University of Zurich[UZH]

Physik-Institut

NLO EW corrections in VH production in the PO framework

Andrea Pattori

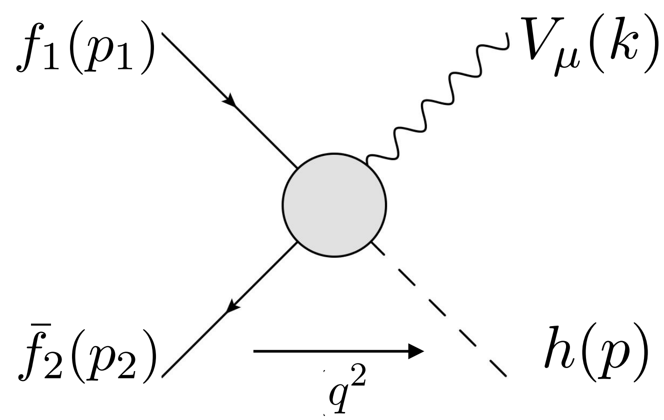
WG2 post-YR4 kickoff

CERN, 08.05.2017

Outline:

- Generalities and motivations
- Sketch of computation
- Results
- Future perspectives and conclusions

Parametrisation of Associated Production (AP) processes with POs:



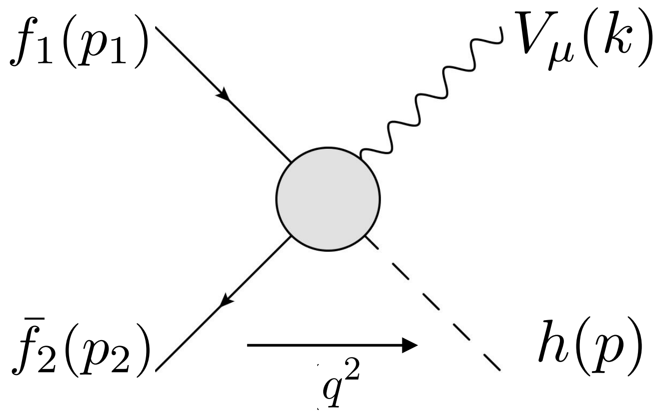
$$V_\mu = W_\mu^\pm, Z_\mu$$

$$\mathcal{A}\left(f_1(p_1)\bar{f}_2(p_2) \to V(k)h(p)\right) = 2\,i\,\frac{M_V^2}{v}\,\bar{f}_2(p_2)\gamma_\nu f_1(p_1)\epsilon_\mu^{V*}(k)$$

$$\times\left[F_L^{f_1 f_2 V}(q^2)\,\eta^{\mu\nu} + F_T^{f_1 f_2 V}(q^2)\,\frac{q^\mu k^\nu - (q\cdot k)\eta^{\mu\nu}}{M_V^2} + F_{CP}^{f_1 f_2 V}(q^2)\frac{\epsilon^{\mu\nu\alpha\beta}q_\alpha k_\beta}{M_V^2}\right]$$

POs in Associated Higgs Production

Parametrisation of Associated Production (AP) processes with POs:



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- **Longitudinal:** $F_L^{f_1 f_2 V}(q^2) = \kappa_{VV}\frac{g_V^{f_1\bar{f}_2}}{P_V(q^2)} + \frac{\epsilon_V^{f_1 f_2}}{M_V^2}\,,$
- **Transverse:** $F_T^{f_1 f_2 V}(q^2) = \epsilon_{VV}\frac{g_V^{f_1\bar{f}_2}}{P_V(q^2)} + \delta_{VZ}\,\epsilon_{Z\gamma}\frac{e\,Q_{f_1}}{q^2}\,,$
- **CP-odd:** $F_{CP}^{f_1 f_2 V}(q^2) = \epsilon_{VV}^{CP}\frac{g_V^{f_1\bar{f}_2}}{P_V(q^2)} - \delta_{VZ}\,\epsilon_{Z\gamma}^{CP}\frac{e\,Q_{f_1}}{q^2}\,,$

Pseudo Observables

Purposes

$$\mathcal{A}\left(f_1(p_1)\bar{f}_2(p_2) \to V(k)h(p)\right) = 2\,i\,\frac{M_V^2}{v}\,\bar{f}_2(p_2)\gamma_\nu f_1(p_1)\epsilon_\mu^{V*}(k)$$
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Such analytical decomposition is <u>well motivated at threshold</u>.

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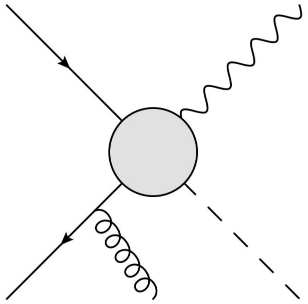
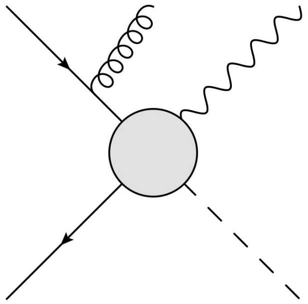
Such analytical decomposition is well motivated at threshold.

- QCD (& QED) gives distortions due to IR physics (Greljo)

e.g.  ,  , …

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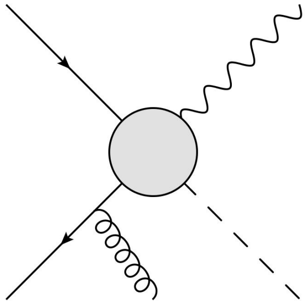
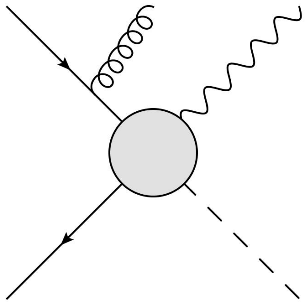
e.g.  ,  , …

- At high energy ⇒ kinematic deformation due to EW sector

Assumptions and approximations

Frame of the computation:

- Kinematic region:
  - on-shell external momenta
  - $S \sim T \sim U \sim E^2 \gg M_W^2$

- Retaining only double-logarithmic (DL) corrections (Sudakov double logarithms):

$$\log^2\left(\frac{S}{M^2}\right) , \qquad \log^2\left(\frac{T}{M^2}\right) , \qquad \log^2\left(\frac{U}{M^2}\right)$$

- Effective expansion parameter: $v/E \ll 1$

  Neglecting terms order $\mathcal{O}\left(v^2/E^2\right)$

  ↳ drawback: $\left(\frac{1}{P_Z(q^2)} \sim \frac{1}{P_W(q^2)} \sim \frac{1}{P_A(q^2)}\right) + \mathcal{O}\left(v^2/E^2\right)$

Brief outline of the computation

computation of DL contributions

Computation performed in a diagrammatic fashion:

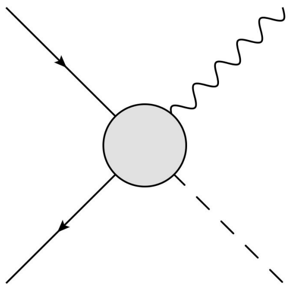
I. Determination of Feynman diagrams giving DL contributions

II. Derivation of a master formula for those Feynman diagrams

III. Careful computation of all contributions

computation of DL contributions

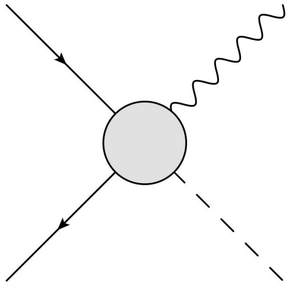
Tree-level process:



I. Which 1-loop diagrams give DLs? Pozzorini, hep-ph/0201077

Feynman gauge computation:

computation of DL contributions

Tree-level process: 

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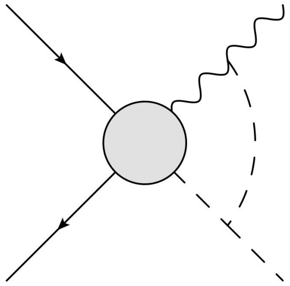
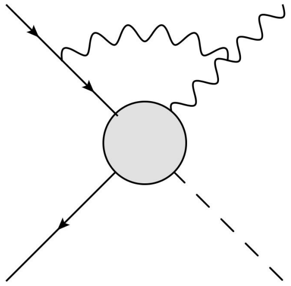
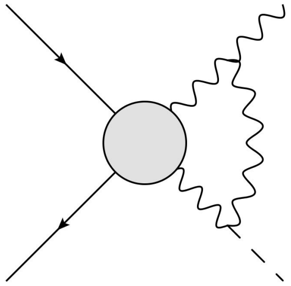
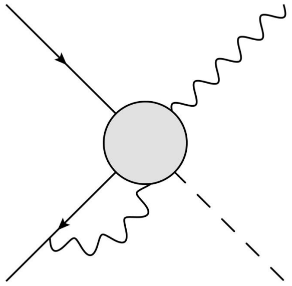
1. Topologies ⇒ particle exchange between external legs

e.g.  ,  ,  , … no: 

computation of DL contributions

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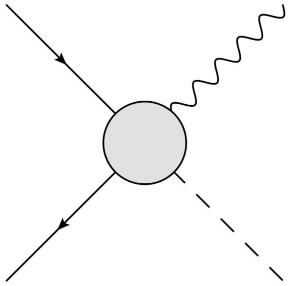

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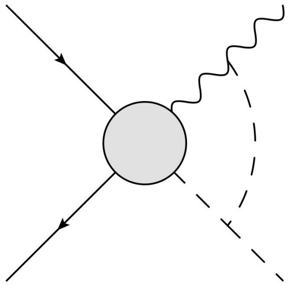
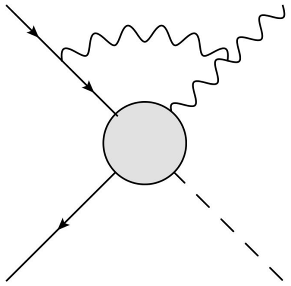
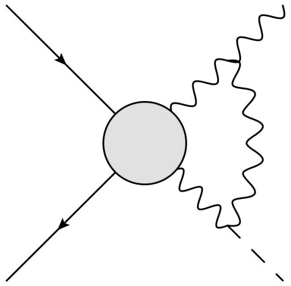
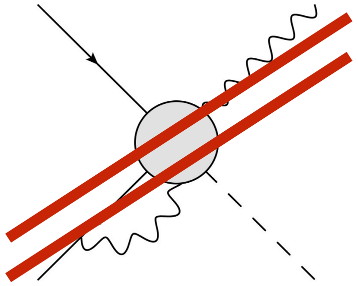
e.g.  ,  ,  , …   no: 

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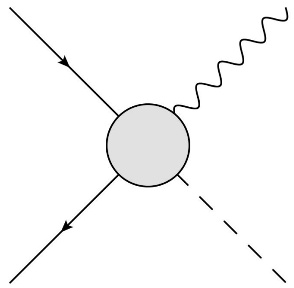

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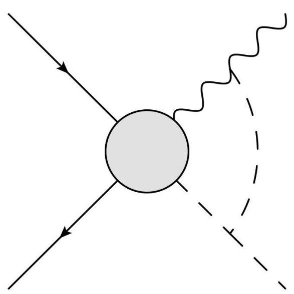
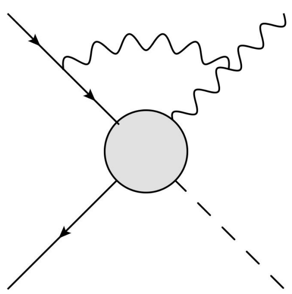
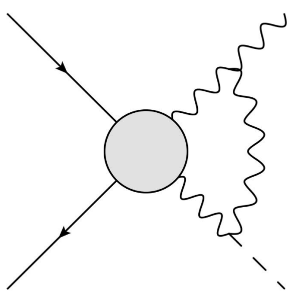
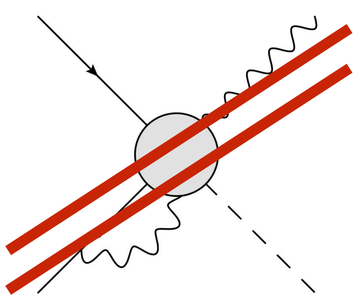
e.g.  ,  ,  , … no: 

2. Loop momentum ⇒ soft and collinear exchanged particle

computation of DL contributions

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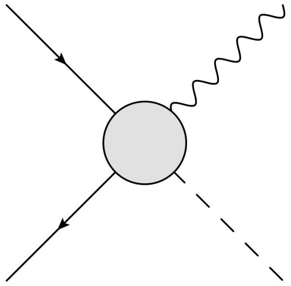

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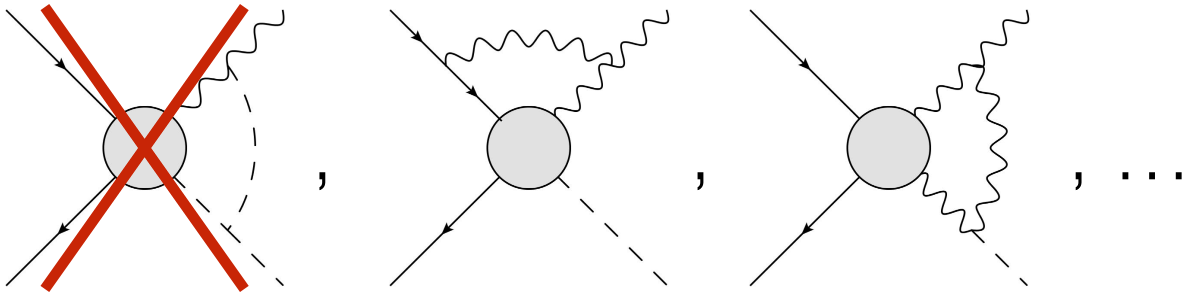
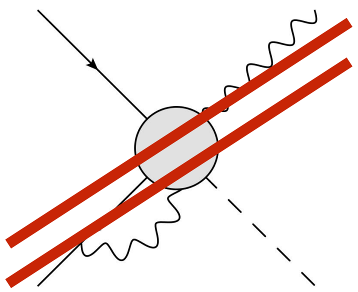


no:

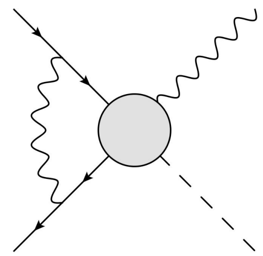
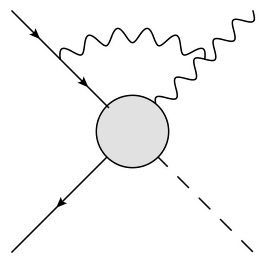
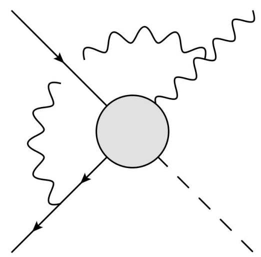
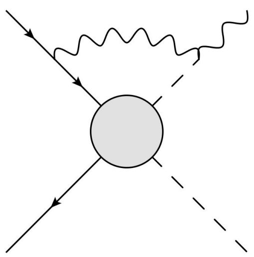
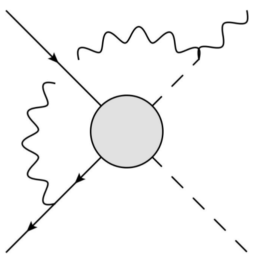
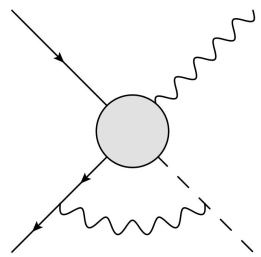
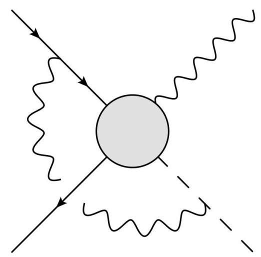
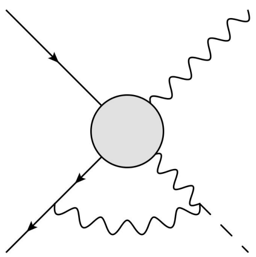
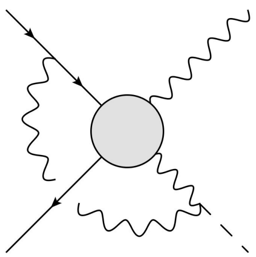
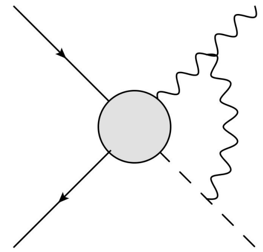
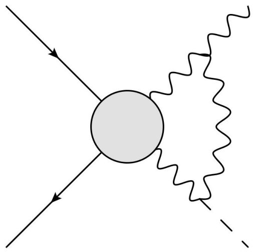
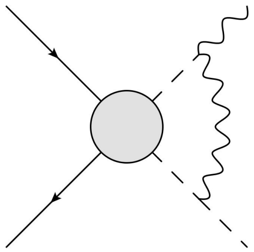


2. Loop momentum ⇒ soft and collinear exchanged particle

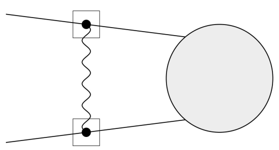
3. v/E expansion ⇒ exchanged particle: vector boson

computation of DL contributions

All possible topologies giving rise to DL mass singularities:

	A	B
I		$\emptyset$
II	1:  , 2: 	1:  , 2: 
III	1:  , 2: 	1:  , 2: 
IV		1:  , 2: 

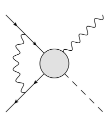
II. Master formula for DL contributions



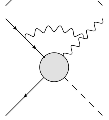
$$= \frac{1}{(4\pi)^2}\,\eta_{\mu\nu} R_i^\mu\, R_j^\nu\, \mathcal{M}_0 \left[-i\,(4\pi)^2 \int \frac{\mathrm{d}^d q}{(2\pi)^d} \frac{1}{D_i D_j D_V} \right]$$

$$= \frac{1}{(4\pi)^2}\,\eta_{\mu\nu} R_i^\mu\, R_j^\nu\, \mathcal{M}_0 \cdot \frac{1}{4\,p_i\!\cdot\! p_j} \mathrm{DL}(2\,p_i\!\cdot\! p_j, V, \varphi_i, \varphi_j) \quad .$$

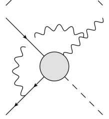
III. Careful computation of all contributions



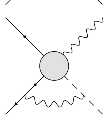
$$= \frac{\alpha}{4\pi}\, I^{\bar V_s}_{f_1' f_1} I^{V_s}_{\bar f_2' \bar f_2} \cdot \mathrm{DL}(S, V_s, f_1, f_2) \cdot \mathcal{M}_0^{f_1' \bar f_2' \bar V h} \ ,$$



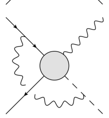
$$= \frac{\alpha}{4\pi}\, I^{\bar V_s}_{f_1' f_1} I^{V_s}_{\bar V' \bar V} \cdot \mathrm{DL}(T, V_s, f_1, V) \cdot \left(\mathcal{M}_0^{f_1' \bar f_2 \bar V' h} + \frac{p_1\!\cdot\!\epsilon_V}{T} k^\rho\, \mathcal{G}_{0\,\rho}^{f_1' \bar f_2 \bar V' h} \right) \ ,$$



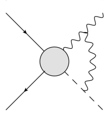
$$= \frac{\alpha}{4\pi}\, I^{\bar V_s}_{\bar f_2' \bar f_2} I^{V_s}_{\bar V' \bar V} \cdot \mathrm{DL}(U, V_s, f_2, V) \cdot \left(\mathcal{M}_0^{f_1 \bar f_2' \bar V' h} + \frac{p_2\!\cdot\!\epsilon_V}{U} k^\rho\, \mathcal{G}_{0\,\rho}^{f_1 \bar f_2' \bar V' h} \right) \ ,$$



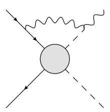
$$= \frac{\alpha}{4\pi}\, \kappa_{VV} I^{\bar V_s}_{\bar f_2' \bar f_2} I^{V}_{\phi_{V_s} h} \cdot \mathrm{DL}(T, V_s, f_2, h) \cdot \mathcal{M}_0^{f_1 \bar f_2' \bar V \phi_{V_s}} \ ,$$



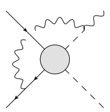
$$= \frac{\alpha}{4\pi}\, \kappa_{VV} I^{\bar V_s}_{f_1' f_1} I^{V}_{\phi_{V_s} h} \cdot \mathrm{DL}(U, V_s, f_1, h) \cdot \mathcal{M}_0^{f_1' \bar f_2 \bar V \phi_{V_s}} \ ,$$



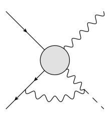
$$= \frac{\alpha}{4\pi}\, \kappa_{VV} I^{\bar V_s}_{\bar V' \bar V} I^{V_s}_{\phi_{V_s} h} \cdot \mathrm{DL}(S, V_s, V, h) \cdot \left(\mathcal{M}_0^{f_1 \bar f_2 \bar V' \phi_{V_s}} + \frac{p_h\!\cdot\!\epsilon_V}{S} k^\rho\, \mathcal{G}_{0\,\rho}^{f_1 \bar f_2 \bar V' \phi_{V_s}} \right) \ ,$$



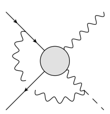
$$= -\frac{\alpha}{4\pi}\, e\, \Upsilon^{\phi'}_{V V_s} I^{\bar V_s}_{f_1' f_1}\, \frac{v}{T} \cdot \mathrm{DL}(T, V_s, f_1, V) \cdot p_1\!\cdot\!\epsilon_V\, \mathcal{M}_0^{f_1' \bar f_2 \bar\phi' h} \ ,$$



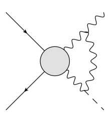
$$= -\frac{\alpha}{4\pi}\, e\, \Upsilon^{\phi'}_{V V_s} I^{\bar V_s}_{\bar f_1' \bar f_1}\, \frac{v}{U} \cdot \mathrm{DL}(U, V_s, f_2, V) \cdot p_2\!\cdot\!\epsilon_V\, \mathcal{M}_0^{f_1 \bar f_2' \bar\phi' h} \ ,$$



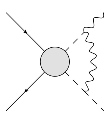
$$= \frac{\alpha}{4\pi}\, e\, \kappa_{V_s V_s} \Upsilon^{h}_{V_s V_s} I^{\bar V_s}_{\bar f_2' \bar f_2} \frac{v}{T} \cdot \mathrm{DL}(T, V_s, f_2, h) \cdot \epsilon_V^\mu\, p_2^\nu\, \mathcal{G}_{0\,\mu\nu}^{f_1 \bar f_2' \bar V V_s} \ ,$$



$$= \frac{\alpha}{4\pi}\, e\, \kappa_{V_s V_s} \Upsilon^{h}_{V_s V_s} I^{\bar V_s}_{f_1' f_1} \frac{v}{U} \cdot \mathrm{DL}(U, V_s, f_1, h) \cdot \epsilon_V^\mu\, p_1^\nu\, \mathcal{G}_{0\,\mu\nu}^{f_1' \bar f_2 \bar V V_s} \ ,$$



$$= \frac{\alpha}{4\pi}\, e\, \kappa_{V_s V_s}\, \Upsilon^{h}_{V_s V_s} I^{\bar V_s}_{V V'} \frac{v}{S} \cdot \mathrm{DL}(S, V_s, V, h) \cdot \left(\epsilon_V^\mu\, k^\nu - \frac{1}{2} \epsilon_V^\nu\, k^\mu \right) \mathcal{G}_{0\,\mu\nu}^{f_1 \bar f_2 \bar V' V_s} \ ,$$

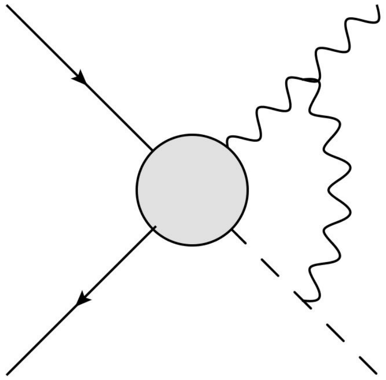


$$= -\frac{\alpha}{4\pi}\, e\, \kappa_{V_s V_s}\, \Upsilon^{\Phi'}_{V \bar V_s}\, I^{V_s}_{\bar\phi'' h} \frac{v}{S} \cdot \mathrm{DL}(S, V_s, V, h) \cdot p_h\!\cdot\!\epsilon_V \mathcal{M}_0^{f_1 \bar f_2 \bar\Phi' \bar\phi''} \ .$$

POs and loop computations

use of PO parametrisation into a loop computation?

is it consistent?



POs and loop computations

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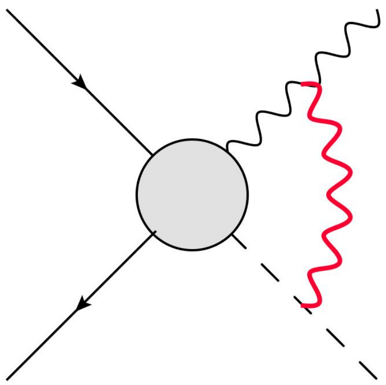


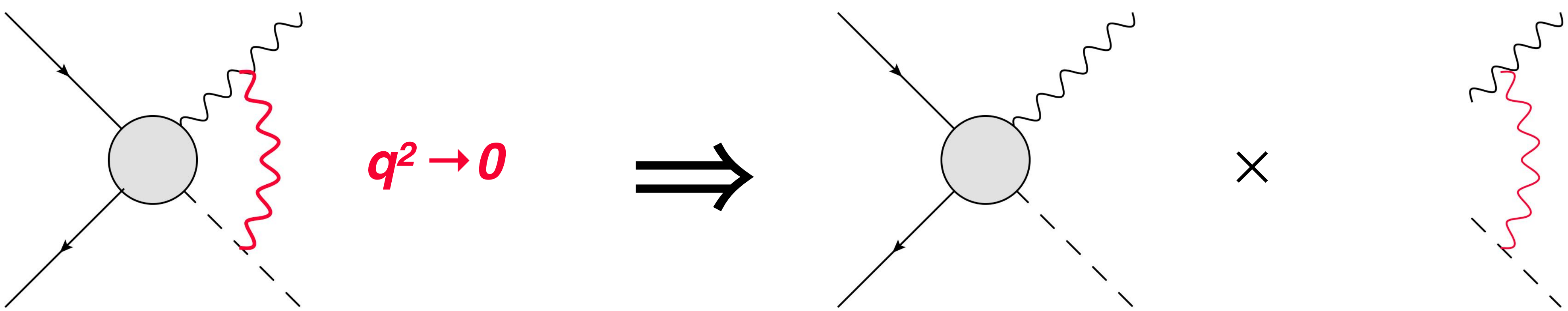
$q^2 \to 0$

loop + soft q^μ

POs and loop computations

use of PO parametrisation into a loop computation?

is it consistent?



loop + soft q^μ $\Rightarrow$ on-shell VH production $\times$ soft re-scattering

POs and loop computations

use of PO parametrisation into a loop computation?

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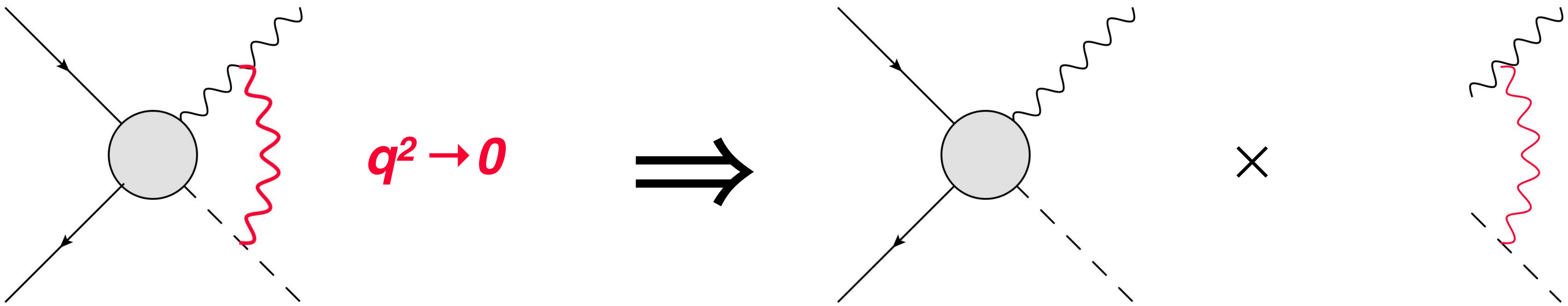

loop + soft q^μ $\Rightarrow$ on-shell VH production $\times$ soft re-scattering

on-shell VH production	soft re-scattering
PO parametrisation	master formula for DLs

Results

results

$$\mathcal{A}\left(f_1(p_1)\bar{f}_2(p_2) \to V(k)h(p)\right) = 2\,i\,\frac{M_V^2}{v}\,\bar{f}_2(p_2)\gamma_\nu f_1(p_1)\epsilon_\mu^{V*}(k)$$
$$\times\left[F_L^{f_1 f_2 V}(q^2)\eta^{\mu\nu} + F_T^{f_1 f_2 V}(q^2)\frac{q^\mu k^\nu - (q\cdot k)\eta^{\mu\nu}}{M_V^2} + F_{CP}^{f_1 f_2 V}(q^2)\frac{\epsilon^{\mu\nu\alpha\beta}q_\alpha k_\beta}{M_V^2}\right]$$

- **Longitudinal:** $F_L^{f_1 f_2 V}(q^2) = \kappa_{VV}\frac{g_V^{f_1\bar{f}_2}}{P_V(q^2)} + \frac{\epsilon_V^{f_1 f_2}}{M_V^2}\,,$
- **Transverse:** $F_T^{f_1 f_2 V}(q^2) = \epsilon_{VV}\frac{g_V^{f_1\bar{f}_2}}{P_V(q^2)} + \delta_{VZ}\,\epsilon_{Z\gamma}\frac{e\,Q_{f_1}}{q^2}\,,$
- **CP-odd:** $F_{CP}^{f_1 f_2 V}(q^2) = \epsilon_{VV}^{CP}\frac{g_V^{f_1\bar{f}_2}}{P_V(q^2)} - \delta_{VZ}\,\epsilon_{Z\gamma}^{CP}\frac{e\,Q_{f_1}}{q^2}\,,$

κ_{ZZ}, κ_{WW} $\epsilon_Z^{f_1 f_2}$, $\epsilon_W^{f_1 f_2}$

ϵ_{ZZ}, ϵ_{WW}, $\epsilon_{Z\gamma}$

ϵ_{ZZ}^{CP}, ϵ_{WW}^{CP}, $\epsilon_{Z\gamma}^{CP}$

$$\mathcal{A}\left(f_1(p_1)\bar{f}_2(p_2) \to V(k)h(p)\right) = 2\,i\,\frac{M_V^2}{v}\,\bar{f}_2(p_2)\gamma_\nu f_1(p_1)\epsilon_\mu^{V*}(k)$$
$$\times\left[F_L^{f_1 f_2 V}(q^2)\eta^{\mu\nu} + F_T^{f_1 f_2 V}(q^2)\frac{q^\mu k^\nu - (q\cdot k)\eta^{\mu\nu}}{M_V^2} + F_{CP}^{f_1 f_2 V}(q^2)\frac{\epsilon^{\mu\nu\alpha\beta}q_\alpha k_\beta}{M_V^2}\right]$$

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- **Transverse:** $F_T^{f_1 f_2 V}(q^2) = \epsilon_{VV}\frac{g_V^{f_1\bar{f}_2}}{P_V(q^2)} + \delta_{VZ}\,\epsilon_{Z\gamma}\frac{e\,Q_{f_1}}{q^2}$,
- **CP-odd:** $F_{CP}^{f_1 f_2 V}(q^2) = \epsilon_{VV}^{CP}\frac{g_V^{f_1\bar{f}_2}}{P_V(q^2)} - \delta_{VZ}\,\epsilon_{Z\gamma}^{CP}\frac{e\,Q_{f_1}}{q^2}$,

κ_{ZZ}, κ_{WW} | $\epsilon_Z^{f_1 f_2}$, $\epsilon_W^{f_1 f_2}$

ϵ_{ZZ}, ϵ_{WW}, $\epsilon_{Z\gamma}$

ϵ_{ZZ}^{CP}, ϵ_{WW}^{CP}, $\epsilon_{Z\gamma}^{CP}$

EW corrections mix POs among themselves

But only within the same “class” (same tensor and pole structure)

results

$$\mathcal{A}\left(f_1(p_1)\bar{f}_2(p_2) \to V(k)h(p)\right) = 2\,i\,\frac{M_V^2}{v}\,\bar{f}_2(p_2)\gamma_\nu f_1(p_1)\epsilon_\mu^{V*}(k)$$
$$\times\left[F_L^{f_1 f_2 V}(q^2)\eta^{\mu\nu} + F_T^{f_1 f_2 V}(q^2)\frac{q^\mu k^\nu - (q\cdot k)\eta^{\mu\nu}}{M_V^2} + F_{CP}^{f_1 f_2 V}(q^2)\frac{\epsilon^{\mu\nu\alpha\beta}q_\alpha k_\beta}{M_V^2}\right]$$

- **Longitudinal:** $F_L^{f_1 f_2 V}(q^2) = \kappa_{VV}\frac{g_V^{f_1 \bar{f}_2}}{P_V(q^2)} + \frac{\epsilon_V^{f_1 f_2}}{M_V^2}\,,$
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$\kappa_{ZZ},\ \kappa_{WW}$ $\quad$ $\epsilon_Z^{f_1 f_2},\ \epsilon_W^{f_1 f_2}$

$\epsilon_{ZZ},\ \epsilon_{WW},\ \epsilon_{Z\gamma}$

$\epsilon_{ZZ}^{CP},\ \epsilon_{WW}^{CP},\ \epsilon_{Z\gamma}^{CP}$

EW corrections mix POs among themselves

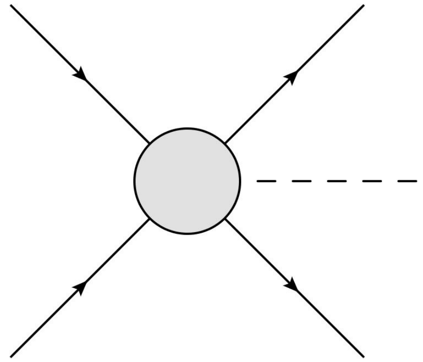
But only within the same “class” (same tensor and pole structure)

e.g:

$$\kappa_{ZZ} \to \kappa_{ZZ} + \frac{\alpha}{\pi}\left[\kappa_{ZZ}\left((\dots)\log^2\frac{S}{M_Z^2} + \dots\right) + \kappa_{WW}\left((\dots)\log^2\frac{S}{M_W^2} + \dots\right)\right]\,,$$
$$\epsilon_{ZZ} \to \epsilon_{ZZ} + \frac{\alpha}{\pi}\left[\epsilon_{ZZ}\left((\dots)\log^2\frac{S}{M_Z^2} + \dots\right) + \epsilon_{WW}\left((\dots)\log^2\frac{S}{M_W^2} + \dots\right) + \epsilon_{Z\gamma}(\dots)\right]\,,$$

Future perspectives

- Montecarlo simulations of the impact of such DL EW corrections
- Inclusion of these corrections into the PO tool
- Extension of the computation to other interesting processes (e.g. vector boson fusion)



Conclusions

- NLO EW corrections can be sizeable when far from threshold
- Computation of relevant loop EW correction (i.e. DLs) can be consistently performed within the PO framework
- Those corrections introduce a mixing between POs, but a very contained and reasonable one
- Study of EW corrections will be pushed further and could be also extended to other processes