Subleading effects for future lepton colliders

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Introduction

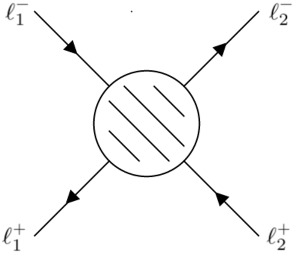
Goal

NLO precision calculation of a leptonic scattering process

$$\ell_1^- \ell_1^+ \to \ell_2^- \ell_2^+$$

Motivation

- Future lepton colliders opens new energy-regimes
- Experimentally easily accessible process
- Able to polarize initial particles $\to$ effects?



Introduction

Problem

- Elementary particles not gauge-invariant
- Fundamental requirement in order to represent measurable quantities
- Strong agreement between standard perturbation and experiments

Question

Why does the usual approach work so well?

Introduction

Solution

1. Start with a gauge-invariant (GI) description of particles, combine fermions with Higgs field h
   $\ell^{\pm} \to L^{\pm} = h\ell^{\pm}$
2. Fröhlich-Morchio-Strocchi (FMS) mechanism relates quantities of GI particles to perturbation theory[1][2][3]
   $L^{\pm} \xrightarrow{FMS} \ell^{\pm}$
3. LO contribution equal to regular calculations
   $\langle L^{\pm}...\rangle = \langle \ell^{\pm}...\rangle +$ Higher orders

[1] Fröhlich, Morchio, and Strocchi 1980
[2] For a review see Maas 2019
[3] For the lepton composite-operator see Afferrante et al. 2021

Introduction

Our initial process

1. Use four-point function of composite electron-positron scattering to muon-antimuon[4]
$\langle E^- E^+ M^- M^+ \rangle$

2. FMS expansion in elementary e, μ and h
$\langle E^- E^+ M^- M^+ \rangle = \langle e^- e^+ \mu^- \mu^+ \rangle + \langle h e^- e^+ \mu^- \mu^+ \rangle + \dots$

3. Leads to additional contributions in the (differential) cross section

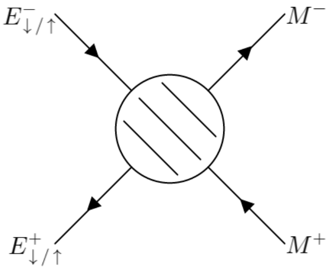
4. Effects of GI approach are compatible with data so far, but...

[4]Egger, Maas, and Sondenheimer 2017

Introduction

Central questions

- Are the additional contributions relevant in high-energy collisions?
- Can better precision in low-energy results resolve these contributions?
- How are different initial helicity configurations affected?



Research

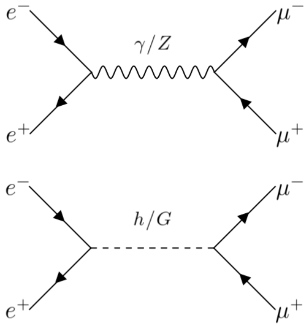
Approach

- Calculate (differential) cross section from standard matrix elements $\mathcal{M}_S$ up to NLO for inital states $E^-E^+,\ E^-_\uparrow E^+_\uparrow, E^-_\uparrow E^+_\downarrow\ ... \rightarrow M^-M^+$
- Include contributions from the GI approach $d\sigma_{FMS} \propto |\mathcal{M}_S + \mathcal{M}_{FMS}|^2$
- Compare results between both approaches $\frac{d\sigma_{FMS}}{d\sigma} \propto 1 + \frac{2Re(\mathcal{M}_S\mathcal{M}^*_{FMS})}{|\mathcal{M}_S|^2} + \frac{|\mathcal{M}_{FMS}|^2}{|\mathcal{M}_S|^2}$

Tree-level

Results

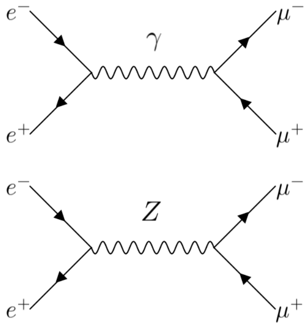
- Four contributions to the tree-level cross sections
  $d\sigma \propto |\mathcal{M}_\gamma + \mathcal{M}_Z + \mathcal{M}_h + \mathcal{M}_G|^2$
- No effects from the FMS approach
  $d\sigma_{FMS} = d\sigma$
- γ and Z main contributions



Tree-level

Results

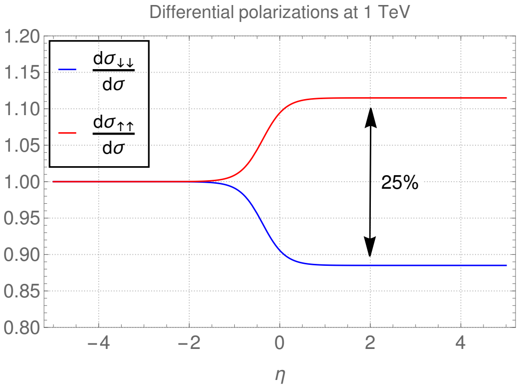
- External masses can be neglected
- For massless external particles only helicity configurations $e^-_\downarrow e^+_\downarrow$ and $e^-_\uparrow e^+_\uparrow$ survive
- Scalar effects vanish as Yukawa-coupling $\propto m_{e/\mu}$
- Compare different initial helicity cross sections $d\sigma_{\downarrow\downarrow}$ and $d\sigma_{\uparrow\uparrow}$



Tree-level

Highlights

- Polarization effects remain visible at high energies
- Helicity most relevant for forward-scattering



One-loop level

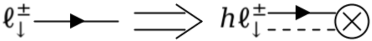
First remarks

- FMS terms couple for massless external states only to fields with negative helicity $L^{\pm}_{\downarrow} = h\ell^{\pm}_{\downarrow}, L^{\pm}_{\uparrow} = \ell^{\pm}_{\uparrow}$
- Leads to matrix elements with up to four additional Higgs contributions $\rightarrow$ 16 possible sets of matrix elements
$\langle E^{-}_{\downarrow} E^{+}_{\downarrow} M^{-}_{\downarrow} M^{+}_{\downarrow} \rangle$
$\rightarrow \langle e^{-}_{\downarrow} e^{+}_{\downarrow} \mu^{-}_{\downarrow} \mu^{+}_{\downarrow} \rangle + \langle h e^{-}_{\downarrow} e^{+}_{\downarrow} \mu^{-}_{\downarrow} \mu^{+}_{\downarrow} \rangle + \ \ldots + \langle h e^{-}_{\downarrow} h e^{+}_{\downarrow} h \mu^{-}_{\downarrow} h \mu^{+}_{\downarrow} \rangle$
- No difference to standard perturbation in process $E^{-}_{\uparrow} E^{+}_{\uparrow} \rightarrow M^{-}_{\uparrow} M^{+}_{\uparrow}$
- Strongest amplification possibly for experimental setup of $E^{-}_{\downarrow} E^{-}_{\downarrow} \rightarrow M^{-} M^{+}$

One-loop level

Feynman diagrams

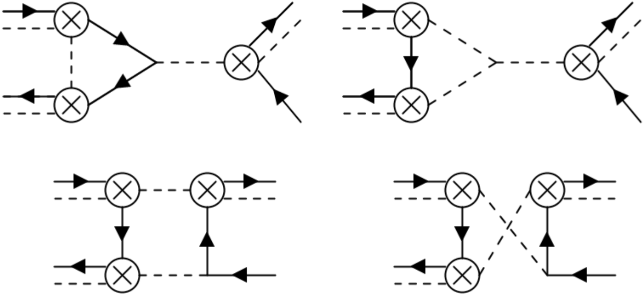
- Same topologies for loop diagrams for one Higgs insertion in FMS contributions
- Composite state contributes as special interaction vertex $\rightarrow$ allows for diagrams with Yukawa term in external states
- Diagrams more restricted for more Higgs insertions
- How do these two aspects interplay?



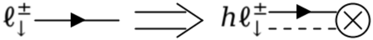
One-loop level

Three Higgs insertions

- $he^-_\downarrow he^+_\downarrow \to h\mu^-_\downarrow \mu^+_\uparrow$



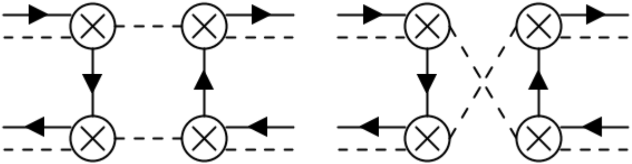
- Only triangle and box diagrams



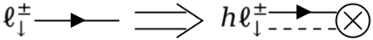
One-loop level

Four Higgs insertions

- $he_{\downarrow}^{-}\, he_{\downarrow}^{+} \rightarrow h\mu_{\downarrow}^{-}\, h\mu_{\downarrow}^{+}$



- Only box diagrams



One-loop level

Overview

- Generation of helicity one-loop diagrams with QGraf [5] for different helicities
- Strong difference in position of Higgs insertion

$$h_1 e^- h_2 e^+ \to h_3 \mu^- h_4 \mu^+$$

Helicity	No FMS	h_1	$h_1 h_2$	$h_1 h_3$	$h_1 h_2 h_3$	$h_1 h_2 h_3 h_4$
↓↓↓↓	197	181	21	224	21	9
↓↓↓↑	206	238	21	27	9	0
↓↓↑↑	196	181	22	0	0	0
↓↑↓↑	266	31	0	13	0	0
↓↑↑↓	265	31	0	0	0	0
↑↑↑↑	197	0	0	0	0	0

[5] Nogueira 2022

Future research

Next steps

- Deal with WF-renormalization and external composite states
- Calculation of $d\sigma$ for different inital and final leptons
- Include external masses

  $\rightarrow$ Spin treatment for chirality $\neq$ helicity

  $\rightarrow$ Increased number of contributions

Summary

- Gauge-invariant description of the SM particles leads to composite-operator formalism
  $\ell^{\pm} \rightarrow L^{\pm} = h\ell^{\pm}$
- Yields further matrix amplitudes and therefore adds to the differential cross section
  $d\sigma_{FMS} \propto |\mathcal{M}_S + \mathcal{M}_{FMS}|^2$
- Effects on leptons could be relevant for future high-energy and precisions measurements in FCC-ee, CLIC, ILC...

References I

- Fröhlich, J, G Morchio, and F Strocchi (1980). "Higgs phenomenon without a symmetry breaking order parameter". In: *Physics Letters B* 97.2, pp. 249–252.
- Maas, Axel (2019). "Brout–Englert–Higgs physics: From foundations to phenomenology". In: *Progress in Particle and Nuclear Physics* 106, pp. 132–209.
- Afferrante, Vincenzo et al. (2021). "Testing the mechanism of lepton compositeness". In: *SciPost Physics* 10.3. DOI: 10.21468/scipostphys.10.3.062. URL: https://doi.org/10.21468%2Fscipostphys.10.3.062.
- Egger, Larissa, Axel Maas, and René Sondenheimer (2017). "Pair production processes and flavor in gauge-invariant perturbation theory". In: *Modern Physics Letters A* 32.38, p. 1750212.

References II

- Nogueira, Paulo (Mar. 1, 2022). *QGraf*. Version 3.5.1. URL: http://cfif.ist.utl.pt/~paulo/qgraf.html.
- Shtabovenko, Vladyslav, Rolf Mertig, and Frederik Orellana (2020). "FeynCalc 9.3: New features and improvements". In: *Computer Physics Communications* 256, p. 107478.