$+VV pr
- NLO correc
- Detailed stu

13 TeV σ[fb]		SR1	SR2	SR3
$t\bar{t}H(H \to WW^*)$	NLO+PS	$1.54^{+5.1\%\ +2.2\%}_{-9.0\%\ -2.6\%} \pm 0.02$	$1.47^{+5.2\%\ +2.0\%}_{-9.0\%\ -2.4\%} \pm 0.02$	$0.095^{+7.4\%\ +2.0\%}_{-9.7\%\ -2.4\%} \pm 0.002$
	LO+PS	$1.401^{+35.6\%\ +2.1\%}_{-24.4\%\ -2.2\%} \pm 0.008$	$1.355^{+35.2\%\ +2.0\%}_{-24.1\%\ -2.2\%} \pm 0.008$	$0.0855^{+34.9\%\ +2.0\%}_{-24.0\%\ -2.2\%} \pm 0.0007$
$K = 1.10$	K^{PS}	1.10 ± 0.02	1.09 ± 0.02	1.11 ± 0.02
$t\bar{t}H(H \to ZZ^*)$	NLO+PS	$0.0437^{+5.5\%\ +2.3\%}_{-9.2\%\ -2.8\%} \pm 0.0004$	$0.119^{+6.3\%\ +2.1\%}_{-9.6\%\ -2.5\%} \pm 0.002$	$0.0170^{+5.0\%\ +2.0\%}_{-8.5\%\ -2.4\%} \pm 0.0003$
	LO+PS	$0.0404^{+36.1\%\ +2.2\%}_{-24.6\%\ -2.3\%} \pm 0.0002$	$0.1092^{+35.3\%\ +2.0\%}_{-24.2\%\ -2.2\%} \pm 0.0008$	$0.0152^{+34.7\%\ +1.9\%}_{-23.9\%\ -2.1\%} \pm 0.0001$
$K = 1.10$	K^{PS}	1.08 ± 0.01	1.09 ± 0.02	1.12 ± 0.02
$t\bar{t}H(H \to \tau^+\tau^-)$	NLO+PS	$0.563^{+4.6\%\ +2.2\%}_{-8.8\%\ -2.7\%} \pm 0.007$	$0.669^{+6.0\%\ +2.1\%}_{-9.4\%\ -2.6\%} \pm 0.008$	$0.0494^{+7.1\%\ +2.1\%}_{-9.9\%\ -2.5\%} \pm 0.0007$
	LO+PS	$0.513^{+35.9\%\ +2.2\%}_{-24.5\%\ -2.3\%} \pm 0.003$	$0.611^{+35.4\%\ +2.1\%}_{-24.2\%\ -2.2\%} \pm 0.003$	$0.0438^{+35.1\%\ +2.0\%}_{-24.1\%\ -2.2\%} \pm 0.0003$
$K = 1.10$	K^{PS}	1.10 ± 0.02	1.10 ± 0.01	1.13 ± 0.02
$t\bar{t}W^\pm$	NLO+PS	$5.77^{+15.1\%\ +1.6\%}_{-12.7\%\ -1.2\%} \pm 0.07$	$2.44^{+13.1\%\ +1.7\%}_{-11.6\%\ -1.4\%} \pm 0.01$	-
	LO+PS	$4.57^{+27.7\%\ +1.8\%}_{-20.2\%\ -1.9\%} \pm 0.03$	$1.989^{+27.5\%\ +1.8\%}_{-20.0\%\ -1.9\%} \pm 0.007$	-
$K = 1.22$	K^{PS}	1.26 ± 0.02	1.23 ± 0.01	-
$t\bar{t}Z/\gamma^*$	NLO+PS	$1.61^{+7.7\%\ +2.0\%}_{-10.5\%\ -2.5\%} \pm 0.02$	$2.70^{+9.0\%\ +2.0\%}_{-11.2\%\ -2.5\%} \pm 0.03$	$0.280^{+9.8\%\ +1.9\%}_{-11.0\%\ -2.3\%} \pm 0.003$
	LO+PS	$1.422^{+36.8\%\ +2.2\%}_{-24.9\%\ -2.3\%} \pm 0.008$	$2.21^{+36.4\%\ +2.1\%}_{-24.7\%\ -2.2\%} \pm 0.01$	$0.221^{+35.8\%\ +2.0\%}_{-24.4\%\ -2.2\%} \pm 0.001$
$K = 1.23$	K^{PS}	1.13 ± 0.02	1.23 ± 0.01	1.27 ± 0.01
$t\bar{t}W^+W^-$	NLO+PS	$0.288^{+8.0\%\ +2.3\%}_{-11.1\%\ -2.6\%} \pm 0.003$	$0.201^{+7.4\%\ +2.1\%}_{-10.7\%\ -2.3\%} \pm 0.003$	$0.0116^{+6.9\%\ +2.2\%}_{-10.2\%\ -2.3\%} \pm 0.0002$
	LO+PS	$0.260^{+38.4\%\ +2.3\%}_{-25.5\%\ -2.3\%} \pm 0.001$	$0.181^{+38.0\%\ +2.2\%}_{-25.3\%\ -2.2\%} \pm 0.001$	$0.01073^{+37.7\%\ +2.2\%}_{-25.1\%\ -2.2\%} \pm 0.00008$
$K = 1.10$	K^{PS}	1.11 ± 0.01	1.11 ± 0.01	1.08 ± 0.02
$t\bar{t}t\bar{t}$	NLO+PS	$0.340^{+27.5\%\ +5.5\%}_{-25.8\%\ -6.4\%} \pm 0.004$	$0.211^{+27.4\%\ +5.2\%}_{-25.6\%\ -6.1\%} \pm 0.003$	$0.0110^{+27.0\%\ +5.0\%}_{-25.5\%\ -5.9\%} \pm 0.0002$
	LO+PS	$0.271^{+80.9\%\ +4.6\%}_{-41.5\%\ -4.6\%} \pm 0.001$	$0.166^{+80.3\%\ +4.4\%}_{-41.4\%\ -4.4\%} \pm 0.001$	$0.00871^{+79.8\%\ +4.2\%}_{-41.2\%\ -4.2\%} \pm 0.00007$
$K = 1.22$	K^{PS}	1.26 ± 0.02	1.27 ± 0.02	1.26 ± 0.03
13 TeV σ[ab]		SR1	SR2	SR3
$t\bar{t}ZZ$	NLO+PS	$9.60^{+3.5\%\ +1.8\%}_{-8.4\%\ -1.8\%} \pm 0.06$	$5.02^{+3.7\%\ +1.8\%}_{-8.3\%\ -1.7\%} \pm 0.04$	$0.249^{+7.2\%\ +1.9\%}_{-9.6\%\ -1.8\%} \pm 0.009$
	LO+PS	$9.71^{+36.3\%\ +1.9\%}_{-24.5\%\ -1.9\%} \pm 0.02$	$5.08^{+35.9\%\ +1.9\%}_{-24.3\%\ -1.9\%} \pm 0.02$	$0.250^{+35.5\%\ +1.9\%}_{-24.2\%\ -1.9\%} \pm 0.004$
$K = 0.99$	K^{PS}	0.99 ± 0.01	0.99 ± 0.01	1.00 ± 0.04
$t\bar{t}W^\pm Z$	NLO+PS	$62.0^{+9.0\%\ +2.2\%}_{-10.2\%\ -1.6\%} \pm 0.7$	$27.9^{+9.2\%\ +2.3\%}_{-10.3\%\ -1.7\%} \pm 0.5$	$0.91^{+7.2\%\ +2.4\%}_{-9.2\%\ -1.7\%} \pm 0.02$
	LO+PS	$60.2^{+32.2\%\ +2.4\%}_{-22.6\%\ -2.3\%} \pm 0.3$	$26.4^{+32.0\%\ +2.4\%}_{-22.5\%\ -2.2\%} \pm 0.2$	$0.893^{+31.9\%\ +2.4\%}_{-22.4\%\ -2.2\%} \pm 0.009$
$K = 1.06$	K^{PS}	1.03 ± 0.01	1.06 ± 0.02	1.02 ± 0.02

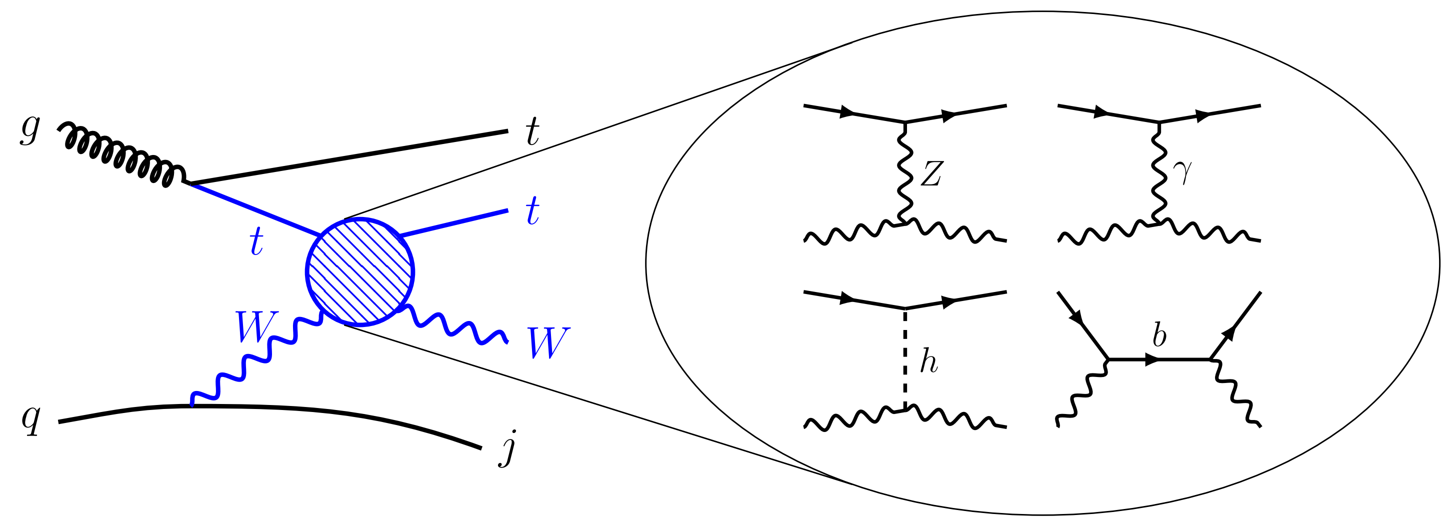




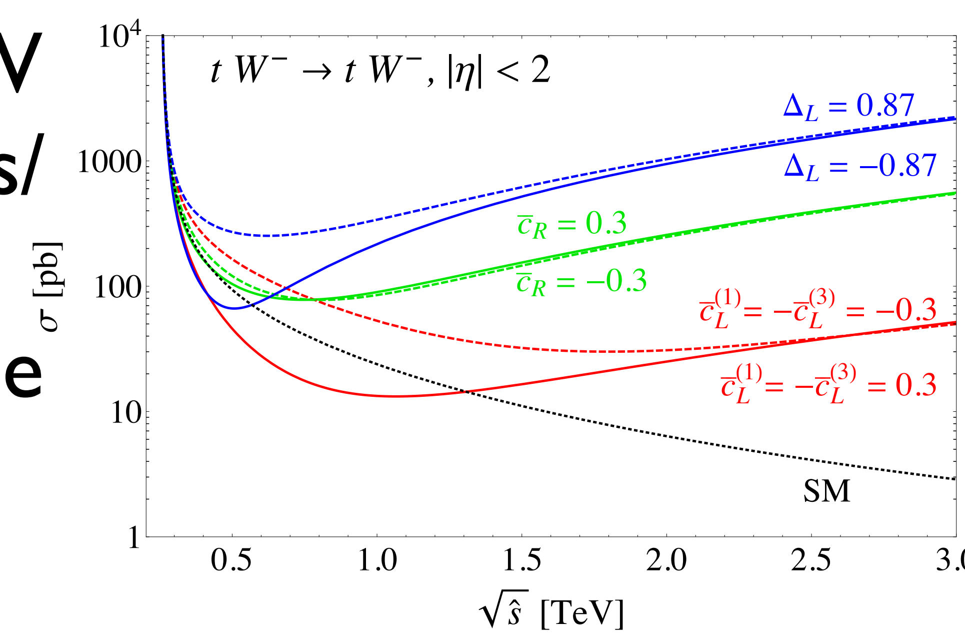
What can $t\bar{t}V$ tell us about new physics?

tW scattering

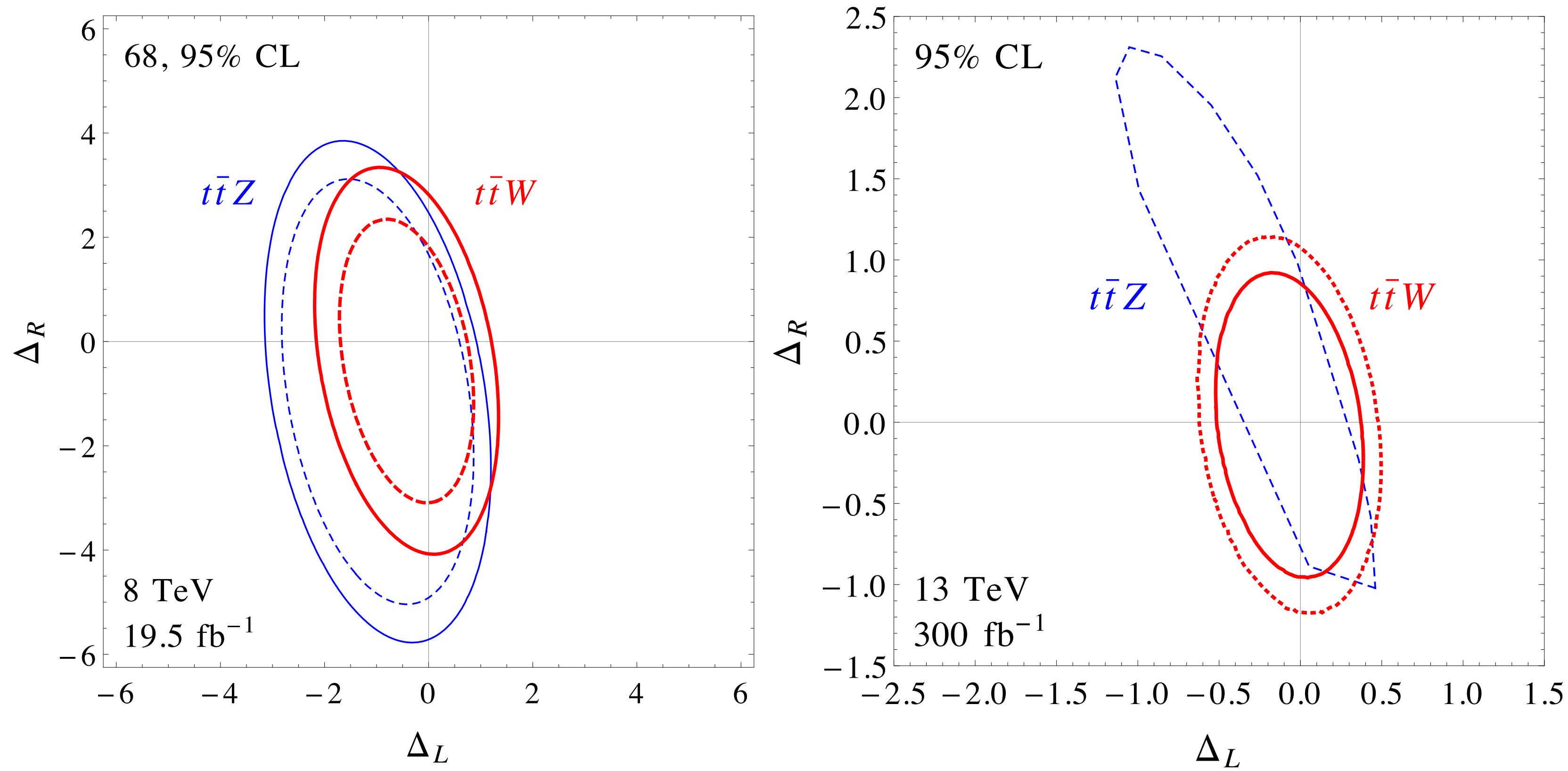
Dror, Farina, Salvioni, Serra, arXiv:1511.03674



- $t\bar{t}W(j)$ at order $\alpha_s\alpha^3$ includes the $tW \rightarrow tW$ scattering. High sensitivity to the top-Higgs/Z/gamma couplings
- If e.g. the top-Z couplings deviates from the SM value, the amplitude grows as ~s
- Extracting the $tW \rightarrow tW$ scattering contribution from $t\bar{t}W$ production makes it possible to set bounds on top-Z couplings



Indirect limits on t-Z couplings from tW scattering



- Recasting the CMS $t\bar{t}W$ measurements at 8 TeV gives better bounds on t-Z coupling than the direct CMS $t\bar{t}Z$ measurement
- Further improvements can come from a dedicated analysis of $t\bar{t}Wj$ at 13 TeV

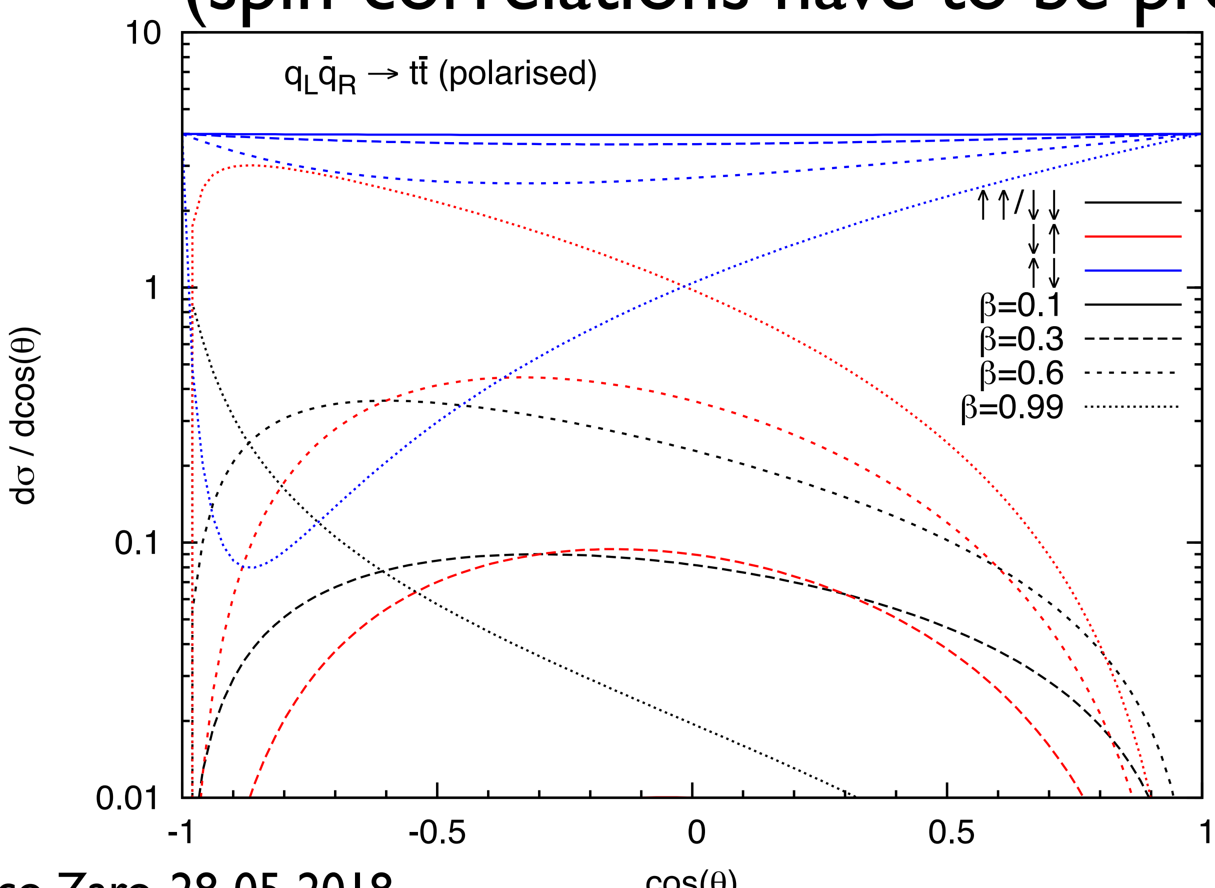
Top asymmetry and polarisation in $t\bar{t}W$

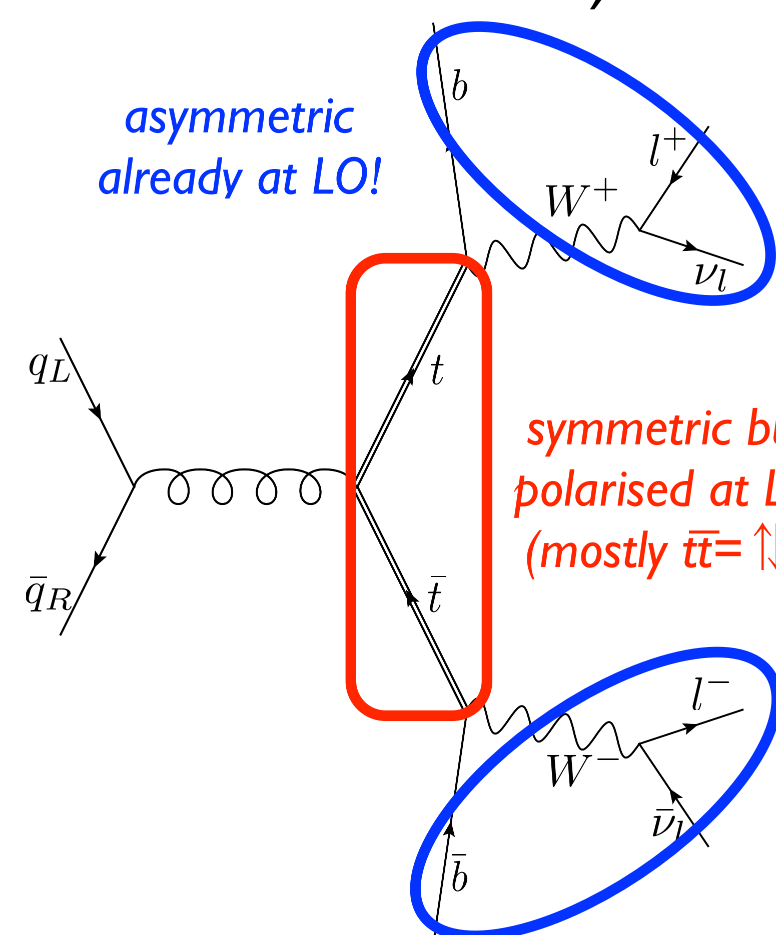
Maltoni, Mangano, Tsinikos, MZ, arXiv:1406.3262

- Top asymmetry and polarisation can provide useful (indirect) informations on the nature of new physics
- A measurement of the top asymmetry does not seem feasible at the FCC, because $t\bar{t}$ is essentially produced via gg only
- $t\bar{t}W$ production can be an alternative
  - $q\bar{q}$ induced at LO, has a rather large asymmetry at NLO
    - A_t^{tt}=0.45, A_t^{ttW}=2.24 @LHC RunII
    - A_t^{tt}=0.12, A_t^{ttW}=1.85 @FCC
  - Top quarks are highly polarised

Polarised top production

- The radiation of a W boson from the initial line has the effect of polarising the light quarks for details see Parke, Shadmi, hep-ph:9606419
  - $t\bar{t}W$ is totally analogous to polarised $q\bar{q}\rightarrow t\bar{t}$ scattering
  - $t\bar{t}$ pair is highly polarised (↑↓ dominates at threshold)
  - The top decay products are asymmetric already at LO (spin-correlations have to be preserved in the simulation)





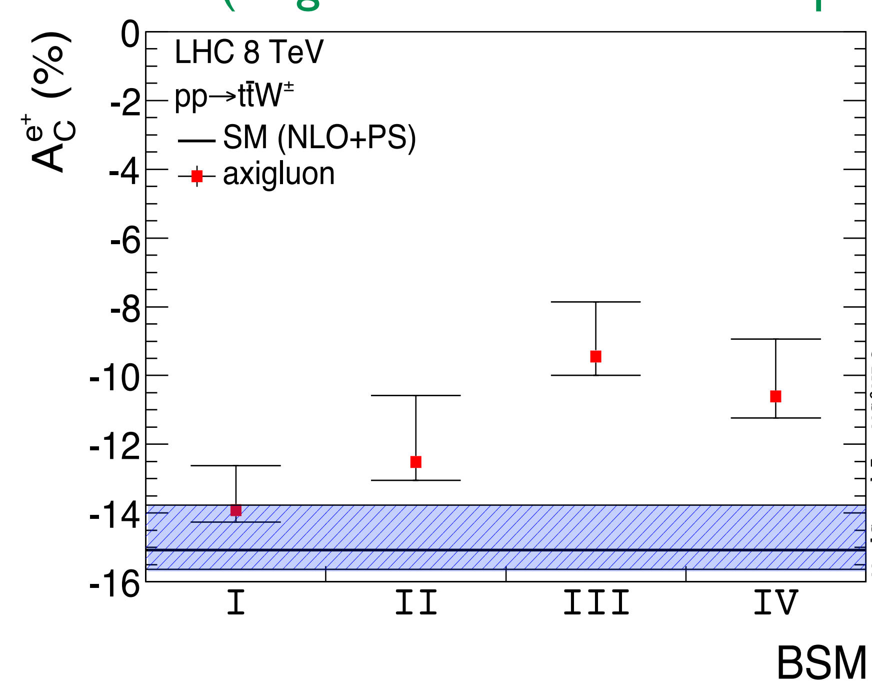
Decay product asymmetries and prospects for LHC and FCC measurements

		8 TeV	13 TeV	14 TeV	33 TeV	100 TeV
$t\bar{t}$	σ(pb)	$198^{+15\%}_{-14\%}$	$661^{+15\%}_{-13\%}$	$786^{+14\%}_{-13\%}$	$4630^{+12\%}_{-11\%}$	$30700^{+13\%}_{-13\%}$
	$A_c^t(\%)$	$0.72^{+0.14}_{-0.09}$	$0.45^{+0.09}_{-0.06}$	$0.43^{+0.08}_{-0.05}$	$0.26^{+0.04}_{-0.03}$	$0.12^{+0.03}_{-0.02}$
$t\bar{t}W^{\pm}$	σ(fb)	$210^{+11\%}_{-11\%}$	$587^{+13\%}_{-12\%}$	$678^{+14\%}_{-12\%}$	$3220^{+17\%}_{-13\%}$	$19000^{+20\%}_{-17\%}$
	$A_c^t(\%)$	$2.37^{+0.56}_{-0.38}$	$2.24^{+0.43}_{-0.32}$	$2.23^{+0.43}_{-0.33}$	$1.95^{+0.28}_{-0.23}$	$1.85^{+0.21}_{-0.17}$
	$A_c^b(\%)$	$8.50^{+0.15}_{-0.10}$	$7.54^{+0.19}_{-0.17}$	$7.50^{+0.24}_{-0.22}$	$5.37^{+0.22}_{-0.30}$	$3.36^{+0.15}_{-0.19}$
	$A_c^e(\%)$	$-14.83^{-0.65}_{+0.95}$	$-13.16^{-0.81}_{+1.12}$	$-12.84^{-0.81}_{+1.11}$	$-9.21^{-0.87}_{+1.05}$	$-4.94^{-0.63}_{+0.72}$

Expected sensitivity on asymmetries (100% efficiencies, …)

$t\bar{t}W$: $\delta A/A$	t	b	e/μ
8TeV 40fb^{-1}	209 %	58 %	33 %
14TeV 300fb^{-1}	45 %	13 %	8 %
14TeV 3ab^{-1}	14 %	4 %	2 %
100TeV 3ab^{-1}	3 %	2 %	1 %

BSM effects (axigluon with different couplings)



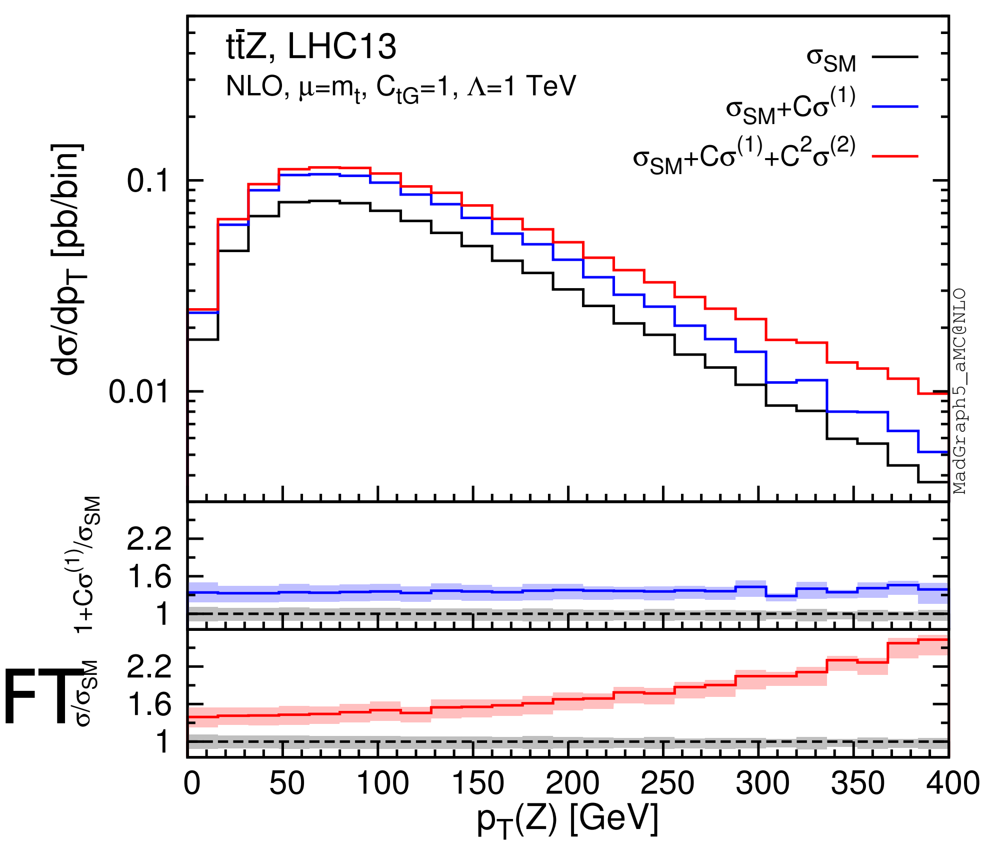
$t\bar{t}Z$ (and $t\bar{t}\gamma$) in the SMEFT@NLO

Bylund, Maltoni, Tsinikos, Vryonidou, Zhang, arXiv:1601.08193

13TeV	$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tW}$
$\sigma_{i,LO}^{(1)}$	$286.7^{+38.2\%}_{-25.5\%}$	$78.3^{+40.4\%}_{-26.6\%}$	$51.6^{+40.1\%}_{-26.4\%}$	$-0.20(3)^{+88.0\%}_{-230.0\%}$
$\sigma_{i,NLO}^{(1)}$	$310.5^{+5.4\%}_{-9.7\%}$	$90.6^{+7.1\%}_{-11.0\%}$	$57.5^{+5.8\%}_{-10.3\%}$	$-1.7(2)^{+31.3\%}_{-49.1\%}$
K-factor	1.08	1.16	1.11	8.5

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}\gamma^\mu\tau^I Q)$$
$$O_{\varphi Q}^{(1)} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}\gamma^\mu Q)$$
$$O_{\varphi t} = i\frac{1}{2}y_t^2\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}\gamma^\mu t)$$
$$O_{tW} = y_t g_w(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y(\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{tG} = y_t g_s(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu},$$

- Operators involving top and weak bosons are among the least constrained at the LHC
- SMEFT upgraded to NLO-QCD accuracy, including mixing and extra operators. UFO Model available
- K-factors not same for different operators
- Applying SM K-factors may not be enough for high-precision studies)
- Effects from (dim-6)^2 operators can be large; EFT validity to be discussed case-by-case



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13TeV	$\mathcal{O}_{tG}$	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi t}$	$\mathcal{O}_{tW}$
$\sigma_{i,LO}^{(1)}$				
$\sigma_{i,NLO}^{(1)}$				
K-factor				

$$O_{\varphi Q}^{(3)} = i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu\tau^I Q\right)$$

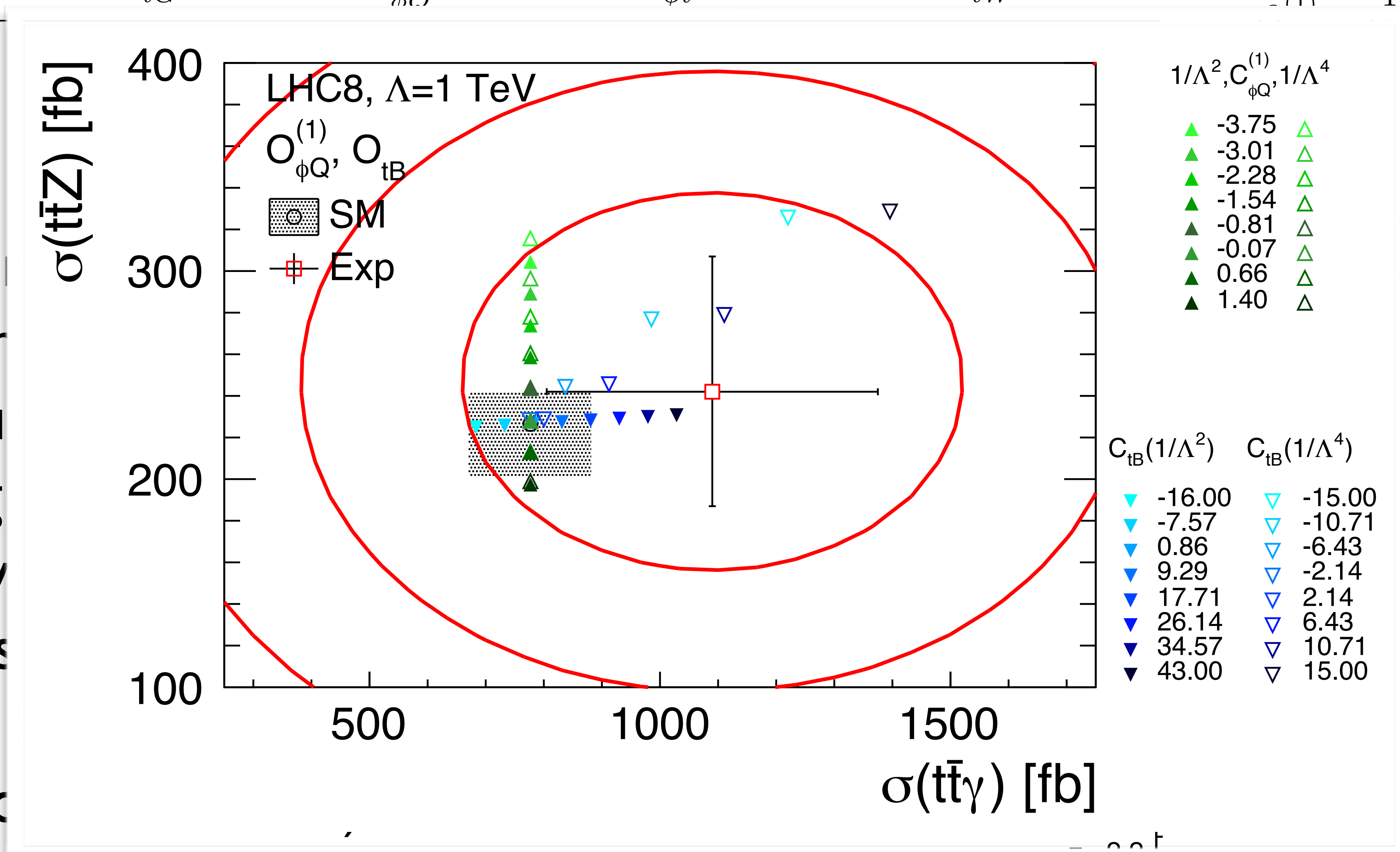
$$\ldots y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$$

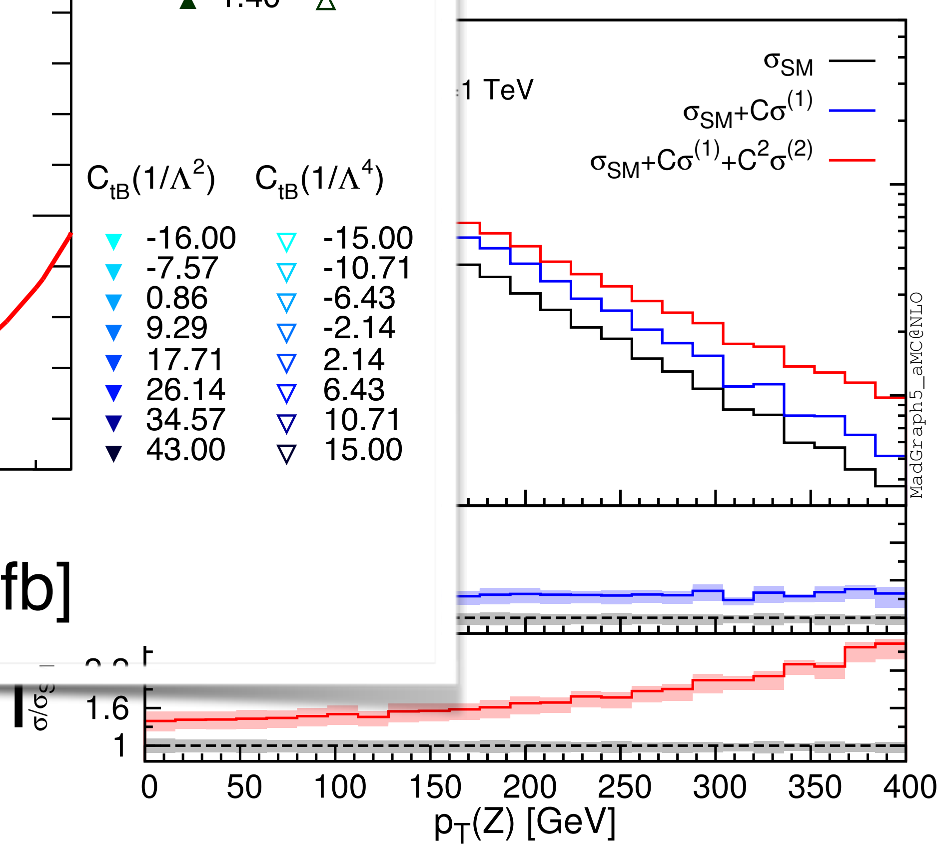
$$\ldots \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right)$$

$$\ldots (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$

$$\ldots (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$

$$\ldots (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu},$$





- Operato… among th…
- SMEFT u… including… Model av…
- K-factors…
- Applying… high-prec…
- Effects from (dim-6)² operators can be large; EFT validity to be discussed case-by-case

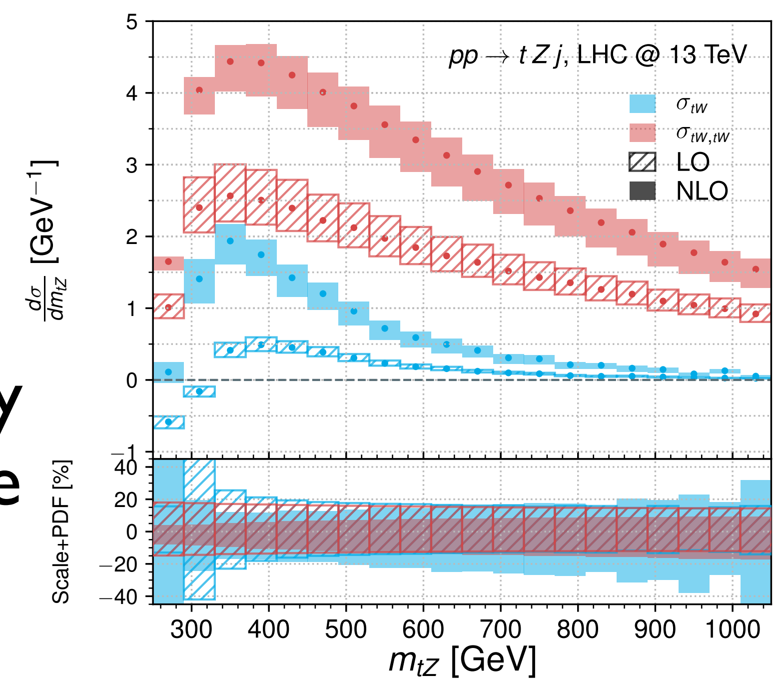
tZ

Degrande, Maltoni, Mimasu, Vryonidou, Zhang, arXiv:1804.07773

$\lambda_b,\ \lambda_W,\ \lambda_t$	SM	$\mathcal{O}_{t\varphi}$	$\mathcal{O}_{\varphi Q}^{(3)}$	$\mathcal{O}_{\varphi W}$	$\mathcal{O}_{tW}$	$\mathcal{O}_{HW}$
$-,0,-$	s^0	s^0	$\sqrt{s(s+t)}$	s^0	s^0	$\sqrt{s(s+t)}$
$-,0,+$	$\frac{1}{\sqrt{s}}$	$m_t\sqrt{-t}$	$m_t\sqrt{-t}$	$\frac{1}{\sqrt{s}}$	$\frac{m_W s}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$
$-,-,-$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$	$m_W\sqrt{-t}$	$\frac{m_W s}{\sqrt{-t}}$	$m_t\sqrt{-t}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,-,+$	$\frac{1}{s}$	s^0	s^0	$-$	$\sqrt{s(s+t)}$	$\frac{1}{s}$
$-,+,-$	$\frac{1}{\sqrt{s}}$	$-$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
$-,+,+$	s^0	$-$	s^0	s^0	s^0	$\frac{1}{s}$

$\mathcal{O}_W$	$\varepsilon_{IJK}\, W^I_{\mu\nu}\, W^{J,\nu\rho}\, W^{K,\mu}_{\rho}$	$\mathcal{O}^{(3)}_{\varphi Q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I \varphi\big)\big(\bar{Q}\,\gamma^\mu\, \tau^I Q\big) + \text{h.c.}$
$\mathcal{O}_{\varphi W}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) W_I^{\mu\nu}\, W^I_{\mu\nu}$	$\mathcal{O}^{(1)}_{\varphi Q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{Q}\,\gamma^\mu\, Q\big) + \text{h.c.}$
$\mathcal{O}_{\varphi WB}$	$(\varphi^\dagger \tau_I \varphi)\, B^{\mu\nu} W^I_{\mu\nu}$	$\mathcal{O}_{\varphi t}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{t}\,\gamma^\mu\, t\big) + \text{h.c.}$
$\mathcal{O}_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$\mathcal{O}_{\varphi tb}$	$i\big(\tilde{\varphi}\, D_\mu\, \varphi\big)\big(\bar{t}\,\gamma^\mu\, b\big) + \text{h.c.}$
$\mathcal{O}_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$\mathcal{O}^{(1)}_{\varphi q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{q}_i\,\gamma^\mu\, q_i\big) + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$\left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\, t\, \tilde{\varphi} + \text{h.c.}$	$\mathcal{O}^{(3)}_{\varphi q}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \tau_I \varphi\big)\big(\bar{q}_i\,\gamma^\mu\, \tau^I q_i\big) + \text{h.c.}$
$\mathcal{O}_{tW}$	$i\big(\bar{Q}\sigma^{\mu\nu}\, \tau_I\, t\big)\, \tilde{\varphi}\, W^I_{\mu\nu} + \text{h.c.}$	$\mathcal{O}_{\varphi u}$	$i\big(\varphi^\dagger \overleftrightarrow{D}_\mu\, \varphi\big)\big(\bar{u}_i\,\gamma^\mu\, u_i\big) + \text{h.c.}$
$\mathcal{O}_{tB}$	$i\big(\bar{Q}\sigma^{\mu\nu}\, t\big)\, \tilde{\varphi}\, B_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,1)}_{Qq}$	$\big(\bar{q}_i\,\gamma_\mu\, \tau_I q_i\big)\big(\bar{Q}\,\gamma^\mu\, \tau^I Q\big)$
$\mathcal{O}_{tG}$	$i\big(\bar{Q}\sigma^{\mu\nu}\, T_A\, t\big)\, \tilde{\varphi}\, G^A_{\mu\nu} + \text{h.c.}$	$\mathcal{O}^{(3,8)}_{Qq}$	$\big(\bar{q}_i\,\gamma_\mu\, \tau_I T_A q_i\big)\big(\bar{Q}\,\gamma^\mu\, \tau^I T^A Q\big)$

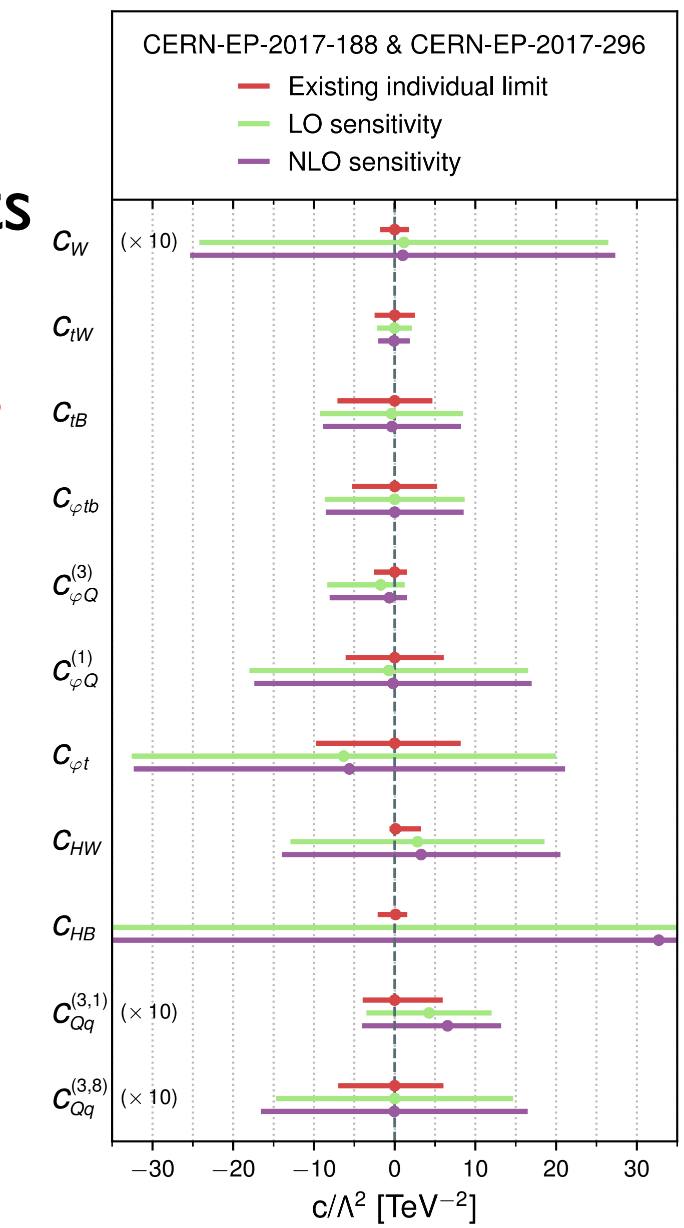
- tZ (and tH) can be very interesting probes of new physics
- For tZ, the cross section is comparable to $t\bar{t}Z$ (800 fb)
- In the SM, delicate cancellations appear among diagrams, which are spoiled by BSM effects, even for operators without energy-growing interactions (e.g $O_{t\varphi}$)
- NLO corrections can modify the cross-section sensitivity on a given operator, specially on the SM-EFT interference

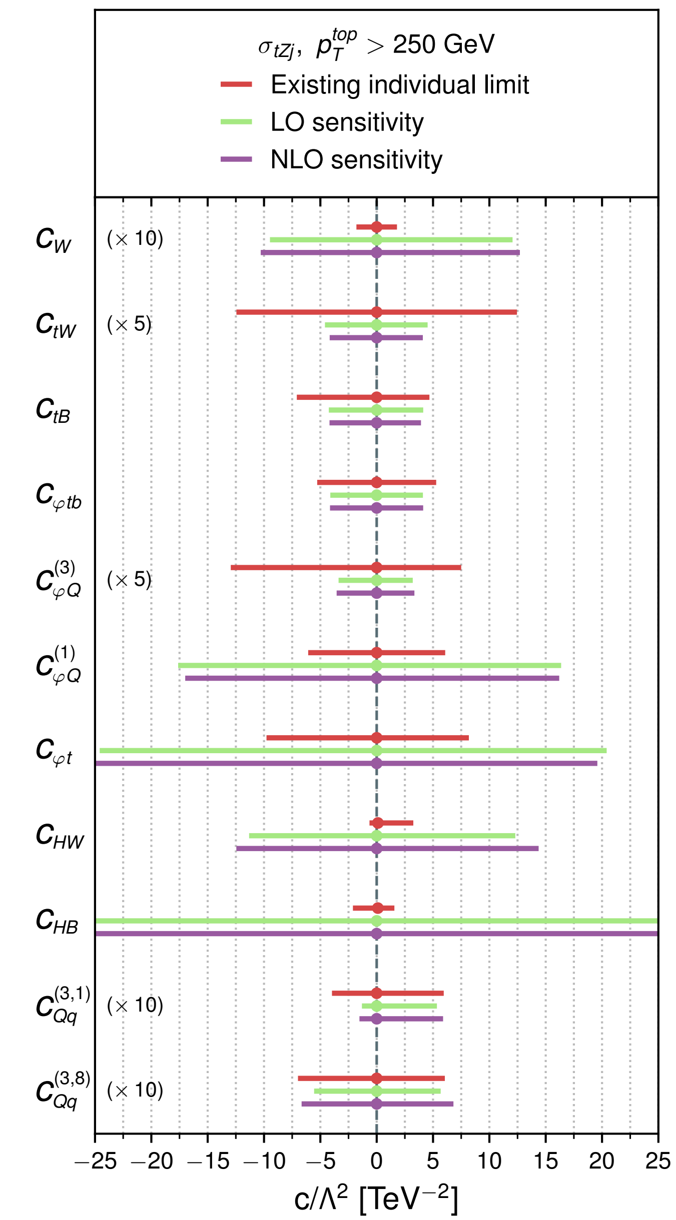


σ_{tW}	$2.66(4)^{+18.8[0.9]\%}_{-15.3[1.0]\%} \pm 11.4\%$	$13.0(1)^{+15.8[2.1]\%}_{-22.8[0.0]\%} \pm 1.2\%$	4.90
$\sigma_{tW,tW}$	$48.16(4)^{+10.0[1.7]\%}_{-5.8[1.9]\%} \pm 11.3\%$	$80.00(4)^{+7.9[1.3]\%}_{-14.7[1.6]\%} \pm 1.9\%$	1.66

Limits from tZ and tH

- Limits from current measurements (LO and NLO) are in general looser than other existing bounds (except for O_{tW})
- Effects enhanced in tail of distributions at the HL-LHC
- SMEFT global fits can be performed at the LHC





Is a 1% measurement of y_t possible? ttZ and the FCC can help…

Mangano, Plehn, Reimitz, Schell, Shao, arXiv:1507.08169

- $t\bar{t}H$ and $t\bar{t}Z$ are quite similar processes, with rather large theoretical uncertainties (~10%).
  - Dominant production mode (gg) has identical diagrams
    Correlated QCD corrections, scale and α_S systematics

NLO QCD	$\sigma(t\bar{t}H)$ [pb]	$\sigma(t\bar{t}Z)$ [pb]	$\sigma(t\bar{t}H)/\sigma(t\bar{t}Z)$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

  - Almost identical kinematics boundaries (m_Z~m_H)
    Correlated PDF and m_t systematics

100TeV	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
MSTW2008	$0.585^{+1.29\%+0.0526\%}_{-2.02\%-0.0758\%}$
CT10	$0.584^{+1.27\%+0.189\%}_{-1.99\%-0.260\%}$
NNPDF2.3	$0.584^{+1.29\%+0.0493\%}_{-2.01\%-0.0493\%}$

	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
default	$0.585^{+1.29\%}_{-2.02\%}$
$\mu_0 = m_t + m_{H,Z}/2$	$0.580^{+1.16\%}_{-1.80\%}$
$m_t = y_t v = 174.1$ GeV	$0.592^{+1.27\%}_{-2.00\%}$
$m_t = y_t v = 172.5$ GeV	$0.576^{+1.27\%}_{-1.99\%}$
$m_H = 126.0$ GeV	$0.575^{+1.25\%}_{-1.95\%}$

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  - Almost identical kinematics boundaries ($m_Z \sim m_H$) Correlated PDF and m_t systematics

100T[illegible]	[illegible]
MSTW[illegible]	[illegible]
CT[illegible]	[illegible]
NNPDF2.3	$0.584^{+1.29\%+0.0493\%}_{-2.01\%-0.0493\%}$

[illegible]	[illegible]9%
[illegible]	[illegible]2%
[illegible]	[illegible]6%
[illegible]	[illegible]0%
$m_t = y_t v = 174.1$ GeV	$0.592^{+1.27\%}_{-2.00\%}$
$m_t = y_t v = 172.5$ GeV	$0.576^{+1.27\%}_{-1.99\%}$
$m_H = 126.0$ GeV	$0.575^{+1.25\%}_{-1.95\%}$

With 20ab^{-1}, the ratio N_H/N_Z can be measured at 1% (stat. unc.)

Conclusions

- At least two good reasons to look at $t\bar{t}W$ and $t\bar{t}Z$: they appear as background to the Higgs and to many BSM searches and they can shed light on new physics affecting the top weak couplings
- Current SM predictions have decent perturbative accuracy, which we are bound to live with for quite some time
- $t\bar{t}W$ and $t\bar{t}Z$ show complementary sensitivity to new physics:
  - asymmetry and t-W scattering in $t\bar{t}W$
  - sensitivity to HD operators through rate and distributions for $t\bar{t}Z$
- LHC measurements of these processes are just started… Potentially large improvements ahead!

Backup

EW corrections for ttW/Z/H: setup

more in Frixione, Hirschi, Shao, Zaro, arXiv:1504.03446

- EW corrections computed in the $\alpha(m_Z)$ scheme (G_μ also available)
- Particle masses:
  - m_t=173.3 GeV	m_H=125 GeV
  - m_W=80.385 GeV	m_Z=91.188 GeV
- NNPDF2.3 QED PDF, quoted uncertainties @68%CL
- Ren./Fac. scale choice:

$$\mu = \frac{H_T}{2}$$

- LO+NLO QCD scale uncertainties in the range

$$\frac{1}{2}\mu \leq \mu_R, \mu_F \leq 2\mu$$

Results for $t\bar{t}H$ and $t\bar{t}Z$: total rates (within boosted cuts)

$t\bar{t}H$: σ(pb)	13 TeV
LO QCD	$3.617 \cdot 10^{-1}$ $(1.338 \cdot 10^{-2})$
NLO QCD	$1.073 \cdot 10^{-1}$ $(3.230 \cdot 10^{-3})$
LO EW	$4.437 \cdot 10^{-3}$ $(3.758 \cdot 10^{-4})$
LO EW no γ	$-1.390 \cdot 10^{-3}$ $(-2.452 \cdot 10^{-5})$
NLO EW	$-4.408 \cdot 10^{-3}$ $(-1.097 \cdot 10^{-3})$
NLO EW no γ	$-4.919 \cdot 10^{-3}$ $(-1.131 \cdot 10^{-3})$
HBR	$3.216 \cdot 10^{-3}$ $(2.496 \cdot 10^{-4})$

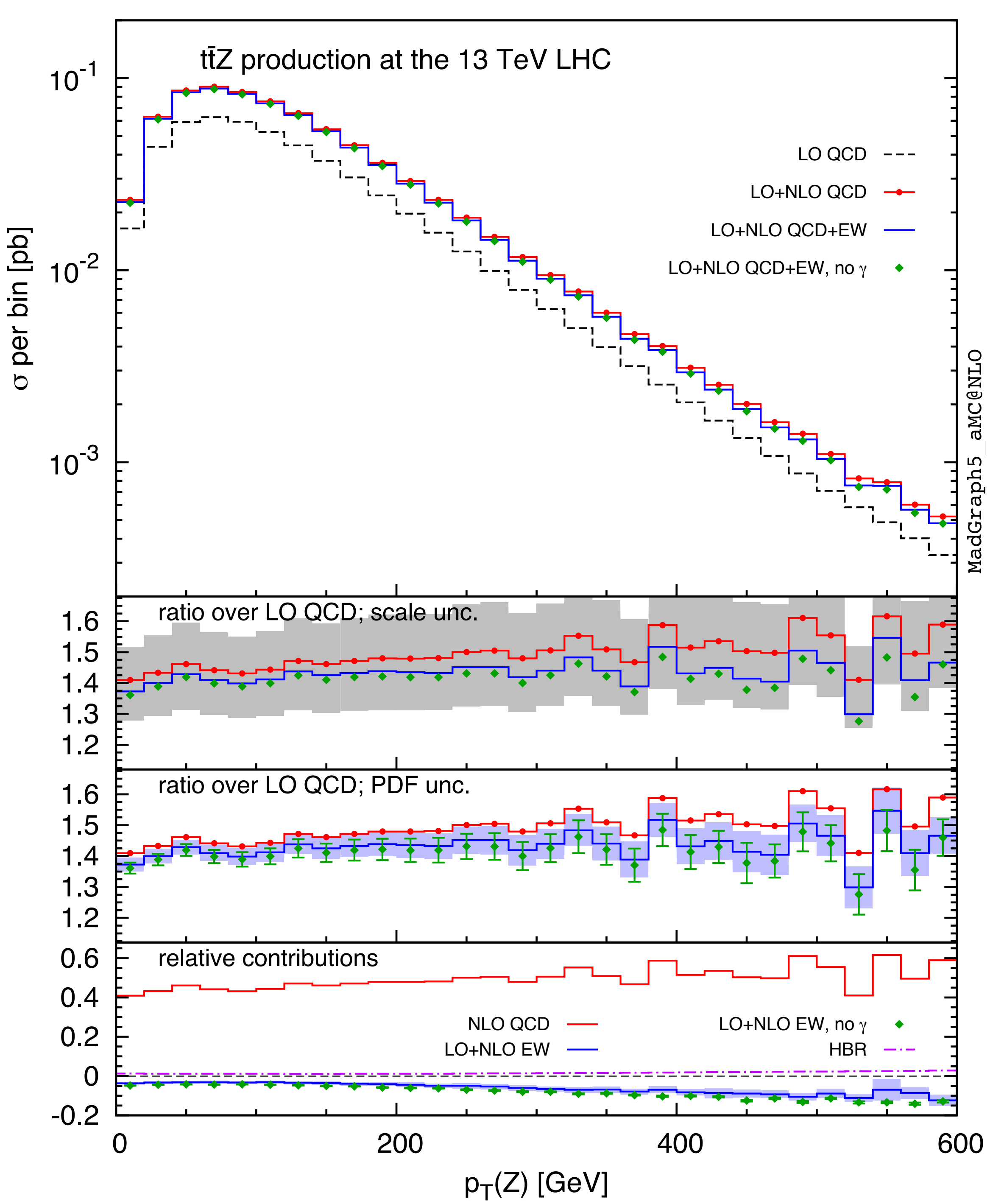
$t\bar{t}Z$: σ(pb)	13 TeV
LO QCD	$5.282 \cdot 10^{-1}$ $(1.955 \cdot 10^{-2})$
NLO QCD	$2.426 \cdot 10^{-1}$ $(7.856 \cdot 10^{-3})$
LO EW	$-2.172 \cdot 10^{-4}$ $(4.039 \cdot 10^{-4})$
LO EW no γ	$-5.771 \cdot 10^{-3}$ $(-6.179 \cdot 10^{-5})$
NLO EW	$-2.017 \cdot 10^{-2}$ $(-2.172 \cdot 10^{-3})$
NLO EW no γ	$-2.158 \cdot 10^{-2}$ $(-2.252 \cdot 10^{-3})$
HBR	$5.056 \cdot 10^{-3}$ $(4.162 \cdot 10^{-4})$

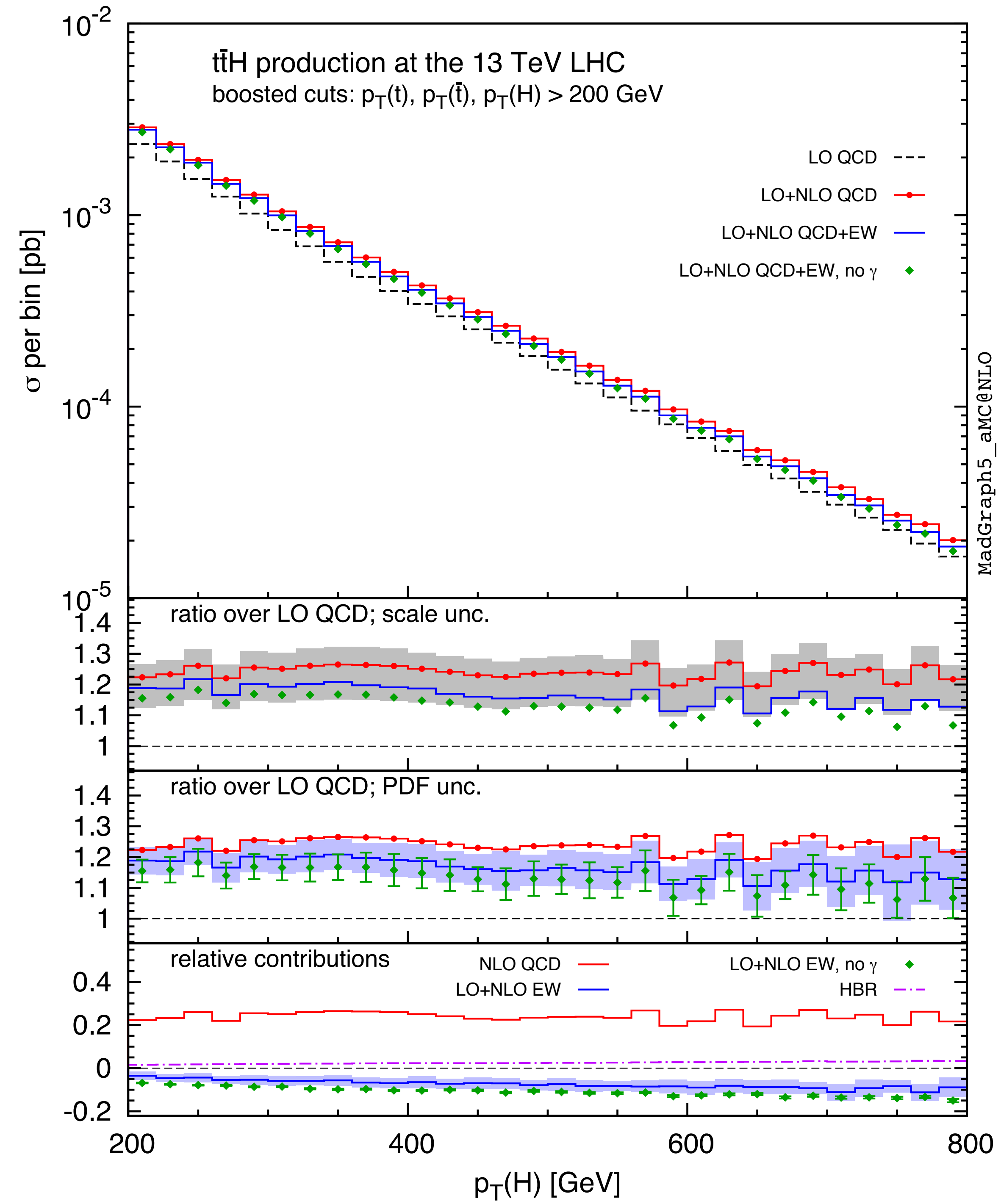
$t\bar{t}H$: $\delta(\%)$	13 TeV
NLO QCD	$29.7^{+6.8}_{-11.1} \pm 2.8$ $(24.2^{+4.8}_{-10.6} \pm 4.5)$
LO EW	1.2 ± 0.9 (2.8 ± 2.0)
LO EW no γ	-0.4 ± 0.0 (-0.2 ± 0.0)
NLO EW	-1.2 ± 0.1 (-8.2 ± 0.3)
NLO EW no γ	-1.4 ± 0.0 (-8.5 ± 0.2)
HBR	0.89 (1.87)

$t\bar{t}Z$: $\delta(\%)$	13 TeV
NLO QCD	$45.9^{+13.2}_{-15.5} \pm 2.9$ $(40.2^{+11.1}_{-15.0} \pm 4.7)$
LO EW	0.0 ± 0.7 (2.1 ± 1.6)
LO EW no γ	-1.1 ± 0.0 (-0.3 ± 0.0)
NLO EW	-3.8 ± 0.2 (-11.1 ± 0.5)
NLO EW no γ	-4.1 ± 0.1 (-11.5 ± 0.3)
HBR	0.96 (2.13)

- NLO EW correction have modest impact on inclusive xsect, but can be important in the boosted regime (same order of QCD uncertainties)
- Boosted regime enhances photon contribution in LO-EW
- HBR contributions remain small

Results for $t\bar{t}H$ and $t\bar{t}Z$: distributions





Results for $t\bar{t}W$: total rates (within boosted cuts)

$t\bar{t}W^+$: σ(pb)	13 TeV
LO QCD	$2.496 \cdot 10^{-1}$ $(7.749 \cdot 10^{-3})$
NLO QCD	$1.250 \cdot 10^{-1}$ $(4.624 \cdot 10^{-3})$
LO EW	0
LO EW no γ	0
NLO EW	$-1.931 \cdot 10^{-2}$ $(-1.490 \cdot 10^{-3})$
NLO EW no γ	$-1.988 \cdot 10^{-2}$ $(-1.546 \cdot 10^{-3})$
HBR	$9.677 \cdot 10^{-3}$ $(5.743 \cdot 10^{-4})$

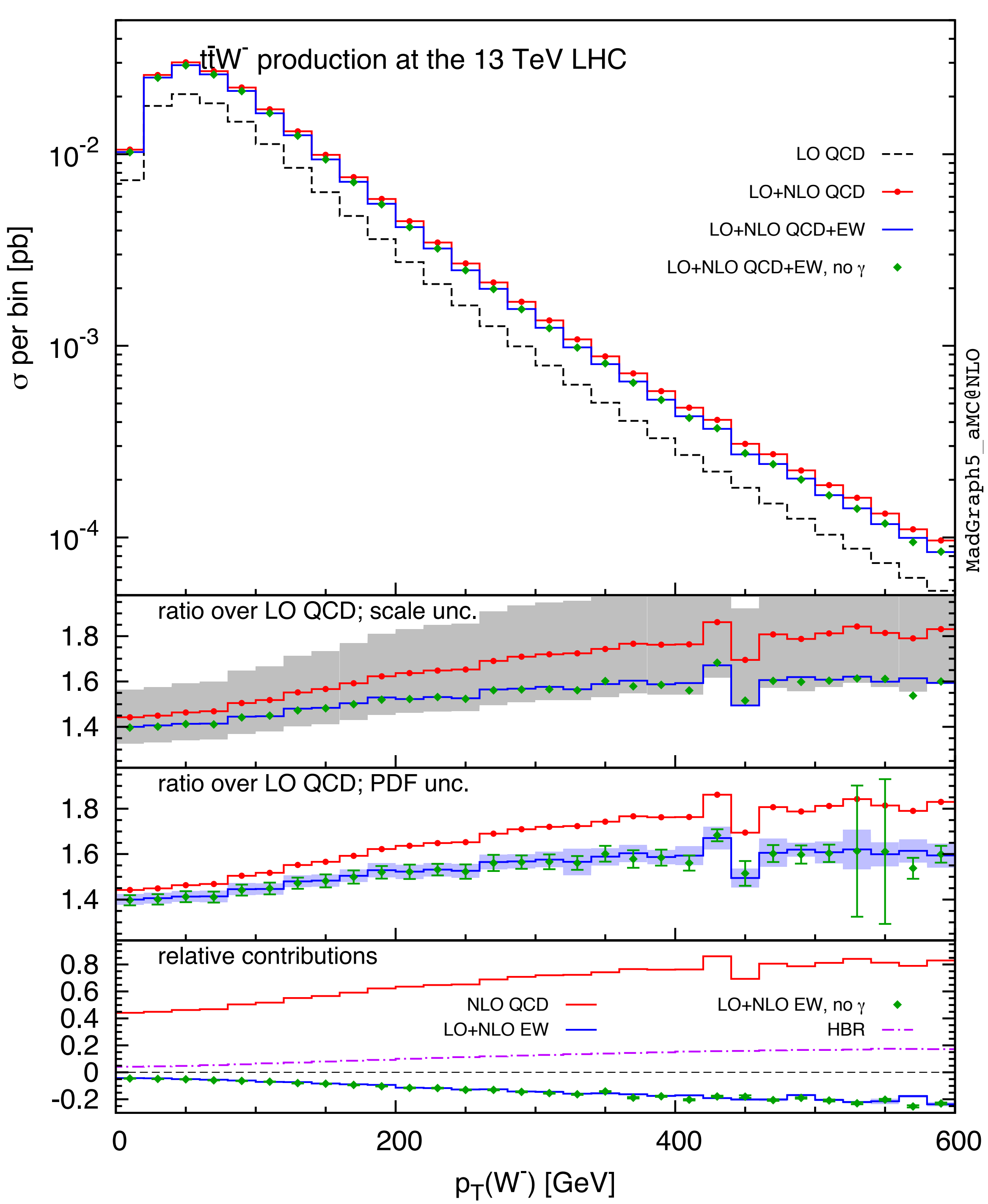
$t\bar{t}W^-$: σ(pb)	13 TeV
LO QCD	$1.265 \cdot 10^{-1}$ $(3.186 \cdot 10^{-3})$
NLO QCD	$6.515 \cdot 10^{-2}$ $(2.111 \cdot 10^{-3})$
LO EW	0
LO EW no γ	0
NLO EW	$-8.502 \cdot 10^{-3}$ $(-5.838 \cdot 10^{-4})$
NLO EW no γ	$-8.912 \cdot 10^{-3}$ $(-6.094 \cdot 10^{-4})$
HBR	$8.219 \cdot 10^{-3}$ $(4.781 \cdot 10^{-4})$

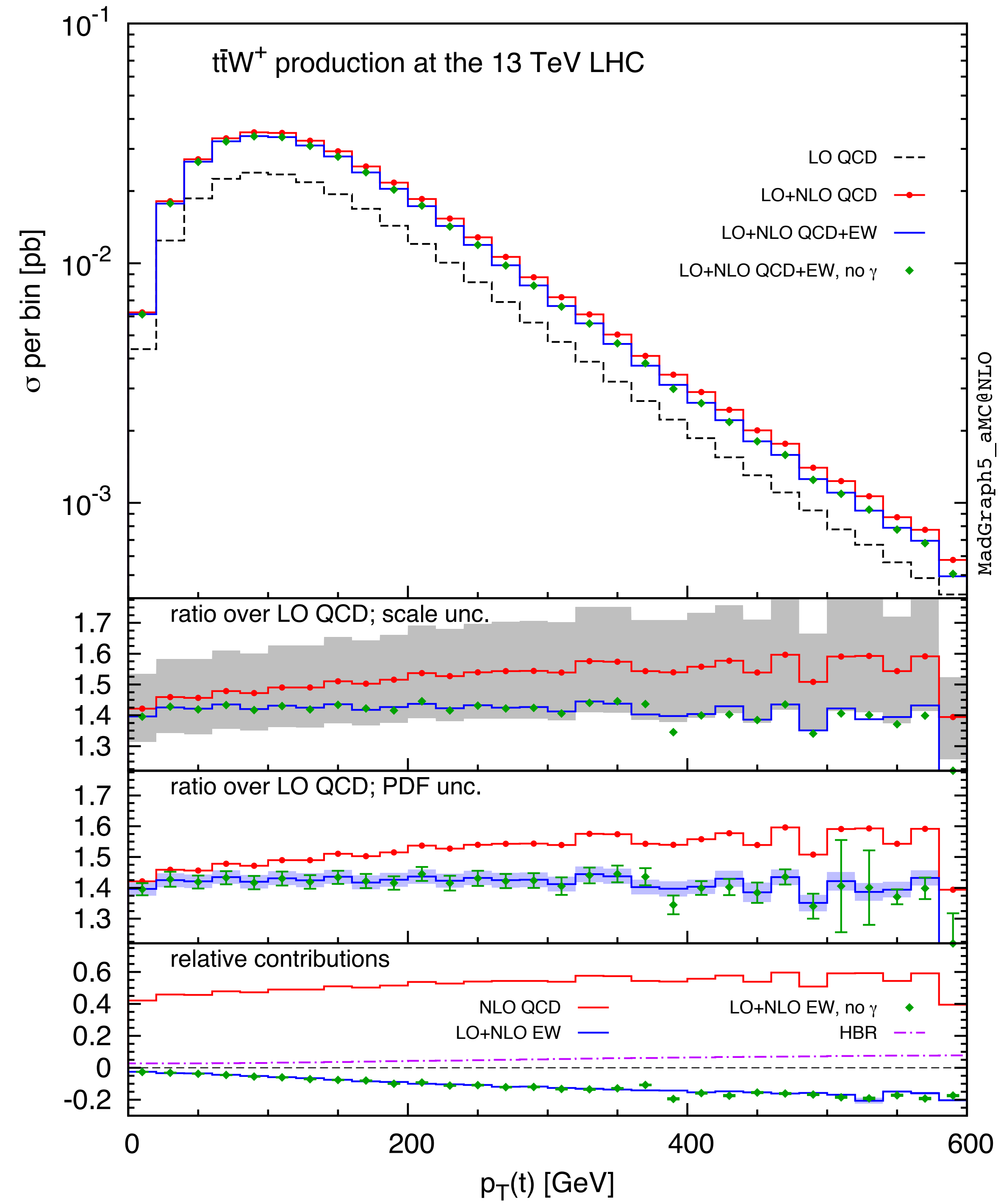
$t\bar{t}W^+$: $\delta(\%)$	13 TeV
NLO QCD	$50.1^{+14.2}_{-13.5} \pm 2.4$ $(59.7^{+18.9}_{-17.7} \pm 3.1)$
LO EW	0
LO EW no γ	0
NLO EW	-7.7 ± 0.2 (-19.2 ± 0.7)
NLO EW no γ	-8.0 ± 0.2 (-20.0 ± 0.5)
HBR	3.88 (7.41)

$t\bar{t}W^-$: $\delta(\%)$	13 TeV
NLO QCD	$51.5^{+14.8}_{-13.8} \pm 2.8$ $(66.3^{+21.7}_{-19.6} \pm 3.9)$
LO EW	0
LO EW no γ	0
NLO EW	-6.7 ± 0.2 (-18.3 ± 0.8)
NLO EW no γ	-7.0 ± 0.2 (-19.1 ± 0.6)
HBR	6.50 (15.01)

- EW corrections larger than $t\bar{t}H/Z$, in particular with boosted cuts
- HBR enhanced by parton luminosities: $t\bar{t}WW$ has gg, $t\bar{t}W$ only $q\bar{q}$

Results for $t\bar{t}W$: distributions





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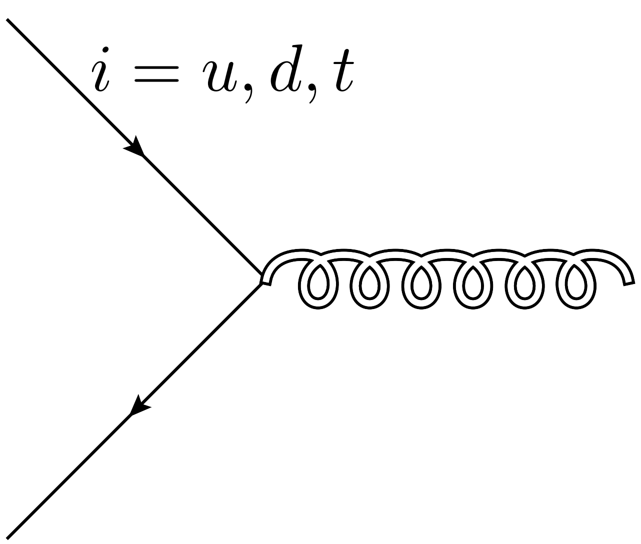
  - Extra color octet G which couples differently to quarks of different chiralities and to u/d and heavy quarks



$$= \quad \lambda^a \left(\frac{1-\gamma_5}{2} g_L^i + \frac{1+\gamma_5}{2} g_R^i \right) \gamma^\mu$$

ttW asymmetry: A look BSM

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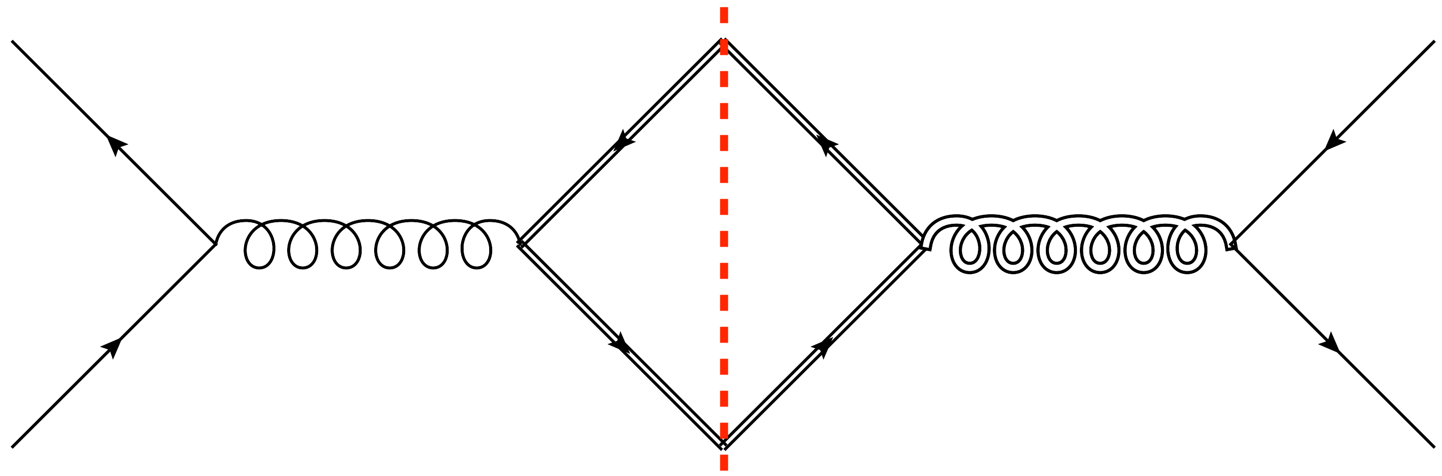
  - Extra color octet G which couples differently to quarks of different chiralities and to u/d and heavy quarks
  - The interference between the gluon and axigluon gives an asymmetry at LO



Benchmark scenarios:

Light, universal G		Heavy, non-universal G	
I (left)	II (axial)	III (left)	IV (axial)
m_G=200GeV		m_G=2TeV	
Γ_G=50GeV		Γ_G=1.123TeV	Γ_G=0.742TeV
$g^u{}_L=g^d{}_L=0.5g_s$	$g^u{}_L=g^d{}_L=-0.4g_s$	$g^u{}_L=g^d{}_L=-0.8g_s$	$g^u{}_L=g^d{}_L=0.6g_s$
$g^u{}_R=g^d{}_R=0$	$g^u{}_R=g^d{}_R=0.4g_s$	$g^u{}_R=g^d{}_R=0$	$g^u{}_R=-0.6g_s$ $g^d{}_L=0$
$g_t{}^{R,L}=-g_u{}^{R,L}$		$g^t{}_R=0$ $g^t{}_L=6g_s$	$g^t{}_R=-g^t{}_L=4g_s$

W boson polarises light quarks: σ=0 in right-handed scenarios

Combination of BSM and SM asymmetries

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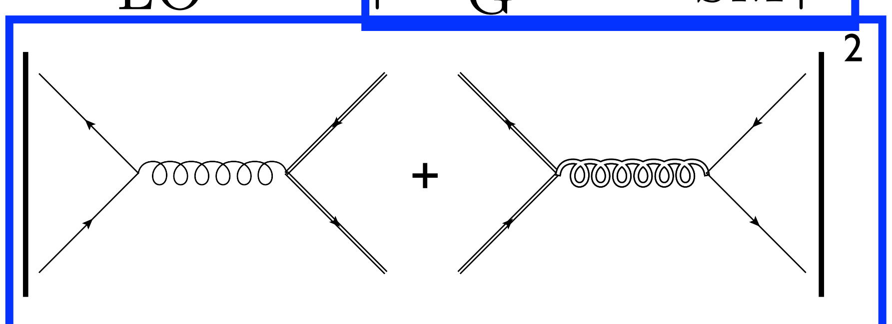

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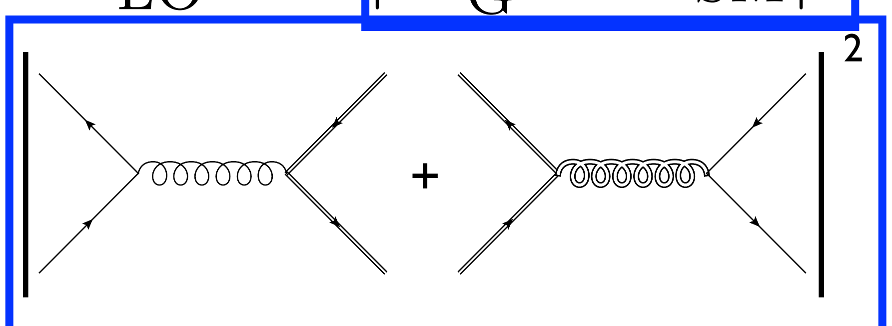

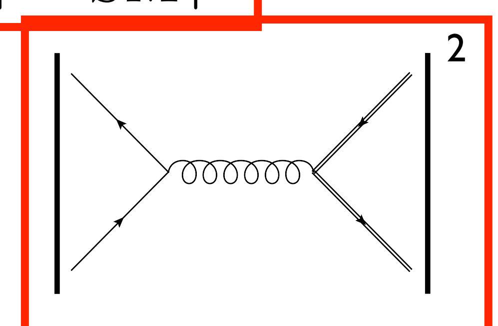

already in σ_{NLO}

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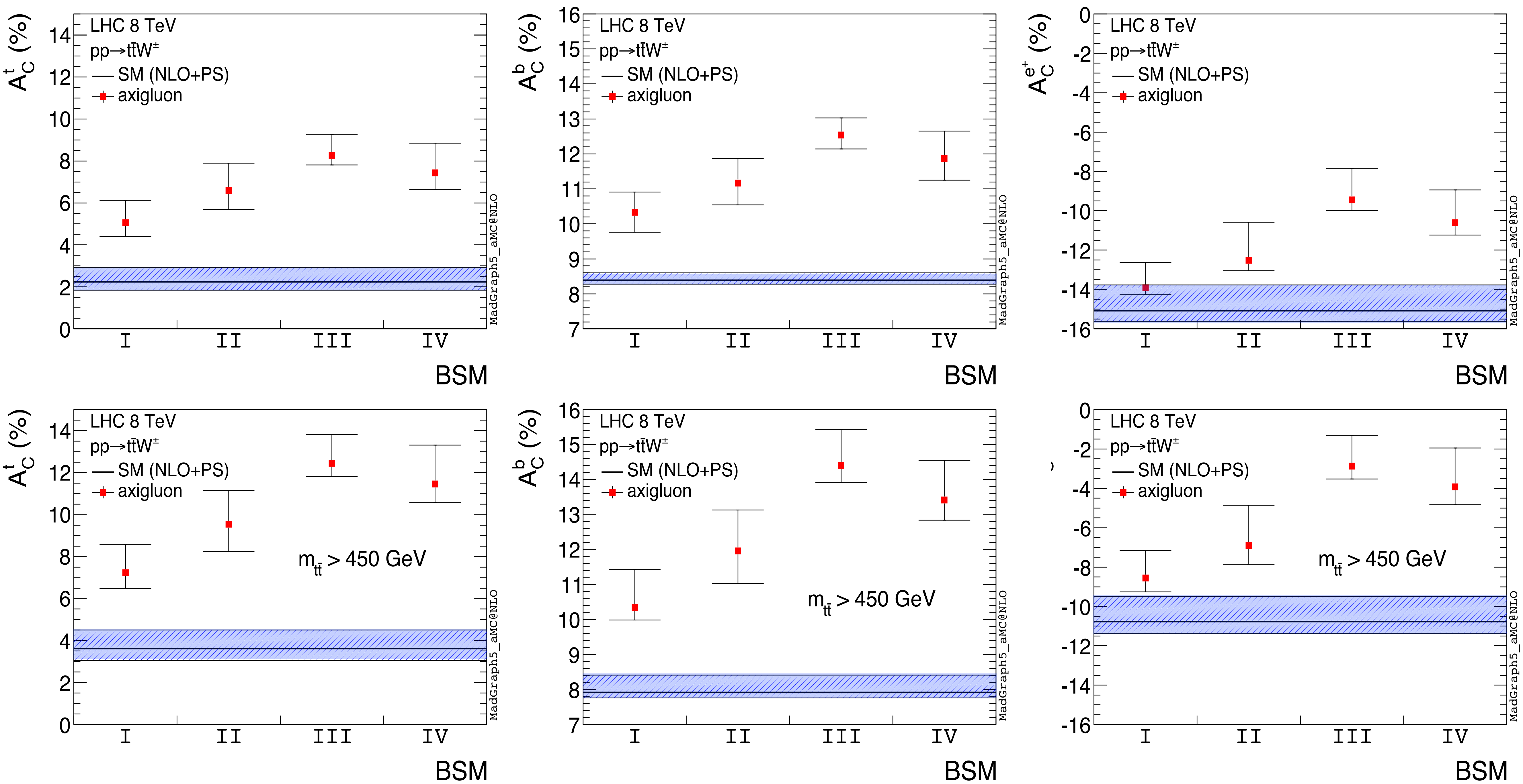
$$\sigma^{\rm BSM}_{\rm LO} = |M_{\tilde{\rm G}} + M_{\rm SM}|^2 - |M_{\rm SM}|^2$$

$$A_C = \frac{\sigma^{\rm SM}_{NLO}}{\sigma_{\rm tot}} A_C^{\rm SM} + \frac{A^{\rm BSM}_{\rm LO}}{\sigma_{\rm tot}} A_C^{\rm BSM}$$

Results


LHC 8 TeV
pp→tt̄W±
SM (NLO+PS)
axigluon
A_C^t (%)
A_C^b (%)
$A_C^{e^+}$ (%)
$m_{t\bar{t}}$ > 450 GeV
I
II
III
IV
BSM
MadGraph5_aMC@NLO