Higgs-strahlung at the LHC in the inert doublet model: Full NLO EW and QCD corrections

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Higgs 2023

Outline

The inert doublet model(IDM) Lagrangian[**Deshpande:1977rw**]:

$$\mathcal{L}_{IDM}^{\text{scalar}} = (D^\mu \Phi_1)^\dagger D_\mu \Phi_1 + (D^\mu \Phi_2)^\dagger D_\mu \Phi_2 - V_{\text{IDM}}(\Phi_1, \Phi_2)$$

The interaction potential: **discrete $\mathbb{Z}_2$ symmetry**

$$\begin{aligned} V_{\text{IDM}}(\Phi_1, \Phi_2) = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 \\ + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right] \end{aligned} \quad (1)$$

Two Higgs doublets:

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix} \quad \text{and} \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(X + iA) \end{pmatrix}$$

DM candidate:

Φ_2 not couple to SM fermions $\Rightarrow$ Stable **DM** candidate: **X**

The relations between original and physical parameters:

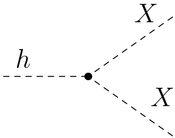
$$\lambda_1 = \frac{M_h^2}{2v^2}, \qquad \lambda_5 = \frac{M_X^2 - M_A^2}{v^2},$$

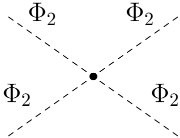
$$\lambda_4 = \lambda_5 + 2\frac{M_A^2 - M_{H^\pm}^2}{v^2}, \qquad \lambda_L = \frac{2(M_X^2 - \mu_2^2)}{v^2}$$

$$\lambda_3 = \lambda_L - \lambda_4 - \lambda_5, \qquad \mu_2^2 = M_X^2 - \lambda_L \frac{v^2}{2}.$$

Independent parameters(physical):

$$\left\{ M_X,\ M_A,\ M_{H^\pm},\ \lambda_L(\text{h-X-X}),\ \lambda_2(|\Phi_2|^4) \right\}$$

λ_L :


λ_2 :


1) Theoretical constraints:

- Perturbativity
- Vacuum Stability
- Unitarity

2) Collider constraints:

- Direct search from LEP
- Diphoton signatures
- Invisible Higgs decay
- Electroweak Precision Observables
- Direct search at the LHC

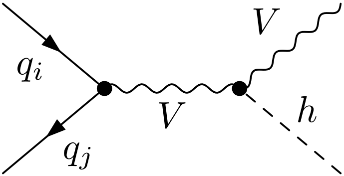
	M_X(GeV)	M_A(GeV)	$M_{H^\pm}$(GeV)	λ_L	(λ_3, λ_A)
BP0	70	571	571	1	(11.61,11.61)
BP1	500	500	500	7.07692	(7.08,7.08)
BP2	220	320	320	2.30769	(4.09,4.09)

3) Dark matter constraints:

- Dark matter Relic Density, $0.096 < \Omega h^2 < 0.144$.
- Dark matter direct detection, $|\lambda_L| \times 10^3 < 6 \times (M_X/100\ \text{GeV})^{3/2}$.

	M_X(GeV)	M_A(GeV)	$M_{H^\pm}$(GeV)	$\lambda_L(10^{-3})$	(λ_3, λ_A)
BP3	59	113	123	1.0	(0.38, 031)
BP4	60	68	150	0.0	(0.62,0.03)
BP5	550	551	552	19.3	(0.09,0.06)

- Gluon-gluon fusion, VBF, Higgs-strahlung
- The tree-level (parton level): pure SM

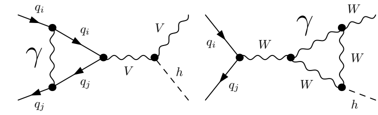


where $q_i, q_j = u, d, s, c, b$ in five flavor scheme.

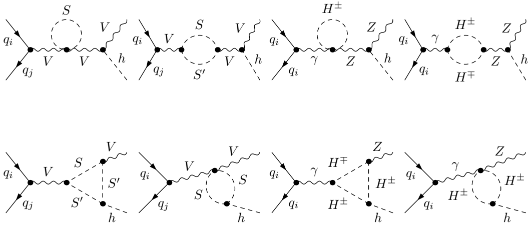
- New physics effects at NLO.
- NLO QCD corrections are SM **[Ciccolini:2003jy, Denner:2011id]**.

Higgs-strahlung at LHC
$\hookrightarrow$ NLO EW corrections

- Virtual photon exchange (UV and IR)



- Virtual corrections of $S = A, X, H^{\pm}$ (UV)



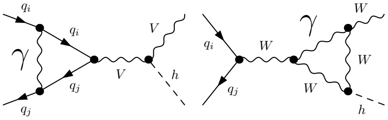
The G_μ-scheme for electric charge e, [Denner:1991kt]

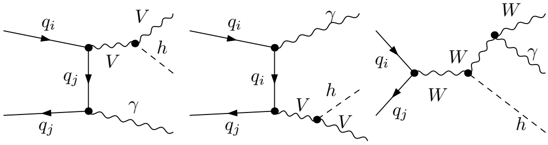
$$\delta Z_e^{G_\mu} = \delta Z_e^{\alpha(0)} - \frac{1}{2}\triangle r. \quad (2)$$

Cancelled the UV singularities:

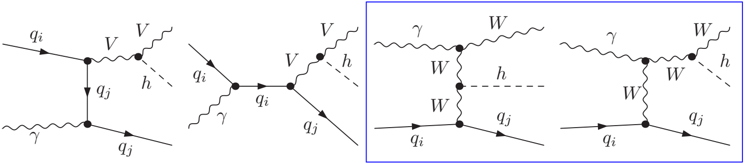
$$\sigma^{\text{nlo}}_{\text{UV-finite}}\left(\frac{1}{\epsilon_{IR}^2}, \frac{1}{\epsilon_{IR}}\right) = \sigma_{\text{V}}\left(\frac{1}{\epsilon_{IR}^2}, \frac{1}{\epsilon_{IR}}, \frac{1}{\epsilon_{\text{UV}}}\right) + \sigma_{\text{VC}}\left(\frac{1}{\epsilon_{\text{UV}}}\right).$$

- Virtual corrections(IR)
- Real photon radiation (IR)





- γ-induced corrections (collinear singularities)



Subtracting the IR singularities

1): Two cutoff phase space slicing **2):Dipole subtraction**

- Two cutoff phase space slicing(TCPSS, δ_s, δ_c) **[Harris:2001sx]**:

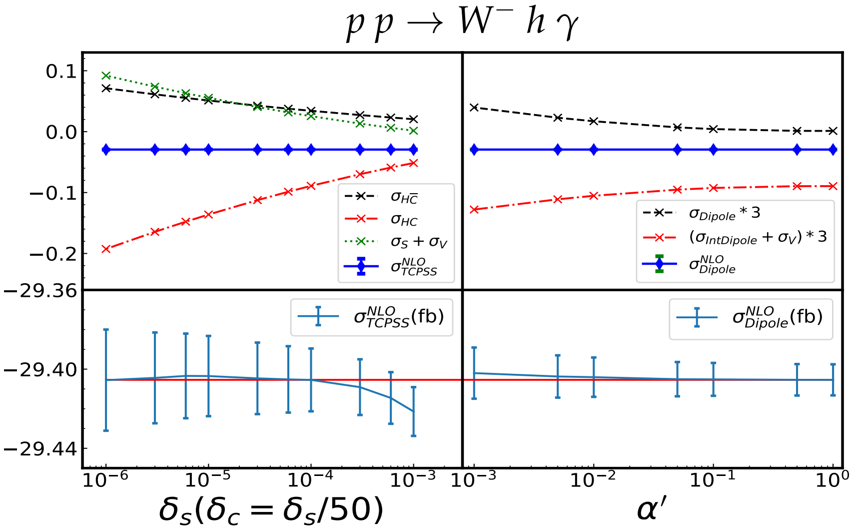
$$\sigma^{\text{TCPSS}}_{\text{IR-Finite}} = \sigma_{\text{V}}(\frac{1}{\epsilon_{\text{IR}}}, \frac{1}{\epsilon^2_{\text{IR}}}) + \sigma_{\text{S}}(\delta_s, \frac{1}{\epsilon_{\text{IR}}}, \frac{1}{\epsilon^2_{\text{IR}}}) + \sigma_{\text{coll}}(\delta_s, \delta_c, \frac{1}{\epsilon_{\text{IR}}}) + \sigma_{\text{H}\overline{\text{C}}}(\delta_s, \delta_c)$$

- Dipole subtraction(DS) **[Catani:1996jh]**:

$$\sigma^{\text{DS}}_{\text{IR-Finite}} = \int_3 \underbrace{\left[d\sigma_R - d\sigma^A\right]}_{d\sigma_{\text{Dipole}}} + \int_2 \left[d\sigma_V + \underbrace{\int_1 d\sigma^A}_{d\sigma_{\text{IntDipole}}}\right]$$

$$= \sigma_{\text{Dipole}}(\alpha') + \left[\sigma_V(\frac{1}{\epsilon_{\text{IR}}}, \frac{1}{\epsilon^2_{\text{IR}}}) + \sigma_{\text{IntDipole}}(\alpha', \frac{1}{\epsilon_{\text{IR}}}, \frac{1}{\epsilon^2_{\text{IR}}})\right].$$

- Results checking:



SloopS

NLO model

Lanhep

FeynArts
FormCalc

Fortran Code(UV counter terms)

- **Virtual**
  1. UV singlarity
  2. **Loop function**
     - ✓ LoopTools
     - ✓ LT_modified
     - ✓ Collier
  3. IR singularity

     DR: $\frac{1}{\varepsilon_{IR}^2} + \frac{1}{\varepsilon_{IR}}$
     or
     MR: $\mathrm{Log}(\lambda_{\gamma/g})$

     1): DS
     2): TCPSS
- **Real**
  1. Soft singularity
  2. Coll singularity

NLO Results

The cross checking between Madgraph and SloopS:

		Madgraph	SloopS
Zh	LO	0.6021(5)	0.6022(1)
	NLO(QCD)	0.825(2)	0.824(1)
W^-h	LO	0.4282(4)	0.4283(1)
	NLO(QCD)	0.528(2)	0.5279(2)
W^+h	LO	0.6803(6)	0.6804(2)
	NLO(QCD)	0.839(3)	0.8420(4)
H^+H^-	LO	0.00800(2)	0.007996(3)
	NLO(QCD)	0.00930(2)	0.009338(4)

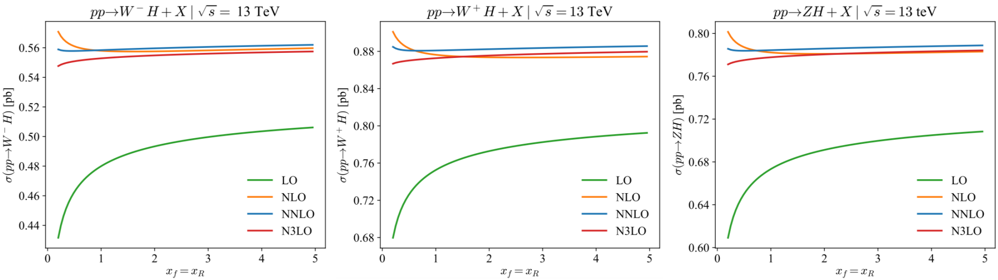
More things:

https://lapth.cnrs.fr/projects/PrecisionCalculations/idm_at_1loop

Arxiv:1906.11269, 2101.02165, 2101.02166, 2101.02167, 2101.02170

Higgs-strahlung at LHC
$\hookrightarrow$ The choice of scales

The **[Baglio:2022wzu]** given the N^{3}LO QCD corrections results for Higgs-strahlung in SM



The NLO QCD corrections can reach the accuracy of N^{3}LO when $x > 2$, especially for Zh production.

The default renormalization and factorisation scales

$$\mu_R = \mu_F = 2 * (M_V + M_h)$$

The contributions of γ-induced:

		13 TeV(pb)			14 TeV(pb)		
		$\sigma_{\rm EW}^{\rm SM\,\prime}(\Delta_{\rm EW}^{\rm SM\,\prime})$	$\sigma_{\gamma-\rm induced}^{\rm SM}(\Delta_{\gamma}^{\rm SM})$	$\sigma_{\rm EW}^{\rm SM}(\Delta_{\rm EW}^{\rm SM})$	$\sigma_{\rm EW}^{\rm SM\,\prime}(\Delta_{\rm EW}^{\rm SM\,\prime})$	$\sigma_{\gamma-\rm induced}^{\rm SM}(\Delta_{\gamma}^{\rm SM})$	$\sigma_{\rm EW}^{\rm SM}(\Delta_{\rm EW}^{\rm SM})$
SM	Zh	0.6140 (-4.92%)	-$\mathcal{O}(10^{-5})$	0.6139 (-4.93%)	0.6915 (-4.93%)	-$\mathcal{O}(10^{-5})$	0.6814 (-4.94%)
	W^-h	0.4304 (-6.40%)	0.02080 (4.52%)	0.4512 (-1.87%)	0.4798 (-6.42%)	0.02430 (4.74%)	0.5041 (-1.69%)
	W^+h	0.6802 (-6.56%)	0.03251 (4.47%)	0.7127 (-2.10%)	0.7484 (-6.58%)	0.03755 (4.69%)	0.7860 (-1.89%)

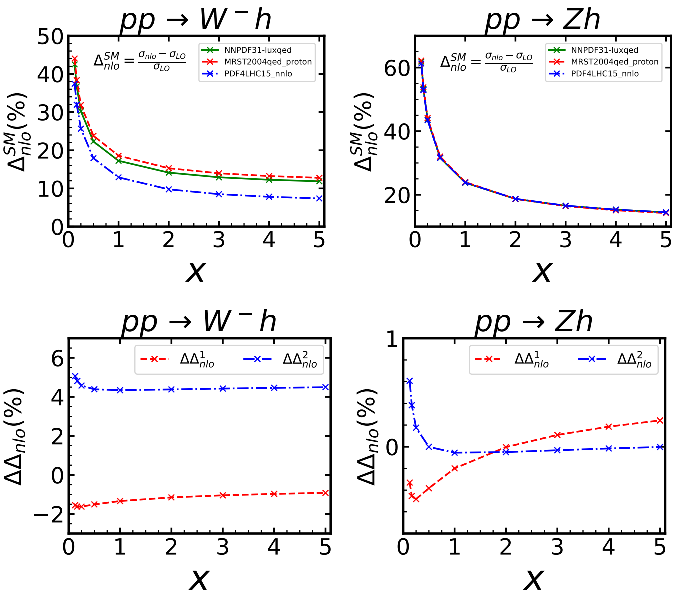
	$P_T^W = 20$ GeV	$P_T^W = 100$ GeV	$P_T^W = 200$ GeV	$P_T^W = 240$ GeV
W^-h	$\sim 4.5\%$	$\sim 2.3\%$	$\sim 0.9\%$	$\sim 0.7\%$
W^+h	$\sim 4.5\%$	$\sim 2.3\%$	$\sim 1\%$	$\sim 0.8\%$

Table: The results of NLO EW corrections.

Three PDF sets:

- NNPDF31-luxqed
- MRST2004qed
- PDF4LHC15_nnlo

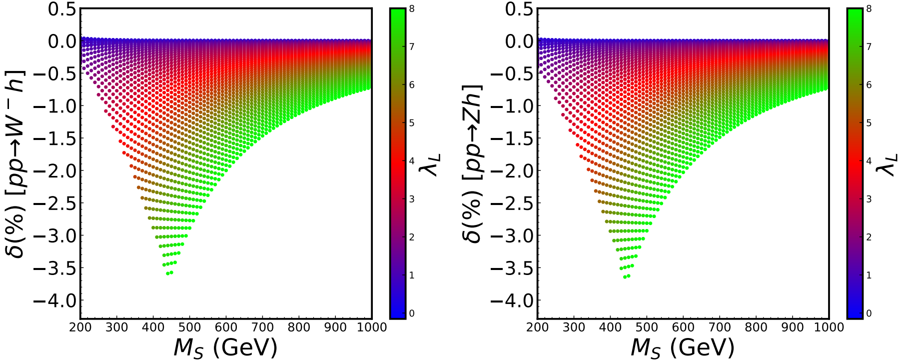
PDFs Uncertainty $\sim 2\%$



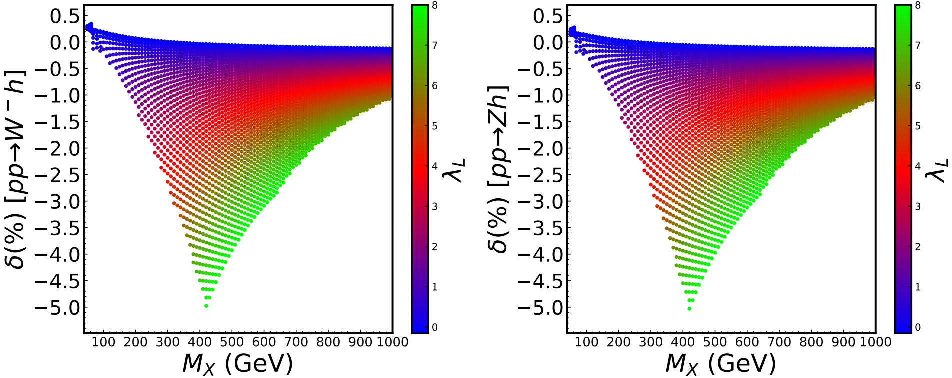
The K-factor for new physics corrections

$$\delta = \frac{\sigma^{NLO}_{IDM} - \sigma^{NLO}_{SM}}{\sigma^{LO}_{SM}} \times 100\% = \frac{\sigma^{virt-EW}_{IDM} - \sigma^{virt-EW}_{SM}}{\sigma^{LO}_{SM}} \times 100\%.$$

- $M_X = M_A = M_{H^\pm} = M_S$, full degenerate masses of new scalars



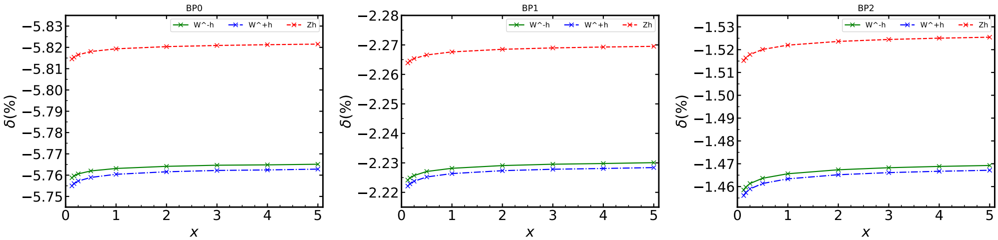
- $\Delta M = M_A - M_X = 100$ GeV with $M_A = M_{H^\pm}$, X is lightest neutral scalar



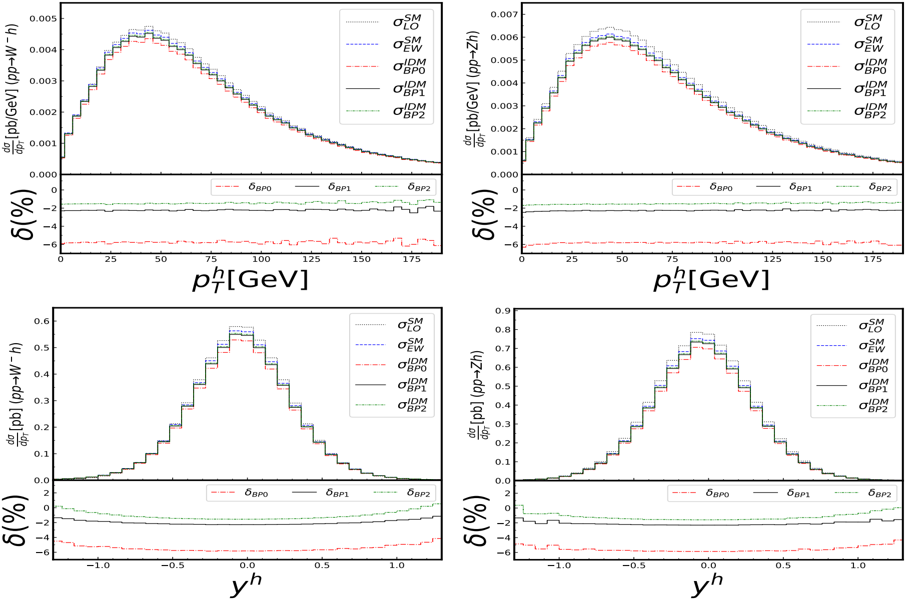
- The results of NLO corrections, scale dependence and distributions for BP0, BP1 and BP2

Numerical results
↪ Results without DM constraints

14 TeV	$pp \to Vh$	σ_{LO} (pb)	$\Delta_{EW}(\%)$	$\delta(\%)$
BP0	Zh	0.7168(2)	-10.8	-5.81
	W^-h	0.5127(3)	-7.44	-5.76
	W^+h	0.8011(5)	-7.65	-5.76
BP1	Zh	0.7168(2)	-7.21	-2.27
	W^-h	0.5127(3)	-3.90	-2.23
	W^+h	0.8011(5)	-4.12	-2.23
BP2	Zh	0.7168(2)	-6.47	-1.52
	W^-h	0.5127(3)	-3.14	-1.47
	W^+h	0.8011(5)	-3.35	-1.46



Numerical results
↪ Results without DM constraints



The results with the DM constraints(BP3-5):

14 TeV	$pp \to Vh$	$\sigma_{\rm EW}^{\rm IDM}$(pb)	$\sigma_{\rm NLO}^{\rm IDM}$ (pb)	$\Delta_{EW}(\%)$	$\delta(\%)$
BP3	Zh	0.6819(2)	0.8516(4)	-4.87	0.07
	W^-h	0.5051(1)	0.5850(2)	-1.48	0.20
	W^+h	0.7875(2)	0.9179(5)	-1.70	0.19
BP4	Zh	0.6814(2)	0.8510(4)	-4.95	$\mathcal{O}(10^{-3})$
	W^-h	0.5059(1)	0.5857(2)	-1.33	0.35
	W^+h	0.7887(2)	0.9191(5)	-1.55	0.34
BP5	Zh	0.6814(2)	0.8510(4)	-4.95	-$\mathcal{O}(10^{-3})$
	W^-h	0.5041(1)	0.5840(2)	-1.68	-$\mathcal{O}(10^{-3})$
	W^+h	0.7859(2)	0.9164(5)	-1.89	-$\mathcal{O}(10^{-3})$

New Physics (δ) smaller than PDFs uncertainty ($\sim$ 2%)

Summary

- The DS and TCPSS have been implemented in `SloopS` Framework.
- The γ-induced has a significant contribution for Wh production.
- In the Higgs-strahlung process, the IDM has a significant new physics effects for collider, but we need more depth exploration for DM.
- Outlook
  - Calculating the NLO corrections for the new scalars pair productions at LHC, especially for H^+H^-.
  - We are planning a full automation for BSM NLO calculations `SloopS`.

Thanks

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- A. Denner, S. Dittmaier, S. Kallweit and A. Muck, JHEP **03** (2012), 075 doi:10.1007/JHEP03(2012)075 [arXiv:1112.5142 [hep-ph]].
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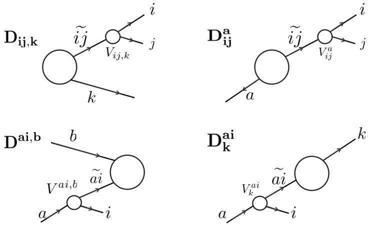
- S. Catani and M. H. Seymour, Phys. Lett. B **378** (1996), 287-301 doi:10.1016/0370-2693(96)00425-X [arXiv:hep-ph/9602277 [hep-ph]].
- J. Baglio, C. Duhr, B. Mistlberger and R. Szafron, JHEP **12** (2022), 066 doi:10.1007/JHEP12(2022)066 [arXiv:2209.06138 [hep-ph]].

For the radiation processes, the NLO cross section

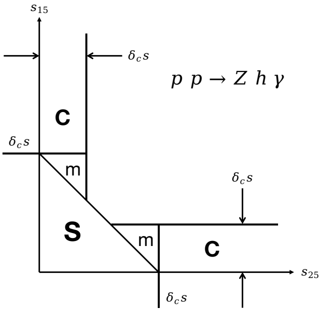
$$\sigma^{\mathrm{DS}}_{\text{IR-Finite}} = \sigma_R + \sigma_V = \int_3 \underbrace{\left[d\sigma_R - d\sigma^A\right]}_{d\sigma_{\mathrm{Dipole}}} + \int_2 \left[d\sigma_V + \underbrace{\int_1 d\sigma^A}_{d\sigma_{\mathrm{IntDipole}}}\right]$$
$$= \left[\sigma_V\left(\frac{1}{\epsilon_{\mathrm{IR}}}, \frac{1}{\epsilon^2_{\mathrm{IR}}}\right) + \sigma_{\mathrm{IntDipole}}\left(\alpha', \frac{1}{\epsilon_{\mathrm{IR}}}, \frac{1}{\epsilon^2_{\mathrm{IR}}}\right)\right] + \sigma_{\mathrm{Dipole}}(\alpha'). \quad (3)$$



- $d\sigma^A$ works as a local counterterm, implying that the subtraction occurs at the amplitude squared level.
- $$d\sigma^A = \sum_{\text{dipoles}} d\sigma^0 \otimes dV_{\text{dipole}}.$$

The dV_{dipole} are dipole factors which are **independent of process**, while **depend on the types of splitting**.

Cuts : δ_s and δ_c



- **Soft Region:** $0 < E_\gamma < E_{\min} = \delta_s\sqrt{s}/2$

$$d\sigma_S = d\sigma^0 \times \delta_{\text{soft}} \sim \frac{1}{\epsilon_{IR}^2} + \frac{1}{\epsilon_{IR}} + \text{Finite} + \mathcal{O}(\epsilon_{IR})$$

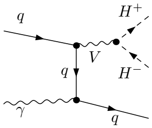
- **HC:** $E_\gamma > E_{\min},\ (s_{15}, s_{25}) < \delta_c s; s_{ij} = (p_i + p_j)^2$
  In this region, the collinear singularities are absorbed into PDFs.
- **H$\overline{\text{C}}$:** $E_\gamma > E_{\min},\ (s_{15}, s_{25}) > \delta_c s$
  Making Monte-Carlo integration in $d = 4$, directly.

Slicing the phase space by two cuts (δ_s, δ_c)

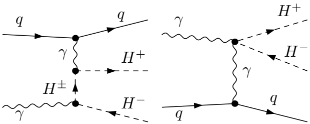
$$\sigma^{\text{TCPSS}}_{\text{IR-Finite}} = \sigma_V\left(\frac{1}{\epsilon_{\text{IR}}}, \frac{1}{\epsilon^2_{\text{IR}}}\right) + \sigma_S\left(\delta_s, \frac{1}{\epsilon_{\text{IR}}}, \frac{1}{\epsilon^2_{\text{IR}}}\right) + \sigma_{\text{coll}}\left(\delta_s, \delta_c, \frac{1}{\epsilon_{\text{IR}}}\right) + \sigma_{\text{H}\overline{\text{C}}}(\delta_s, \delta_c)$$

The γ-induced contributions for production of charged Higgs pair:

1):



2):



There are two splitting types and born process

- 1): $\gamma \to q + q;\ qq \to H^{\pm}H^{\mp}$
- 2): $q \to \gamma + q;\ \gamma\gamma \to H^{\pm}H^{\mp}$

The counter term $d\sigma^{A}$ in DS scheme

$$d\sigma^{A} = d\sigma_{qq\to H^{\pm}H^{\mp}}(p^2)\cdot V_{\gamma\to q+q}(p^2) + d\sigma_{\gamma\gamma\to H^{\pm}H^{\mp}}\left(g^{\mu\nu}, p^{\mu}p^{\nu}\right)\cdot V_{q\to\gamma+q}\left(g^{\mu\nu}, p^{\mu}p^{\nu}\right)$$