

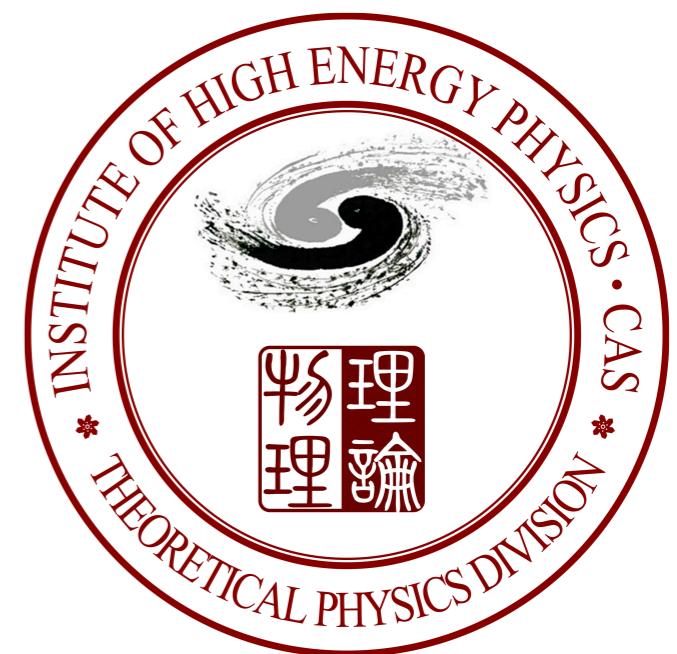
SMEFT at NLO

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Multi-Boson Interactions (MBI 2019) workshop
26 August 2019, Aristotle University of Thessaloniki

Based on on-going project with C. Degrande, G. Durieux, F. Maltoni,
K. Mimasu, and E. Vryonidou



- Motivation
- Some recent results
- Automation @ NLO in QCD
- Towards automation @ NLO in EW

Why EFT @ NLO

Why EFT @ NLO

- EFT is renormalizable order by order in $1/\Lambda$.

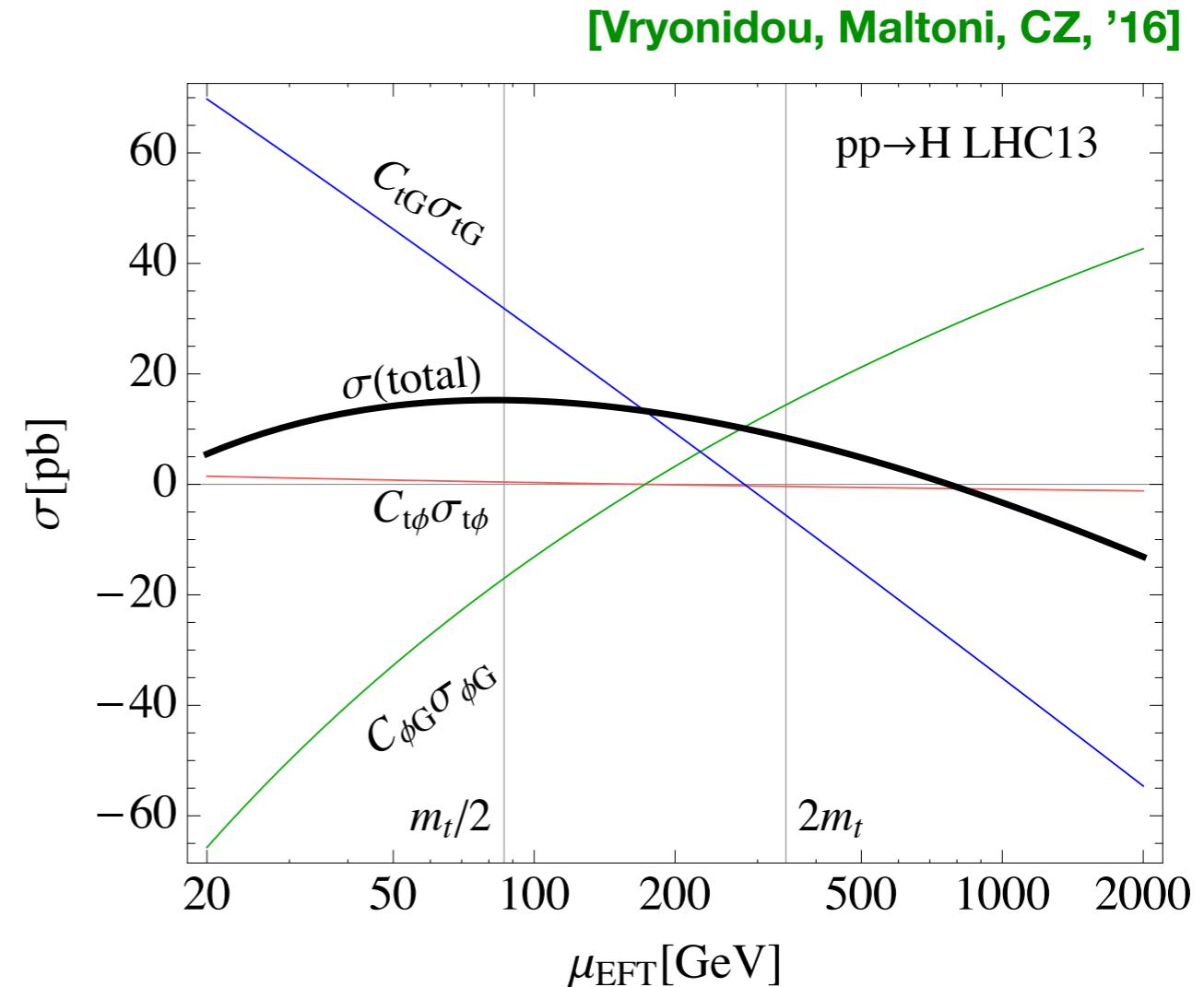
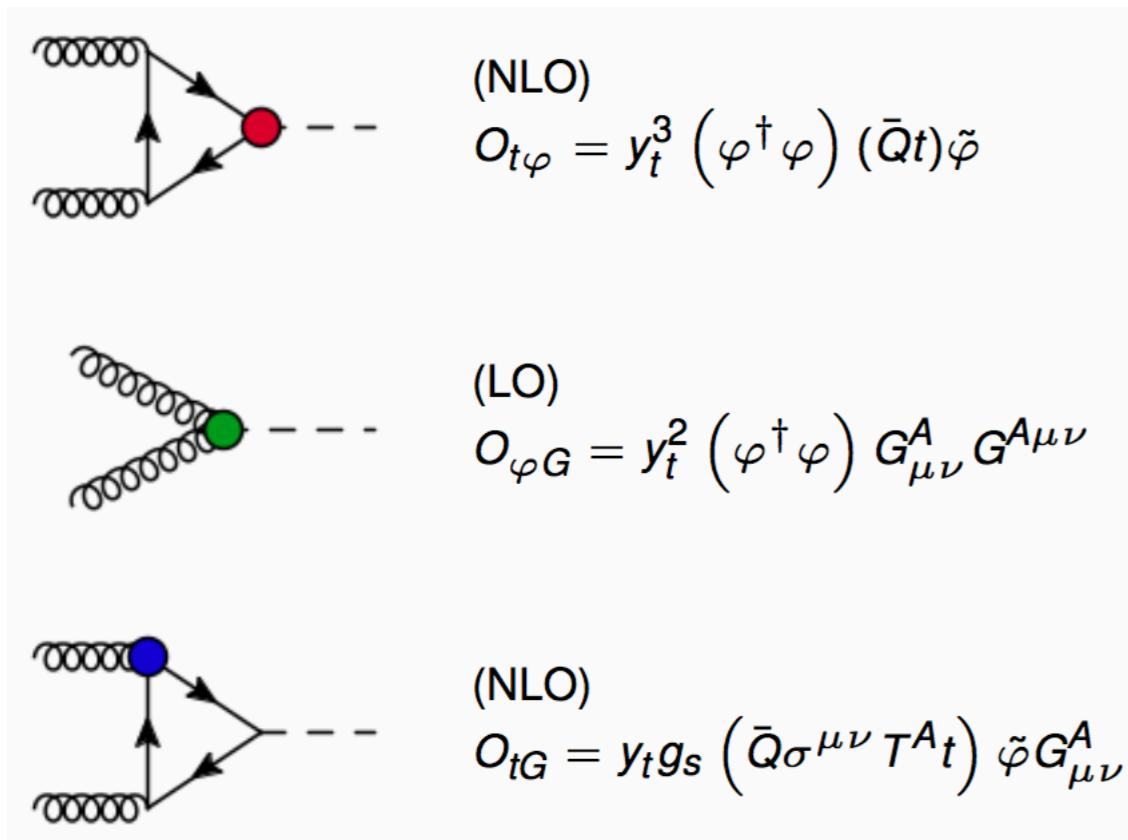
“Non-renormalizable theories... are as renormalizable as renormalizable theories”, Weinberg ’2009

- We need higher-order corrections for two classes of reasons:
 - **Same as for SM:** QCD corrections are important at hadron colliders; EW corrections are important for accuracy and for specific areas of phase space and observables; NLO corrections affect normalization, shapes, scale and PDF uncertainties.
 - **Specific issues for SMEFT at dim>4:** NLO could be the first order where non-trivial EFT structure becomes manifest: RG mixing, μ EFT scale dependence, new contributions arise at NLO, . . .

Running & mixing

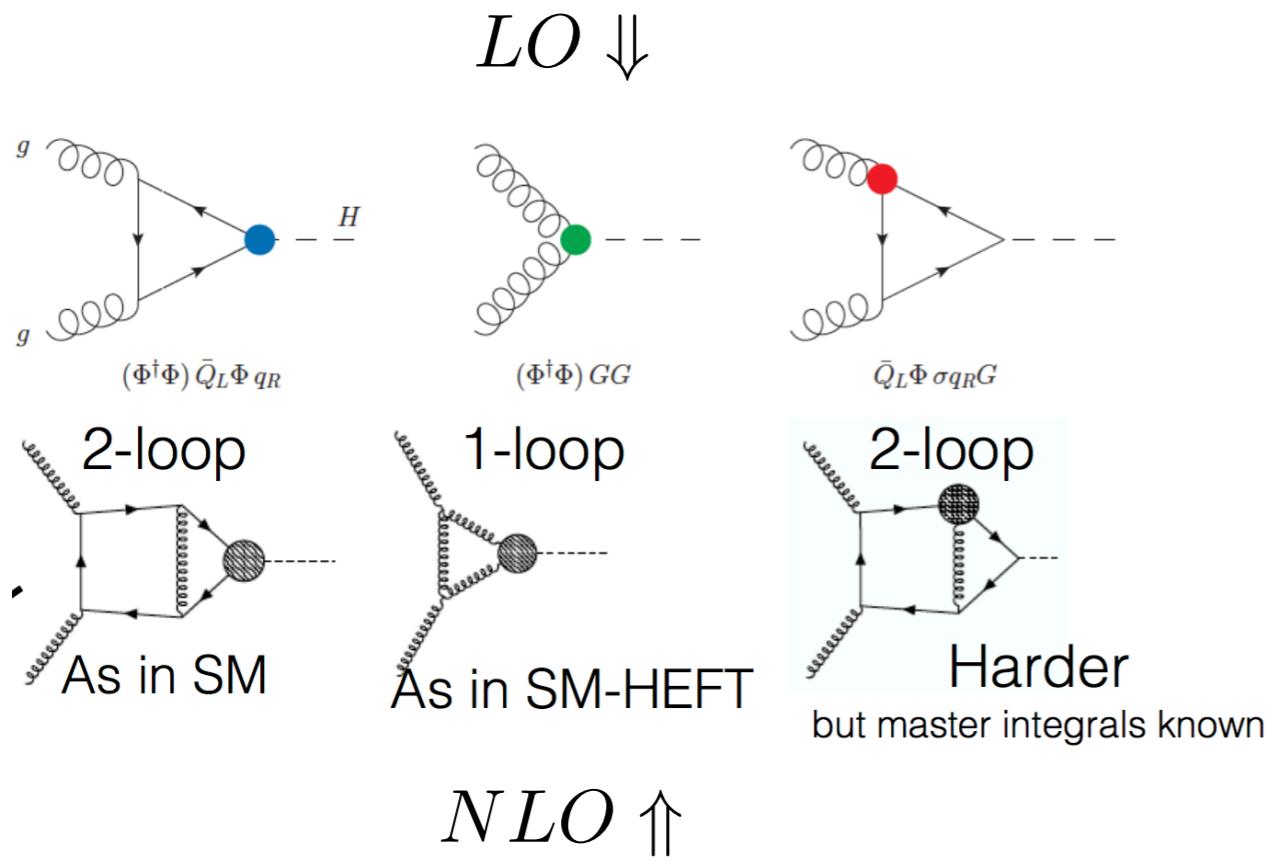
- Scale separation: coefficients are matched to **BSM at scale Λ** , but are probed at much lower scales ($\sim m_H$).
- Coefficients are defined with MSbar scheme to take care of the logs.
- This means coefficients depend on the scale at which they are defined.
- RG mixing
$$\frac{dC_i(\mu)}{d \log \mu} = \frac{\alpha}{\pi} \gamma_{ij} C_j(\mu)$$
[R. Alonso et al., '13,'14]
- One immediate consequence is that assumptions about some coefficients being zero at low scales are not valid.
- Important for scale uncertainty.

gg>H: 1-loop

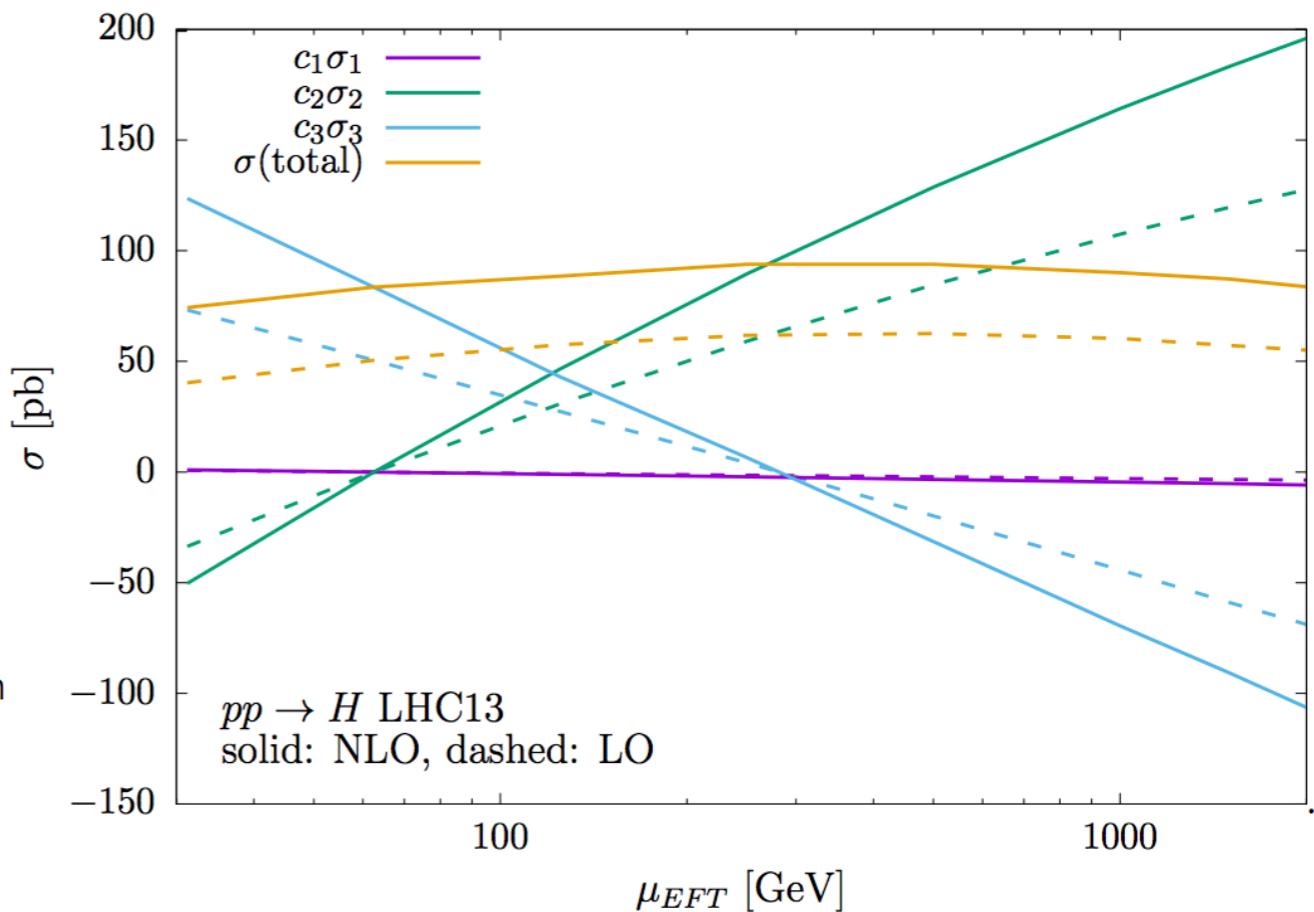


- Scale dependence of (LO) $O_{\phi G}$, from running coef., cancels that of (NLO) O_{tG} , from the loop.
- Only global point of view could make sense. To estimate TH uncertainty, must sum all operators.

gg>H: even higher order



[Deutschmann, Duhr, Maltoni, Vryonidou, '17]



SMEFT prediction can be improved order by order, provided that all relevant operators are considered

Genuine NLO corrections can be large

$$\sigma = C_1 \cdot (\mu_{EFT}) \sigma_{\text{tree}} + C_2 \frac{\alpha_{EW}}{\pi} \left(\log \frac{Q^2}{\mu_{EFT}^2} \sigma_{\log} + \sigma_{\text{fin}} \right)$$

- **RG logs of SMEFT** is process and observable-**independent**, but does not fully capture the NLO corrections.
- In fact, they are NOT part of NLO correction from a bottom-up point of view => they are often not relevant in measurements, unless the same measurement probes very different scales.

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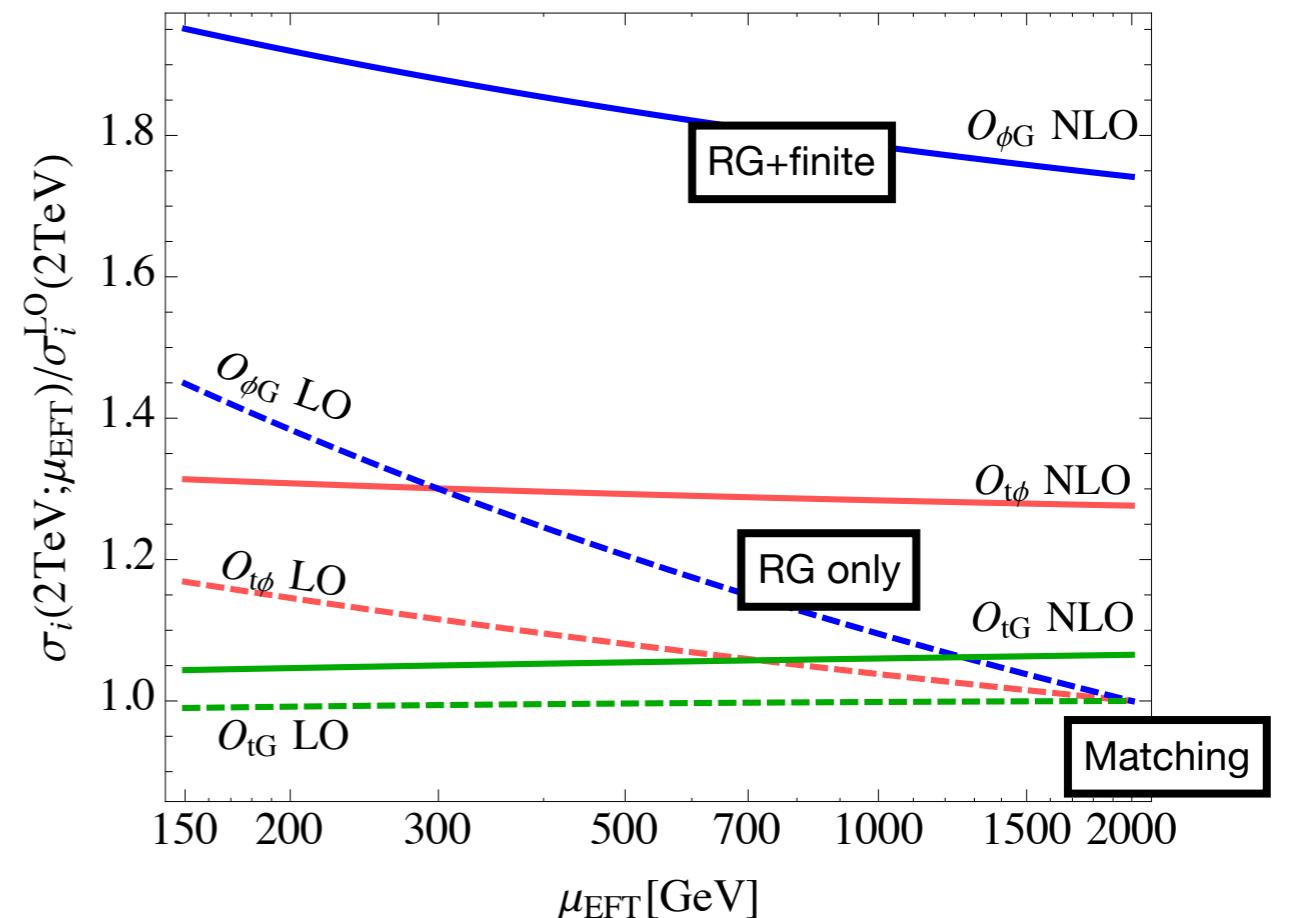
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- **RG logs of SMEFT** is process and observable-**independent**, but does not fully capture the NLO corrections.
- In fact, they are NOT part of NLO correction from a bottom-up point of view => they are often not relevant in measurements, unless the same measurement probes very different scales.
- In contrast, **the finite terms** depend on processes and observables. **They need to be studied on a process-by-process basis.**
- Often, they are the **dominant effects**.

pp>ttH dim6 @ NLO: RG vs full NLO

[Vryonidou, Maltoni, CZ, '16]

- Suppose a full theory is matched to an EFT with $O_{t\phi}$, $O_{\phi G}$, O_{tG} at 2 TeV.
- We can compute σ at LO $\mu = 2$ TeV, where we normalize results to 1.
- We can also improve these results by running the theory to m_t , and do another LO calculation. This increases σ by $0 \sim 50\%$ depending on operators.
- However the full NLO corrections are much larger.
- Finite (QCD) corrections can be very important. Similar observations in H and Z decay, see e.g. [R. Gauld, '16], [C. Hartmann, '16] and many other full one-loop calculations.

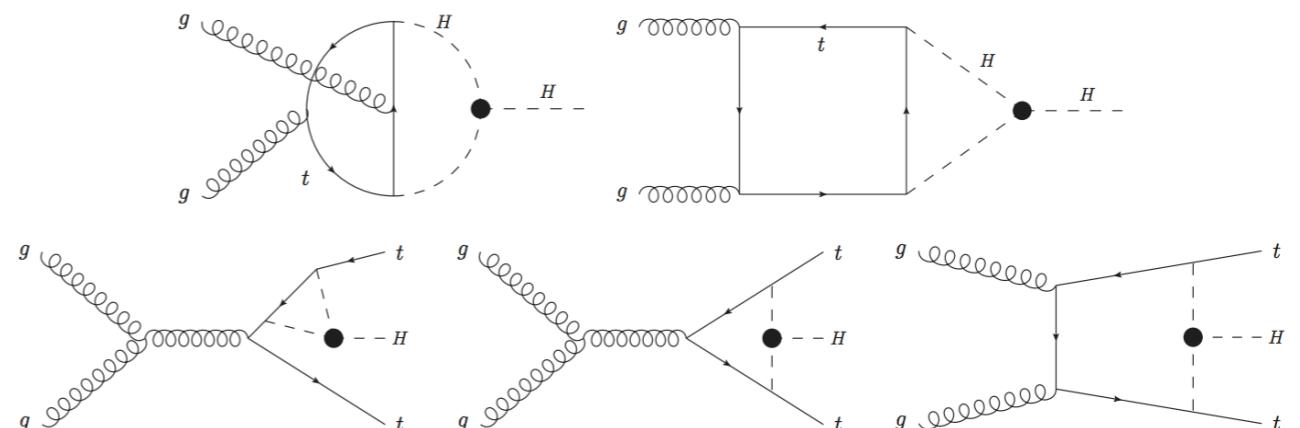


Using RG as a proxy to NLO could be misleading.

Loop-induced measurements, e.g. HHH

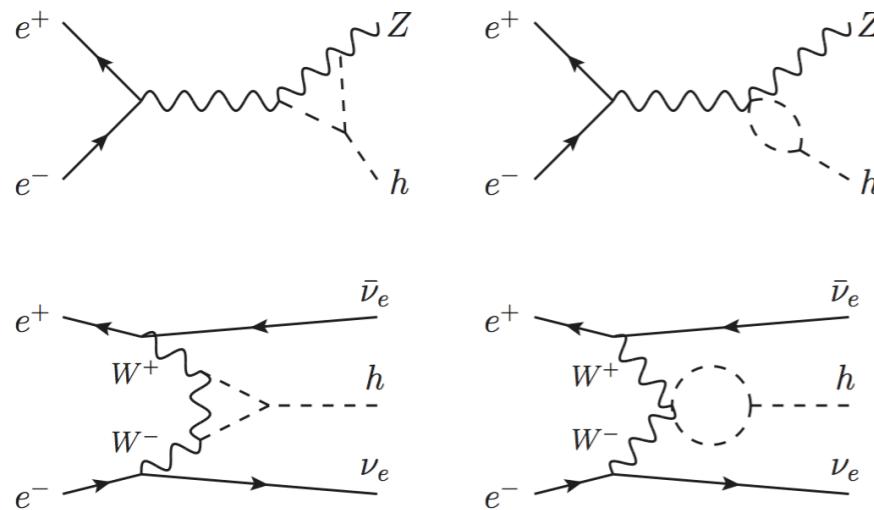
- Some times operators could first show up at 1-loop.
- This could imply new chances to measure certain coeffs. that are difficult at LO.
- The trilinear Higgs coupling, κ_λ , is a good example.

Indirectly measuring κ_λ , LHC:



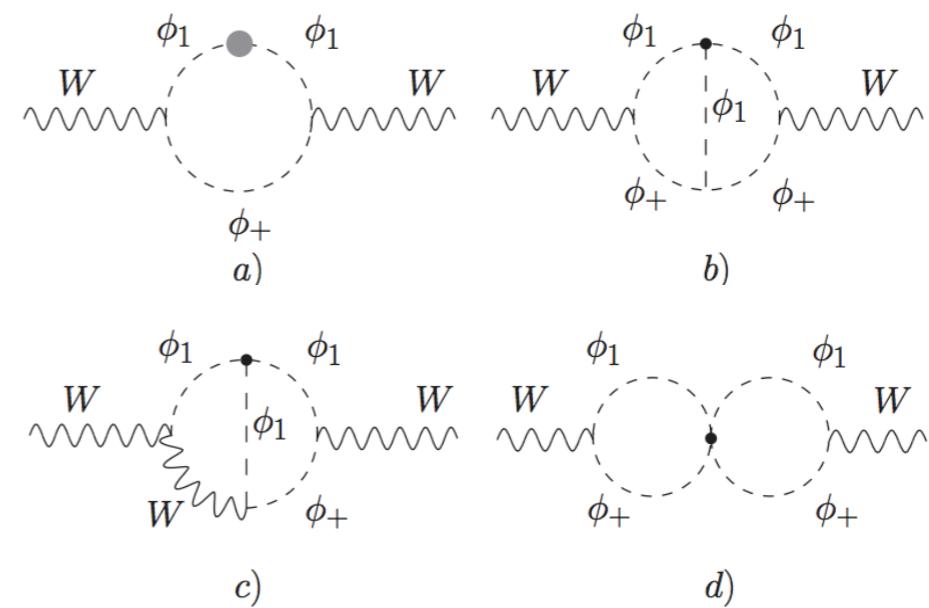
[G. Degrassi et al., '16] [Gorbahn&Haisch, '16]

At the ee colliders:



[M. McCullough, '13] [S. D. Vita et al., '17]

Using EWPO at 2 loop:



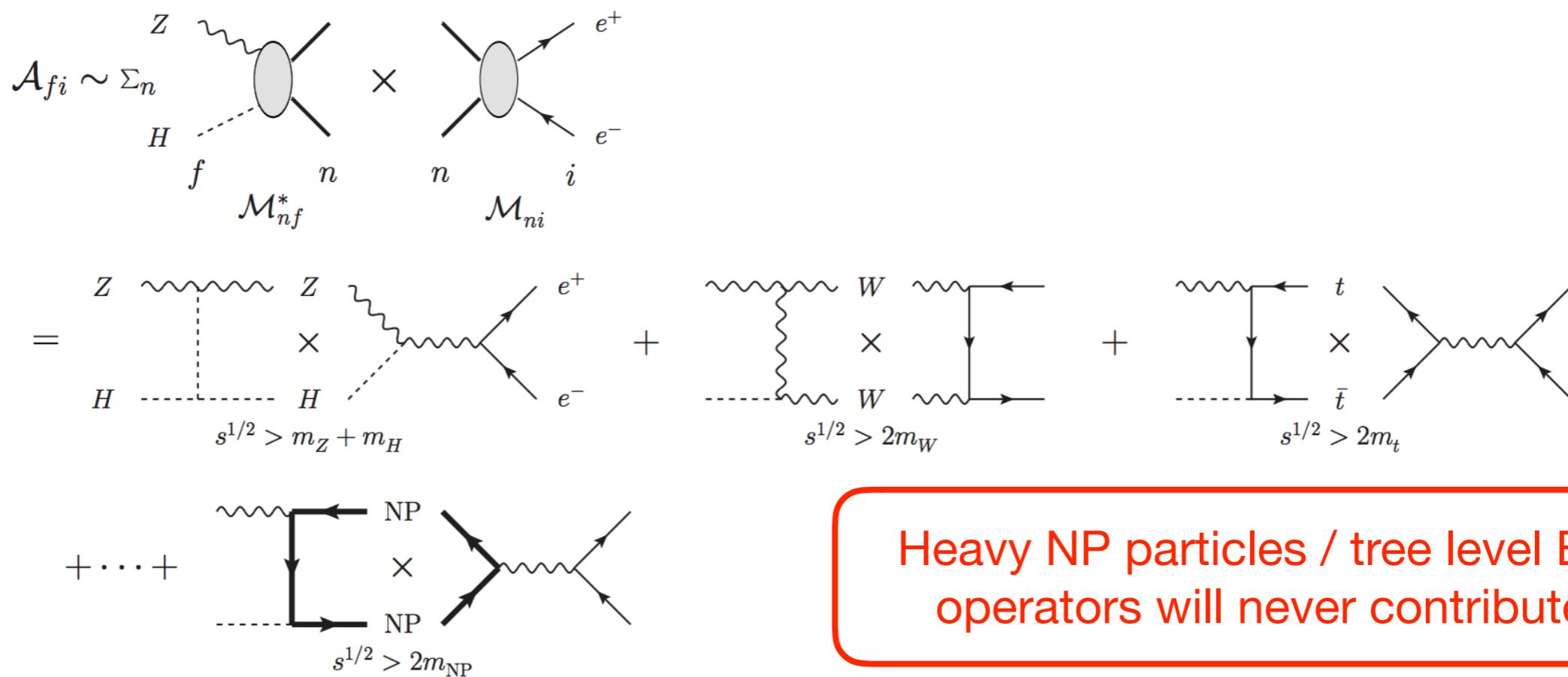
[Degrassi, Fedele, Giardino 1702.01737]

Loop-induced measurements: from indirect to direct

[J. Nakamura & A. Shivaji 1812.01576]

- Choosing the “right” observable (naive time-reversal odd) could turn the indirect loop measurement into a “direct” measurement.

If T (or equally CP) is conserved, T-odd observables
are proportional to the absorptive part



Loop-induced measurements: from indirect to direct

- Consider $Z(-\rightarrow ll) + H$

[J. Nakamura & A. Shivaji 1812.01576]

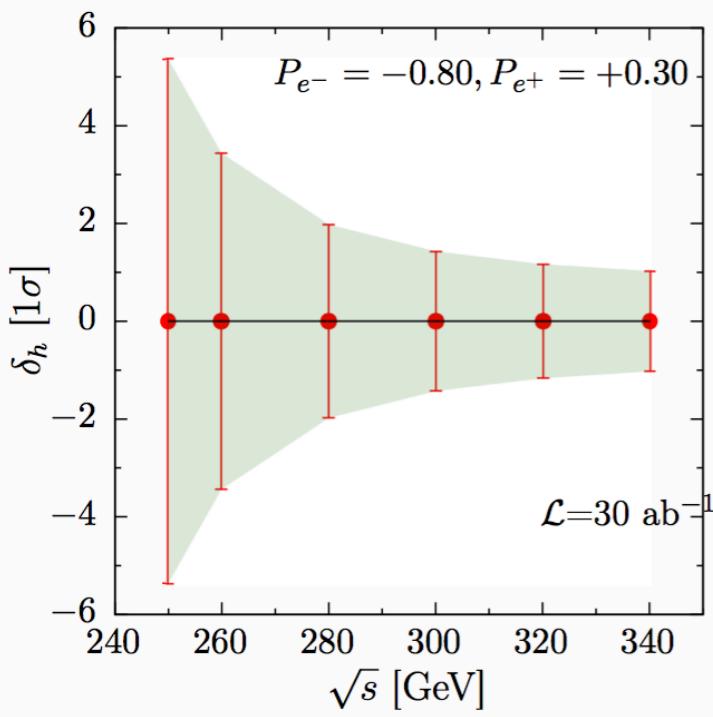
Under T transformation without interchanging the initial and final states,

$$\frac{d^3\sigma}{d\cos\Theta d\cos\theta d\phi} \rightarrow \underbrace{F_1(1 + \cos^2\theta) + F_2(1 - 3\cos^2\theta) + F_3 \sin 2\theta \cos\phi + F_4 \sin^2\theta \cos 2\phi}_{T\text{-even}} + \underbrace{F_5 \cos\theta + F_6 \sin\theta \cos\phi - F_7 \sin\theta \sin\phi - F_8 \sin 2\theta \sin\phi - F_9 \sin^2\theta \sin 2\phi}_{T\text{-odd}}$$

Define T-odd asymmetries (A_7, A_8, A_9) by

$$A_{(7,8,9)} \equiv \frac{F_{(7,8,9)}}{F_1}, \quad A_7 \propto \frac{N(\sin\phi > 0) - N(\sin\phi < 0)}{N(\sin\phi > 0) + N(\sin\phi < 0)} \text{ etc}$$

8/11



Difficult method, but

- Useful method to directly constrain HHH below 340
- Provide additional observable to isolate HHH from other couplings, should be added to a global H/EW fit

Loop-induced measurements can be “direct measurements”

One last reason for going NLO

If it's “free”

```
MG5_aMC>import model SMEFT  
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(imagine this is all you need to get NLO+PS events for any process any operators. . . then why not?)

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Some recent results

Higgs

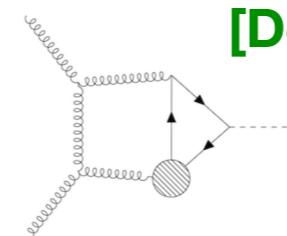
- Single Higgs (ggH)

- Yukawa and GGH: NLO+NLL, scaled with NNLO+NNLL in SM.

[Grazzini et al.;'17]

- Top chromo dipole: NLO+PS (two loop)

[Deutschmann, Duhr, Maltoni, Vryonidou '18]



- Double Higgs

- NLO, with top mass, non-linear EFT

[G. Buchalla et al.; JHEP 1809 (2018) 057]

- NNLO QCD (heavy top mass limit)

[de Florian, Fabre, Mazzitelli; JHEP 1710 (2017) 215]

- CPV operators NLO QCD (heavy top mass limit)

[Grober, Muhlleitner, Spira; 1705.05314]

- H decay

- eHDECAY, SILH operators, all relevant QCD corrections, partial EW corrections.

[Contino et al.; Comp. Phys. Comm. 185 (2014) 3412]

- Full one-loop:

$\gamma\gamma$ [Hartmann, Trott '15] [Dawson, Giardino '18] [A. Dedes et al. '18], γZ [Dedes, Suxho, Trifyllis '19],

ZZ [Dawson, Giardino '18], WW [Dawson, Giardino '18],

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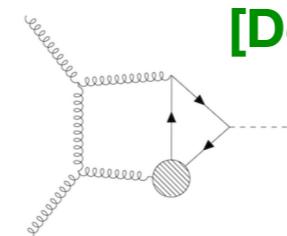
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Gauge fixing and H decay

[A. Dedes et al.; JHEP 1706 (2017) 143]

[M. Misiak et al.; JHEP 1902 (2019) 051]

[Helset, Paraskevas, Trott; PRL120 (2018), 251801]

[A. Dedes et al. '18] [Dedes, Suxho, Trifyllis '19]

1. In any EFT with linearly realised gauge symmetry and to any $1/\Lambda^N$ order:

- ▶ bosonic bilinear terms can be reduced to form with at most two derivatives – guideline for basis construction (SMEFT Warsaw basis has this feature).
- ▶ SM-like linear R_ξ gauge fixing applies, with standard propagators and relations between gauge boson, Goldstone and ghost masses. Contributions from new operators appear in ghost vertices only.

2. *Mathematica* SmeftFR package calculating Feynman rules in physical field basis and R_ξ gauge available (www.fuw.edu.pl/smeft).

3. Example of a non-trivial SMEFT loop calculation: $h \rightarrow \gamma\gamma$ and $h \rightarrow Z\gamma$ decays.

- ▶ testing field for Feynman rules, gauge invariance and renormalization procedures.
- ▶ compact final expression - useful input for SMEFT fits and finding bounds on parameters.

Janusz Rosiek, talk at HEFT 2019 at Louvain-la-Neuve

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H decay

$$\mathcal{R}_{h \rightarrow \gamma\gamma(Z\gamma)} \equiv 1 + \delta\mathcal{R}_{h \rightarrow \gamma\gamma(Z\gamma)} = \frac{\Gamma(\text{EXP}, h \rightarrow \gamma\gamma(Z\gamma))}{\Gamma(\text{SM}, h \rightarrow \gamma\gamma(Z\gamma))}$$

$$\begin{aligned} \delta\mathcal{R}_{h \rightarrow \gamma\gamma} &\simeq 0.06 \left(\frac{C_{1221}^{\ell\ell} - C_{11}^{\varphi\ell(3)} - C_{22}^{\varphi\ell(3)}}{\Lambda^2} \right) + 0.12 \left(\frac{C^{\varphi\square} - \frac{1}{4}C^{\varphi D}}{\Lambda^2} \right) \\ &- 0.01 \left(\frac{C_{22}^{e\varphi} + 4C_{33}^{e\varphi} + 5C_{22}^{u\varphi} + 2C_{33}^{d\varphi} - 3C_{33}^{u\varphi}}{\Lambda^2} \right) \\ &- \left[48.04 - 1.07 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{\varphi B}}{\Lambda^2} - \left[14.29 - 0.12 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{\varphi W}}{\Lambda^2} \\ &+ \left[26.62 - 0.52 \log \frac{\mu^2}{M_W^2} \right] \frac{C^{\varphi WB}}{\Lambda^2} + \left[0.16 - 0.22 \log \frac{\mu^2}{M_W^2} \right] \frac{C^W}{\Lambda^2} \\ &+ \left[2.11 - 0.84 \log \frac{\mu^2}{M_W^2} \right] \frac{C_{33}^{uB}}{\Lambda^2} + \left[1.13 - 0.45 \log \frac{\mu^2}{M_W^2} \right] \frac{C_{33}^{uW}}{\Lambda^2} \\ &- \left[0.03 + 0.01 \log \frac{\mu^2}{M_W^2} \right] \frac{C_{22}^{uB}}{\Lambda^2} - \left[0.01 + 0.00 \log \frac{\mu^2}{M_W^2} \right] \frac{C_{22}^{uW}}{\Lambda^2} \\ &+ \left[0.03 + 0.01 \log \frac{\mu^2}{M_W^2} \right] \frac{C_{33}^{dB}}{\Lambda^2} - \left[0.02 + 0.01 \log \frac{\mu^2}{M_W^2} \right] \frac{C_{33}^{dW}}{\Lambda^2} \\ &+ \left[0.02 + 0.00 \log \frac{\mu^2}{M_W^2} \right] \frac{C_{33}^{eB}}{\Lambda^2} - \left[0.01 + 0.00 \log \frac{\mu^2}{M_W^2} \right] \frac{C_{33}^{eW}}{\Lambda^2} + \dots, \end{aligned}$$

Comparing to previous studies:

- Exploit linear R_ξ -gauges.
- Provide analytic proof of gauge invariance, exact cancellation of independent ξA , ξW , ξZ parameters - strict cross check of the result.

Higgs+EW

- HAWK
 - VBF & VH, with HVV anomalous couplings, NLO in QCD

- VBFNLO
 - General V/H production @NLO in QCD, with anomalous HVV/3V/4V couplings

- VH with MCFM + POWHEG-BOX
 - NLO QCD +PS event generation for Higgs/EW operators (SILH)

- HELatNLO, MG5_aMC@NLO
 - FeynRules/NLOCT/UFO implementation of Higgs/EW operators
 - VH, VBF & other process of interest

- V/VH/VBF in POWHEG-BOX
 - With larger set of operators

- WW with MCFM + POWHEG-BOX
 - TGC & quark vertex operators.

- Z decay
 - [Hartmann, Shepherd, Trott '17], [Dawson, Ismai '18]

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- VBF & VH, with HVV anomalous couplings, NLO in QCD

<http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk>

- VBFNLO

[Baglio et al.; arXiv:1404.3940]

<https://www.itp.kit.edu/vbfnlo>

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<http://powhegbox.mib.infn.it>

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[Degrande, et al.; EPJC 77 (2017) 4, 262]

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[Alioli, et al.; JHEP 1808 (2018) 205]

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[Baglio, Dawson, Lewis; PRD99 (2019), 035029]

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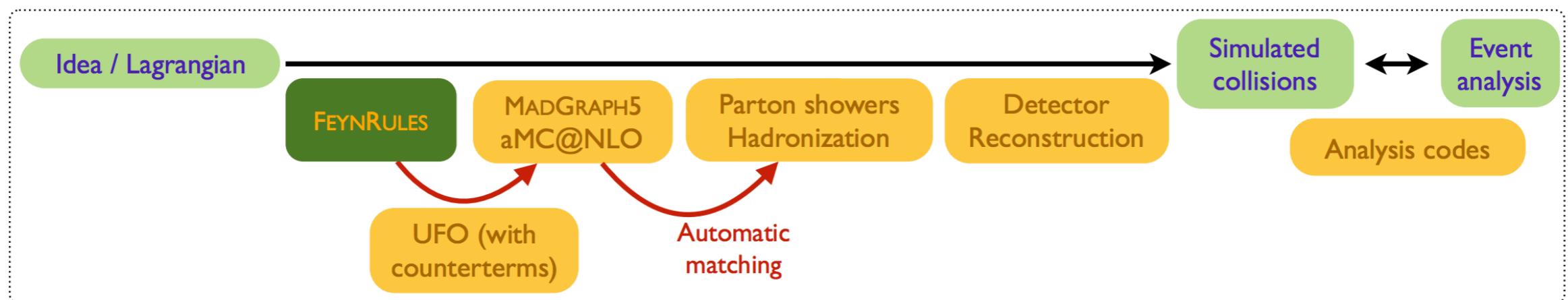
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VH with SILH operators

[Degrande, et al.; EPJC 77 (2017) 4, 262]

- Implementation following the standard FR/MG chain:

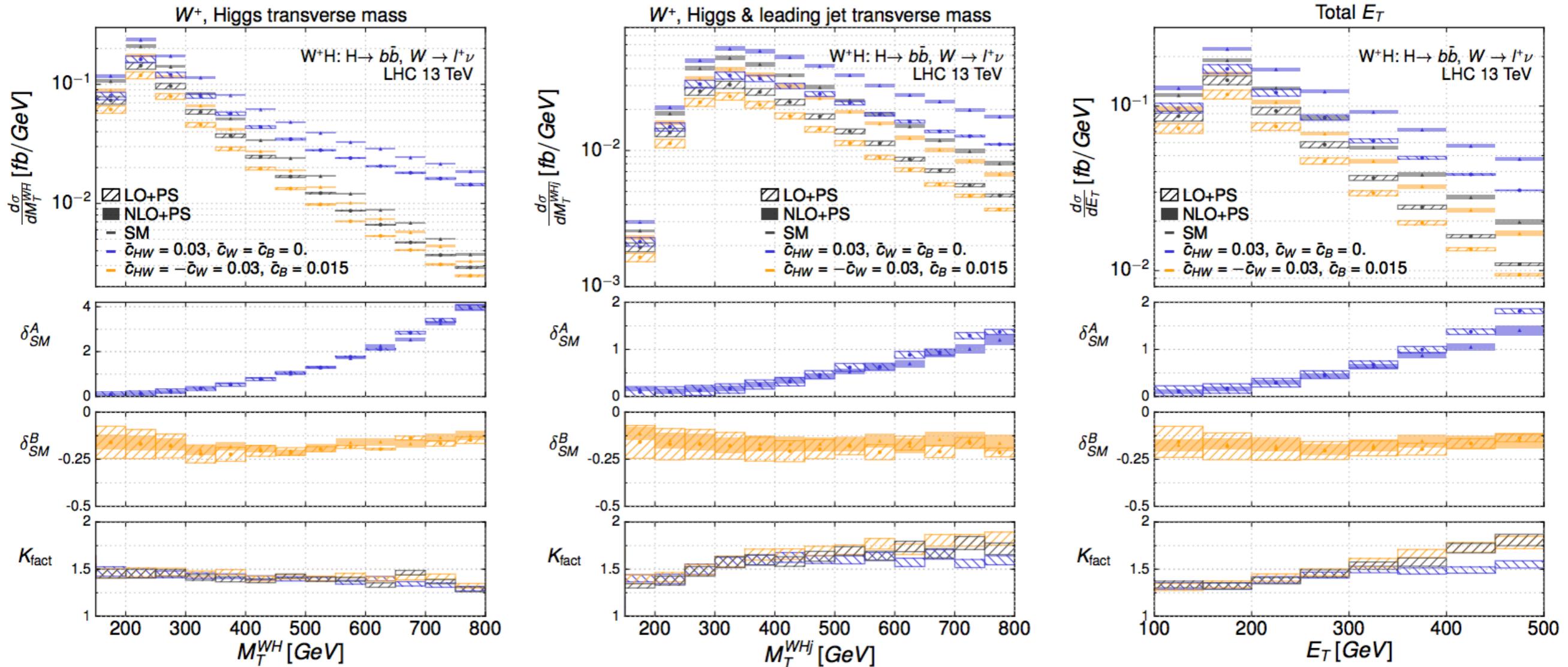


- 5 SILH operators.
- Indirect contributions by shifting the input parameters are taken into account.
- VH, VBF studied, but in general any other process of interest.

$$\begin{aligned}\mathcal{L} = \mathcal{L}_{\text{SM}} + & \frac{g'^2}{4\Lambda^2} \bar{c}_{BB} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu} \\ & + \frac{ig}{2\Lambda^2} \bar{c}_W [\Phi^\dagger T_{2k} \overleftrightarrow{D}_\mu \Phi] D_\nu W^{k,\mu\nu} \\ & + \frac{ig'}{2\Lambda^2} \bar{c}_B [\Phi^\dagger \overleftrightarrow{D}_\mu \Phi] \partial_\nu B^{\mu\nu} \\ & + \frac{ig}{\Lambda^2} \bar{c}_{HW} [D_\mu \Phi^\dagger T_{2k} D_\nu \Phi] W^{k,\mu\nu} \\ & + \frac{ig'}{\Lambda^2} \bar{c}_{HB} [D_\mu \Phi^\dagger D_\nu \Phi] B^{\mu\nu} .\end{aligned}$$

VH with SILH operators

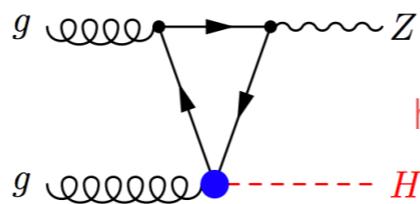
[Degrade, et al.; EPJC 77 (2017) 4, 262]



- K factor in general not sensitive to different operators, but reduction of TH uncertainties helps to disentangle BSM effects.
- LO and NLO predictions do not overlap.

Higgs+EW+Top

- VH at NNLO
 - Top loop induced contributions



[Harlander et al.; JHEP 1805 (2018) 089]

<https://web.physik.rwth-aachen.de/~harlander/software/vh@nnlo/>

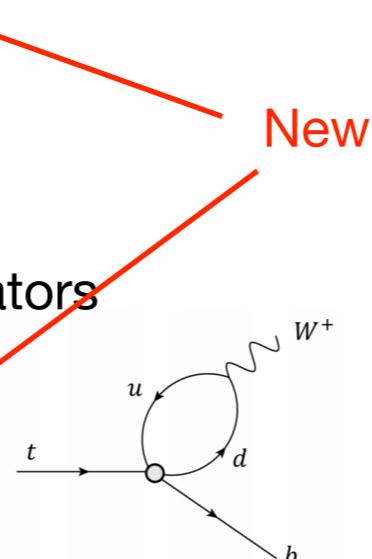
- Single top production
 - s-/t-channels and t+W, tbW+4f operators
 - t-channel production+decay, CPV
 - +off-shell effects and larger set of OPs

[CZ; PRL 116 (2016) 162002]

[de Beurs et al.; EPJC 78 (2018) 919]

[Neumann & Sullivan; JHEP 1906 (2019) 022]

- Top decay and W-helicity
 - W-helicity, FCNC; 2-fermion + 2q2l operators
 - + 4-f operators that first appear at NLO



[CZ; PRD 90 (2014) 014008]

[Boughezal et al.; 1907.00997]

- More tops
 - tt, ttV, ttH, tVj/tHj
 - Loop induced HZ, Hj, HH, ...

[CZ and Franzosi; PRD91 (2015) 114010]

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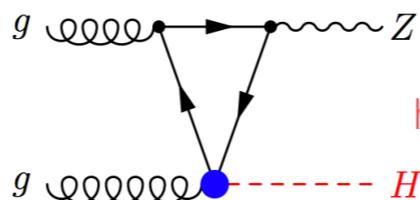
- GGG operator in multijet

[Hirschi et al.; JHEP 1807 (2018) 093]

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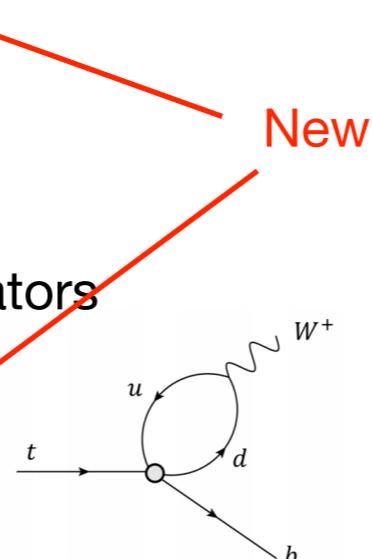
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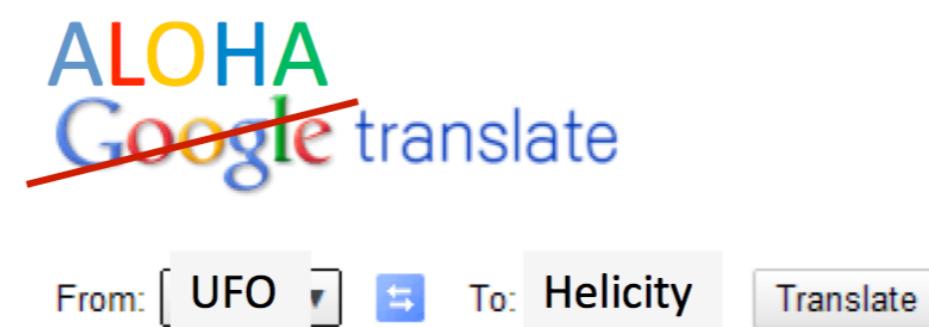
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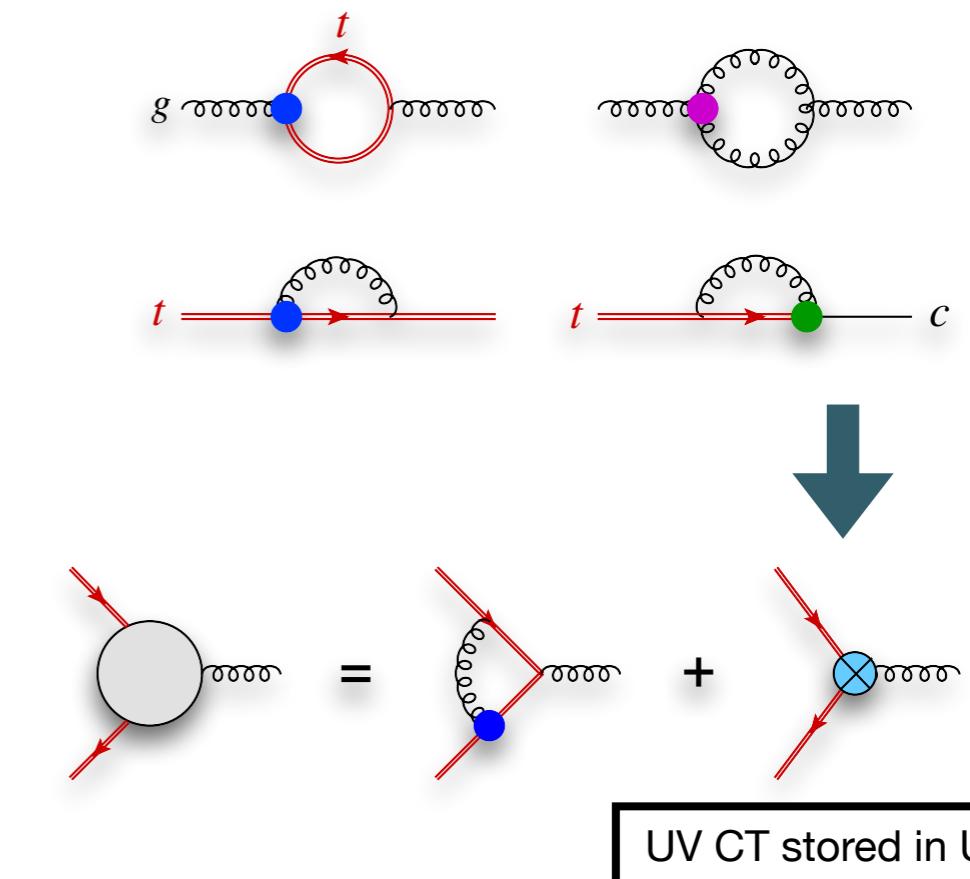
Automation @ NLO in QCD

BSM @ NLO with MadGraph5_aMC@NLO

- NLO @ QCD is automated in the SM and can be extended to dim-6.
- All higher-dimensional Lorentz structures are supported in **UFO**. [1108.2040 Degrade et al.]
- **ALOHA** translates Lorentz structures in UFO to helicity amplitude subroutines. [1108.2041 de Aquino et al.]
- The SM is implemented as a UFO
 - Most features for simulation in SM can be (in principle) extended to BSM (and EFT), provided the UFO is given.
- **Many NLO UFO models:** <https://feynrules.irmp.ucl.ac.be/wiki/NLOModels>

EFT @ NLO with MadGraph5_aMC@NLO

- Virtual correction: need to provide the **Dim-6 UV and R2 counterterms**.
 - UV CTs contain the **MSbar running & mixing of operators**, and the **dim-6 modifications to the on-shell renormalization**.
 - R2 occurs due to numerical techniques only evaluating 4-dimensional part of loop amplitude (while we need the **D-dimensional**)
- Real correction: soft/collinear behavior and matching is not (in principle) affected by higher dim operators.
[Englert, Russell, White; PRD99 035019]
- NLOCT** is being developed to automatically provide dim-6 CTs.
[Degrande; CPC197 (2015) 239-262]
- However, in SMEFT new **technical issues** arise, evanescent OP, anomaly,...

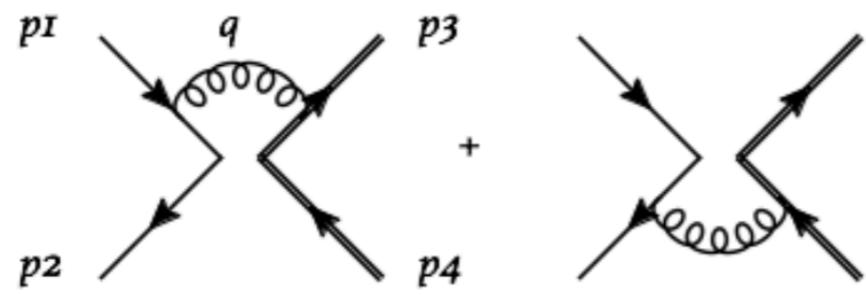


Evanescence operators

- Four-fermion operators: 25 basis operators in 4-dimension, so any other four-fermion structure (e.g. generated by loops) can be reduced to their linear combination.
- This is not true in D-dimension where we calculate loops, because the naive Fierz identities will not work.
- Need to enlarge the basis operators by including the set of “evanescent operators”, which vanishes in 4-dimension. Standard solution in flavor physics.
- As a result, the renormalization scheme is not uniquely specified just by “MSbar”. It needs to be specified by **MSbar + a particular choice of evanescent operator basis**.
- Results depend on the evanescent operator basis, but this dependence will be canceled once combined with matching to a UV theory at the loop level.

Evanescent operators

- E.g. $qq \rightarrow tt$

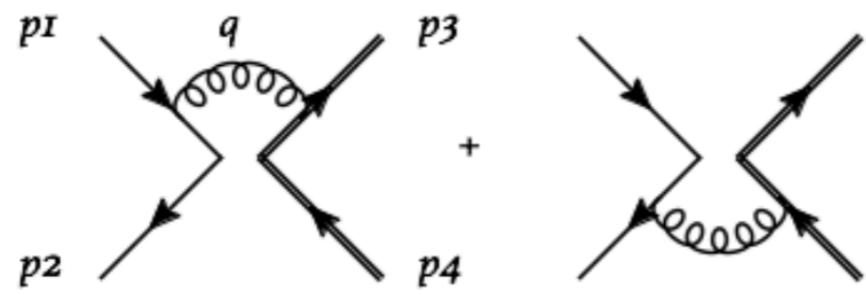


Color factor

$$M_1 \supset \frac{C}{\Lambda^2} g_s^2 [\text{CF}] \left(2 \int_0^1 dx \int_0^{1-x} dy \right) \int \frac{d^D l}{(2\pi)^D} \frac{l^\alpha l^\beta}{(l^2 - \Delta)^3} [\gamma^\nu \gamma_\alpha \gamma^\mu P_R \otimes \gamma_\mu \gamma_\beta \gamma_\nu P_R]$$

Evanescence operators

- E.g. $qq \rightarrow tt$



Evnsct. OP

$$\gamma^\mu \gamma^\nu \gamma^\rho P_R \otimes \gamma_\rho \gamma_\nu \gamma_\mu P_R = -E + [4 - (12 - 4a)\varepsilon] \gamma^\mu P_R \otimes \gamma_\mu P_R$$

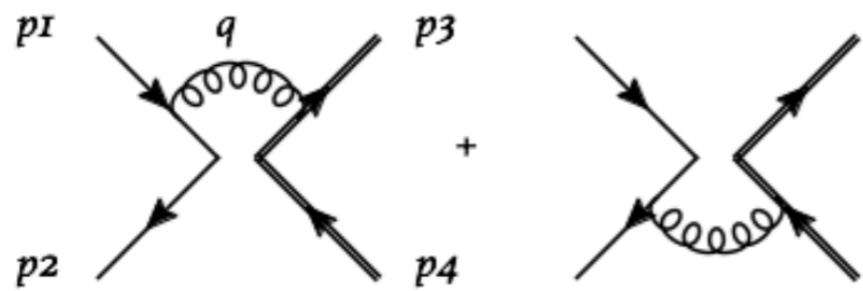
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$a=1$ corresponds to **[Buras, Misiak, Urban; NPB586 (2000) 397]**

Evanescent operators

- E.g. qq>tt



Color factor

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Evnsct. OP

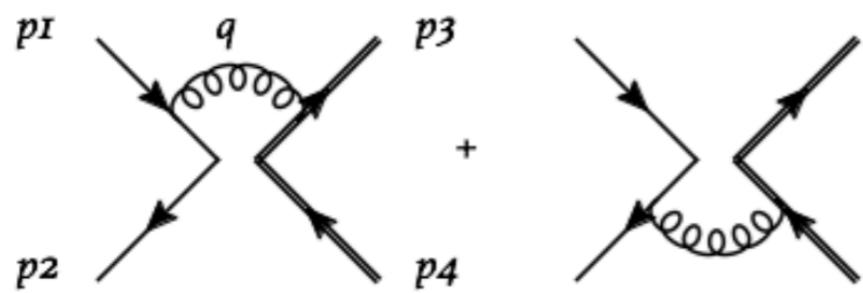
$$\gamma^\mu \gamma^\nu \gamma^\rho P_R \otimes \gamma_\rho \gamma_\nu \gamma_\mu P_R = -E + [4 - (12 - 4a)\varepsilon] \gamma^\mu P_R \otimes \gamma_\mu P_R$$

a=1 corresponds to **[Buras, Misiak, Urban; NPB586 (2000) 397]**

$$= \frac{iC}{\Lambda^2} \frac{g_s^2}{(4\pi)^2} (4\pi)^\varepsilon \Gamma(1 + \varepsilon) [\text{CF}] \left(2 \int_0^1 dx \int_0^{1-x} dy \right) \frac{1}{4} \left(\frac{1}{\varepsilon} - \log \Delta \right) \{-E + [4 - (12 - 4a)\varepsilon][\gamma^\mu P_R \otimes \gamma_\mu P_R]\}$$

Evanescence operators

- E.g. qq>tt



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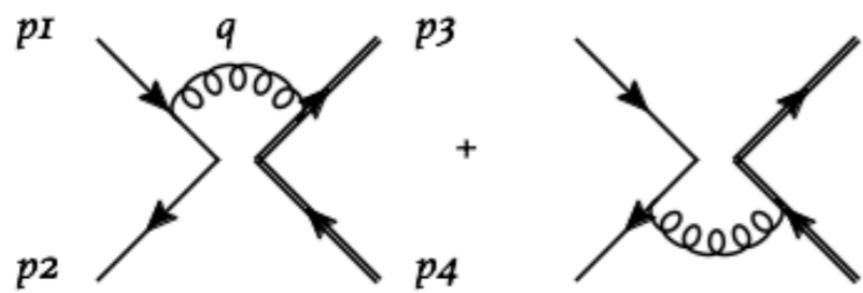
Cancelled by
mixing CT of Evnsct OP

Color factor

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~~Cancelled by mixing CT of Evnsct OP~~

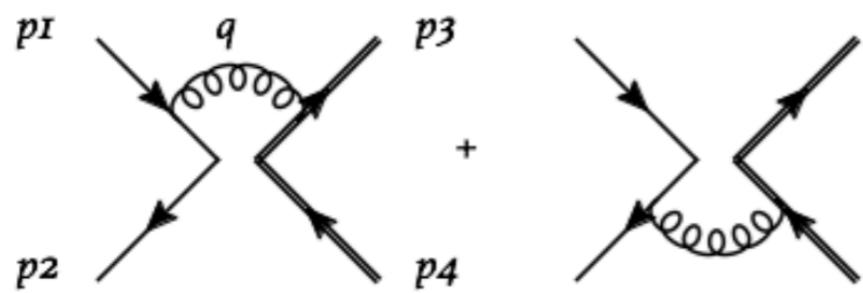
Color factor

$$M_1 \supset \frac{C}{\Lambda^2} g_s^2 [\text{CF}] \left(2 \int_0^1 dx \int_0^{1-x} dy \right)$$

$$\int \frac{d^D l}{(2\pi)^D} \frac{l^\alpha l^\beta}{(l^2 - \Delta)^3} [\gamma^\nu \gamma_\alpha \gamma^\mu P_R \otimes \gamma_\mu \gamma_\beta \gamma_\nu P_R]$$

Evanescent operators

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Canceled by
mixing CT of Evnsct OP

Vanishes in 4D

Remaining
scheme dependence
that enters R2

Color factor

$$M_1 \supset \frac{C}{\Lambda^2} g_s^2 [\text{CF}] \left(2 \int_0^1 dx \int_0^{1-x} dy \right) \int \frac{d^D l}{(2\pi)^D} \frac{l^\alpha l^\beta}{(l^2 - \Delta)^3} [\gamma^\nu \gamma_\alpha \gamma^\mu P_R \otimes \gamma_\mu \gamma_\beta \gamma_\nu P_R]$$

Gauge anomaly

- **Gauge anomaly** may arise due to dim-6 operators, e.g. in ggZ or ggff

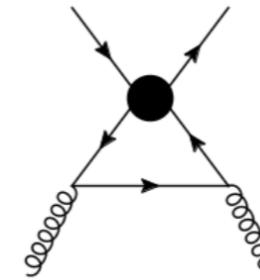
- When this happens, the loop depends on scheme of the calculation and in particular gamma5.

- In principle, this should be canceled with a **Wess-Zumino term**, from non-decoupling part when heavy physics is integrated out.

- Physics effect can be large! e.g. in gg>gZ', significantly overestimates the rate.

[Fox, Low, Zhang; '18]

- This term can be determined by requiring SU(3) is not broken.
- This does not necessarily imply that BSM has a potential anomaly problem!



$$O_V = -\frac{1}{2}(\bar{t}_L \gamma_\mu t_L)(\bar{e}_R \gamma^\mu e_R)$$

$$\begin{aligned} M(cns) = & -\frac{C_V g_s^2}{16\pi^2} \left(\frac{1}{2} \delta_{AB} \right) (\bar{e}_R \gamma_\mu e_R) \frac{1}{s} \\ & \epsilon_{\mu\nu\rho\sigma} [s(2m^2 C_0(0, 0, s, m^2, m^2, m^2) + 1/3) \epsilon_2^\nu \epsilon_3^\rho (k_2 - k_3)^\sigma \\ & - 2(2m^2 C_0(0, 0, s, m^2, m^2, m^2) + 1) (\epsilon_2 \cdot k_3) \epsilon_3^\nu k_2^\rho k_3^\sigma \\ & + 2(2m^2 C_0(0, 0, s, m^2, m^2, m^2) + 1) (\epsilon_3 \cdot k_2) \epsilon_2^\nu k_2^\rho k_3^\sigma] \\ & \text{(using the consistent anomaly,} \\ & \text{-- } (p+q)^\mu \mathcal{M}_{\mu\nu\rho}^{ab} = p^\mu \mathcal{M}_{\nu\mu\rho}^{ab} = q^\mu \mathcal{M}_{\nu\rho\mu}^{ab} \neq 0) \end{aligned}$$

This violates SU(3) Ward Identity

$$\text{WZ term: } \epsilon^{\mu\nu\rho\sigma} (\bar{e}_R \gamma_\mu e_R) \left(G_\nu^a \partial_\rho G_\sigma^a + \frac{1}{3} g_s \epsilon^{abc} G_\nu^a G_\rho^b G_\sigma^c \right)$$

Towards automatic SMEFT @ NLO

As a first step, we focus on the implementation Warsaw basis operators with the $U(3)^3 \times U(2)^2$ flavor symmetry hypothesis:

- Similar to Minimal Flavor Violation keeping only top mass non-zero
- Top operators as independent d.o.f to 1st & 2nd generations (diagonal)
- All operators affecting top/Higgs/EW processes
- Including 4F operators consistent with flavor symmetry
- Validation against existing implementations:

[CZ; PRL 116 (2016) 162002]

[CZ; PRD 90 (2014) 014008]

[Hirschi et al.; JHEP 1807 (2018) 093]

[CZ and Franzosi; PRD91 (2015) 114010]

[Bylund et al.; JHEP 1605 (2016) 052]

[Maltoni, Vryonidou, CZ; JHEP 1610 (2016) 123]

[Degrande et al.; JHEP 1810 (2018) 005]

Standard Model Effective Theory at Next-to-Leading-Order in QCD

Céline Degrande, Gauthier Durieux, Fabio Maltoni, Ken Mimasu, Eleni Vryonidou & Cen Zhang

A complete implementation of the SMEFT compatible with NLO QCD predictions.

The implementation is based on the Warsaw basis of operators and includes all degrees of freedom consistent with the following symmetry assumptions:

- CP-conservation.
- $U(2)_Q \times U(2)_u \times U(3)_d \times U(3)_L \times U(3)_e$ flavor symmetry.

The CKM matrix is approximated as a unit matrix. The flavor symmetry imposes that only the top quark is massive. The model therefore implements the 5-flavor scheme for PDFs. The bosonic operators are implemented as in the Warsaw basis employing the M_Z , M_W , G_F scheme of Electroweak input parameters.

The Standard Model input parameters that need to be specified are:

M_Z , M_W , G_F , M_H , M_t , $\alpha_S(M_Z)$

The fermionic degrees of freedom (2 & 4 fermion operators) are defined according to the common standards and prescriptions established by the LHC TOP WG for the EFT interpretation of top-quark measurements at the LHC (see the [dim6top page](#) for more information). This model has been validated at LO with the dim6top implementation.

A new coupling order, [NP](#), is added to the model for the SMEFT interactions. It is assigned through the universal cutoff parameter, [Lambda](#), which takes a default value of 1 TeV^2 and can be modified along with the Wilson coefficients in the param card.

The [definitions.pdf](#) document specifies the operators definitions, normalisations and coefficient names in the UFO model

Usage notes

Restriction cards

Because of the mixture of LO/NLO compatible operators included in the model, restriction cards must be used to access the SMEFT interactions.

Default loading of the model

```
> import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO
```

will load the pure SM without any effective operators.

The [LO](#) restriction card should be used when importing the model for LO generation:

```
> import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-LO
```

For NLO QCD generation, the [NLO](#) restriction card should be used when importing the model:

```
> import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-NLO
```

This invokes a restricted set of operators for which the required counterterms are implemented.

(missing 4F and 3G operators)

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The fermionic measurement

MG5_aMC>import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-NLO

A new coupling with the Wils

MG5_aMC>generate p p > t t H~ QCD=2 QED=1 NP=2 [QCD]

The [definition](#)

Usage notes

MG5_aMC>output

Restriction cards

Because of the

Default loading

MG5_aMC>launch

```
> import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO
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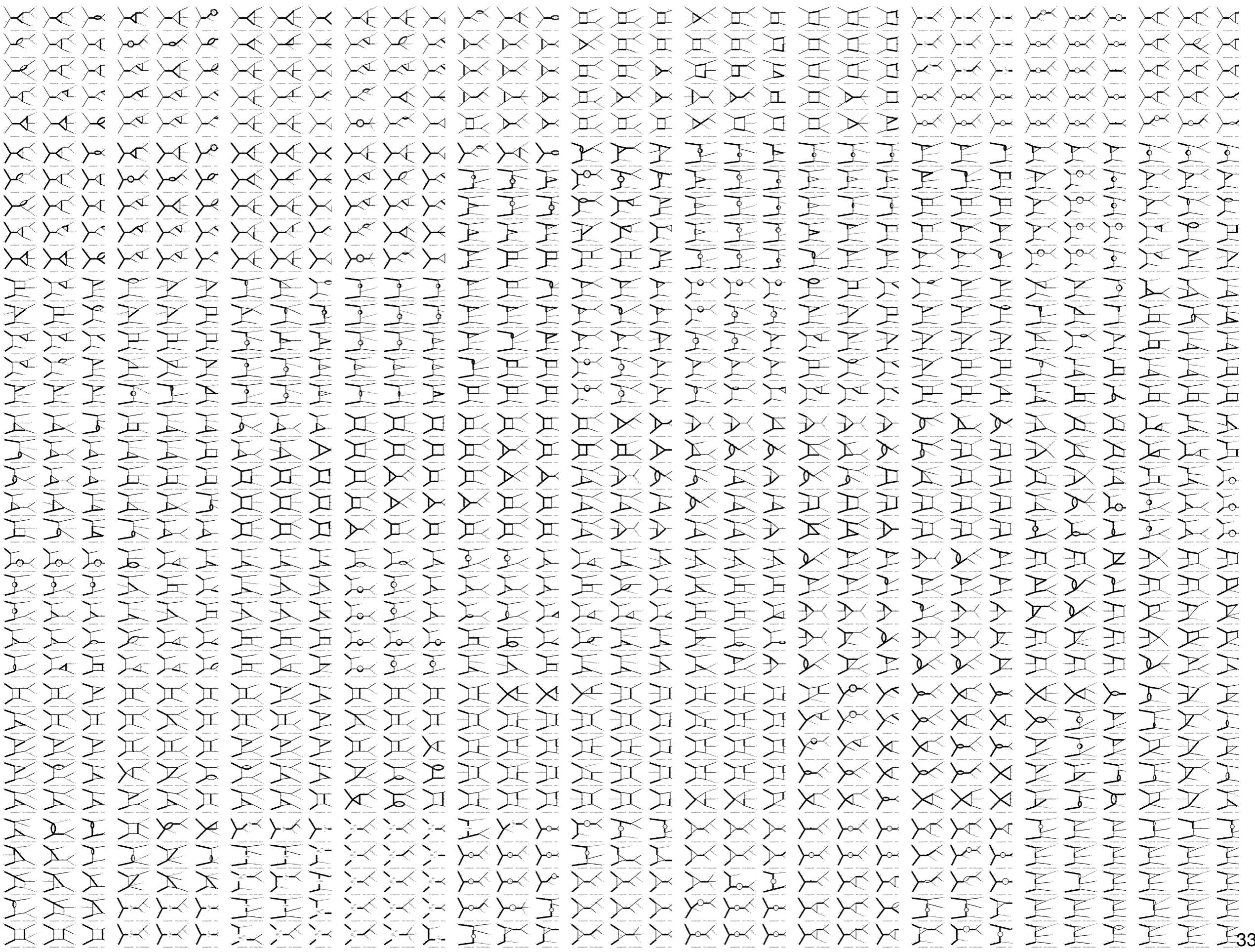
```
> import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-LO
```

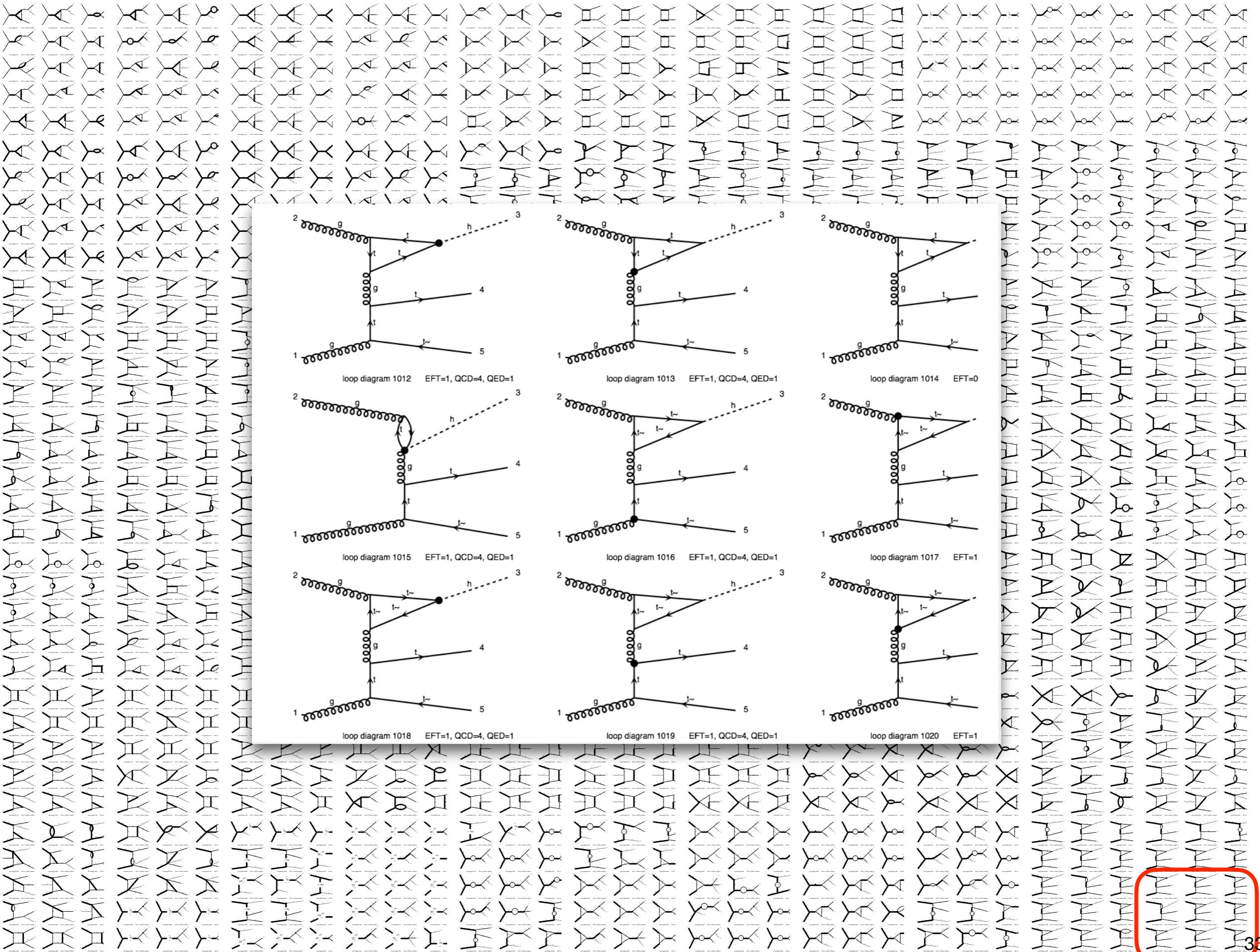
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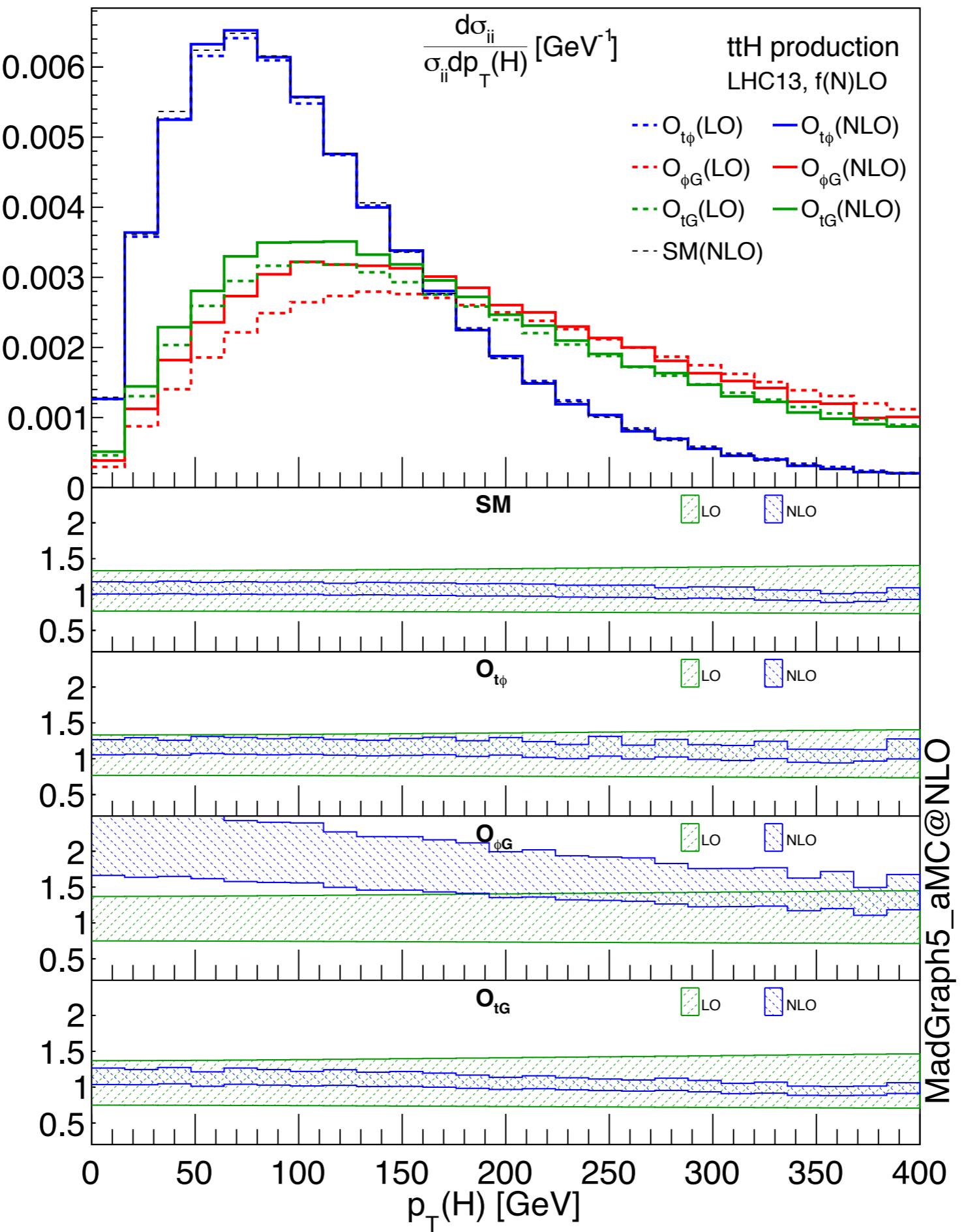
```
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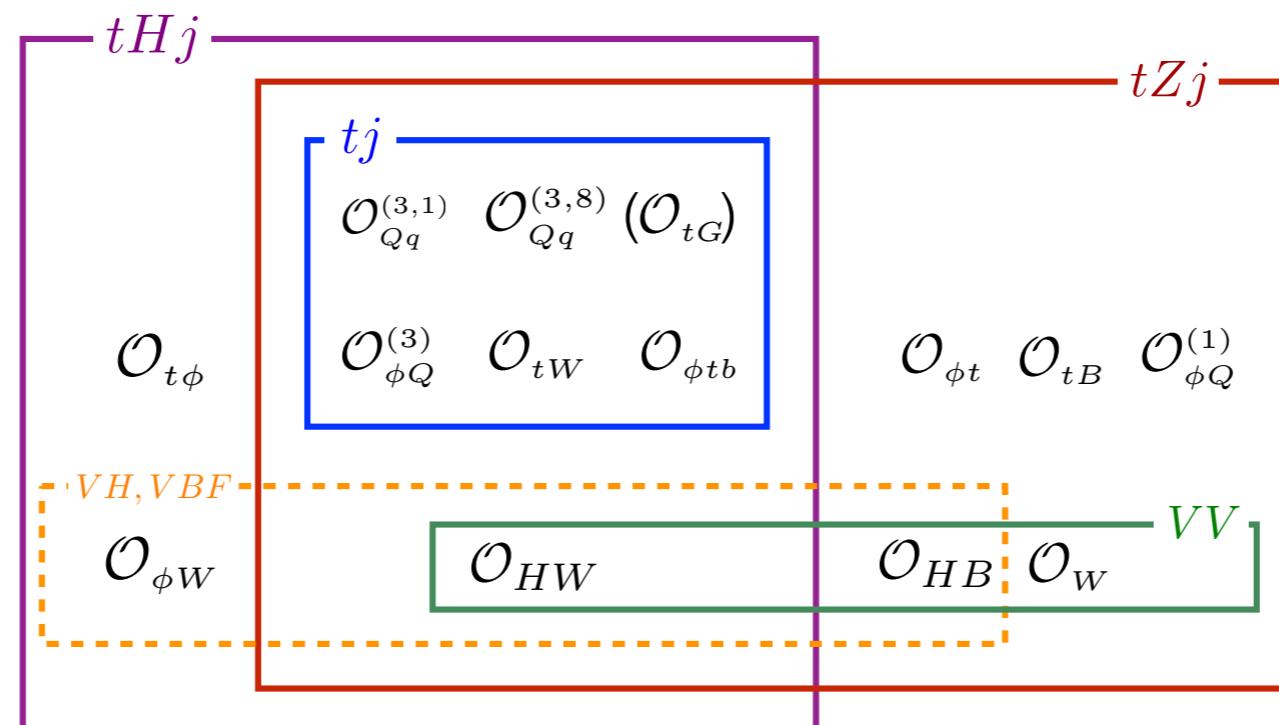


Application 1. Single top + X, $X = Z, H$

[Degrande et al.; JHEP 1810 (2018) 005]

Application 1: single top associated production

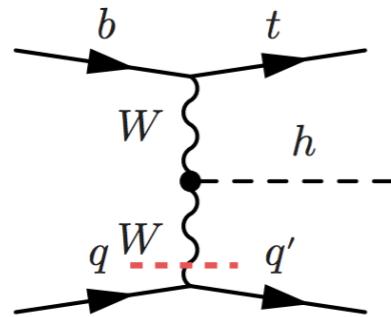
- As a case study, consider $p\ p \rightarrow t\ j\ X, X = Z, H$.
- A useful test for putting together Higgs/EW/Top OPs.



- “Unitarity cancellations”: announced sensitivity at high mass.

Application 1: single top associated production

tHj ($tZj = h \rightarrow Z$)

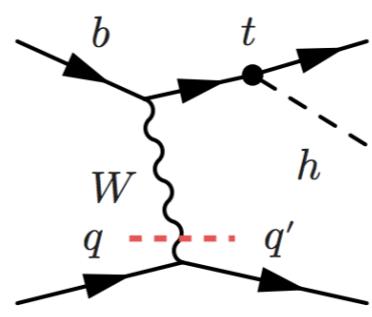


$$\mathcal{O}_{\varphi W} : \varphi^\dagger \varphi W_i^{\mu\nu} W_{\mu\nu}^i$$

HWY

TGC

$$\mathcal{O}_W : \epsilon^{ijk} W_{i,\mu\nu} W_j^{\nu\rho} W_{k,\rho}^{\mu}$$

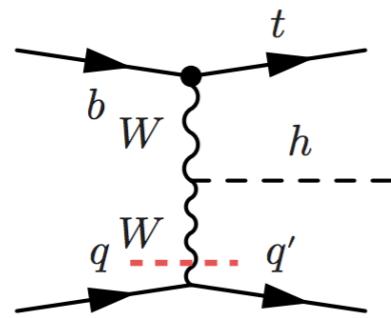


$$\mathcal{O}_{t\varphi} : (\varphi^\dagger \varphi) (\bar{Q} t) \tilde{\varphi}$$

top Yukawa

ttZ coupling

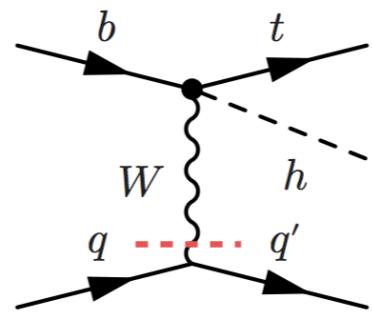
$$\mathcal{O}_{\varphi t} : i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t} \gamma^\mu t)$$



$$\mathcal{O}_{\varphi Q}^{(3)} : i(\varphi^\dagger \overleftrightarrow{D}_\mu^i \varphi)(\bar{Q} \gamma^\mu \sigma_i Q)$$

Wtb vertex

$$\mathcal{O}_{\varphi tb} : i(\tilde{\varphi} D_\mu \varphi)(\bar{b} \gamma^\mu t)$$



$$\mathcal{O}_{\varphi Q}^{(3)} : i(\varphi^\dagger \overleftrightarrow{D}_\mu^i \varphi)(\bar{Q} \gamma^\mu \sigma_i Q)$$

Contact terms

$$\mathcal{O}_{tB} : (\bar{Q} \sigma_{\mu\nu} t) \tilde{\varphi} B^{\mu\nu}$$

- The tXj channels access the $2 \rightarrow 2$ sub-amplitudes, probe the energy dependence due to unitarity cancellation spoiled by BSM effects, and reveal the rich interplay between EFT operators from different sectors.
- See also
 - [Maltoni,Paul,Stelzer,Willenbrock,'01] [Biswas,Gabrielli,Mele,12]
 - [Farina,Grojean,Maltoni,Salvioni,Thamm,'12][Demartin,Maltoni,Mawatari,Zaro,'15]
 - [Dror,Farina,Salvioni,Serra,'16] [Maltoni,Mantani,Mimasu,'19]

Single top associated production: helicity amplitudes

tHj 2>2 sub-amplitude: bW>tH

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

$\mathcal{O}_{\phi tb}, \lambda_b = +$

λ_t	λ_W	0	+	-
+	$\sqrt{s(s+t)}$	$m_W \sqrt{-t}$	$\frac{1}{\sqrt{s}}$	
-	$m_t \sqrt{-t}$	s^0	s^0	

Single top associated production: helicity amplitudes

tZj 2>2 sub-amplitude: bW>tZ

$\lambda_b, \lambda_W, \lambda_t, \lambda_Z$	SM	$\mathcal{O}_{\phi Q}^{(3)}$	$\mathcal{O}_{\phi Q}^{(1)}$	$\mathcal{O}_{\phi t}$	\mathcal{O}_{tB}	\mathcal{O}_{tW}	\mathcal{O}_W	\mathcal{O}_{HW}	\mathcal{O}_{HB}
- , 0 , - , 0	s^0	$\sqrt{s(s+t)}$	-	-	-	$\frac{s^0}{\sqrt{-t}}$	s^0	$\sqrt{s(s+t)}$	s^0
- , 0 , + , 0	$\frac{1}{\sqrt{s}}$	$m_t \sqrt{-t}$	$m_t \sqrt{-t}$	$m_t \sqrt{-t}$	$m_Z \sqrt{-t}$	$\frac{m_W(2s+3t)}{\sqrt{-t}}$	-	$m_t \sqrt{-t}$	$m_t \sqrt{-t}$
- , - , - , 0	$\frac{1}{\sqrt{s}}$	$m_W \sqrt{-t}$	-	-	-	-	$\frac{m_W(s+2t)}{\sqrt{-t}}$	$m_W \sqrt{-t}$	$\frac{1}{\sqrt{s}}$
- , - , + , 0	$\frac{1}{s}$	s^0	s^0	s^0	s^0	$\sqrt{s(s+t)}$	s^0	s^0	$\frac{1}{\sqrt{s}}$
- , 0 , - , -	$\frac{1}{\sqrt{s}}$	$m_W \sqrt{-t}$	-	-	$m_t \sqrt{-t}$	$m_t \sqrt{-t}$	$\frac{m_W(s+2t)}{\sqrt{-t}}$	$\frac{m_W(ss_W^2+2t)}{\sqrt{-t}}$	$\frac{m_W s}{\sqrt{-t}}$
- , 0 , - , +	$\frac{1}{\sqrt{s}}$	-	-	-	-	-	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{m_W(s+t)}{\sqrt{-t}}$
- , 0 , + , -	s^0	s^0	s^0	-	-	s^0	s^0	s^0	s^0
- , 0 , + , +	$\frac{1}{s}$	s^0	s^0	s^0	$\sqrt{s(s+t)}$	$\sqrt{s(s+t)}$	-	s^0	s^0
- , + , - , 0	$\frac{1}{\sqrt{s}}$	-	-	-	-	-	$\frac{m_W(s+t)}{\sqrt{-t}}$	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
- , + , + , 0	s^0	s^0	-	-	-	s^0	-	s^0	$\frac{1}{s}$
- , - , - , -	s^0	s^0	s^0	-	s^0	s^0	s^0	s^0	s^0
- , - , - , +	$\frac{1}{s}$	-	-	-	-	-	$\sqrt{s(s+t)}$	s^0	s^0
- , - , + , -	$\frac{1}{\sqrt{s}}$	-	-	-	-	$\frac{m_Z(s_W^2 t - 3 c_W^2 (2s+t))}{\sqrt{-t}}$	-	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$
- , - , + , +	-	-	-	-	$m_W \sqrt{-t}$	$m_Z \sqrt{-t}$	$m_t \sqrt{-t}$	$m_t \sqrt{-t}$	$m_t \sqrt{-t}$
- , + , - , -	$\frac{1}{s}$	-	-	-	-	-	$\sqrt{s(s+t)}$	s^0	s^0
- , + , - , +	s^0	s^0	-	-	-	-	-	s^0	s^0
- , + , + , -	$\frac{1}{\sqrt{s}}$	-	-	-	-	-	$m_t \sqrt{-t}$	$m_t \sqrt{-t}$	$m_t \sqrt{-t}$
- , + , + , +	$\frac{1}{\sqrt{s}}$	-	-	-	-	$\frac{m_W(s+t)}{\sqrt{-t}}$	-	$\frac{1}{\sqrt{s}}$	$\frac{1}{\sqrt{s}}$

$\mathcal{O}_{\phi tb}, \lambda_b, \lambda_t = +, +$

		λ_W	0	+	-
		λ_Z	$\sqrt{s(s+t)}$	$m_W \sqrt{-t}$	-
λ_W	0	$\sqrt{s(s+t)}$	$m_W \sqrt{-t}$	-	
λ_W	+	$m_Z \sqrt{-t}$	s^0	-	
λ_W	-	-	-	s^0	

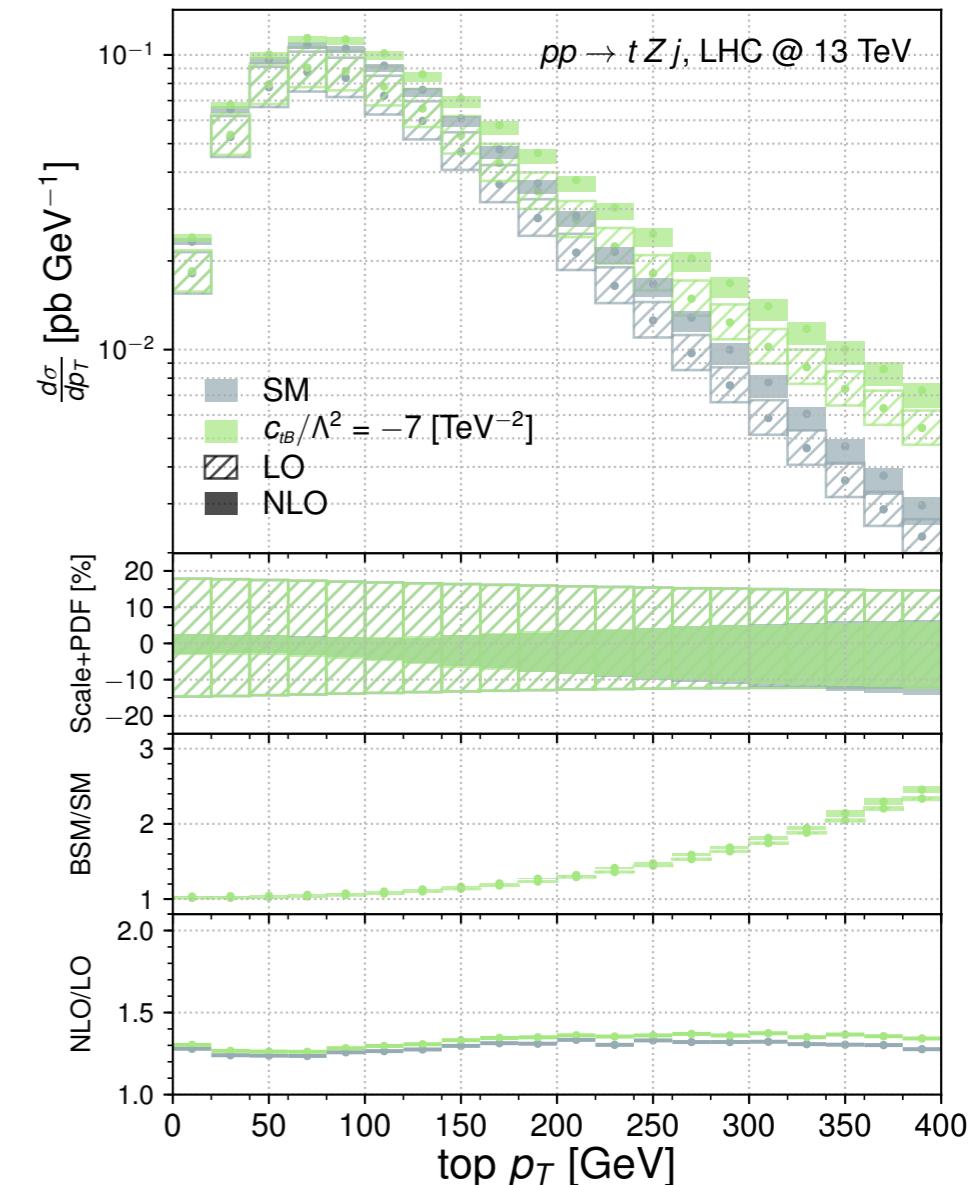
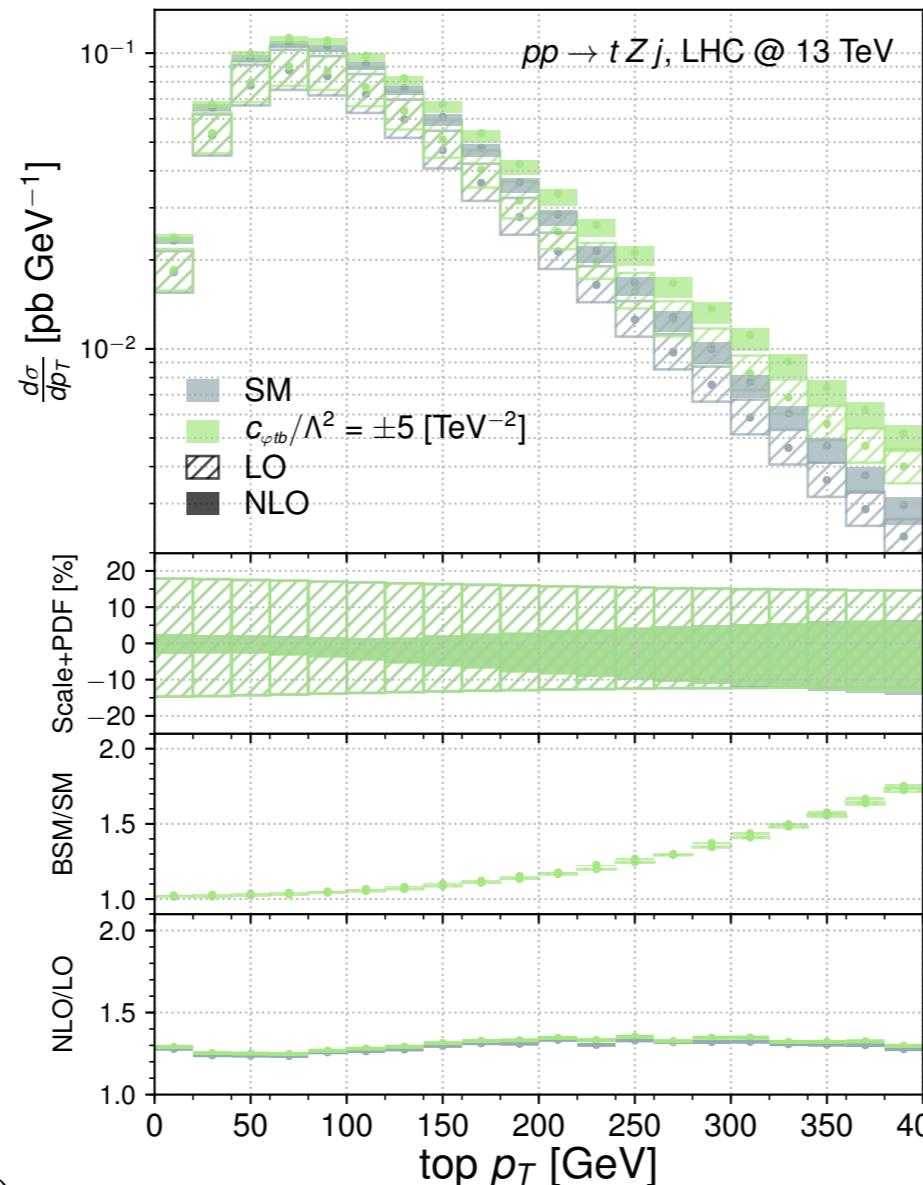
$\mathcal{O}_{\phi tb}, \lambda_b, \lambda_t = +, -$

		λ_W	0	+	-
		λ_Z	0	-	s^0
λ_W	0	0	-	s^0	
λ_W	+	s^0	-	-	
λ_W	-	s^0	-	-	

Single top associated production: selected results

- K-factors (of the operator contributions) are not universal, ranging from $1.1 \sim 1.7$
- Reduction of scale/PDF uncertainties.
- Deviation $\sim 20\%$ within current constraints (OtW and OtB).
- Deviations amplified with large pT.
- Projected limits are competitive for OPs:

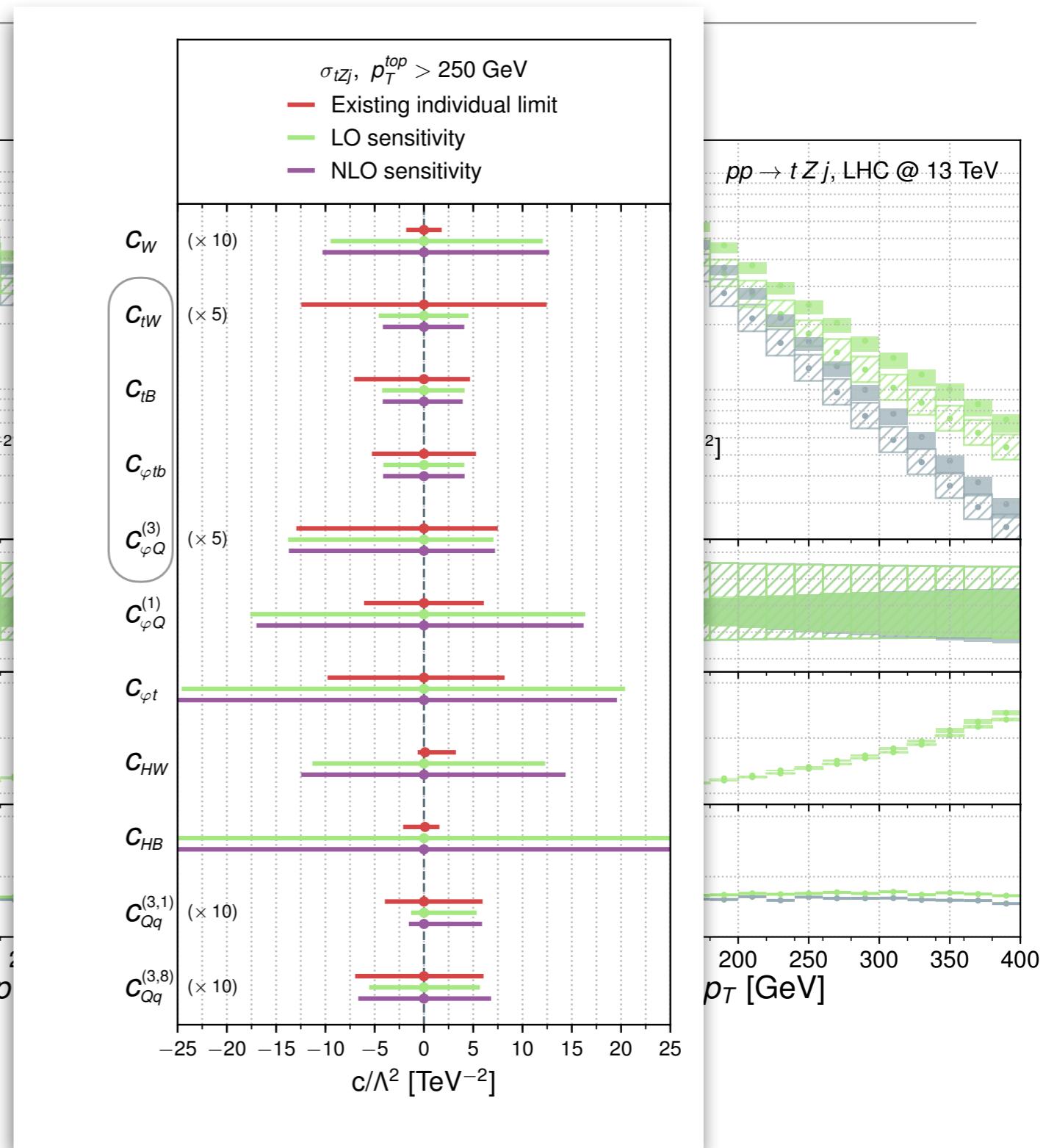
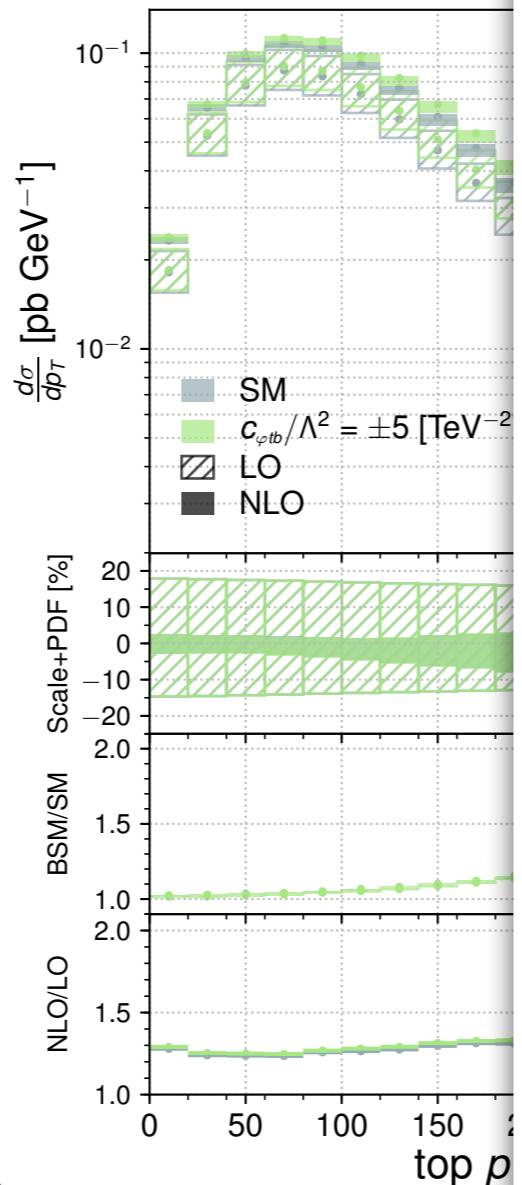
$$c_{tW}, c_{tB}, c_{\varphi tb}, c_{\varphi Q}^{(3)}$$



Single top associated production: selected results

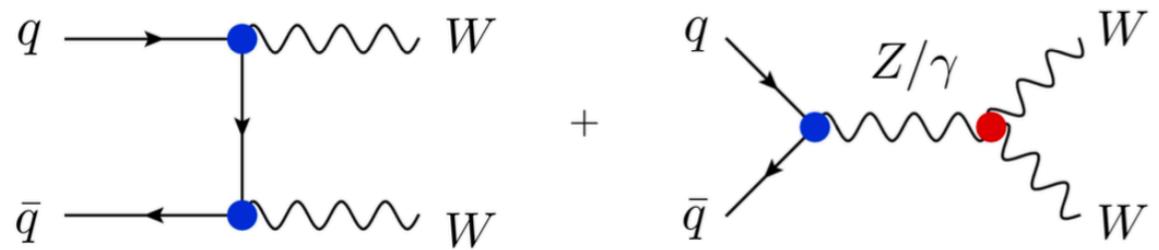
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Application 2. Diboson

Application 2: diboson



$$\begin{aligned} \mathcal{L}_{V\bar{q}q} &= \sqrt{g^2 + g'^2} Z_\mu \left[\sum_{f \in u,d} \bar{f}_L \gamma_\mu \left(T_f^3 - s_W^2 Q_f + \delta g_L^{Zf} \right) f_L + \sum_{f \in u,d} \bar{f}_R \gamma_\mu \left(-s_W^2 Q_f + \delta g_R^{Zf} \right) f_R \right] \\ &+ \frac{g}{\sqrt{2}} \left(W_\mu^+ \bar{u}_L \gamma_\mu \left(I_3 + \delta g_L^{Wq} \right) d_L + \text{h.c.} \right). \end{aligned} \quad (3)$$

$$\begin{aligned} \mathcal{L}_{\text{TGC}} &= ie (W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+) A_\nu + ie [(1 + \delta \kappa_\gamma) A_{\mu\nu} W_\mu^+ W_\nu^-] \\ &+ ig c_W [(1 + \delta g_{1,z}) (W_{\mu\nu}^+ W_\mu^- - W_{\mu\nu}^- W_\mu^+) Z_\nu + (1 + \delta \kappa_z) Z_{\mu\nu} W_\mu^+ W_\nu^-] \\ &+ i \frac{e}{m_W^2} \lambda_\gamma W_{\mu\nu}^+ W_{\nu\rho}^- A_{\rho\mu} + i \frac{g c_W}{m_W^2} \lambda_z W_{\mu\nu}^+ W_{\nu\rho}^- Z_{\rho\mu}. \end{aligned}$$

$\delta g_L^{Zu}, \delta g_R^{Zu}, \delta g_L^{Zd}, \delta g_R^{Zd}$

$\delta \kappa_\gamma, \delta g_{1z}, \lambda_\gamma$

- TGC dominant assumption: the quark couplings are well constrained. Lets focus on TGC...
- But the LEP constraints on are not strong enough to make them negligible... **[Z. Zhang 1610.01618]**

[Baglio, Dawson, Lewis; PRD99 (2019), 035029]

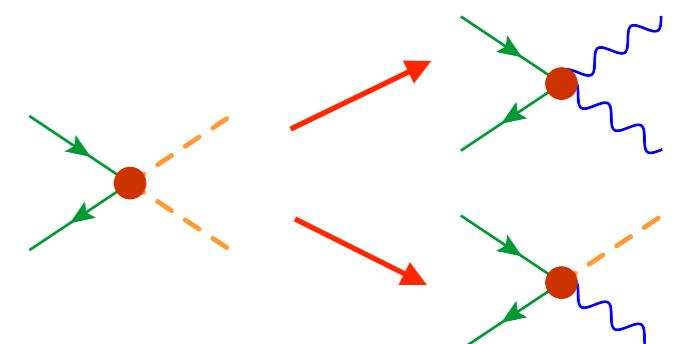
- In fact, in the future, WW/WZ/WH/ ZH will give the best bounds on quark vertices.

$$\mathcal{O}_L^{(3)} = (\bar{Q}_L \sigma^a \gamma^\mu Q_L) (i H^\dagger \sigma^a \overset{\leftrightarrow}{D}_\mu H)$$

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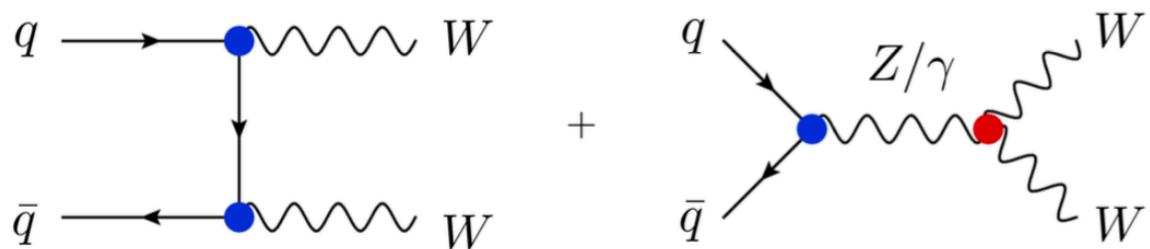
[R. Franceschini et al. 1712.01310]

[S. Banerjee et al. 1807.01796]

[Grojean, Montull, Riembau 1810.05149]

See also talk by R. Gupta

Application 2: diboson

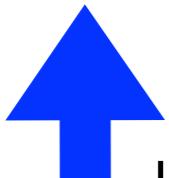


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$\delta g_L^{Zu}, \delta g_R^{Zu}, \delta g_L^{Zd}, \delta g_R^{Zd}$

$\delta \kappa_\gamma, \delta g_{1z}, \lambda_\gamma$



Let's try this one

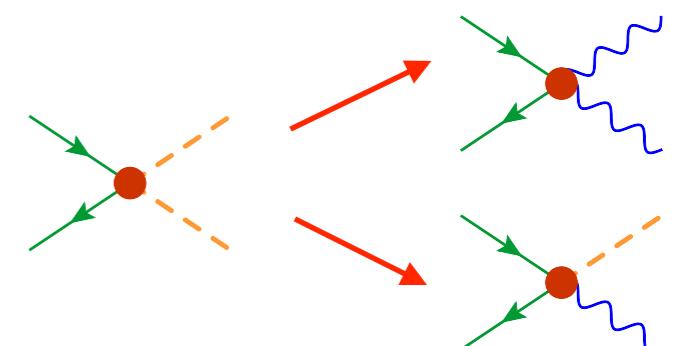
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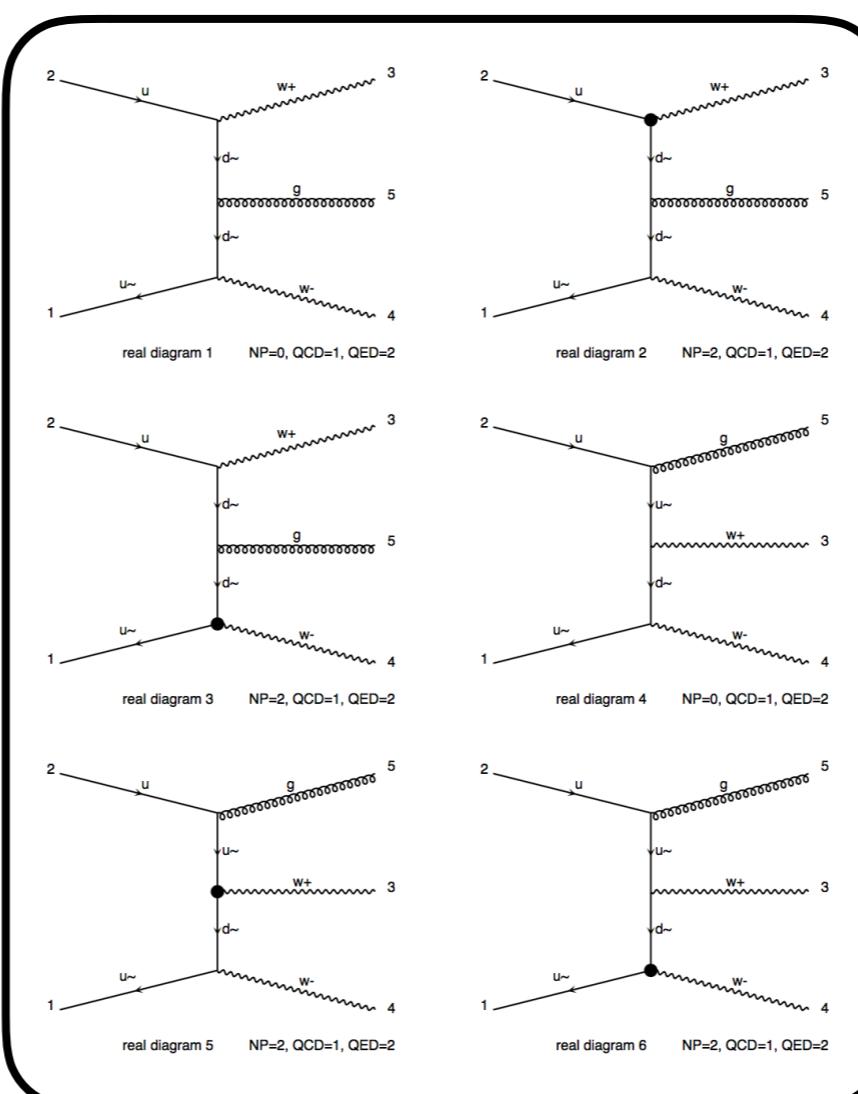
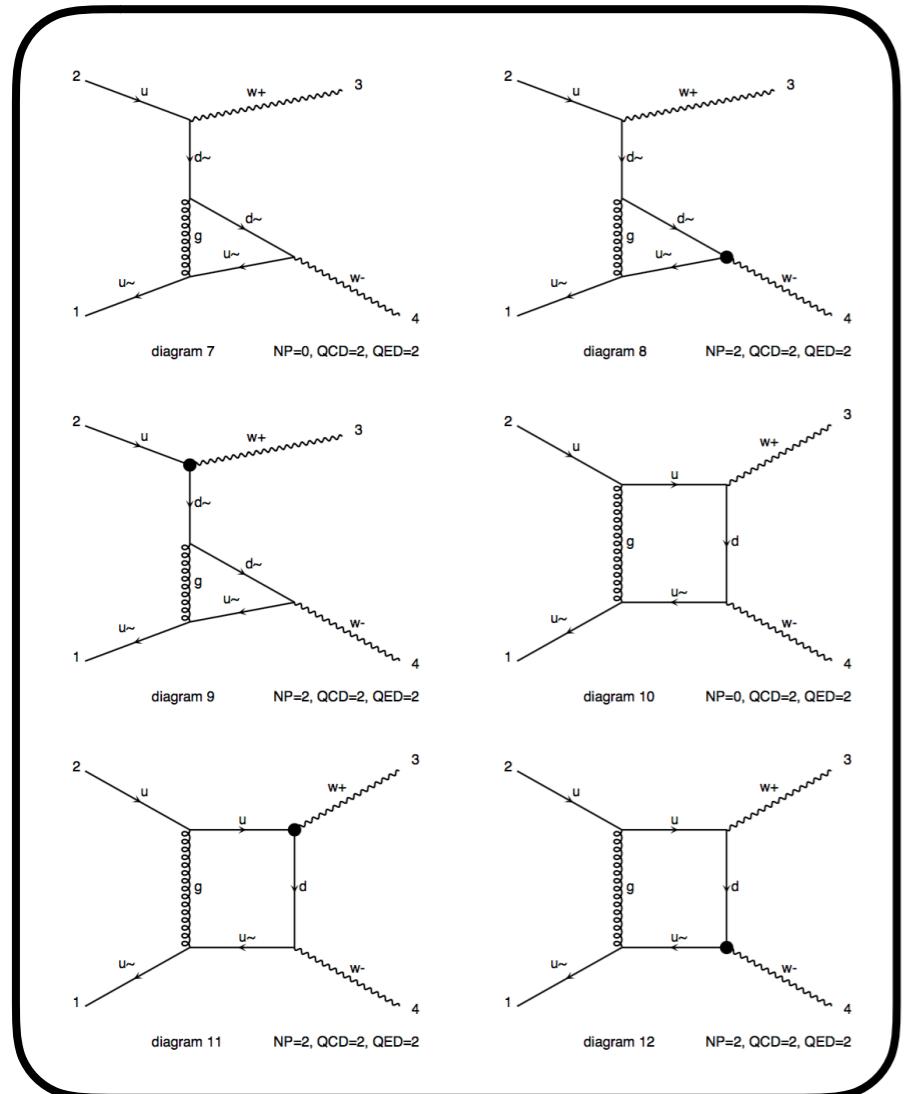
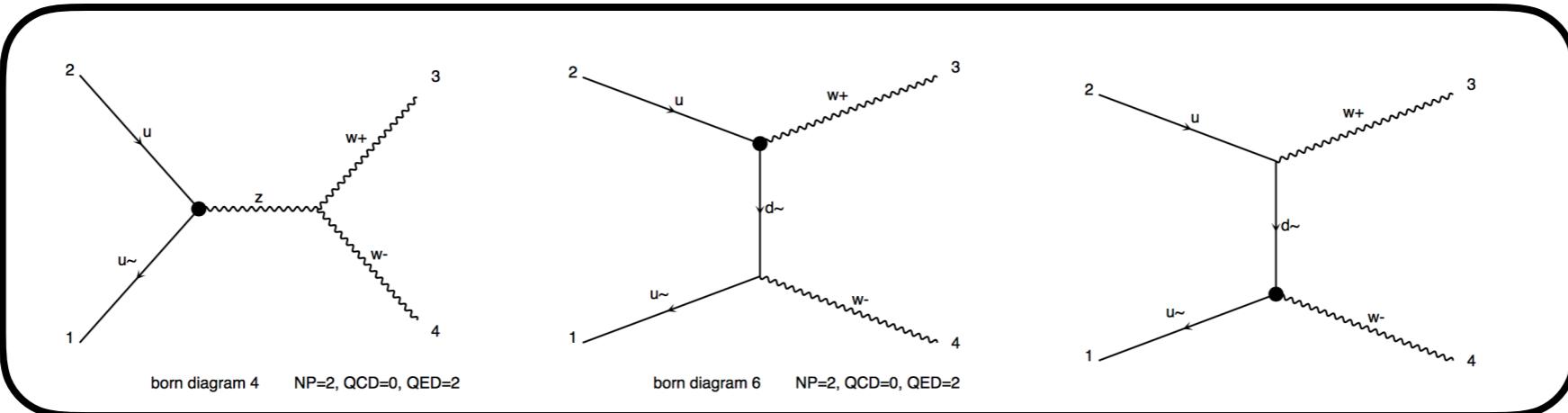
[Grojean, Montull, Riembau 1810.05149]

See also talk by R. Gupta

MG5_aMC>import model SMEFTatNLO_U2_2_U3_3_cG_4F_LO_UFO-NLO

MG5_aMC>generate p p > w+ w- \$\$ t t~ QCD=0 QED=2 NP=2 [QCD]

Remove resonances in real diagrams

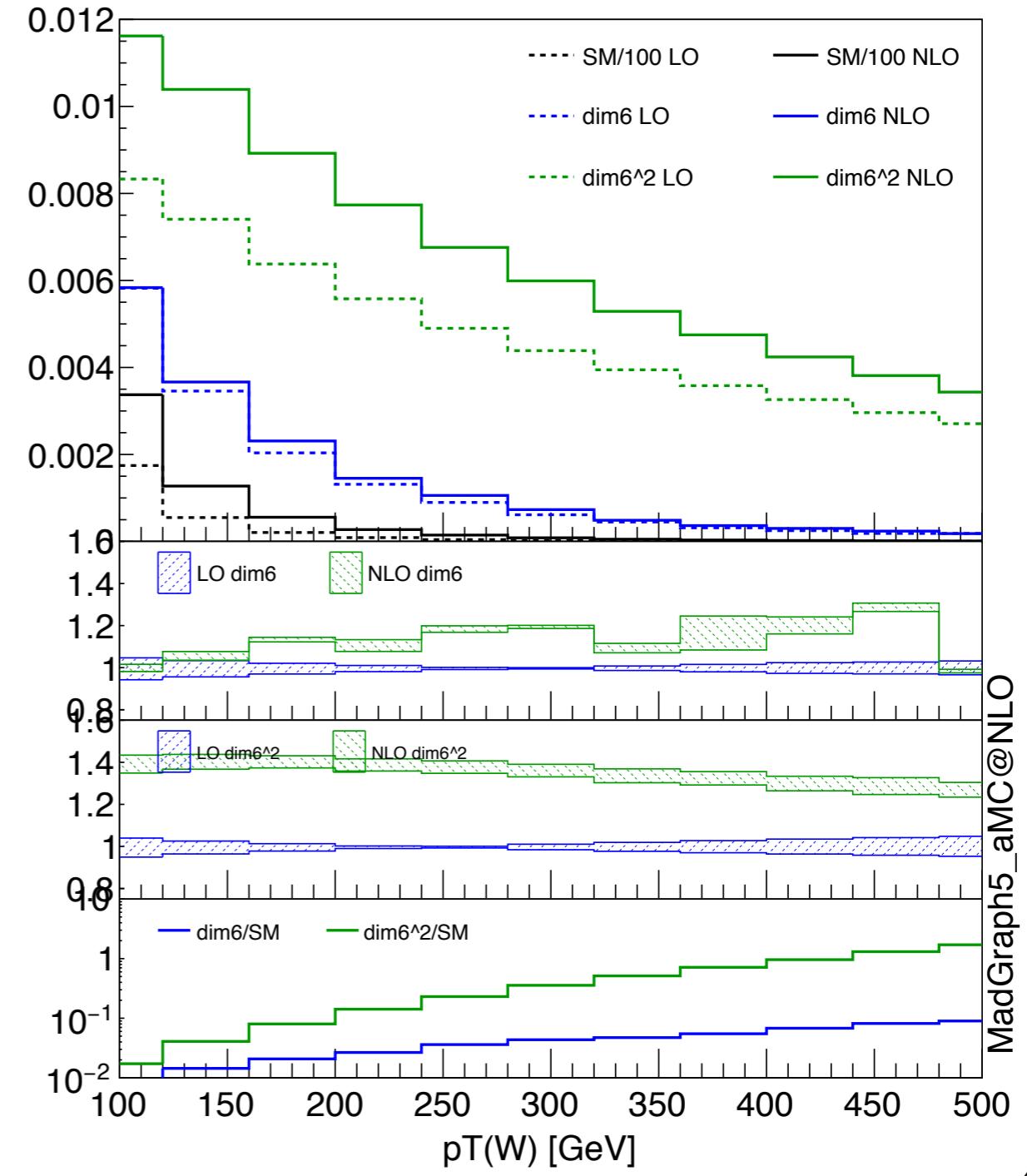
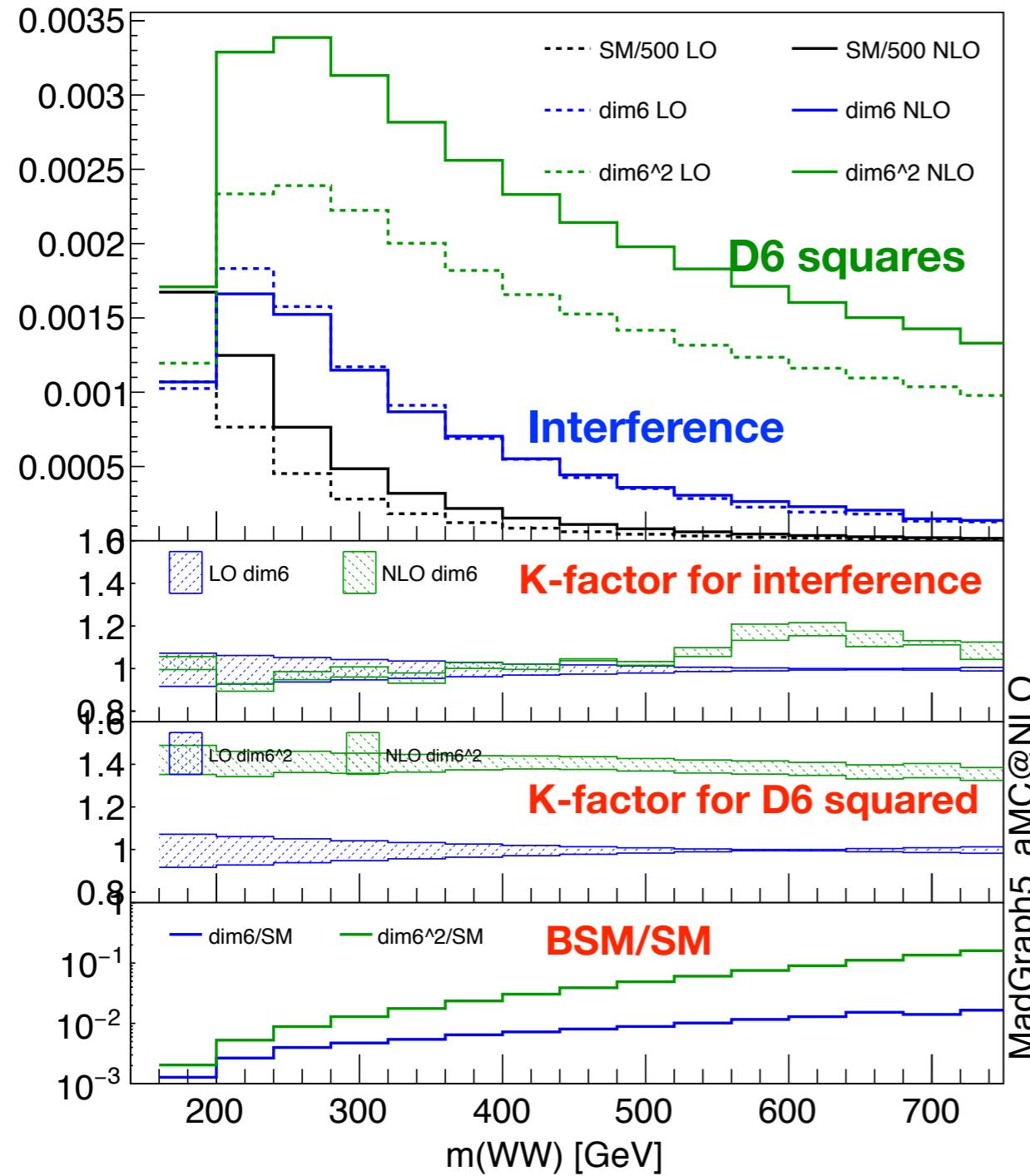


```
#####
## INFORMATION FOR DIM6
#####
Block dim6
1 1.000000e+03 # Lambda

#####
## INFORMATION FOR DIM62F
#####
Block dim62f
10 1.000000e+00 # cpqi
12 0.000000e+00 # c3pqi
14 0.000000e+00 # cpu
16 0.000000e+00 # cpd
```

Application 2: diboson

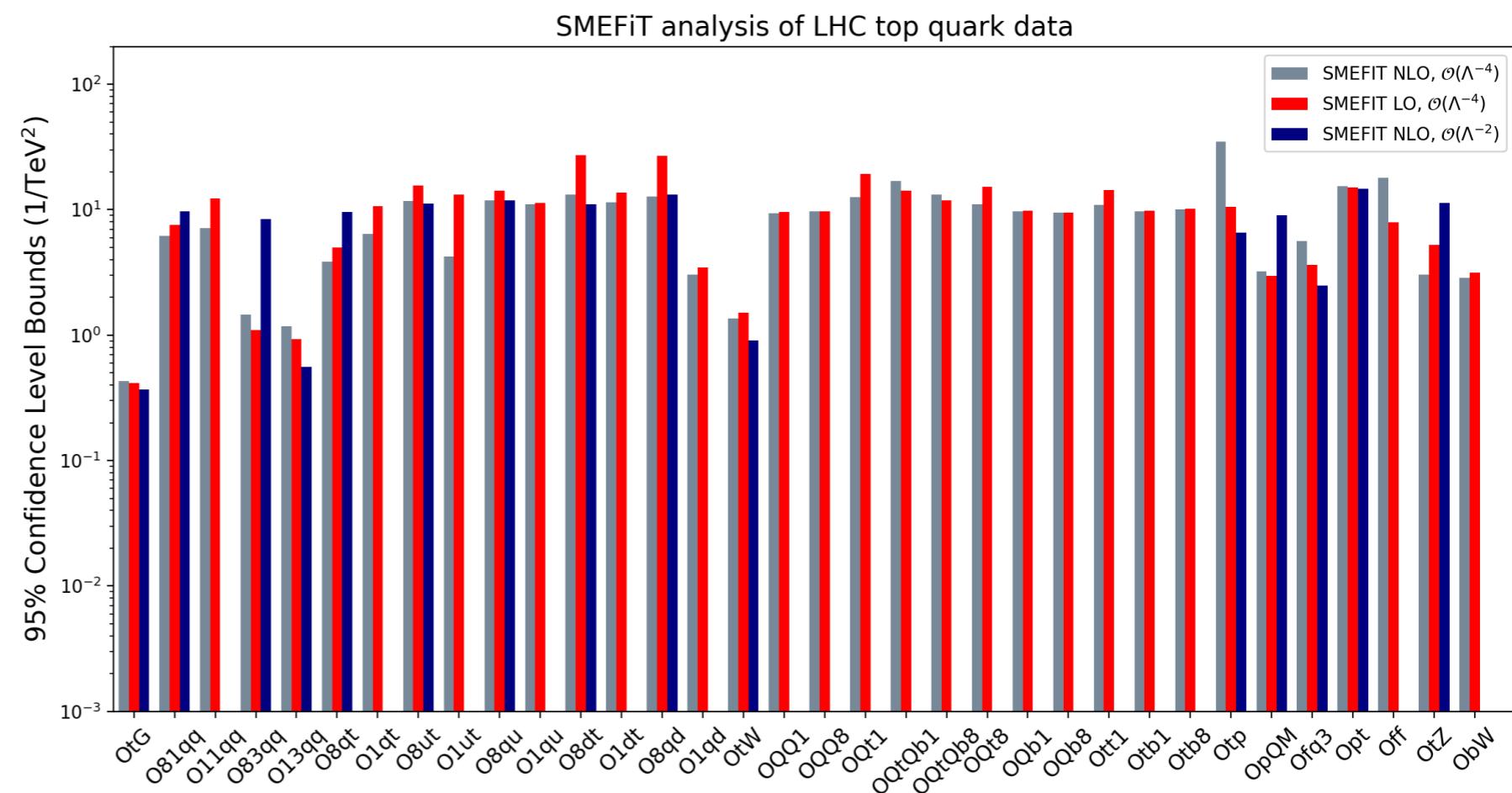
$pp \rightarrow W^+W^-$ with $c_{\varphi q}^{(1)} = 1$



Application 3: NLO global fit (top)

[Hartland, Maltoni, Nocera, Rojo, Slade, Vryonidou, **CZ 19**]

- Theory predictions from **MG5_aMC@NLO**, i.e. operator contributions are mostly at NLO in QCD
- Parametrization & operator basis etc. are consistent with TOP working group EFT recommendation



See also TopFitter, A. Buckley et al. '15

Towards automatic EW corrections

Automatic EW NLO based on reweighting: HHH

H trilinear coupling at one loop:

<https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/HiggsSelfCoupling>

[Maltoni, Pagani, Shivaji, Zhao 1709.08649]

Higgs Trilinear self-coupling determination through one-loop effects

Authors : Xiaoran Zhao [email](#) and Ambresh Shivaji [email](#)

Proposals have been made to access information on the Higgs self-coupling by accurately measuring cross sections and distributions using single-Higgs processes, see for instance [arXiv:1607.04251](#).

This page contains the codes for generating events in processes **p p > VH, VBF, tHj** and **ttH** and **H > 4l** including the effect of trilinear Higgs self coupling at one-loop.

Please cite: Fabio Maltoni, Davide Pagani, Ambresh Shivaji and Xiaoran Zhao [arXiv:1709.08649](#)

trilinear-FF (The Form-factor code to run VH, VBF and Hto4l) FF [download](#)

In this folder we provide:

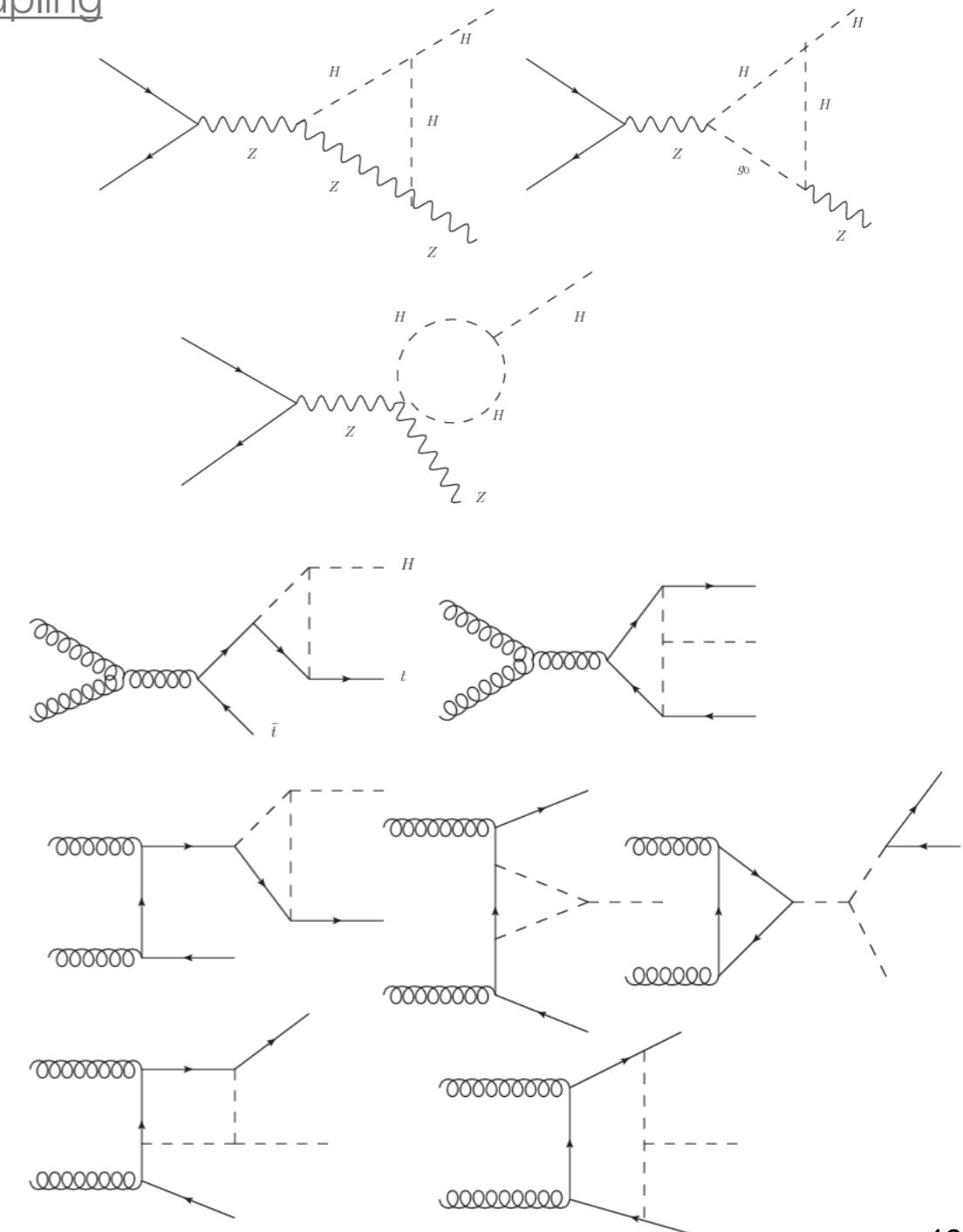
- 'loop_hvv' : the UFO model folder with modified VVH vertices due to trilinear couplings at one-loop
- "hvvcoef.cpp": C++ implementation of form factors
- "Makefile" : to generate static library (libhvvcoef.a) which is used during event generation
- "ReadMe.txt" : explains how to use the code step by step and benchmarking for HZ process

trilinear-RW (The Reweighting code to run VH, VBF, tHj and ttH) RW [download](#)

In this folder we provide:

- 'hhh-model': the UFO model file to be used
- "gevirt.sh": auxiliary script to generate virtual EW subprocesses
- "vvh-loop_diagram_generation.py" : to select right set of one-loop diagrams in VH, VBF and tHj
- "tth-loop_diagram_generation.py" : to select right set of one-loop diagrams in ttH
- "check_OLP.f": reweighting code
- "makefile" : makefile for reweighting code
- "ReadMe.txt" : explains how to use the code step by step and benchmarking for HZ process
- we also provide 'example_hz' folder which contains a simple script to build the reweighting code for HZ as an example

(All calculations are done in G/μ scheme and benchmarking is done with MG5_aMC_v2_5_5)

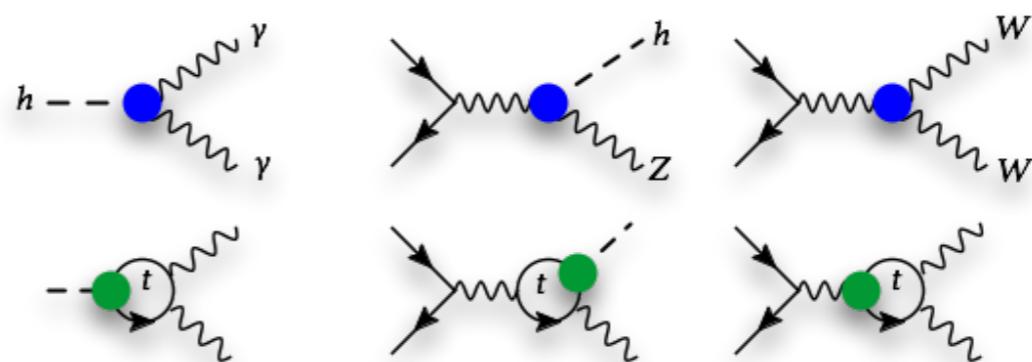


Automatic EW NLO based on reweighting: top couplings

Top operators entering at one loop lead to complication in future precision Higgs measurements.

- Higgs/diboson channels can reach $\sim 1\%$ or even better precision with future lepton collider. When this happens, we want to be able to disentangle

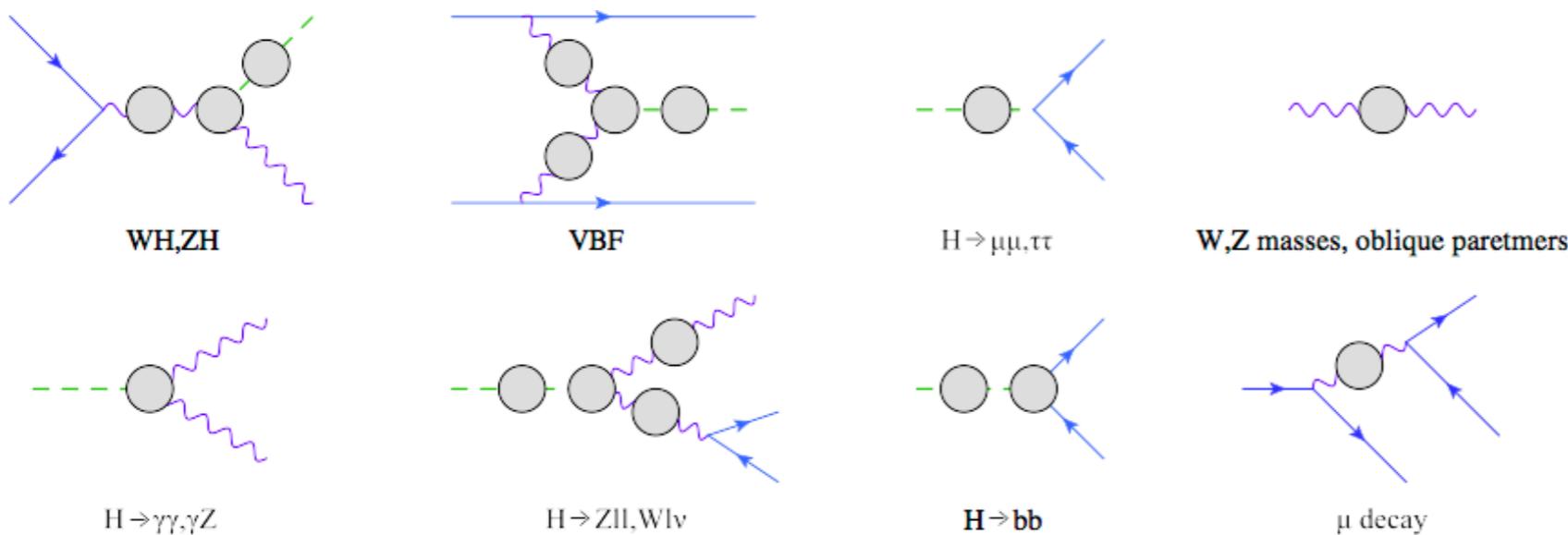
- **H coupling tree level** and
- **Top coupling loop level?**



- At future CC even below ttbar threshold, it's possible to probe top EW couplings with good precision (better than HL-LHC).
- Strong correlation between top/H couplings \rightarrow top uncertainty will downgrade precision on H couplings.

Automatic EW NLO based on reweighting

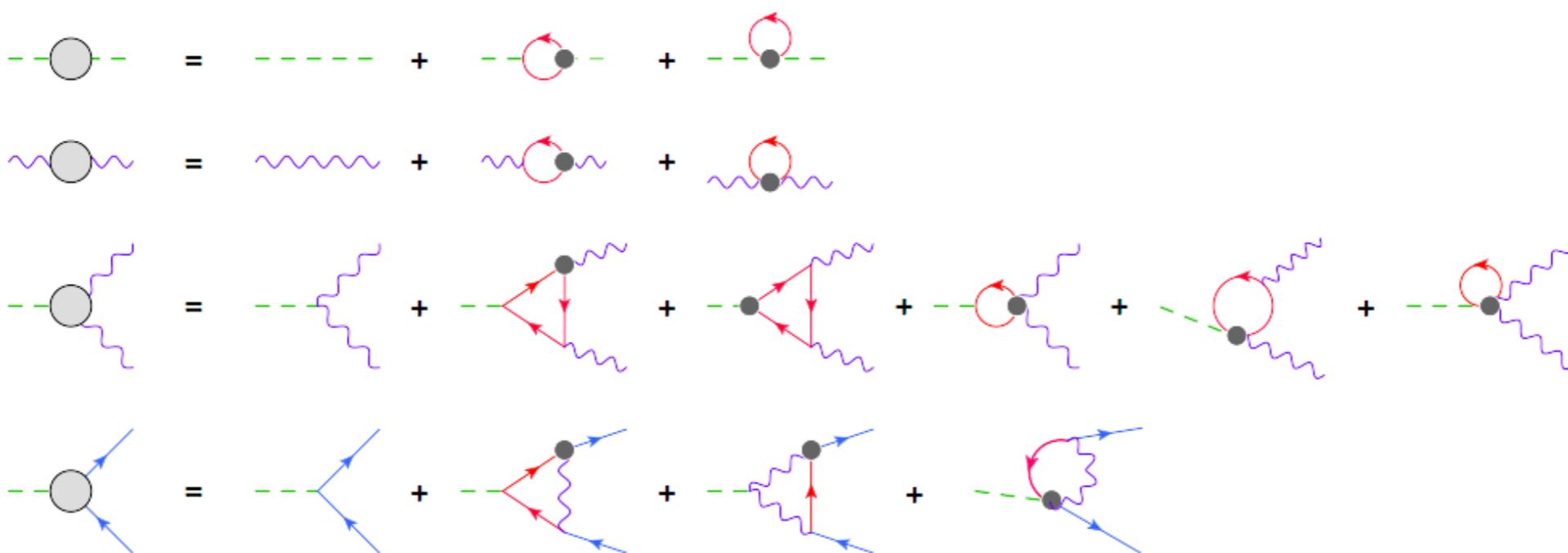
Top coupling at one loop:



[Vryonidou, CZ '18]

All dim-6 top loop contributions in Higgs

Automated with
MG5_aMC@NLO



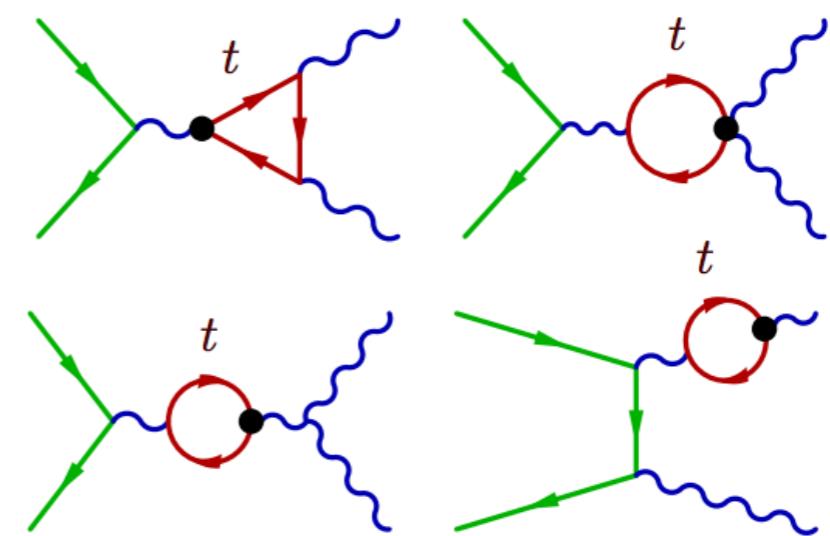
RG mixing

	$O_{\varphi t}$	$O_{\varphi Q}^{(+)}$	$O_{\varphi Q}^{(-)}$	$O_{\varphi tb}$	O_{tW}	O_{tB}	$O_{t\varphi}$
$O_{\varphi WB}$	$\frac{1}{3s_W c_W}$	$\frac{1}{3s_W c_W}$	$-\frac{1}{6s_W c_W}$	0	$-\frac{5y_t}{2ec_W}$	$-\frac{3y_t}{2es_W}$	0
$O_{\varphi D}$	$-6 \frac{y_t^2}{e^2}$	$3 \frac{y_t^2 - y_b^2}{e^2}$	$3 \frac{y_t^2 - y_b^2}{e^2}$	$-6 \frac{y_t y_b}{e^2}$	0	0	0
$O_{\varphi \square}$	$-\frac{3}{2} \frac{y_t^2}{e^2}$	$-\frac{3y_t^2 + 6y_b^2}{2e^2}$	$\frac{6y_t^2 + 3y_b^2}{2e^2}$	$3 \frac{y_t y_b}{e^2}$	0	0	0
$O_{\varphi W}$	0	$\frac{1}{4s_W^2}$	$-\frac{1}{4s_W^2}$	0	$\frac{3y_t}{2es_W}$	0	0
$O_{\varphi B}$	$\frac{1}{3c_W^2}$	$\frac{1}{12c_W^2}$	$\frac{1}{12c_W^2}$	0	0	$\frac{5y_t}{2ec_W}$	0
O_W	0	$\frac{1}{es_W}$	$-\frac{1}{es_W}$	0	0	0	0
O_B	$\frac{4}{3ec_W}$	$\frac{1}{3ec_W}$	$\frac{1}{3ec_W}$	0	0	0	0
$O_{b\varphi}$	0	$-\frac{y_b}{2c_W^2}$ $+ y_b \frac{8\lambda - 3y_t^2 - 5y_b^2}{4e^2}$	$y_b \frac{-4\lambda + 3y_t^2 + 7y_b^2}{4e^2}$	$\frac{3y_t}{4s_W^2}$ $- y_t \frac{2\lambda + y_t^2 - 6y_b^2}{2e^2}$	$\frac{y_t y_b}{2es_W}$	0	$\frac{3y_t y_b}{4e^2}$
$O_{\mu\varphi}$	0	$-\frac{3y_\mu(y_t^2 + y_b^2)}{2e^2}$	$\frac{3y_\mu(y_t^2 + y_b^2)}{2e^2}$	$\frac{3y_t y_b y_\mu}{e^2}$	0	0	$\frac{3y_t y_\mu}{2e^2}$
$O_{\tau\varphi}$	0	$-\frac{3y_\tau(y_t^2 + y_b^2)}{2e^2}$	$\frac{3y_\tau(y_t^2 + y_b^2)}{2e^2}$	$\frac{3y_t y_b y_\tau}{e^2}$	0	0	$\frac{3y_t y_\tau}{2e^2}$

$$e^+ e^- \rightarrow W^+ W^-$$

- $e^+ e^- \rightarrow W^+ W^-$: Dim-6 contribution to γWW leads to anomaly.
- In our scheme (KKS) this is reflected by the R2 dependence on the “reading point” when tracing the top loop. E.g.

$$O_{\varphi Q}^{(-)} : \frac{e^3 v^2}{48\pi^2 s_W^2 \Lambda^2} \left\{ \begin{array}{ll} \epsilon^{\mu\nu\rho\sigma}(p_{2\sigma} - p_{3\sigma}) & \gamma \\ \epsilon^{\mu\nu\rho\sigma}(p_{3\sigma} - p_{1\sigma}) & W^+ \\ \epsilon^{\mu\nu\rho\sigma}(p_{1\sigma} - p_{2\sigma}) & W^- \end{array} \right.$$



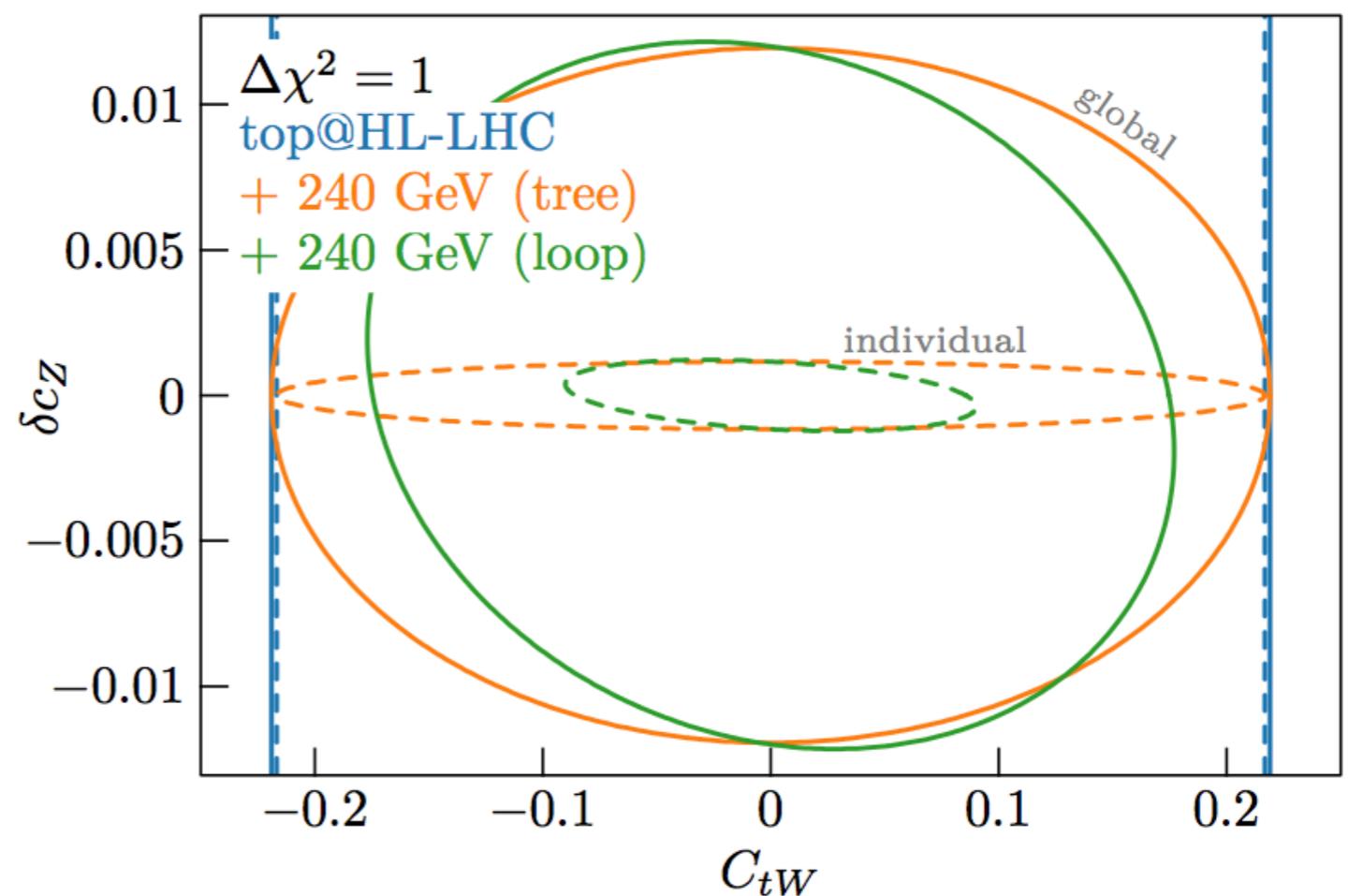
- This is fixed by adding a Wess-Zumino-Witten term.

Global fit at future ee collider: indirect top limits

[Durieux, Gu, Vryonidou, CZ '18]

- HL-LHC gives the **blue limits**.
- A global fit of Higgs data in CC, at LO, will give the **orange contours**, vertical direction.
- A global fit of Higgs data in CC, at NLO including top loops, will also constrain top couplings, giving the **green contours**, both vertical and horizontal.
- Constraining power \sim a factor of 3, reflected by the individual case (dashed line).

On a linear scale, in the $(C_{tW}, \delta c_Z)$ plane:



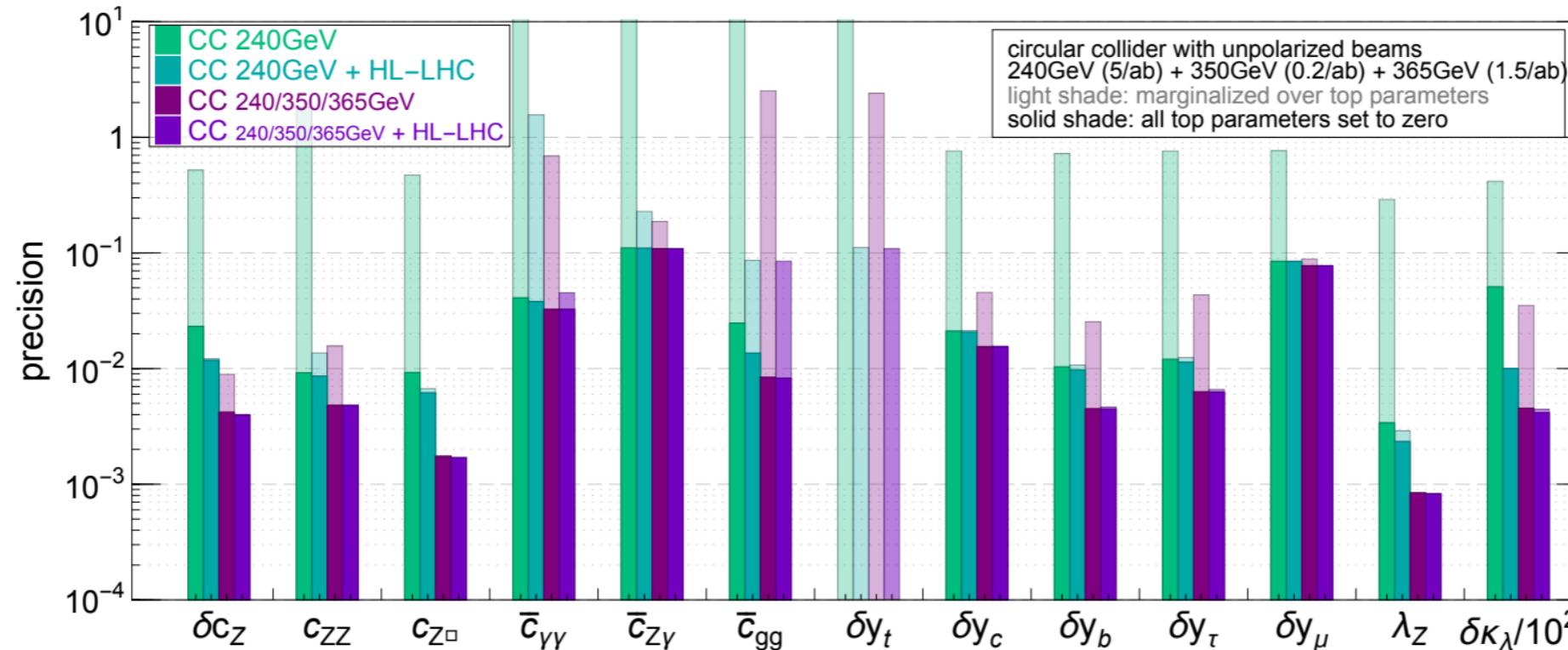
- extra parameter space covered thanks to loop sensitivity
- room for improvement between glo. and ind. constraints

Global fit at future ee collider: H/top interplay

[Durieux, Gu, Vryonidou, CZ '18]

- How does the top-coupling uncertainties downgrade the H precision at future CC?
- Global H + top loop fit, with TH results based on [Vryonidou, CZ '18]

light shades: 12 Higgs op. floated + 6 top op. floated
dark shades: 12 Higgs op. floated + 6 top op. $\rightarrow 0$



Uncertainties on the top have a big effect on the Higgs

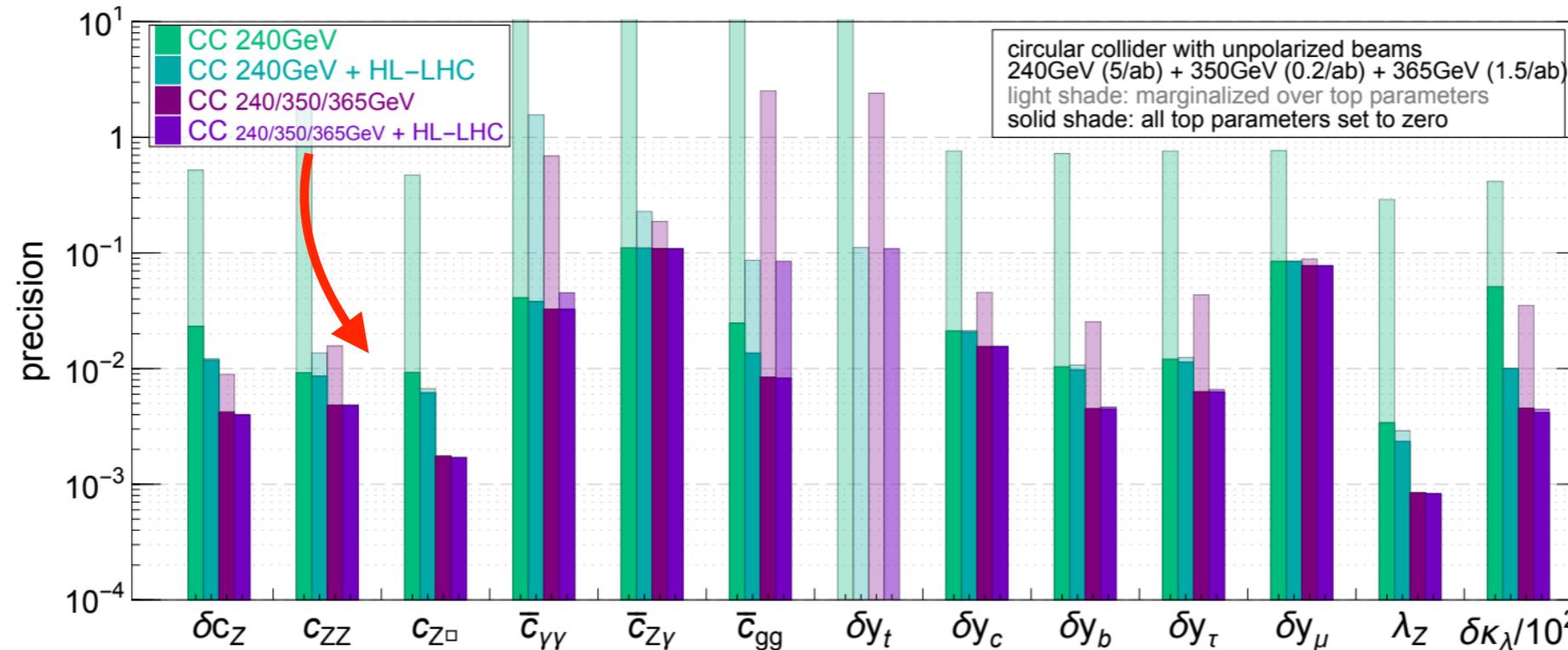
- Higgsstr. run: insufficient
- Higgsstr. run $\oplus e^+e^- \rightarrow t\bar{t}$: large y_t contaminations in various coefficients
- Higgsstr. run \oplus top@HL-LHC: large top contaminations in $\bar{c}_{\gamma\gamma, gg, Z\gamma, ZZ}$
- Higgsstr. run $\oplus e^+e^- \rightarrow t\bar{t} \oplus$ top@HL-LHC: top contam. in \bar{c}_{gg} only

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Summary

- SMEFT at NLO is a lively field.
- We are working on the implementation of **SMEFT in Warsaw basis**, in the form of a **Universal FeynRules Output model**, that can be used by **MadGraph5_aMC@NLO**, to perform **automatic** simulations at **NLO** accuracy in **QCD** matched with **parton shower**.
 - Flavor assumptions are used to simplify the problem. Top/EW/ Higgs operators are included.
 - A current version without 4-fermion and 3-gluon operators is available online.
<http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO>
- We have also started to work on automation of EW corrections.

Thank you for your attention!

Backups