Top-quark and electroweak physics: Theory

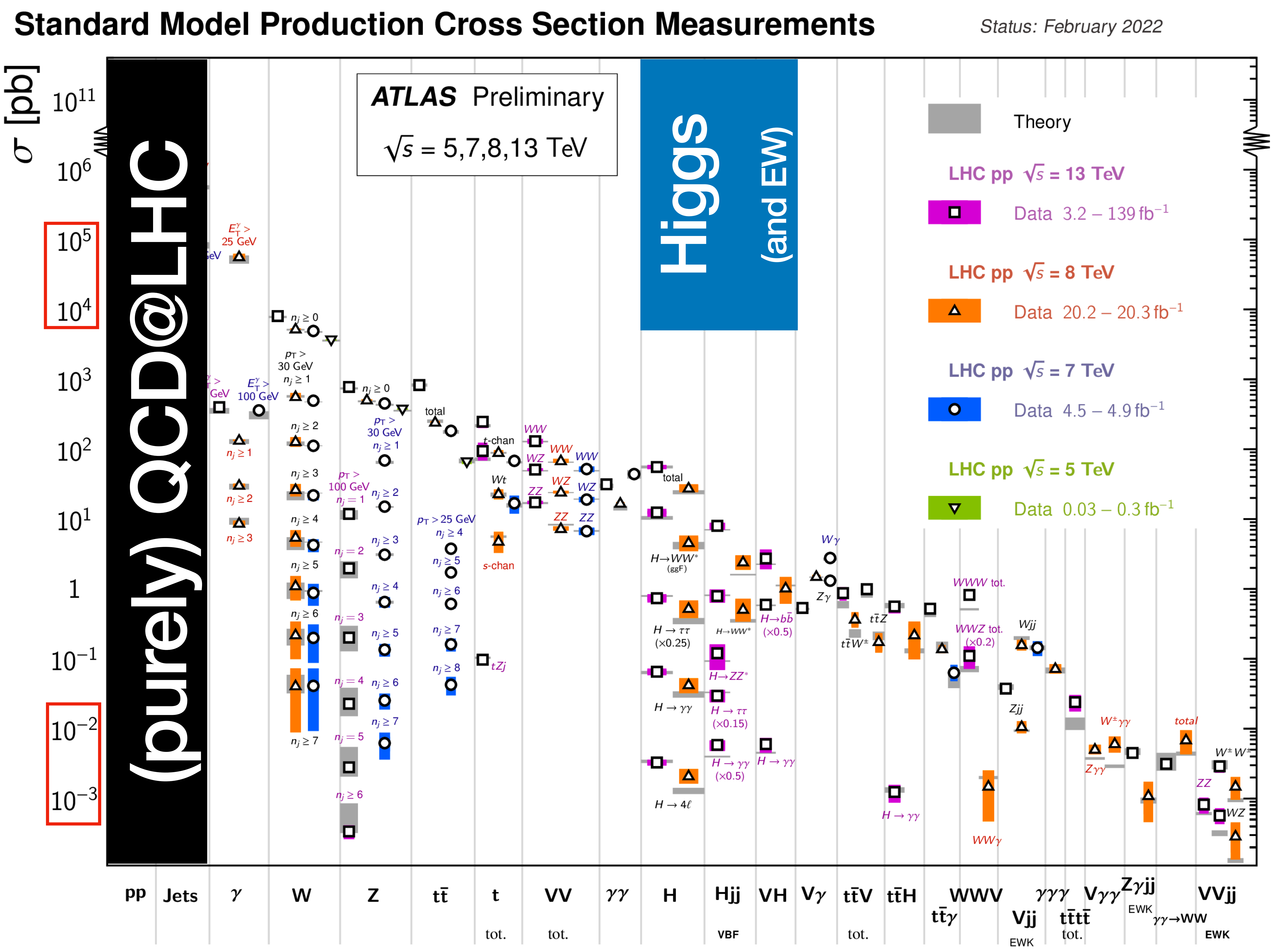
Based on a personal selection of results from this vast subject.

INFN Istituto Nazionale di Fisica Nucleare
SEZIONE DI BOLOGNA

Davide Pagani

QCD@LHC 2022, 28-11-2022, IJCLab Orsay.

Most of physics at LHC is from EW and Top-quark



from QCD@LHC

The LHC is a pp machine therefore QCD effects are everywhere and they can never be neglected, not only for precision but for sensible predictions in general.

to QCD&EW&TOP@LHC:

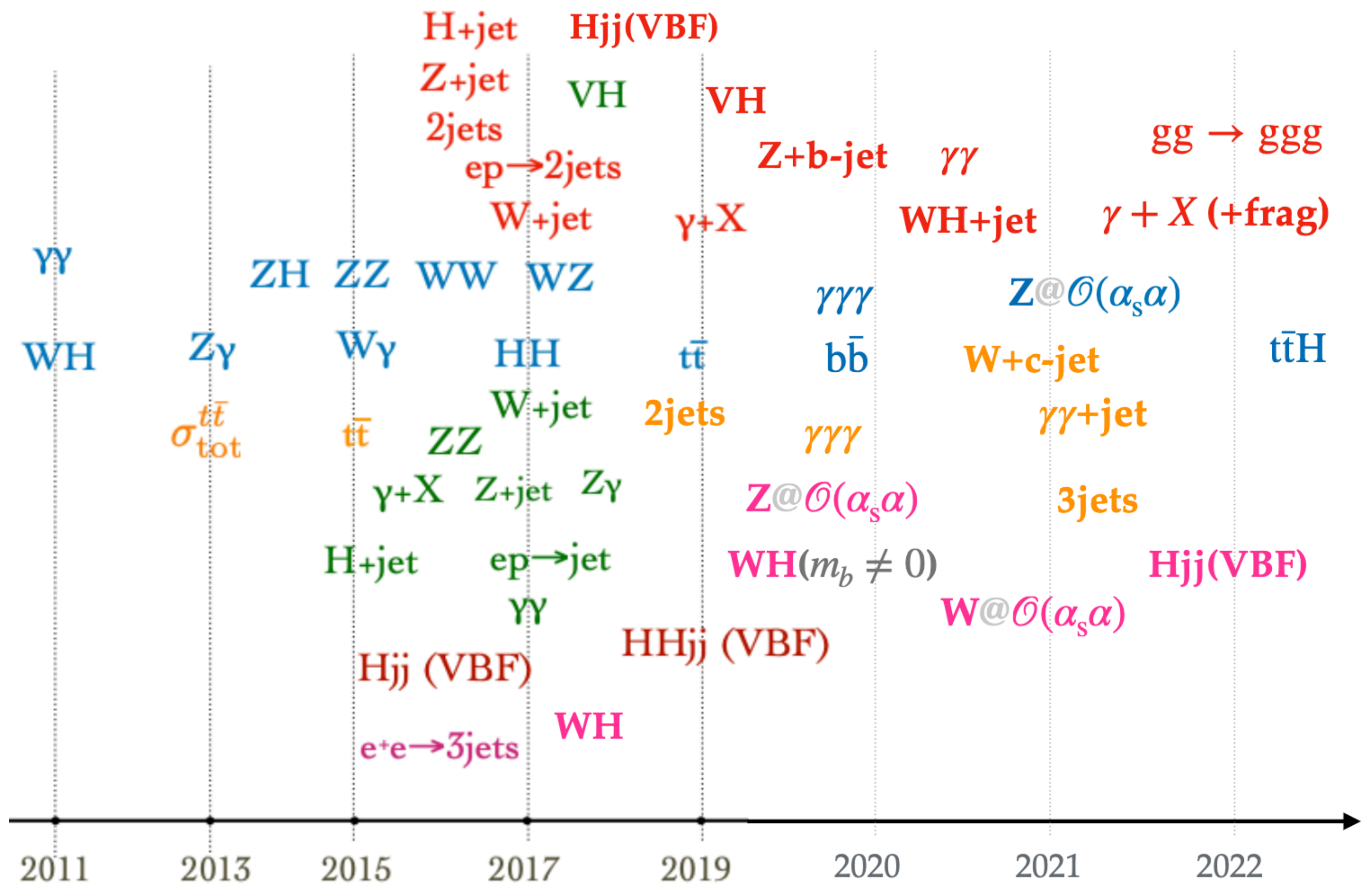
Given the range of energy explored by the LHC, it is almost impossible to be sensitive on neither the EW sector of the SM nor the top-quark physics.

EW&TOP from a QCD/precision perspective

as final states

NNLO QCD corrections have been calculated for many processes and **for a few** of them **even NNNLO QCD** corrections are available: single $H, \gamma^*, W^{\pm}, Z$ and HH, ZH.

NNLO recent timeline



taken from A.Huss talk at
Workshop on Tools for High Precision LHC Simulations
look at it for up-to-date references and citations.

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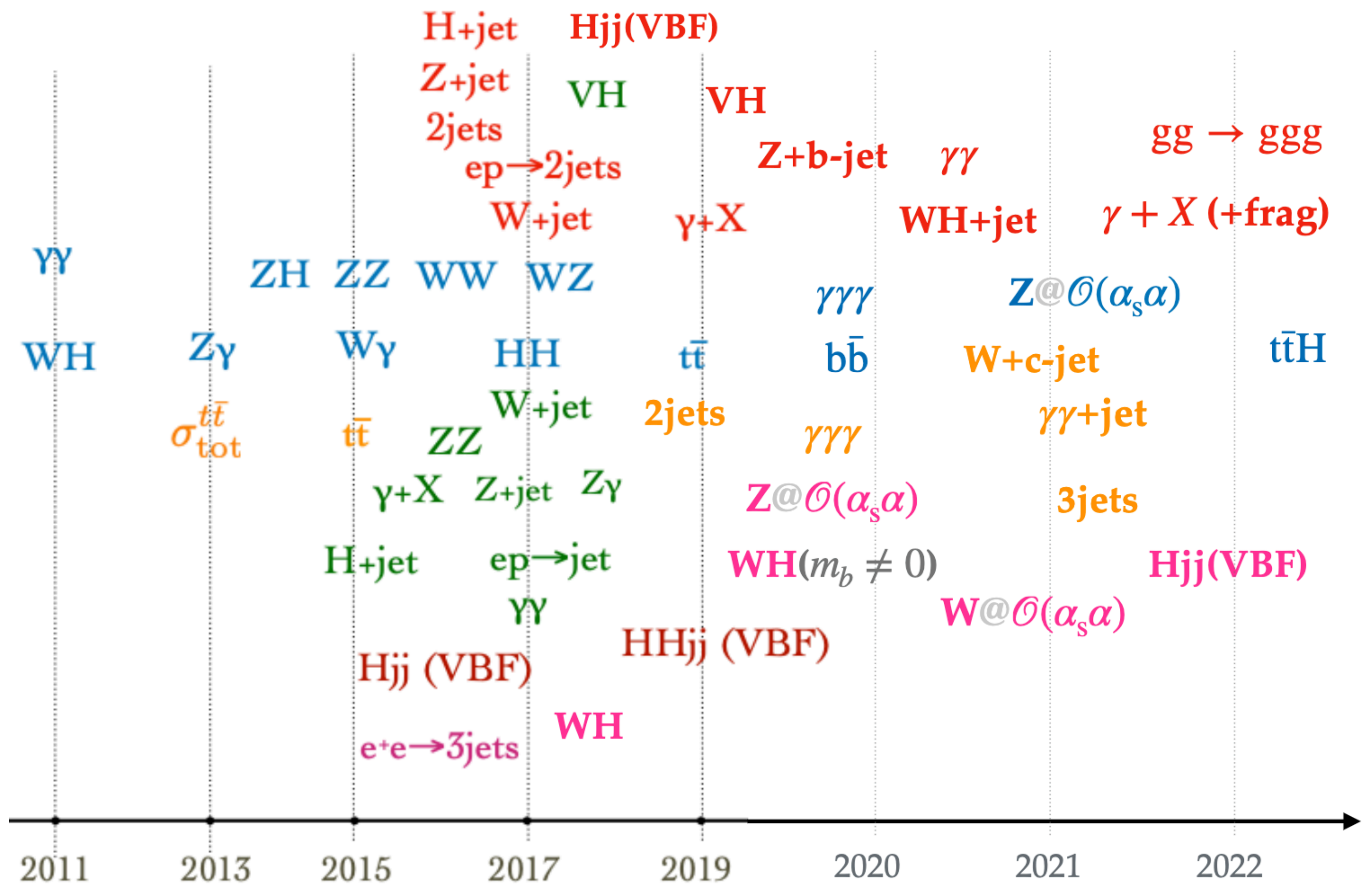

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as loops

Since NNLO QCD is unavoidable at the LHC and:

NNLO QCD $\sim \alpha_s^2 \sim \alpha_{\rm EW} \sim$ **NLO EW**

then also **NLO EW corrections cannot be omitted and typically involve tops.**

NLO EW corrections, as well as Complete NLO* predictions, have been already **automated in fixed-order** calculations for LHC cross sections.

Mixed EW and QCD at NNLO have also started to be computed, and are now available for Z on- and off-shell production.

* Complete NLO consists of all possible SM one-loop corrections beyond the standard NLO QCD and NLO EW.

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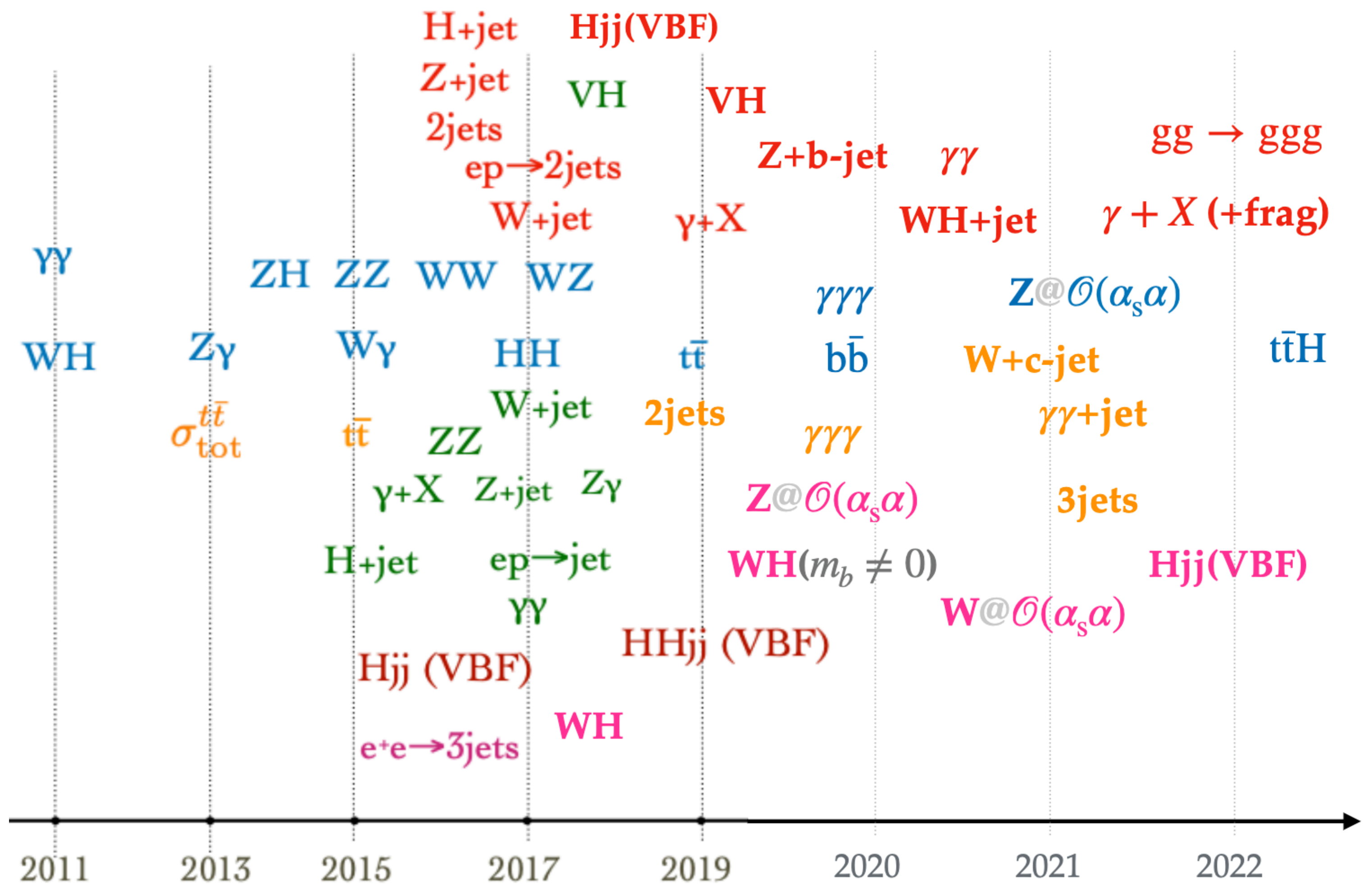

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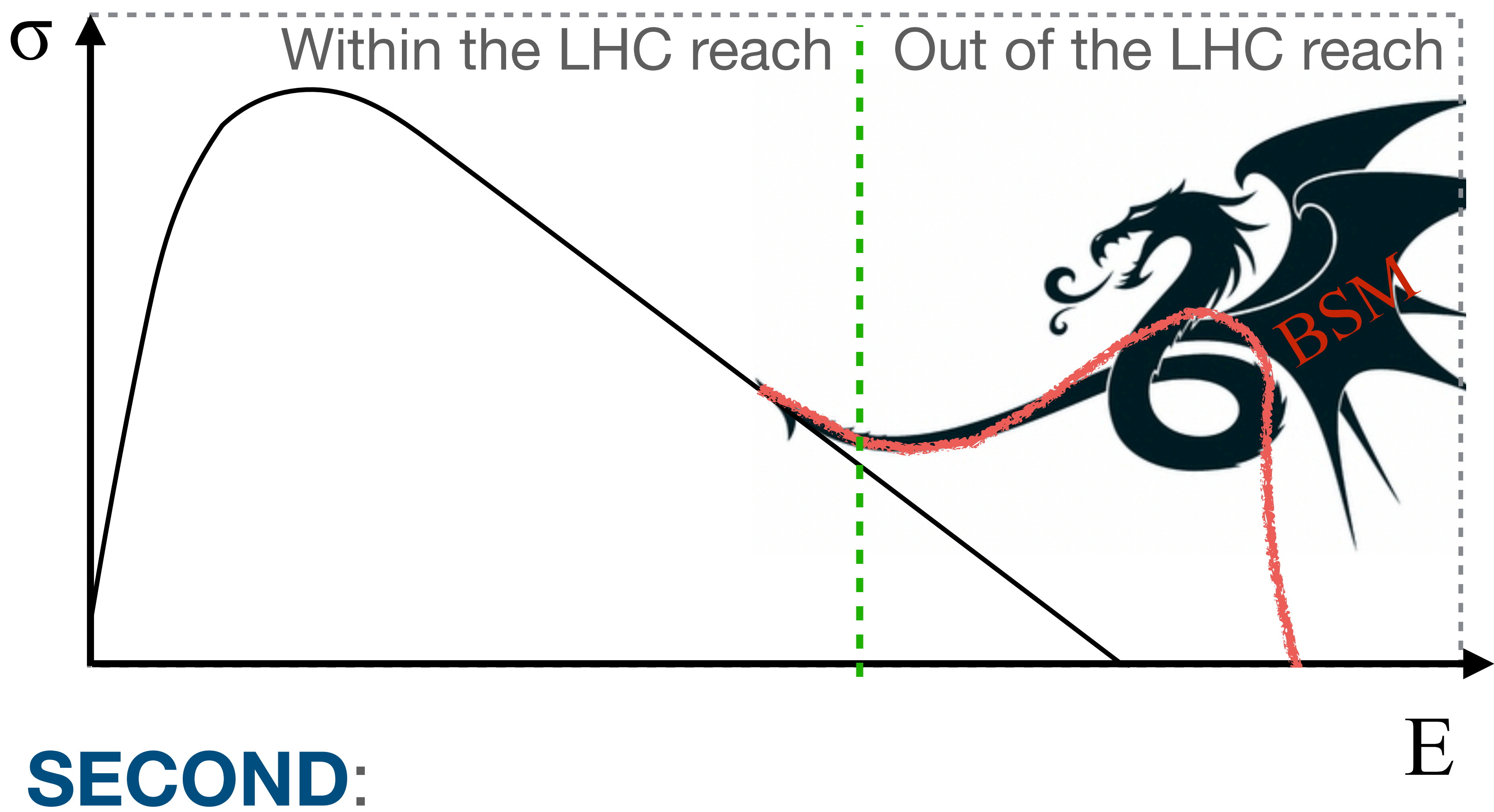
in BSM

FIRST:
many **BSM signatures overlap** with those emerging from top and V bosons final states.
No control of the SM background means no control of the BSM signal.



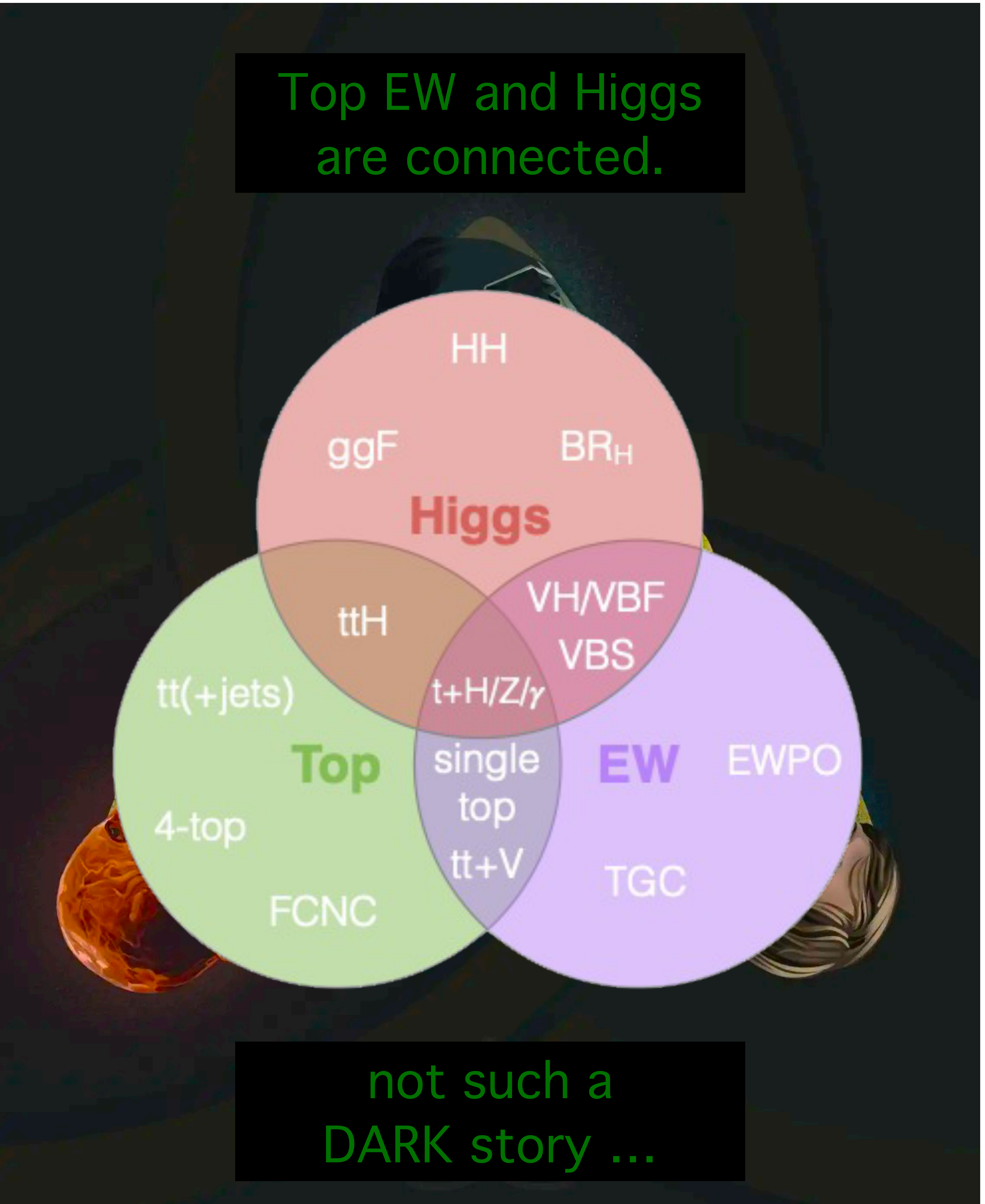
SECOND:
Top-quark, Higgs and V bosons (especially longitudinal polarisations) are the most natural particles to scrutinise in order to detect possible BSM signals.

These three aspects, which are all different, have also mutual influences with each other.

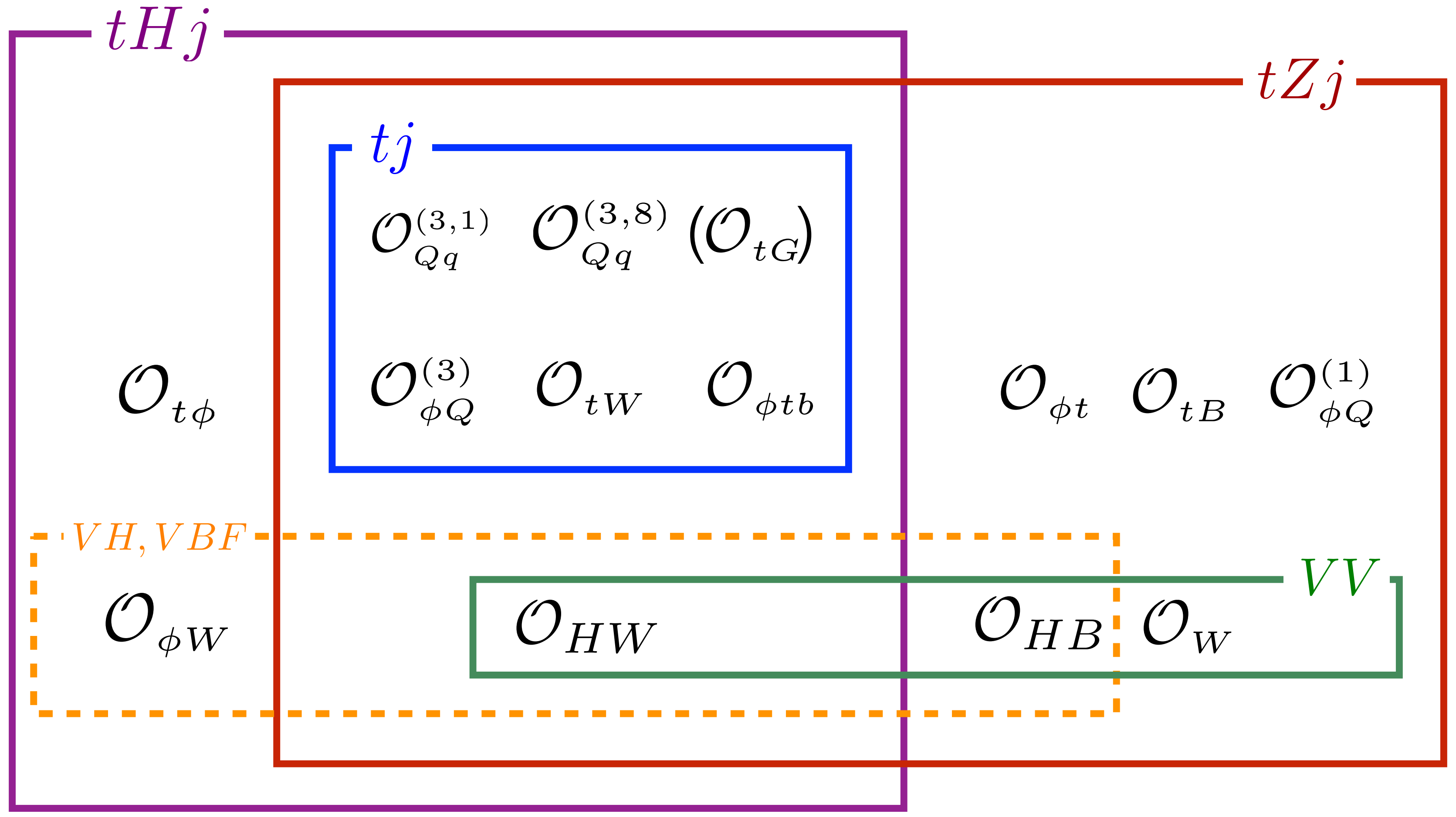
Everything is connected

Don't worry,
I am not going to speak to you about wormholes, time travel or other dimensions ..

Top, EW and Higgs sectors are all connected



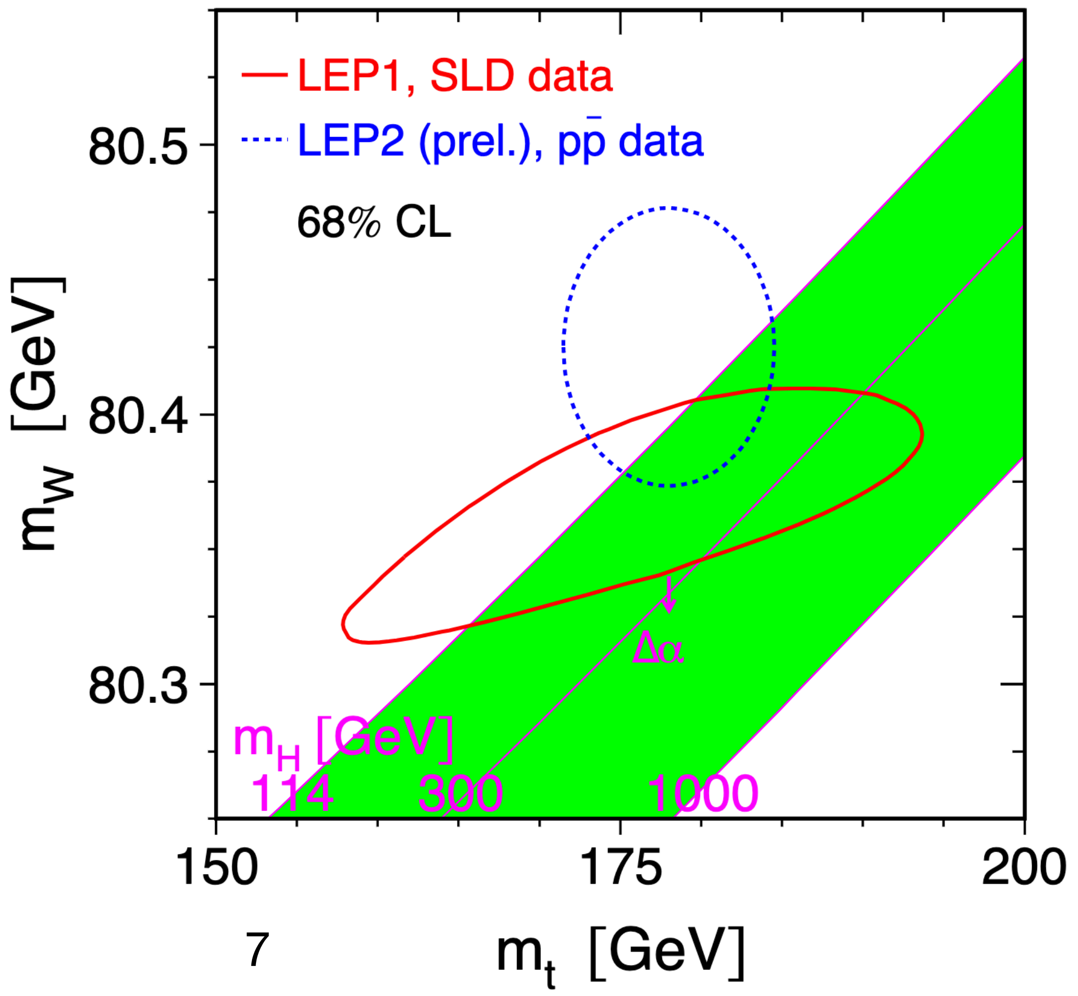
An EFT perspective on BSM (SMEFT)



New Physics in the Top sector has effects in the EW sector and vice versa.

Taken from *Degrande, Maltoni, Mimasu, Vryonidou, Zhang '18*

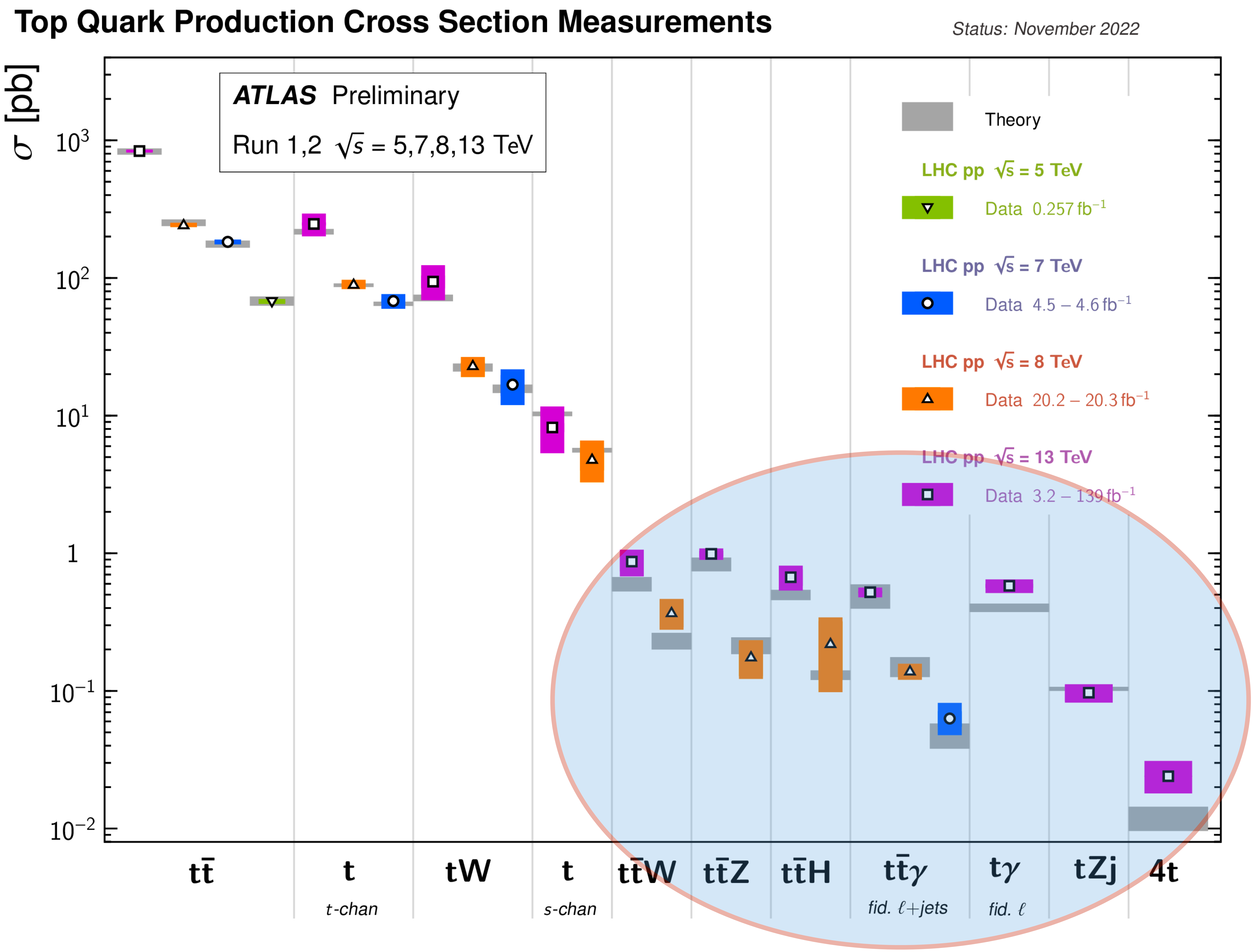
A SM (much older) perspective



SM as a QFT leads to relations between observables of the three different sectors: EW, Top, Higgs.

Taken from "Precision Electroweak Measurements on the Z Resonance", hep-ex/0509008

$t\bar{t}V, tV(j), t\bar{t}t\bar{t}$: the EW interacting tops

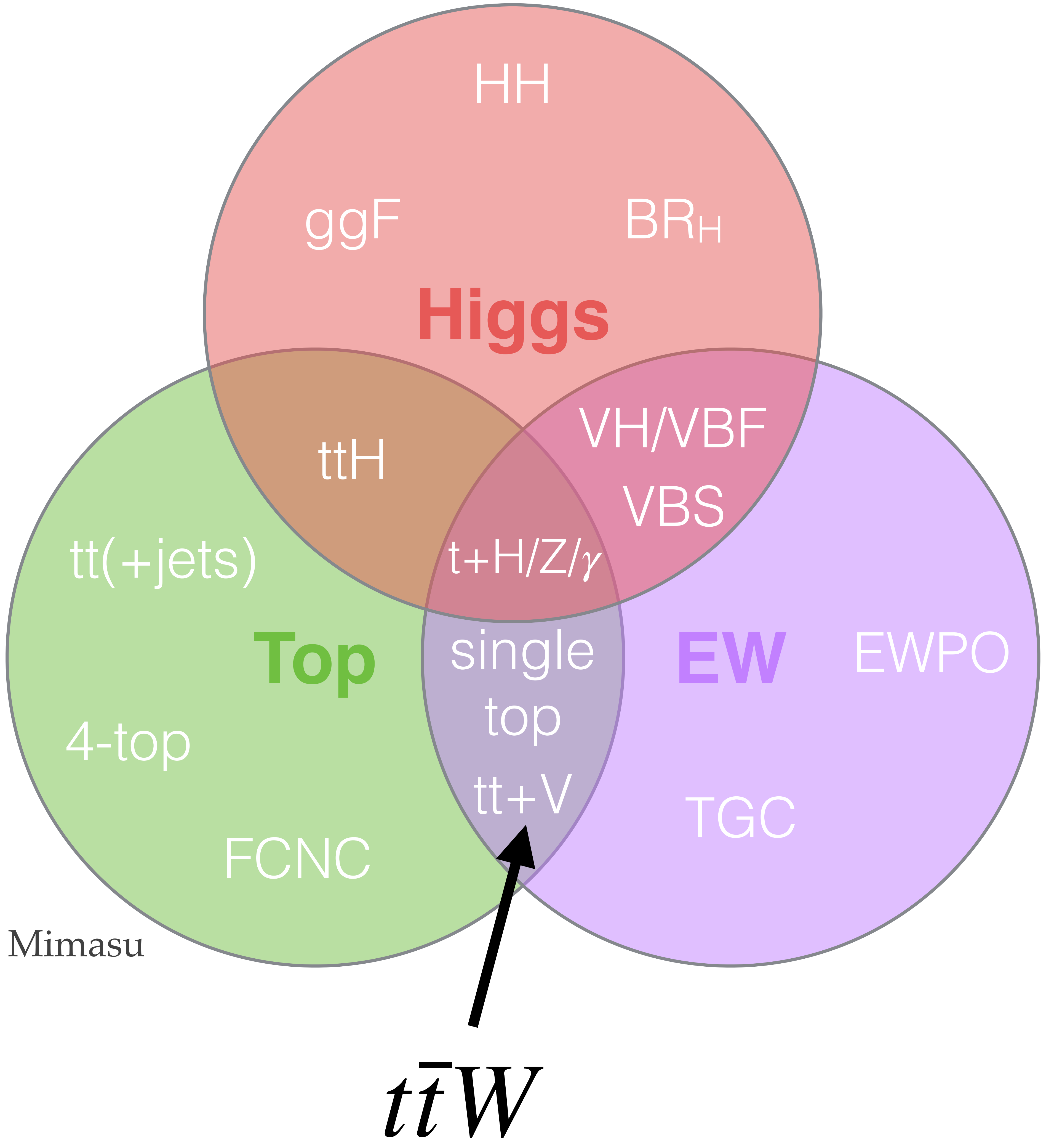


Cross sections are much smaller than in the case of $t\bar{t}$ and single top, but nevertheless they have already been measured.

They are crucial for characterising the interactions of the top quarks with the gauge bosons and the Higgs.

I will focus on them, with a particular attention on $t\bar{t}W$.

$t\bar{t}W$ as representative case



Interplays of different aspects:

- $t\bar{t}W$ is relevant as both signal and background to new physics or to other SM processes ($t\bar{t}H, t\bar{t}t\bar{t}$).
- $t\bar{t}W$ involves both the EW and top sectors.
- For $t\bar{t}W$, both QCD and EW corrections are relevant and mix one into the other.

So far, it is an NLO story:

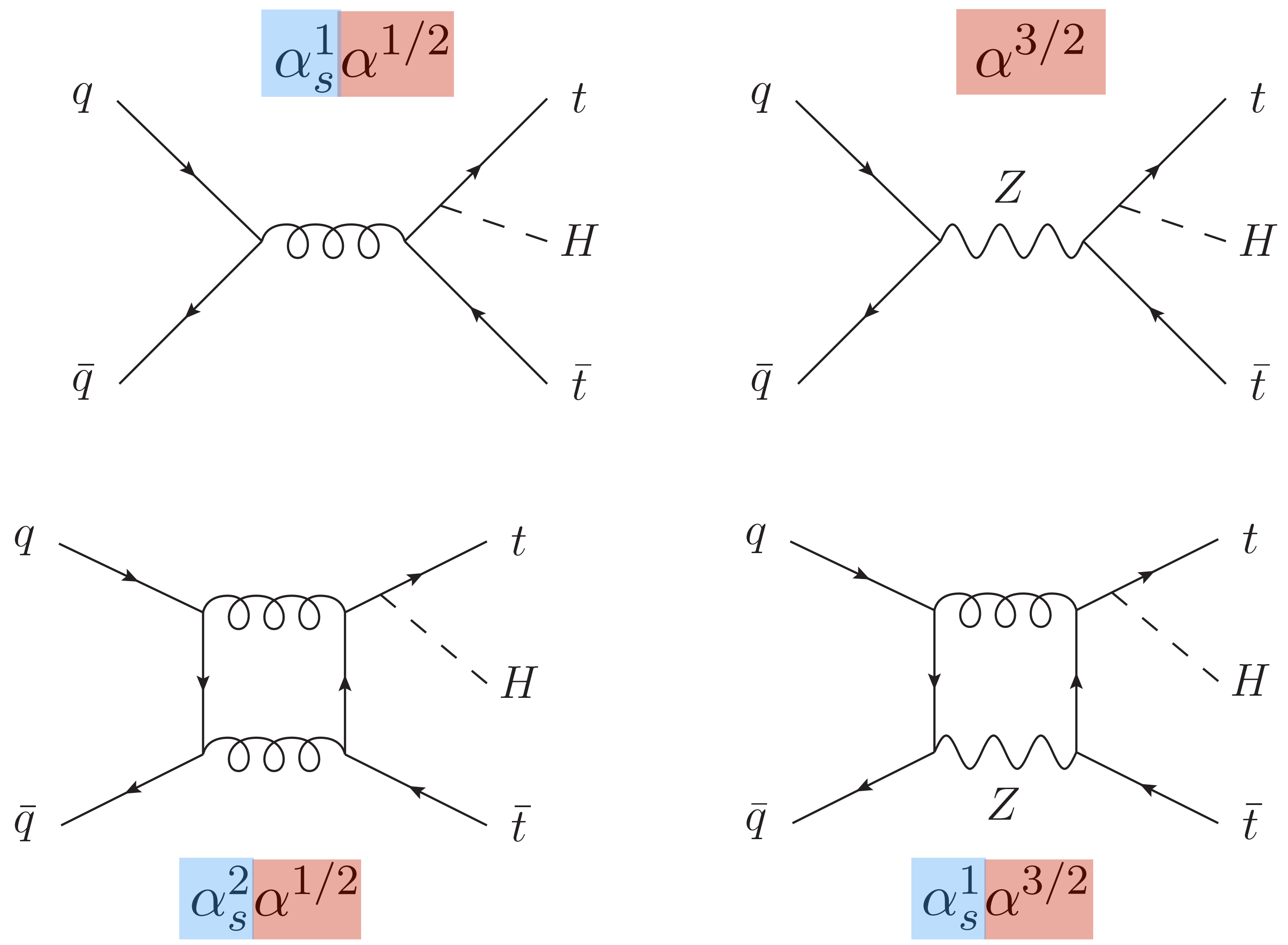
NNLO QCD is not yet available, but several different NLO calculations have been computed, involving different subtleties.

$t\bar{t}V$

NLO corrections

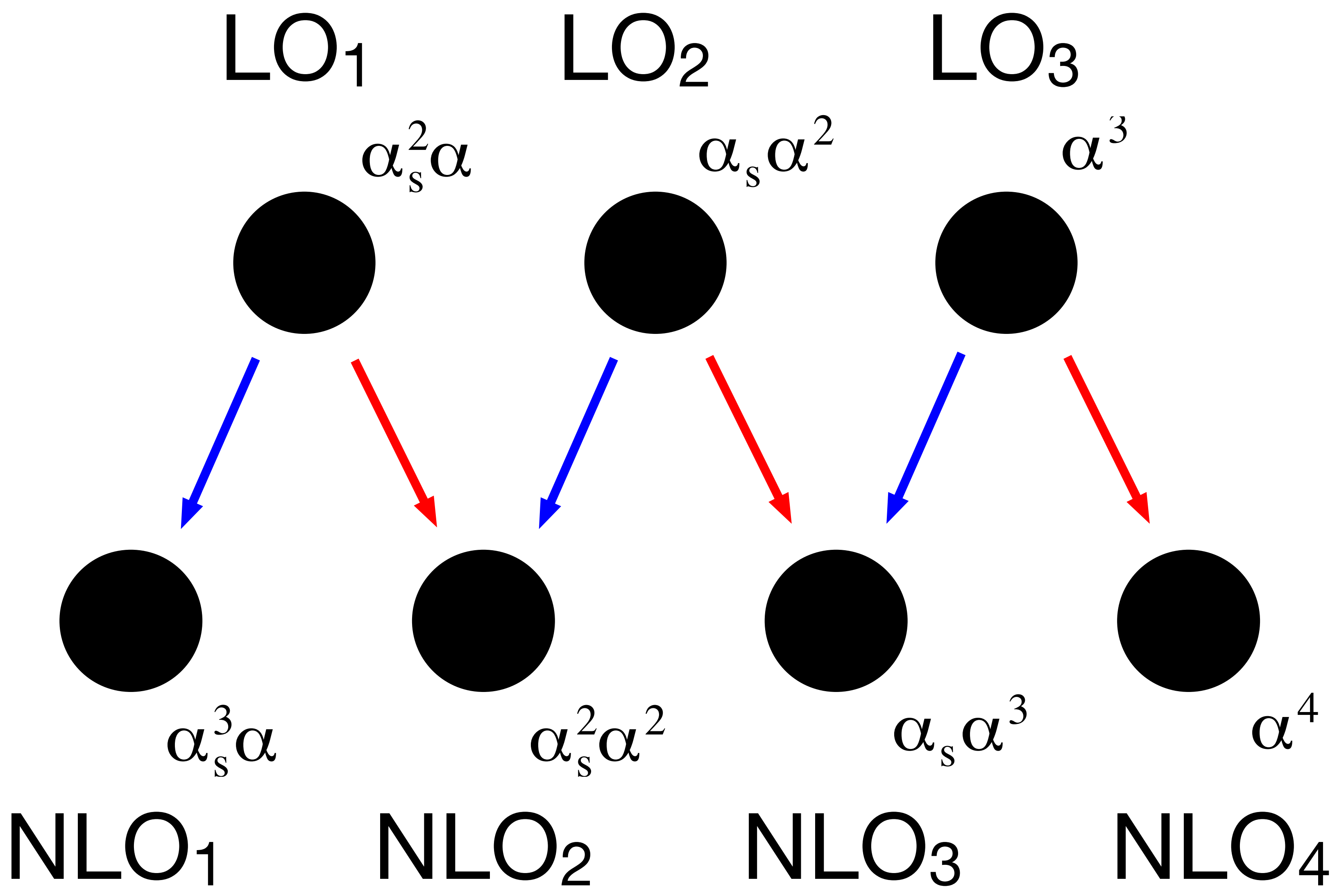
NLO QCD and EW corrections: the Complete-NLO

The complete set of $\mathrm{LO_i}$ and $\mathrm{NLO_i}$ is denoted as **“Complete NLO”**.



$t\bar{t}V$

(as example)



$\mathrm{NLO_1}$ = NLO QCD
$\mathrm{NLO_2}$ = NLO EW

In general, NLO,3 and NLO,4 sizes are **negligible,** **but there are exceptions.**

$t\bar{t}W$: one of the exceptions

13 TeV

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

Naive estimate

LO_2	10
LO_3	1
NLO_1	10
NLO_2	1
NLO_3	0.1

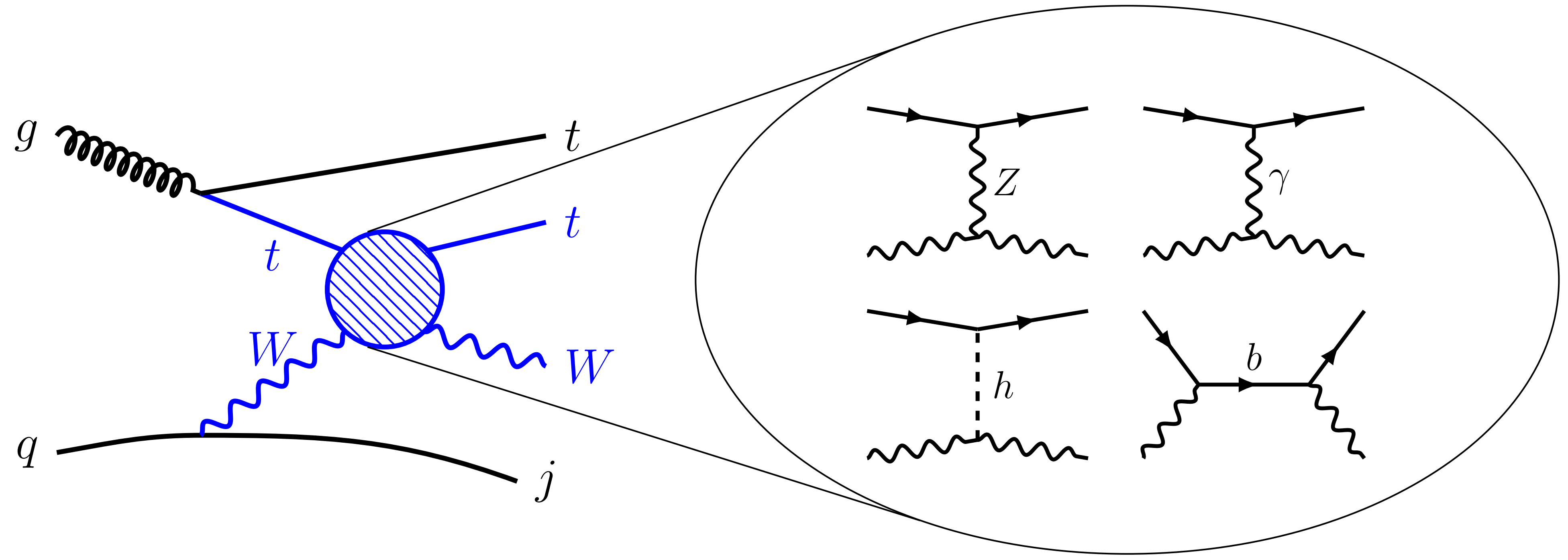
100 TeV

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

NLO3 is typically of the order 0.1%, while in the case of $t\bar{t}W$ is ~ 10 % at the LHC and even more at higher energies.

Number in parentheses refer to the case with a jet veto $p_T(j) > 100$ GeV and $|y(j) < 2.5|$

*Frederix, **DP**, Zaro '17*



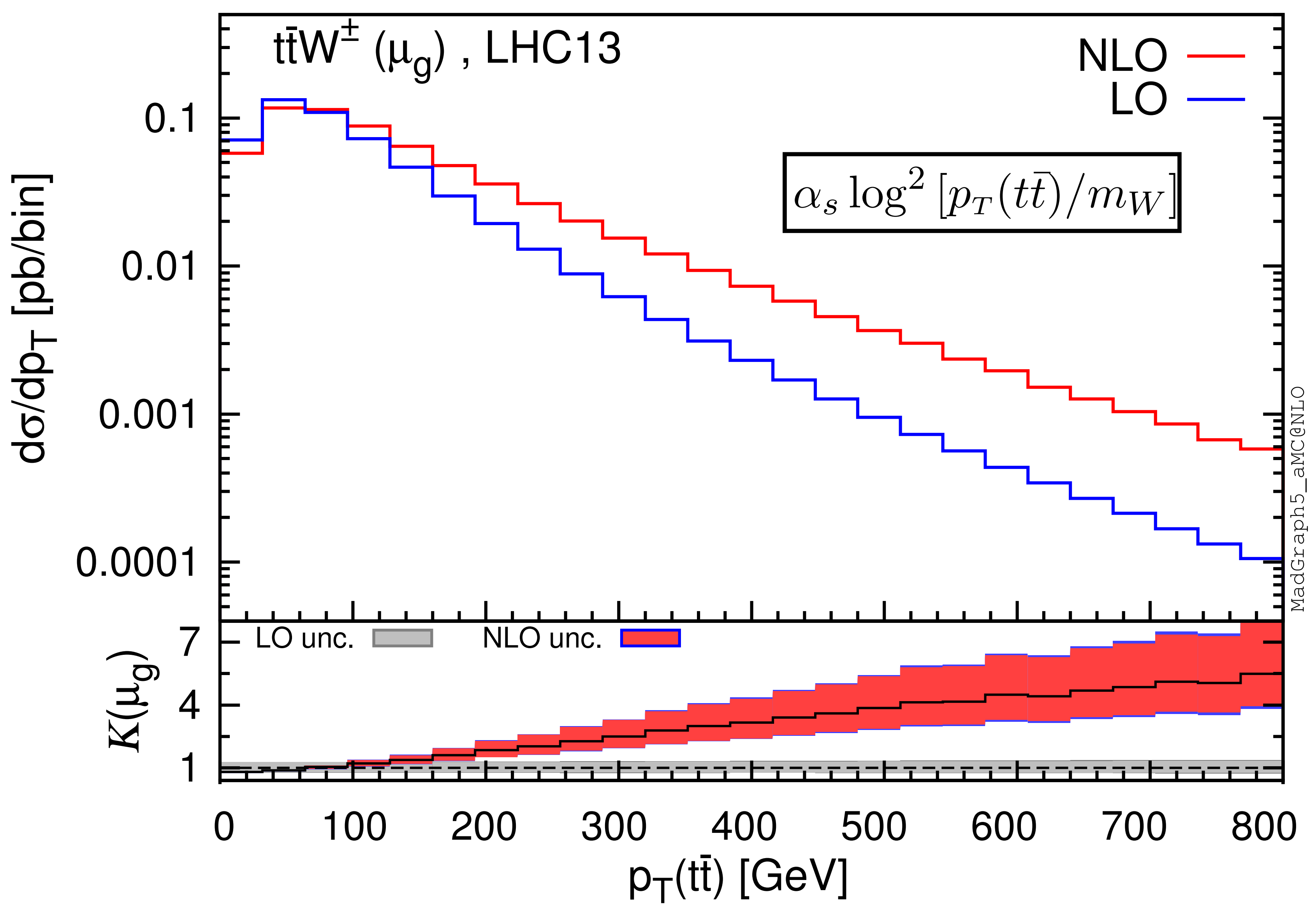
The origin of this effect is the opening of the $tW \to tW$ scattering diagram, which enters only at NLO3.

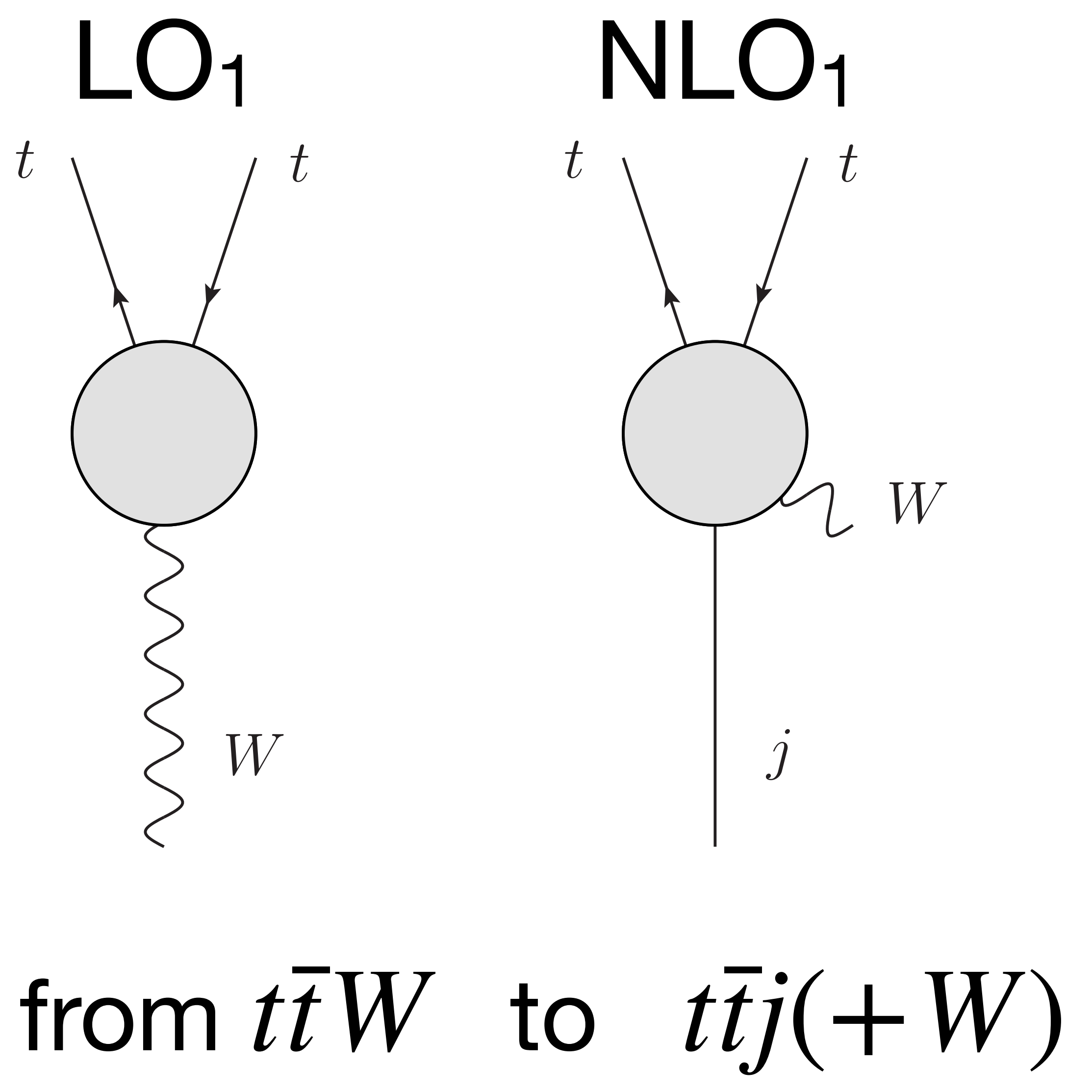
This effect is crucial for the correct description in the SM, but is is also sensitive to the SMEFT operator:

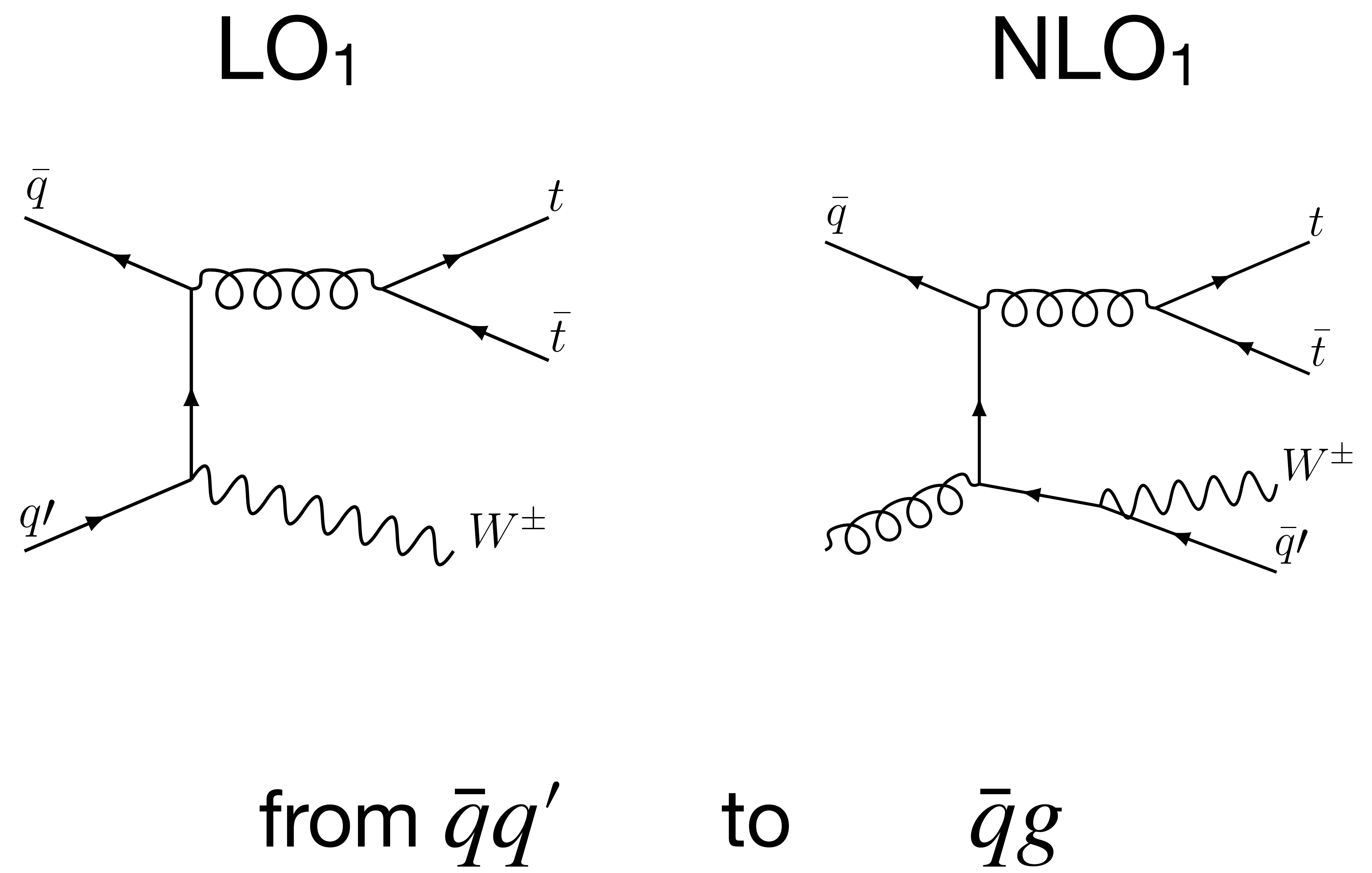
$$\frac{i\bar{c}_R}{v^2} H^\dagger \overleftrightarrow{D}_\mu H \bar{t}_R \gamma^\mu t_R$$

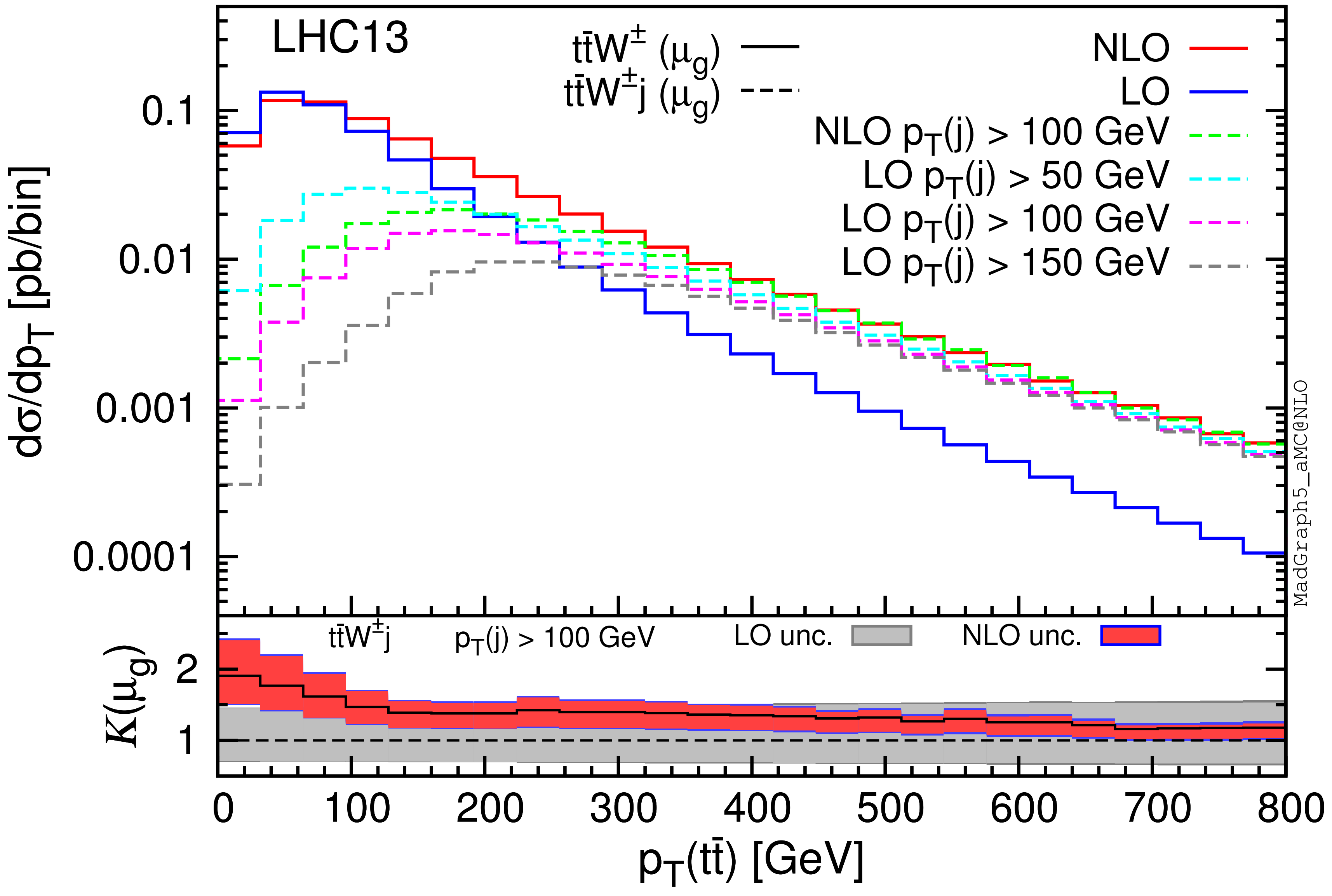
Dror, Farina, Salvioni, Serra '15

$t\bar{t}W$: already at NLO QCD peculiar behaviours









Giant K-factor: $\alpha_s \log^2\left(p_T(t\bar{t})/m_W\right)$

Take-home message:

QCD corrections are large and dominated by **hard QCD radiation (jet) and soft EW radiation (W).**

*Maltoni, **DP**, Tsinikos '15*
Garzelli, Kardos, Papadopoulos, Trocsanyi '12
Campbell, Ellis '12

$t\bar{t}W$ vs. $t\bar{t}Z$, $t\bar{t}\gamma$, $t\bar{t}H$ at 13 TeV

Complete NLO

(N)LO$_i$/ LO$_1$	LO$_2$	LO$_3$	NLO$_1$	NLO$_2$	NLO$_3$	NLO$_4$
ttW	-	1	49.5	-4.5	12.2	<0.01
ttH	0.4	0.7	28.9	1.8	0.5	<0.01
ttZ	-0.7	2.3	44.8	-0.8	0.8	<0.01
ttγ	0.2	1.1	58.6	-2.1	0.8	<0.01

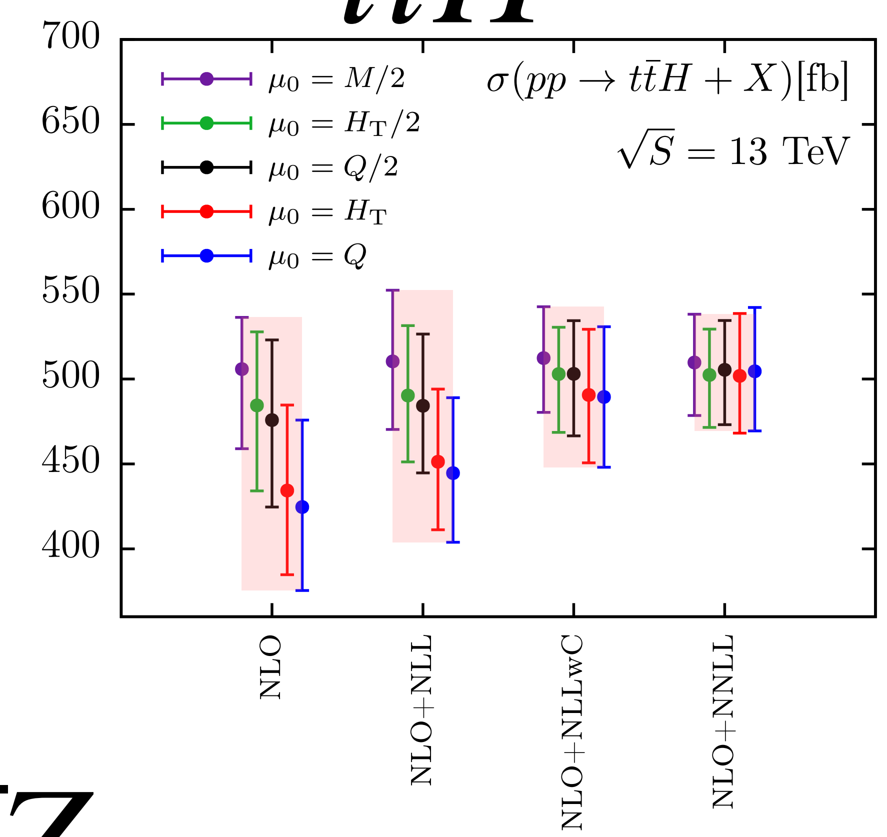
*Frixione, Hirschi, **DP**, Shao, Zaro '15*
*Frederix, **DP**, Zaro '18*
*Frederix, Frixione, Hirschi, **DP**, Shao, Zaro '18*
***DP**, Shao, Zaro '21*

Only $t\bar{t}W$ has this peculiar large NLO$_3$ corrections.

adding NNLL QCD resummation

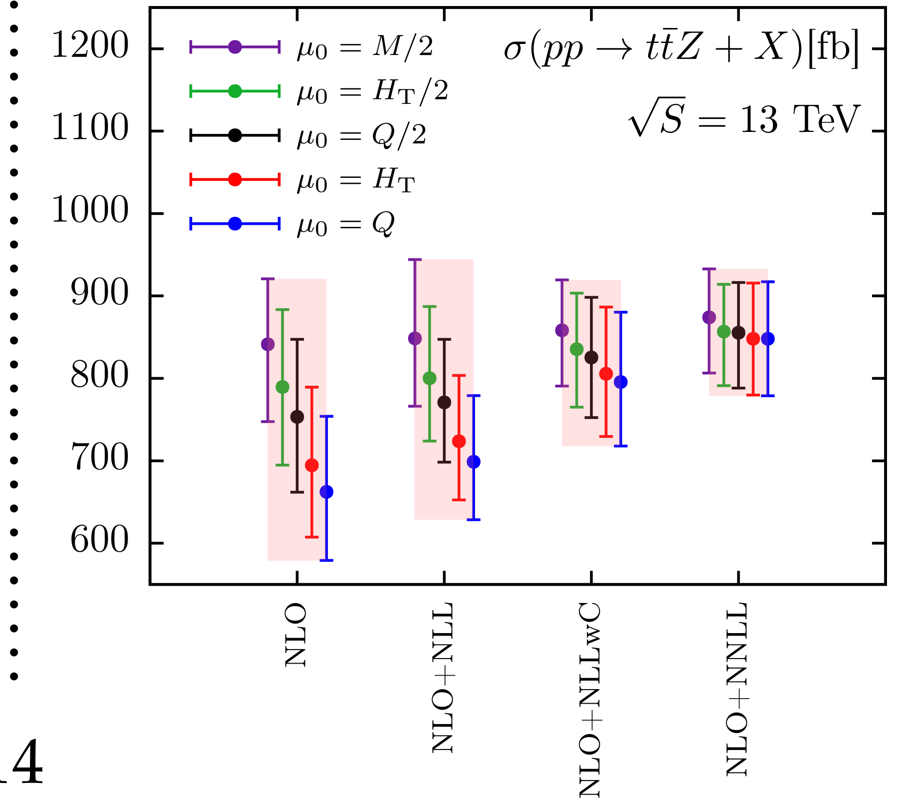
*Broggio, Ferroglia, Frederix, **DP**, Pecjak, Tsinikos '19*
Kulesza, Motyka, Schwartländer, Stebel, Theeuwes '20
based respectively on several Broggio et al. and Kulesza et al.

$t\bar{t}H$

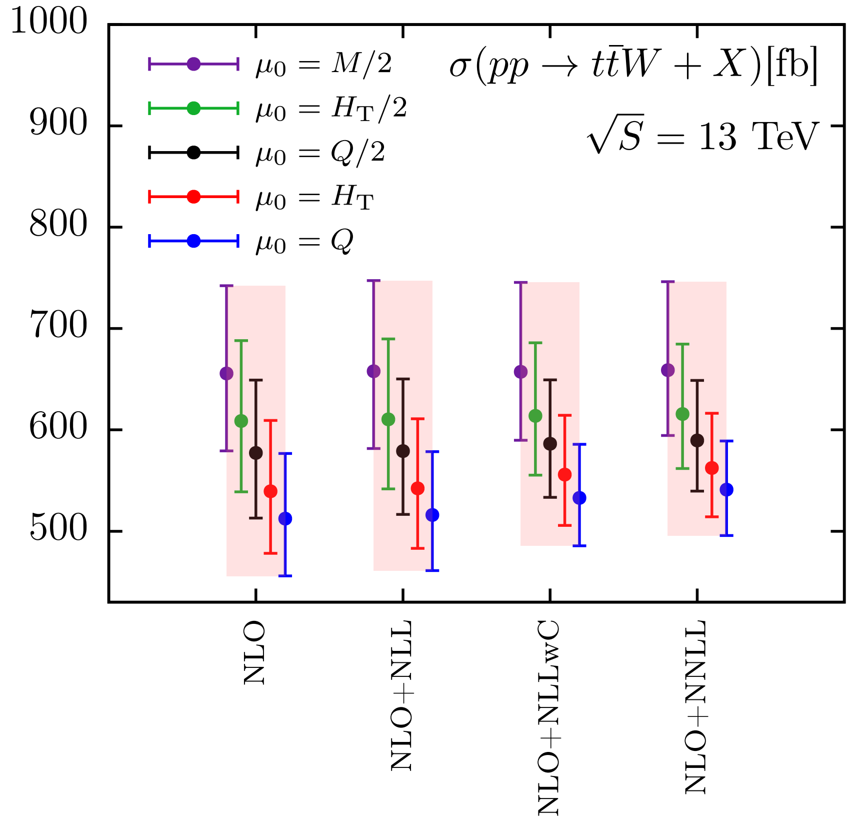


Only $t\bar{t}W$ is dominated by large QCD corrections from hard radiation.
Indeed, at variance with $t\bar{t}Z$ and $t\bar{t}H$, resummation does not decrease uncertainties.

$t\bar{t}Z$

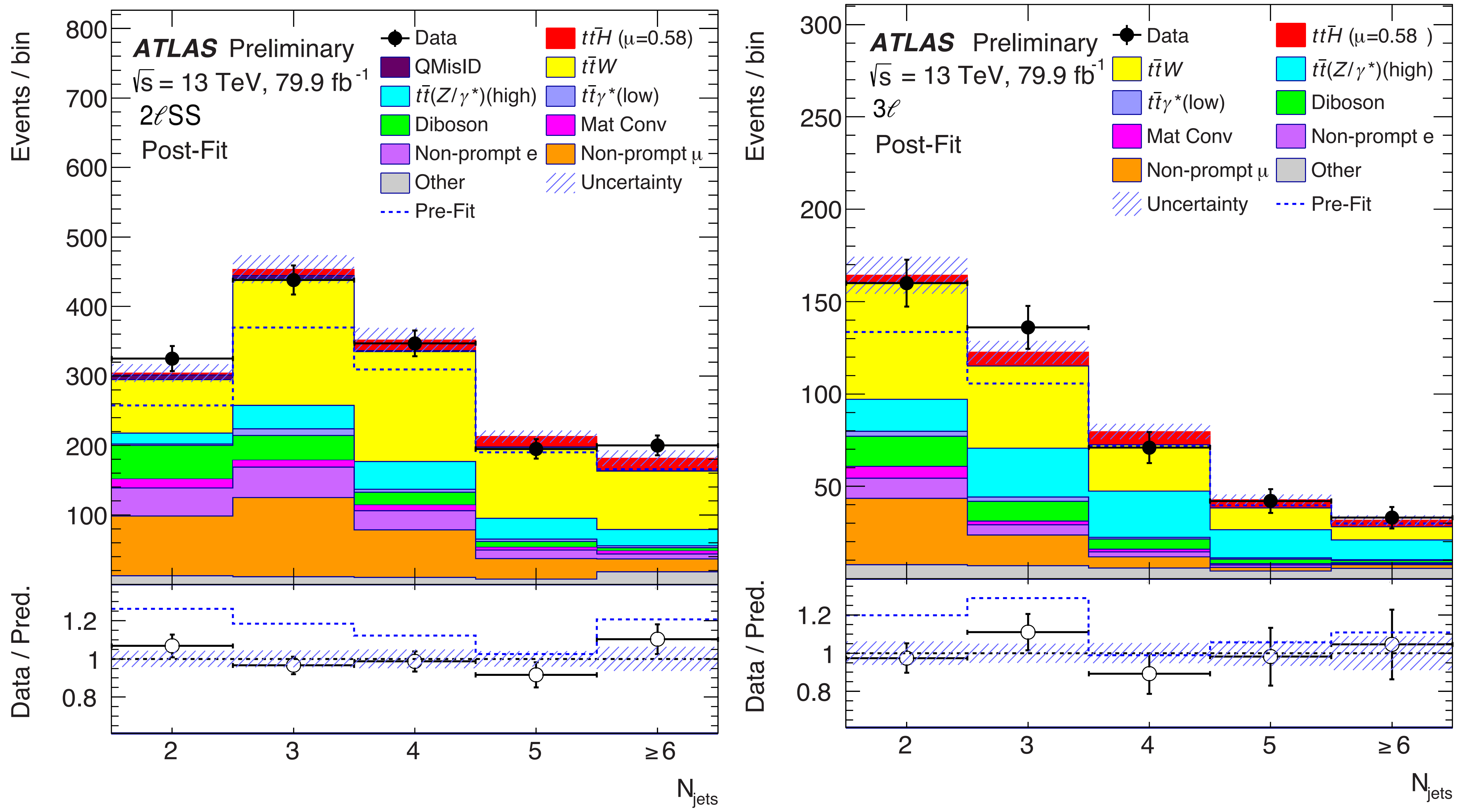


$t\bar{t}W$



$t\bar{t}W$ also special for the experiment ($t\bar{t}H$ bkg.)

Analysis of $t\bar{t}H$ and $t\bar{t}W$ production in multilepton final states with the ATLAS detector



ATLAS CONF Note

ATLAS-CONF-2019-045

The $t\bar{t}W$ background represents the dominant background particularly in the 2ℓSS and 3ℓ channels across multiple event categories, which span a wide range of kinematic regimes. Despite the use of the state-of-art simulations, the accurate modelling of additional QCD radiation in $t\bar{t}W$ production remains challenging. Categories sensitive to the $t\bar{t}W$ background have been introduced to the analysis to study and constrain this background. The jet multiplicity distributions in the 2ℓSS and 3ℓ channels after event selection are shown in Figure 1. Disagreements between the data and the prefit prediction from the simulation are observed. To minimise the dependence of the $t\bar{t}H$ signal extraction on the $t\bar{t}W$ prediction, three independent normalisation factors for the $t\bar{t}W$ background are considered in the likelihood fit: two corresponding to the LJ and HJ categories of the 2ℓSS channel, and one corresponding to the 3ℓ channel categories. The measured normalisation factors are: $\hat{\lambda}^{2\ell\text{LJ}}_{t\bar{t}W} = 1.56^{+0.30}_{-0.28}$, $\hat{\lambda}^{2\ell\text{HJ}}_{t\bar{t}W} = 1.26^{+0.19}_{-0.18}$, and $\hat{\lambda}^{3\ell}_{t\bar{t}W} = 1.68^{+0.30}_{-0.28}$. The

It was manifest also from the data that QCD radiation modelling for $t\bar{t}W$ had to be improved.

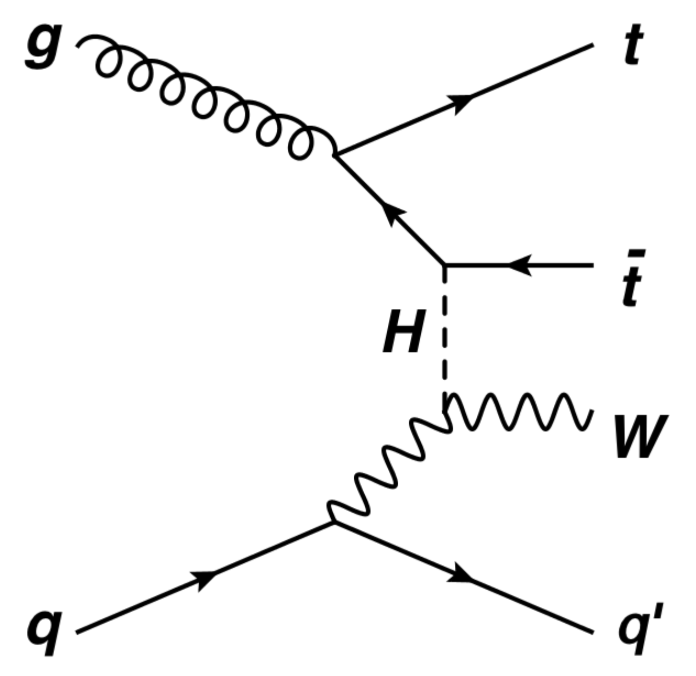
1st Step: Complete NLO + PS

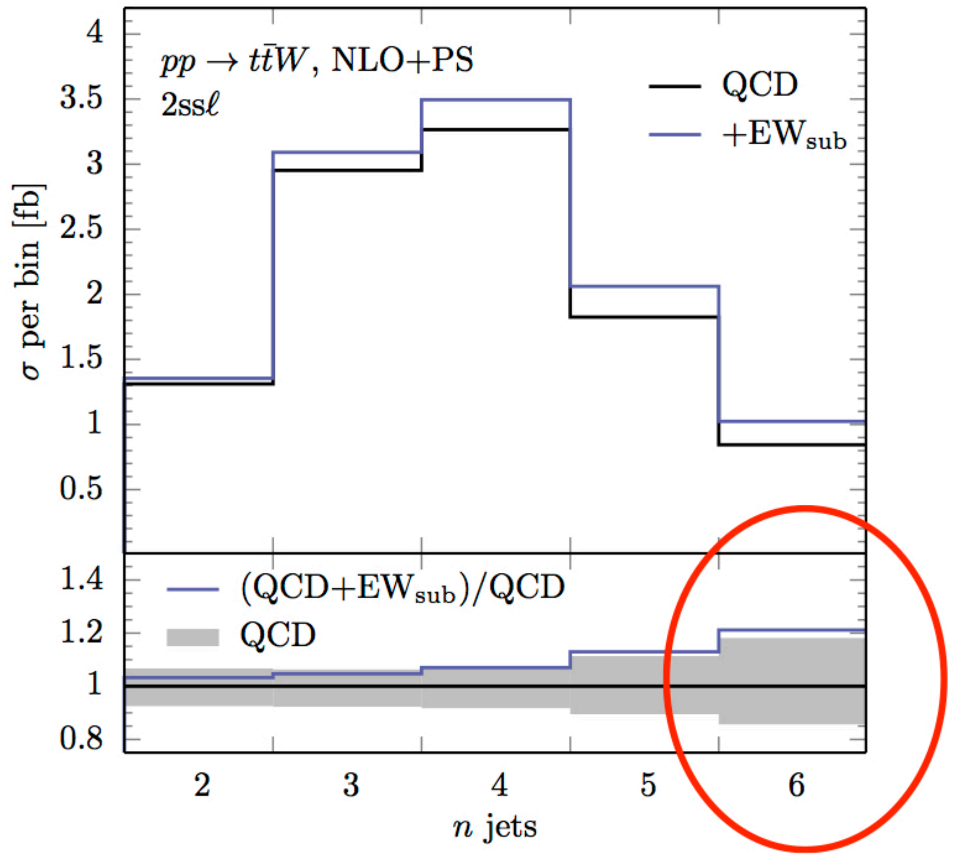
Frederix, Tsinikos `20;* *Febres Cordero, Kraus, Reina `21

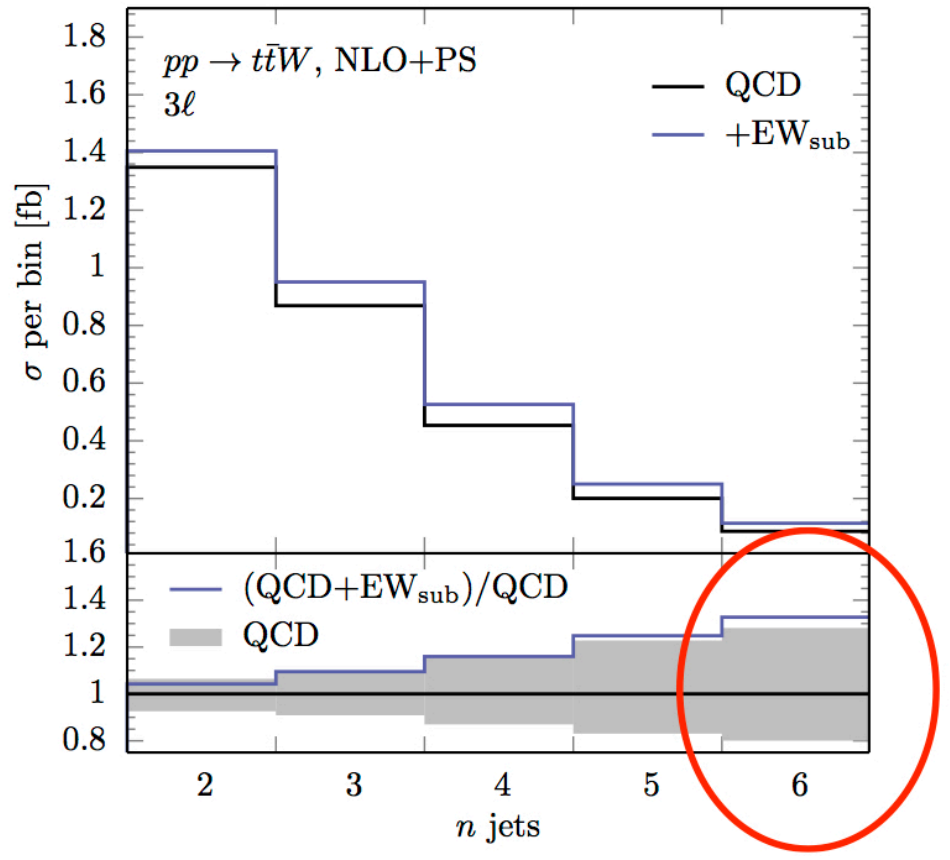
1st Step: Complete NLO + PS

Differential distributions in multilepton signatures (2ssℓ, 3ℓ)

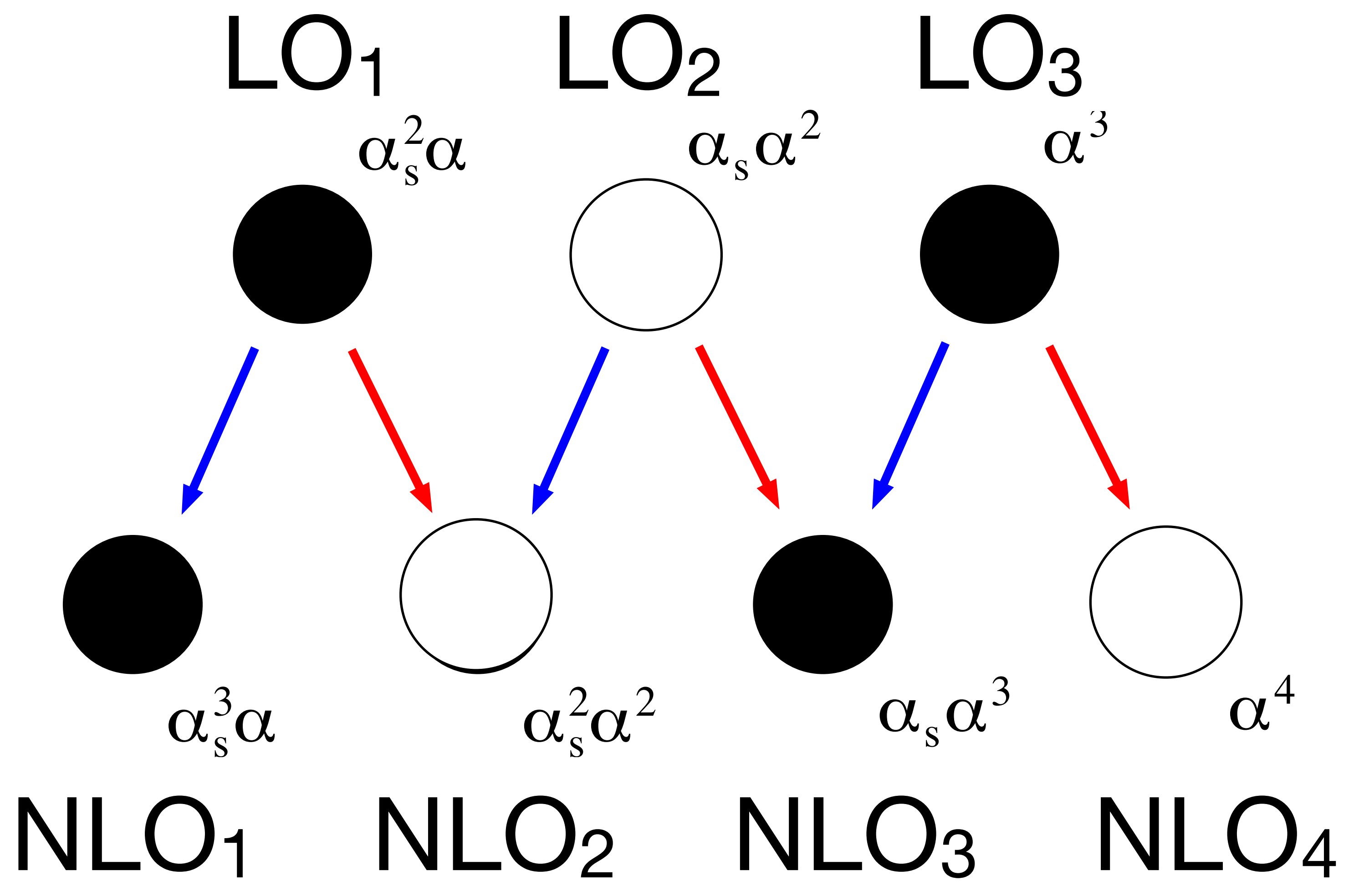
- EW_{sub} structure
  - Extra parton
  - Extra source of radiation
  - Different kinematics
  - Different spin correlations
- Jet multiplicities (large effect at high n)







- Non flat K-factor
- Enhancement of the tails



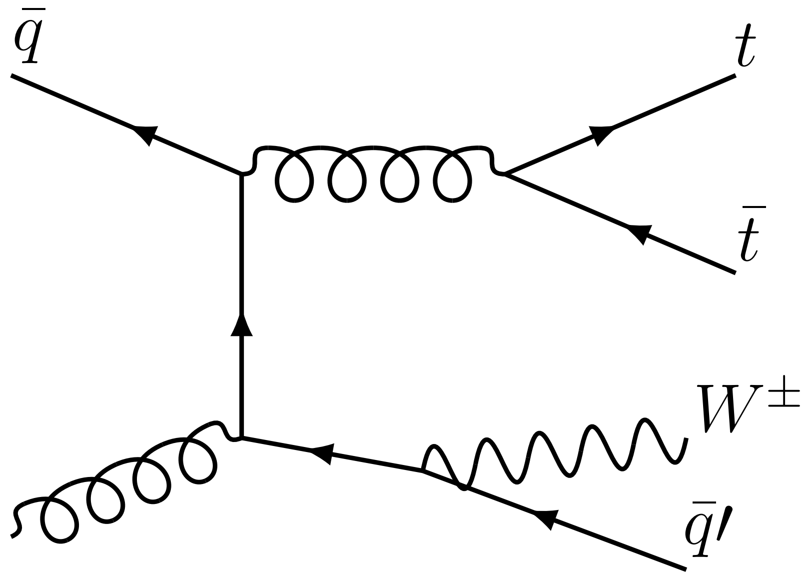
$LO_1 + NLO_1 + LO_3 + NLO_3 = NLO_{QCD} + EW_{sub}$

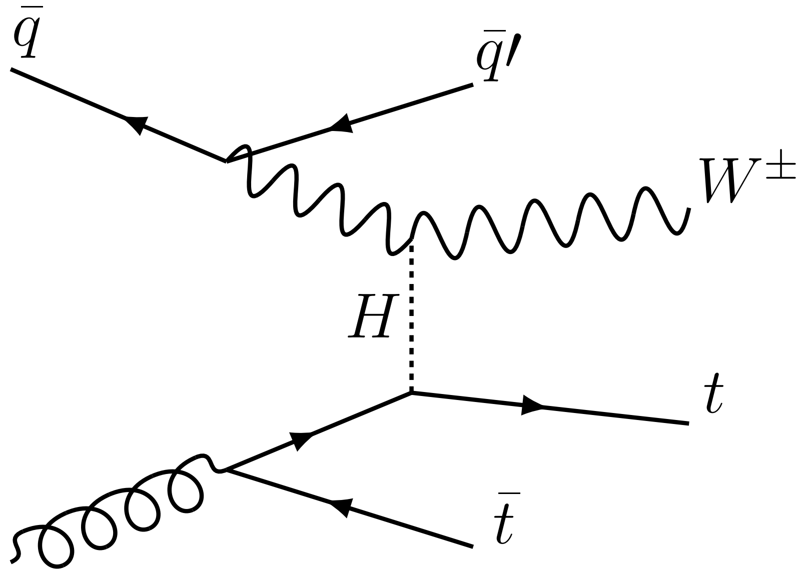
The large component of the Complete NLO, $NLO_{QCD} + EW_{sub}$, plus the parton shower gives new contributions.

Frederix, Tsinikos `20

Slide taken from I. Tsinikos' talk at LHCP2020

2nd Step: improve the merging recipe



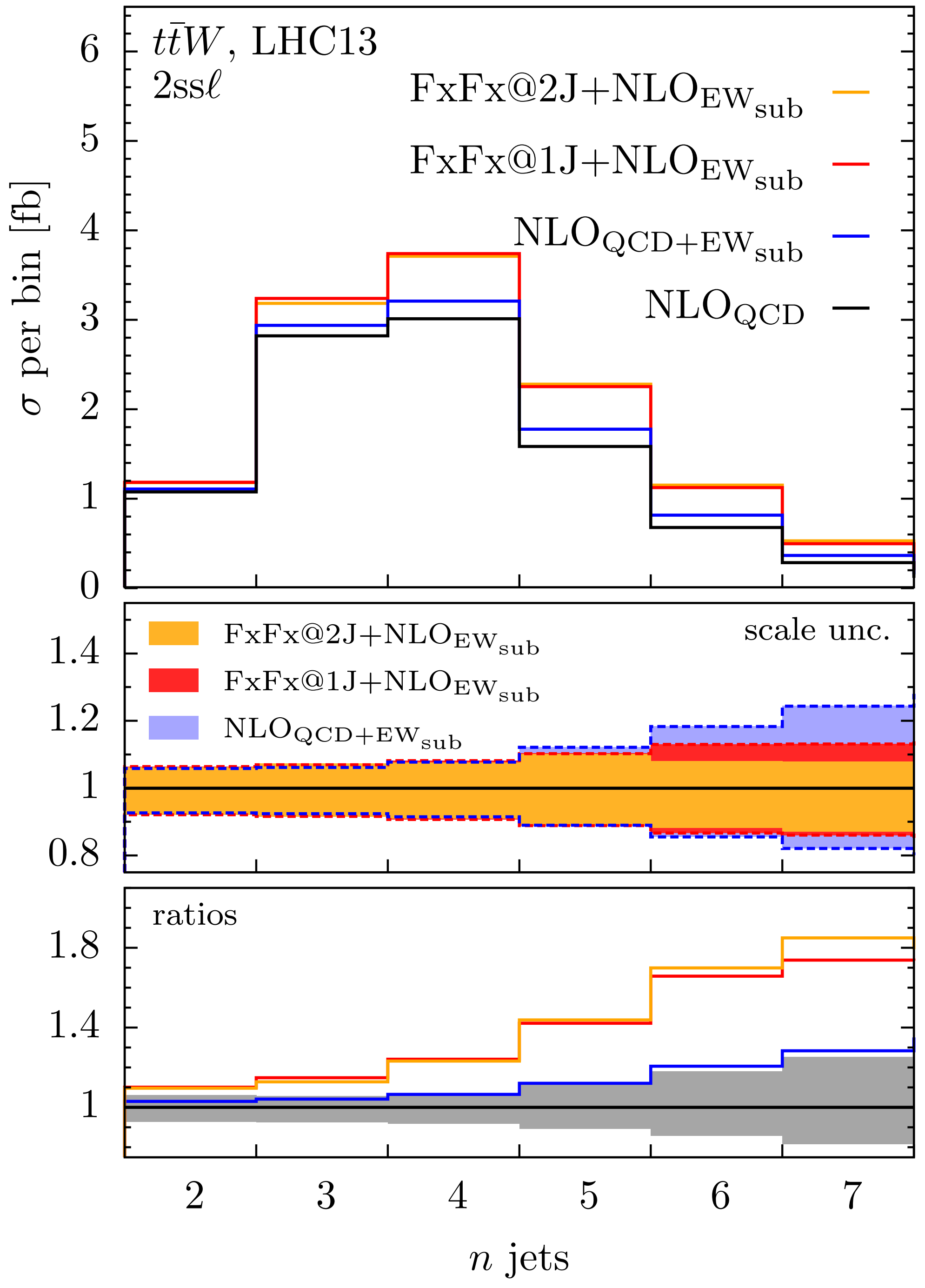


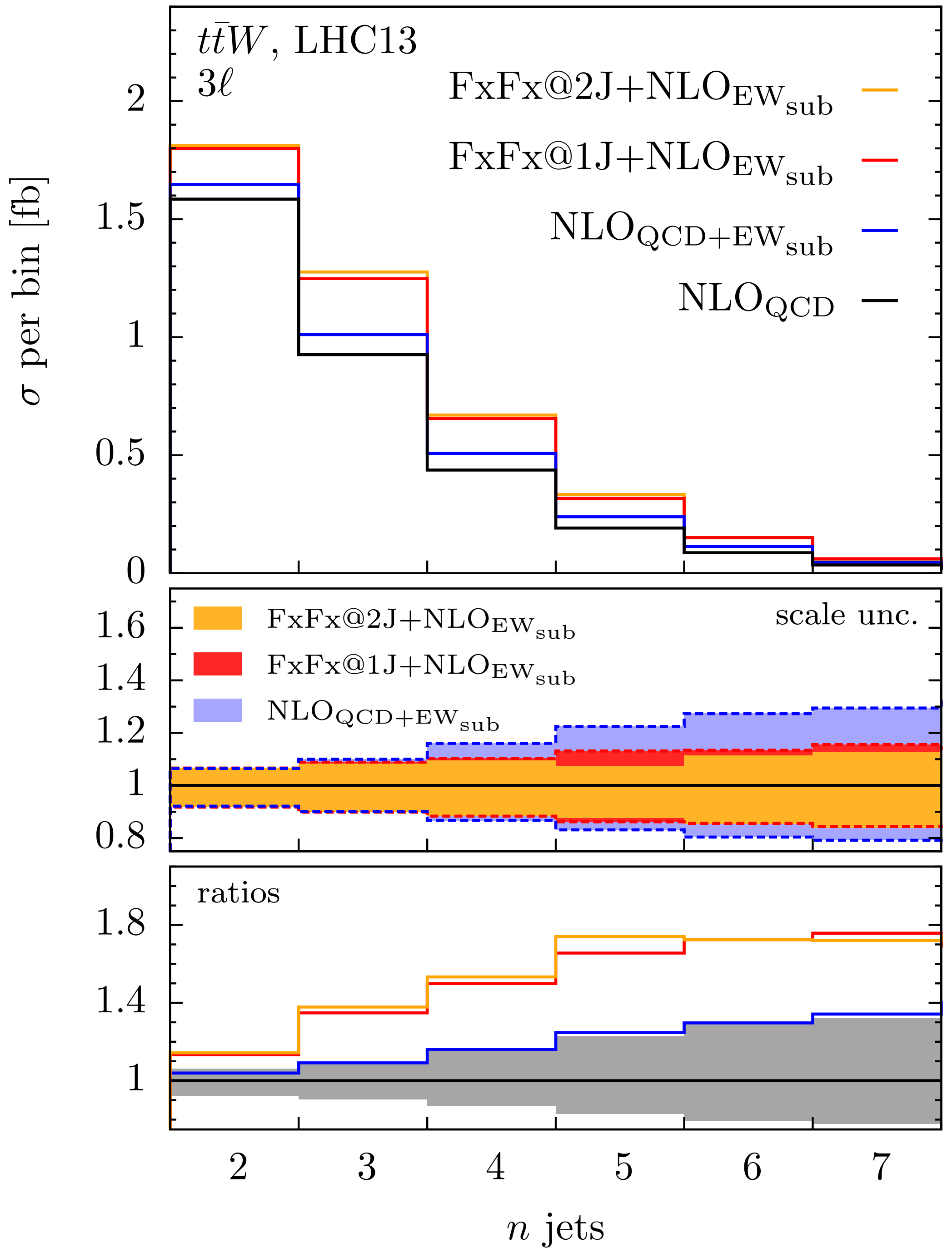
Frederix, Tsinikos `21

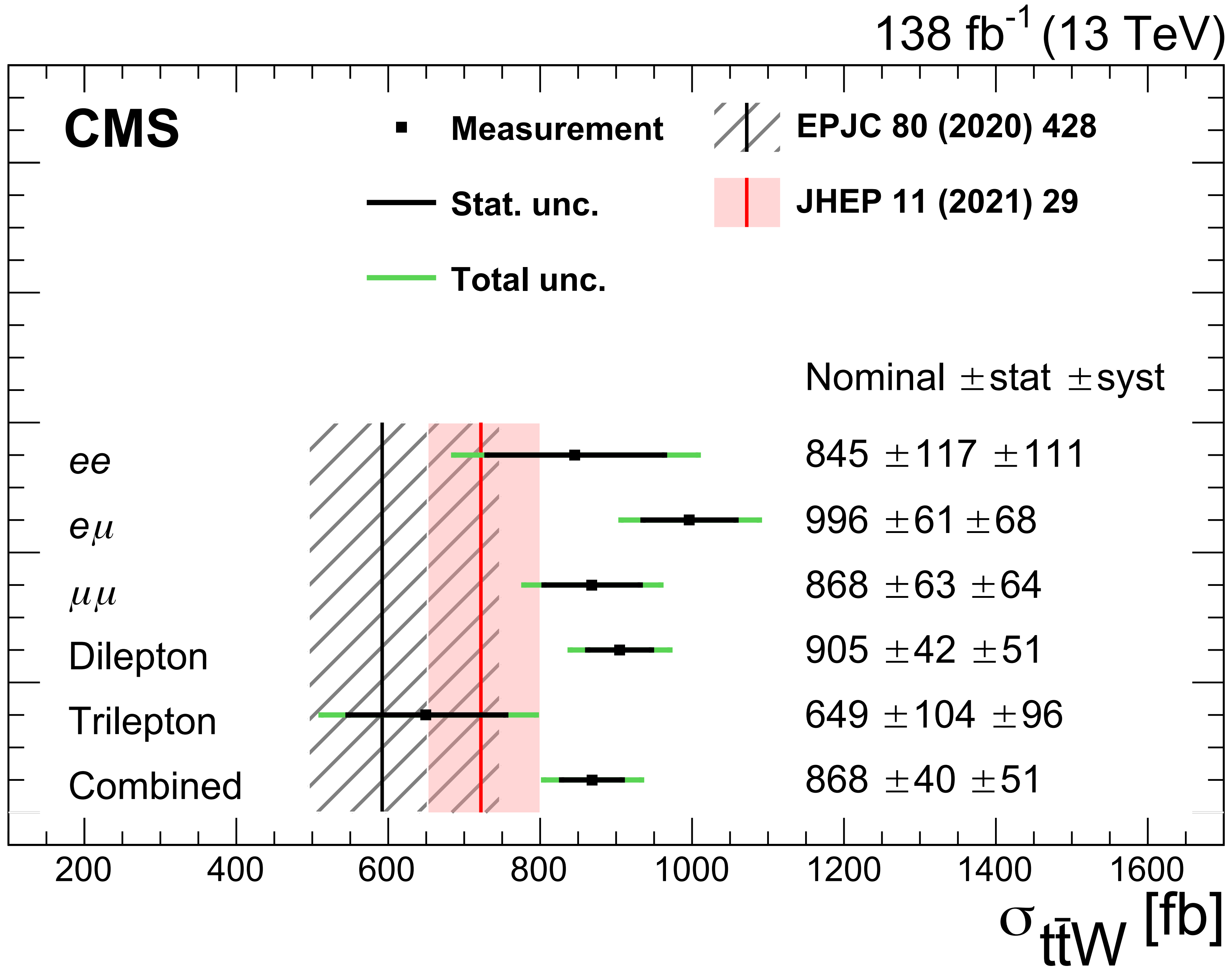
New FxFx merging strategy:

If a quark stems from a $q \to q' W$ splitting, it should be treated differently than QCD jets.

Much less dependence on the merging scale and better description of QCD radiation.







NLO off-shell with $t\bar{t}$ leptonic signature

$t\bar{t}H$

NLO QCD: *Denner, Feger '15*

NLO QCD+EW: *Denner, Pellen '17*

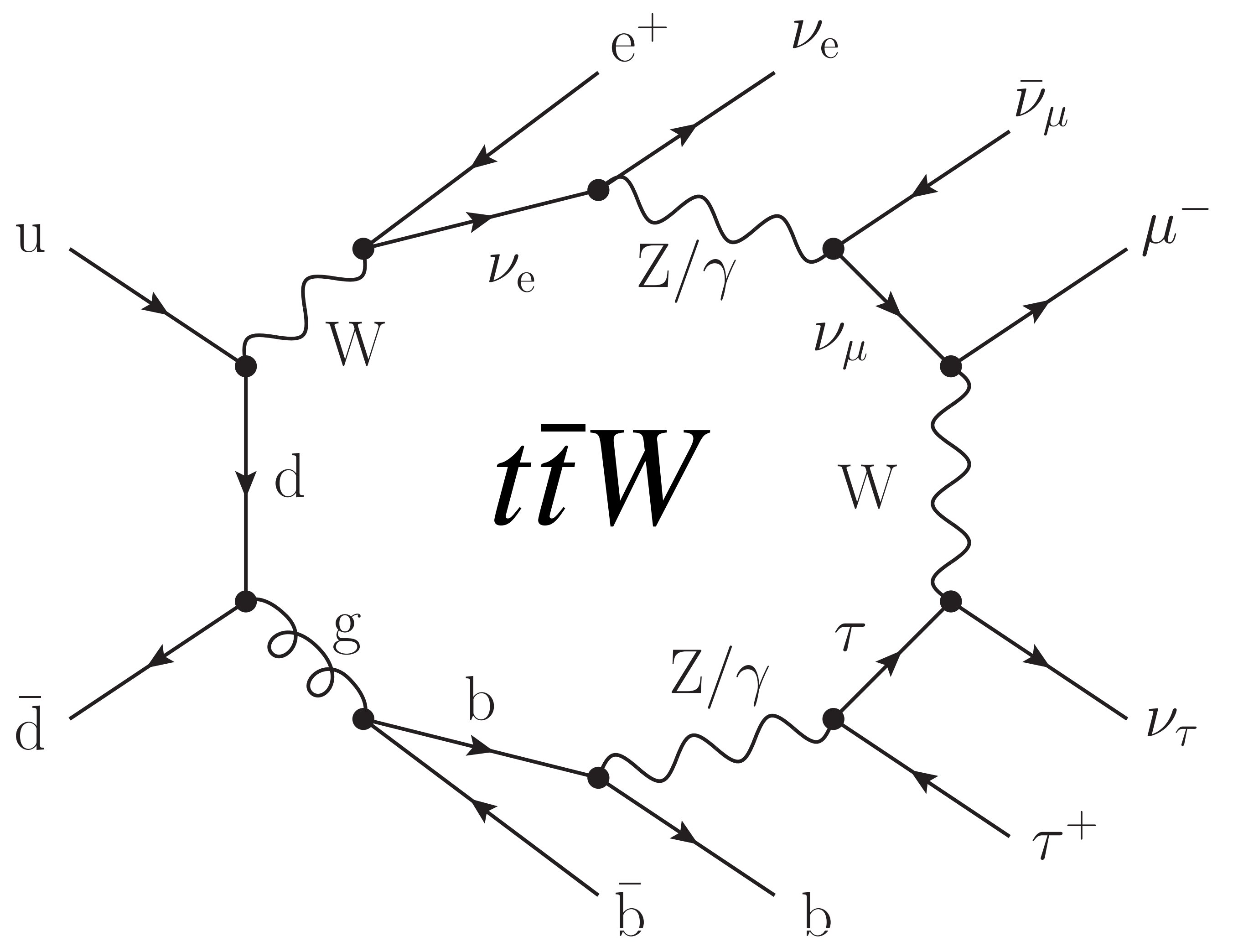
$t\bar{t}Z\ (Z \to \nu_\ell \bar{\nu}_\ell / \ell^+\ell^-)$

NLO QCD: *Bevilacqua, Hartanto, Kraus, Weber, Worek '19, Bevilacqua, Hartanto, Kraus, Nasufi, Worek '22*

$t\bar{t}W\ (W^+ \to \ell^+ \nu_\ell)$

NLO QCD: *Bevilacqua, Bi, Hartanto, Kraus, Worek '20; Denner, Pellicciolі '20*

Complete NLO: *Denner, Pellicciolі ' 21*



Example of non-resonant contribution to one of the $t\bar{t}W$ signatures.

$t\bar{t}\gamma$

NLO QCD: *Bevilacqua, Hartanto, Kraus, Worek '18 and '20*

General comment: very complicated $2 \to 7$ or even $2 \to 8$ calculations.
Results are tremendously important when the off-shell region of one, and especially more than one, particles among tops or V are probed. Otherwise, ***on-shell Narrow-Width Approximation (NWA) is doing fine.***

Off-shell results

$t\bar{t}W$

Modelling Approach	$\sigma^{\rm LO}$ [ab]	$\sigma^{\rm NLO}$ [ab]
full off-shell ($\mu_0 = m_t + m_W/2$)	$106.9^{+27.7\,(26\%)}_{-20.5\,(19\%)}$	$123.2^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
full off-shell ($\mu_0 = H_T/3$)	$115.1^{+30.5\,(26\%)}_{-22.5\,(20\%)}$	$124.4^{+4.3\,(3\%)}_{-7.7\,(6\%)}$
NWA ($\mu_0 = m_t + m_W/2$)	$106.4^{+27.5\,(26\%)}_{-20.3\,(19\%)}$	$123.0^{+6.3\,(5\%)}_{-8.7\,(7\%)}$
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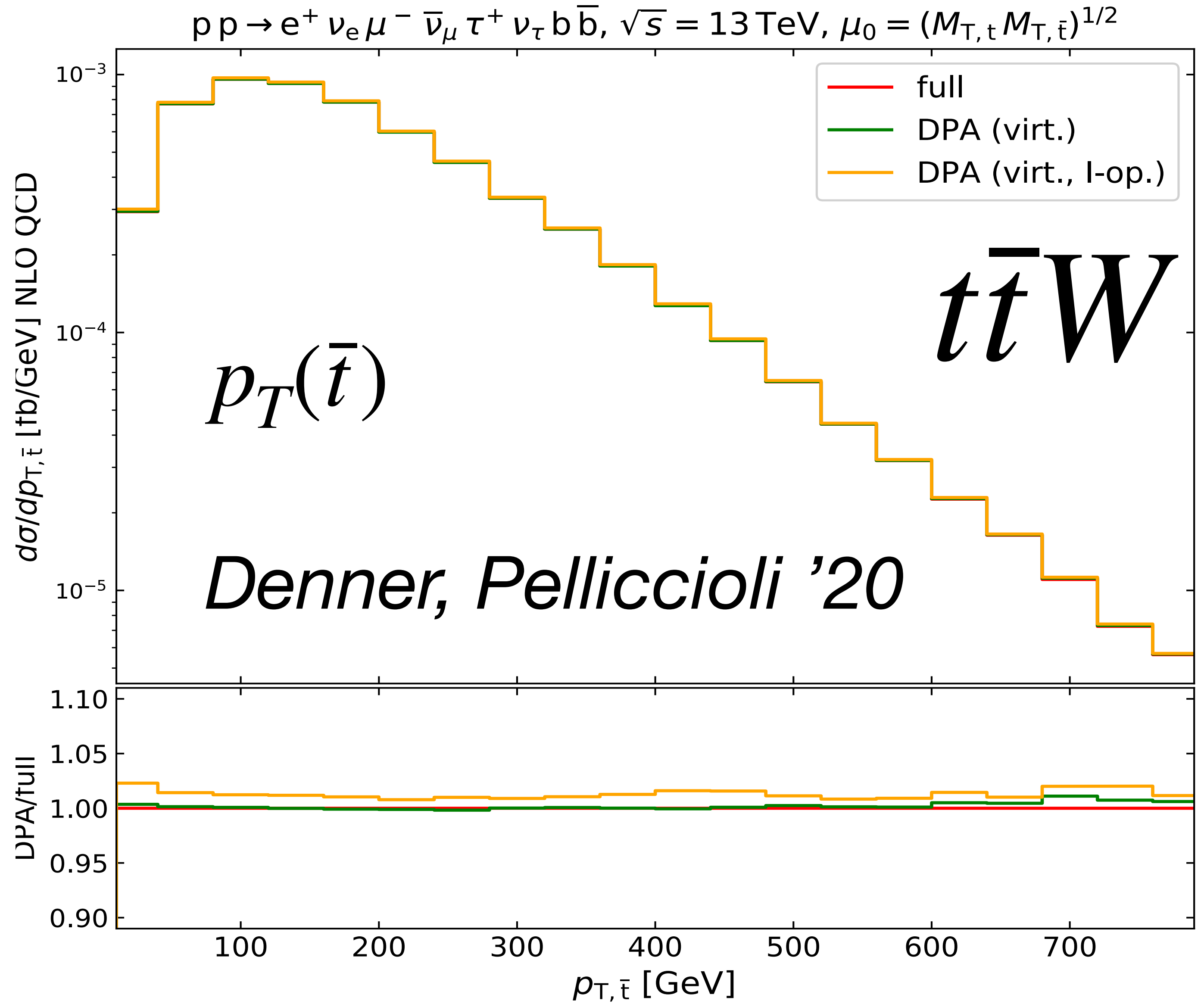
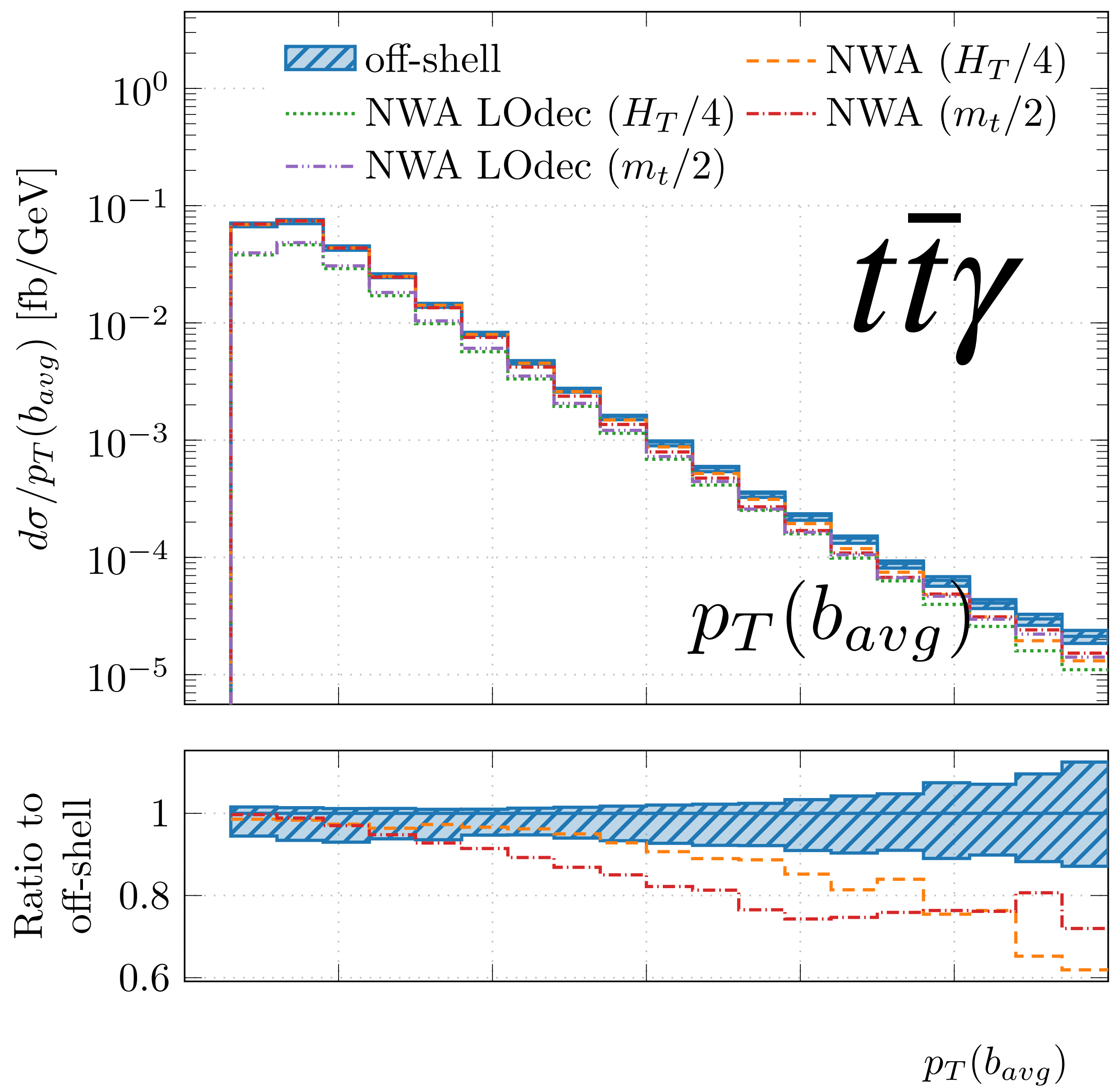
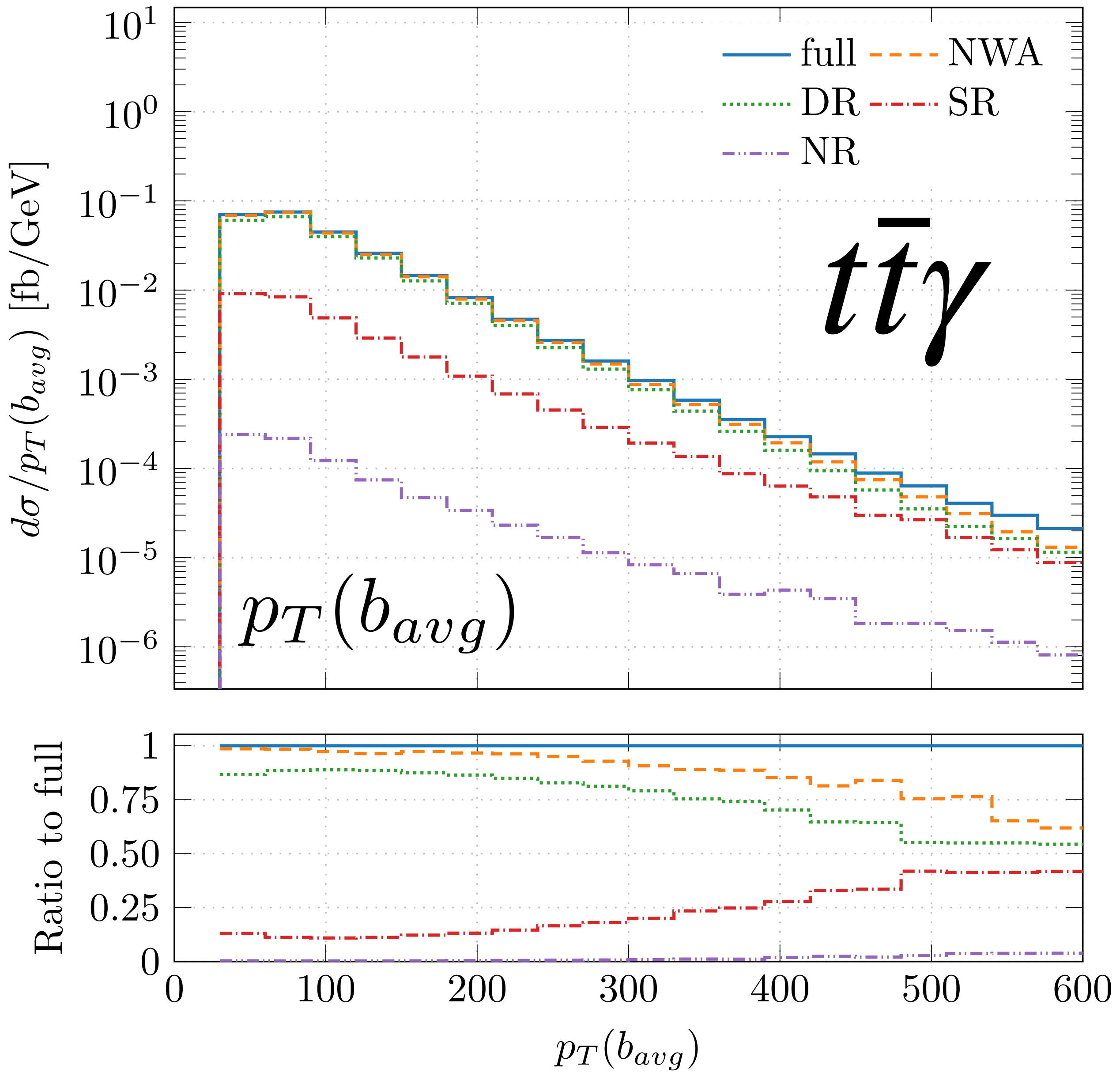
Bevilacqua, Bi, Hartanto, Kraus, Worek '20





If off-shell corrections are large, it means that different topologies (single-resonant, or non-resonant) become relevant.

Bevilacqua, Bi, Hartanto, Kraus, Worek '20



What about NNLO? first results for $t\bar{t}H$

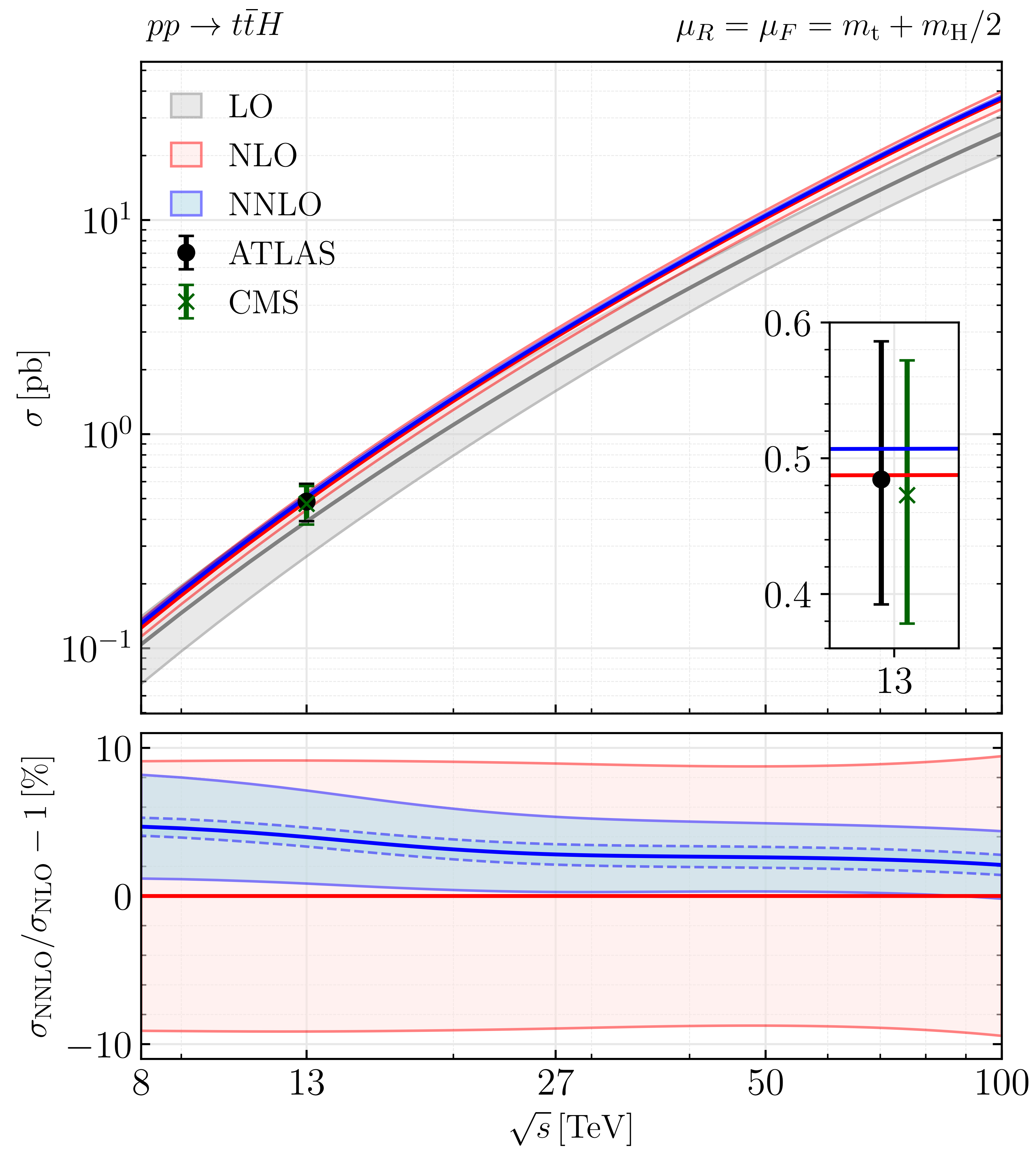
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini '22

	$\sqrt{s} = 13\,\text{TeV}$		$\sqrt{s} = 100\,\text{TeV}$	
σ [fb]	gg	$q\bar{q}$	gg	$q\bar{q}$
σ_{LO}	261.58	129.47	23055	2323.7
$\Delta\sigma_{\text{NLO,H}}$	88.62	7.826	8205	217.0
$\Delta\sigma_{\text{NLO,H}}\|_{\text{soft}}$	61.98	7.413	5612	206.0
$\Delta\sigma_{\text{NNLO,H}}\|_{\text{soft}}$	$-2.980(3)$	$2.622(0)$	$-239.4(4)$	$65.45(1)$

Calculation performed for the total cross section, in the limit of soft-Higgs *for the two-loop amplitude only*.

Taking into account uncertainty from this approximation at NLO, NNLO result leads to a consistent reduction of scale uncertainties, but small corrections to the central value.

We could expect this qualitative behaviour for $t\bar{t}Z$, but not for $t\bar{t}W$.



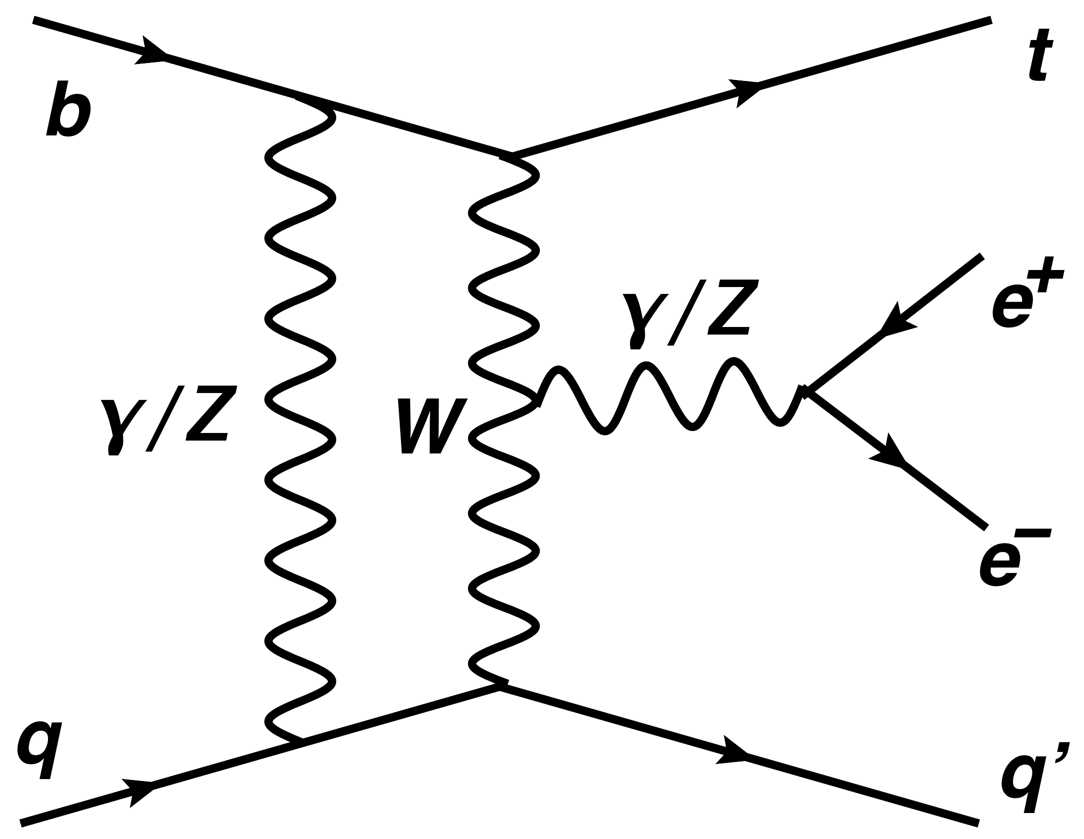
Single-top+V

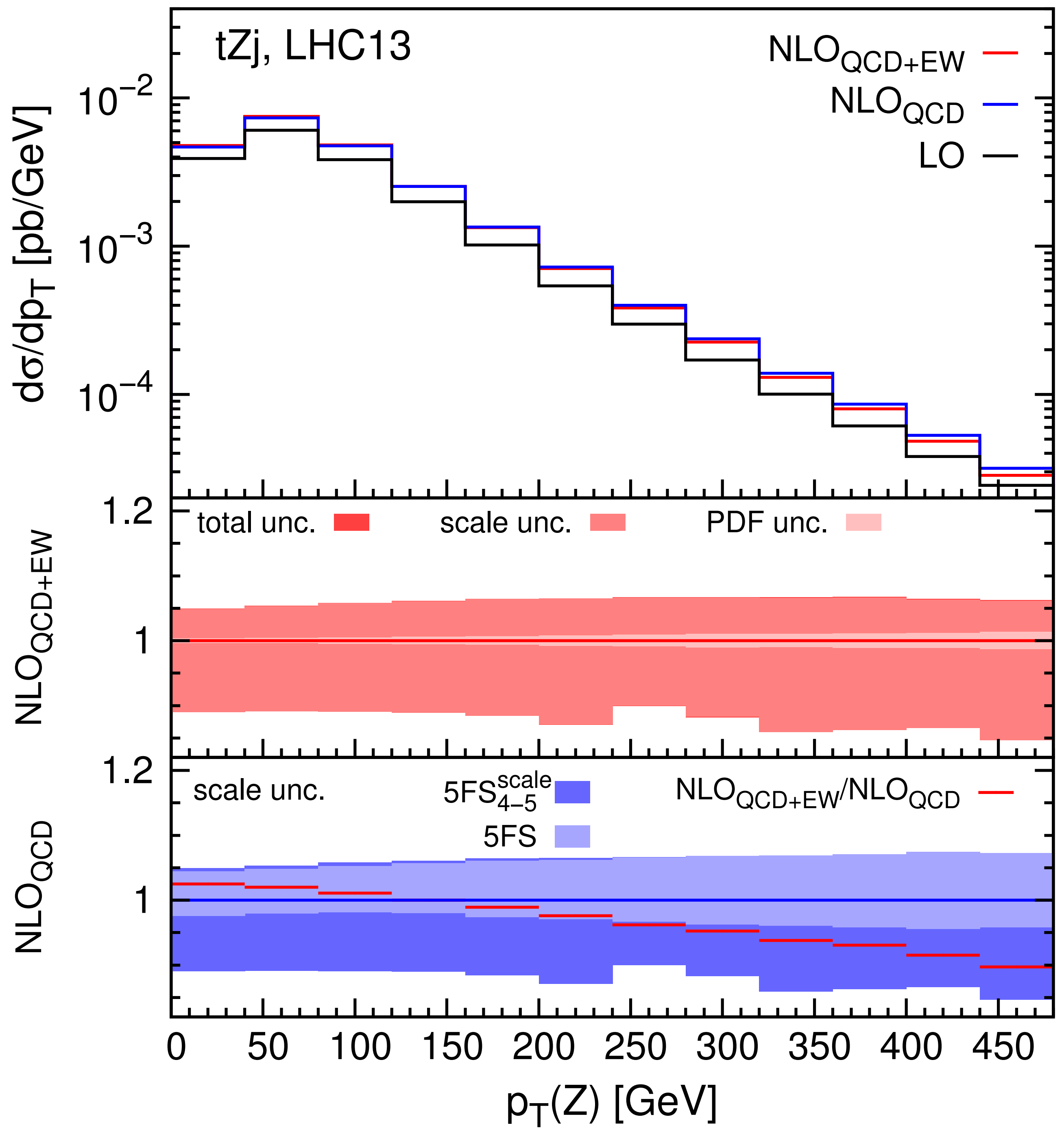
$$V = Z, H, \gamma$$

tHj and tZj: NLO QCD+EW predictions

***DP**, Tsinikos, Vryonidou ’20*

Accuracy	Channel	FS	tHj	tZj
$\mathrm{NLO_{QCD}}$	t-ch., s-ch., tW_h	5FS	$85.1(2)^{+5.4(+6.4\%)}_{-2.3(-2.7\%)}\ {}^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$	$895(2)^{+46(+5.1\%)}_{-16(-1.8\%)}\ {}^{+4(+0.4\%)}_{-4(-0.4\%)}$
		$\mathrm{5FS^{scale}_{4-5}}$	$85.1(2)^{+6.2(+7.2\%)}_{-9.2(-10.9\%)}\ {}^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$	$895(2)^{+50(+5.5\%)}_{-99(-11.1\%)}\ {}^{+4(+0.4\%)}_{-4(-0.4\%)}$
$\mathrm{NLO_{QCD+EW}}$	t-ch., s-ch., tW_h	5FS	$82.2(2)^{+5.6(+6.8\%)}_{-2.4(-2.9\%)}\ {}^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$	$904(2)^{+42(+4.7\%)}_{-19(-2.1\%)}\ {}^{+4(+0.4\%)}_{-4(-0.4\%)}$
		$\mathrm{5FS^{scale}_{4-5}}$	$82.2(2)^{+5.9(+7.2\%)}_{-8.9(-10.9\%)}\ {}^{+0.5(+0.6\%)}_{-0.5(-0.6\%)}$	$904(2)^{+50(+5.5\%)}_{-100(-11.1\%)}\ {}^{+4(+0.4\%)}_{-4(-0.4\%)}$





QCD scale and flavour (4FS vs. 5FS) uncertainties combined in the $\mathrm{5FS^{scale}_{4-5FS}}$.

NLO EW corrections are in general within the QCD uncertainty band only taking into account the flavour-scheme dependence.

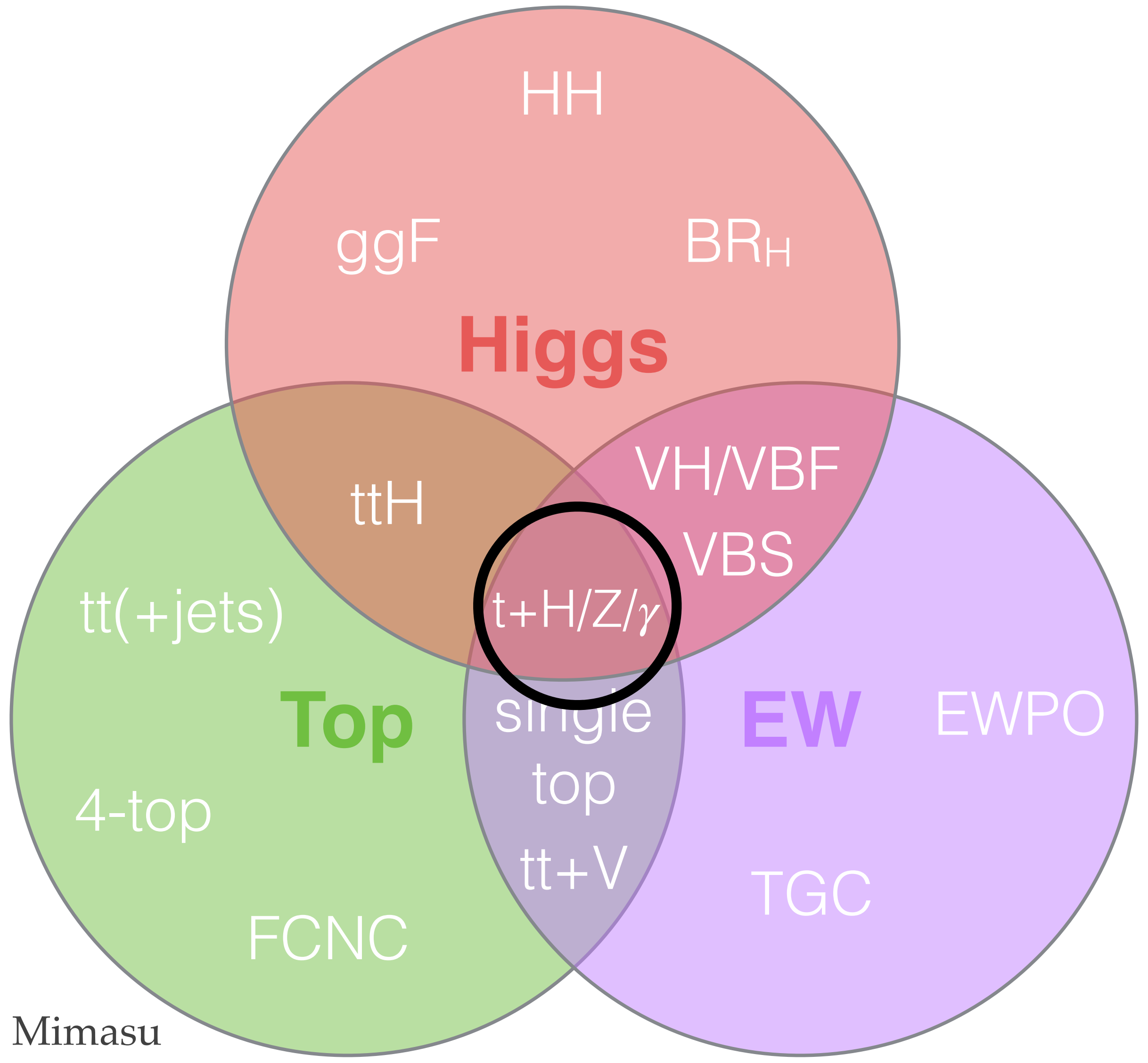
NLO EW corrections mix the different channels (s, t, tW)

Flavour-scheme uncertainty is essential for a realistic estimate of total uncertainties.

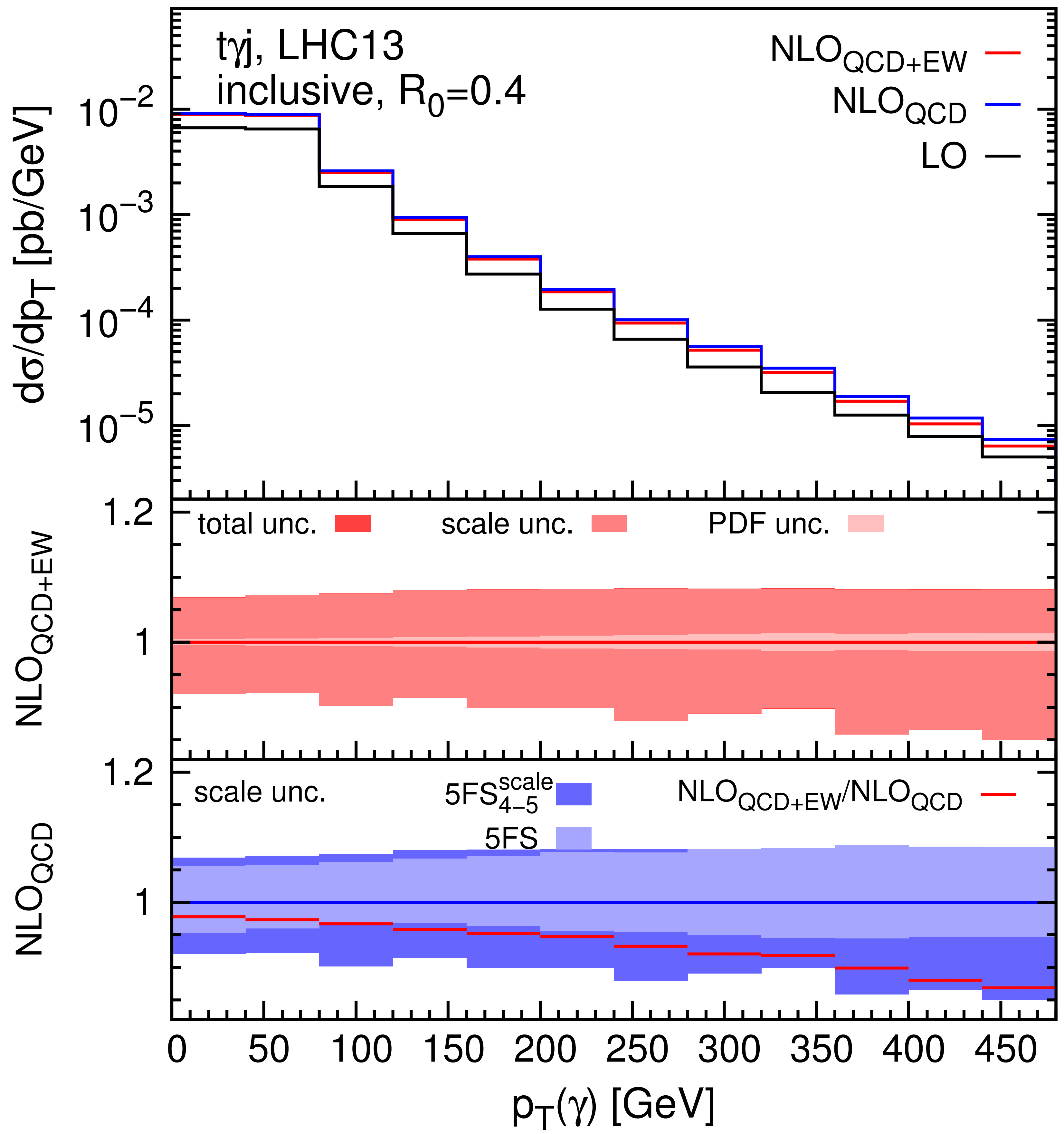
$t\gamma j$: NLO QCD+EW predictions

***DP**, Shao, Tsinikos, Zaro ’21*

Accuracy	Channel	FS	Inclusive [fb]
$\mathrm{NLO_{QCD}}$	t-ch., s-ch., tW_h	5FS	$900(2)^{+52.05(+5.8\%)}_{-36.26(-4.0\%)}$ $^{+4.76(+0.5\%)}_{-4.76(-0.5\%)}$
		$\mathrm{5FS}^{\mathrm{scale}}_{4-5}$	$900(2)^{+63.80(+7.1\%)}_{-73.78(-8.2\%)}$ $^{+4.76(+0.5\%)}_{-4.76(-0.5\%)}$
$\mathrm{NLO_{QCD+EW}}$	t-ch., s-ch., tW_h	5FS	$875(2)^{+55.18(+6.3\%)}_{-33.13(-3.8\%)}$ $^{+4.64(+0.5\%)}_{-4.64(-0.5\%)}$
		$\mathrm{5FS}^{\mathrm{scale}}_{4-5}$	$875(2)^{+62.06(+7.1\%)}_{-71.77(-8.2\%)}$ $^{+4.64(+0.5\%)}_{-4.64(-0.5\%)}$



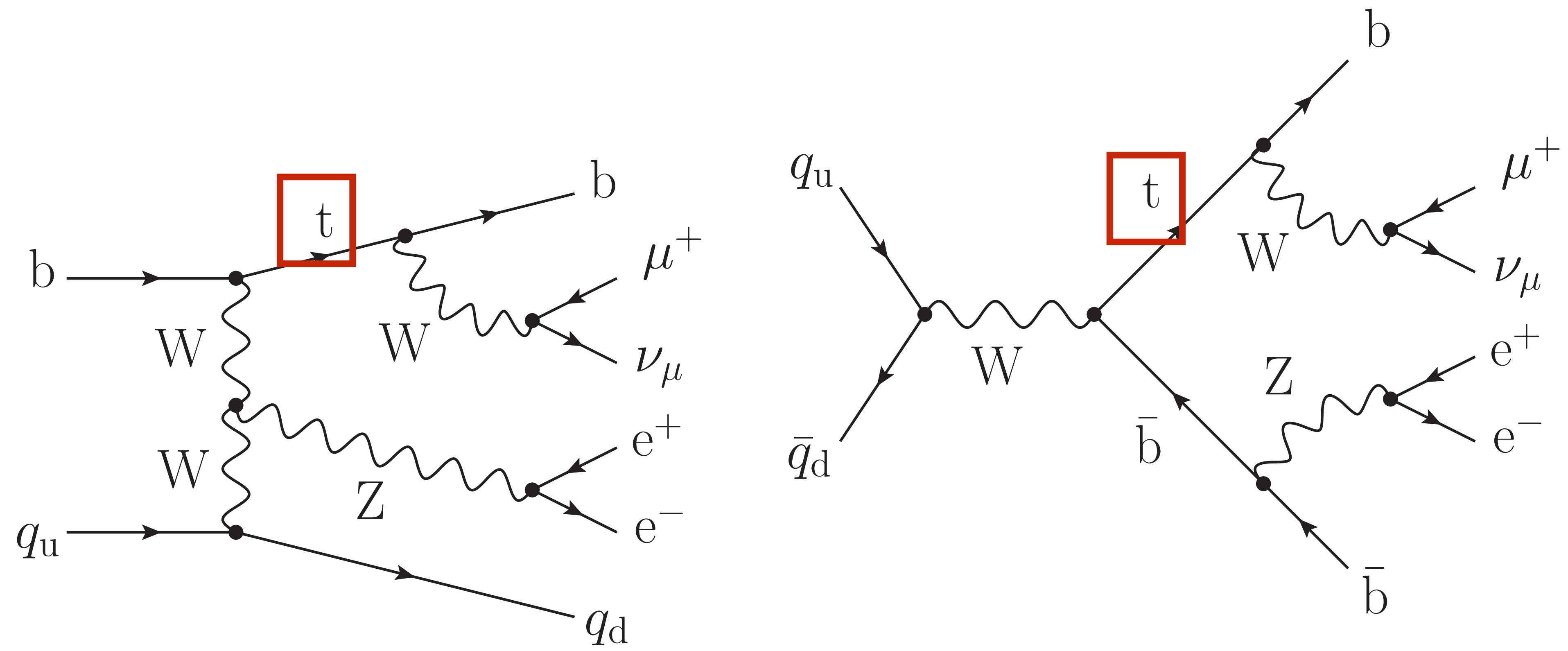
Similar consideration of tZj and tHj, but milder differences between 4FS and 5FS.



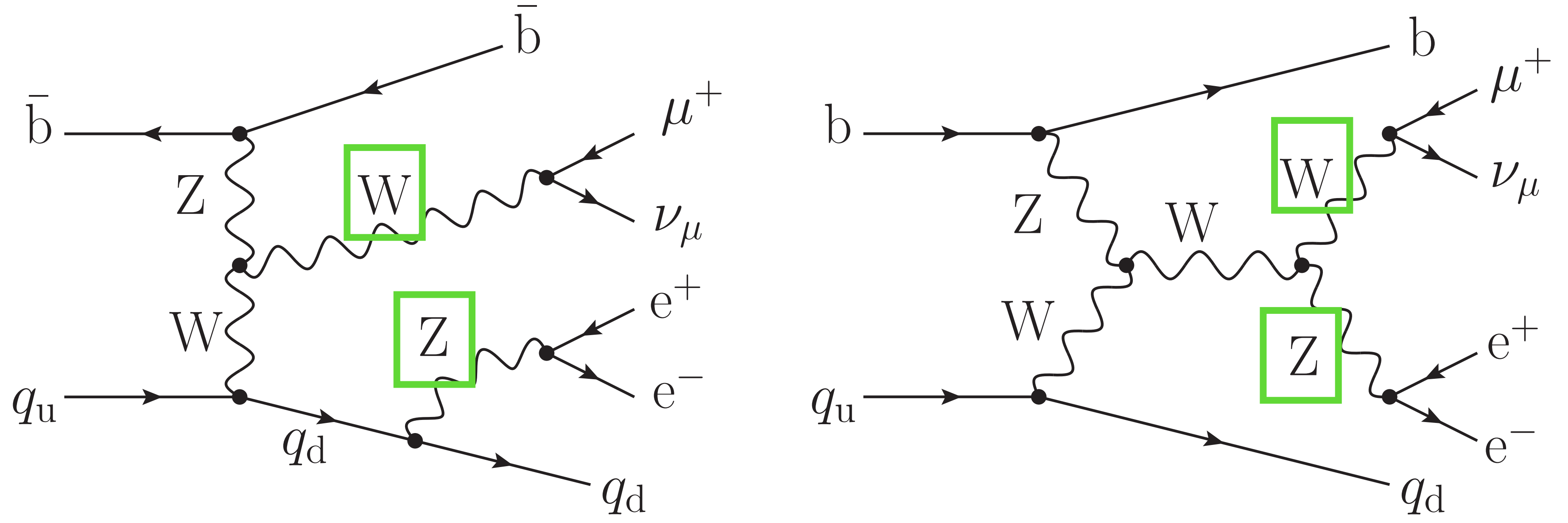
tZj: NLO QCD+EW off-shell effects

Denner, Pellicciolli, Schwan '22

$$\mathrm{pp} \to \mathrm{e}^+\mathrm{e}^-\mu^+\nu_\mu \mathrm{J}\,\mathrm{j_b} + X\,,$$

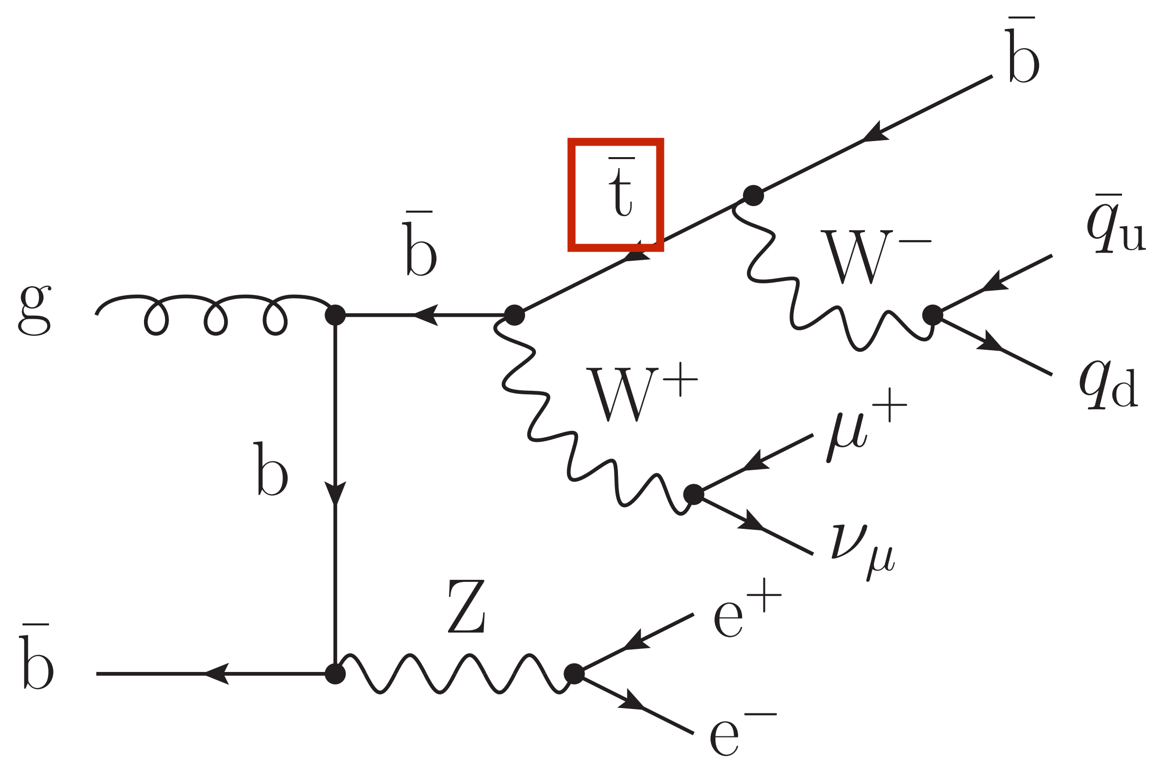


(a) t channel (b) s channel



(c) Non resonant (d) Vector-boson scattering

but also

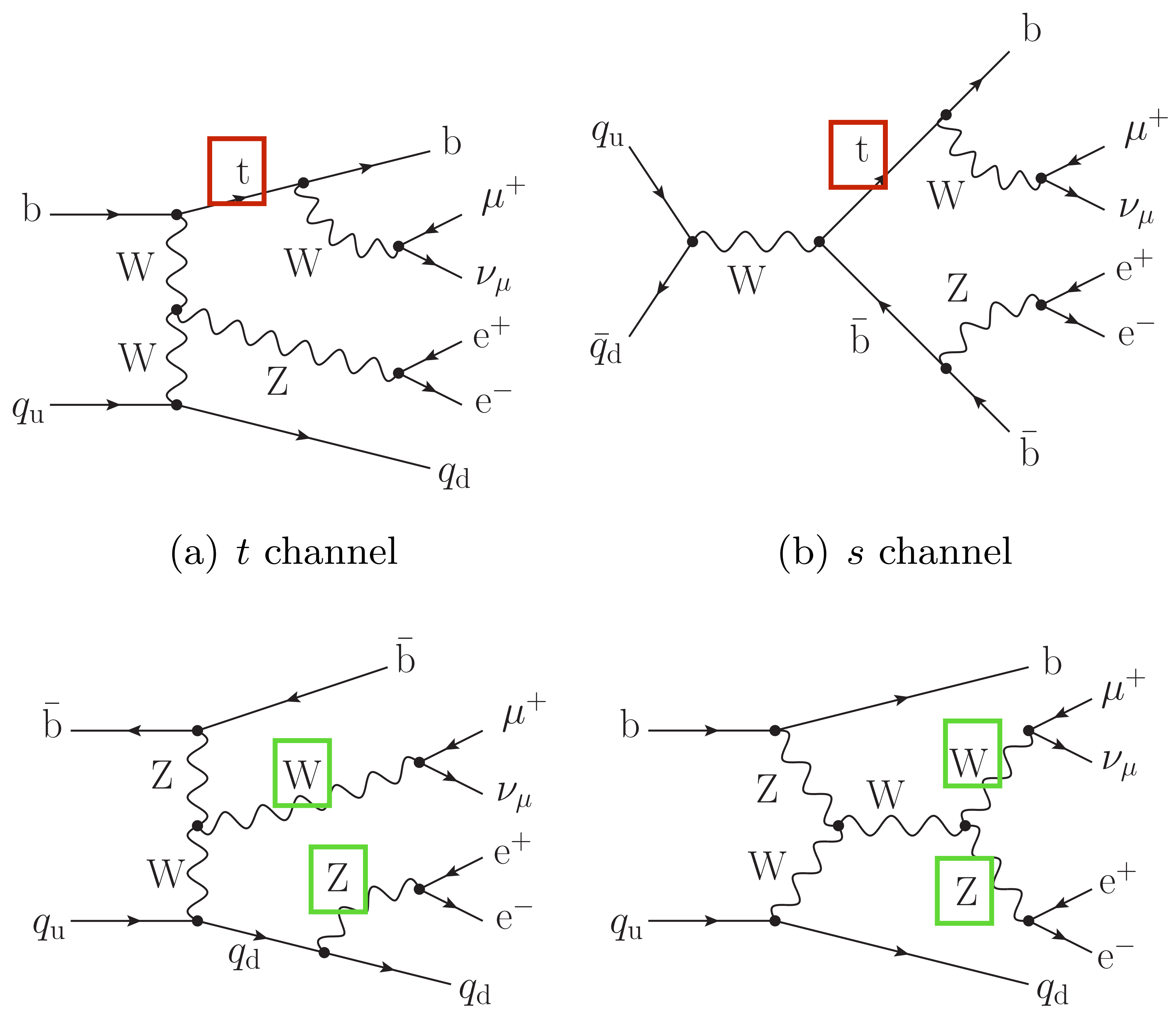


If I start from single-**top** Z production with a leptonically decaying top, NLO QCD corrections give a contribution that is in fact single-**antitop** Z production with a hadronically decaying top!

tZj: NLO QCD+EW off-shell effects

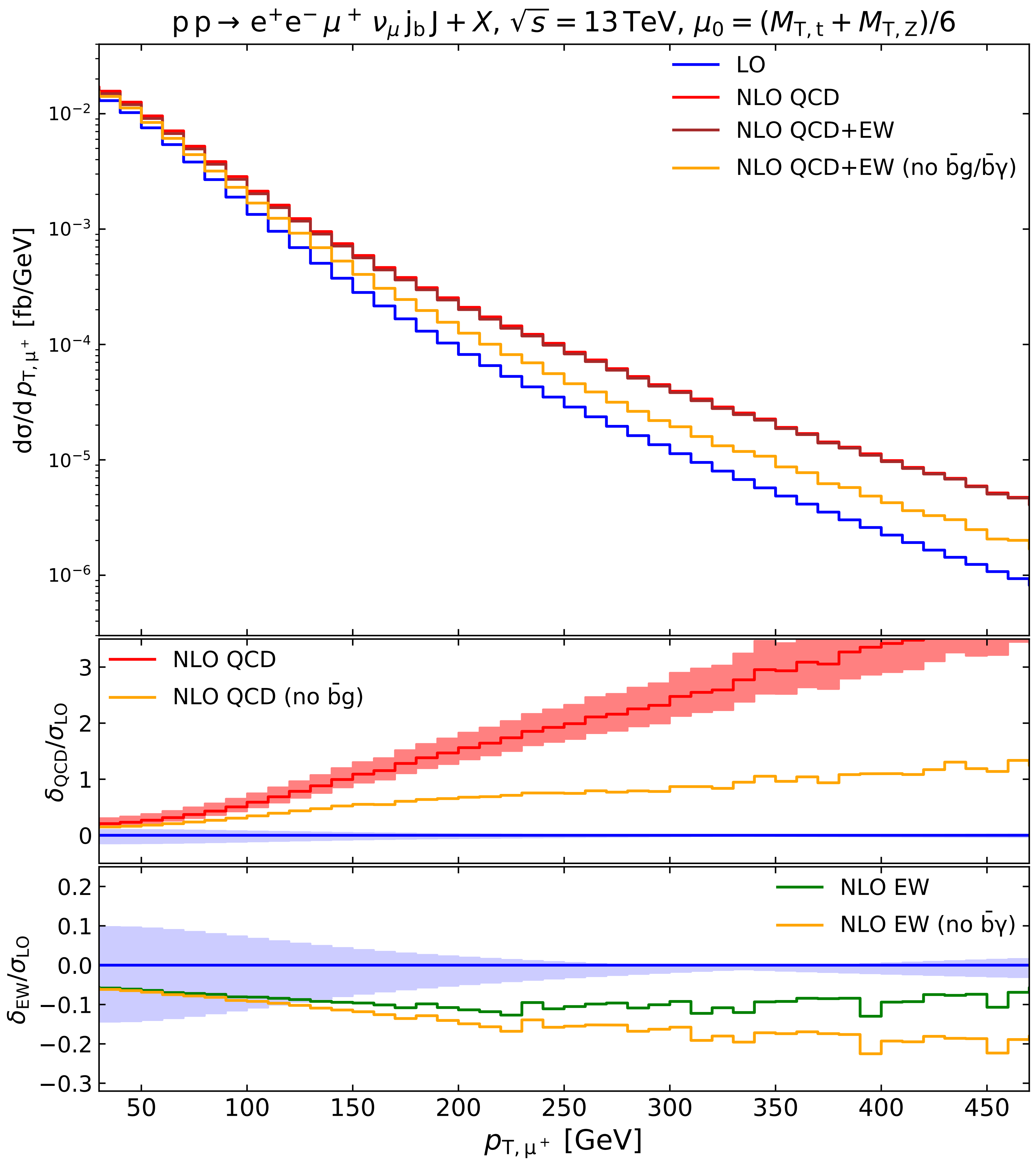
Denner, Pellicciolli, Schwan '22

$$\mathrm{pp} \to \mathrm{e}^+\mathrm{e}^-\mu^+\nu_\mu \mathrm{J}\,\mathrm{j_b} + X\,,$$



(a) t channel (b) s channel

(c) Non resonant (d) Vector-boson scattering

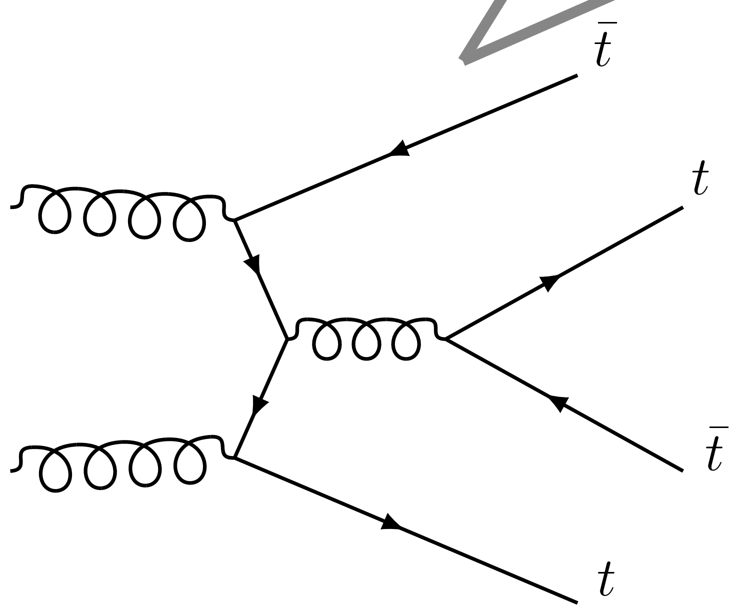


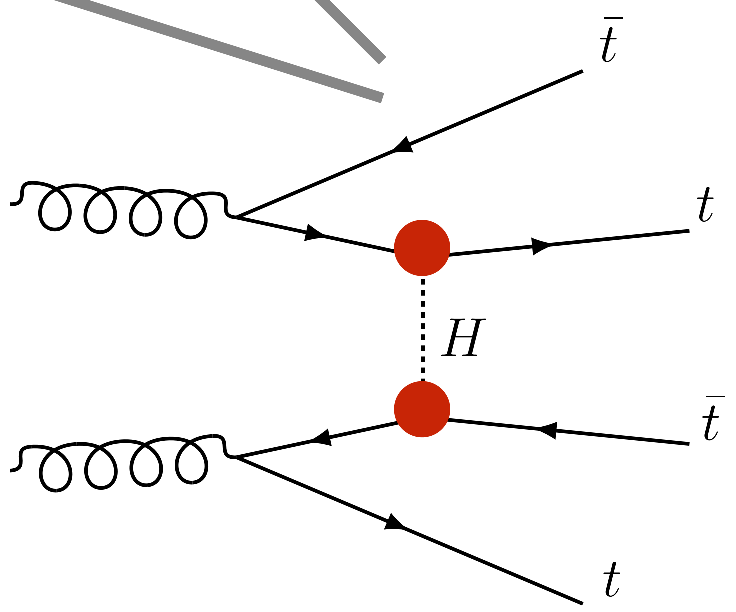
$$t\bar{t}t\bar{t}$$

Complete NLO

*Frederix, **DP**, Zaro '17*

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



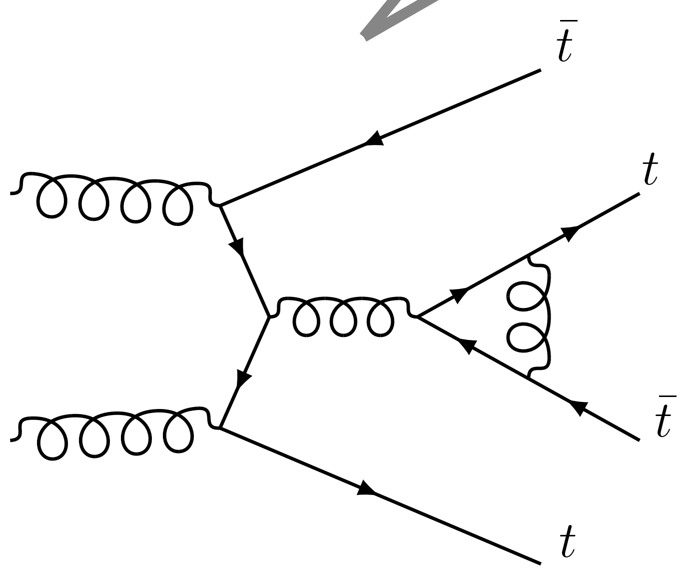


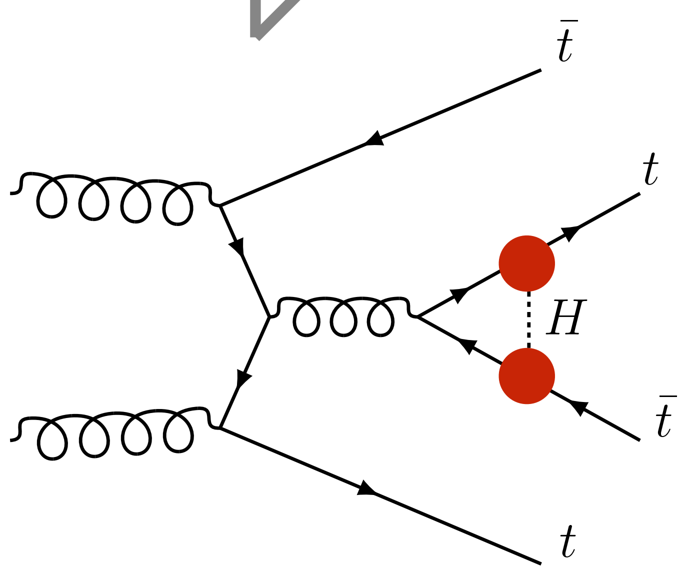
The gg initial-state gives ~90% of the LO cross section at 13 TeV and almost all the cross section at 100 TeV.

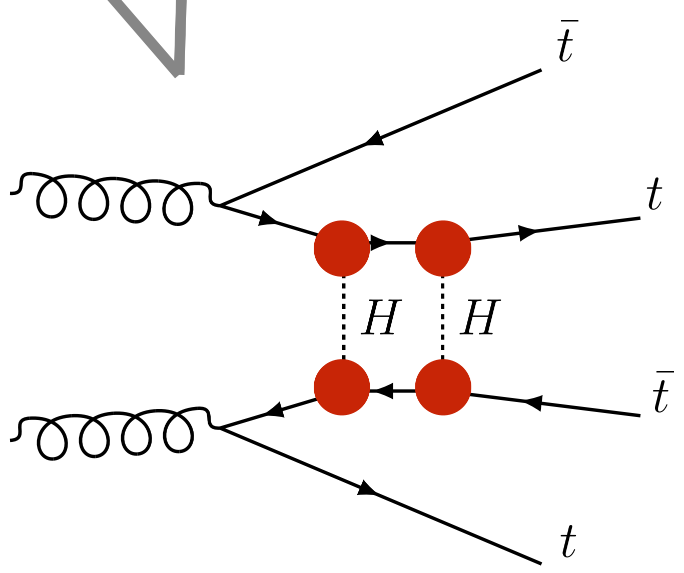
There is no gg contribution to LO4 and LO5.

27

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







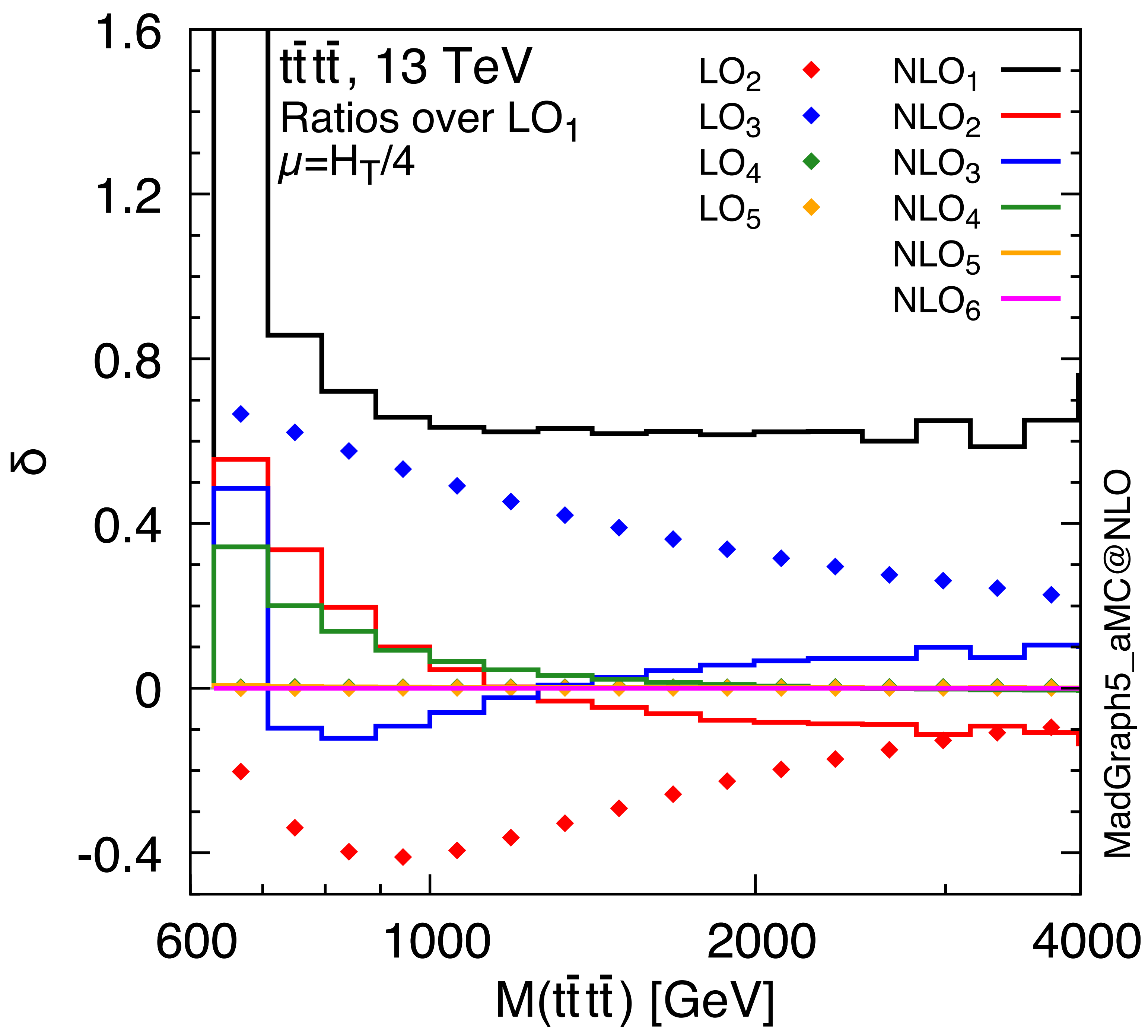
There is no gg contribution to NLO5 and NLO6.

Multiple Higgs-Top and EW-Top interactions can be present.

Complete NLO

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$	Naive estimate
LO_2	-26.0	-28.3	-30.5	10
LO_3	32.6	39.0	45.9	1
LO_4	0.2	0.3	0.4	0.1
LO_5	0.02	0.03	0.05	0.01
NLO_1	14.0	62.7	103.5	10
NLO_2	8.6	-3.3	-15.1	1
NLO_3	-10.3	1.8	16.1	0.1
NLO_4	2.3	2.8	3.6	0.01
NLO_5	0.12	0.16	0.19	0.001
NLO_6	< 0.01	< 0.01	< 0.01	0.0001
$NLO_2 + NLO_3$	-1.7	-1.6	0.9	

Frederix, ***DP****, Zaro '17*



LO2 and LO3 are large and have also large cancellations.

NLO2 and NLO3 are mainly given by 'QCD corrections' on top of LO2 and LO3, so they are large and strongly depend on the scale choice, at variance with standard EW corrections.

Accidentally, relatively to LO1 , NLO2+NLO3 scale dependence almost disappear.

What happens if BSM enters into the game? Anomalous yt ?

Complete NLO: developments

Complete-*LO* + NLO QCD +PS

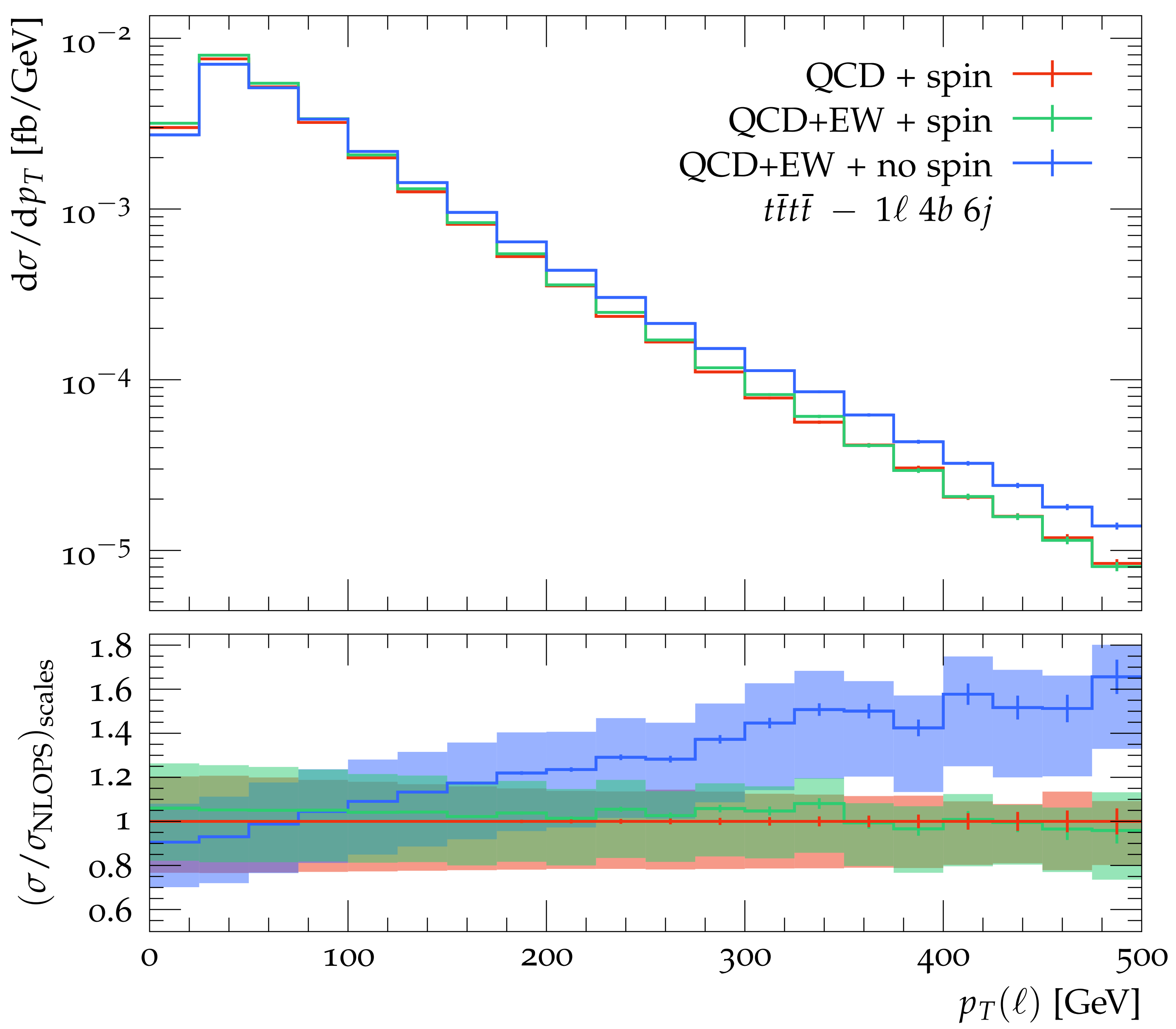
Ježo, Kraus '21

$$t\bar{t}t\bar{t} \;-\; 1\ell\; 4b\; 6j$$

$$\sigma^{\rm spin}_{\rm QCD} = 0.618^{+0.119\ (19\%)}_{-0.142\ (23\%)}\ \text{fb}\ ,$$

$$\sigma^{\rm spin}_{\rm QCD+EW} = 0.649^{+0.117\ (18\%)}_{-0.144\ (22\%)}\ \text{fb}\ ,$$

$$\sigma^{\rm no\text{-}spin}_{\rm QCD+EW} = 0.625^{+0.114\ (18\%)}_{-0.139\ (22\%)}\ \text{fb}\ .$$



Complete NLO: developments

Complete-*LO* + NLO QCD +PS

Unknown

Ježo, Kraus '21

$$t\bar{t}t\bar{t} \;-\; 1\ell\; 4b\; 6j$$

$$\sigma^{\rm spin}_{\rm QCD} = 0.618^{+0.119\ (19\%)}_{-0.142\ (23\%)}\ {\rm fb}\,,$$

$$\sigma^{\rm spin}_{\rm QCD+EW} = 0.649^{+0.117\ (18\%)}_{-0.144\ (22\%)}\ {\rm fb}\,,$$

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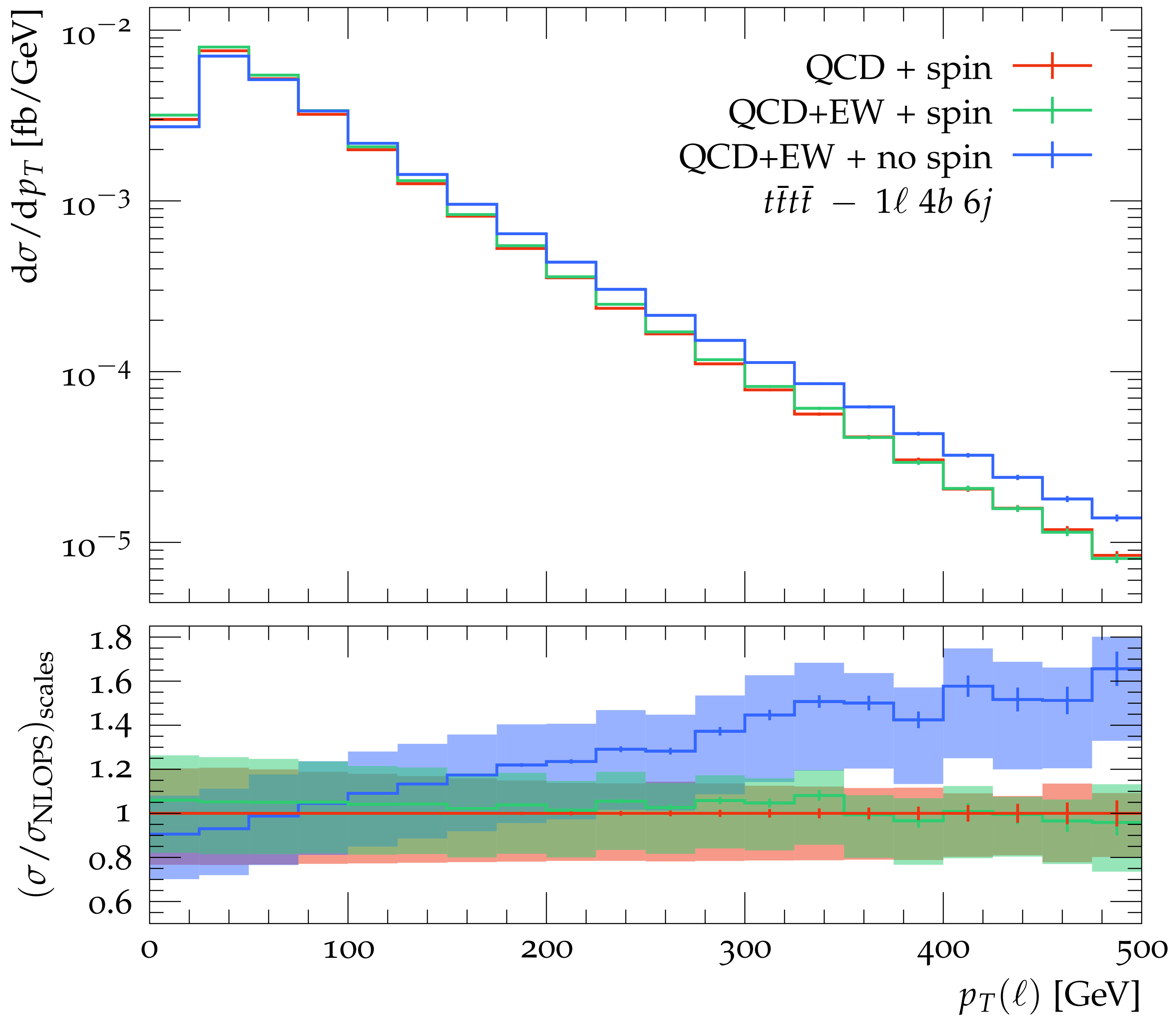
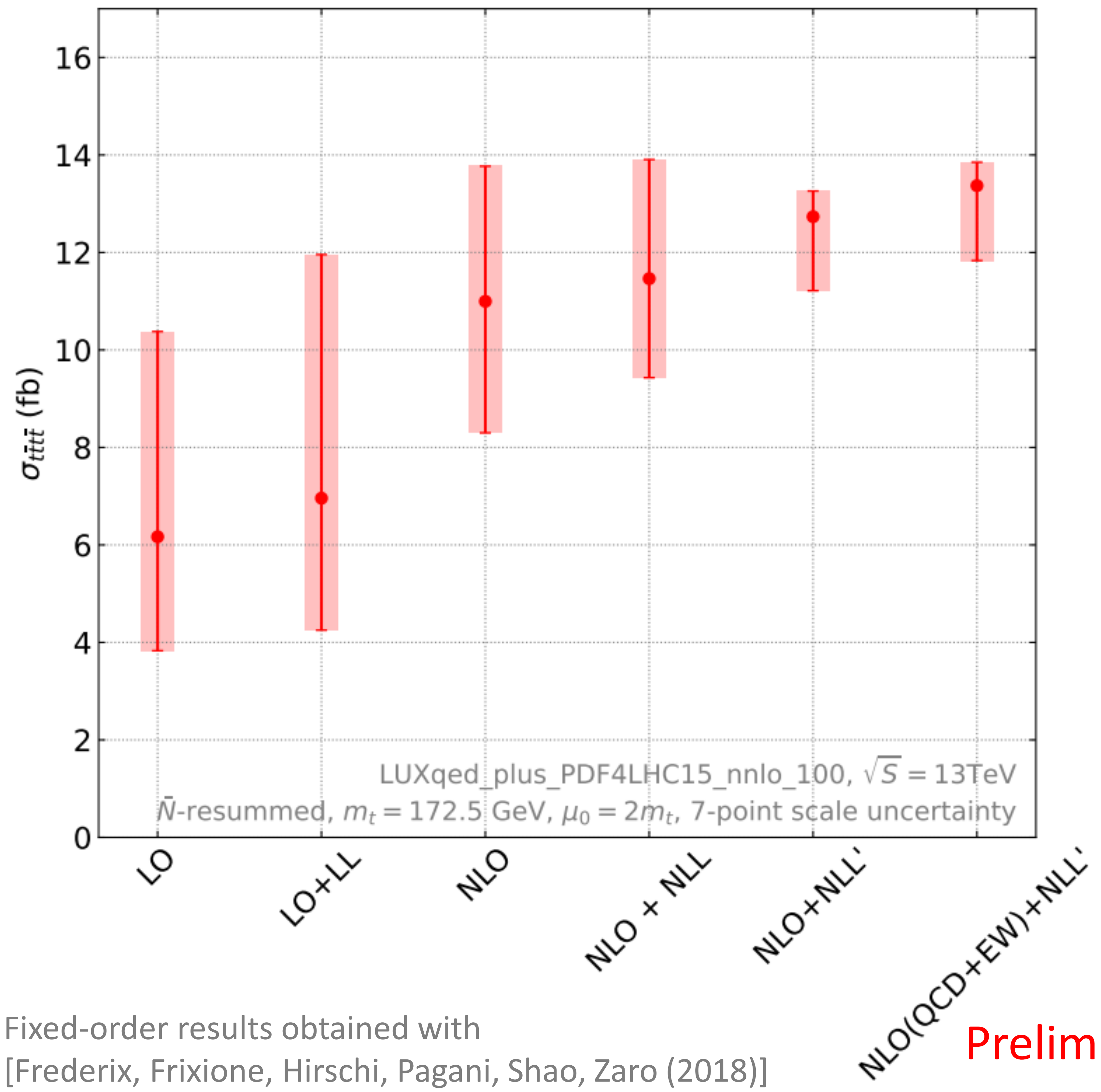


RESUMMATION

Kulesza, van Beekveld, Valero: in preparation

Resummation strongly reduces scale uncertainties.



Fixed-order results obtained with
[Frederix, Frixione, Hirschi, Pagani, Shao, Zaro (2018)]

Preliminary

Conclusions and Outlook

In this talk I have focused on one of the many relevant theoretical aspects in Top and EW physics:
The relevance of higher-order QCD and EW corrections for the “rare” top-quark processes, involving the EW interacting tops.

Even just considering precision physics, many other important studies have been performed for top and EW: for example, all the studies for $t\bar{t}$ production and the multiboson and VBS processes.
Not discussed in this talk.

We have seen how many NLO studies have been performed for $t\bar{t}V$ and especially $t\bar{t}W$.
This demonstrates that besides going to NNLO, there are plenty of phenomenological aspects that can still be explored.

However, first results for NNLO predictions for $t\bar{t}V$ have appeared in $t\bar{t}H$ production.
This is just the beginning of studies aiming at a new level of precision, which has been already achieved for lower multiplicities in the final state.