Precise predictions:
the importance of electroweak corrections

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OUTLINE

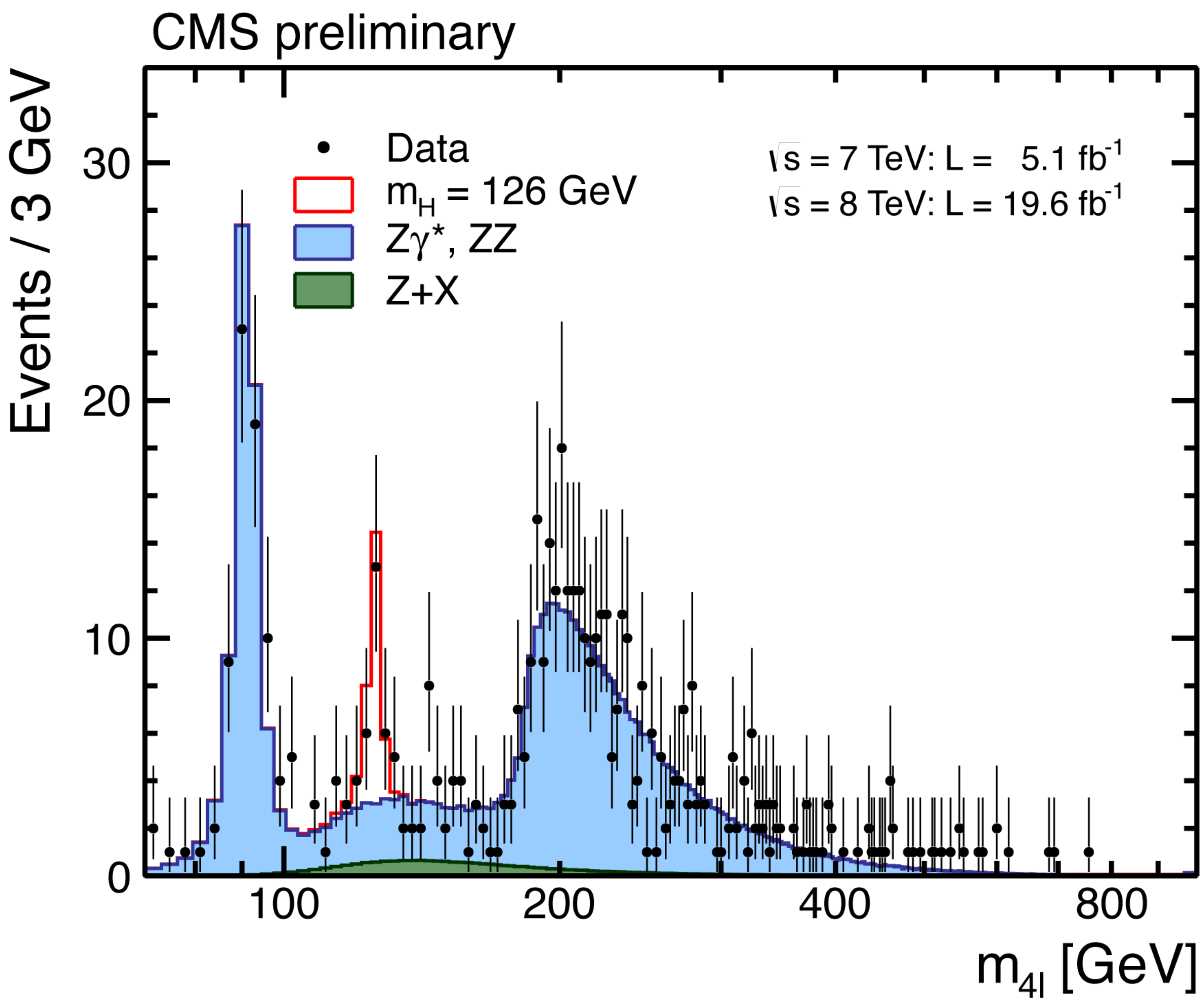
Introduction: precision physics and EW corrections

Automation of EW corrections in Madgraph5_aMC@NLO

Phenomenological results in top-quark physics

Higgs-self couplings from single-Higgs production

! DISCLAIMER !



The topic of this talk is **<u>not</u>** very relevant for the identification of resonances from new physics.

Precise predictions are fundamental for correctly identifying **non-resonant** new physics effects, setting **exclusion limits** and **fully characterize** and understand both resonant and non-resonant new-physics dynamics.

Predictions at the LHC

Every prediction at the LHC starts form here:

Renormalization/factorization scale

$$\sigma_{H_1,H_2}(p_1,p_2) = \sum_{i,j} \int dx_1\, dx_2\, \boxed{f_i^{(H_1)}(x_1,\mu)\ f_j^{(H_2)}(x_2,\mu)}\ \boxed{\hat{\sigma}_{ij}(x_1p_1, x_2p_2, \alpha_S(\mu), \mu)}$$

PDFs

Partonic cross sections

- PDFs are fitted from experimental measurements, only the dependence on μ can be calculated in perturbation theory via DGLAP.
- Partonic cross sections can be calculated in perturbation theory via Feynman diagrams.

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- PDFs are fitted from experimental measurements, only the dependence on μ can be calculated in perturbation theory via DGLAP.
- Partonic cross sections can be calculated in perturbation theory via Feynman diagrams.

Precise predictions at the LHC: for what?

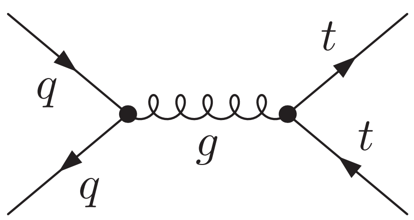
- More precise predictions for the total cross sections. (Total normalization)
- More precise differential distributions. (Kinematic-dependent corrections)
- Reduction of μ dependence. (Theoretical accuracy)

Methods/ Approximations

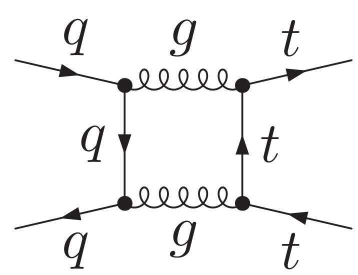
Fixed orders, Resummation, RGE, Parton Shower, Matching, Merging ………….

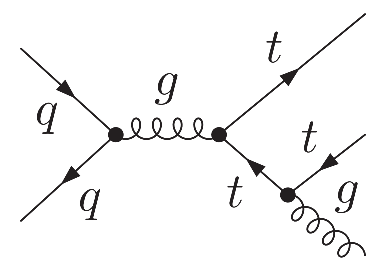
Fixed Order calculations

In the SM, contributions to the partonic cross section can be organized according to the powers of α_s and α (number of loop corrections and real emissions).

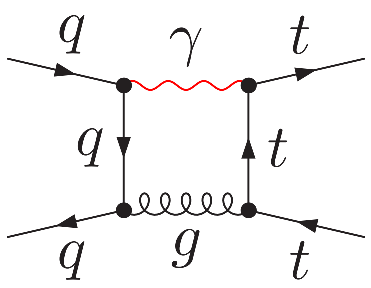


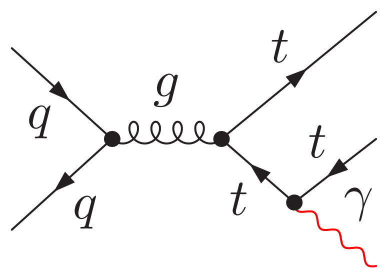
Born LO



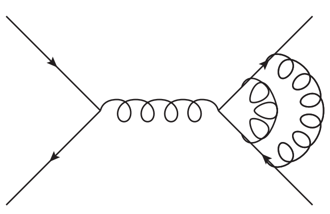


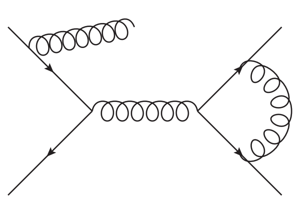
NLO QCD
$\mathcal{O}(\alpha_s)$ corrections





NLO EW
$\mathcal{O}(\alpha)$ corrections





NNLO QCD
$\mathcal{O}(\alpha_s^2)$ corrections

NNLO EW,
NNNLO QCD
.....

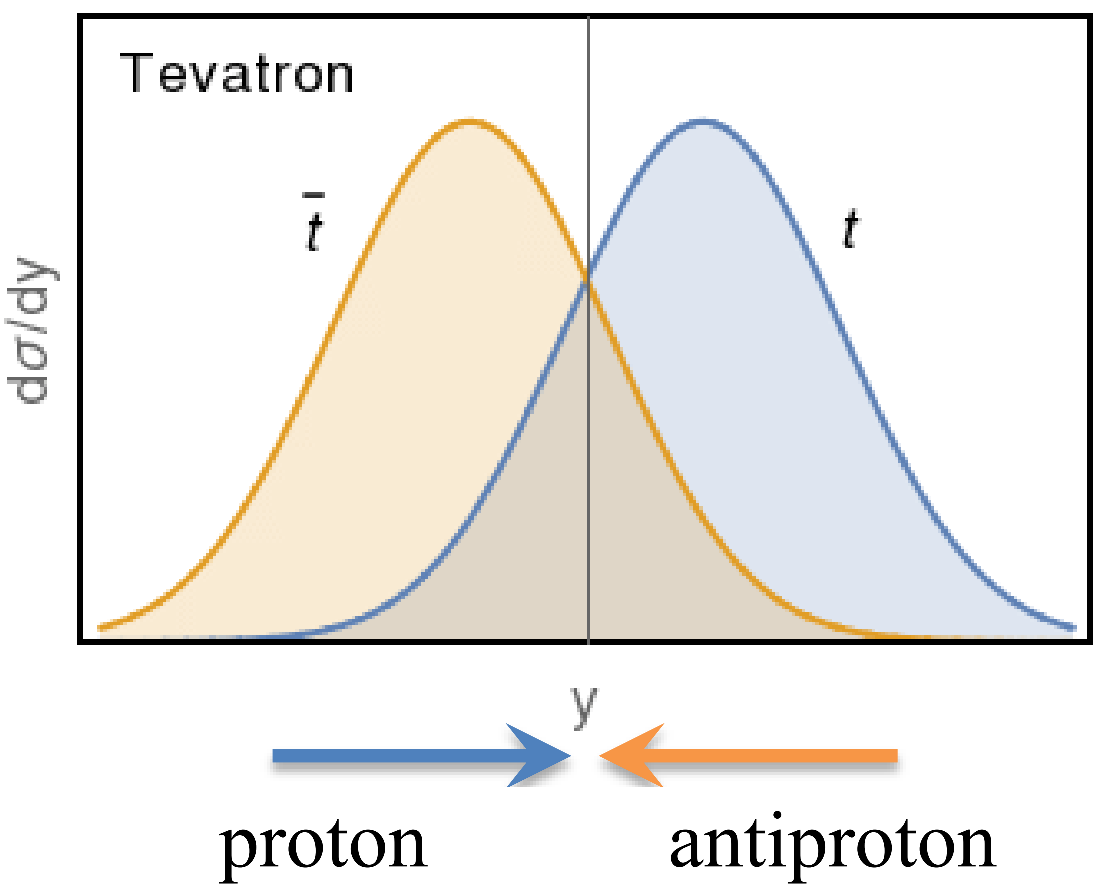
At the LHC, QCD is everywhere.
Nowadays, a "standard" prediction in the SM is at NLO QCD accuracy.

NNLO QCD is expected to be of the same order of NLO EW $\alpha_s^2 \sim \alpha$.

EW corrections grow for large pt (Sudakov logs), so they are not flat. Moreover they in general involve all the SM masses and couplings.

Correct interpretation of the (B)SM signal

A recent story from an other hadron collider: **the top-quark forward-backward asymmetry at the Tevatron.**



$$A_{FB}^{p\bar{p}} = \frac{\sigma(y_t > 0) - \sigma(y_t < 0)}{\sigma(y_t > 0) + \sigma(y_t < 0)}$$

D0 and especially CDF measured values for the forward-backward asymmetry that are larger than the SM prediction.

But which SM prediction?

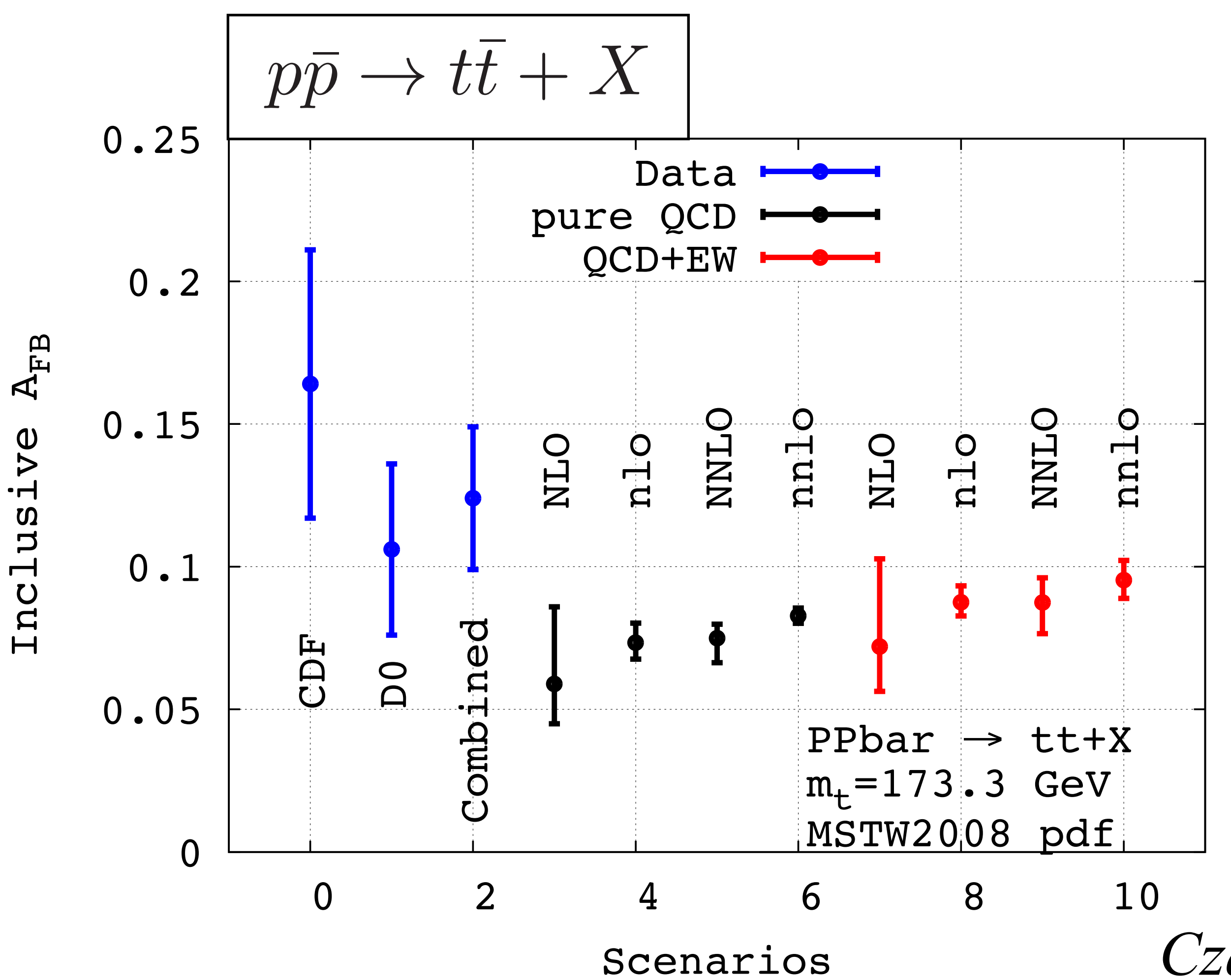
Correct interpretation of the (B)SM signal

A recent story from an other hadron collider: **the top-quark forward-backward asymmetry at the Tevatron.**

Surprisingly (No Sudakov enhancement), the NLO EW induces corrections of order 20-25%.

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

DP, Hollik '11



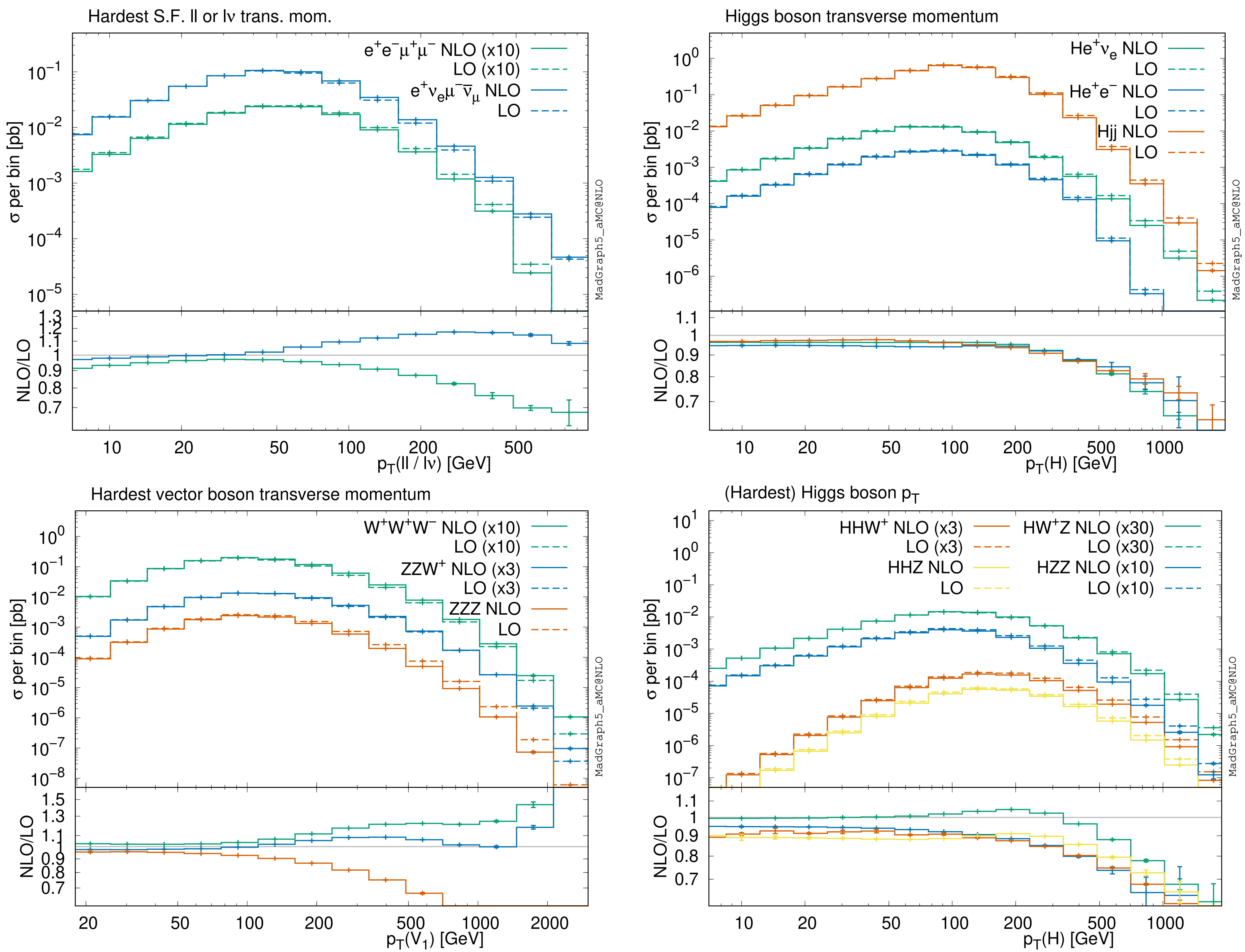
Czakon, Fiedler, Mitov '14

NNLO QCD and NLO EW are essential for a reliable theoretical prediction.

Missing higher-orders in the theoretical predictions may be misinterpreted as BSM signals.

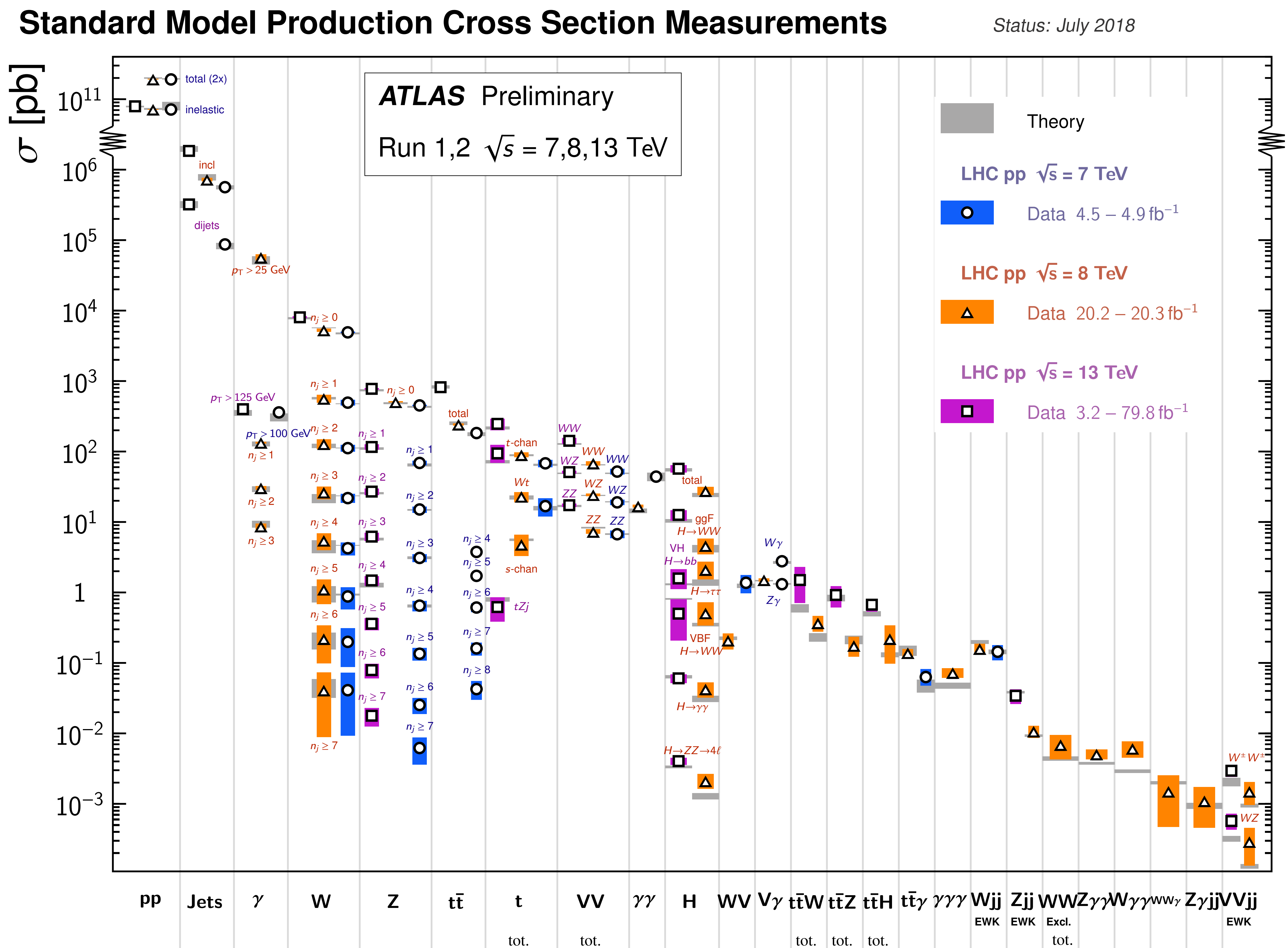
Sudakov enhancement

Not surprisingly, weak corrections at large scales are not negligible for a general process due to the Sudakov Logarithms $\sim \alpha \ln^2\left(\frac{s}{M_W^2}\right)$.

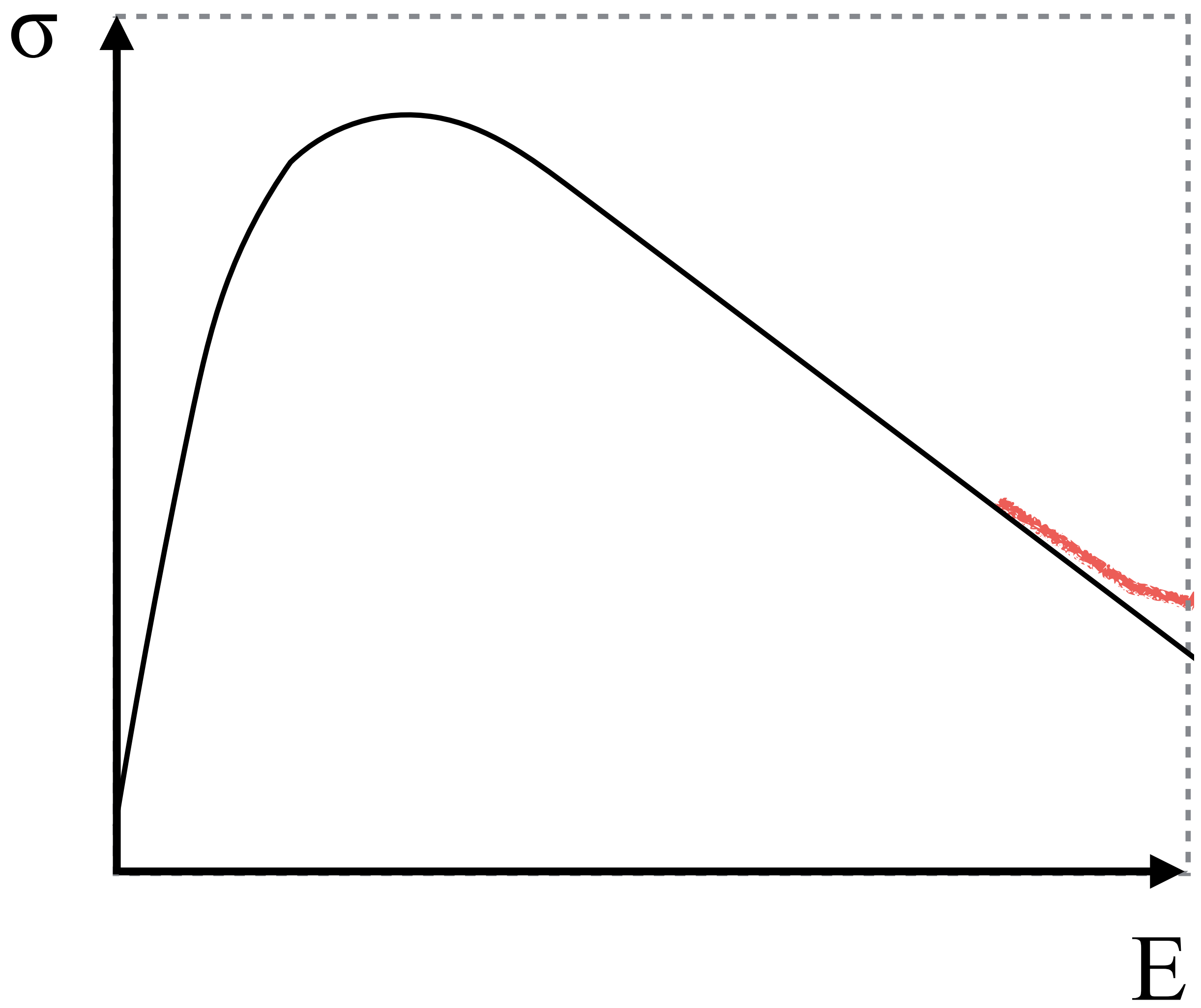


Frederix, Frixione, Hirschi, DP, Shao, Zaro '18

SM at the LHC (is this a desperation plot?)

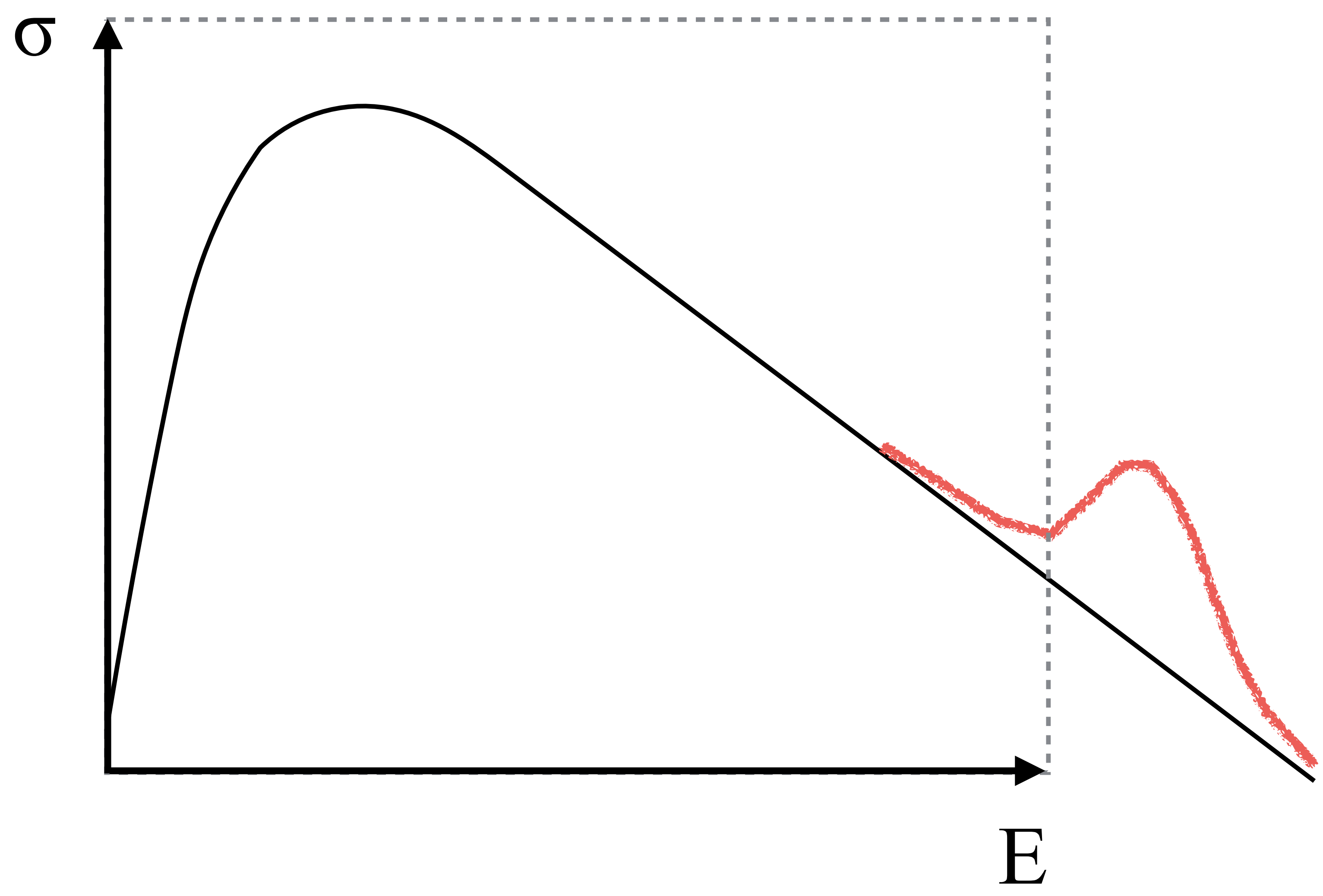


New Physics from differential distributions



With higher luminosity (and higher energy), at the LHC the accuracy of all measurements will in general increase, especially in the tail of distributions.

New Physics from differential distributions



With higher luminosity (and higher energy), at the LHC the accuracy of all measurements will in general increase, especially in the tail of distributions.

Precise predictions are necessary for the current and future measurements at the LHC, especially if no clear sign of new physics will appear. In order to match the experimental precision, NLO EW corrections are essential.

Automation of NLO corrections in Madgraph5_aMC@NLO

What do we mean with automation of EW corrections?

The possibility of calculating QCD and EW corrections for SM processes (matched to shower effects) with a process-independent approach.

```
generate process [QCD]
output process_QCD
```

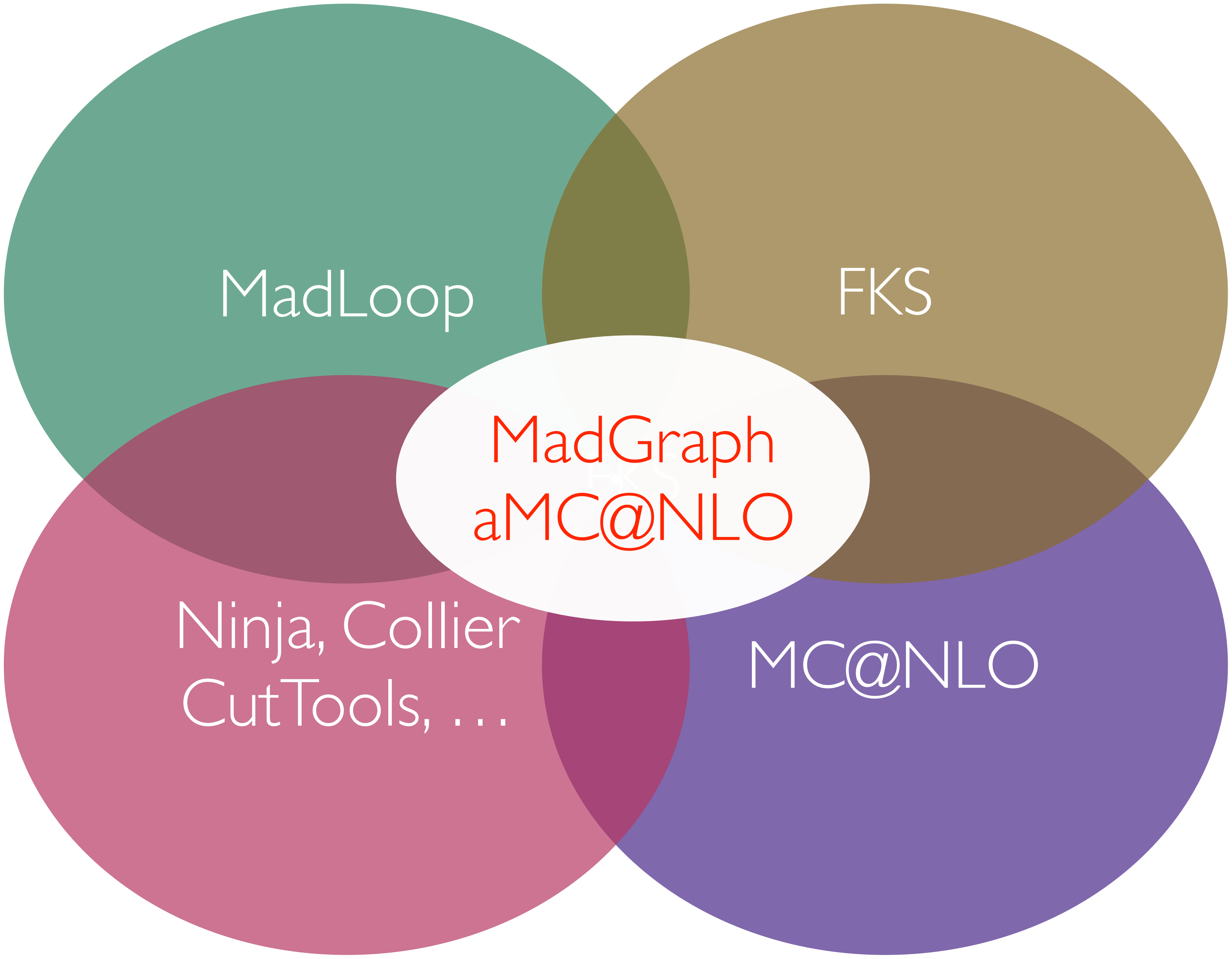
```
generate process [QCD EW]
output process_QCD_EW
```

The automation of NLO QCD has already been achieved, but we need higher precision to match the experimental accuracy at the LHC and future colliders.

- NNLO QCD complete automation is out of our theoretical capabilities at the moment.
- NLO EW and NNLO QCD corrections are of the same order ($\alpha_s^2 \sim \alpha$), but NLO EW corrections **can be automated.** Moreover effects such as Sudakov logarithms or photon FSR can enhance their size.

Automation of NLO corrections in Madgraph5_aMC@NLO

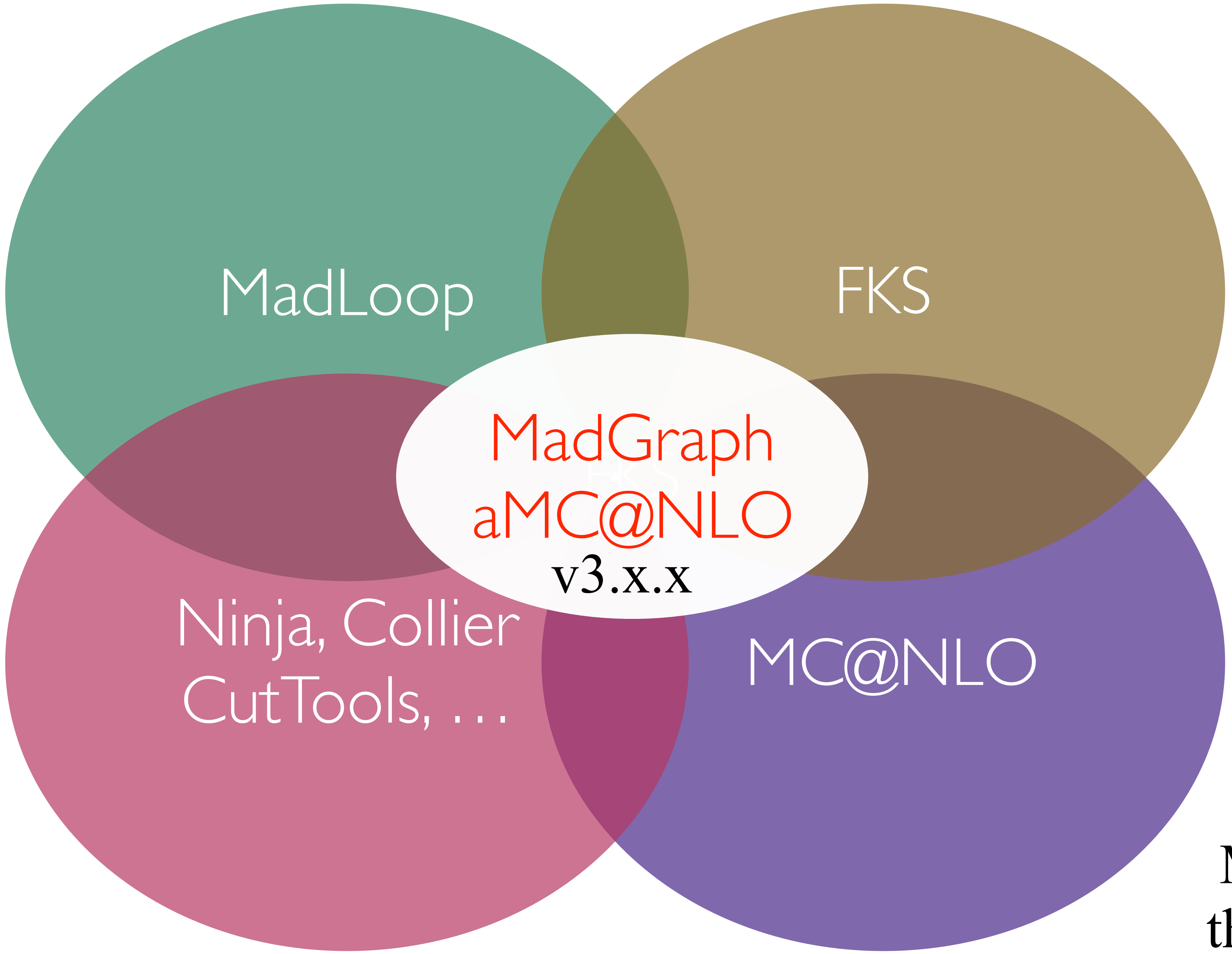
The **complete automation** had already been achieved for **QCD**.



Alwall, Frederix, Frixione, Hirschi, Maltoni, Mattelaer, Shao, Stelzer, Torrielli, Zaro ‘14

Automation of NLO corrections in Madgraph5_aMC@NLO

The **complete automation** is now available also for combined **QCD and EW**.



Frederix, Frixione, Hirschi, DP, Shao, Zaro '18

Matching with the shower is in progress

What is new from QCD to EW?

- Many more loop diagrams, involving the photon and the W, Z and H bosons.
- Z, W bosons and top quark intermediate resonances are often involved in a generic process. Complex mass scheme is necessary.
- New R2 and UV counterterms are necessary.
- A richer structure of interferences of tree and one-loop diagrams due to different possible perturbative orders combinations. Same situation for real radiations
- FKS subtractions of singularities has to be extended in order to account for singularities due to photons and the aforementioned richer structure of interferences
- Jets definitions have to be modified in order to be IR safe.

All these problems have been solved and implemented in the new version (v3) of Madgraph5_aMC@NLO

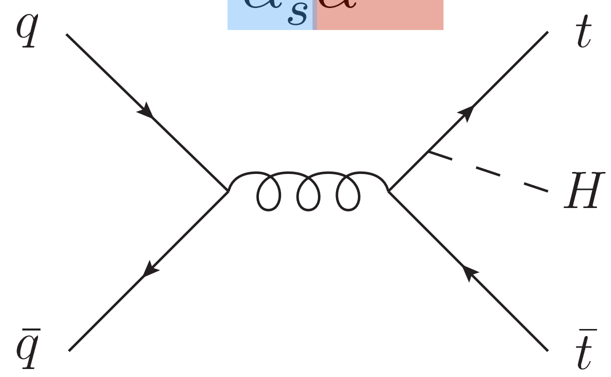
We also provided FKS formulas for fragmentation functions, but they have not been implemented yet. At the moment, NLO EW to FS photons not available.

Structure of NLO EW-QCD corrections

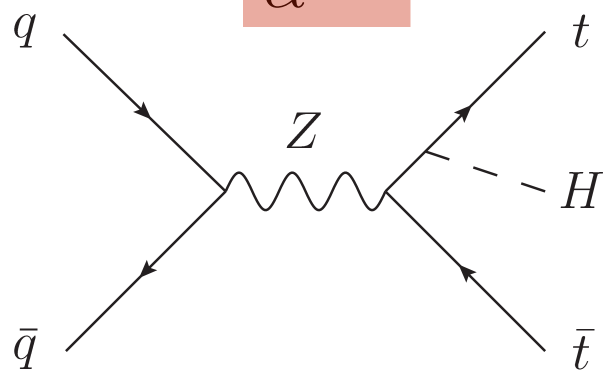
$t\bar{t}H$

as example

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



$\alpha^{3/2}$

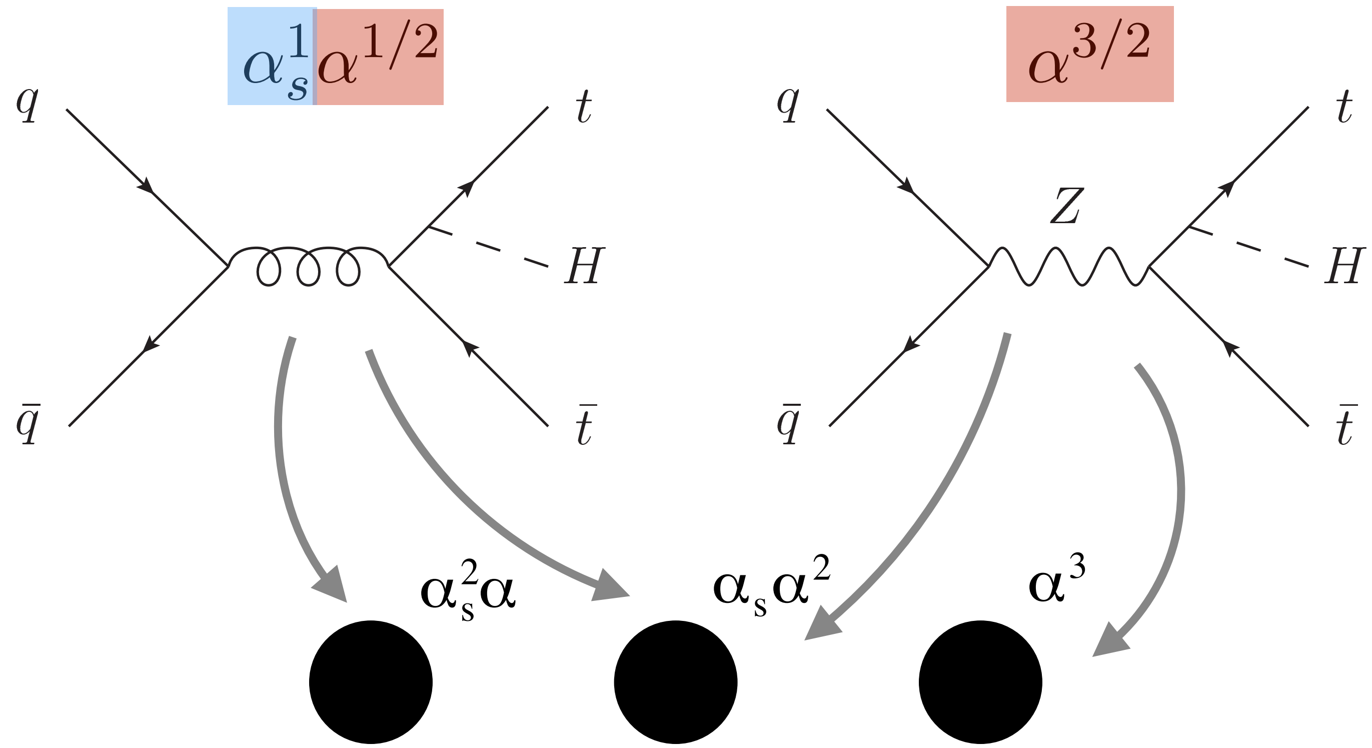


LO

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

Structure of NLO EW-QCD corrections

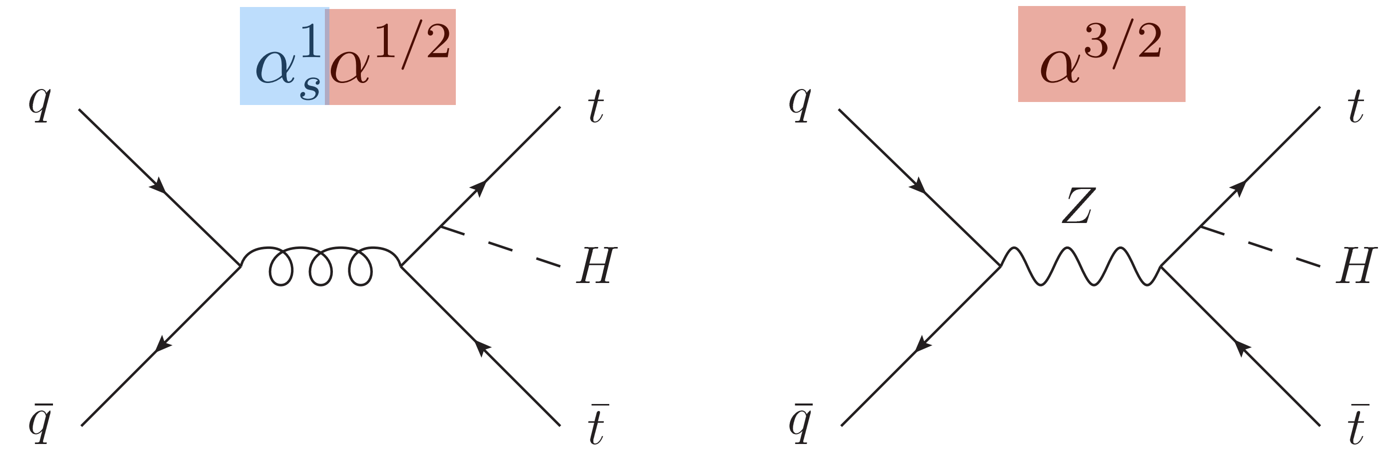
$t\bar{t}H$
as example

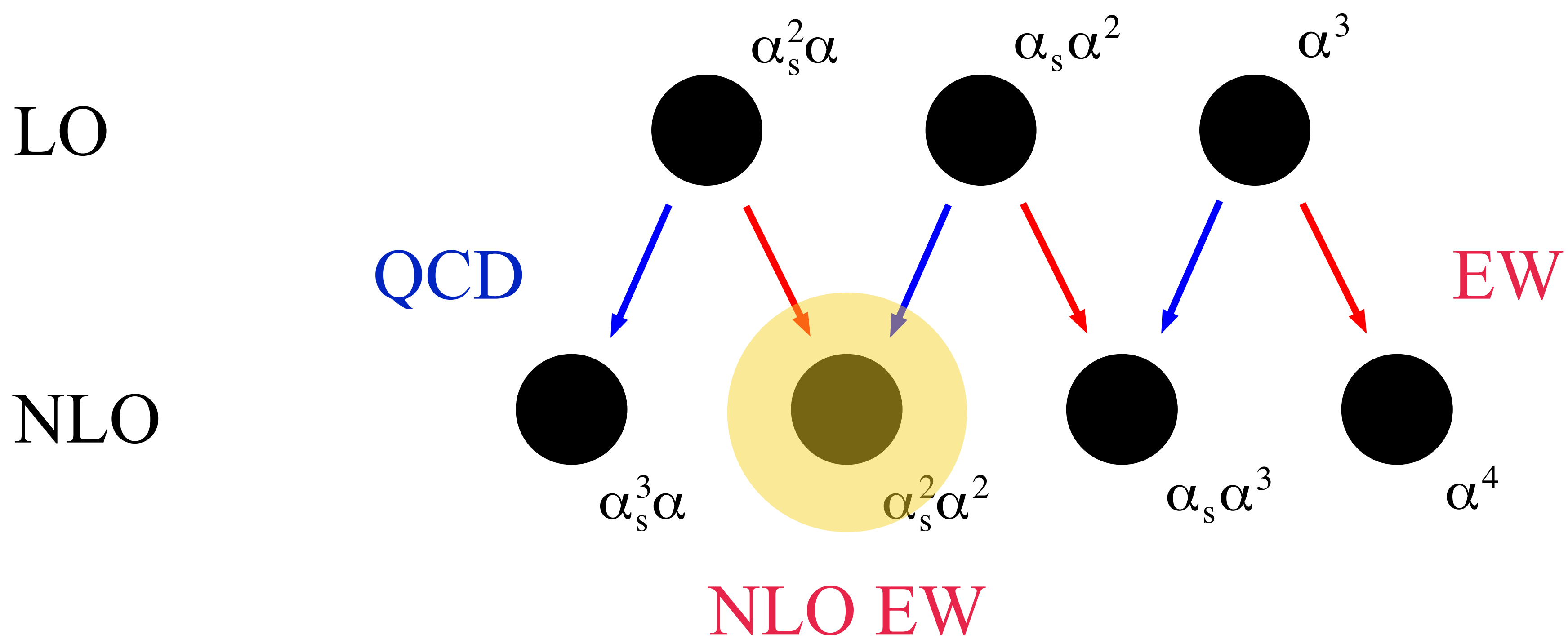


LO

Structure of NLO EW-QCD corrections

$t\bar{t}H$
as example

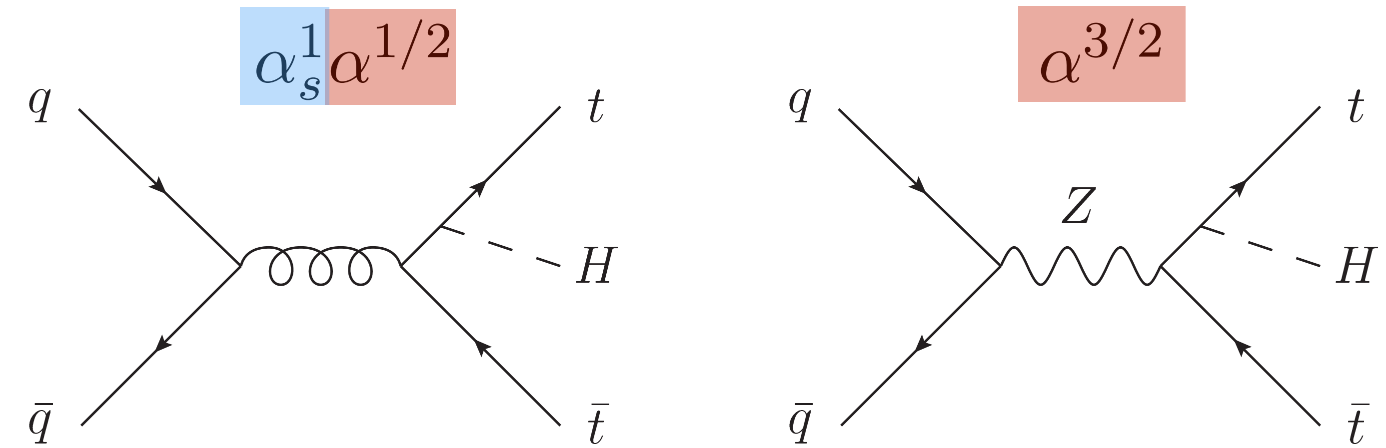


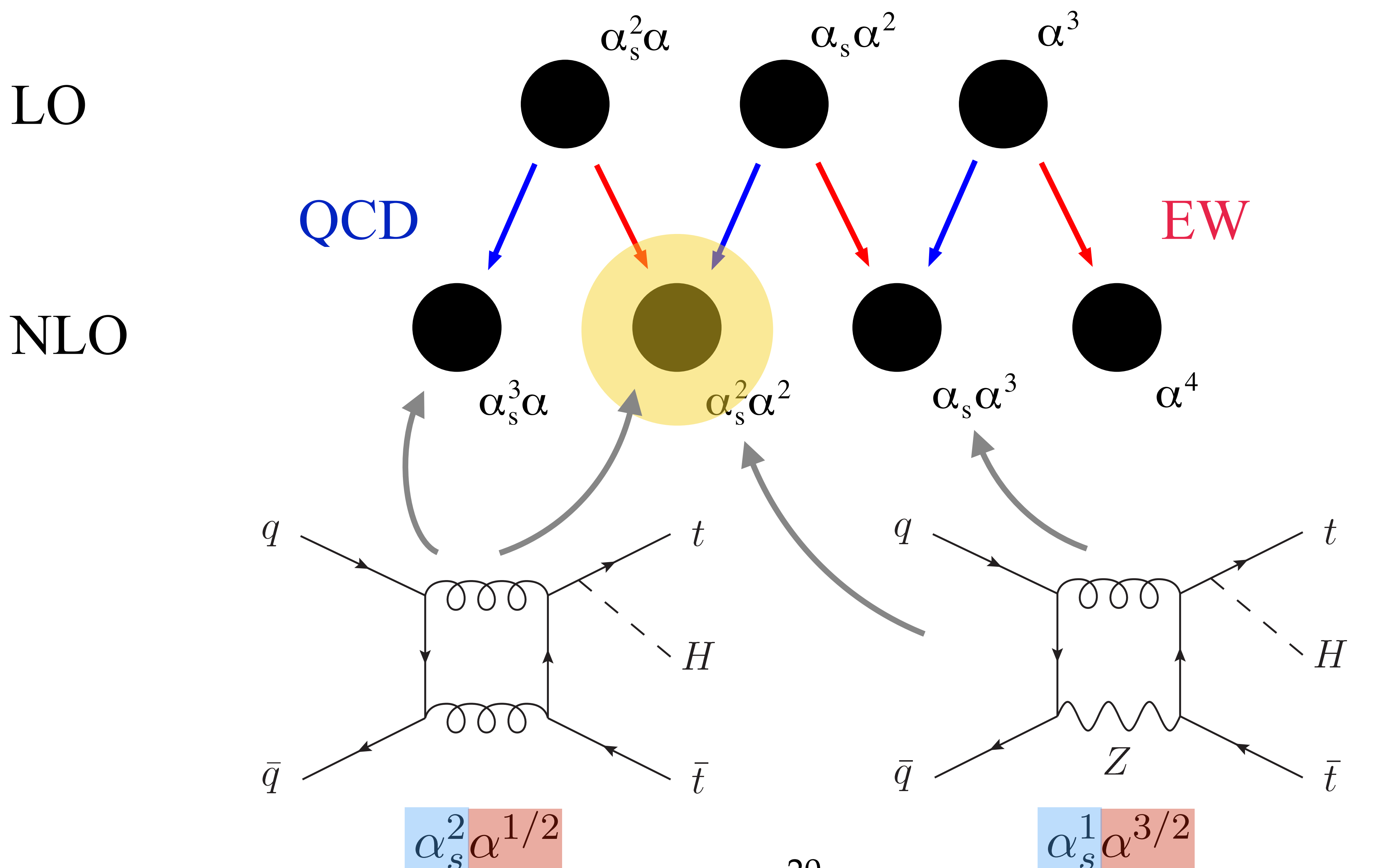


Structure of NLO EW-QCD corrections

$t\bar{t}H$

as example

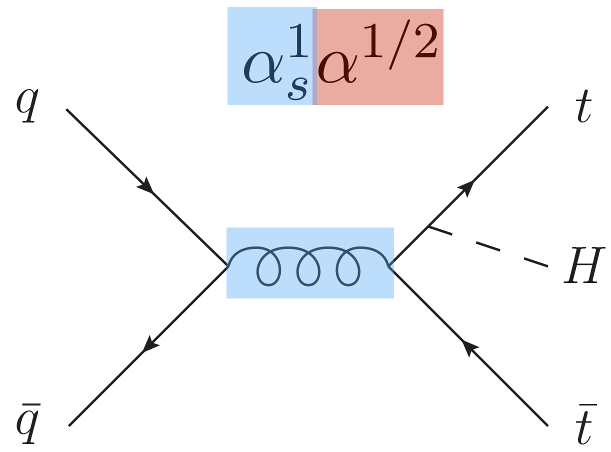


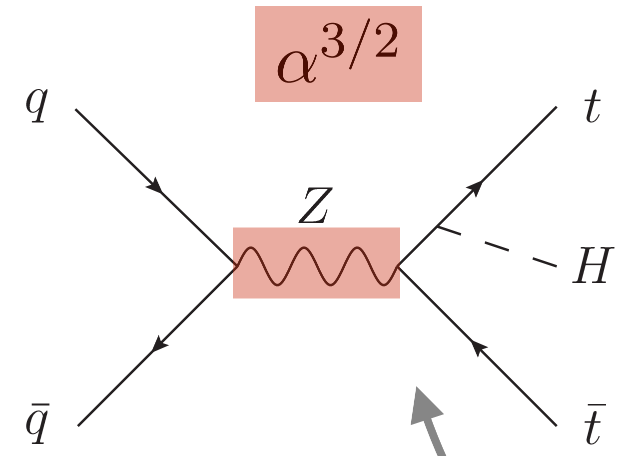


Structure of NLO EW-QCD corrections

$t\bar{t}H$

as example

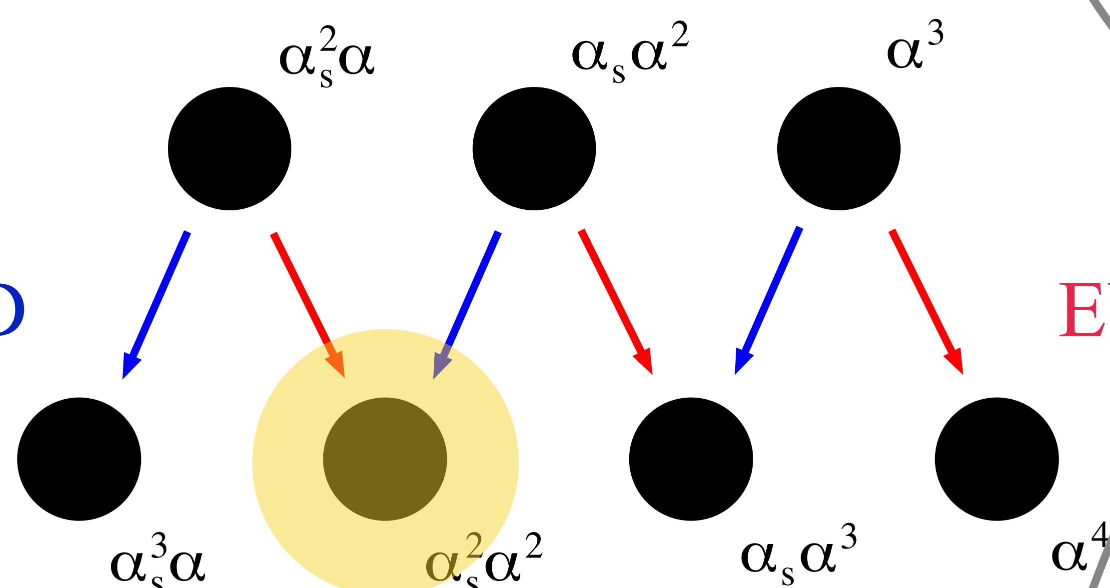




LO

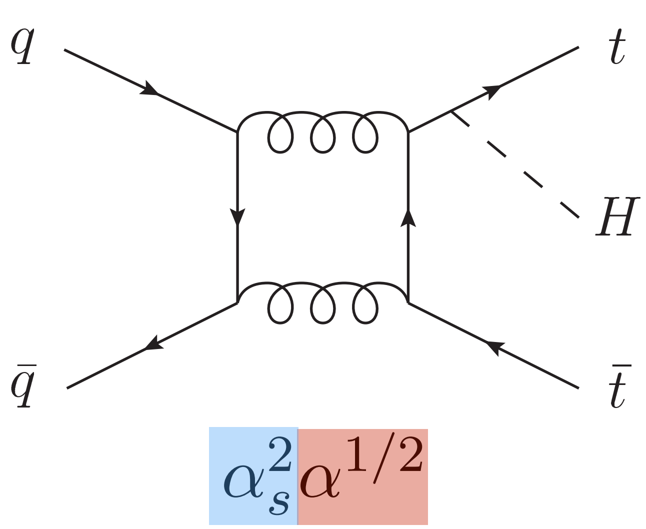
NLO

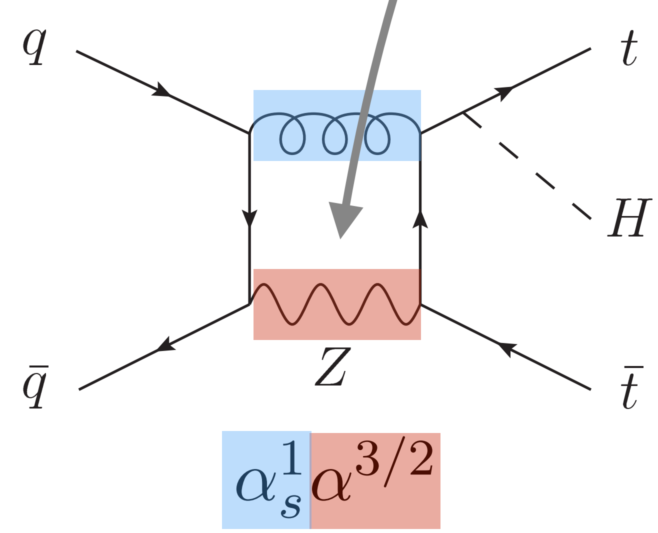
QCD



EW

If it is a photon, there are new IR singularities



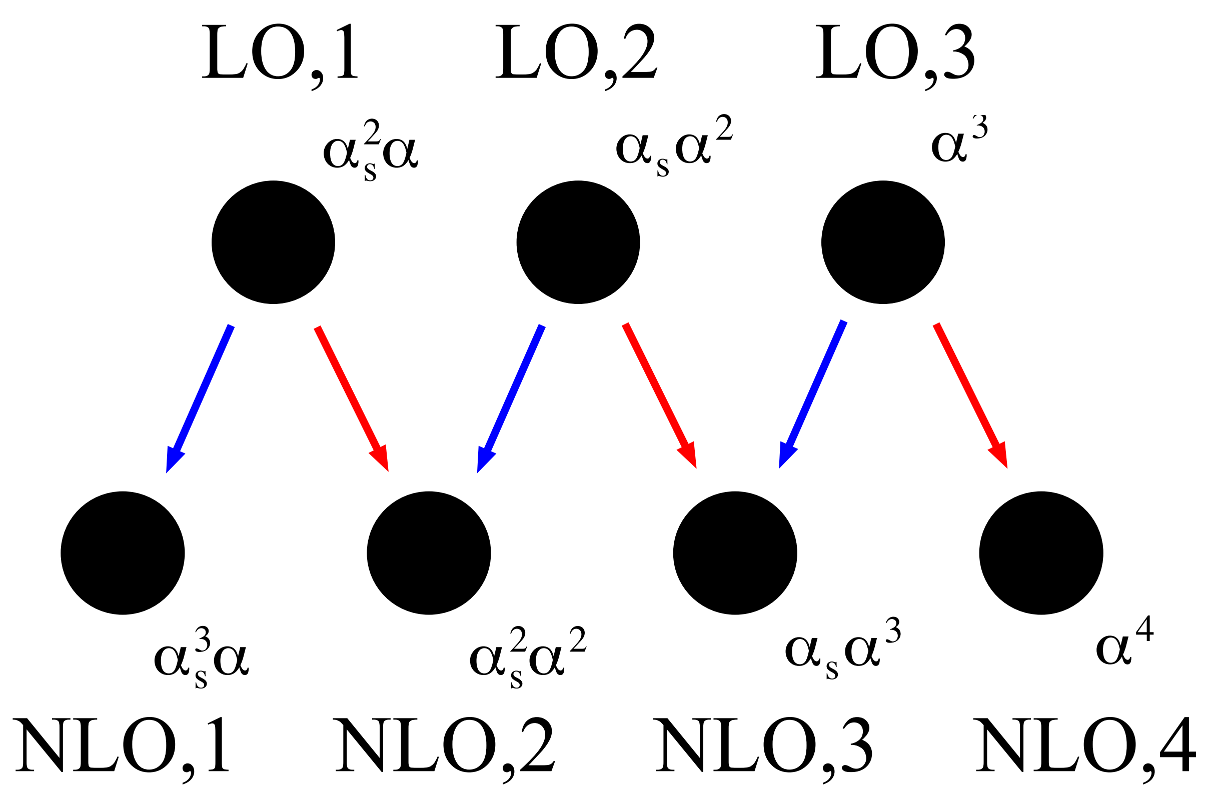


Structure of NLO EW-QCD corrections

$t\bar{t}H$

as example

All the LO,i and NLO,i can be calculated in a completely automated way. We denote the complete set of LO,i and NLO,i as **“Complete NLO”**.



NLO,1 = NLO QCD
NLO,2 = NLO EW

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

Results: NLO EW

just type:

```
set complex mass scheme true
import model loop_qcd_qed_sm_Gmu
generate process [QED]
output process_NLO_EW_corrections
```

And then wait for the results …………..

Results: NLO EW

Process	Syntax	Cross section (in pb)		Correction (in %)
		LO	NLO	
$pp \to e^+\nu_e$	`p p > e+ ve QCD=0 QED=2 [QED]`	$5.2498 \pm 0.0005 \cdot 10^3$	$5.2113 \pm 0.0006 \cdot 10^3$	-0.73 ± 0.01
$pp \to e^+\nu_e j$	`p p > e+ ve j QCD=1 QED=2 [QED]`	$9.1468 \pm 0.0012 \cdot 10^2$	$9.0449 \pm 0.0014 \cdot 10^2$	-1.11 ± 0.02
$pp \to e^+\nu_e jj$	`p p > e+ ve j j QCD=2 QED=2 [QED]`	$3.1562 \pm 0.0003 \cdot 10^2$	$3.0985 \pm 0.0005 \cdot 10^2$	-1.83 ± 0.02
$pp \to e^+e^-$	`p p > e+ e- QCD=0 QED=2 [QED]`	$7.5367 \pm 0.0008 \cdot 10^2$	$7.4997 \pm 0.0010 \cdot 10^2$	-0.49 ± 0.02
$pp \to e^+e^- j$	`p p > e+ e- j QCD=1 QED=2 [QED]`	$1.5059 \pm 0.0001 \cdot 10^2$	$1.4909 \pm 0.0002 \cdot 10^2$	-1.00 ± 0.02
$pp \to e^+e^- jj$	`p p > e+ e- j j QCD=2 QED=2 [QED]`	$5.1424 \pm 0.0004 \cdot 10^1$	$5.0410 \pm 0.0007 \cdot 10^1$	-1.97 ± 0.02
$pp \to e^+e^-\mu^+\mu^-$	`p p > e+ e- mu+ mu- QCD=0 QED=4 [QED]`	$1.2750 \pm 0.0000 \cdot 10^{-2}$	$1.2083 \pm 0.0001 \cdot 10^{-2}$	-5.23 ± 0.01
$pp \to e^+\nu_e\mu^-\bar{\nu}_\mu$	`p p > e+ ve mu- vm~ QCD=0 QED=4 [QED]`	$5.1144 \pm 0.0007 \cdot 10^{-1}$	$5.3019 \pm 0.0009 \cdot 10^{-1}$	$+3.67 \pm 0.02$
$pp \to He^+\nu_e$	`p p > h e+ ve QCD=0 QED=3 [QED]`	$6.7643 \pm 0.0001 \cdot 10^{-2}$	$6.4914 \pm 0.0012 \cdot 10^{-2}$	-4.03 ± 0.02
$pp \to He^+e^-$	`p p > h e+ e- QCD=0 QED=3 [QED]`	$1.4554 \pm 0.0001 \cdot 10^{-2}$	$1.3700 \pm 0.0002 \cdot 10^{-2}$	-5.87 ± 0.02
$pp \to Hjj$	`p p > h j j QCD=0 QED=3 [QED]`	$2.8268 \pm 0.0002 \cdot 10^0$	$2.7075 \pm 0.0003 \cdot 10^0$	-4.22 ± 0.01
$pp \to W^+W^-W^+$	`p p > w+ w- w+ QCD=0 QED=3 [QED]`	$8.2874 \pm 0.0004 \cdot 10^{-2}$	$8.8017 \pm 0.0012 \cdot 10^{-2}$	$+6.21 \pm 0.02$
$pp \to ZZW^+$	`p p > z z w+ QCD=0 QED=3 [QED]`	$1.9874 \pm 0.0001 \cdot 10^{-2}$	$2.0189 \pm 0.0003 \cdot 10^{-2}$	$+1.58 \pm 0.02$
$pp \to ZZZ$	`p p > z z z QCD=0 QED=3 [QED]`	$1.0761 \pm 0.0001 \cdot 10^{-2}$	$0.9741 \pm 0.0001 \cdot 10^{-2}$	-9.47 ± 0.02
$pp \to HZZ$	`p p > h z z QCD=0 QED=3 [QED]`	$2.1005 \pm 0.0003 \cdot 10^{-3}$	$1.9155 \pm 0.0003 \cdot 10^{-3}$	-8.81 ± 0.02
$pp \to HZW^+$	`p p > h z w+ QCD=0 QED=3 [QED]`	$2.4408 \pm 0.0000 \cdot 10^{-3}$	$2.4809 \pm 0.0005 \cdot 10^{-3}$	$+1.64 \pm 0.02$
$pp \to HHW^+$	`p p > h h w+ QCD=0 QED=3 [QED]`	$2.7827 \pm 0.0001 \cdot 10^{-4}$	$2.4259 \pm 0.0027 \cdot 10^{-4}$	-12.82 ± 0.10
$pp \to HHZ$	`p p > h h z QCD=0 QED=3 [QED]`	$2.6914 \pm 0.0003 \cdot 10^{-4}$	$2.3926 \pm 0.0003 \cdot 10^{-4}$	-11.10 ± 0.02
$pp \to t\bar{t}W^+$	`p p > t t~ w+ QCD=2 QED=1 [QED]`	$2.4119 \pm 0.0003 \cdot 10^{-1}$	$2.3025 \pm 0.0003 \cdot 10^{-1}$	-4.54 ± 0.02
$pp \to t\bar{t}Z$	`p p > t t~ z QCD=2 QED=1 [QED]`	$5.0456 \pm 0.0006 \cdot 10^{-1}$	$5.0033 \pm 0.0007 \cdot 10^{-1}$	-0.84 ± 0.02
$pp \to t\bar{t}H$	`p p > t t~ h QCD=2 QED=1 [QED]`	$3.4480 \pm 0.0004 \cdot 10^{-1}$	$3.5102 \pm 0.0005 \cdot 10^{-1}$	$+1.81 \pm 0.02$
$pp \to t\bar{t}j$	`p p > t t j QCD=3 QED=0 [QED]`	$3.0277 \pm 0.0003 \cdot 10^2$	$2.9683 \pm 0.0004 \cdot 10^2$	-1.96 ± 0.02
$pp \to jjj$	`p p > j j j QCD=3 QED=0 [QED]`	$7.9639 \pm 0.0010 \cdot 10^6$	$7.9472 \pm 0.0011 \cdot 10^6$	-0.21 ± 0.02
$pp \to tj$	`p p > t j QCD=0 QED=2 [QED]`	$1.0613 \pm 0.0001 \cdot 10^2$	$1.0539 \pm 0.0001 \cdot 10^2$	-0.70 ± 0.02

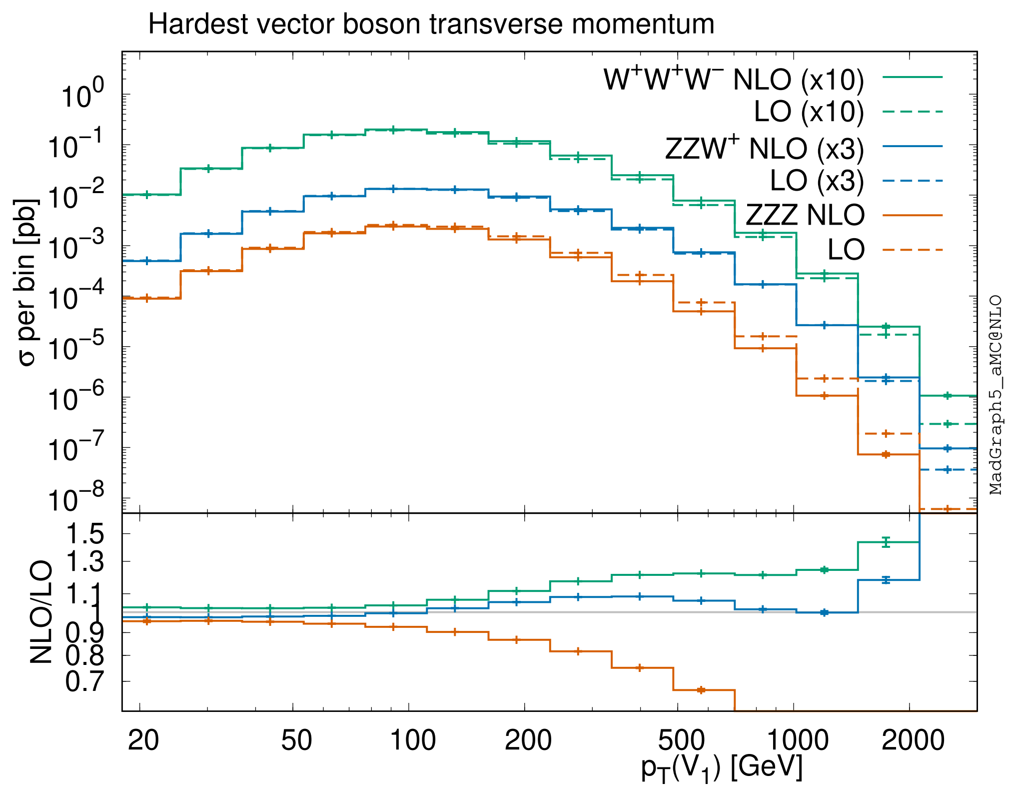
NEW

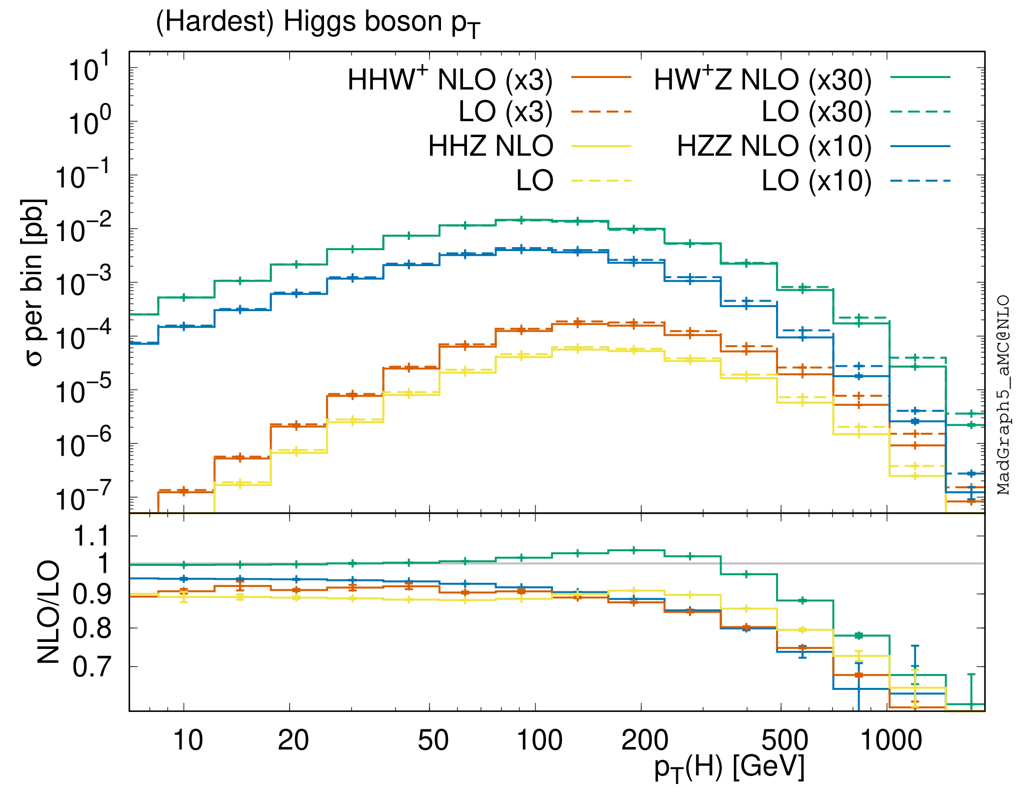
NEW

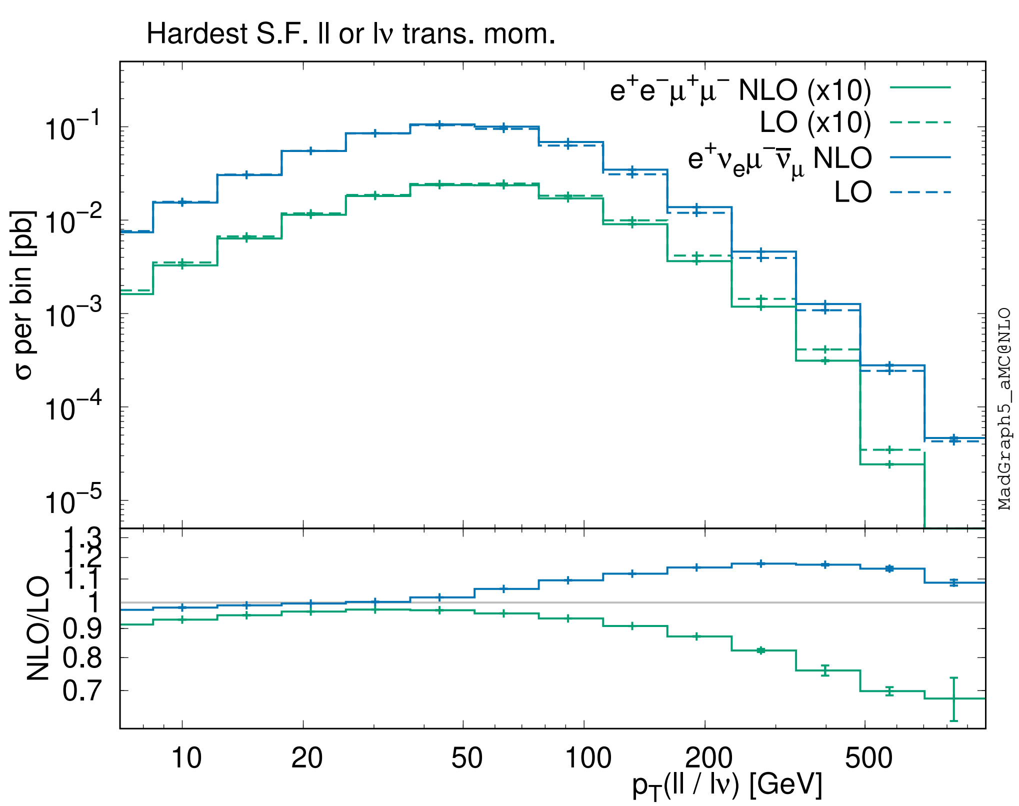
couple of weeks on $\mathcal{O}(200)$ CPUs

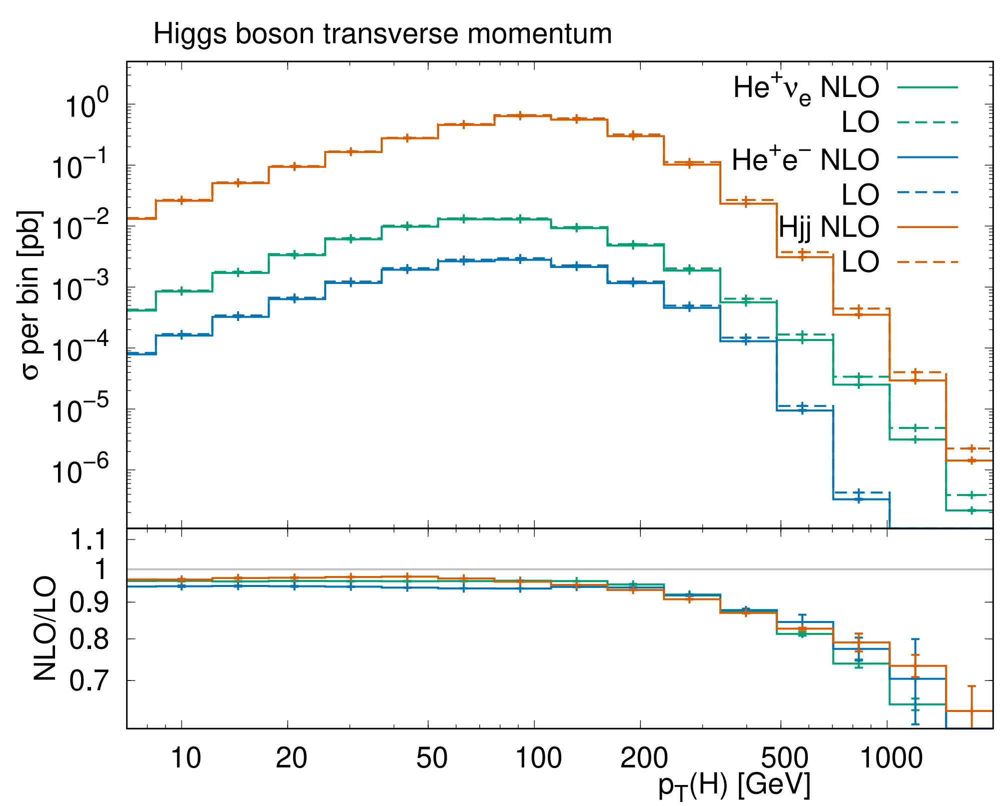
$$\delta_{\rm EW} = \frac{\Sigma_{\rm NLO_2}}{\Sigma_{\rm LO_1}} = \frac{\rm NLO}{\rm LO} - 1\,.$$

Results: NLO EW









Frederix, Frixione, Hirschi, DP, Shao, Zaro ‘18

Results: Complete NLO

just type:

```
set complex mass scheme true
import model loop_qcd_qed_sm_Gmu
generate process QCD=99 QED=99 [QCD QED]
output process_NLO_EW_corrections
```

And then wait for the results …………..

Results: Complete NLO

NEW

	$pp \to t\bar{t}$	$pp \to t\bar{t}Z$	$pp \to t\bar{t}W^+$	$pp \to t\bar{t}H$	$pp \to t\bar{t}j$
LO_1	$4.3803 \pm 0.0005 \cdot 10^{2}$ pb	$5.0463 \pm 0.0003 \cdot 10^{-1}$ pb	$2.4116 \pm 0.0001 \cdot 10^{-1}$ pb	$3.4483 \pm 0.0003 \cdot 10^{-1}$ pb	$3.0278 \pm 0.0003 \cdot 10^{2}$ pb
LO_2	$+0.405 \pm 0.001$ %	-0.691 ± 0.001 %	$+0.000 \pm 0.000$ %	$+0.406 \pm 0.001$ %	$+0.525 \pm 0.001$ %
LO_3	$+0.630 \pm 0.001$ %	$+2.259 \pm 0.001$ %	$+0.962 \pm 0.000$ %	$+0.702 \pm 0.001$ %	$+1.208 \pm 0.001$ %
LO_4					$+0.006 \pm 0.000$ %
NLO_1	$+46.164 \pm 0.022$ %	$+44.809 \pm 0.028$ %	$+49.504 \pm 0.015$ %	$+28.847 \pm 0.020$ %	$+26.571 \pm 0.063$ %
NLO_2	-1.075 ± 0.003 %	-0.846 ± 0.004 %	-4.541 ± 0.003 %	$+1.794 \pm 0.005$ %	-1.971 ± 0.022 %
NLO_3	$+0.552 \pm 0.002$ %	$+0.845 \pm 0.003$ %	$+12.242 \pm 0.014$ %	$+0.483 \pm 0.008$ %	$+0.292 \pm 0.007$ %
NLO_4	$+0.005 \pm 0.000$ %	-0.082 ± 0.000 %	$+0.017 \pm 0.003$ %	$+0.044 \pm 0.000$ %	$+0.009 \pm 0.000$ %
NLO_5					$+0.005 \pm 0.000$ %

$$\frac{\Sigma_{\mathrm{LO}_i}}{\Sigma_{\mathrm{LO}_1}}\,, \qquad i = 2, 3, 4\,,$$

$$\frac{\Sigma_{\mathrm{NLO}_i}}{\Sigma_{\mathrm{LO}_1}}\,, \qquad i = 1, \ldots 5\,;$$

NLO3 in ttW is ~12%:

A thorough phenomenological study is necessary!

Frederix, Frixione, Hirschi, DP, Shao, Zaro ‘18

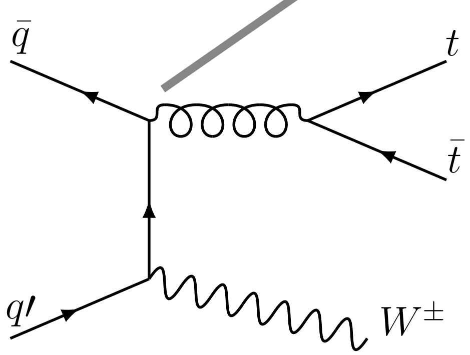
$t\bar{t}W^{\pm}$

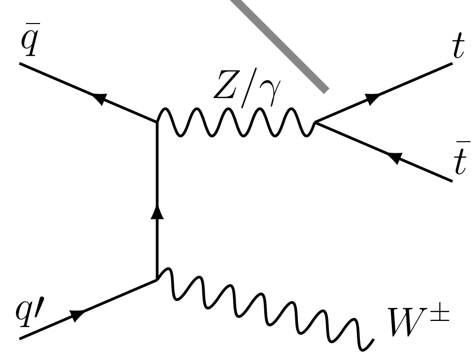
R. Frederix, D.P., M. Zaro
JHEP 1802 (2018) 031 (arXiv:1711.02116)

Complete-NLO

Frederix, DP, Zaro '17

$$\Sigma_{\mathrm{LO}}^{t\bar{t}W^\pm}(\alpha_s,\alpha) = \alpha_s^2\alpha\Sigma_{3,0}^{t\bar{t}W^\pm} + \alpha_s\alpha\Sigma_{3,1}^{t\bar{t}W^\pm} + \alpha^2\Sigma_{3,2}^{t\bar{t}W^\pm}$$
$$\equiv \Sigma_{\mathrm{LO}_1} + \cancel{\Sigma_{\mathrm{LO}_2}} + \Sigma_{\mathrm{LO}_3}\,,$$

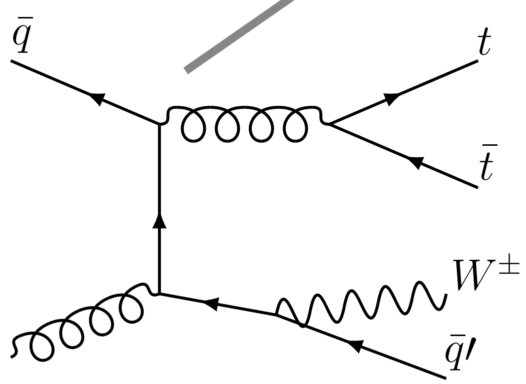


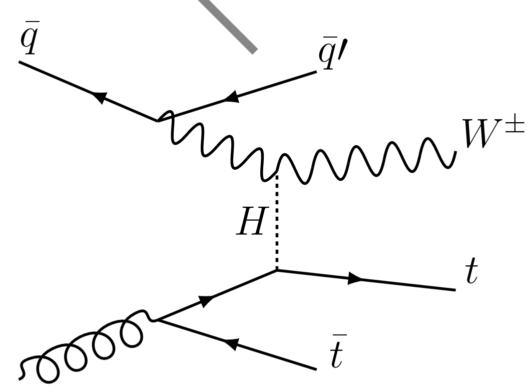


Only initial states without gluons are present.

$\Sigma_{\mathrm{LO}_1} \longrightarrow \mathrm{LO}_{\mathrm{QCD}}$

$$\Sigma_{\mathrm{NLO}}^{t\bar{t}W^\pm}(\alpha_s,\alpha) = \alpha_s^3\alpha\Sigma_{4,0}^{t\bar{t}W^\pm} + \alpha_s^2\alpha^2\Sigma_{4,1}^{t\bar{t}W^\pm} + \alpha_s\alpha^3\Sigma_{4,2}^{t\bar{t}W^\pm} + \alpha^4\Sigma_{4,3}^{t\bar{t}W^\pm}$$
$$\equiv \Sigma_{\mathrm{NLO}_1} + \Sigma_{\mathrm{NLO}_2} + \Sigma_{\mathrm{NLO}_3} + \Sigma_{\mathrm{NLO}_4}\,,$$





$\Sigma_{\mathrm{NLO}_1} \longrightarrow \mathrm{NLO}_{\mathrm{QCD}}$

$\Sigma_{\mathrm{NLO}_2} \longrightarrow \mathrm{NLO}_{\mathrm{EW}}$

MadGraph5_aMC@NLO

Cross sections: order by order

$$\delta_{(\mathrm{N})\mathrm{LO}_i}(\mu) = \frac{\Sigma_{(\mathrm{N})\mathrm{LO}_i}(\mu)}{\Sigma_{\mathrm{LO}_{\mathrm{QCD}}}(\mu)}$$

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

13 TeV

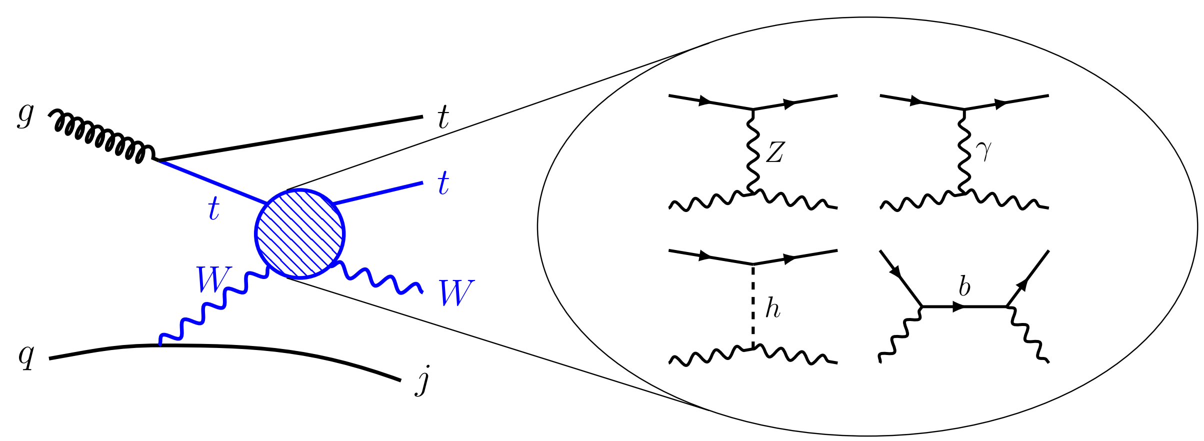
$\delta[\%]$	$\mu = H_T/4$	$\mu = H_T/2$	$\mu = H_T$	Naive estimate
LO_2	-	-	-	10
LO_3	0.8	0.9	1.1	1
NLO_1	34.8 (7.0)	50.0 (25.7)	63.4 (42.0)	10
NLO_2	$-4.4\,(-4.8)$	$-4.2\,(-4.6)$	$-4.0\,(-4.4)$	1
NLO_3	11.9 (8.9)	12.2 (9.1)	12.5 (9.3)	0.1
NLO_4	$0.02\,(-0.02)$	$0.04\,(-0.02)$	$0.05\,(-0.01)$	0.01

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)

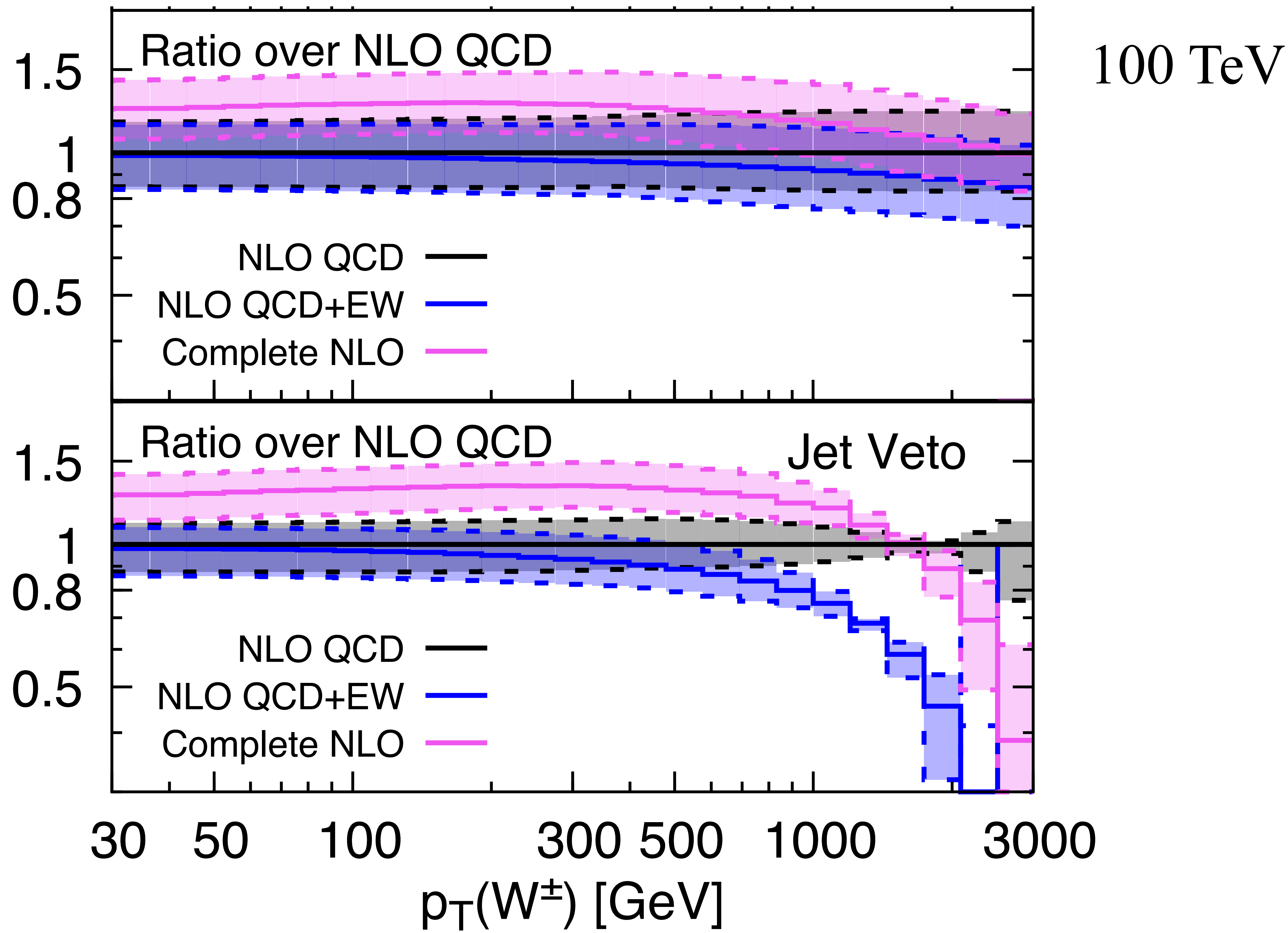
NLO3 is large and it is not suppressed by the jet veto (numbers in parentheses) as much as NLO QCD corrections.

NLO QCD corrections depend on the scale, while NLO EW and NLO3 do not.



Frederix, DP, Zaro '17

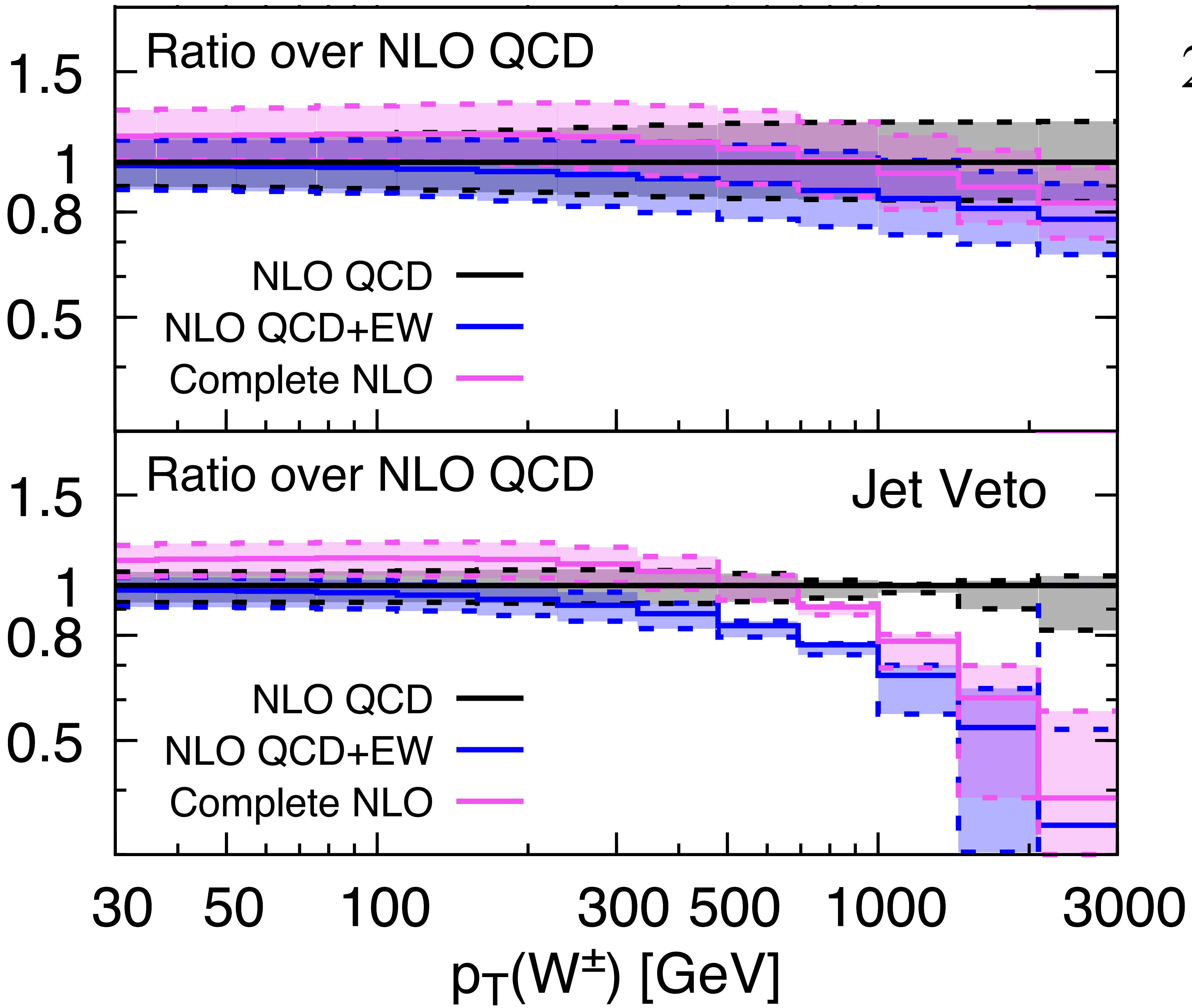
Distributions



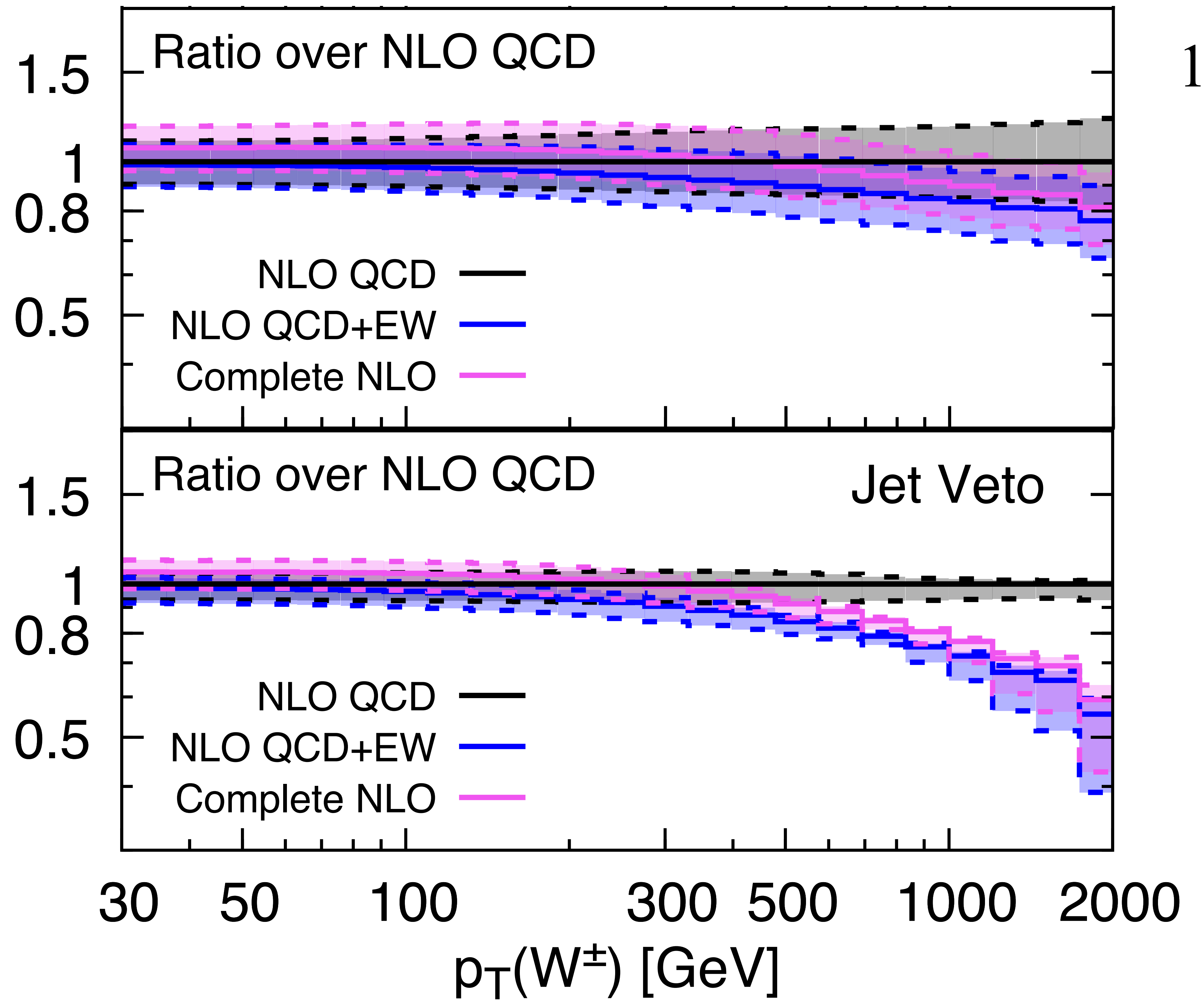
Frederix, DP, Zaro '17

Distributions

27 TeV



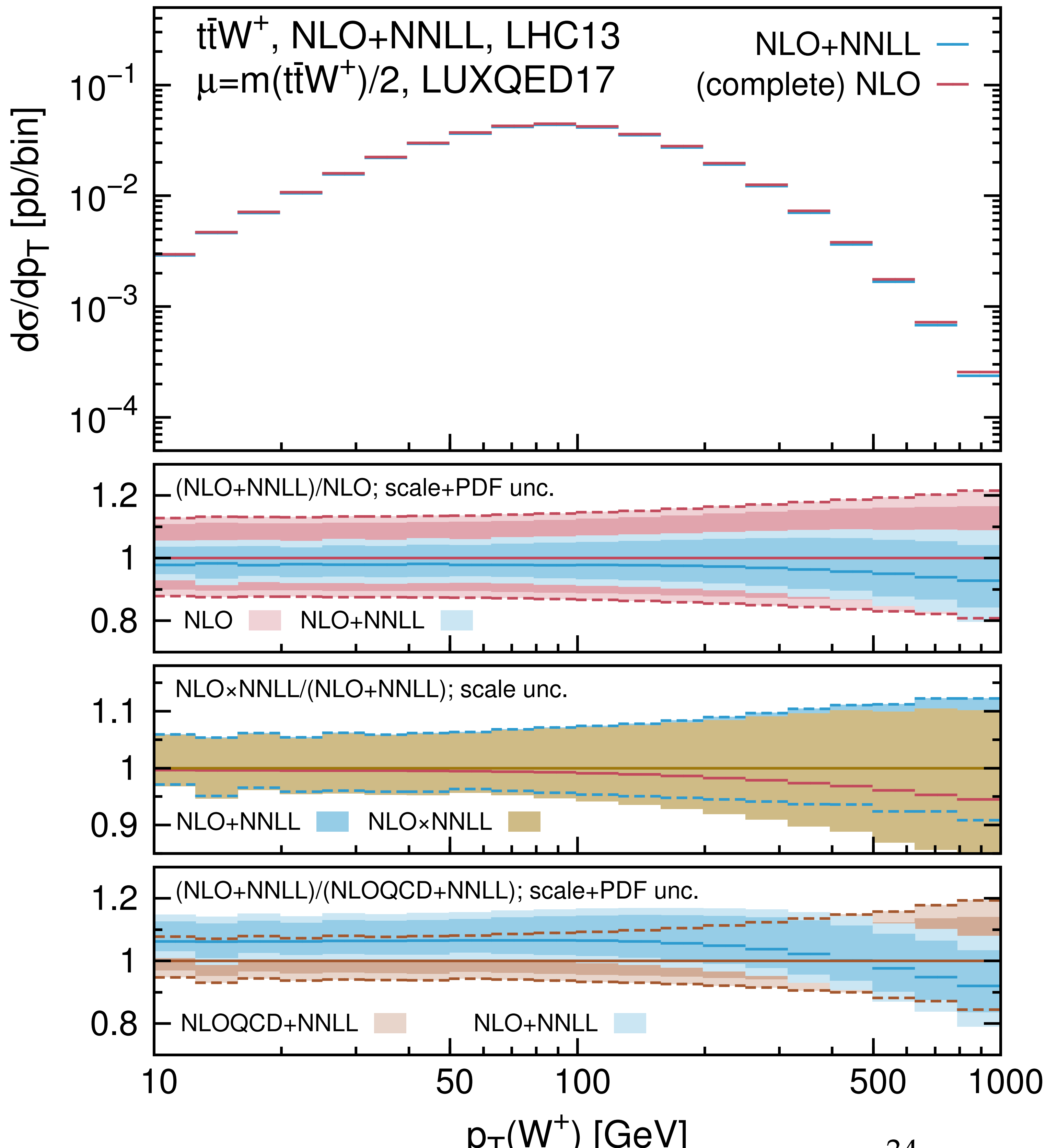
Distributions



13 TeV

Frederix, DP, Zaro '17

And including resummation



Broggio, Ferroglia Frederix, Pagani, Pecjak, Tsinikos arXiv 19xx.xxxxx

Including NNLL resummation of soft-gluon effects, scale uncertainties are reduced.
They are of the same order of EW effects.

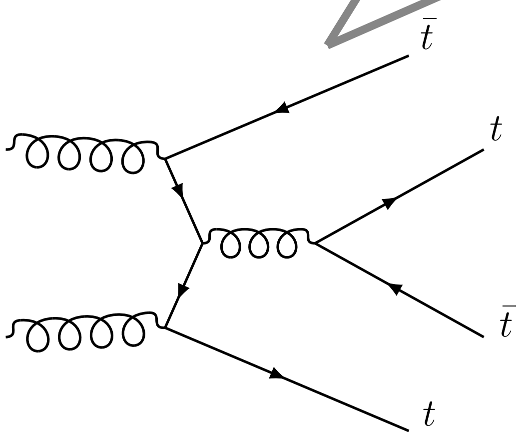
$t\bar{t}t\bar{t}$

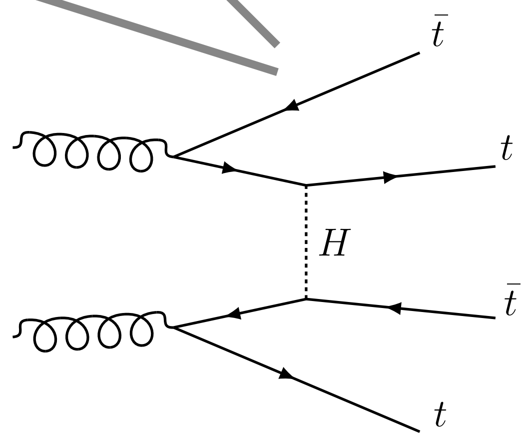
R. Frederix, D.P., M. Zaro
JHEP 1802 (2018) 031 (arXiv:1711.02116)

Complete-NLO

$$\Sigma^{t\bar{t}t\bar{t}}_{\mathrm{LO}}(\alpha_s,\alpha) = \alpha_s^4\Sigma^{t\bar{t}t\bar{t}}_{4,0} + \alpha_s^3\alpha\Sigma^{t\bar{t}t\bar{t}}_{4,1} + \alpha_s^2\alpha^2\Sigma^{t\bar{t}t\bar{t}}_{4,2} + \alpha_s^3\alpha\Sigma^{t\bar{t}t\bar{t}}_{4,3} + \alpha^4\Sigma^{t\bar{t}t\bar{t}}_{4,4}$$
$$\equiv \Sigma_{\mathrm{LO}_1} + \Sigma_{\mathrm{LO}_2} + \Sigma_{\mathrm{LO}_3} + \Sigma_{\mathrm{LO}_4} + \Sigma_{\mathrm{LO}_5}\,.$$

Frederix, DP, Zaro '17

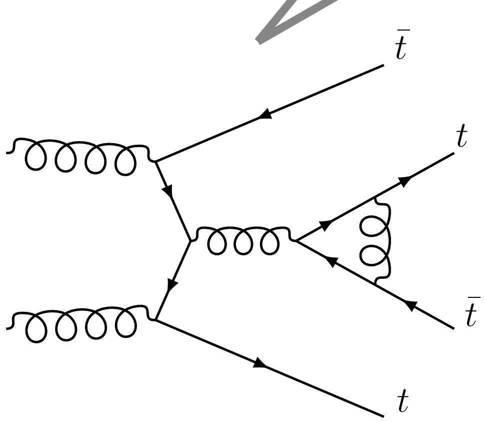


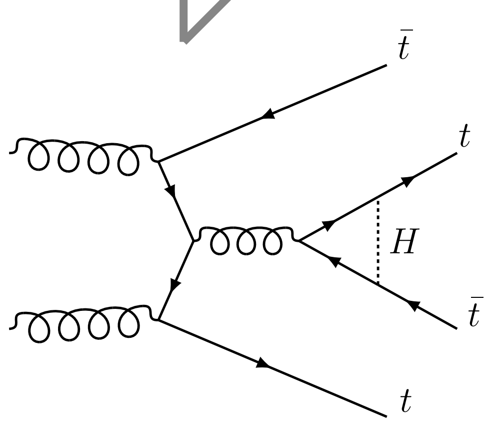


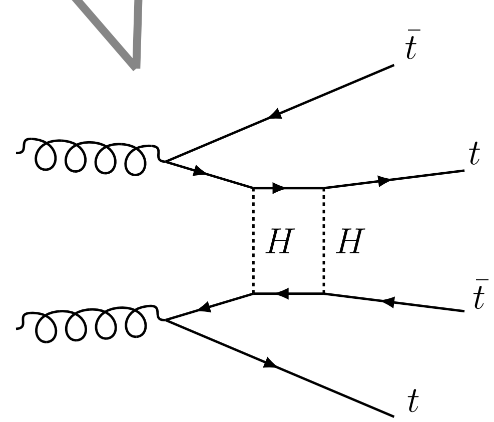
The gg initial state amounts to ~90% of LO cross section at 13 TeV and almost all the cross section at 100 TeV.

There is no gg contribution at LO4 and LO5.

$$\Sigma^{t\bar{t}t\bar{t}}_{\mathrm{NLO}}(\alpha_s,\alpha) = \alpha_s^5\Sigma^{t\bar{t}t\bar{t}}_{5,0} + \alpha_s^4\alpha^1\Sigma^{t\bar{t}t\bar{t}}_{5,1} + \alpha_s^3\alpha^2\Sigma^{t\bar{t}t\bar{t}}_{5,2} + \alpha_s^2\alpha^3\Sigma^{t\bar{t}t\bar{t}}_{5,3} + \alpha_s^1\alpha^4\Sigma^{t\bar{t}t\bar{t}}_{5,4} + \alpha^5\Sigma^{t\bar{t}t\bar{t}}_{5,5}$$
$$\equiv \Sigma_{\mathrm{NLO}_1} + \Sigma_{\mathrm{NLO}_2} + \Sigma_{\mathrm{NLO}_3} + \Sigma_{\mathrm{NLO}_4} + \Sigma_{\mathrm{NLO}_5} + \Sigma_{\mathrm{NLO}_6}\,.$$







There is no gg contribution at NLO4 and NLO5.

MadGraph5_aMC@NLO

36

Cross sections

13 TeV

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-26.0	-28.3	-30.5
LO_3	32.6	39.0	45.9
LO_4	0.2	0.3	0.4
LO_5	0.02	0.03	0.05
NLO_1	14.0	62.7	103.5
NLO_2	8.6	-3.3	-15.1
NLO_3	-10.3	1.8	16.1
NLO_4	2.3	2.8	3.6
NLO_5	0.12	0.16	0.19
NLO_6	< 0.01	< 0.01	< 0.01
$\mathrm{NLO}_2 + \mathrm{NLO}_3$	-1.7	-1.6	0.9

Naive estimate

LO_2	10
LO_3	1
LO_4	0.1
LO_5	0.01
NLO_1	10
NLO_2	1
NLO_3	0.1
NLO_4	0.01
NLO_5	0.001
NLO_6	0.0001

100 TeV

$\delta[\%]$	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-18.7	-20.7	-22.8
LO_3	26.3	31.8	37.8
LO_4	0.05	0.07	0.09
LO_5	0.03	0.05	0.08
NLO_1	33.9	68.2	98.0
NLO_2	-0.3	-5.7	-11.6
NLO_3	-3.9	1.7	8.9
NLO_4	0.7	0.9	1.2
NLO_5	0.12	0.14	0.16
NLO_6	< 0.01	< 0.01	< 0.01
$\mathrm{NLO}_2 + \mathrm{NLO}_3$	-4.2	-4.0	2.7

Frederix, DP, Zaro '17

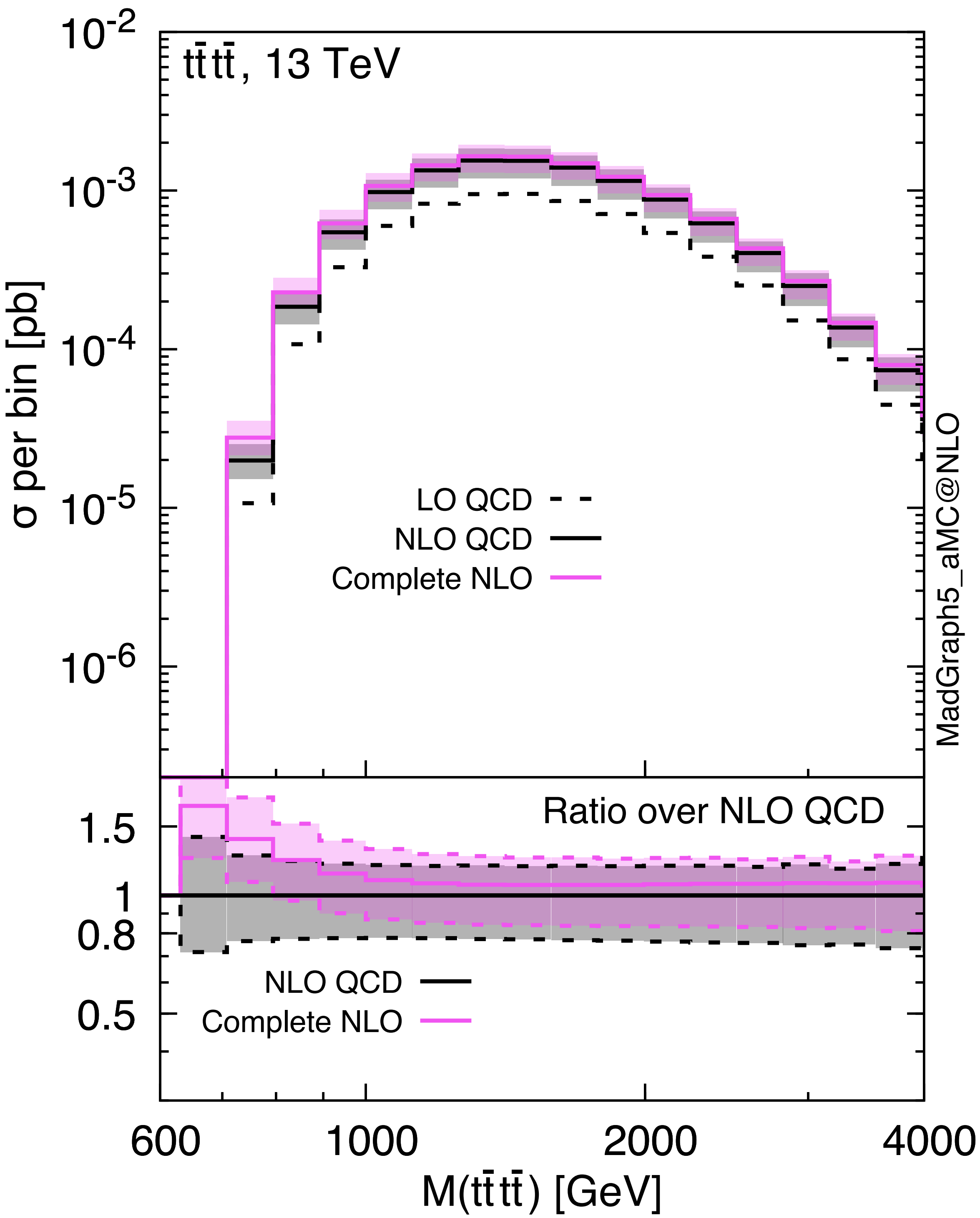
LO_2 and LO_3 are large and have also large cancellations.

NLO_2 and NLO_3 are mainly given by 'QCD corrections' on top of them, so they are large and strongly depend on the scale choice, at variance with standard EW corrections.

Accidentally, relatively to LO_1, NLO_2+NLO_3 scale dependence almost disappears.

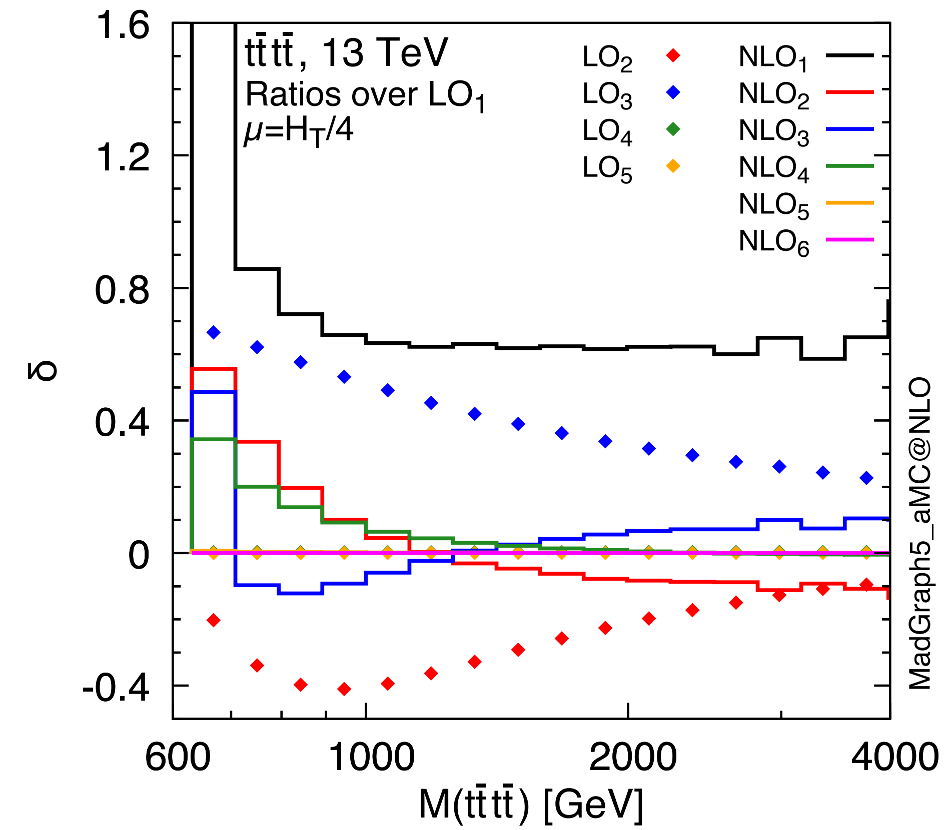
What happens if BSM enters into the game? Anomalous y_t ?

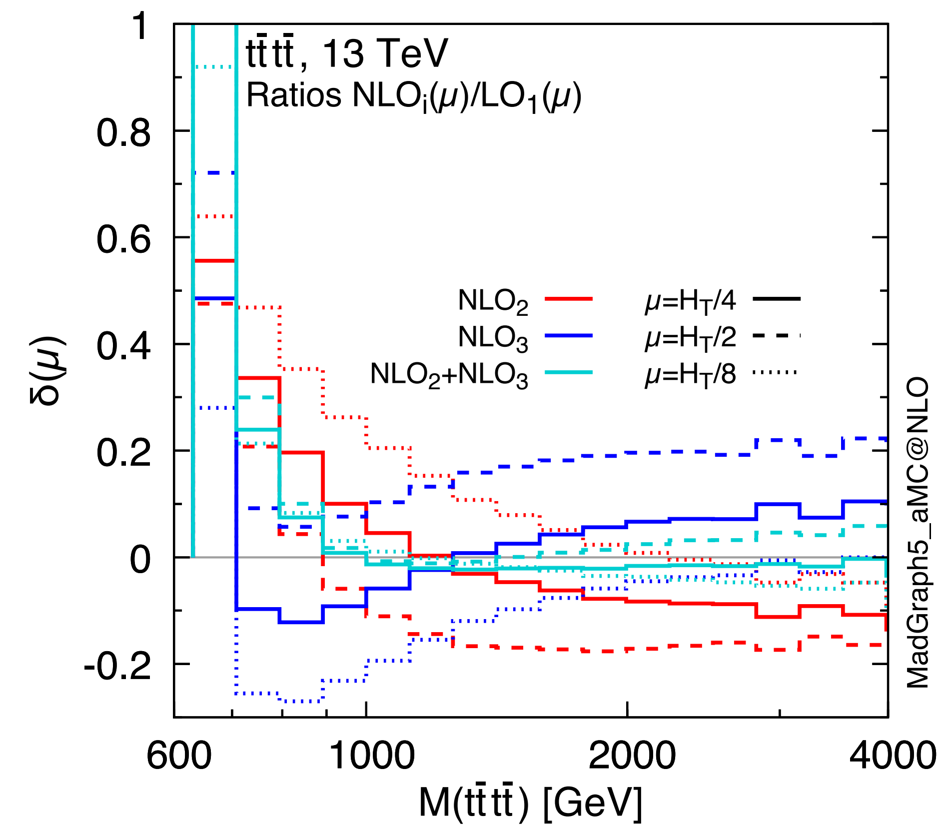
Distributions



13 TeV

Frederix, DP, Zaro '17





Large cancellations among (N)LO2 and (N)LO3 are present also at the differential level.
At the threshold also NLO4 is large.

Combination with NNLO QCD

$$t\bar{t}$$

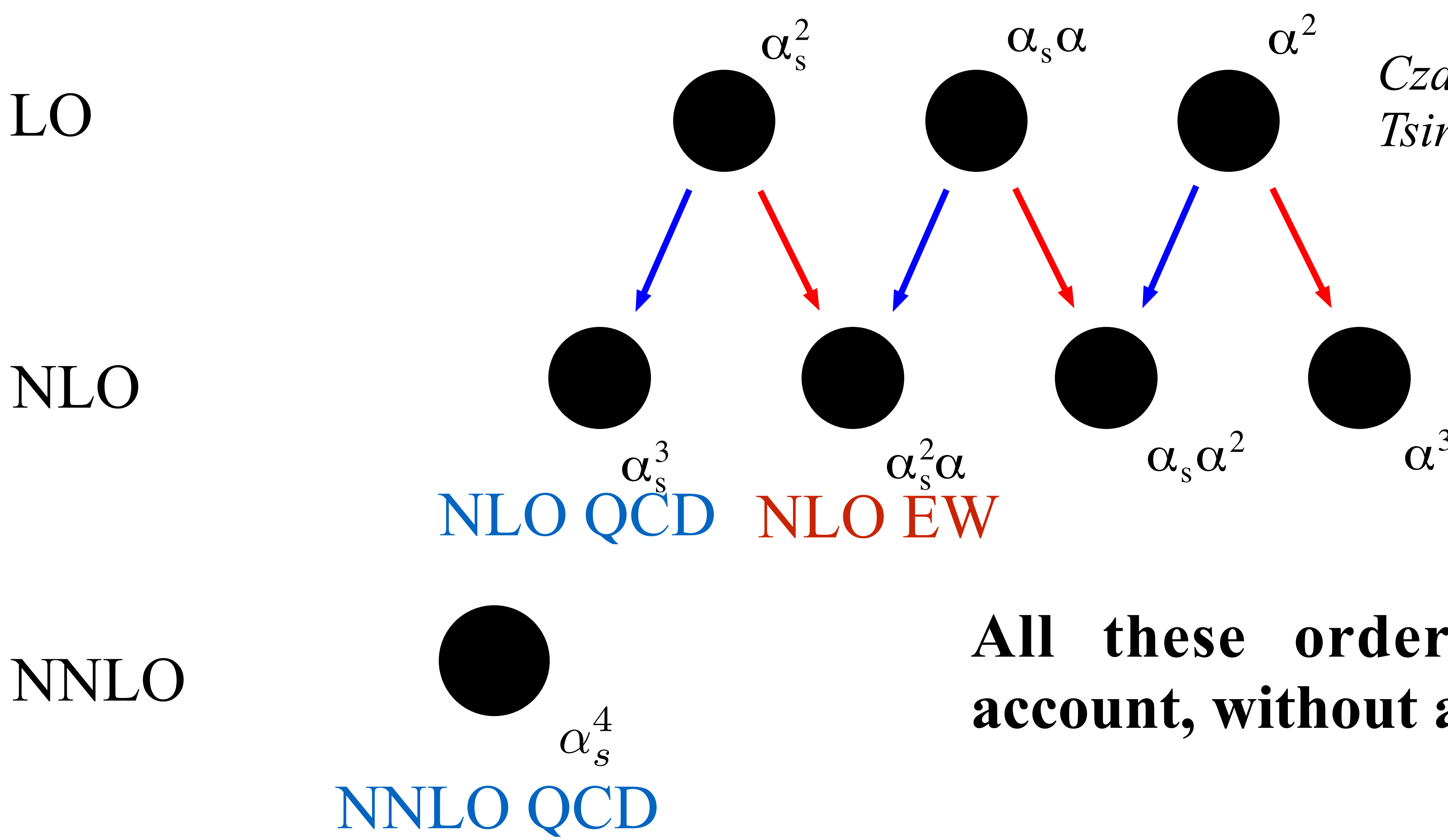
M. Czakon, D. Heymes, A. Mitov, D.P., I.Tsinikos, M. Zaro
JHEP 1710 (2017) 186 (arXiv:1705.04105)

NNLO QCD combined with complete-NLO

The calculation of **NNLO QCD** corrections is based on
Czakon, Fiedler, Mitov '15

The calculation of the **complete NLO** corrections is performed with the EW branch of **MadGraph5_aMC@NLO**.

Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '17

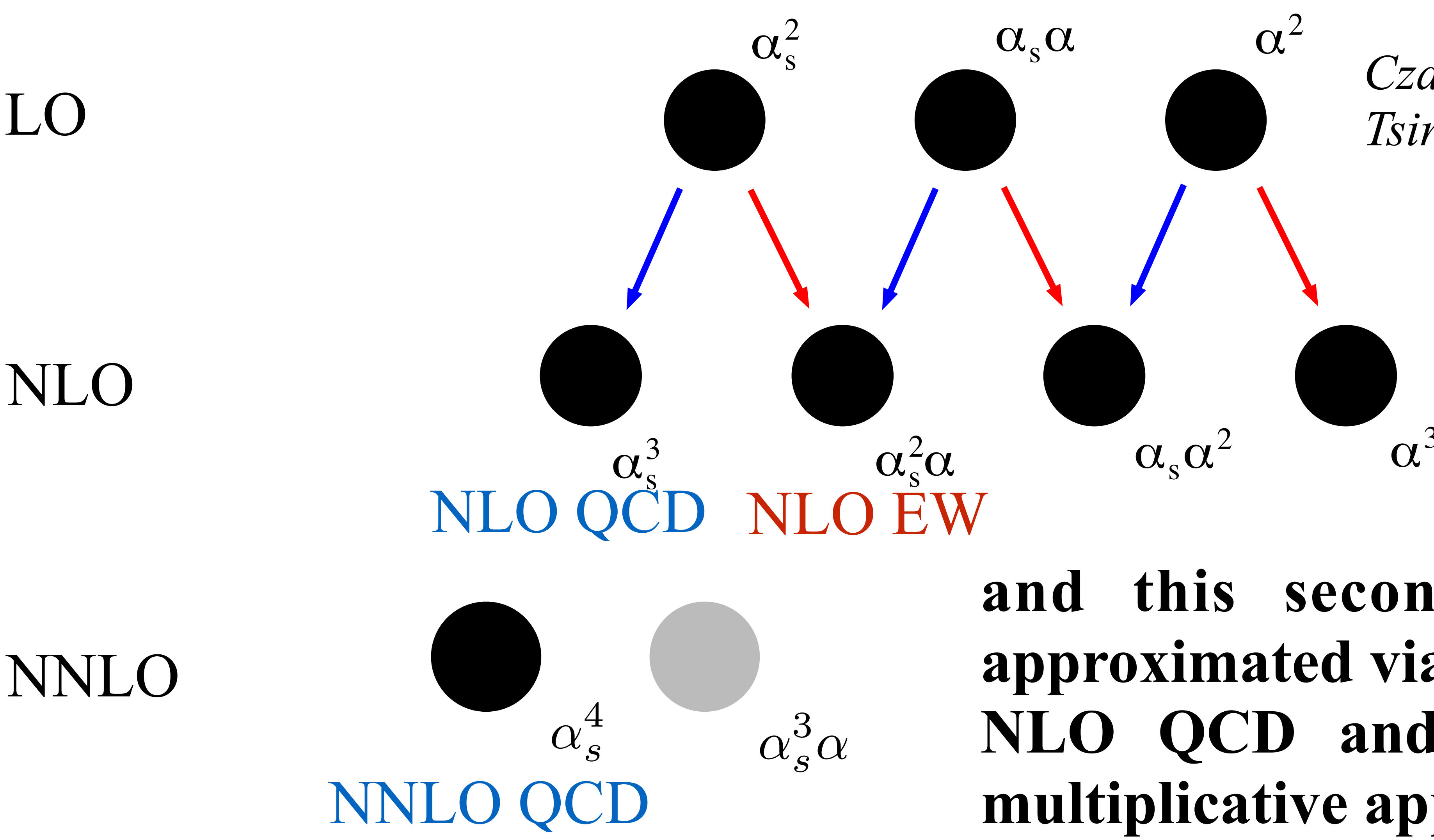


All these orders are taken into account, without any approximation.

NNLO QCD combined with complete-NLO

The calculation of **NNLO QCD** corrections is based on
Czakon, Fiedler, Mitov ’15

The calculation of the **complete NLO** corrections is performed with the EW branch of **MadGraph5_aMC@NLO**.



Czakon, Heymes, Mitov, DP, Tsinikos, Zaro ’17

and this second NNLO term is approximated via the combination of NLO QCD and NLO EW in the multiplicative approach.

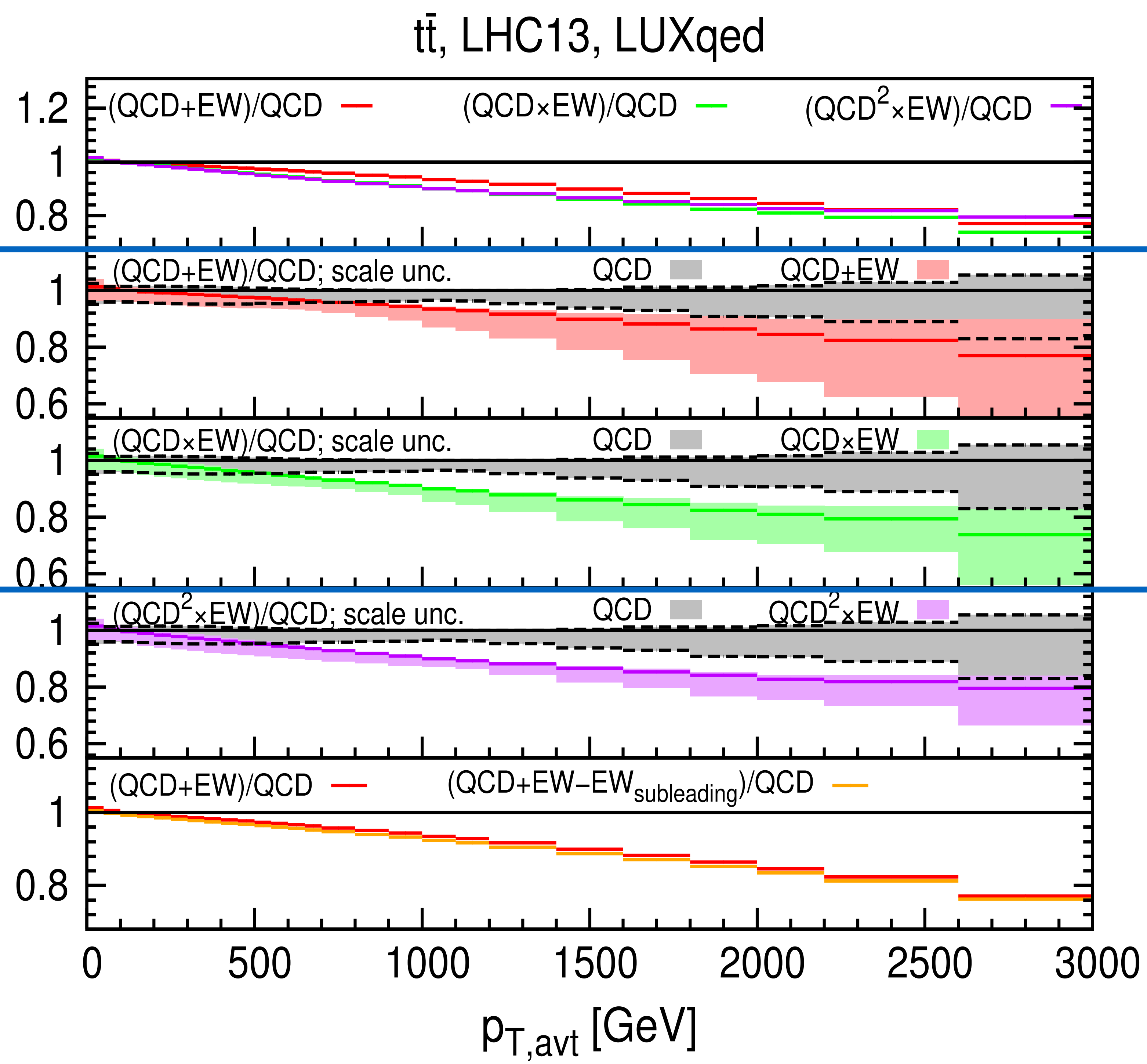
Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '17

$p_{T,\mathrm{avt}}$

13 TeV

ADDITIVE

MULTIPLICATIVE



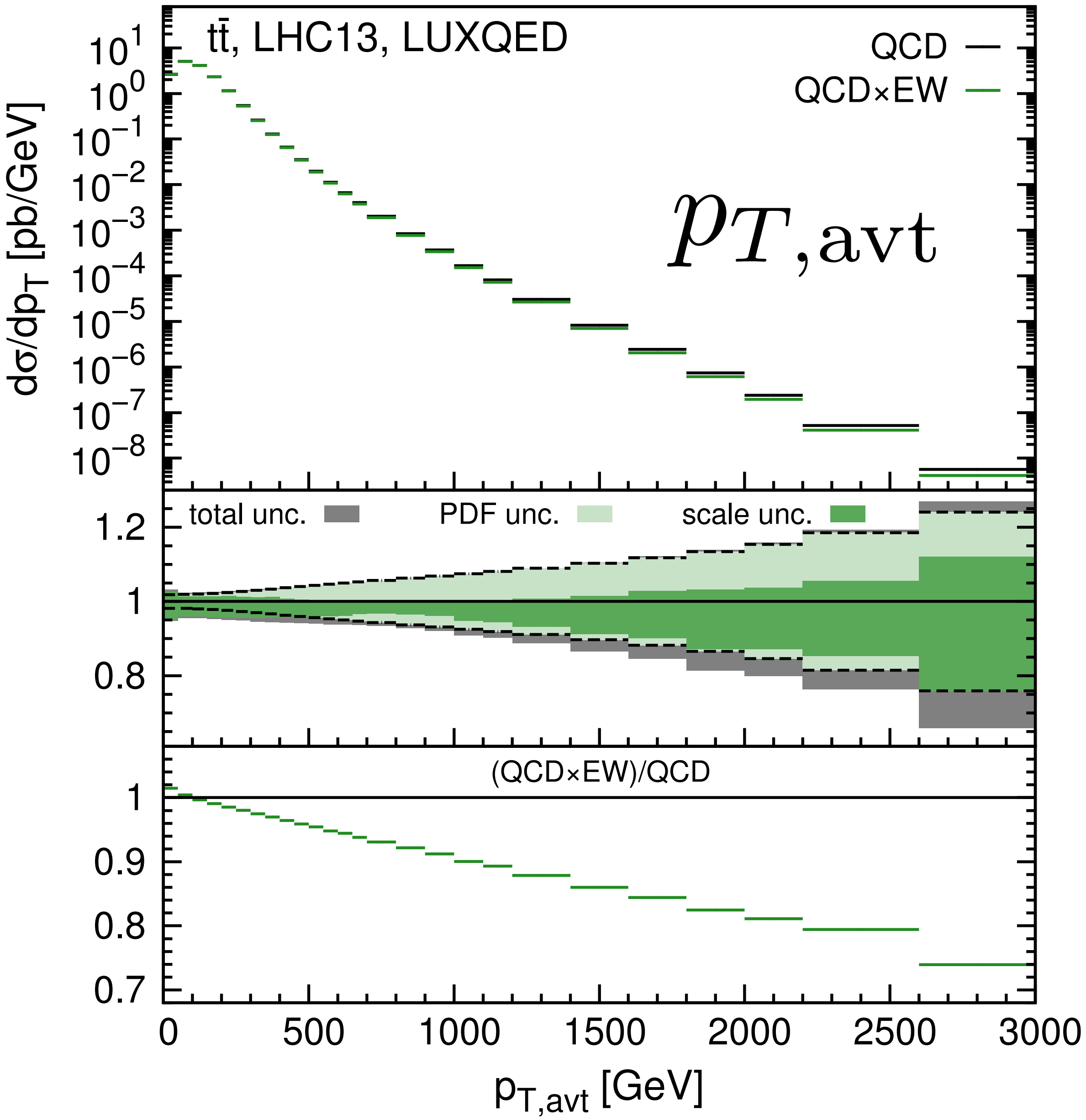
reduction of scale unc. due to EW corrections, QCD and QCDxEW do not overlap (with LUXQED)

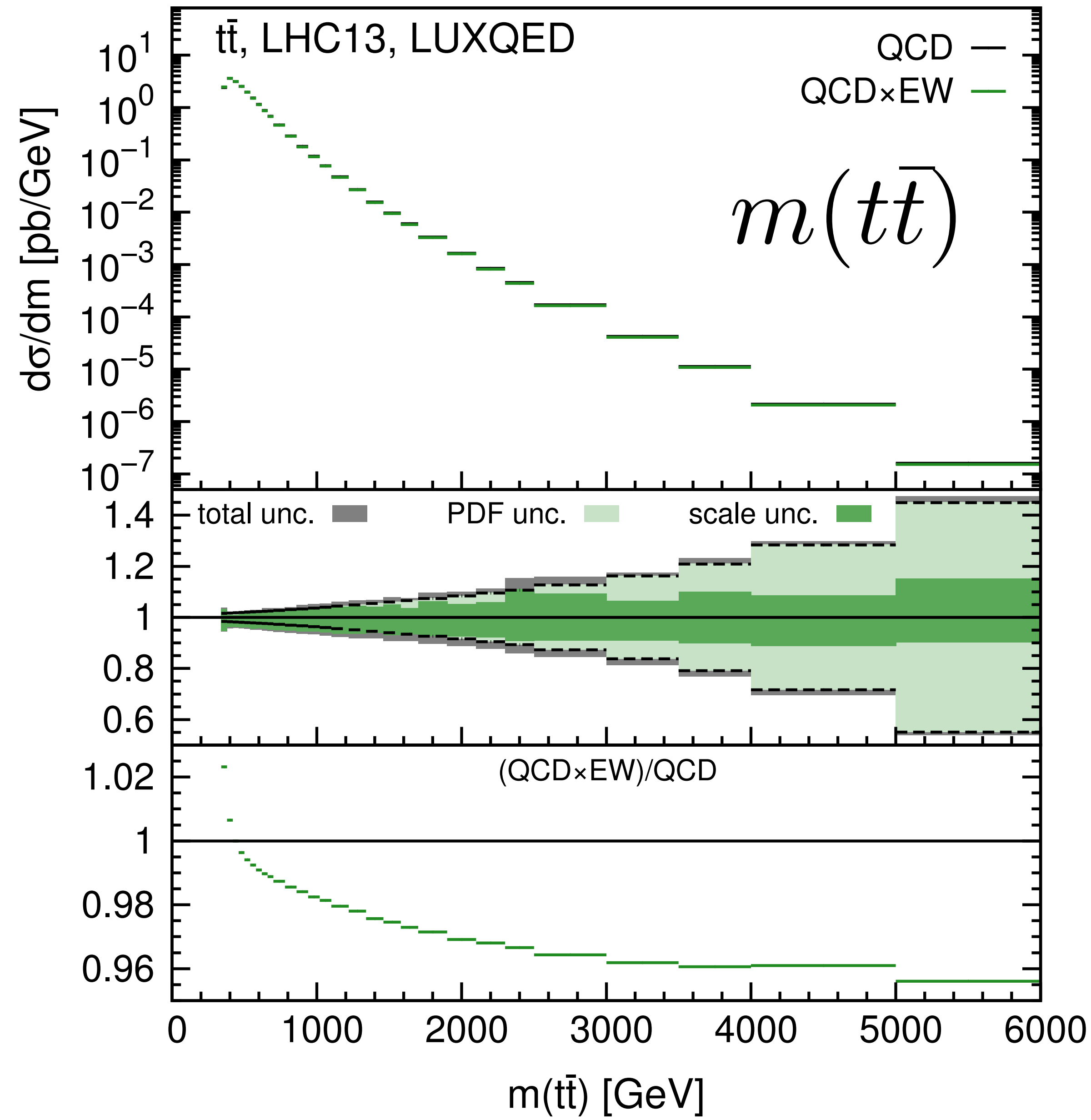
Reference Predictions

already used by CMS and ATLAS,

13 TeV

Czakon, Heymes, Mitov,
DP, Tsinikos, Zaro ’17



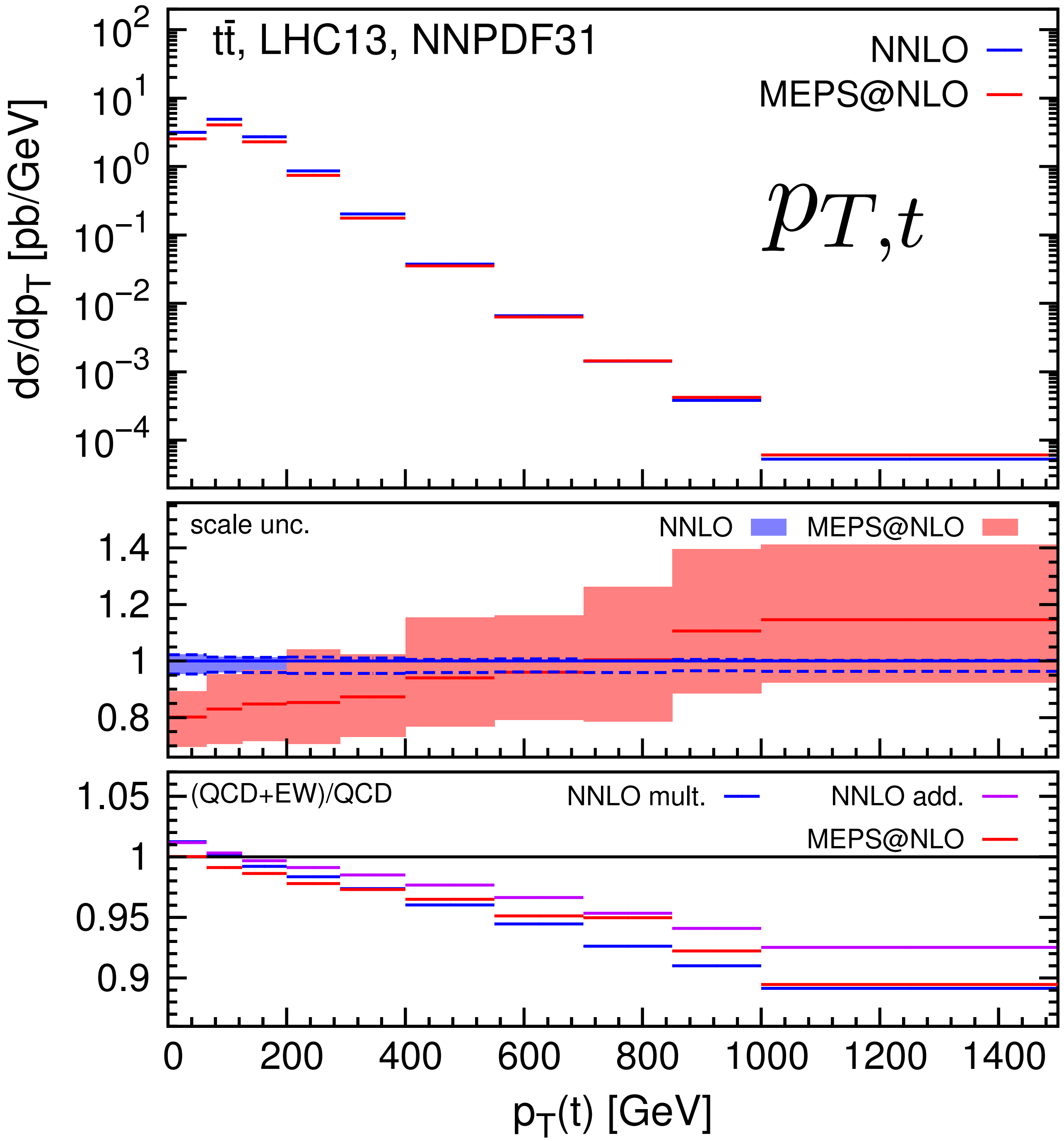


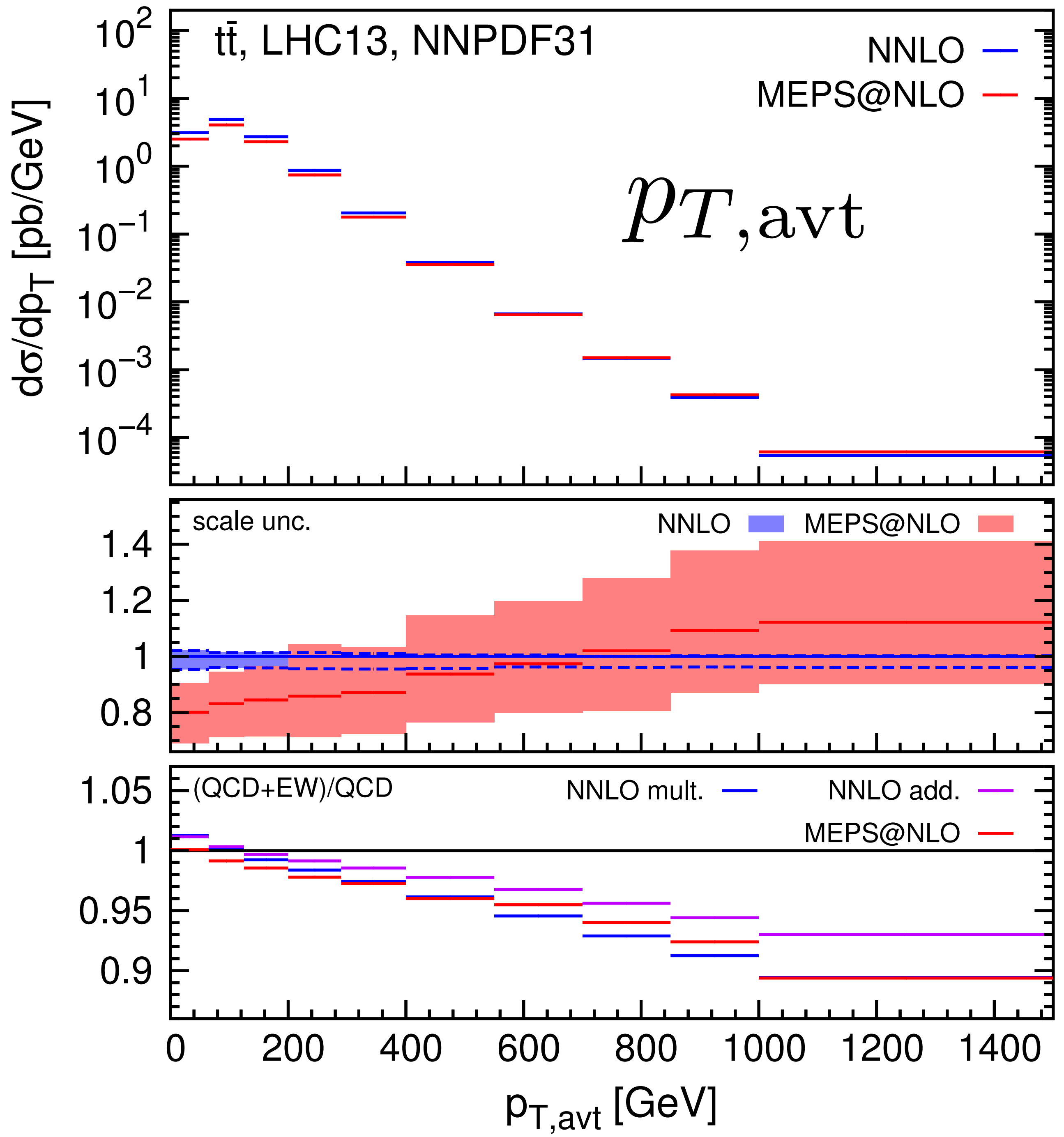
scale unc. ~ PDF unc
EW corrections ~ theory error

scale unc. < PDF unc

NNLO vs MEPS@NLO, including Complete NLO

Czakon, Gütschow, Lindert, Mitov, DP, Papanastasiou Schönherr, Tsinikos, Zaro ‘19

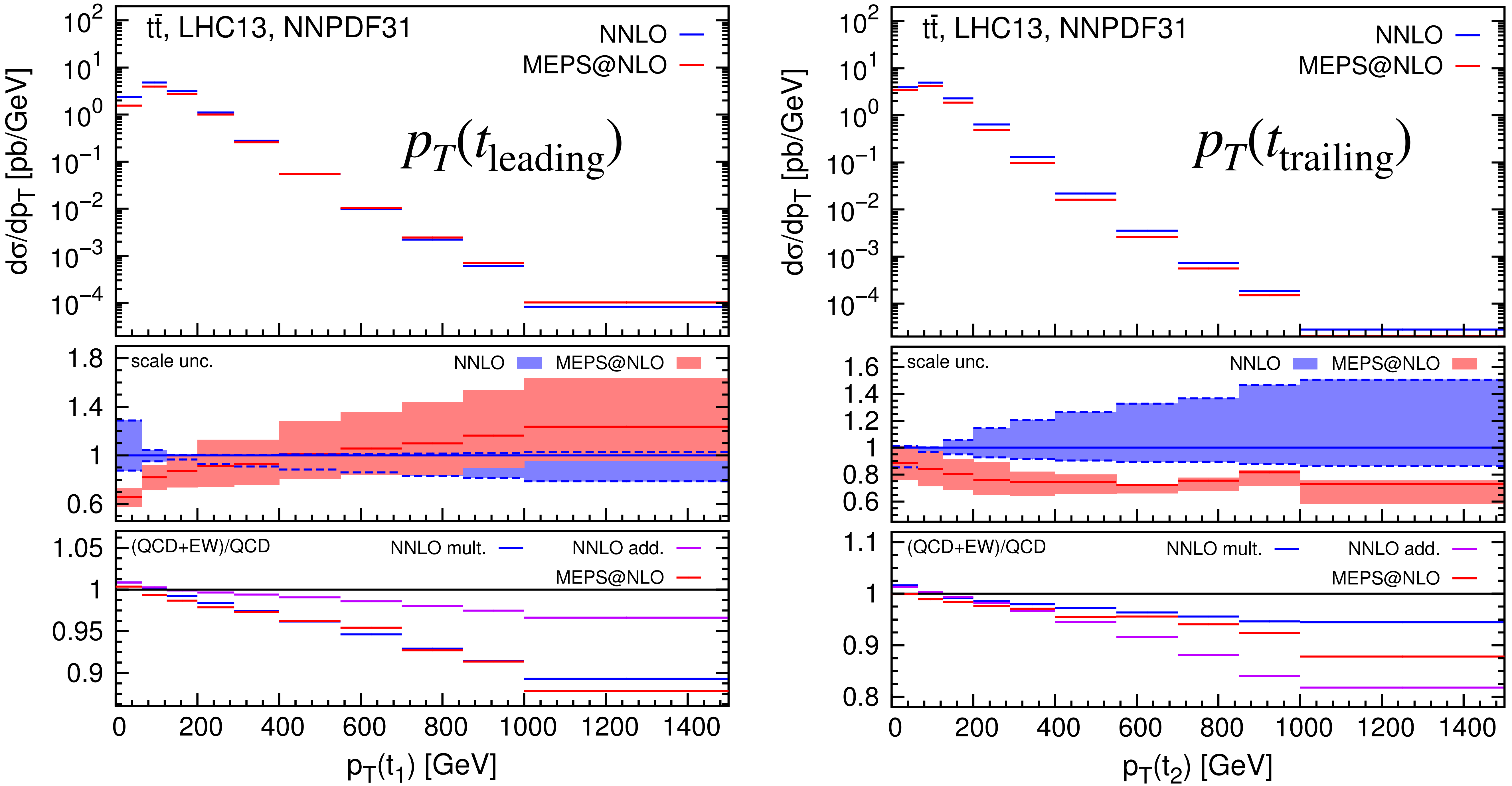




Predictions are **compatible**, with a **smaller scale unc**. for the **NNLO** case.
MEPS@NLO further **supports** the **multiplicative** approach.

NNLO vs MEPS@NLO, including Complete NLO

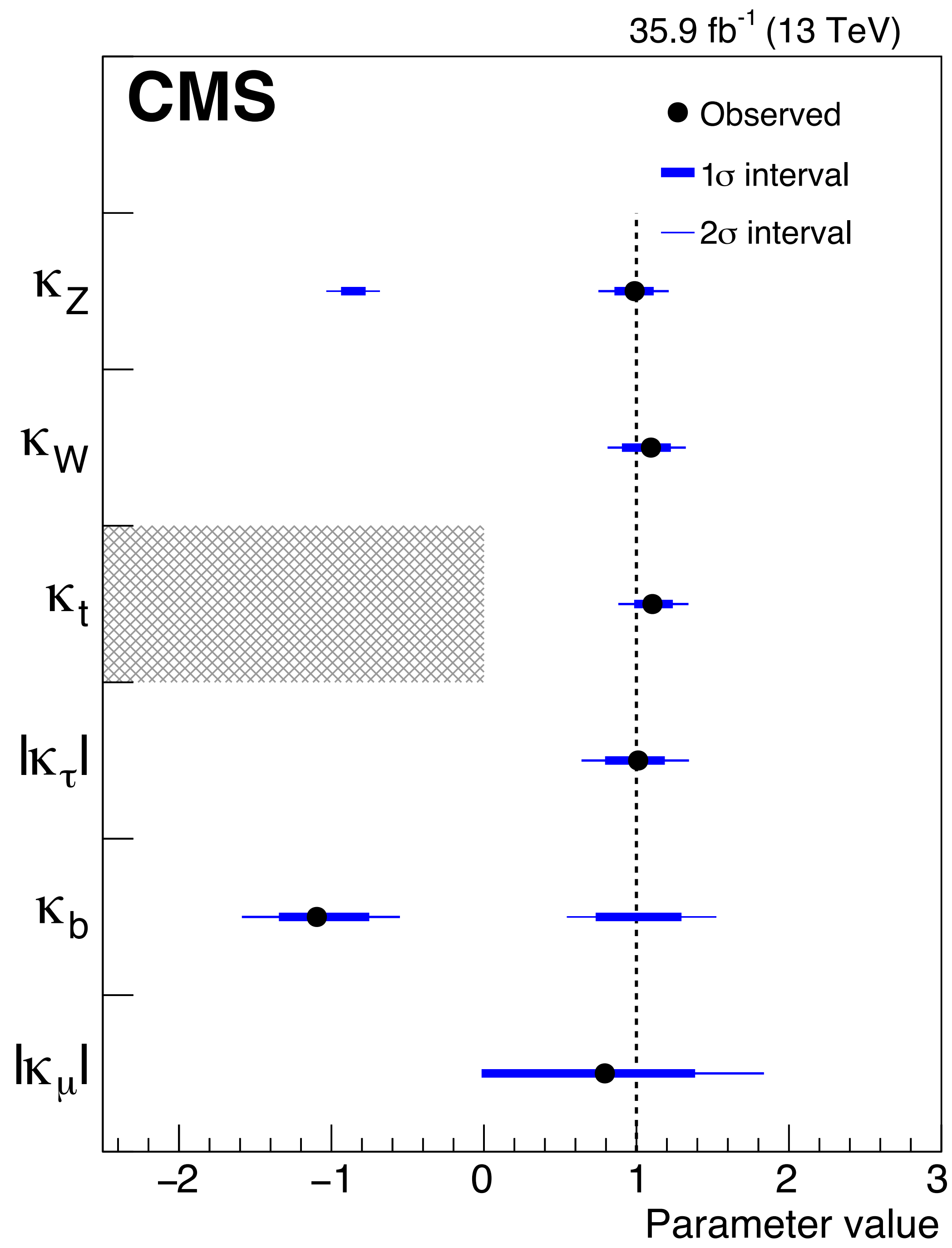
Czakon, Gütschow, Lindert, Mitov, DP, Papanastasiou Schönherr, Tsinikos, Zaro '19

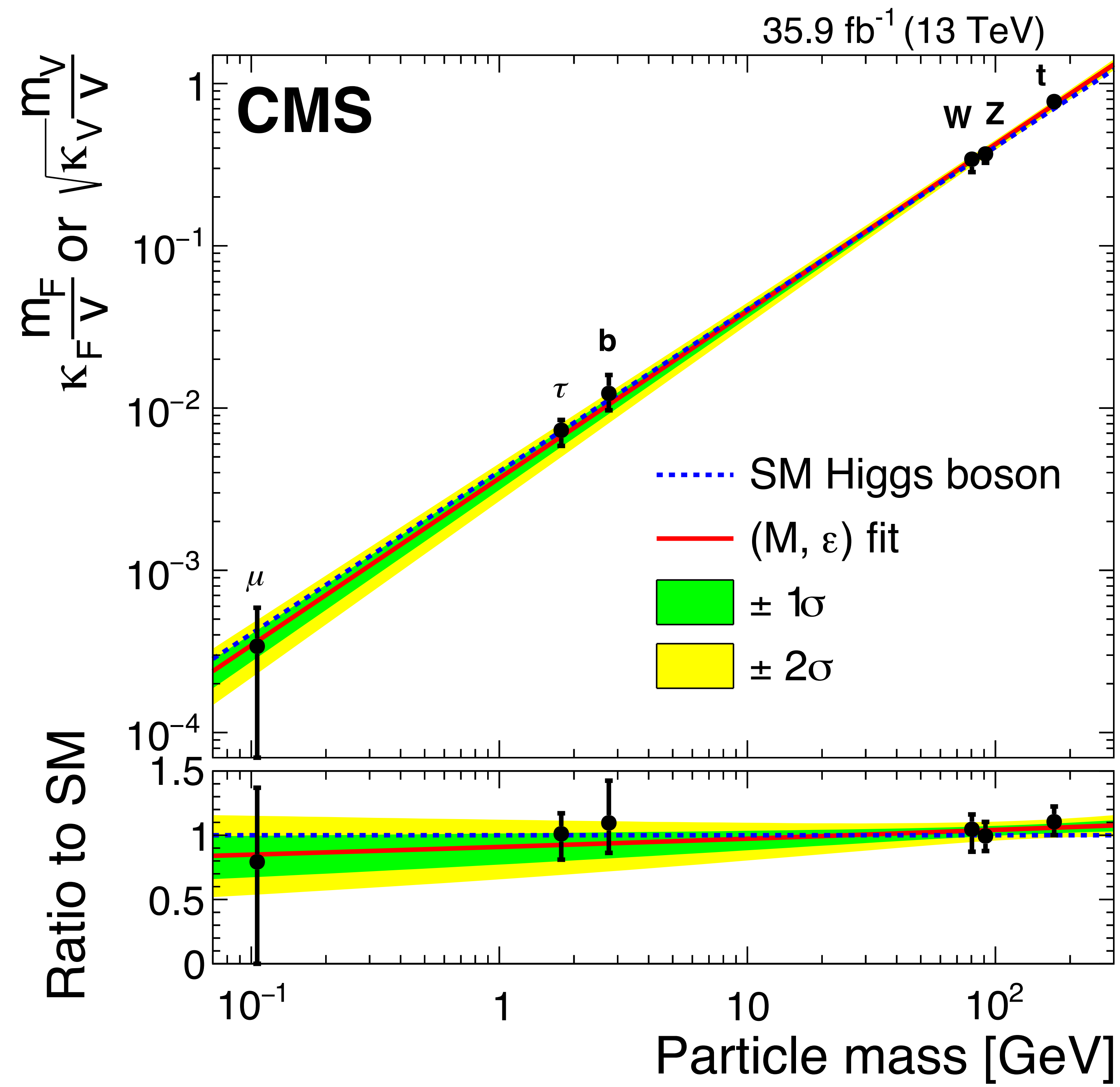


The **pt distribution** for the **softest top** and the region with **small values for the hardest top** are **pathological** at fixed order: **MEPS@NLO cures this problem**.

Higgs self couplings from single Higgs production

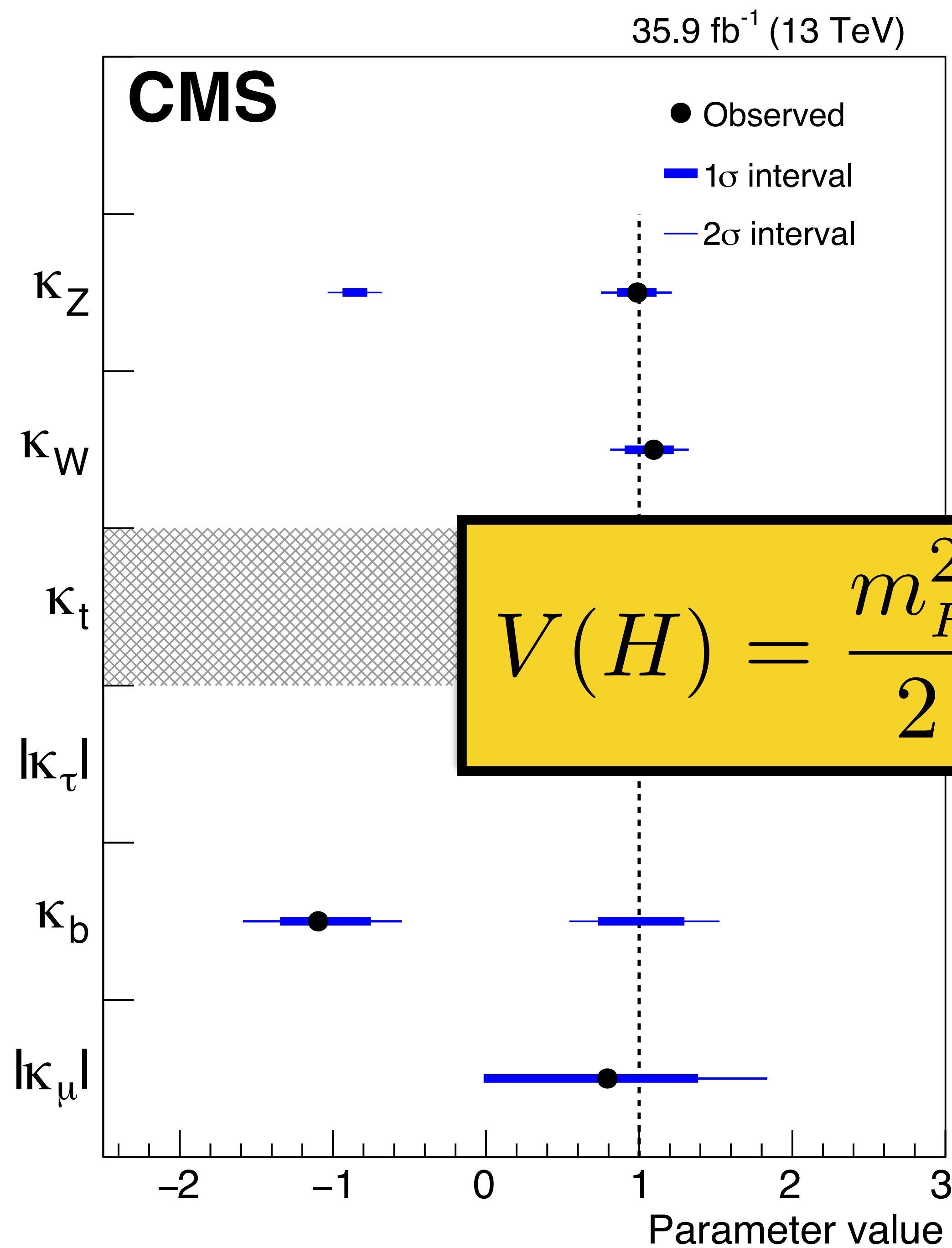
Higgs boson couplings today

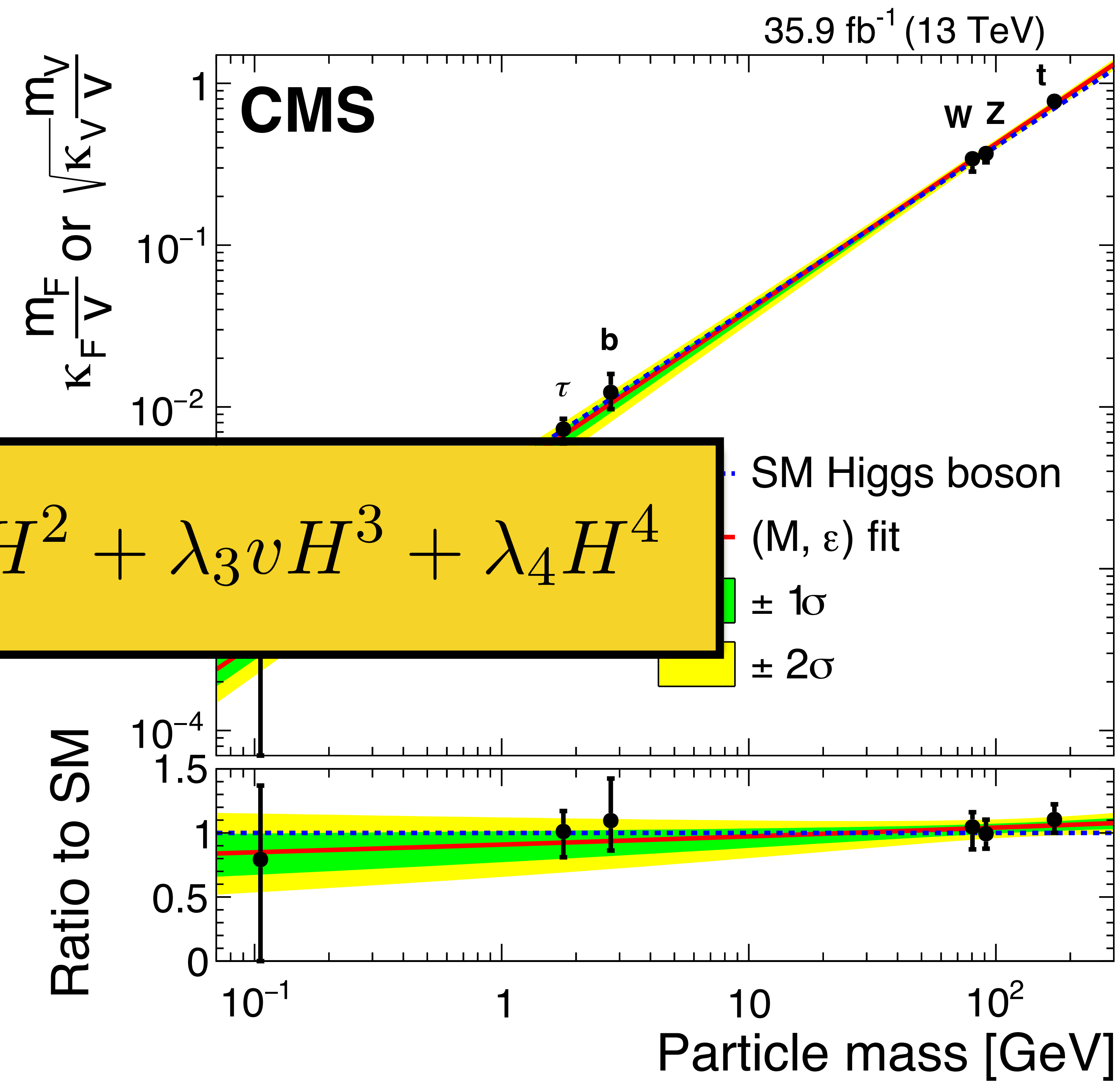




CMS-HIG-17-031

Higgs boson couplings today





$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$

The Higgs Potential

$$V^{\rm SM}(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$$

$$v = (\sqrt{2}G_\mu)^{-1/2} \qquad \mu^2 = \frac{m_H^2}{2}$$

$$V(H) = \frac{m_H^2}{2}H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$

$$\lambda = \frac{m_H^2}{2v^2} \qquad \lambda_3^{\rm SM} = \lambda \qquad \lambda_4^{\rm SM} = \lambda/4$$

The Higgs **self couplings** are **completely determined in the SM** by the vev and the Higgs mass. On the other hand, Higgs self interactions have not been measured yet.

The measurement of the Higgs self couplings is an **important SM test**, essential for the study of the **Higgs potential**.

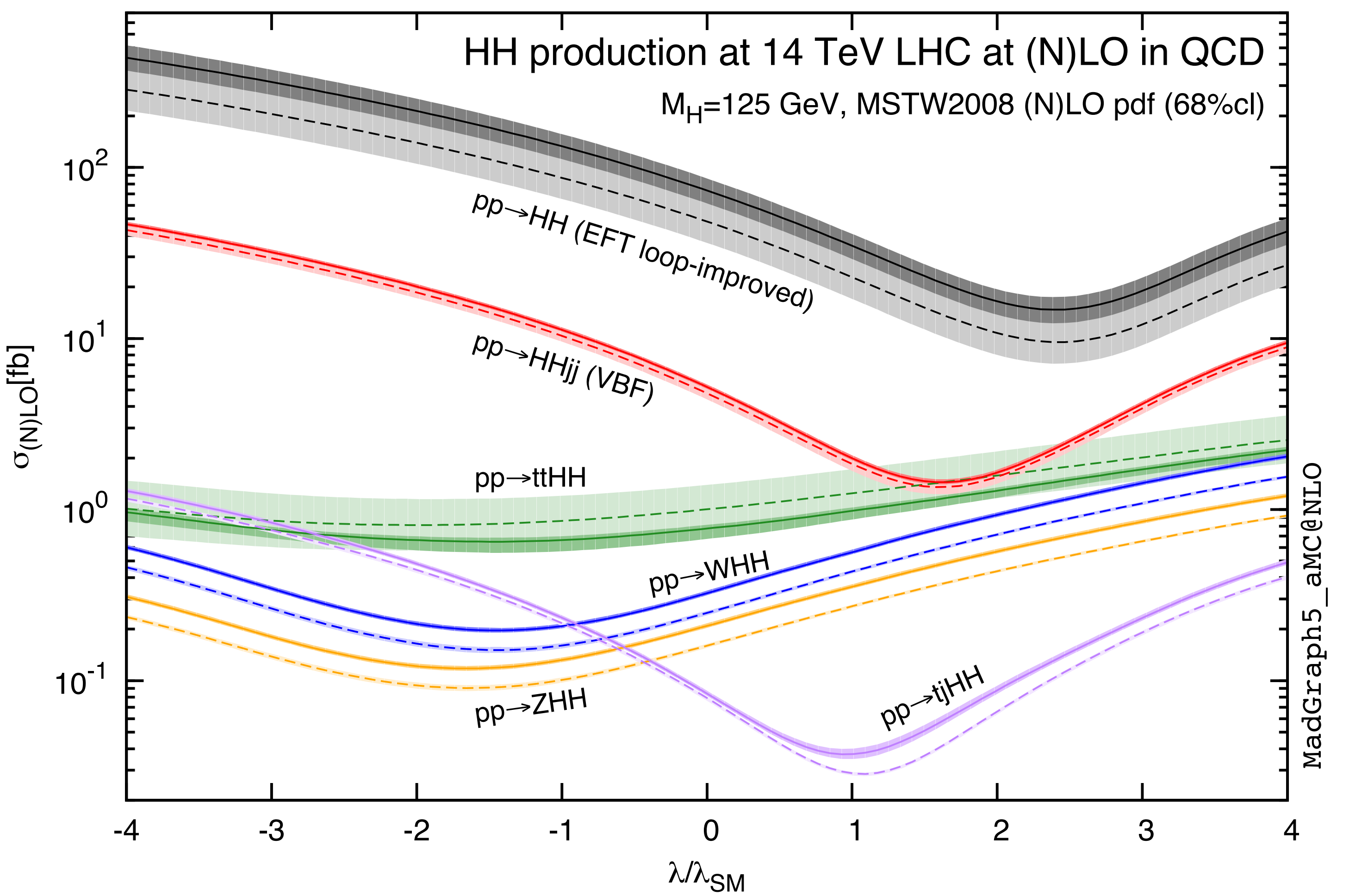
Possible deviations need to be parametrised via **additional parameters**, without altering the value of the Higgs mass and the vev.

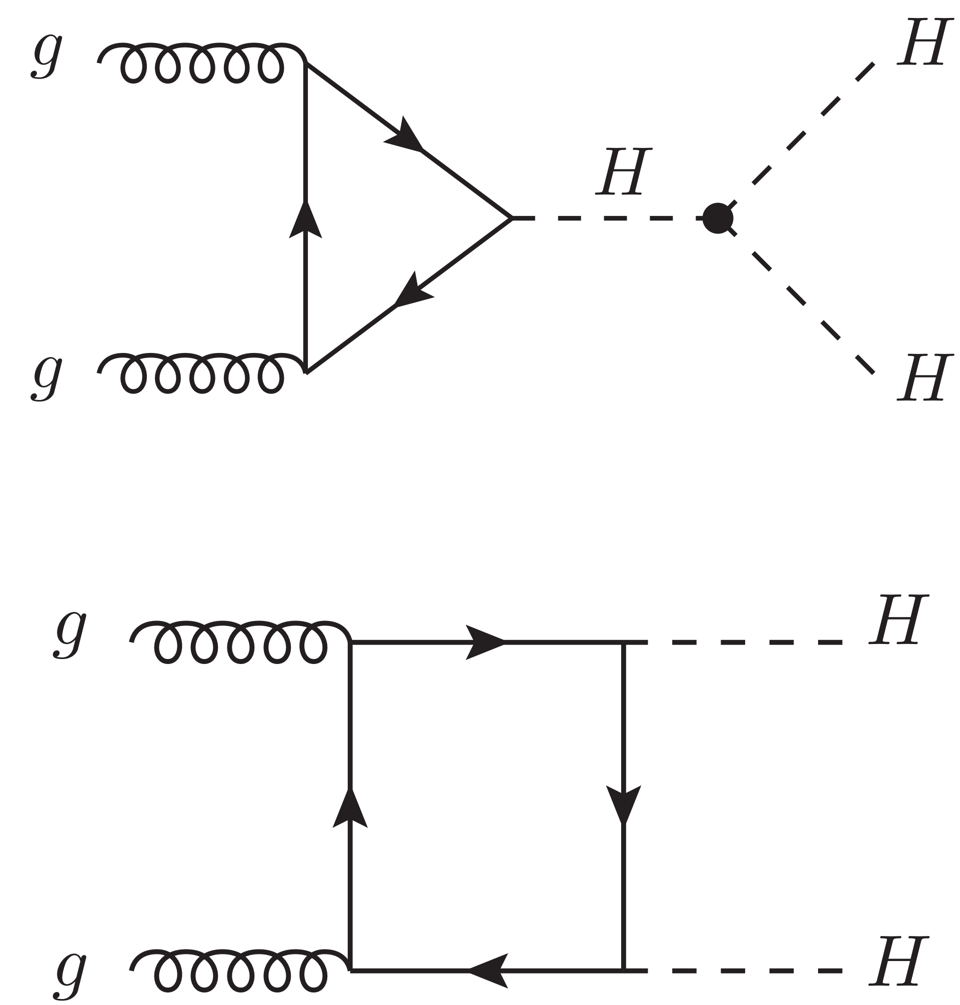
Interpretations of the additional parameters strongly **depend on the theory** assumptions!

How do we measure the Higgs self coupling?

Standard Answer: you need to produce **at least two** Higgs!

Frederix et al. '14

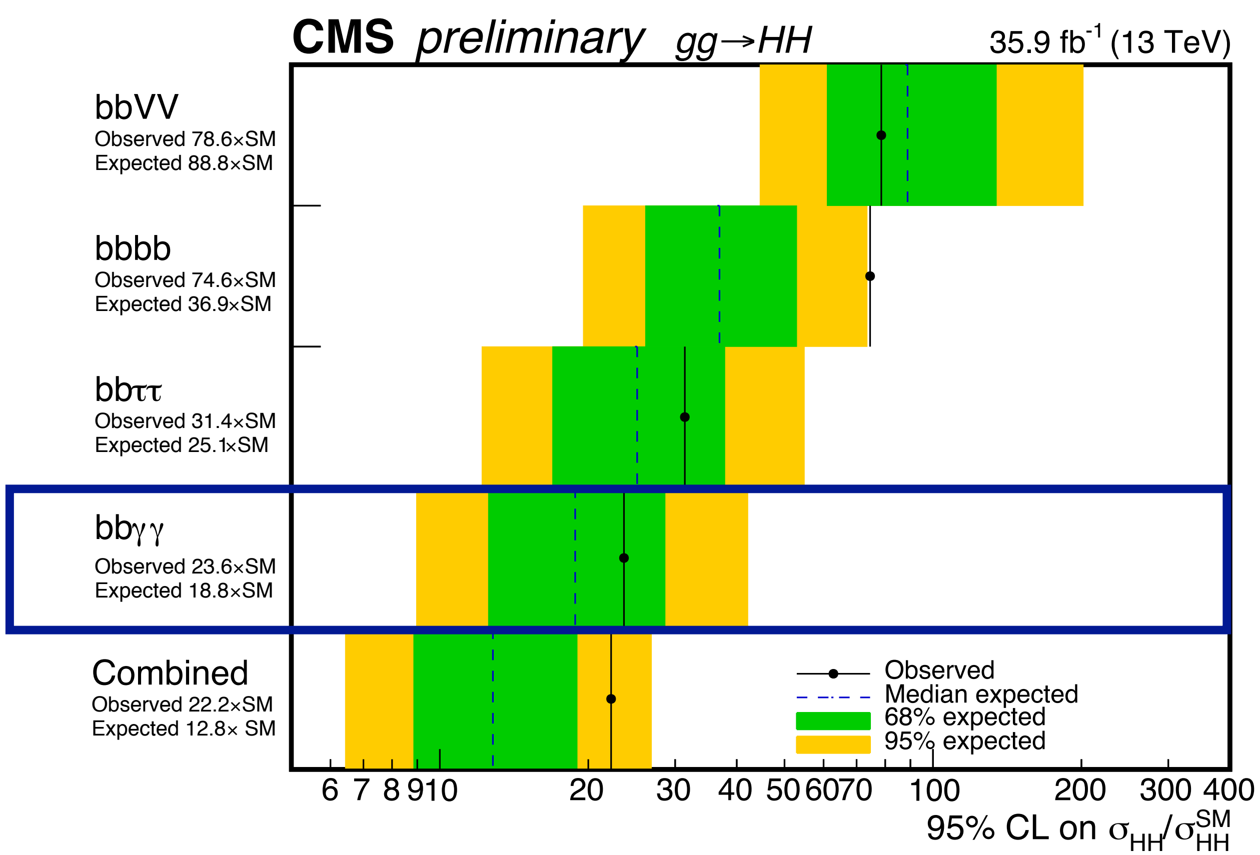


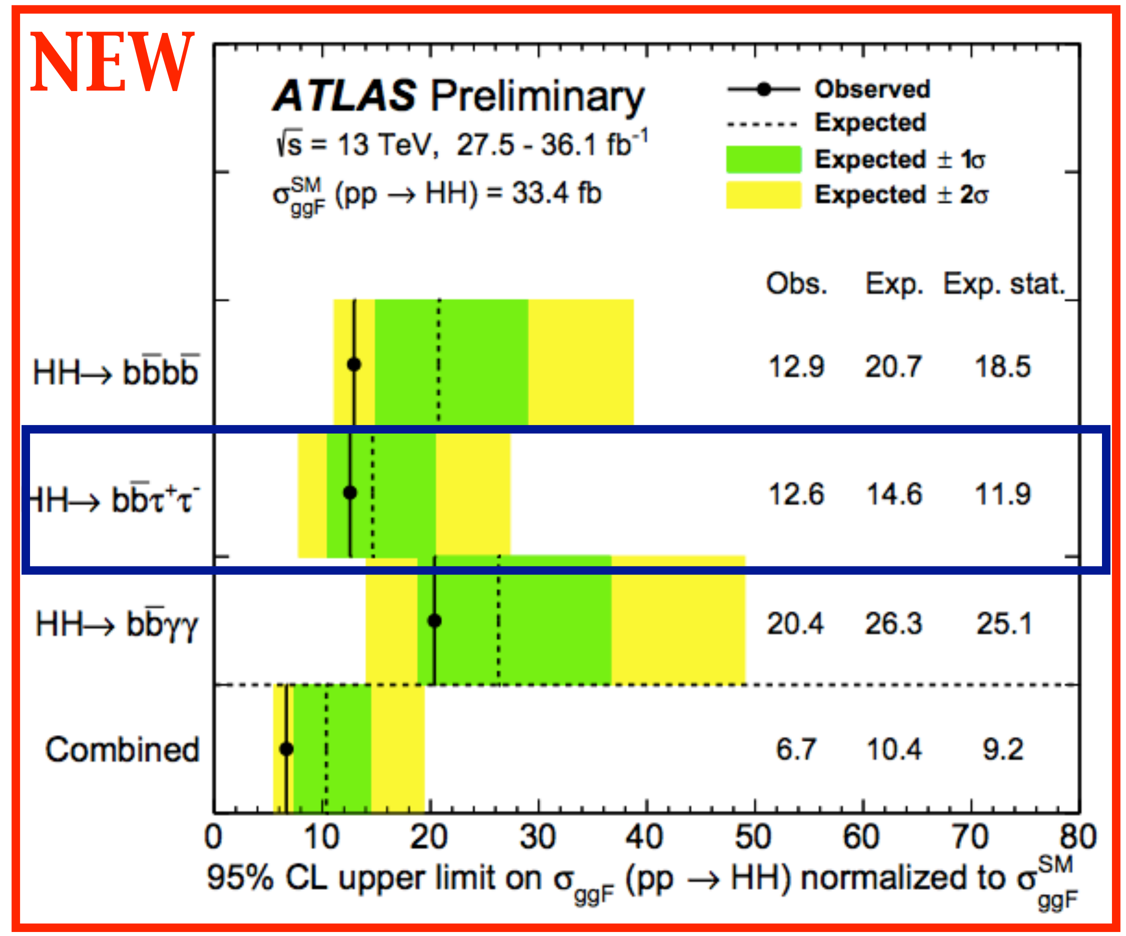


Pheno studies on LHC constraints for κ_λ:

Baur et al. '03. Baglio et al.; Papaefstathiou et al. '12. Barger et al.; Yao '13. de Lima et al.; Englert et al.; Liu and Zhang; Wardrope et al. '14. Azatov et al.; Behr et al.; Cao et al.; Dolan et al.; Lu et al. '15.

Upper limits on σ(pp→HH)





best limit from bbγγ in CMS
bbττ in ATLAS
4b ~2 worse in CMS

theoretical xs error:
~8% not included in ATLAS result

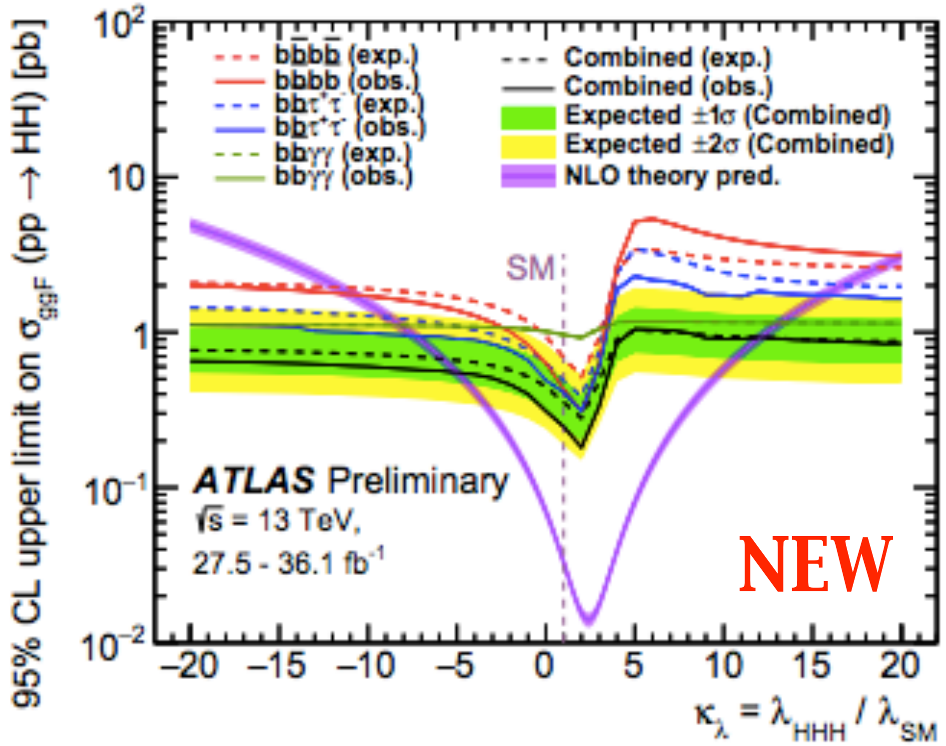
Present limits on κλ

Limits on the cross-section as a function of κ_λ

4b
bbττ
bbγγ
combination

dashed: expected

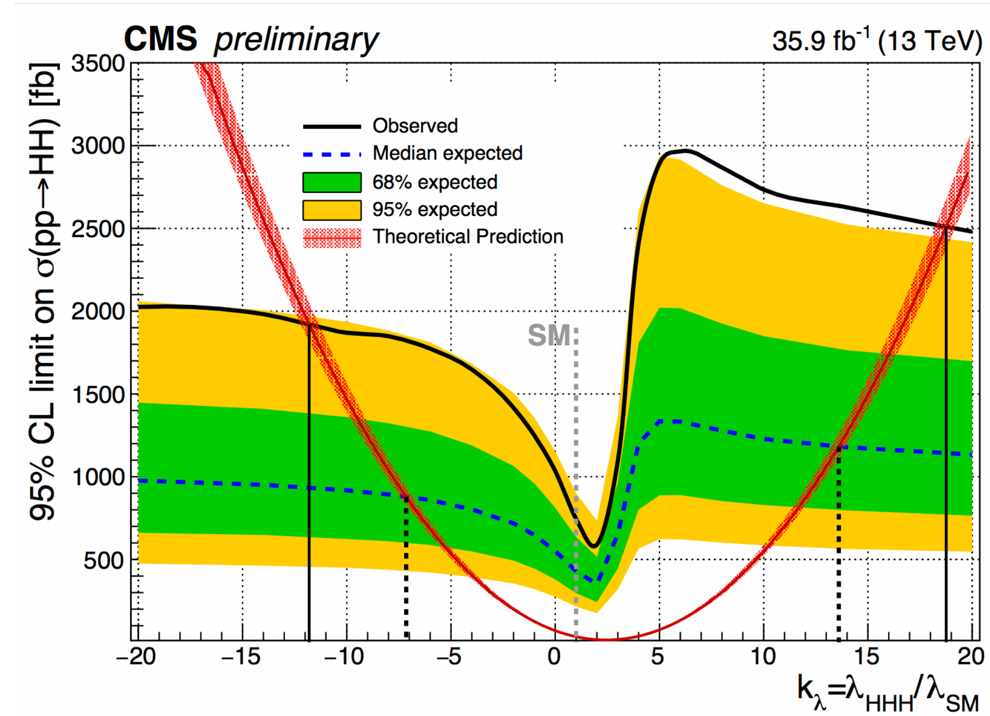
solid: observed



The scale factor κ_λ is observed (expected) to be constrained in the range:

$-5.0 < \kappa_\lambda < 12.1$ $(-5.8 < \kappa_\lambda < 12.0)$

14/19



κλ ∈[-11.8, 18.8] assuming SM top-H coupling
[-7.1, 13.6] expected

ATLAS has presented 3 new results at the workshop:
bbbb, bbττ, bbγγ combination, 4W's and WWbb results

limits are far from SM sensitivity, main interest is to look if there is room for NP to cime in

An additional and complementary strategy for the determination (at the LHC) of the Higgs self coupling would be desirable!

We can exploit at the LHC the
"High Precision for Hard Processes"

HP^2
It is time for something new

Degrassi, Giardino, Maltoni, DP '16

An additional and complementary strategy for the determination (at the LHC) of the Higgs self coupling would be desirable!

We can exploit at the LHC the
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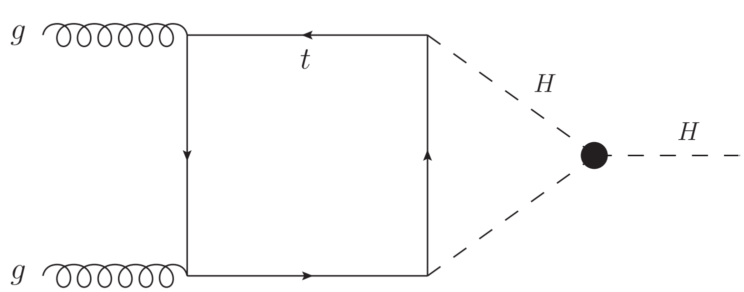
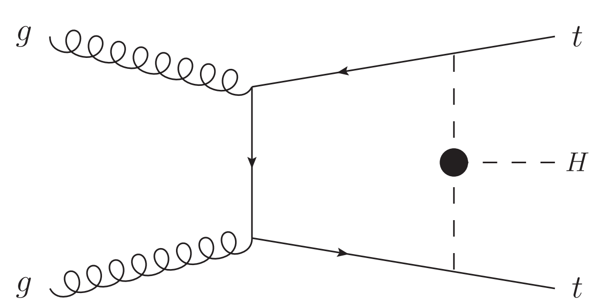
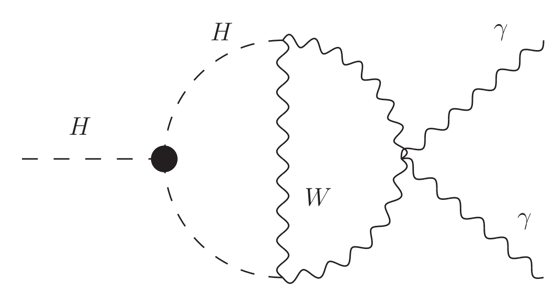
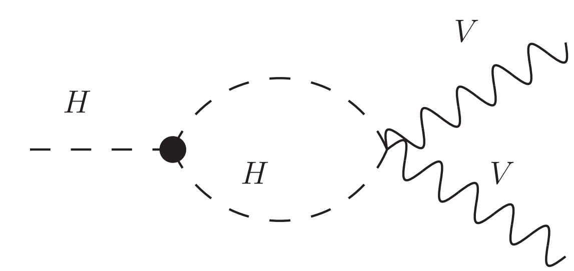
Degrassi, Giardino, Maltoni, DP ’16

and ***probe*** the quantum effects (NLO EW) induced by the Higgs self coupling on single Higgs production and decay modes.









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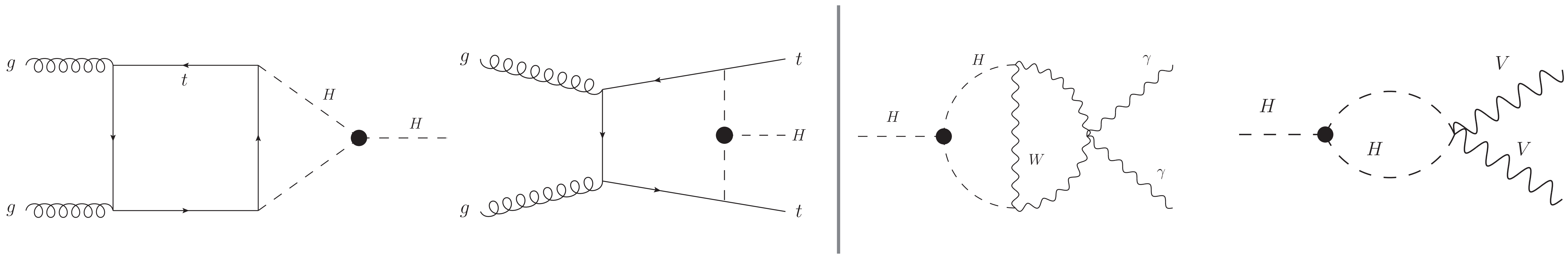

All the single Higgs production and decay processes are affected by an anomalous trilinear (**<u>not quartic</u>**) Higgs self coupling, parametrized by κ_λ.

All the different signal strengths μ_i^f have a different dependence on a single parameter κ_λ, which can thus be constrained via a global fit.

Calculation framework

We assume that the dominant New Physics effects involve the Higgs potential.
At **NLO EW** only the trilinear Higgs self coupling appears; the quartic-coupling dependence enters only at higher orders.

SM

$$V(H) = \frac{m_H^2}{2} H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$

$$m_H^2 = 2\lambda v^2, \lambda_3^{\rm SM} = \lambda, \lambda_4^{\rm SM} = \lambda/4$$

NP parameterised via

$$\lambda_3 \, v \, H^3 \equiv \kappa_\lambda \lambda_3^{\rm SM} \, v \, H^3$$

Degrassi, Giardino, Maltoni, DP '16

The possible range of κ_λ, even before the comparison with data, depends on the underlying theory assumptions and it applies also to double-Higgs analyses.

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Degrassi, Giardino, Maltoni, DP '16

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Equivalent study for only ZH production at e+e- collider in *McCullough '14*

Similar studies in EFT approach for only gluon-fusion with decays into photons in *Gorbahn, Haisch '16,* and for VBF+VH in *Bizon, Gorbahn, Haisch, Zanderighi '16*

Numerical results

Degrassi, Giardino, Maltoni, DP '16

universal

$$\delta\Sigma_{\lambda_3} \equiv \frac{\Sigma_{\rm NLO} - \Sigma_{\rm NLO}^{\rm SM}}{\Sigma_{\rm LO}} = (\kappa_\lambda - 1)\boxed{C_1} + (\kappa_\lambda^2 - 1)\boxed{C_2} + \mathcal{O}(\kappa_\lambda^3\,\alpha^2) \qquad C_2 = \frac{\delta Z_H}{(1-\kappa_\lambda^2 \delta Z_H)}$$

Process and kinetic dependent

$$C_2 = -9.514 \cdot 10^{-4} \text{ for } \kappa_\lambda = \pm 20 \qquad C_2 = -1.536 \cdot 10^{-3} \text{ for } \kappa_\lambda = 1$$

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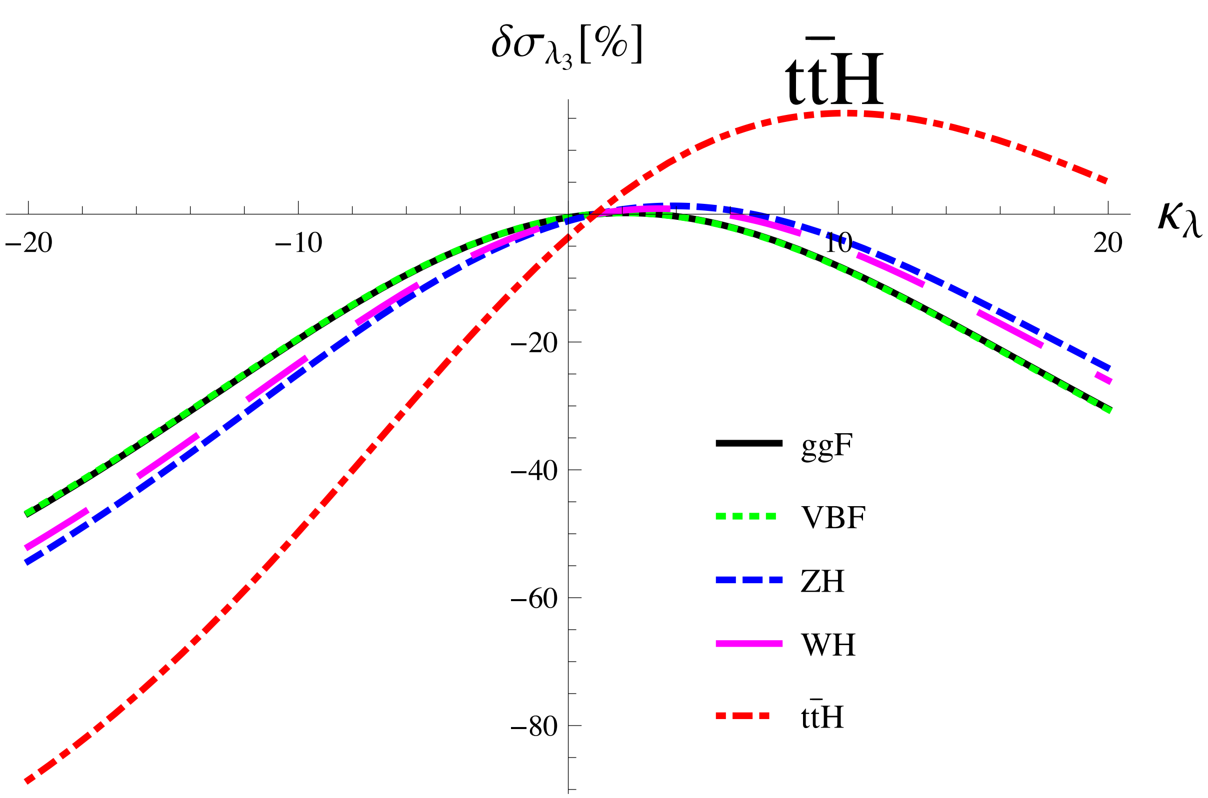
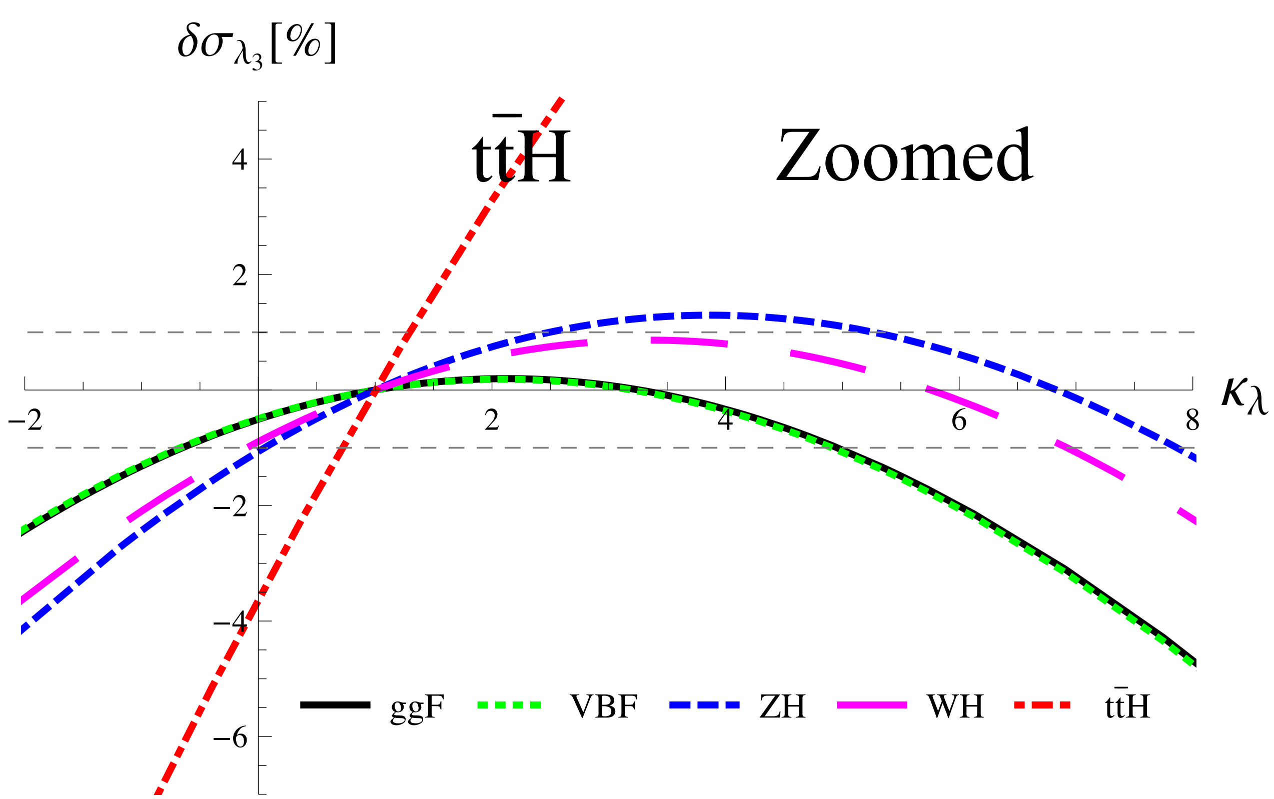
Production: $\delta\sigma_{\lambda_3}$

$C_1^\sigma[\%]$	ggF	VBF	WH	ZH	$t\bar{t}H$
8 TeV	0.66	0.65	1.05	1.22	3.78
13 TeV	0.66	0.64	1.03	1.19	3.51





Numerical results

Degrassi, Giardino, Maltoni, DP '16

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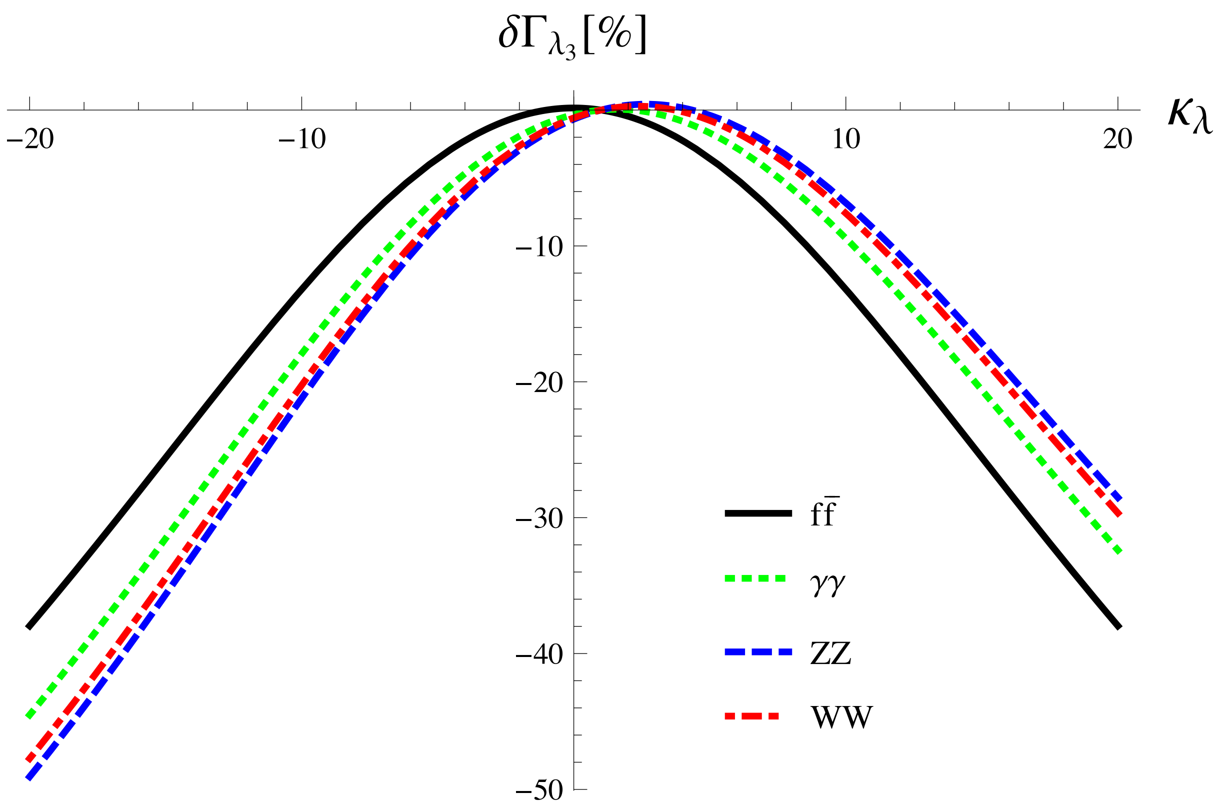
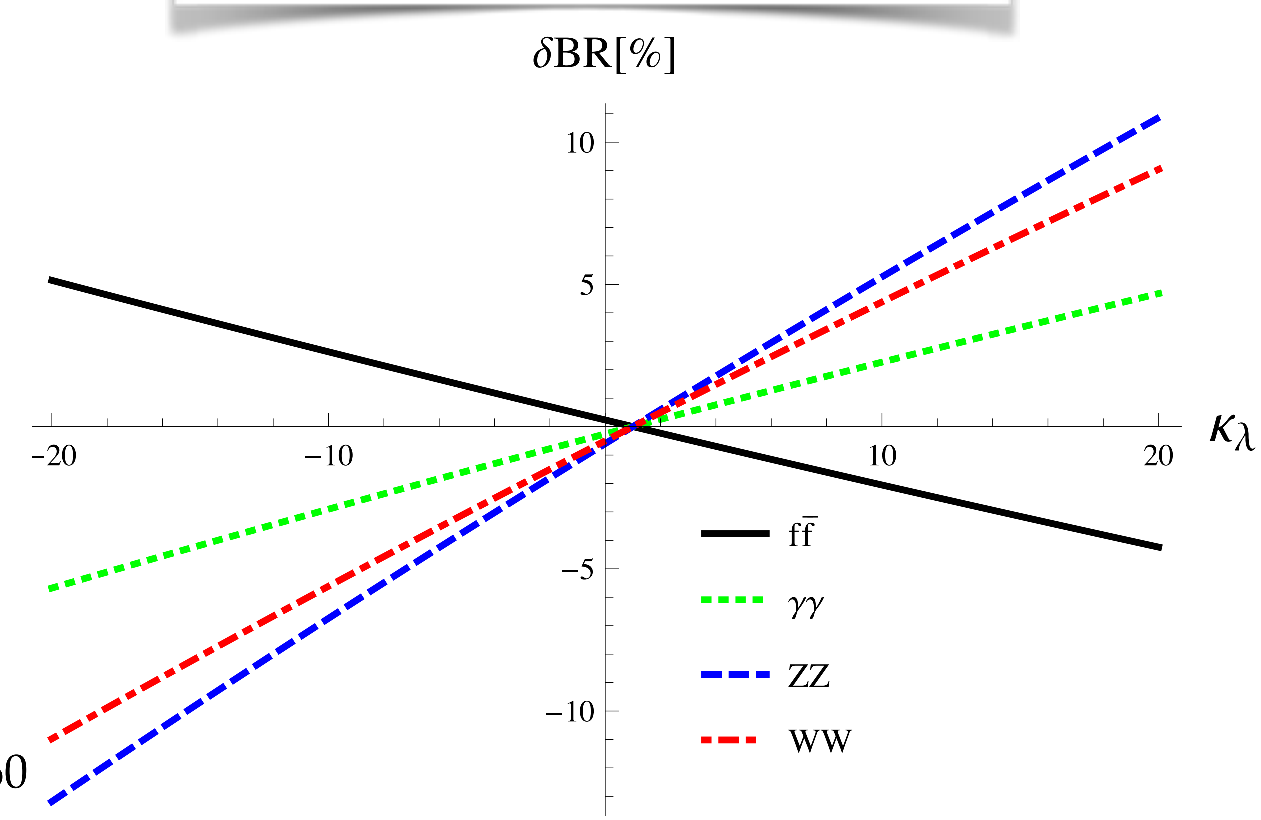
Decay: $\delta\Gamma_{\lambda_3}$ and $\delta{\rm BR}_{\lambda_3}$

$C_1^\Gamma[\%]$	$\gamma\gamma$	ZZ	WW	$f\bar{f}$	gg
on-shell H	0.49	0.83	0.73	0	0.66

$$\delta{\rm BR}_{\lambda_3}(i) = \frac{(\kappa_\lambda - 1)(C_1^\Gamma(i) - C_1^{\Gamma_{\rm tot}})}{1 + (\kappa_\lambda - 1)C_1^{\Gamma_{\rm tot}}}$$

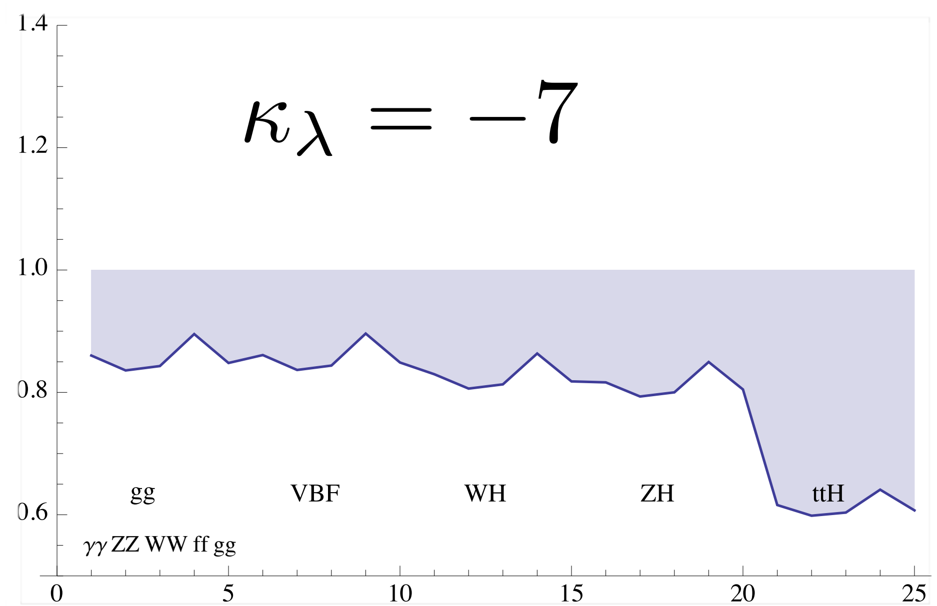


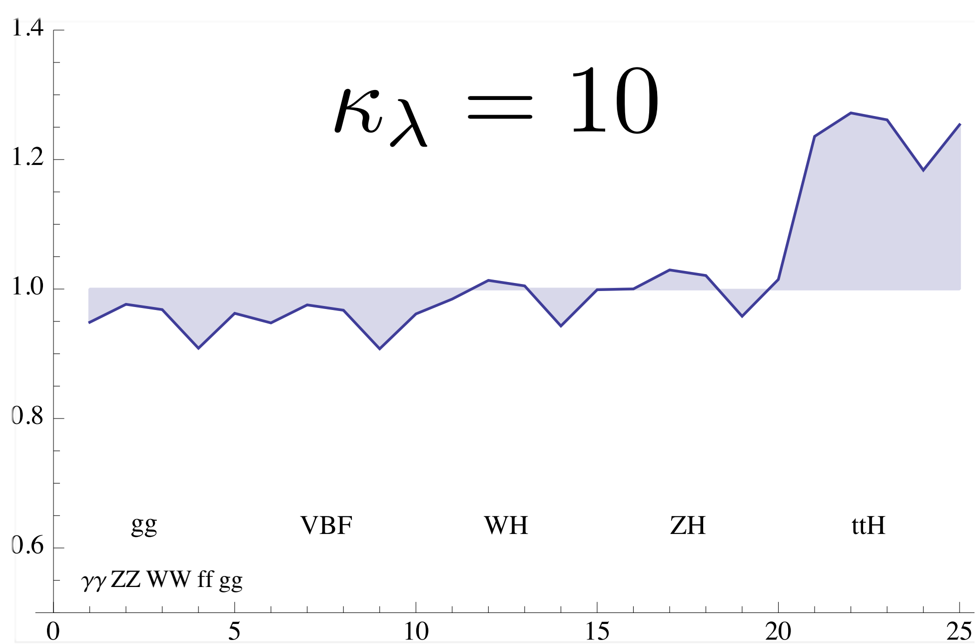


Fitting from LHC current analysis

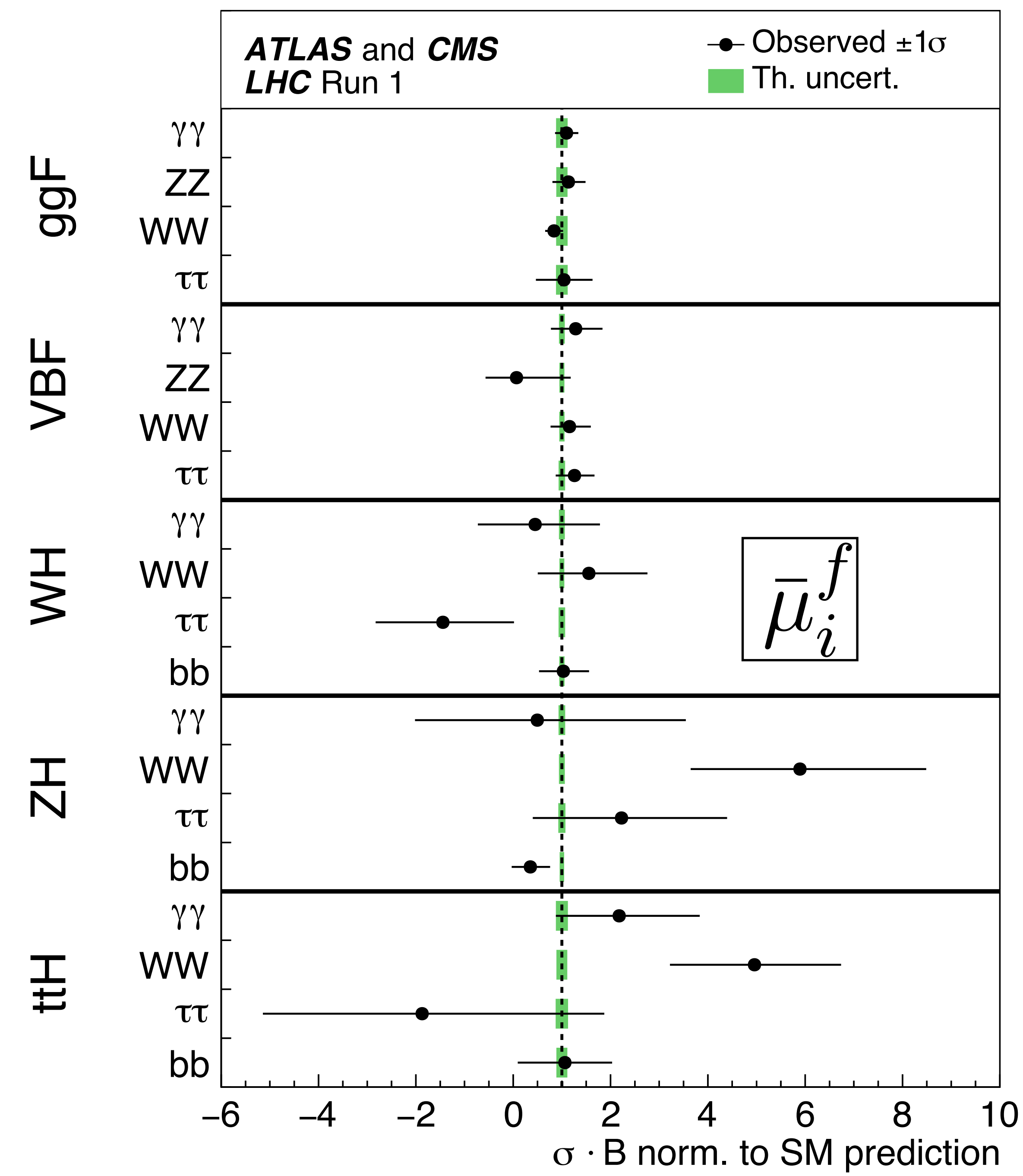
$$i \to H \to f \quad \Rightarrow \quad \mu_i^f \equiv \mu_i \times \mu^f$$

$$\mu_i = 1 + \delta\sigma_{\lambda_3}(i)$$
$$\mu^f = 1 + \delta \mathrm{BR}_{\lambda_3}(f)$$





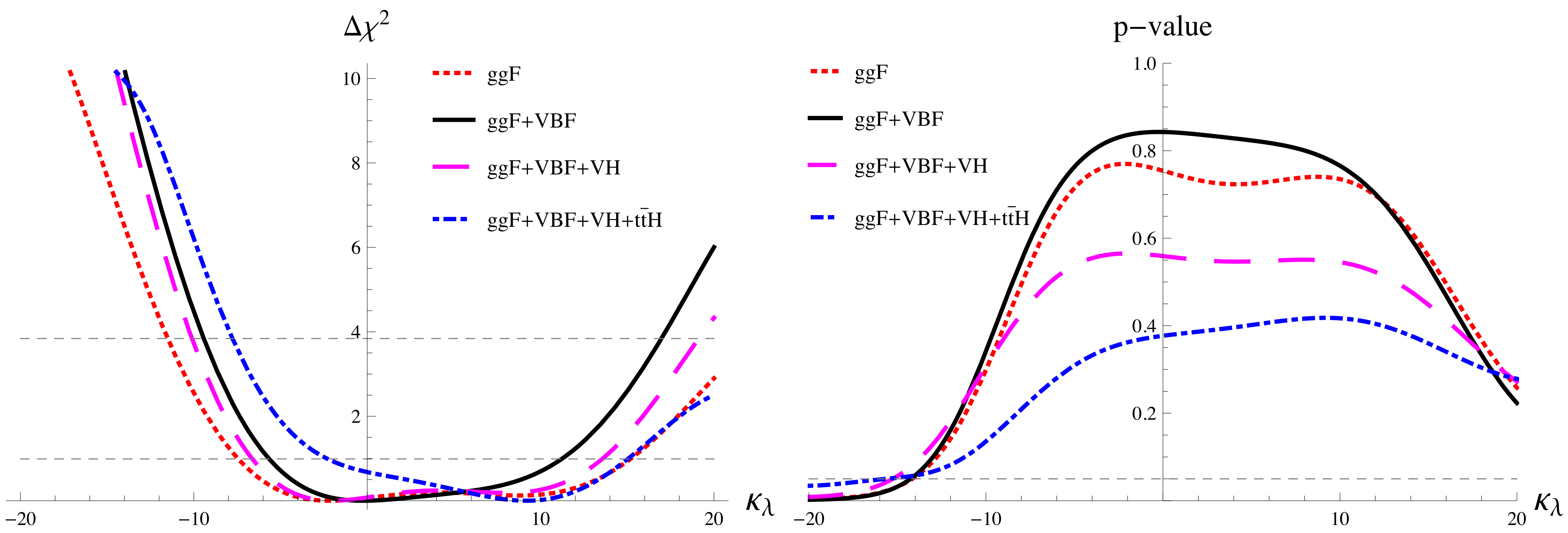
$$\boxed{\mu_i^f(\kappa_\lambda)}$$



$$\boxed{\bar{\mu}_i^f}$$

Results for present data (8 TeV)

Minimization of $$\chi^2(\kappa_\lambda) \equiv \sum_{\bar{\mu}_i^f \in \{\bar{\mu}_i^f\}} \frac{(\mu_i^f(\kappa_\lambda) - \bar{\mu}_i^f)^2}{(\Delta_i^f(\kappa_\lambda))^2}$$



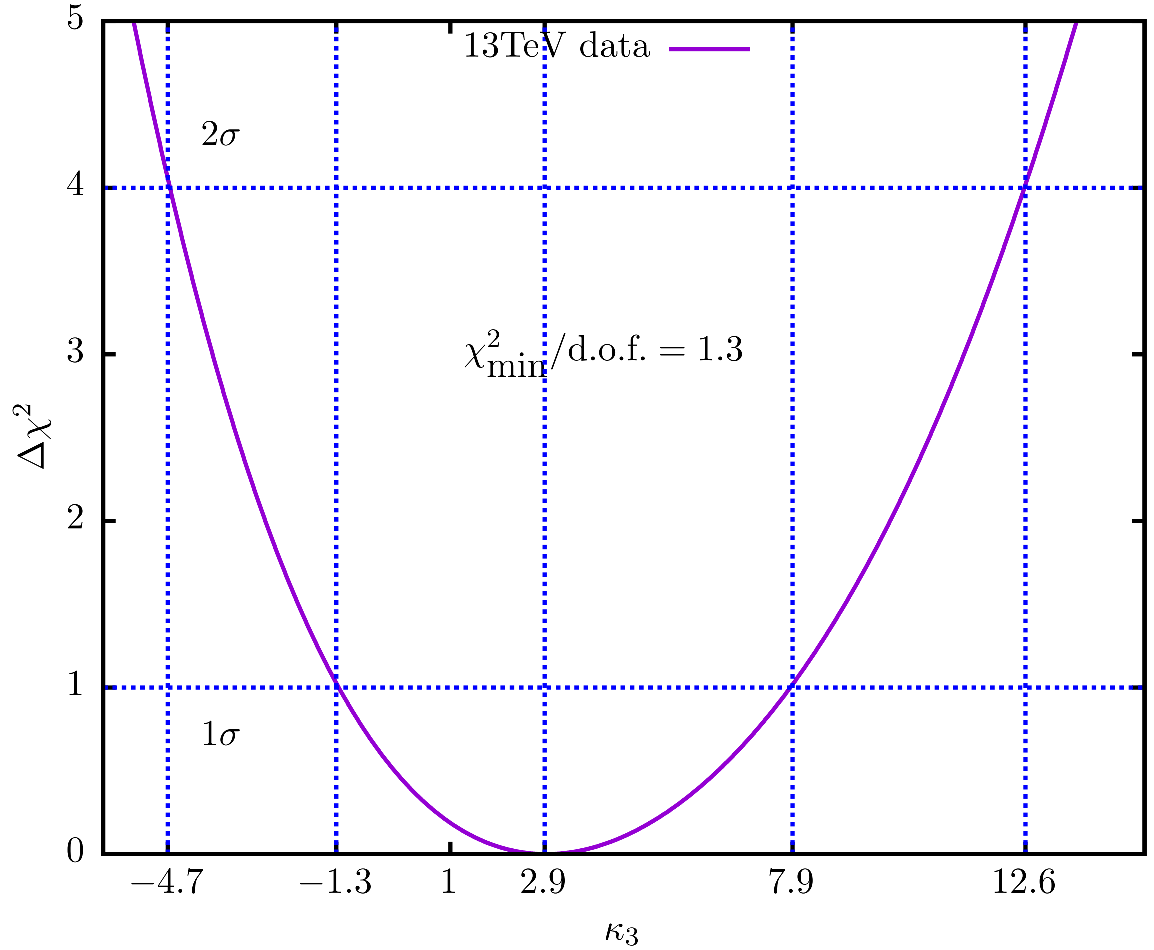
$$\kappa_\lambda^{\text{best}} = -0.24\,, \qquad \kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \qquad \kappa_\lambda^{2\sigma} = [-9.4, 17.0]$$

Degrassi, Giardino, Maltoni, DP '16

Results for present data (13 TeV)

Minimization of

$$\chi^2(\kappa_\lambda) \equiv \sum_{\bar{\mu}_i^f \in \{\bar{\mu}_i^f\}} \frac{(\mu_i^f(\kappa_\lambda) - \bar{\mu}_i^f)^2}{(\Delta_i^f(\kappa_\lambda))^2}$$



plot done by Xiaoran Zhao

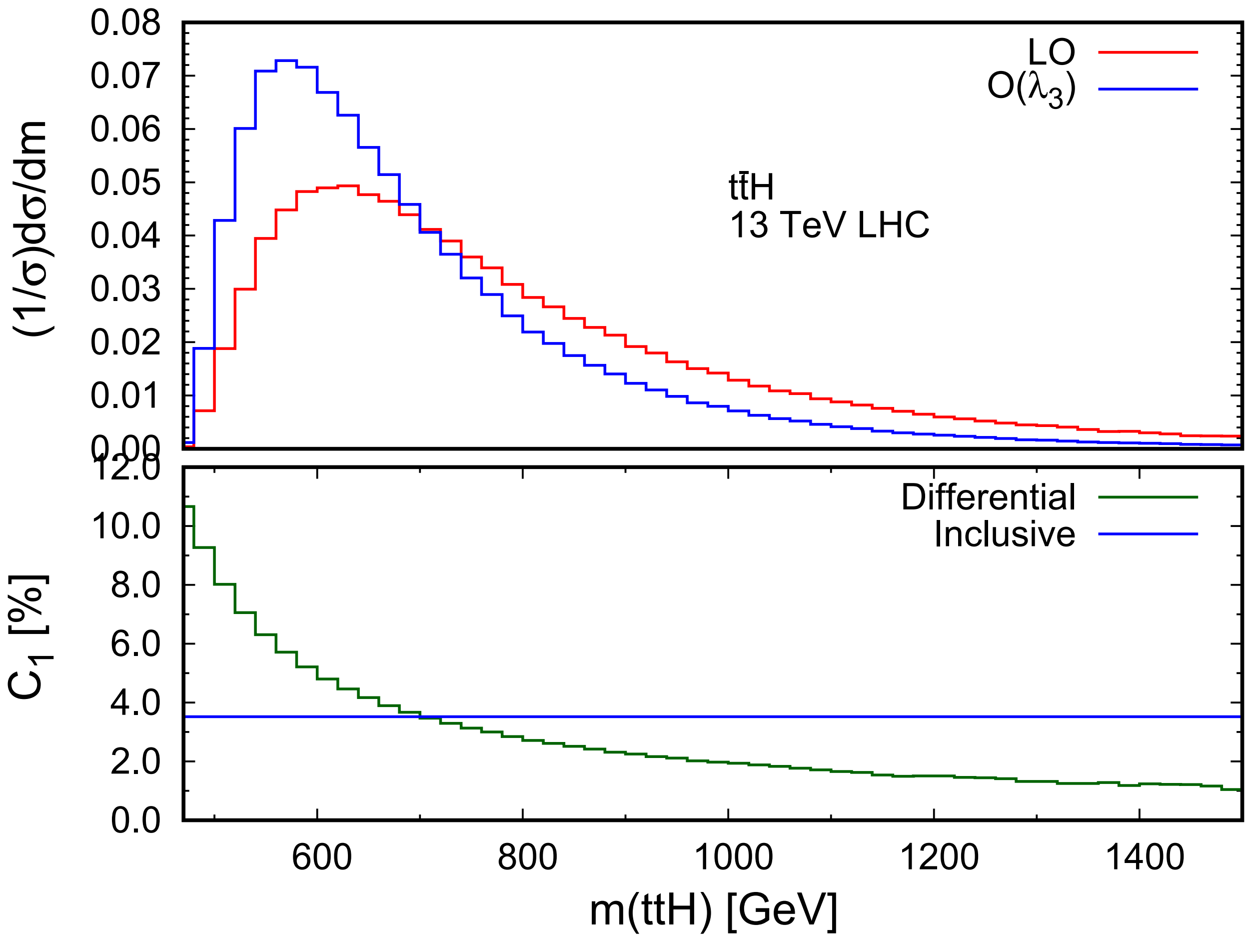
based on CMS-HIG-17-031

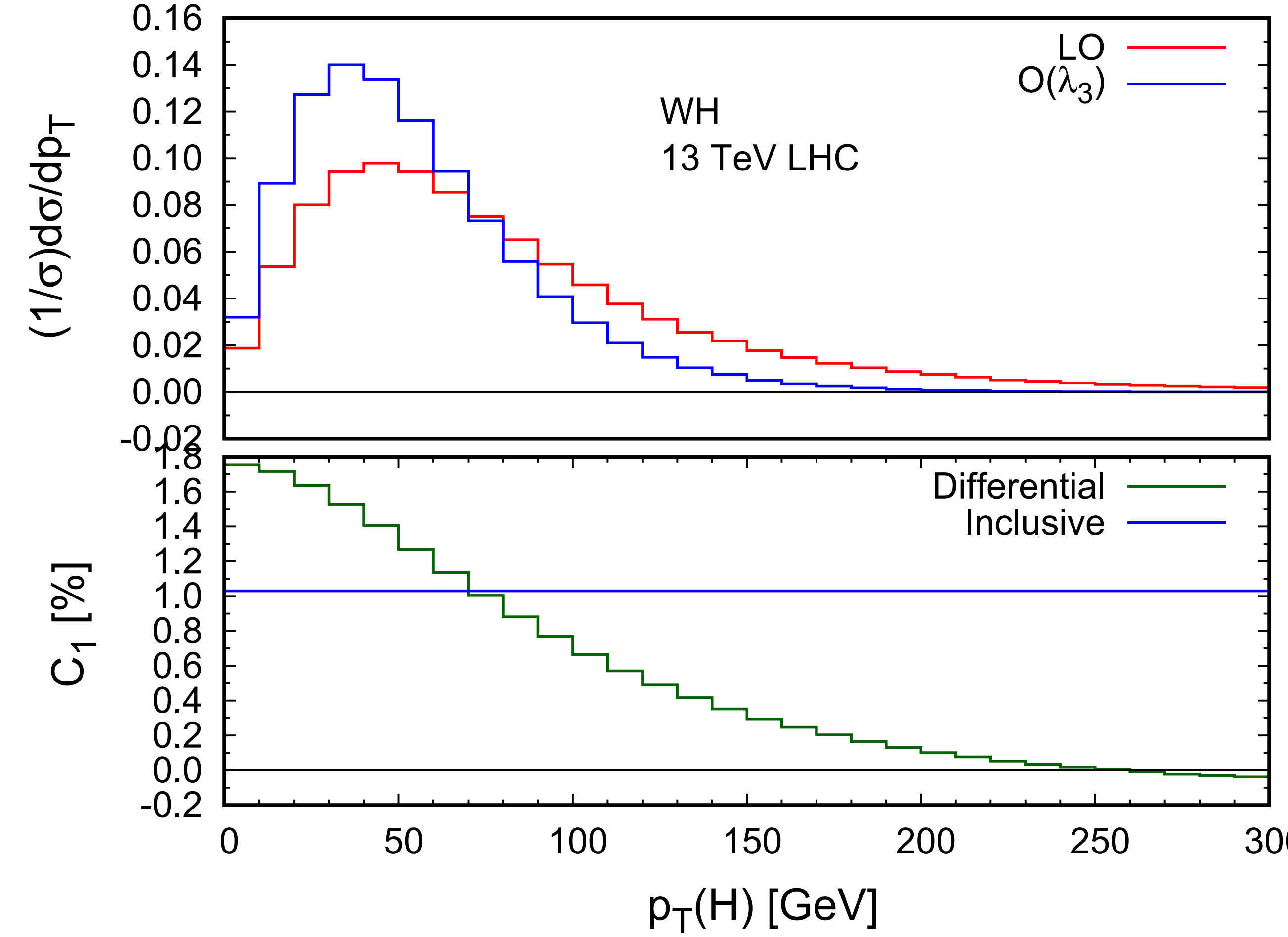
$$\kappa_\lambda^{\rm best} = 2.9\,, \qquad \kappa_\lambda^{1\sigma} = [-1.3, 7.9]\,, \qquad \kappa_\lambda^{2\sigma} = [-4.7, 12.6]$$

EXP double Higgs:

- ATLAS: $-5.0 < \kappa_\lambda < 12.1$
- CMS: $-11.8 < \kappa_\lambda < 18.8$

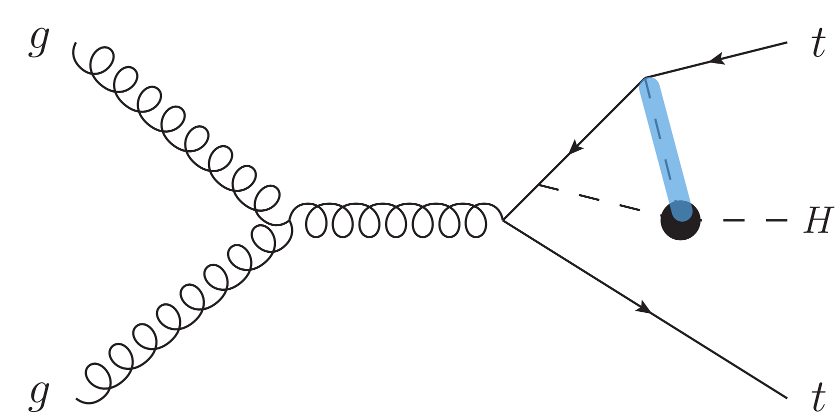
C1: kinematic dependence



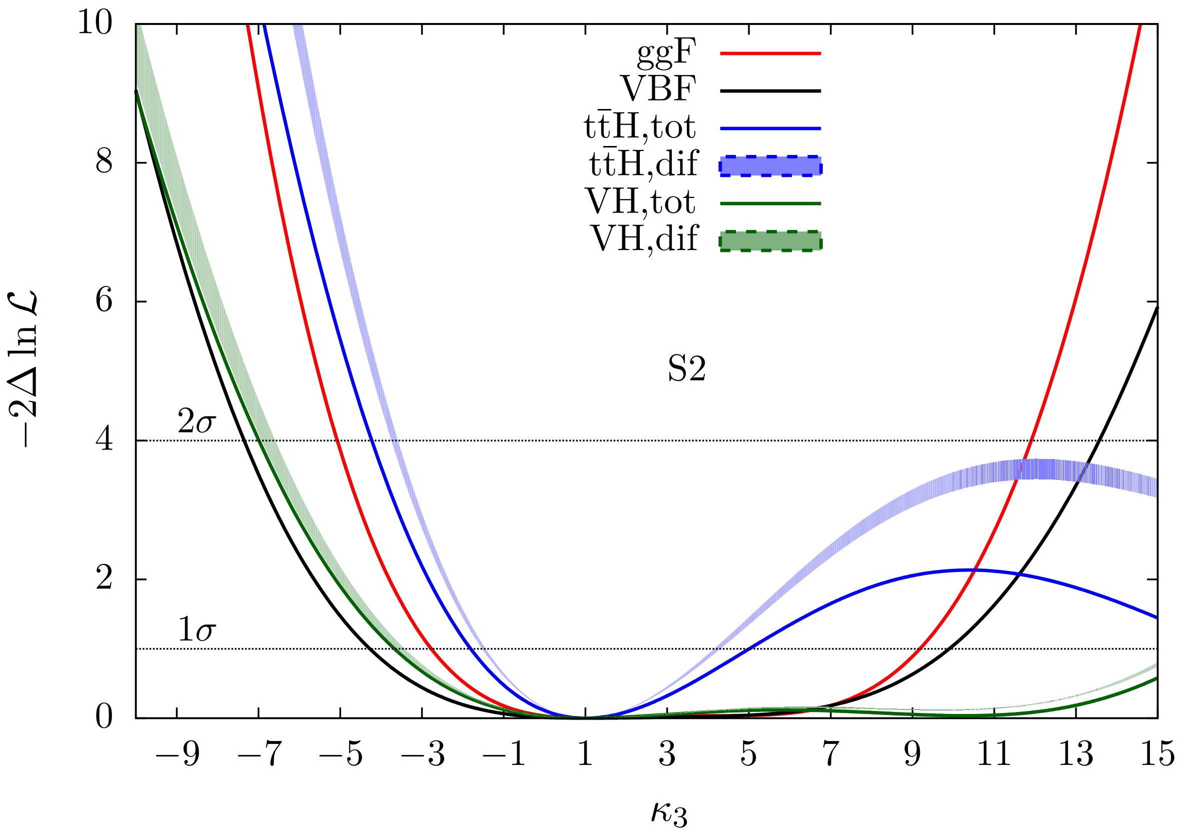


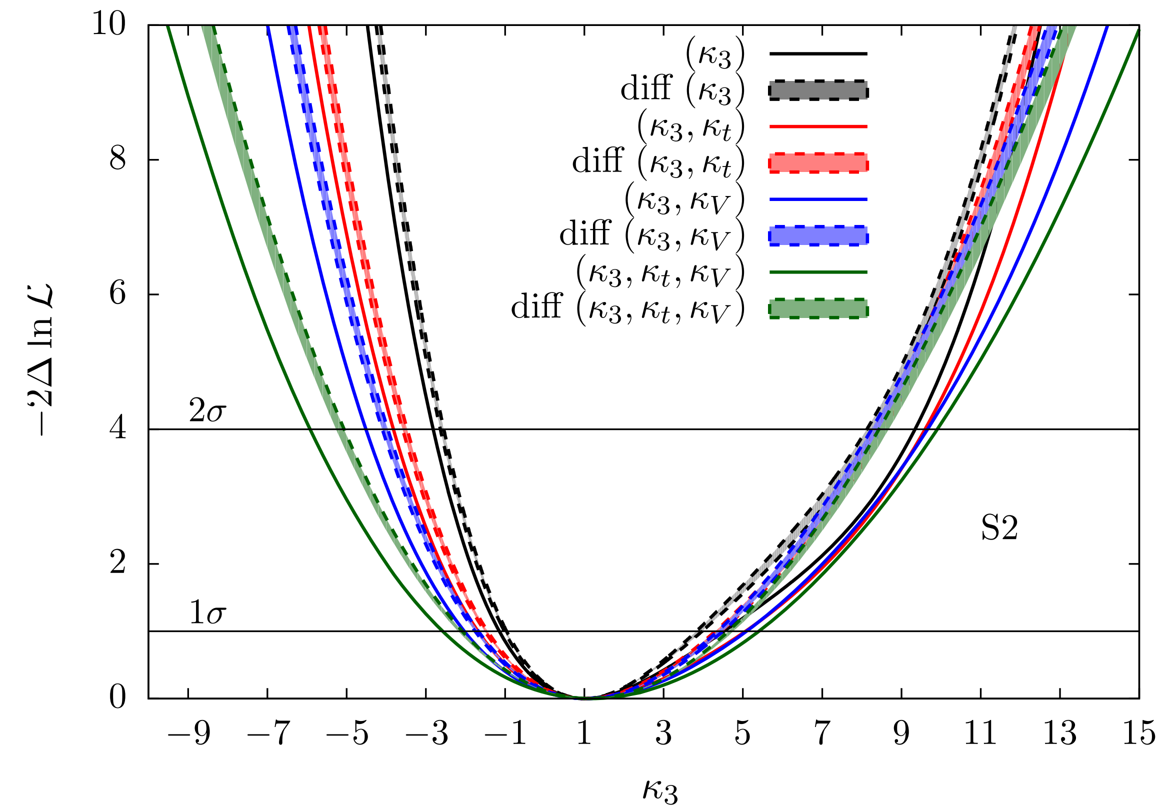
Maltoni, DP, Shivaji, Zhao '17

Contributions to ttH and HV processes can be seen as induced by a Yukawa potential, giving a Sommerfeld enhancement at the threshold.



The relevance of differential information





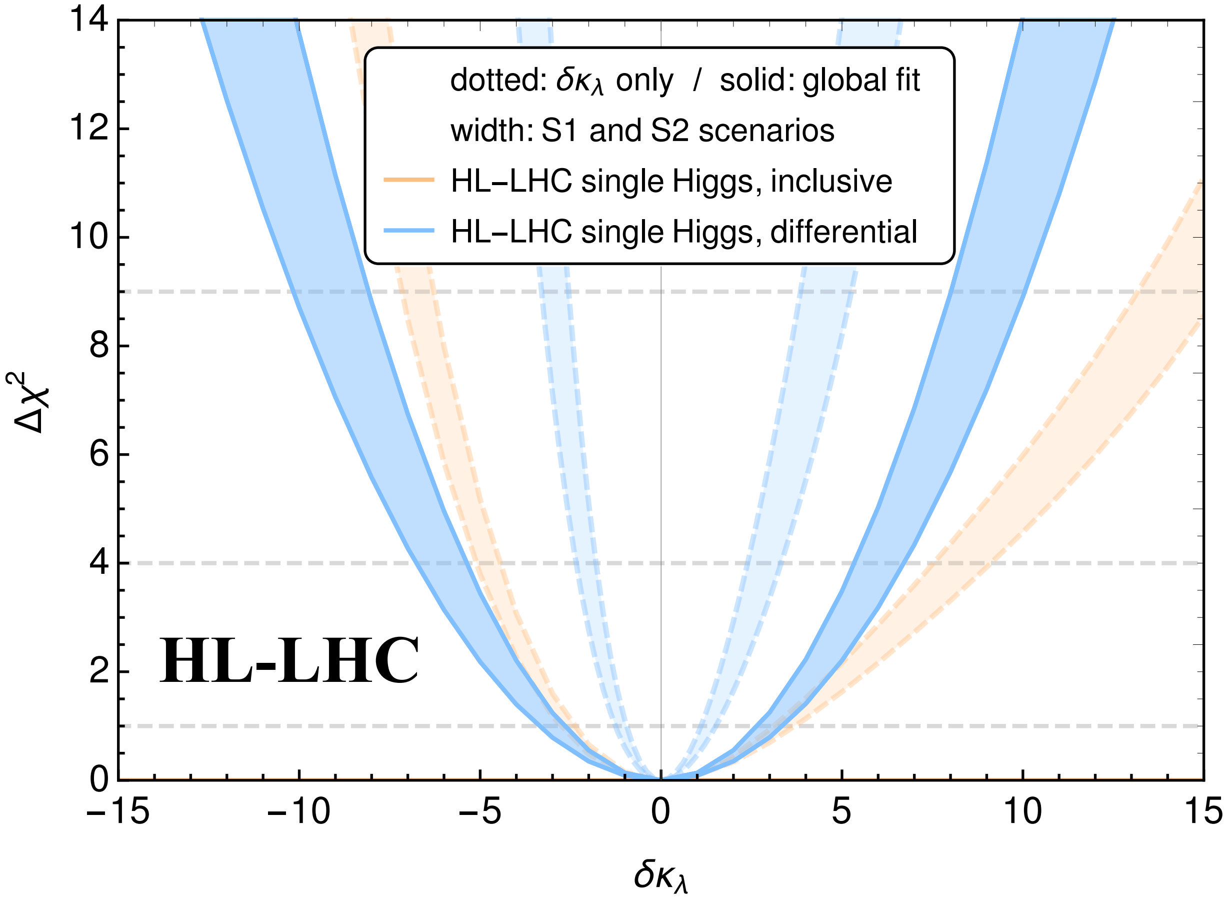
Maltoni, DP, Shivaji, Zhao '17

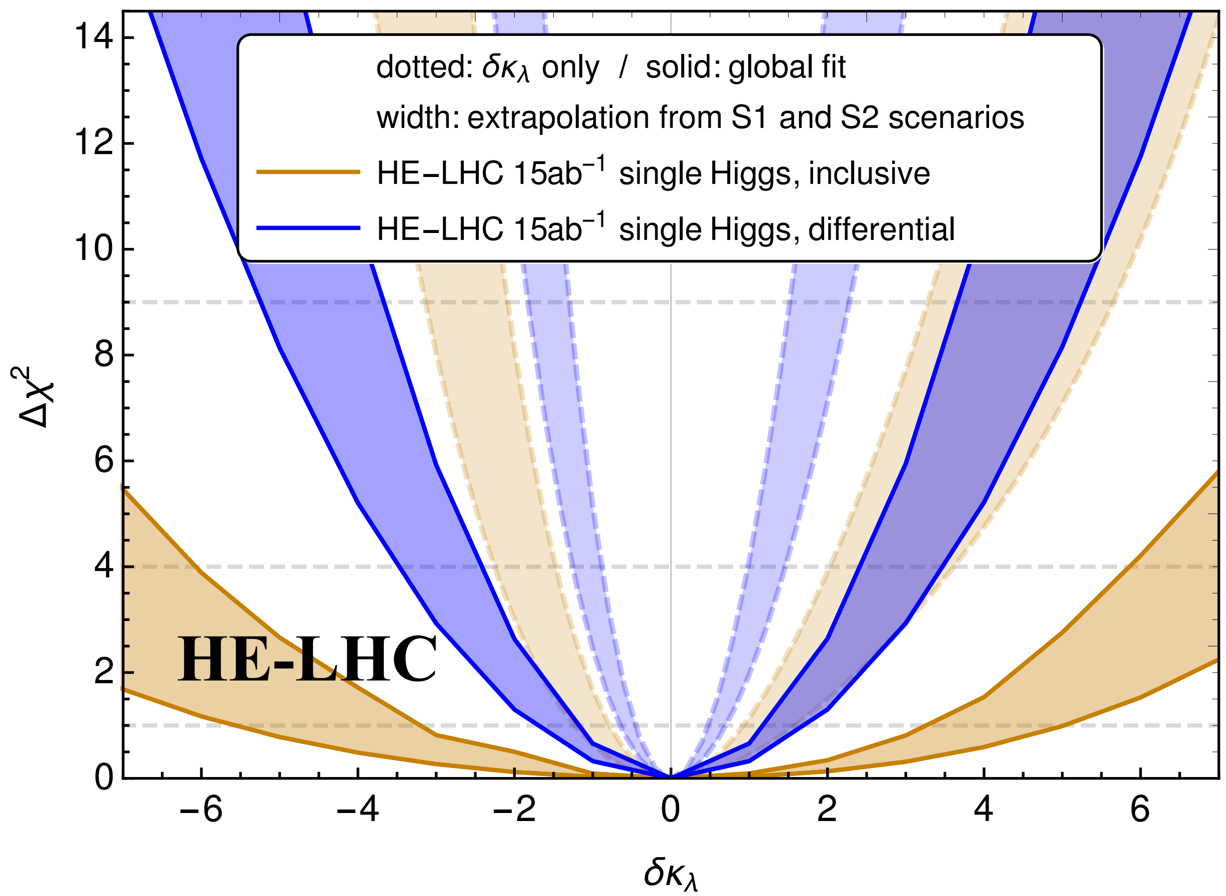
The interplay between additional possible couplings, experimental uncertainties and differential information leads to different results.

In general, differential information improves constraints, especially when additional couplings are considered.

Combined fit with other EFT parameters

Di Vita, Grojean, Panico, Riembau, Vantalon '17 (updated results from HL-HE-LHC report)

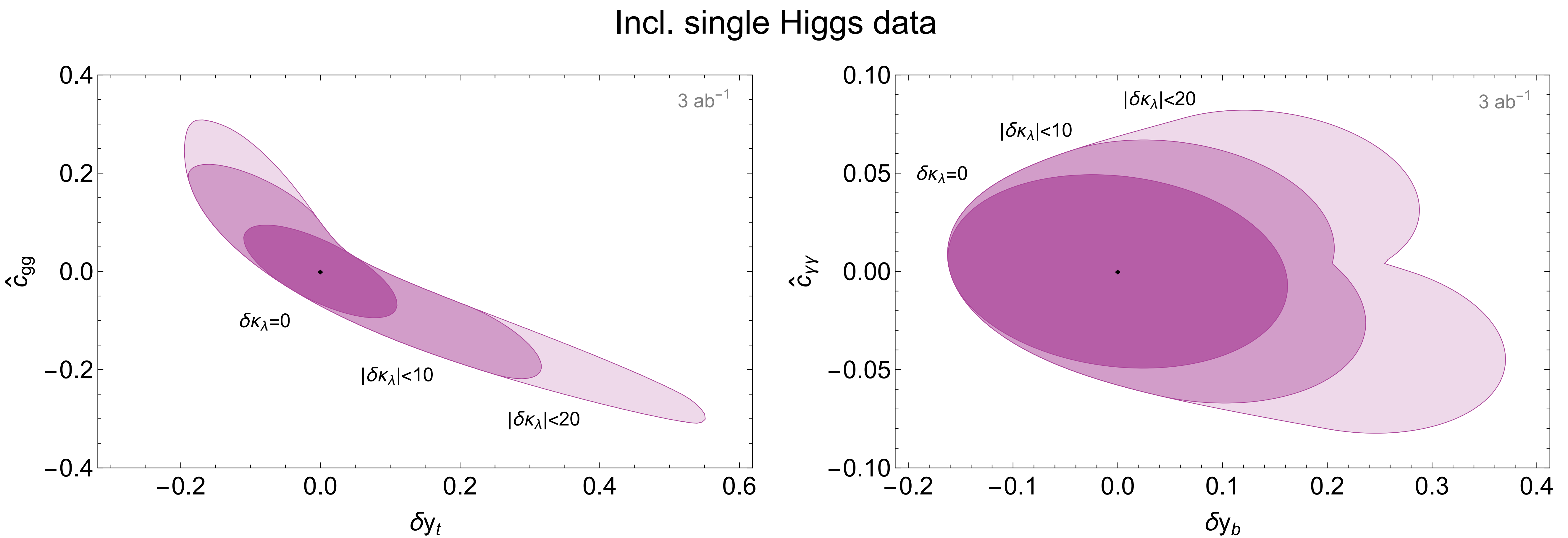




Even with 10 independent parameters, **using differential distributions**, single-Higgs measurements at the HL-LHC can be sensitive to loop-induced anomalous trilinear contributions. Results further improve at HE-LHC (27 TeV).

Single-Higgs differential measurements can improve the constraints from differential measurements in Double Higgs.

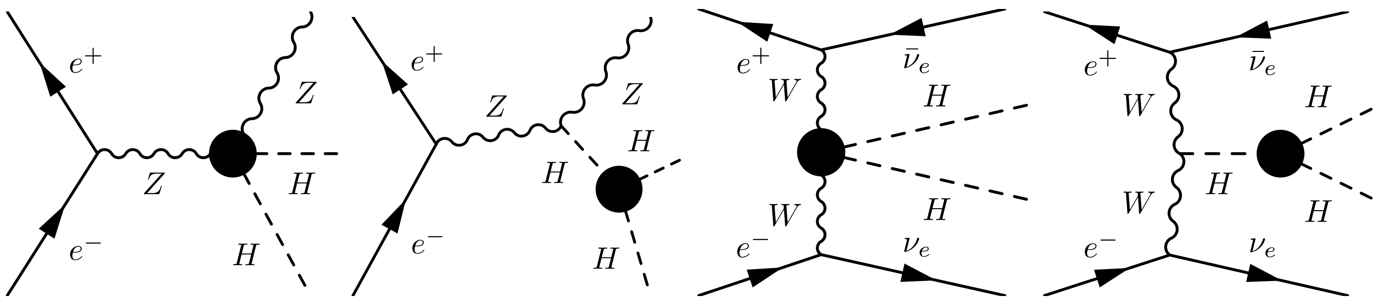
Combined fit with other EFT parameters



Moreover, trilinear loop-induced contributions affect the precision in the determination of the other parameters entering at the tree level.

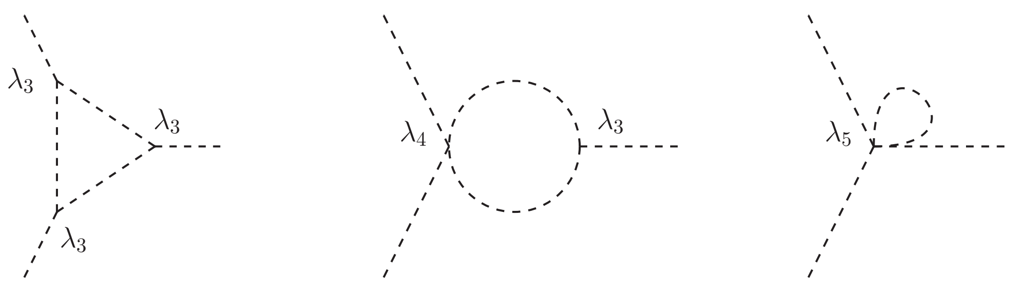
Di Vita, Grojean, Panico, Riembau, Vantalon '17

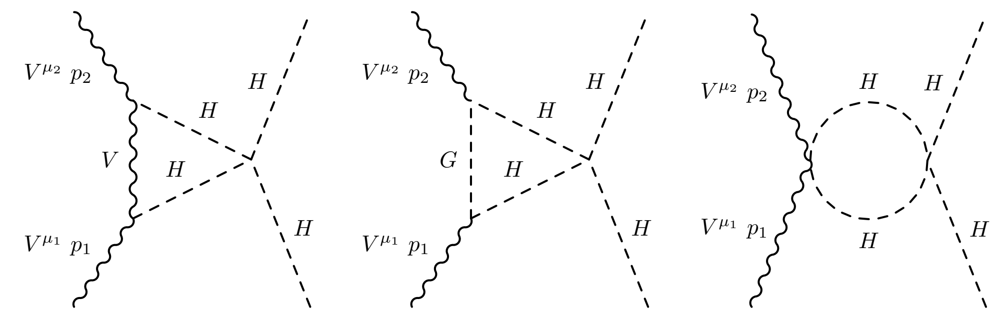
Quartic coupling at lepton colliders



from **triple** in **single** Higgs
to **quartic** in **double** Higgs

Maltoni, DP, Zhao '18





EFT is mandatory, UV divergences have to be renormalised.

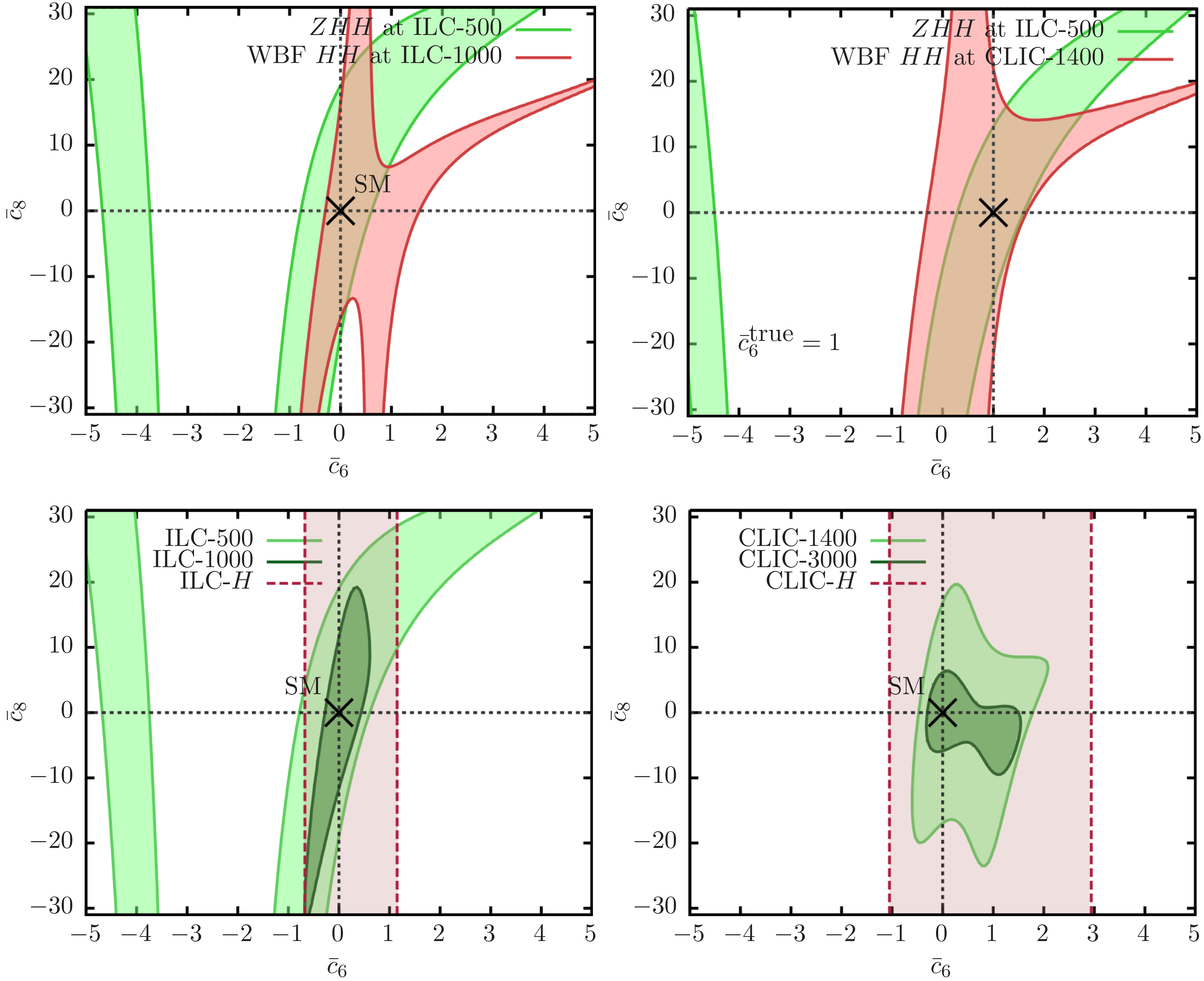
$$\kappa_3 \equiv \frac{\lambda_3}{\lambda_3^{\rm SM}} = 1 + \frac{c_6 v^2}{\lambda \Lambda^2} \equiv 1 + \bar{c}_6 , \qquad \kappa_4 \equiv \frac{\lambda_4}{\lambda_4^{\rm SM}} = 1 + \frac{6 c_6 v^2}{\lambda \Lambda^2} + \frac{4 c_8 v^4}{\lambda \Lambda^4} \equiv 1 + 6\bar{c}_6 + \bar{c}_8$$

$$\begin{aligned} \sigma_{\rm NLO}^{\rm pheno}(HH) &= \sigma_{\rm LO}(HH) + \Delta\sigma_{\bar{c}_6}(HH) + \Delta\sigma_{\bar{c}_8}(HH) \,, \\ \Delta\sigma_{\bar{c}_6}(HH) &= \bar{c}_6^3 \Big[\sigma_{30} + \sigma_{40}\bar{c}_6\Big] \,, \\ \Delta\sigma_{\bar{c}_8}(HH) &= \bar{c}_8 \Big[\sigma_{01} + \sigma_{11}\bar{c}_6 + \sigma_{21}\bar{c}_6^2\Big] \,. \end{aligned}$$

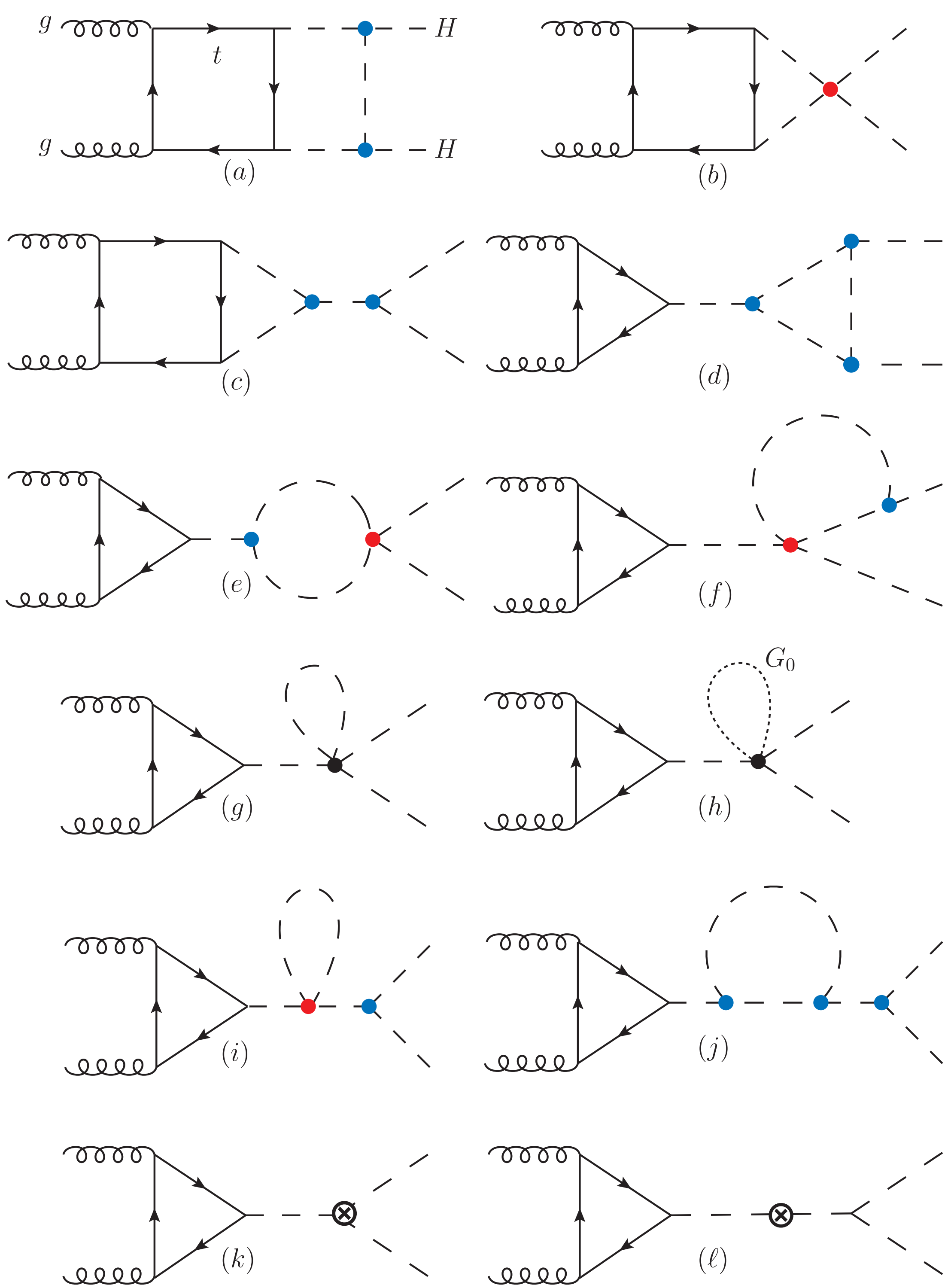
Triple corrections to the triple
Sensitivity quartic

Results

Maltoni, DP, Zhao '18



Quartic coupling at hadron colliders: full result



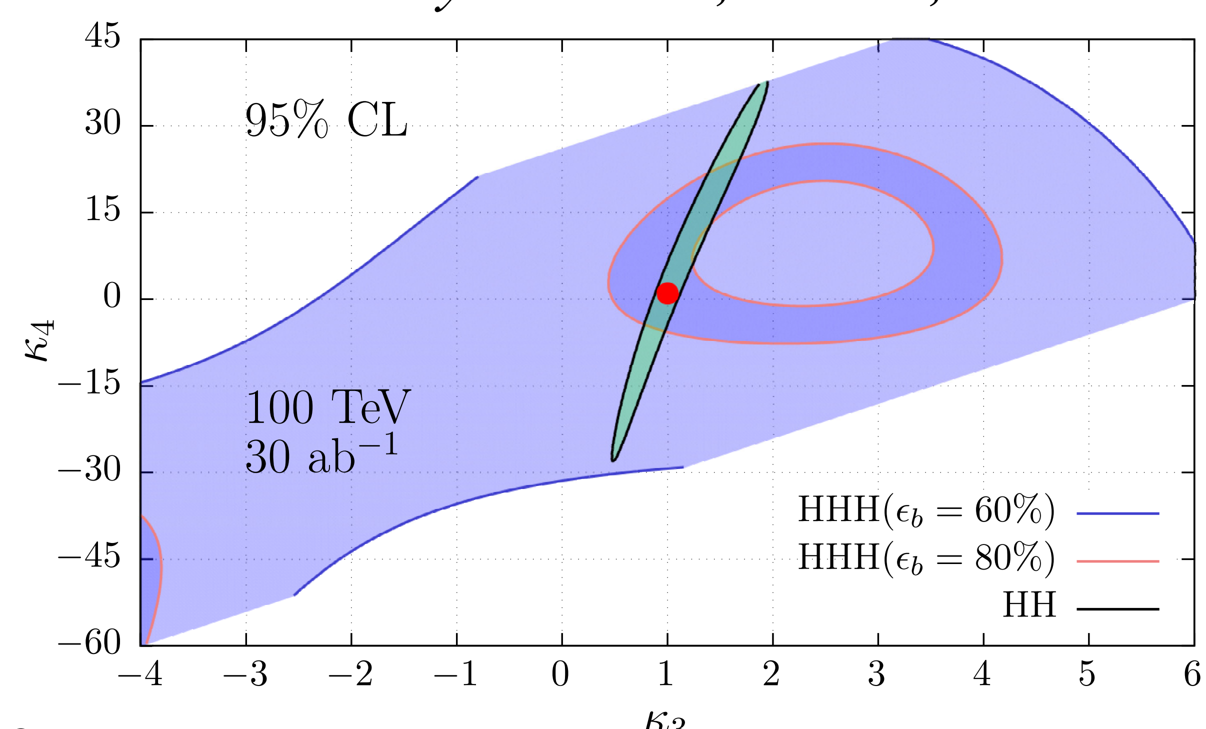
$$\sigma^{\rm pheno}_{\rm NLO} = \sigma_{\rm LO} + \Delta\sigma_{\bar{c}_6} + \Delta\sigma_{\bar{c}_8}$$

$$\Delta\sigma_{\bar{c}_6} = \bar{c}_6^2\left[\sigma_{30}\bar{c}_6 + \sigma_{40}\bar{c}_6^2\right] + \tilde{\sigma}_{20}\bar{c}_6^2\,,$$

$$\Delta\sigma_{\bar{c}_8} = \bar{c}_8\left[\sigma_{01} + \sigma_{11}\bar{c}_6 + \sigma_{21}\bar{c}_6^2\right]$$

All 2-loop contributions from c8 and at c6^3 and c6^4 order are taken into account and renormalised.
The m(HH) distribution is exploited in the analysis.
Only $b\bar{b}\gamma\gamma$ signature is considered.

Similar study in: Bizon, Haisch, Rottoli '18



Duhr, Borowka, Maltoni, DP, Shivaji, Zhao '18

Conclusion

For a correct interpretation of current and future measurements and the possible identification of **BSM** effects, **precise predictions** and therefore **radiative corrections** are **paramount**.

NLO EW corrections cannot be neglected and they can be much larger than order ~ 1% effects, especially in the **tail of the distributions**. (**Sudakov logs**)

Formally **subleading** orders may be in reality **large**. (**Top Physics, VBS**)

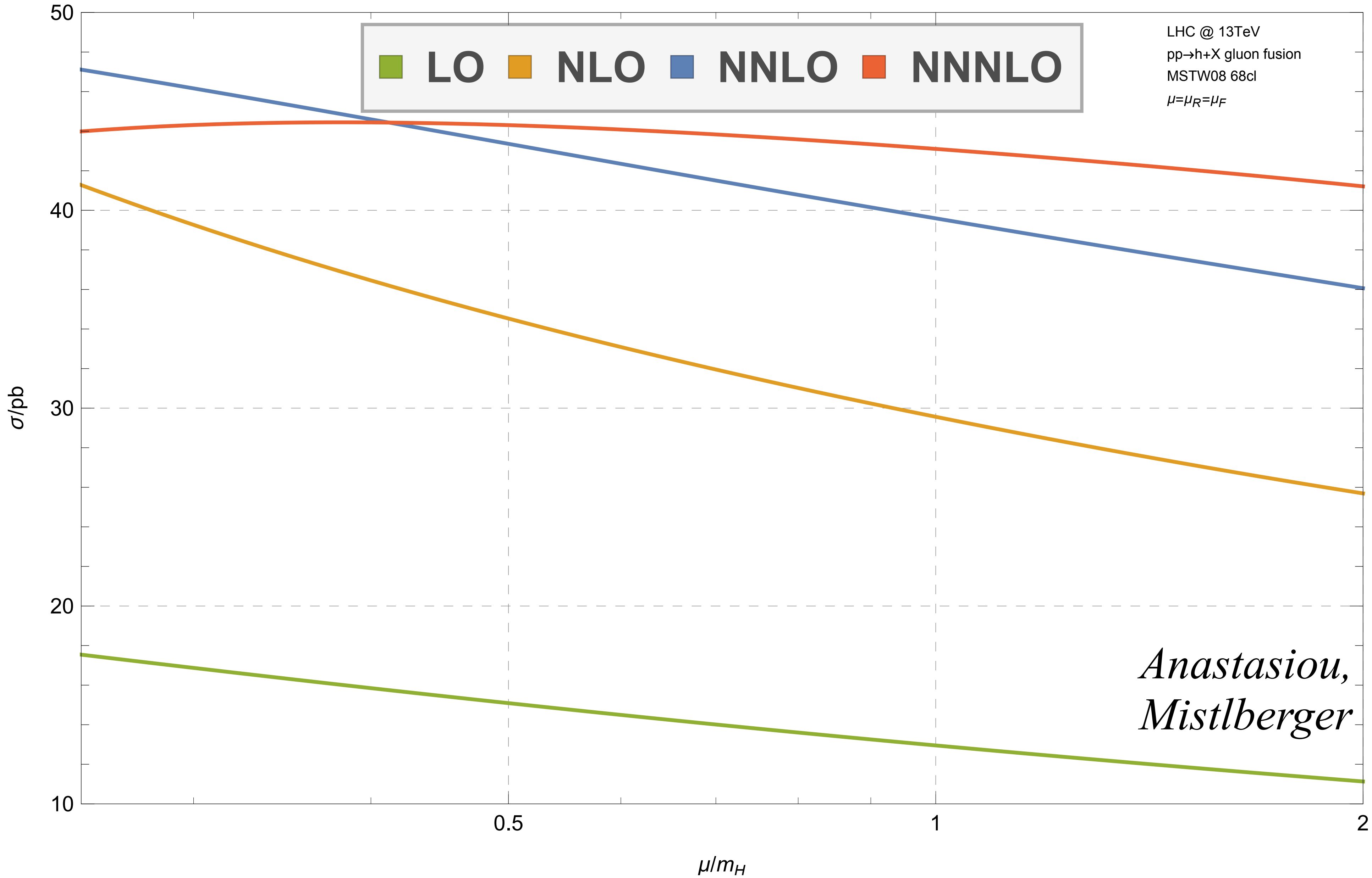
EW corrections, involving additional interactions, can be exploited as proxy for **New Physics** effects via **loop** corrections. (**Higgs self couplings**)

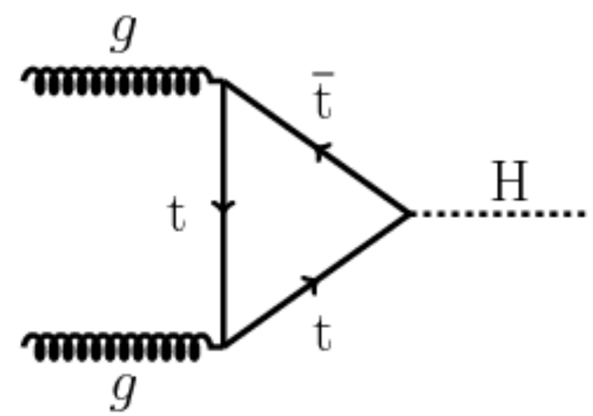
For the **first time,** the calculation of **NLO EW and Complete NLO** corrections can be performed in a **fully automated** way, via the **Madgraph5 _aMC@NLO framework**. Go to https://launchpad.net/mg5amcnlo and download the code!

EXTRA SLIDES

Importance of NNLO (and NNNLO) QCD corrections

An example: H boson production via gluon fusion.

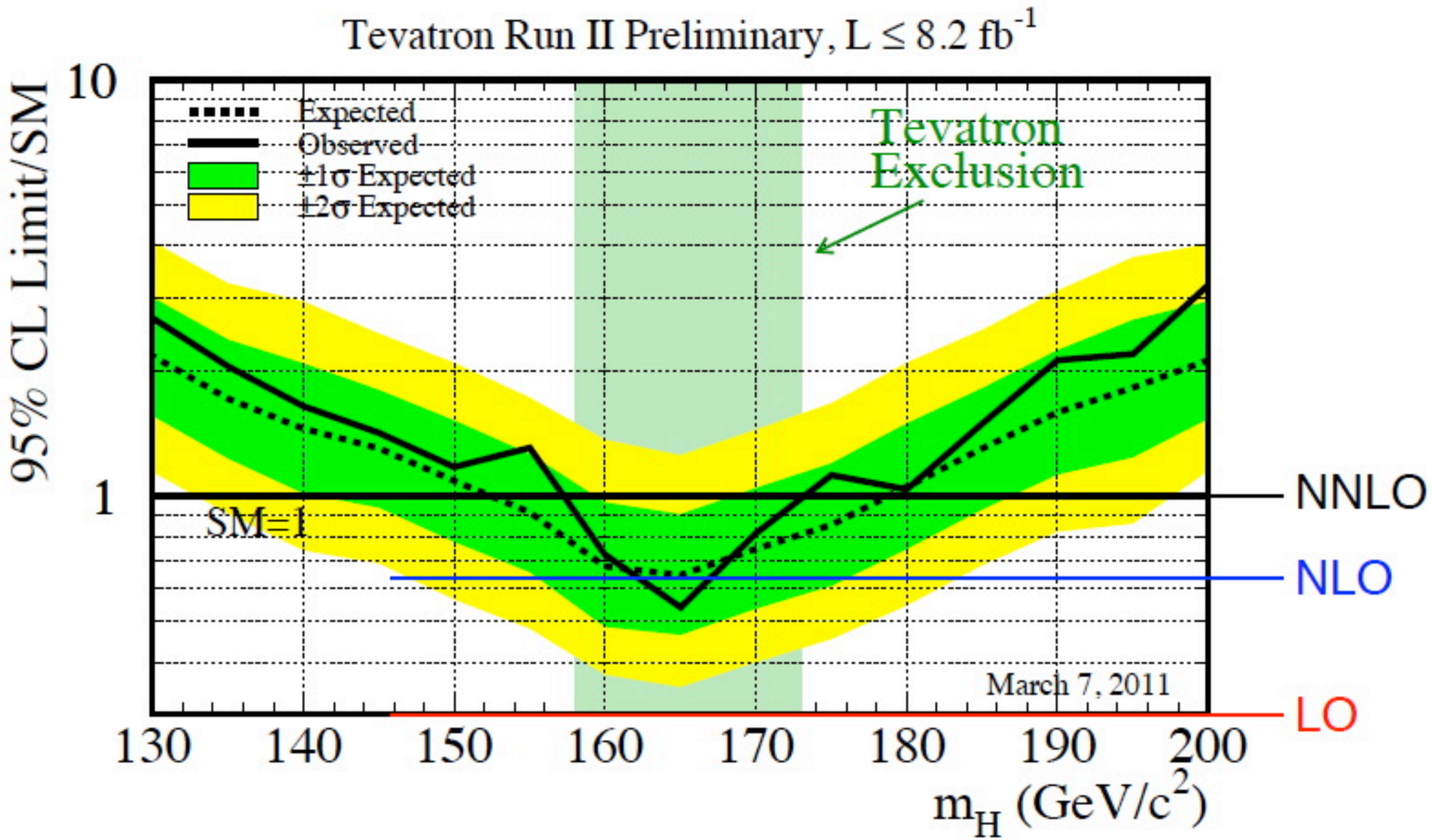




Anastasiou, Duhr, Dulat, Herzog, Mistlberger '15

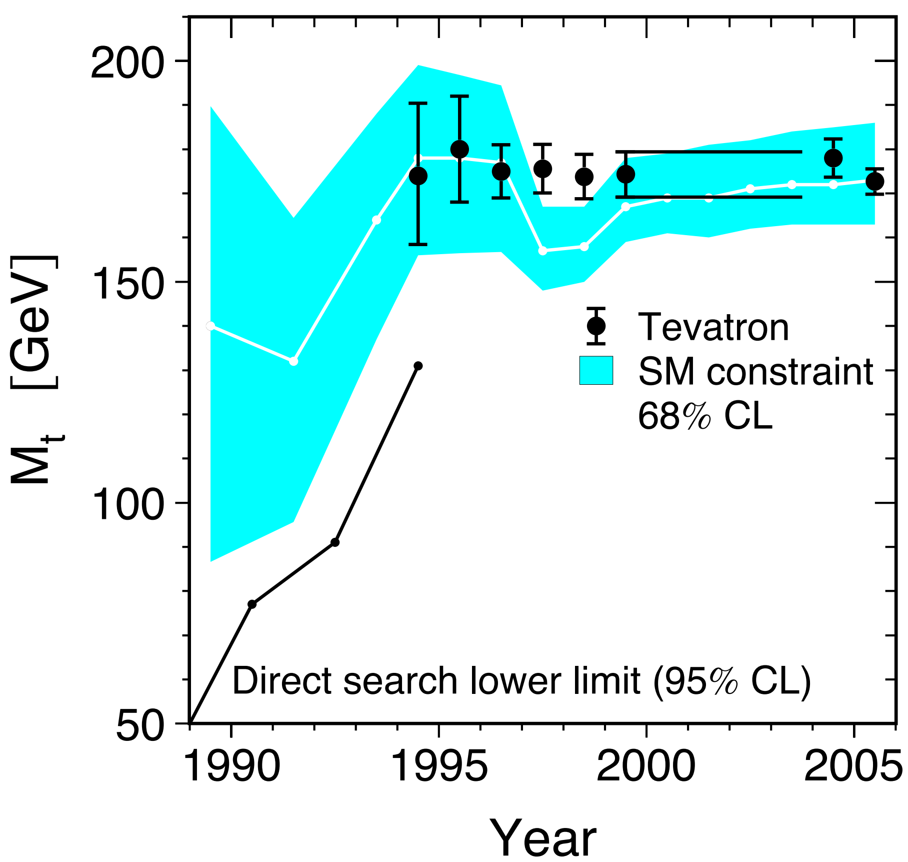
NLO EW corrections are ~ 5 %, i.e., larger than the residual QCD scale uncertainty.

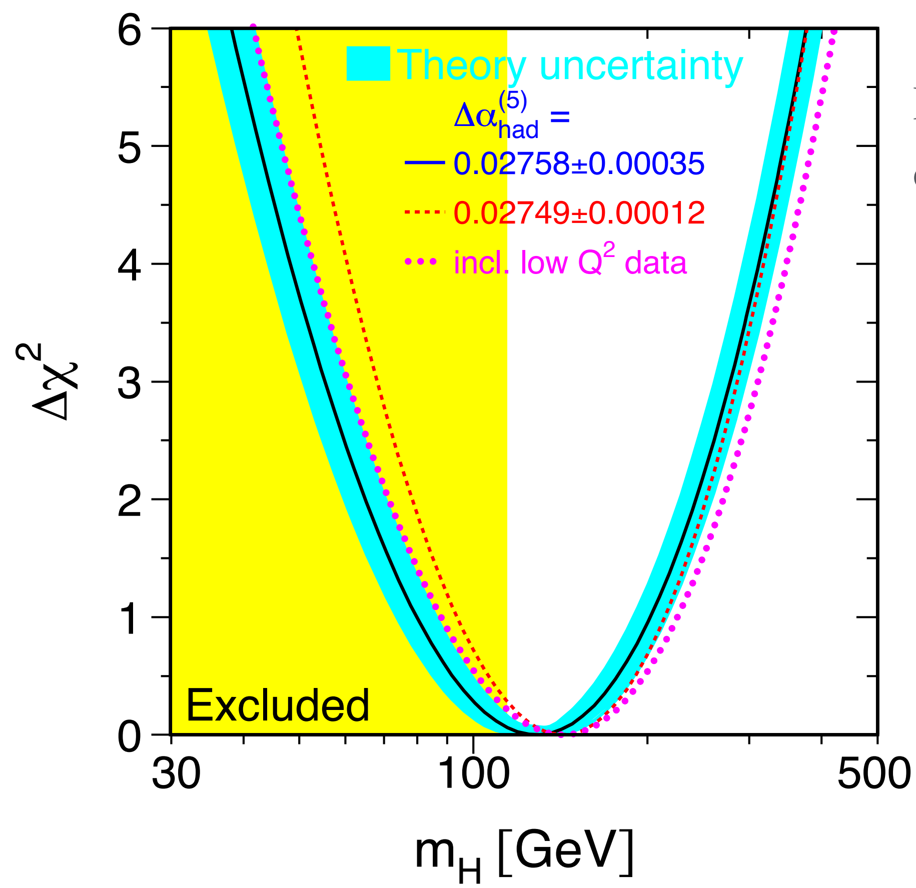
Importance of NLO and NNLO QCD corrections



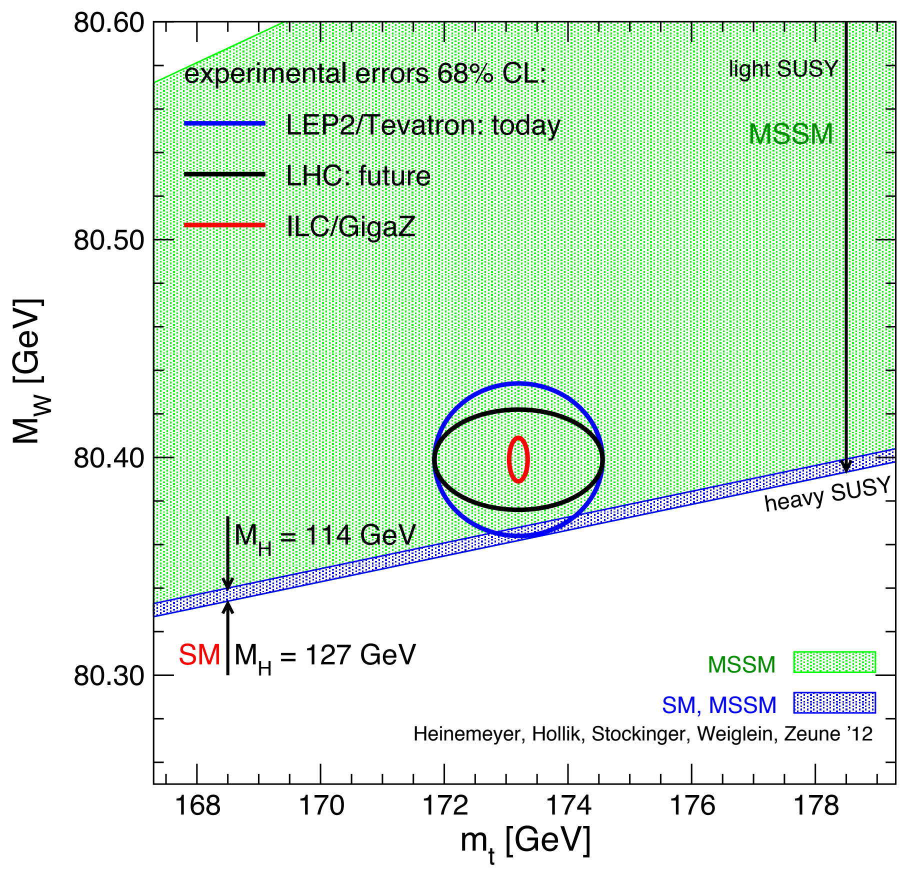
be careful : just illustrative example, not very precise

EWPO (past and future)





Precision Electroweak measurements on the Z resonance hep-ex/0509008



EWPO were crucial in order to constrain the H-boson and top-quark mass.
Today EWPO can be used to check the internal consistency of the SM.
In models where they can be calculated, as in the MSSM, EWPO can be used to constrain the parameter space.

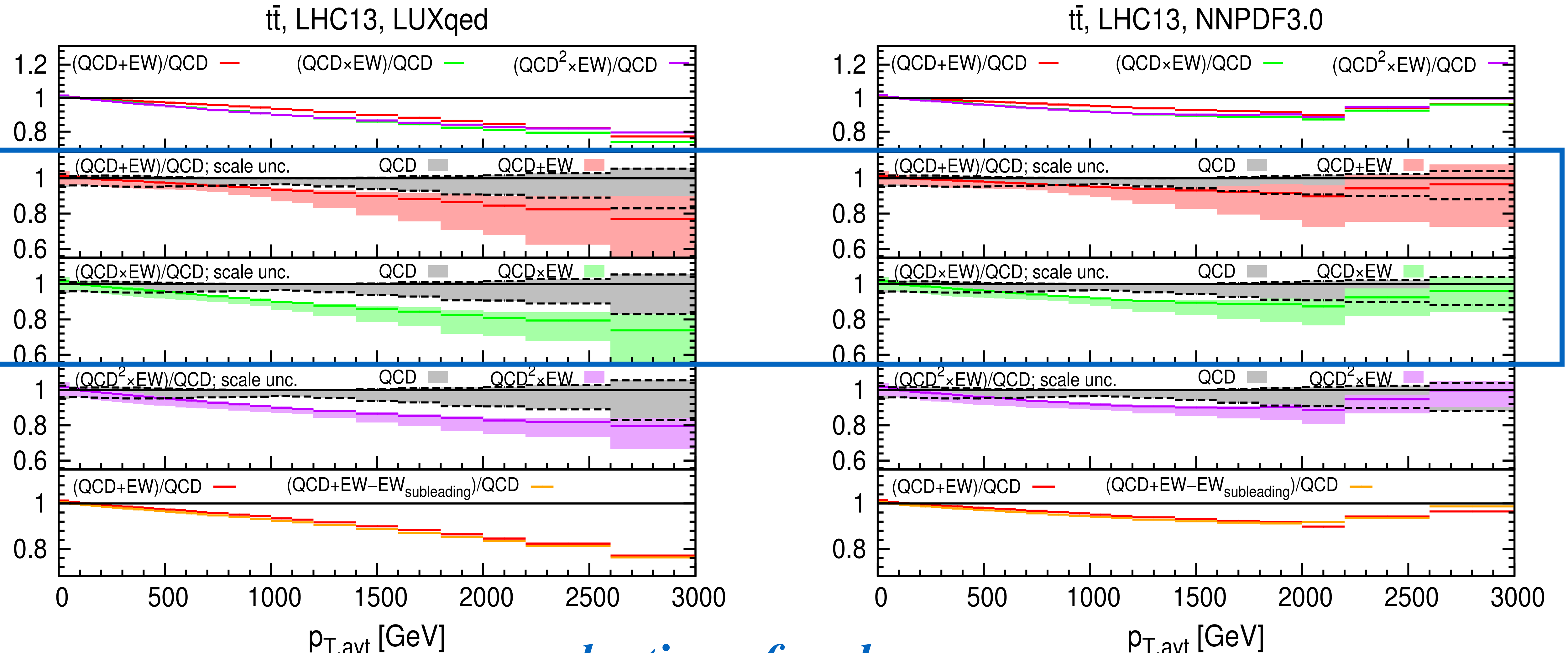
Czakon, Heymes, Mitov, DP, Tsinikos, Zaro '17

$p_{T,\mathrm{avt}}$

13 TeV

ADDITIVE

MULTIPLICATIVE



LUXQED

reduction of scale unc. due to EW corrections, QCD and QCDxEW do not overlap (with LUXQED)

NNPDF3.0QED

The Master Formula

The term $\Sigma_{\rm NLO}$ is the prediction for a generic observable Σ including the effects induced by an anomalous $\lambda_3 \equiv \kappa_\lambda \lambda_3^{\rm SM}$. LO is meant dressed by QCD corrections.

$$\Sigma_{\rm NLO} = Z_H \, \Sigma_{\rm LO} \, (1 + \kappa_\lambda C_1)$$

$$\Sigma_{\rm NLO}^{\rm SM} = \Sigma_{\rm LO} \, (1 + C_1 + \delta Z_H)$$

universal

$$\delta\Sigma_{\lambda_3} \equiv \frac{\Sigma_{\rm NLO} - \Sigma_{\rm NLO}^{\rm SM}}{\Sigma_{\rm LO}} = (\kappa_\lambda - 1)\boxed{C_1} + (\kappa_\lambda^2 - 1)\boxed{C_2} + \mathcal{O}(\kappa_\lambda^3 \, \alpha^2)$$

Process and kinetic dependent

$$C_2 = \frac{\delta Z_H}{(1 - \kappa_\lambda^2 \delta Z_H)}$$

$$\mathcal{O}(\kappa_\lambda^3 \, \alpha^2) \simeq \kappa_\lambda^3 C_1 \delta Z_H \lesssim 10\% \quad \Rightarrow \quad |\kappa_\lambda| \lesssim 20$$

The Master Formula

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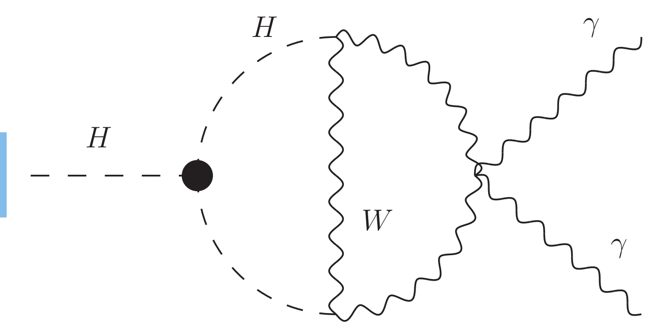
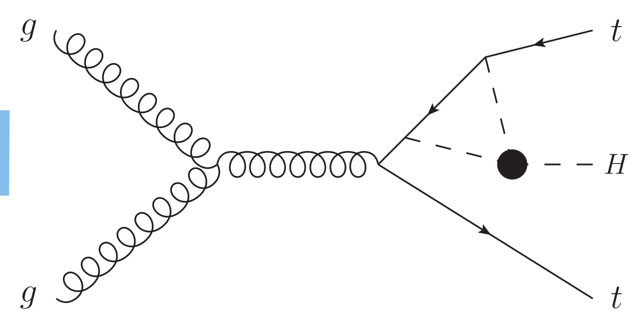
$$\Sigma_{\rm NLO} = Z_H\, \Sigma_{\rm LO}\, (1 + \kappa_\lambda \boxed{C_1})$$

$$C_1^\Gamma = \frac{\int d\Phi\ 2\Re\left(\mathcal{M}^{0*}\mathcal{M}^1_{\lambda_3^{\rm SM}}\right)}{\int d\Phi\ |\mathcal{M}^0|^2}$$



$$= \mathcal{M}^1_{\lambda_3^{\rm SM}} \sim \kappa_\lambda$$

$$C_1^\sigma = \frac{\sum_{i,j}\int dx_1 dx_2 f_i(x_1) f_j(x_2)\, 2\Re\left(\mathcal{M}^{0*}_{ij}\mathcal{M}^1_{\lambda_3^{\rm SM},ij}\right) d\Phi}{\sum_{i,j}\int dx_1 dx_2 f_i(x_1) f_j(x_2)\, |\mathcal{M}^0_{ij}|^2 d\Phi}$$



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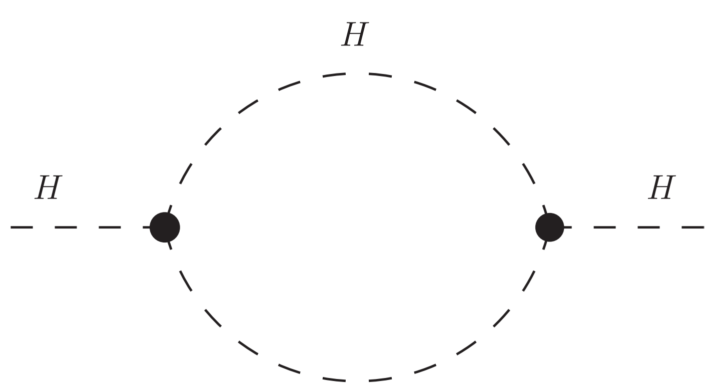
The term $\Sigma_{\rm NLO}$ is the prediction for a generic observable Σ including the effects induced by an anomalous $\lambda_3 \equiv \kappa_\lambda \lambda_3^{\rm SM}$. LO is meant dressed by QCD corrections.

$$\Sigma_{\rm NLO} = \boxed{Z_H}\, \Sigma_{\rm LO} \left(1 + \kappa_\lambda C_1\right)$$

$$Z_H = \frac{1}{1 - \kappa_\lambda^2\, \delta Z_H} \qquad\qquad \delta Z_H = -\frac{9}{16}\,\frac{2(\lambda_3^{\rm SM})^2}{m_H^2\,\pi^2}\left(\frac{2\pi}{3\sqrt{3}} - 1\right)$$



$$\sim \quad \kappa_\lambda^2$$

The wave-function normalization receives corrections that depend quadratically on λ_3.
For large κ_λ, the result cannot be linearized and must be resummed.

$$\kappa_\lambda^2\, \delta Z_H \lesssim 1 \quad \Longrightarrow \quad |\kappa_\lambda| \lesssim 25$$

For a sensible resummation

NLO EW and anomalous couplings

If we modify a SM coupling via $c_i^{\rm SM} \to c_i \equiv \kappa_i c_i^{\rm SM}$, do higher-order computations ***remain in general finite*** (UV cancellation)? **NO**

Exceptions

The renormalization of c_i does not involve EW corrections

Standard "kappa framework"
(No EW corrections possible)

Double Higgs dependence on κ_λ
(No EW corrections possible)

c_i is involved in the renormalization of other couplings, but it is not renormalized

Sensitivity of ttbar production on κ_t
(NLO EW effect)

Kühn et al. '13; Beneke et al. '15

Sensitivity of single Higgs production on κ_λ
(NLO EW effect)

NLO EW and anomalous couplings

If we modify a SM coupling via $c_i^{\rm SM} \to c_i \equiv \kappa_i c_i^{\rm SM}$, do higher-order computations ***remain in general finite*** (UV cancellation)? **NO**

Exceptions

The renormalization of c_i does not involve EW corrections

c_i is involved in the renormalization of other couplings, but it is not renormalized

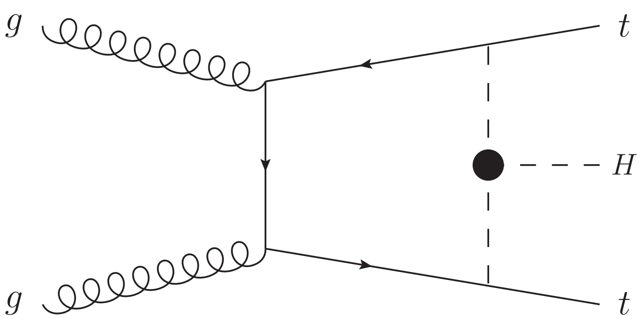
In all cases, $\Lambda_{\rm NP}$ has to be assumed to be not too large in order to have higher-order corrections under control.

In our case, linear EFT (c6) and anomalous coupling (κ_λ) are equivalent at NLO EW.

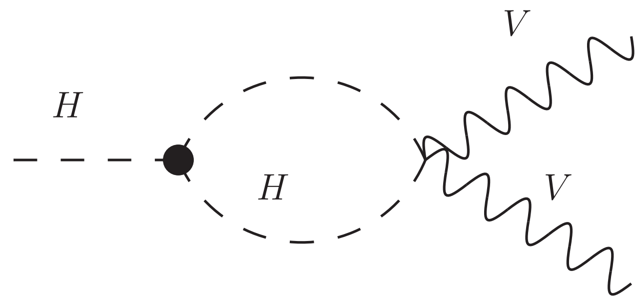
(NLO EW effect)

Calculation of C_1 coefficients

1 Loop Case : *FeynArts, FormCalc, Feyncalc*



ttH



decay and HV, VBF

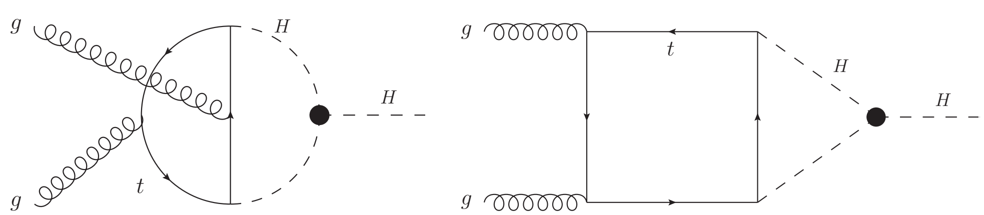
Cannot be expressed via

$\kappa_t \qquad \kappa_Z,\ \kappa_W$

Standard “kappa framework” does not capture the full effect

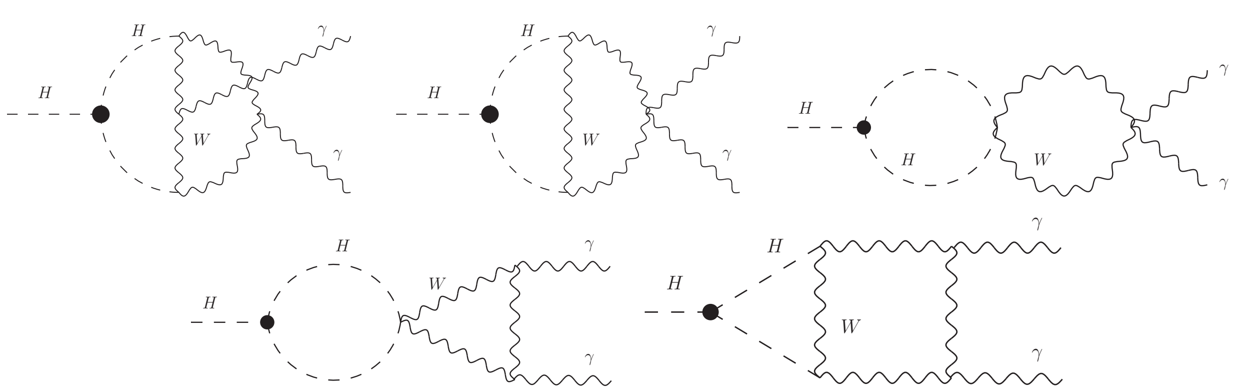
---

2 Loop Case : *FeynArts and expansions*



ggF

Large top-mass expansion with terms up to $\mathcal{O}(m_H^6/m_t^6)$



$H \to \gamma\gamma$

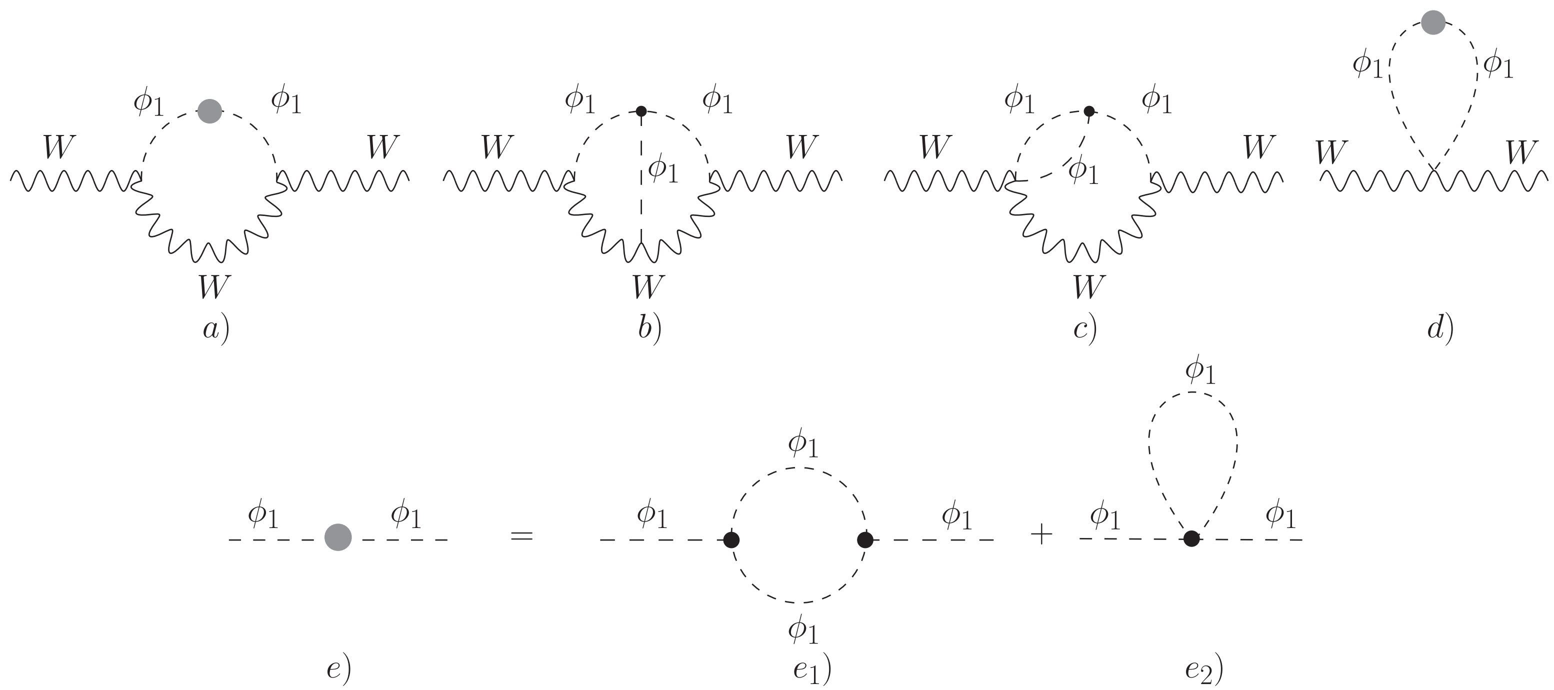
Taylor expansion in $q^2/(4m_W^2)$, $q^2/(4m_H^2)$ up to $\mathcal{O}(q^6/m^6)$

Calculation performed in unitary gauge in order to identify genuine λ_3-dependence and keep only kinematic m_H-dependence

EWPO: dependence on the Higgs self coupling

The trilinear coupling enters the two-loop relations among m_W and $\sin^2\theta_{\rm eff}^{\rm lep}$ and the EW input parameters. At two-loop, there is not dependence on the quadrilinear coupling.

Degrassi, Fedele, Giardino '17



$$m_W^2 = \frac{\hat\rho\, m_Z^2}{2}\left\{1+\left[1-\frac{4\hat A^2}{m_Z^2\hat\rho}(1+\Delta\hat r_W)\right]^{1/2}\right\}$$

$$\sin^2\theta_{\rm eff}^{\rm lep} = \hat k_\ell(m_Z^2)\hat s^2, \qquad \hat k_\ell(m_Z^2) = 1+\delta\hat k_\ell(m_Z^2)$$

$$\hat A = (\pi\hat\alpha(m_Z)/(\sqrt{2}G_\mu))^{1/2}$$

$$\hat s^2 = \frac{1}{2}\left\{1-\left[1-\frac{4\hat A^2}{m_Z^2\hat\rho}(1+\Delta\hat r_W)\right]^{1/2}\right\}$$

$$\hat\rho \equiv \frac{m_W^2}{m_Z^2\hat c^2} = \frac{1}{1-\boxed{Y_{\overline{MS}}}}$$

Terms affected by κλ

$$\frac{G_\mu}{\sqrt{2}} = \frac{\pi\hat\alpha(m_Z)}{2m_W^2\hat s^2}(1+\boxed{\Delta\hat r_W})$$

EWPO: dependence on the Higgs self coupling

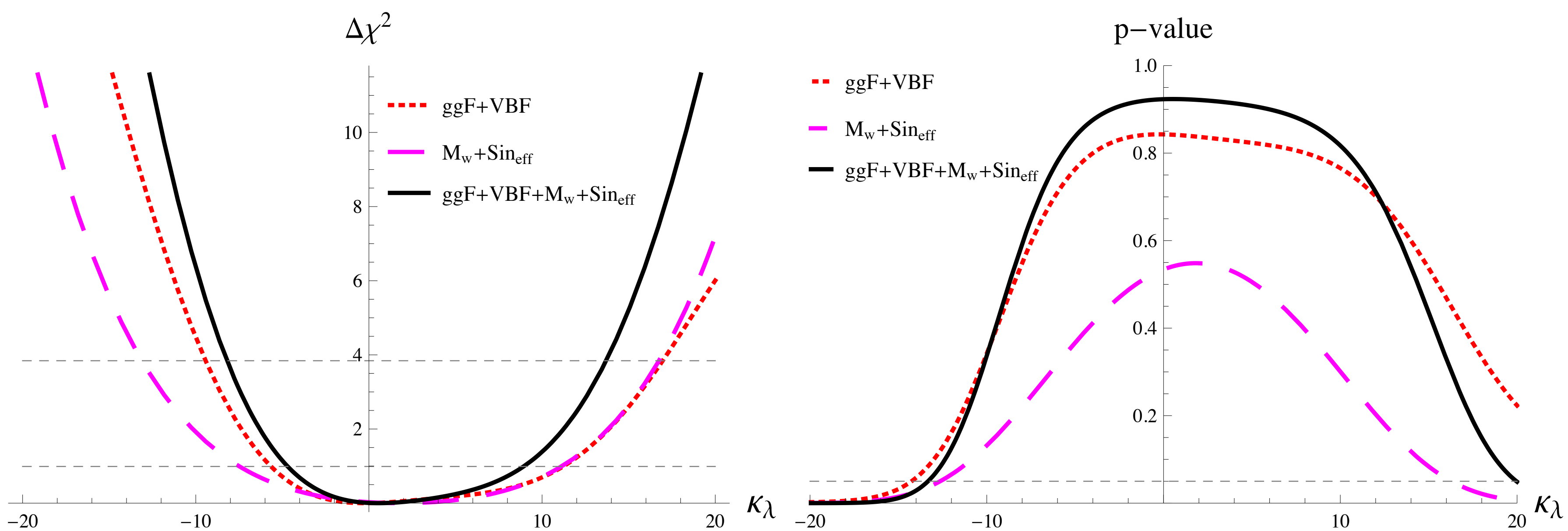
Denoting as O either m_W or $\sin^2\theta_{\rm eff}^{\rm lep}$ one can write

$$O = O^{\rm SM}\left[1 + (\kappa_\lambda - 1)C_1 + (\kappa_\lambda^2 - 1)C_2\right]$$

	C_1	C_2
m_W	6.27×10^{-6}	-1.72×10^{-6}
$\sin^2\theta_{\rm eff}^{\rm lep}$	-1.56×10^{-5}	4.55×10^{-6}

Degrassi, Fedele, Giardino '17

$$m_W = 80.370 \pm 0.019 \text{ GeV}$$
$$\sin^2\theta_{\rm eff}^{\rm lep} = 0.23185 \pm 0.00035$$



ggF+VBF (8TeV)

$$\kappa_\lambda^{\rm best} = -0.24\,, \qquad \kappa_\lambda^{1\sigma} = [-5.6, 11.2]\,, \qquad \kappa_\lambda^{2\sigma} = [-9.4, 17.0]$$

ggF+VBF (8TeV) + EWPO

$$\kappa_\lambda^{\rm best} = 0.5\,, \qquad \kappa_\lambda^{1\sigma} = [-4.7, 8.9]\,, \qquad \kappa_\lambda^{2\sigma} = [-8.2, 13.7]$$

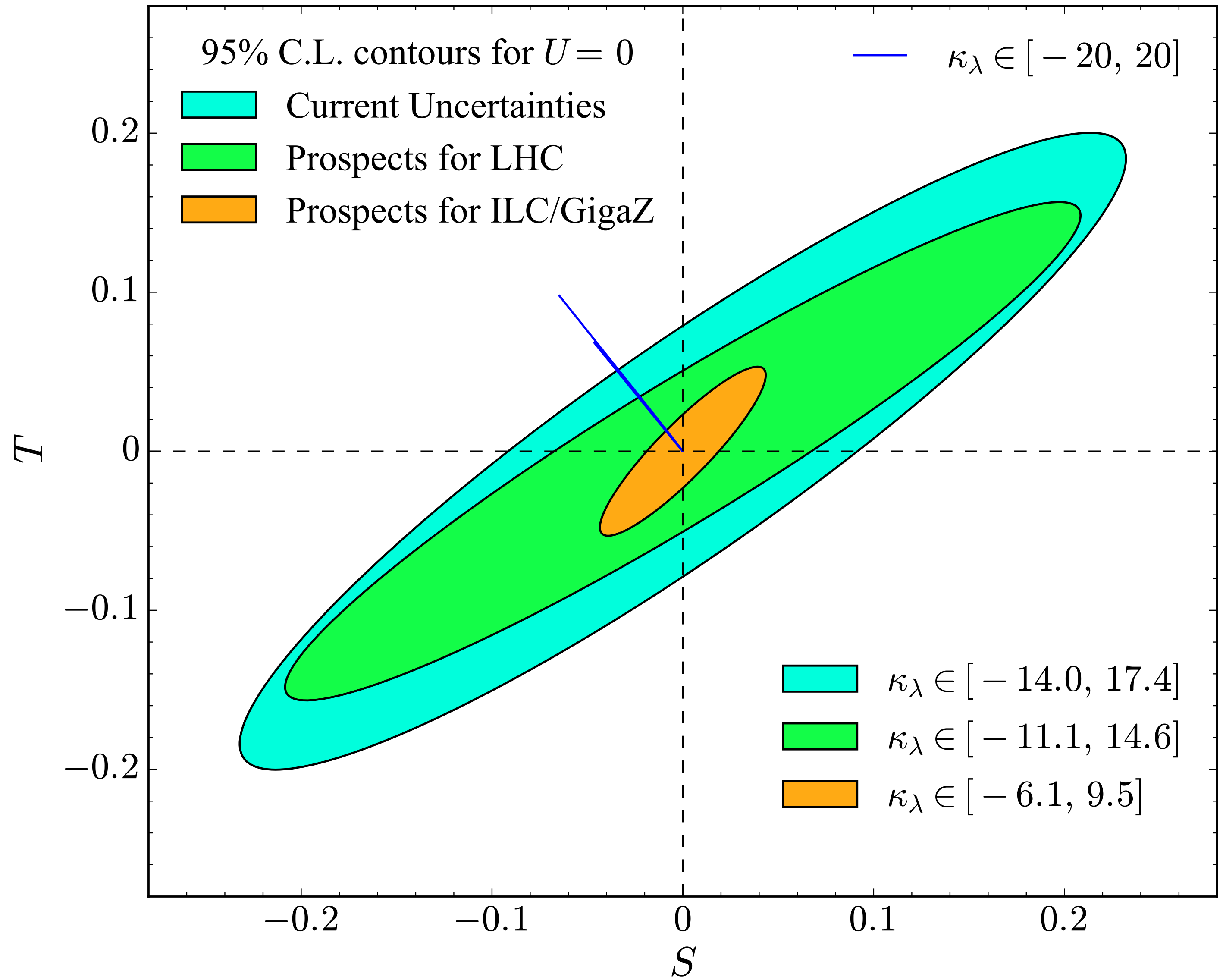
EWPO: dependence on the Higgs self coupling

Equivalent results can be also found looking at S and T oblique parameters.

$$S = -0.000138\,(\kappa_\lambda^2 - 1) + 0.000456\,(\kappa_\lambda - 1)$$
$$T = \quad 0.000206\,(\kappa_\lambda^2 - 1) - 0.000736\,(\kappa_\lambda - 1)$$

$$\Rightarrow \quad -14.0 \leq \kappa_\lambda \leq 17.4$$

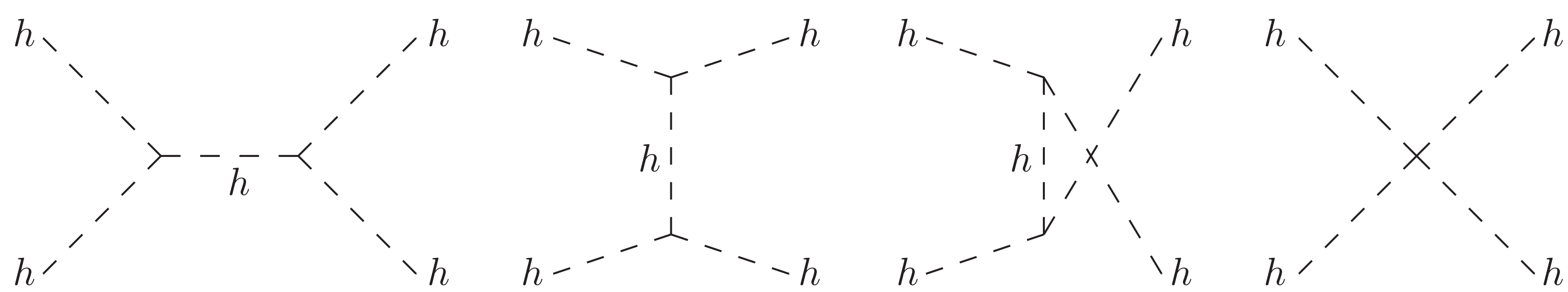
Kribs, Maier, Rzehak, Spannowsky, Waite '17



How large can be the self couplings?

Di Luzio, Gröber, Spannowsky '17

- EFT is not the right framework for extracting bounds on Higgs self couplings from the stability of the vacuum.
- General bounds can be extracted from **perturbativiy arguments**.

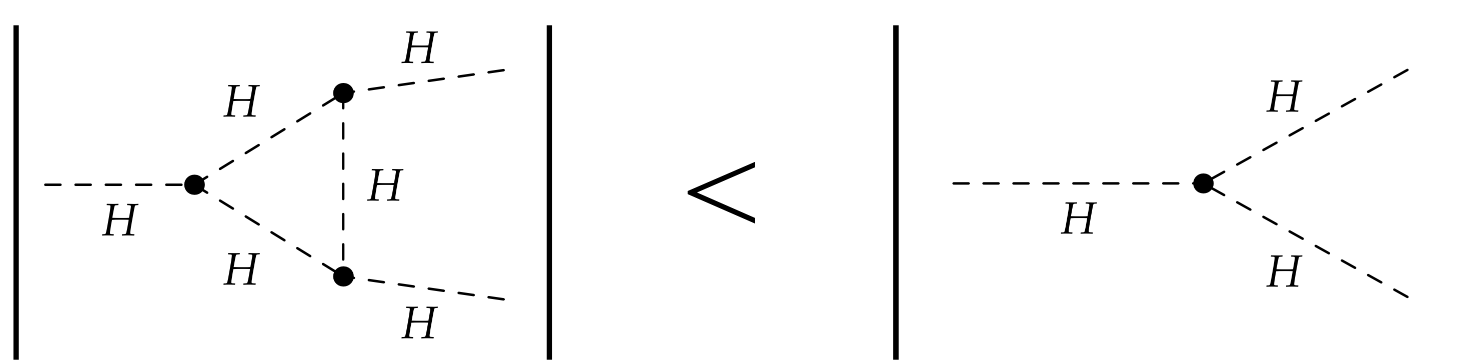


The $J = 0$ partial wave is found to be

$$a^0_{hh\to hh} = -\frac{1}{2}\frac{\sqrt{s(s-4m_h^2)}}{16\pi s}\left[\lambda^2_{hhh}\left(\frac{1}{s-m_h^2} - 2\frac{\log\frac{s-3m_h^2}{m_h^2}}{s-4m_h^2}\right) + \lambda_{hhhh}\right]$$

$$\left|\mathrm{Re}\, a^0_{hh\to hh}\right| < 1/2 \quad \Rightarrow \quad \left|\lambda_{hhh}/\lambda^{\mathrm{SM}}_{hhh}\right| \lesssim 6.5 \quad \text{and} \quad \left|\lambda_{hhhh}/\lambda^{\mathrm{SM}}_{hhhh}\right| \lesssim 65$$

Similar bounds on the trilinear by requiring for any external momenta:



Combined fit with others EFT parameters

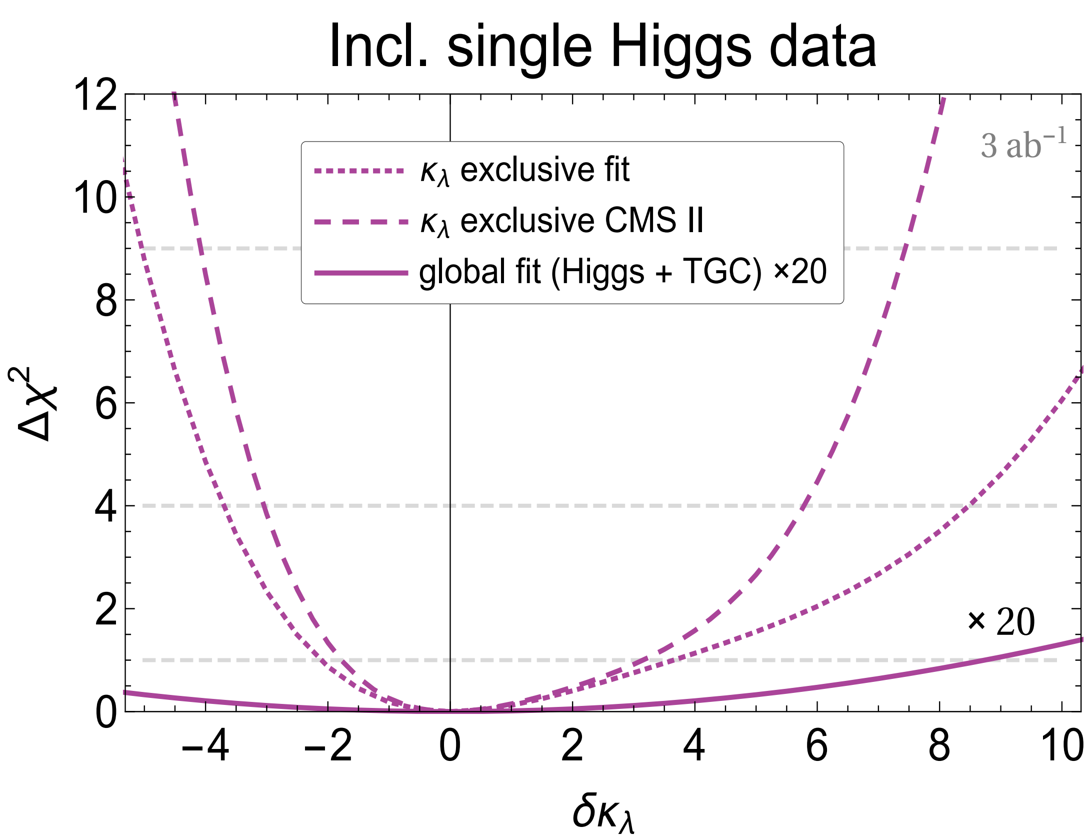
How are limits on κ_λ affected by lifting the condition that Higgs interactions with the other particle are SM-like? *Di Vita, Grojean, Panico, Riembau, Vantalon '17*

Assumptions:

- Consider **all** the possible EFT dimension-6 operators that enter **only** in single Higgs production and decay (10 independent parameters).

tree-level: $\delta c_z, c_{zz}, c_{z\Box}, \hat{c}_{z\gamma}, \hat{c}_{\gamma\gamma}, \hat{c}_{gg}, \delta y_t, \delta y_b, \delta y_\tau$ *loop:* κ_λ

- Consider **only *inclusive*** single-Higgs observable (9 independent constraints)



10 parameters vs 9 constraints —> 1 flat direction so no constraints for the weakest: κ_λ

We moved from 1 to 10: **no Physics in the middle?**
Effect of top chromo-dipole operators (11)?

9 constraints can become 10 (Higgs plus jet, Double Higgs ..), or many (look at distributions)

Combined fit with others EFT parameters

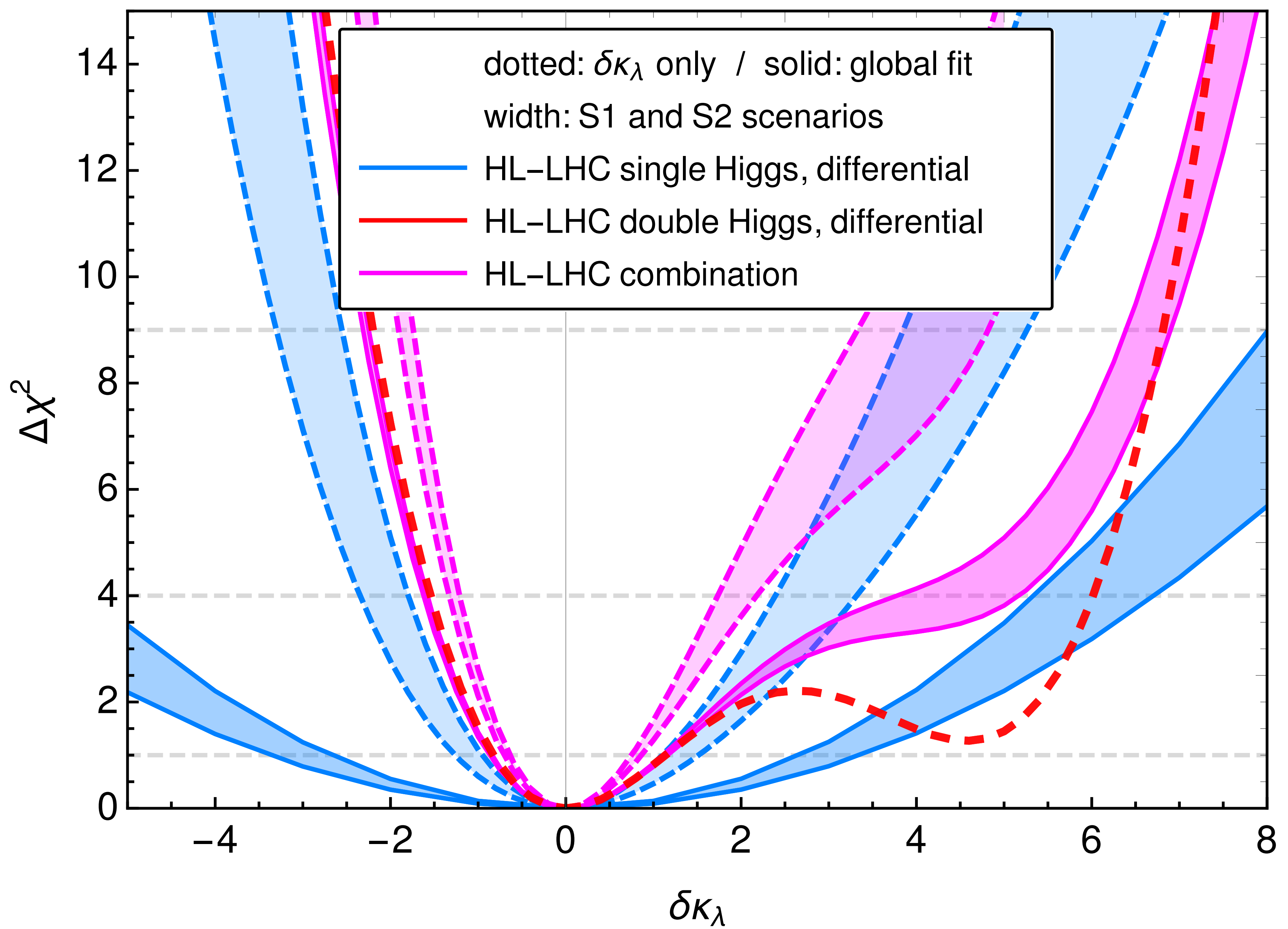
$$
\begin{aligned}
\mathcal{L} \supset \frac{h}{v}\Bigg[& \delta c_w \frac{g^2 v^2}{2} W_\mu^+ W^{-\mu} + \delta c_z \frac{(g^2+g'^2)v^2}{4} Z_\mu Z^\mu \\
& + c_{ww} \frac{g^2}{2} W_{\mu\nu}^+ W_{-\mu\nu} + c_{w\Box} g^2 \left(W_\mu^+ \partial_\nu W_{+\mu\nu} + \text{h.c.}\right) + \hat{c}_{\gamma\gamma} \frac{e^2}{4\pi^2} A_{\mu\nu} A^{\mu\nu} \\
& + c_{z\Box} g^2 Z_\mu \partial_\nu Z^{\mu\nu} + c_{\gamma\Box} g g' Z_\mu \partial_\nu A^{\mu\nu} + c_{zz} \frac{g^2+g'^2}{4} Z_{\mu\nu} Z^{\mu\nu} + \hat{c}_{z\gamma} \frac{e\sqrt{g^2+g'^2}}{2\pi^2} Z_{\mu\nu} A^{\mu\nu}\Bigg] \\
& + \frac{g_s^2}{48\pi^2}\left(\hat{c}_{gg}\frac{h}{v} + \hat{c}_{gg}^{(2)} \frac{h^2}{2v^2}\right) G_{\mu\nu} G^{\mu\nu} - \sum_f \left[m_f \left(\delta y_f \frac{h}{v} + \delta y_f^{(2)} \frac{h^2}{2v^2}\right) \bar{f}_R f_L + \text{h.c.}\right] \\
& - (\kappa_\lambda - 1)\lambda_3^{SM} v h^3 \,, \qquad (2.5)
\end{aligned}
$$

Di Vita, Grojean, Panico, Riembau, Vantalon '17

$$
\begin{aligned}
\delta c_w &= \delta c_z \,, \\
c_{ww} &= c_{zz} + 2\frac{\pi^2 g'^2}{g^2+g'^2} \hat{c}_{z\gamma} + \frac{9\pi^2 g'^4}{2(g^2+g'^2)^2} \hat{c}_{\gamma\gamma} \,, \\
c_{w\Box} &= \frac{1}{g^2-g'^2}\left[g^2 c_{z\Box} + g'^2 c_{zz} - e^2 \frac{\pi^2 g'^2}{g^2+g'^2} \hat{c}_{\gamma\gamma} - (g^2-g'^2)\frac{\pi^2 g'^2}{g^2+g'^2} \hat{c}_{z\gamma}\right], \\
c_{\gamma\Box} &= \frac{1}{g^2-g'^2}\left[2g^2 c_{z\Box} + \left(g^2+g'^2\right) c_{zz} - \pi^2 e^2 \hat{c}_{\gamma\gamma} - \pi^2 \left(g^2-g'^2\right) \hat{c}_{z\gamma}\right], \\
\hat{c}_{gg}^{(2)} &= \hat{c}_{gg} \,, \\
\delta y_f^{(2)} &= 3\delta y_f - \delta c_z \,.
\end{aligned}
$$

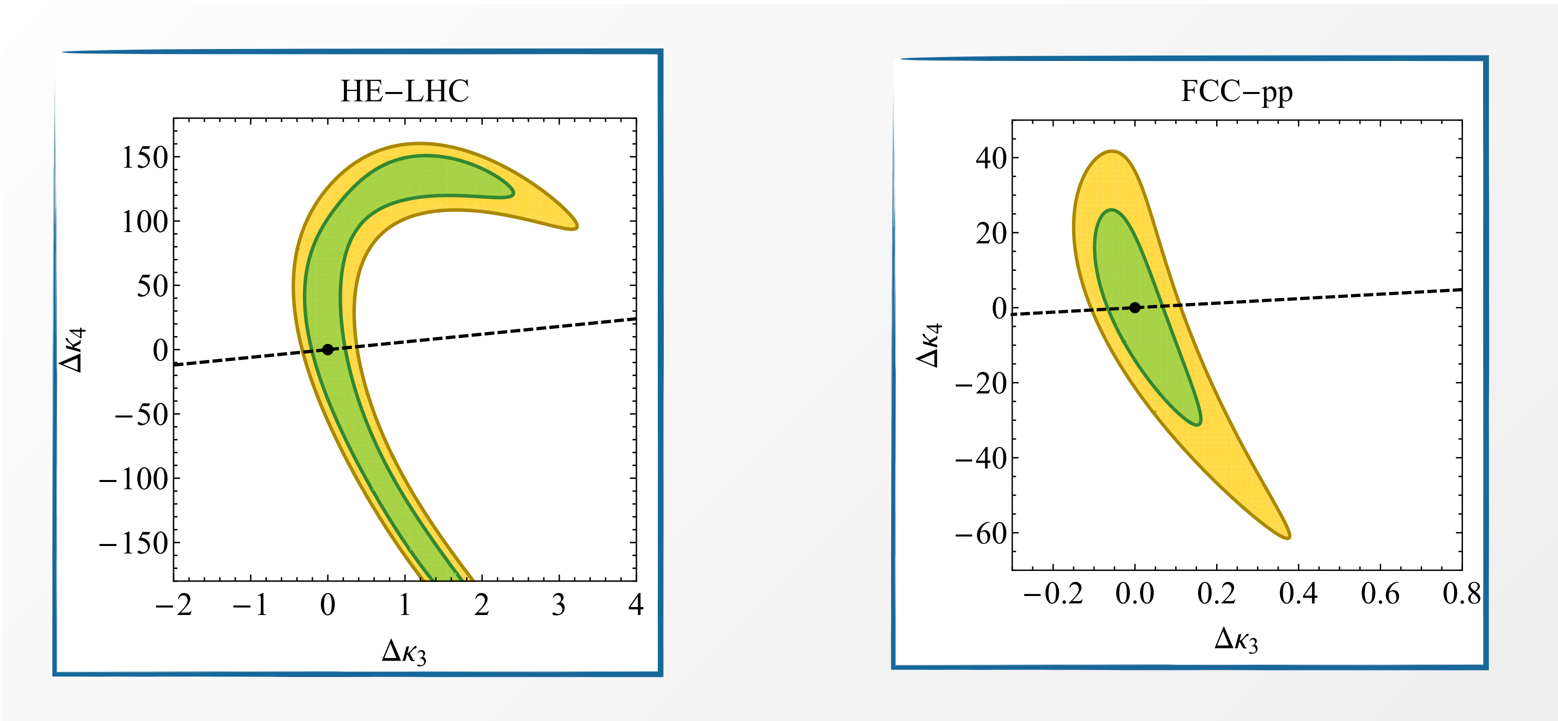
Combined fit with others EFT parameters

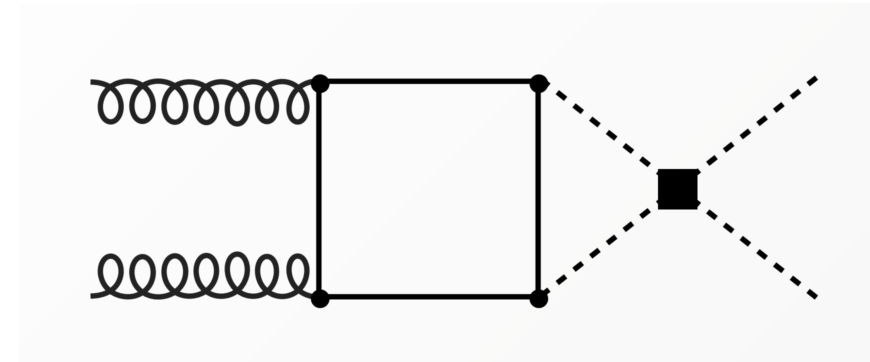
Combination with Double Higgs at HL-LHC.

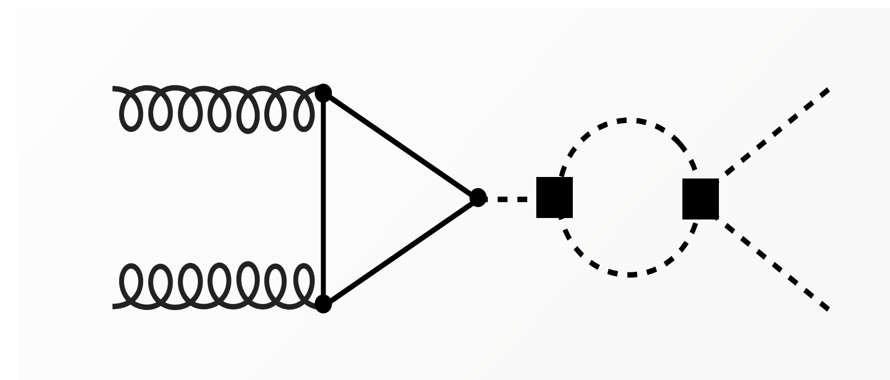


HL- HE-LHC Report WG2

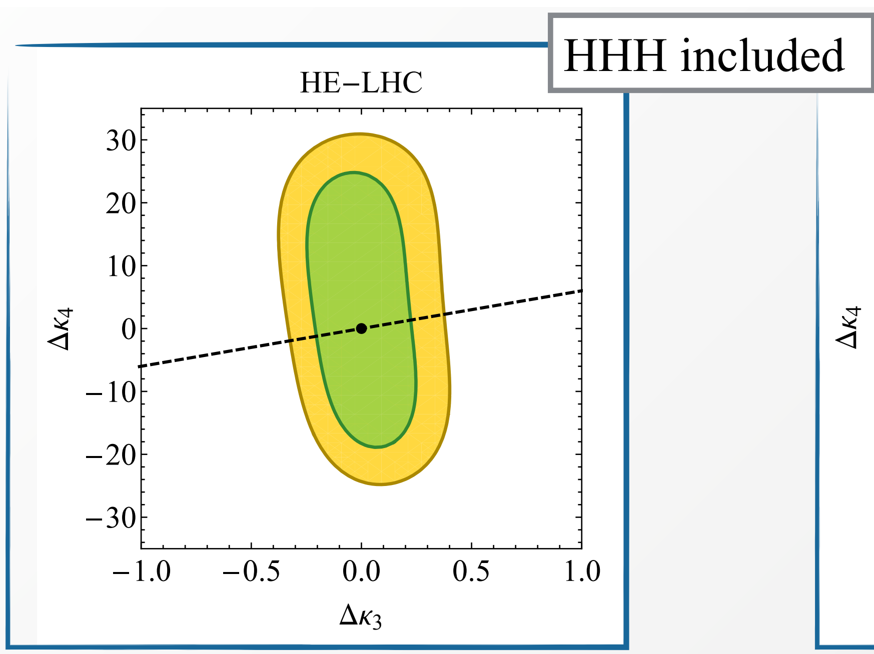
Quartic coupling at hadron colliders: first estimate

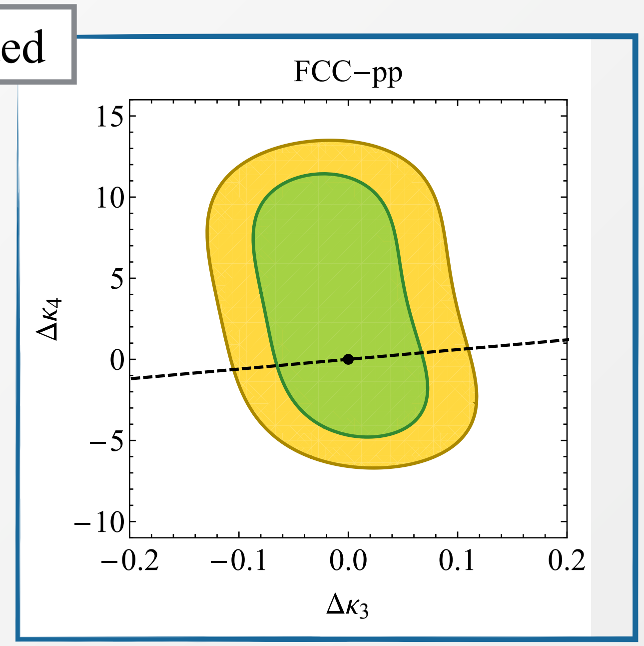






from talk of Luca Rottoli





$\kappa_3 = 1$ $\kappa_4 \in [-20,29]$

Profiling over κ_3 $\kappa_4 \in [-17,25]$

$\kappa_3 = 1$ $\kappa_4 \in [-5,13]$

Profiling over κ_3 $\kappa_4 \in [-4,12]$

The m(HH) distribution is e in the analysis.

Bizon, Haisch, Rottoli '18

$\kappa_3 \sim 1 \rightarrow |\kappa_4| \lesssim 31$

for sensible results (perturbativity)