FLORIDA STATE UNIVERSITY
COLLEGE OF ARTS & SCIENCES

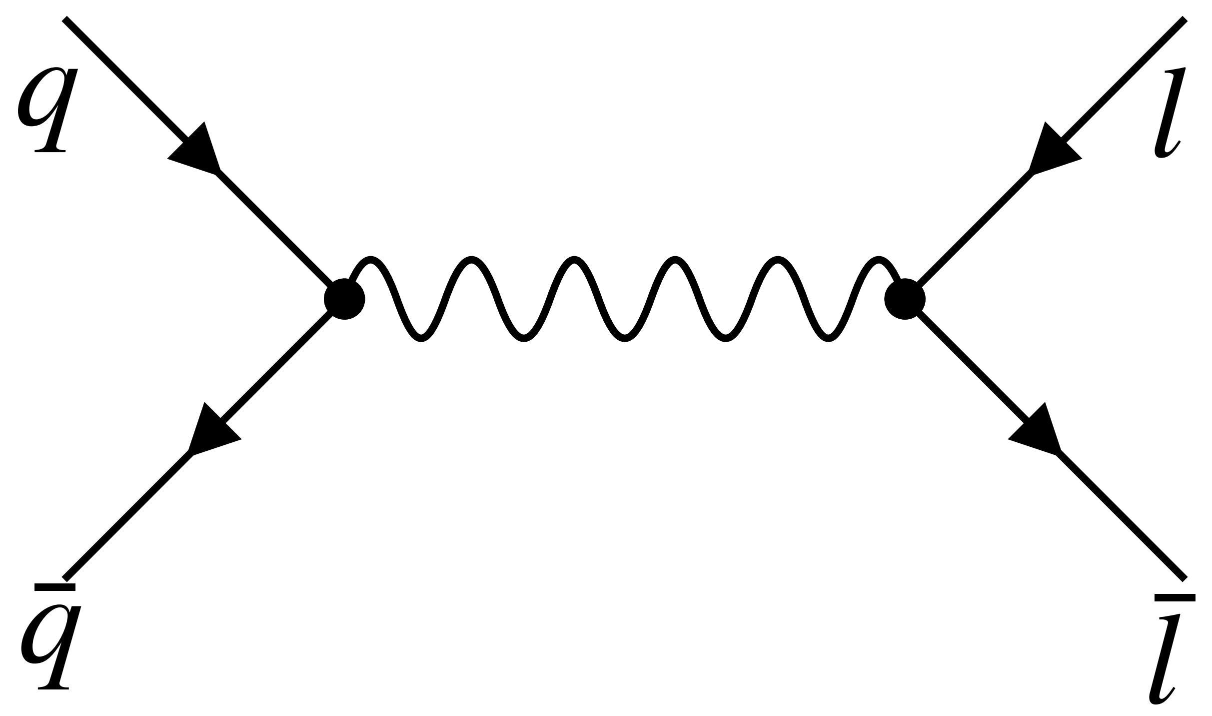
Drell-Yan SMEFT at NLO

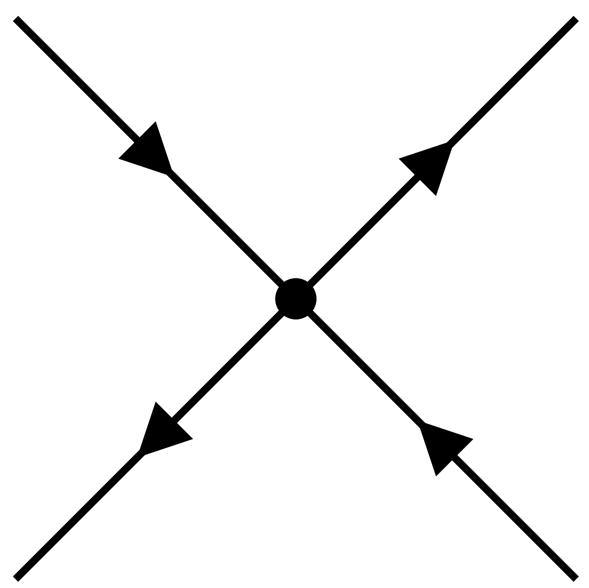
Based on: 1) E. Bagnaschi, LB, S. Dawson, P.P Giardino & A. Vicini, *arXiv (2024)*

Luigi Bellafronte

Prague, Czech Republic *18th July 2024*

Motivation





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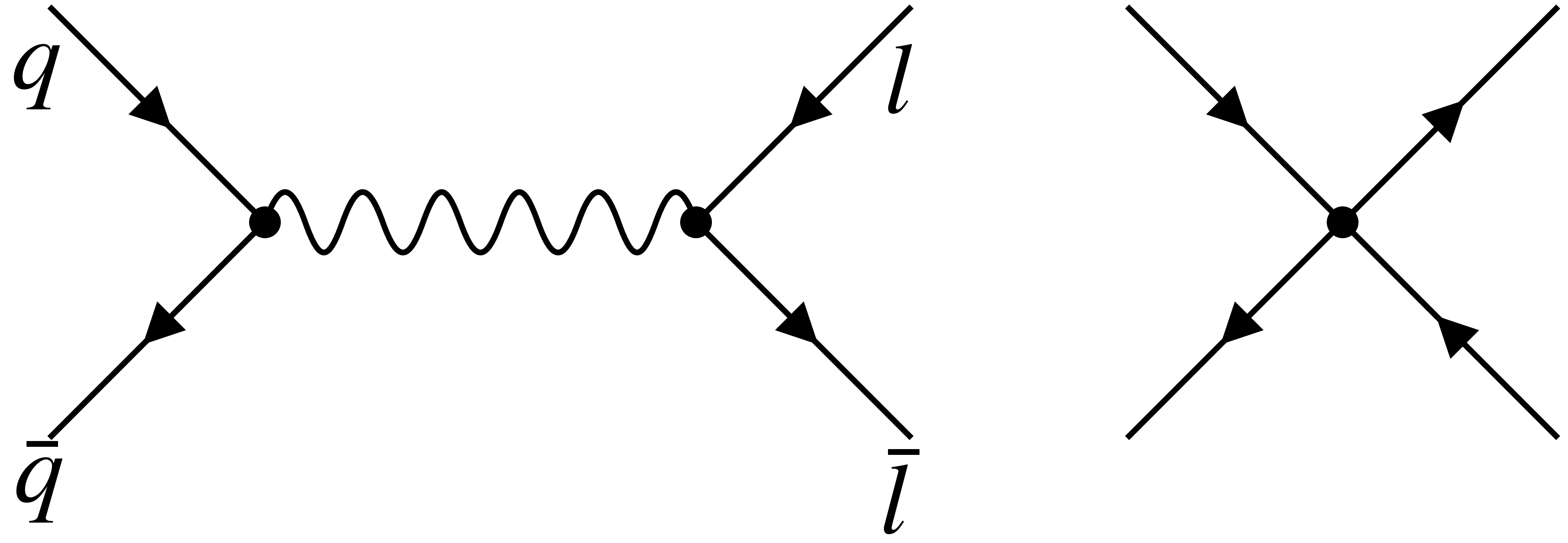
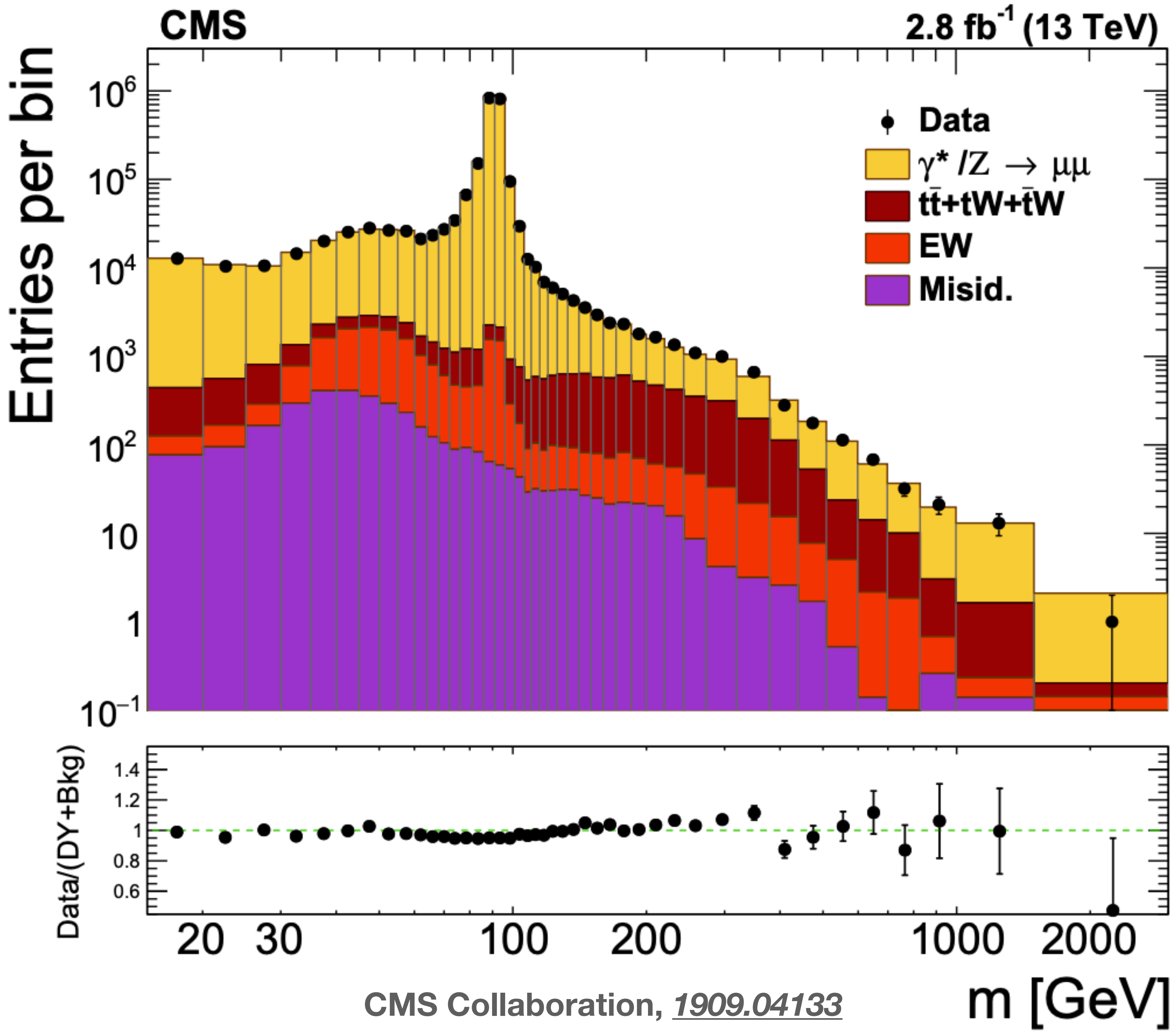


- The neutral Drell Yan process has played an essential role in validating SM predictions. By measuring the cross-section and the kinematic distribution it is an excellent path to investigate the EW sector.
- This process can be an highly sensitive probe for new physics.
- The current predictions for DY production are in excellent agreement with experimental results.
- In the context of EFT, new physics effects may appear at the increasing of the partonic energy scales, requiring precise calculations, that are beyond the existing SM results.

$$\Lambda \sim 1 \text{ TeV}$$



CMS Collaboration, 1909.04133

Definitions

Quark quark ⟶ Lepton Lepton

$m_{u,d,e,\mu,\ldots} = 0$

$$M_{XY} = \left[\overline{u}(p_2)\gamma_\mu P_X u(p_1)\right] \cdot \left[\overline{u}(p_3)\gamma^\mu P_Y u(p_4)\right]$$

$$P_{L,R} = \frac{1 \mp \gamma_5}{2}$$

Tree Level Amplitude

$$A_{LO} = \Sigma_{XY} G_{XY} M_{XY}$$

with

$$G_{XY} = G_{XY}^{SM} + \delta G_{XY}^{SMEFT}$$

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Example: RR up up

$$G_{RR}^{SM} = \frac{8(s - m_W^2)(-m_W^2 + m_Z^2)}{3sv^2(s - m_Z^2)}$$

$$\delta G_{RR}^{SMEFT} = \frac{1}{\Lambda^2}\Big(\frac{C_{\phi D}(4m_W^4 - 4sm_Z^2)}{3s^2 - 3sm_Z^2} + \frac{4(m_W^2 - m_Z^2)C_{\phi e}[22]}{3(s - m_Z^2)} - C_{eu}[2211] + \dots\Big)$$

where $s = (p_1 + p_2)^2$

Definitions

Coefficients LO up up

$$C_{\phi WB}, C_{\phi D}, C^{(3)}_{\phi l}[11], C^{(3)}_{\phi l,}[22], C^{(1)}_{\phi l}[22], C_{\phi e,}[22], C^{(3)}_{\phi q,}[11], C^{(1)}_{\phi q}[11], C_{\phi u,}[11],$$

$$C_{ll,}[1221], C_{ll}[2112], C^{(3)}_{lq}[2211], C^{(1)}_{lq,}[2211], C_{qe}[1122], C_{lu}[2211], C_{eu}[2211]\,.$$

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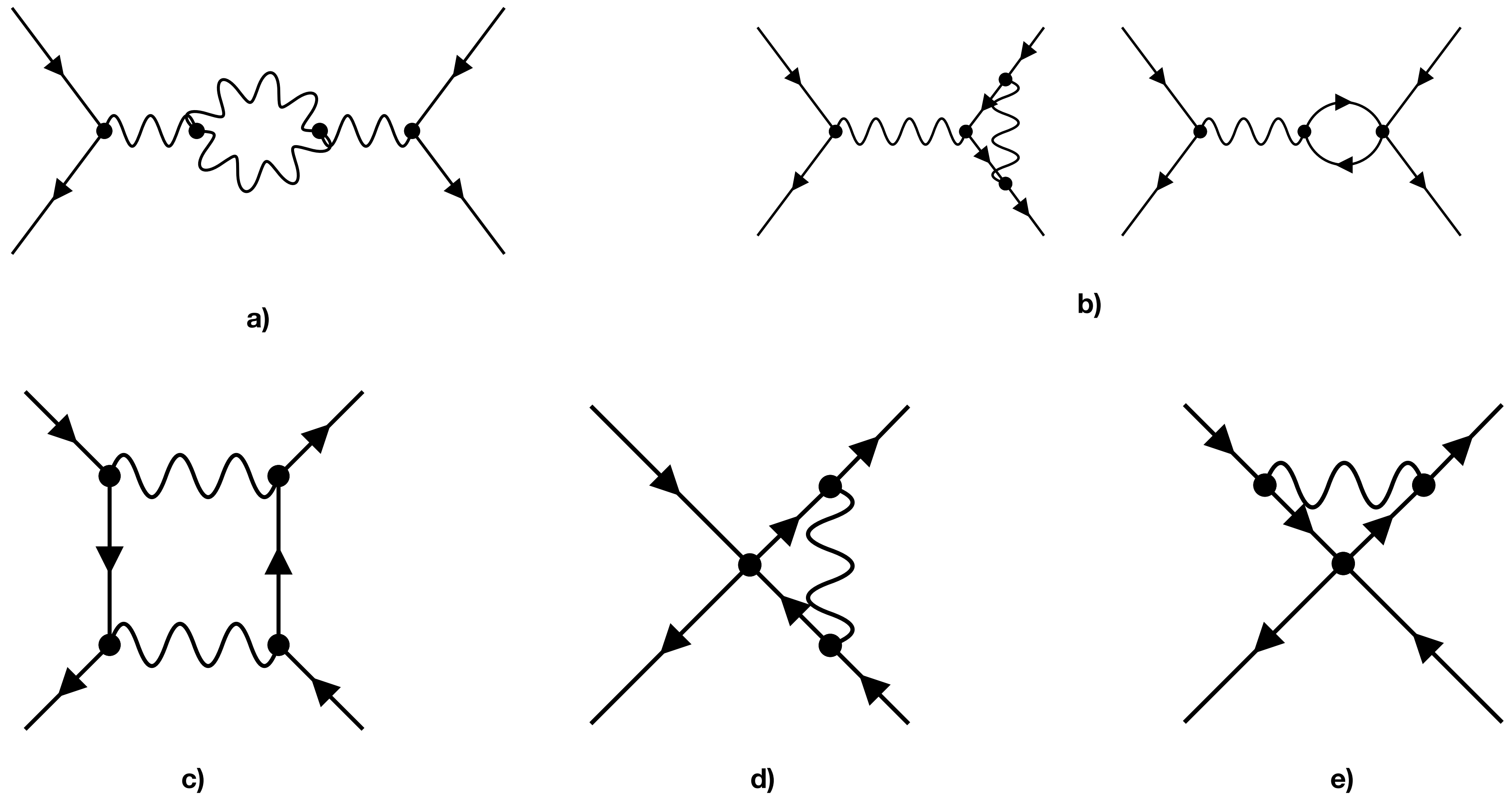
Partonic LO cross section

$$\hat{\sigma}_{LO} = \frac{1}{16\pi s^2}\int_{-s}^{0} dt \mid \overline{A}_{LO}(s,t) \mid^2$$

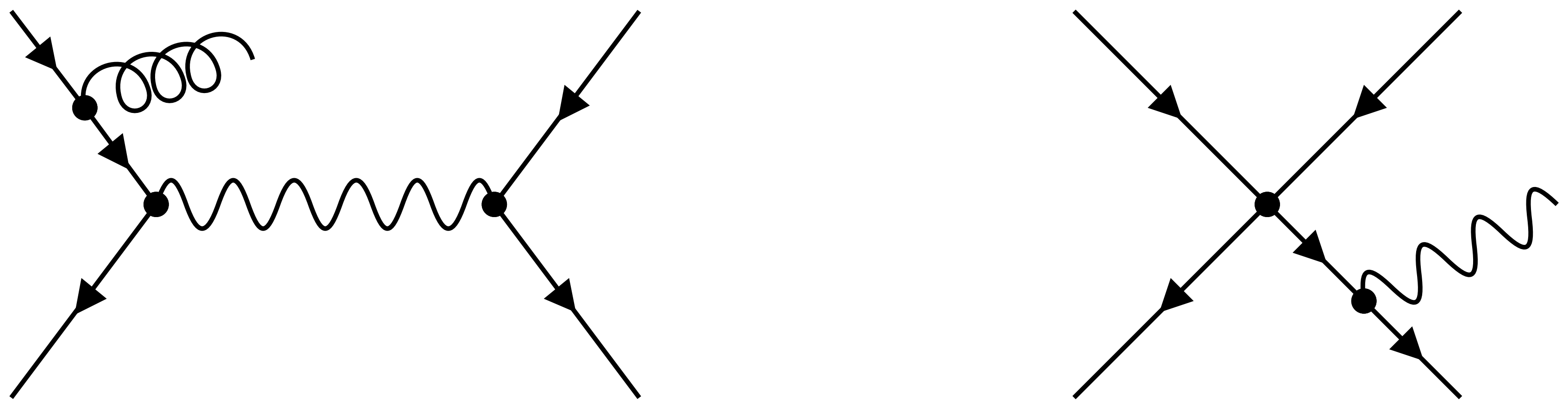
The numerical results of the tree level 4–fermion operators has been extensively studied in the literature.

$V_{CKM} \sim 1$ and $m_{u,d,e,\mu,\ldots} = 0$

Virtual contributions



Real contributions



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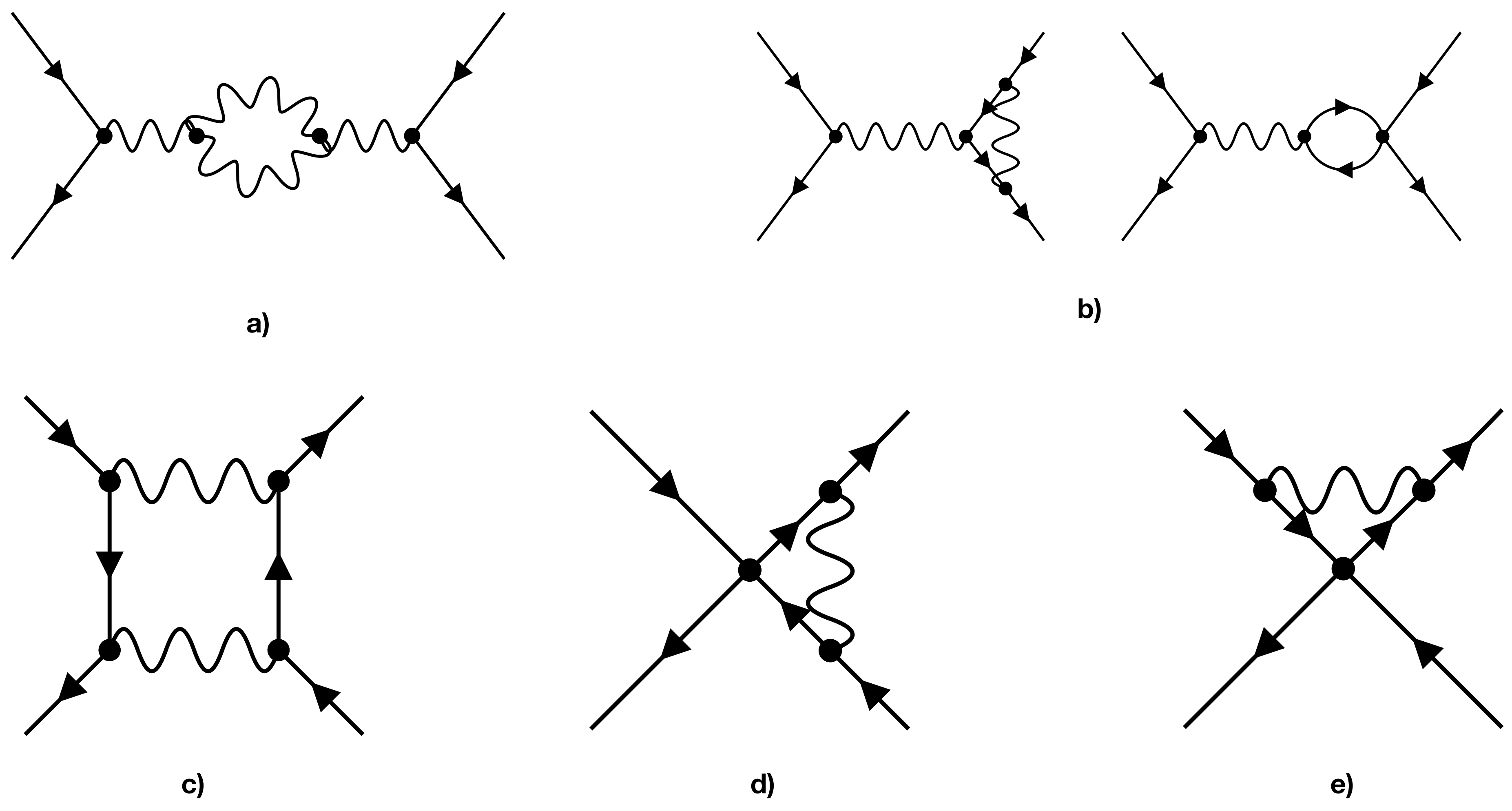

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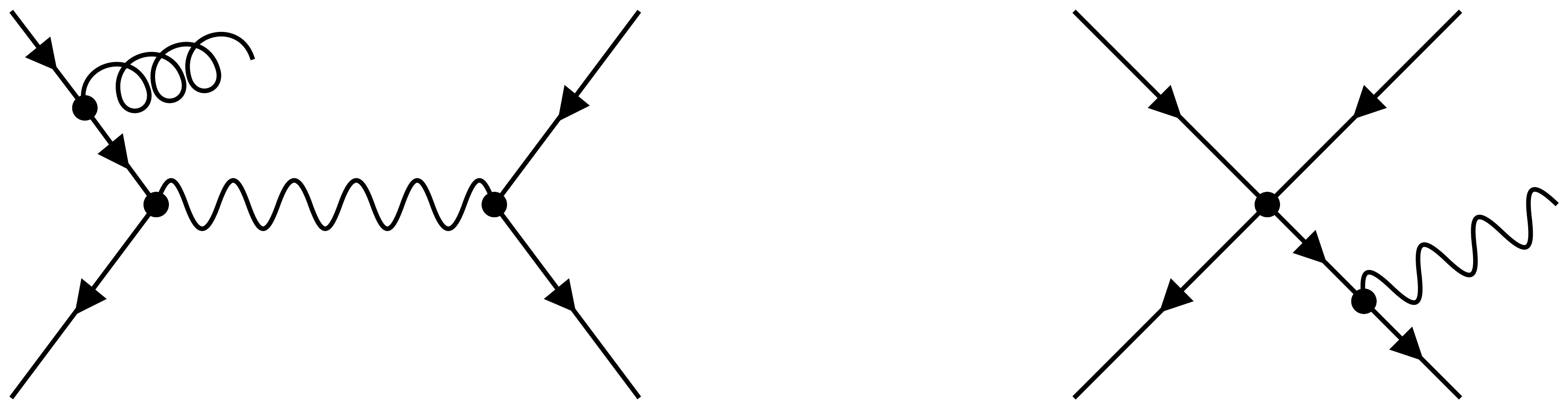

Soft and collinear contributions are proportional to the LO.

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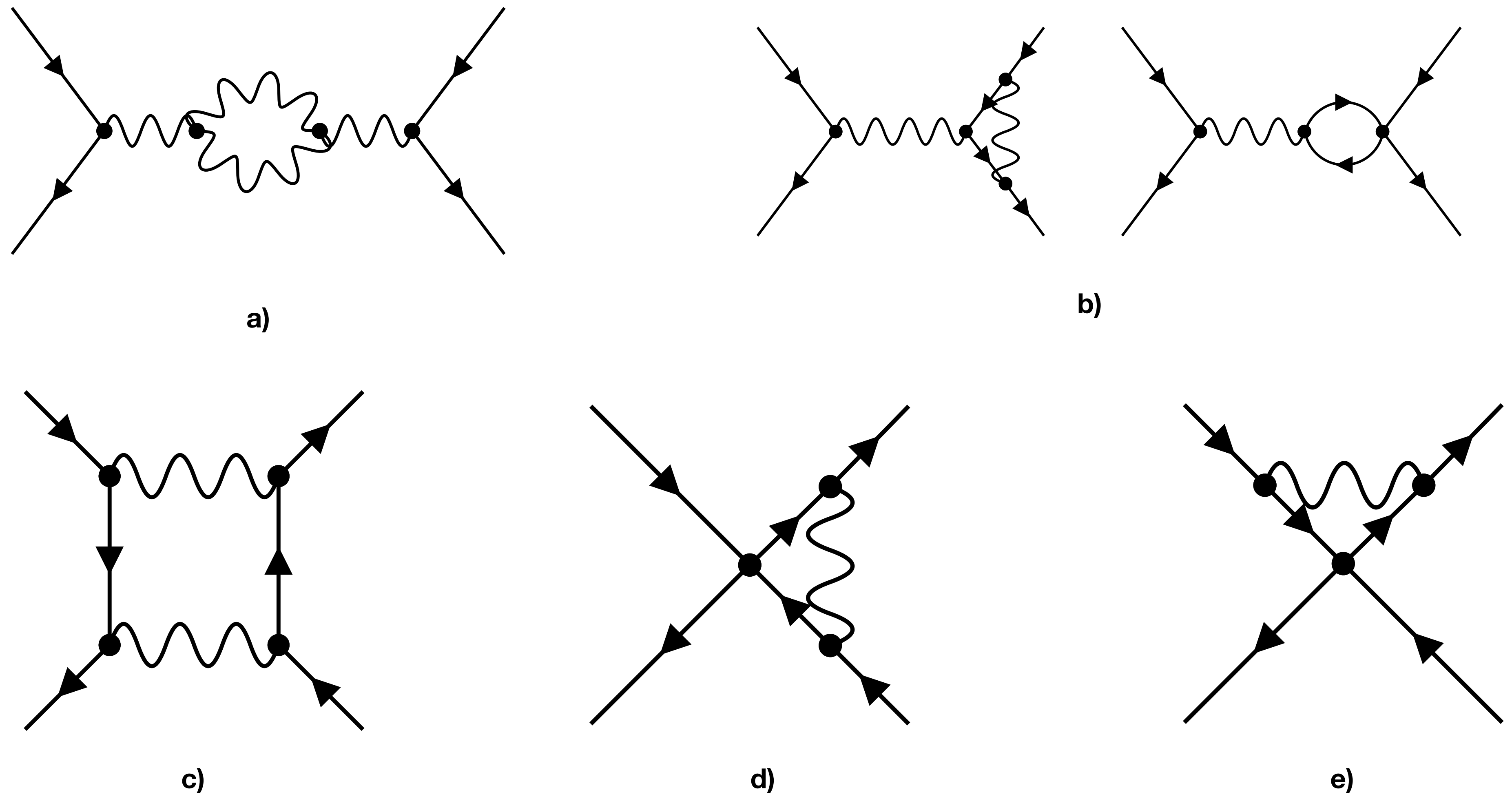
Virtual contributions



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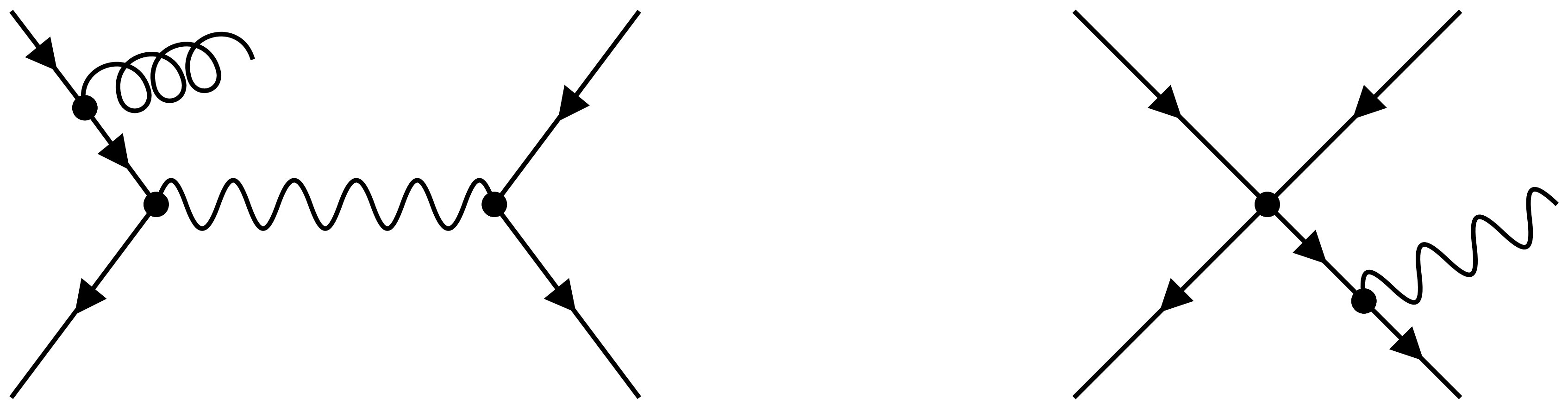
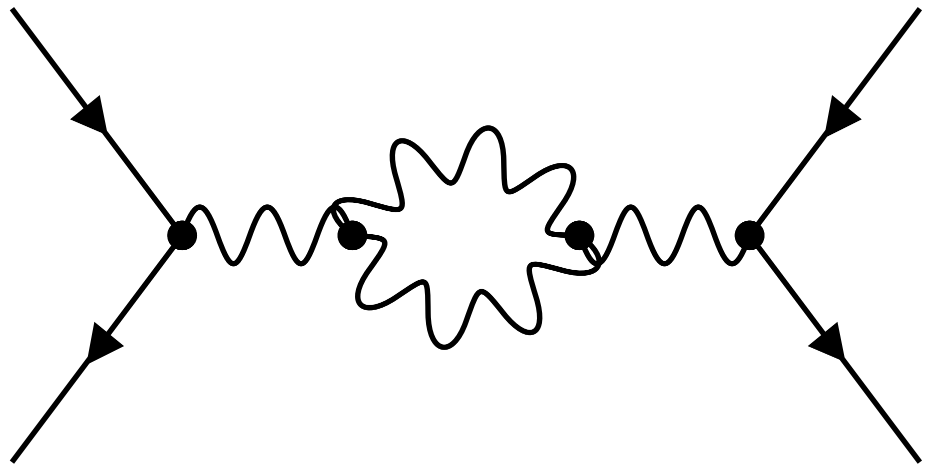


In the following we discuss only the virtual contributions.

NLO: Virtual

Renormalization counterterms



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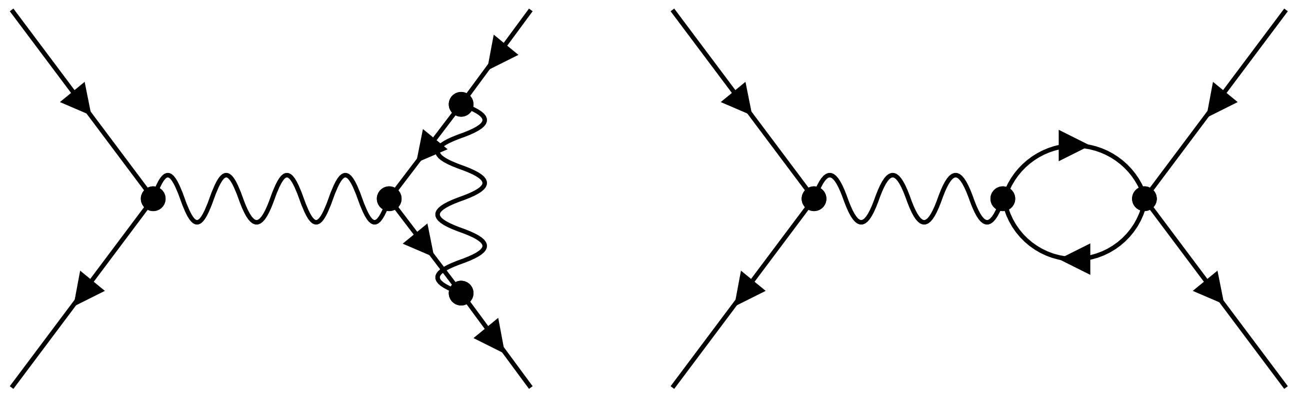

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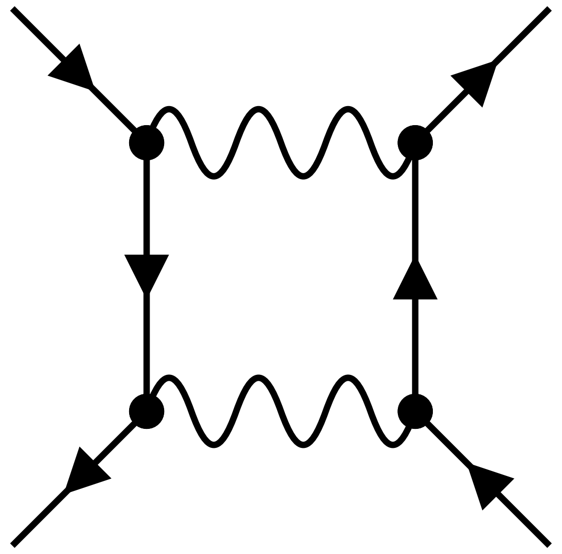
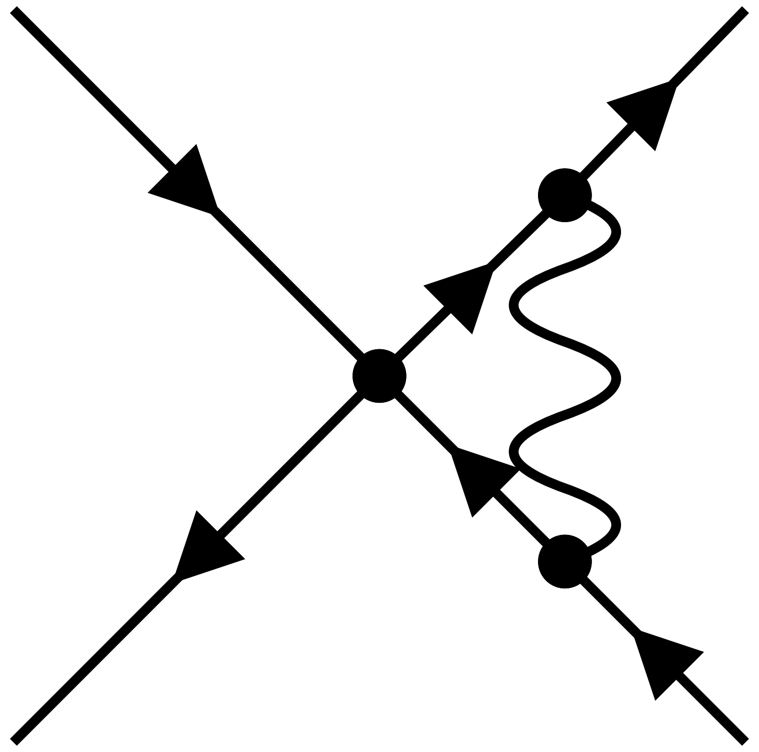


4Fermion Vertex Triangle



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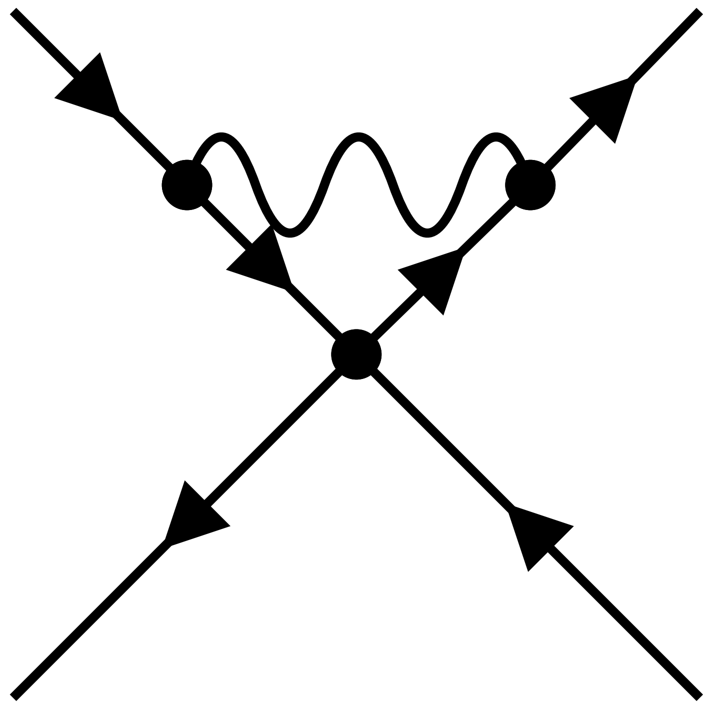

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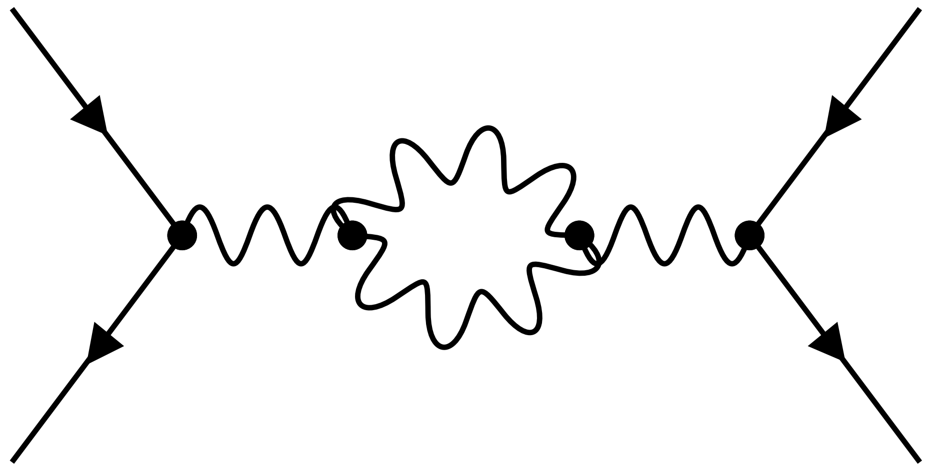

E. Jenkins *et al* 1308.2627
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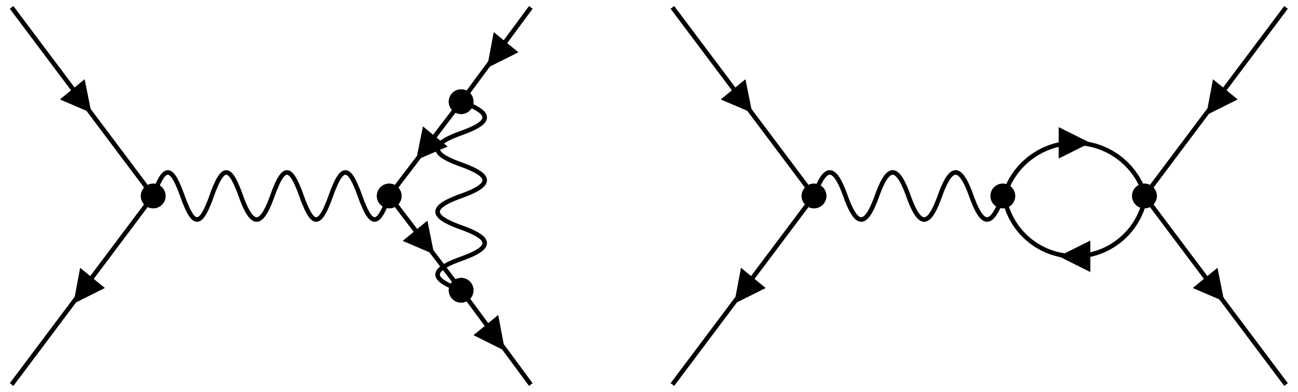

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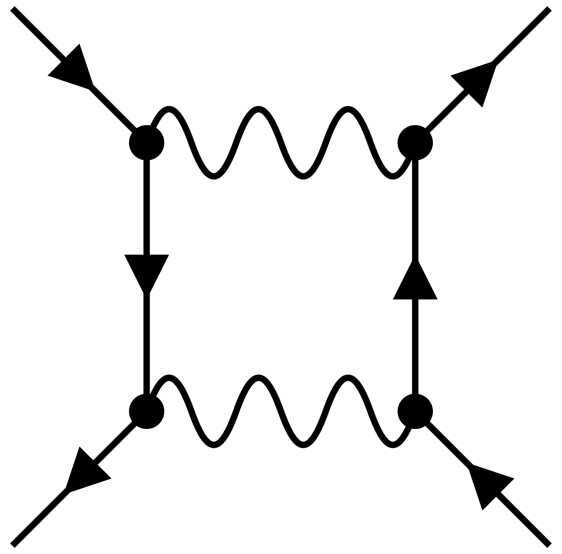

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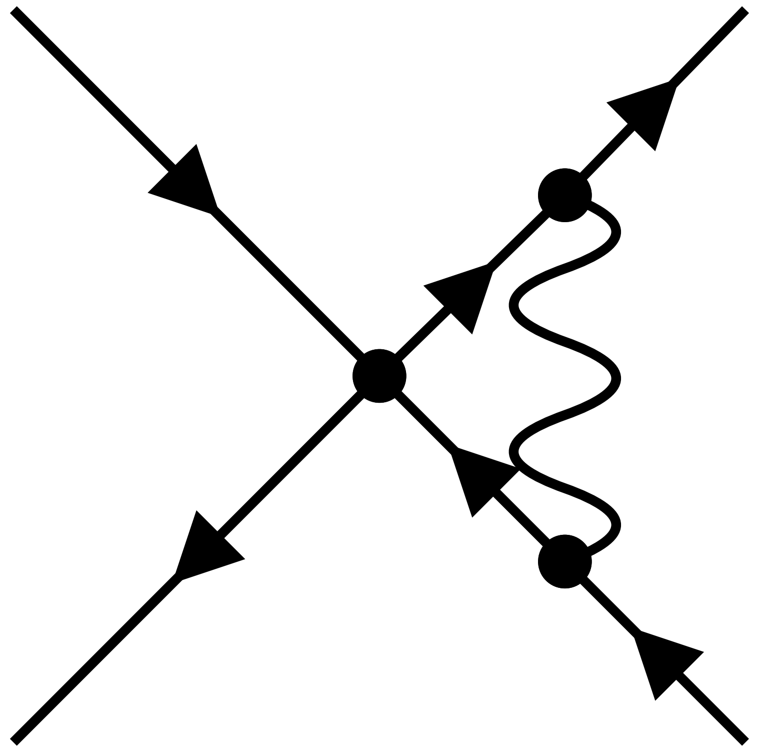

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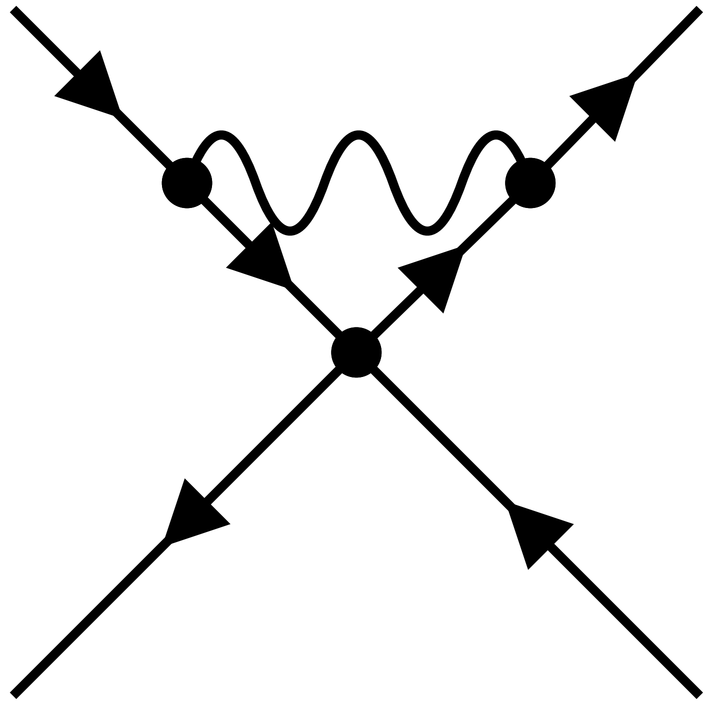

γ^5 problem

The problem emerges because the usual 4-dimensional γ^5 does not have a canonical extension into D dimension.

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In a nutshell

Anti commutation rule

$$\{\gamma^\mu, \gamma^5\} = 0$$

Cyclity of trace

$$Tr[\ldots\gamma^5\gamma^\mu] = Tr[\gamma^\mu\ldots\gamma^5]$$

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It has the significant drawback of violating the chiral symmetry of the SM in all perturbative calculations involving chiral couplings. It is necessary to introduce additional finite counterterms alongside the usual divergent one to all SM interactions and they need to be calculated beyond the $O(\epsilon^0)$. Thus, the renormalization procedure can be very demanding.

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Kreimer Scheme

Method: remarks

- **It is forbidden to use cyclic property of the trace when an odd number of γ^5 is involved.**

- If there is more than one diagram contributing to a given process, all the traces must be read starting at the same point.

- If there is an anomalous axial current is involved, the trace of the anomalous graph must be read starting from an axial vector vertex. In the case of multiple axial vector vertices a symmetric choice of the reading prescription must be used.

- When there are Dirac traces with at most four Dirac gammas and γ^5, the Kreimer scheme is equivalent to the Naive Dimensional Regularization (NDR).

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Kreimer scheme: rules

Anticommutation rules

$$\{\gamma_\mu, \gamma_\nu\} = 2g_{\mu\nu}\,\mathbb{1}$$

$$\{\gamma_\mu, \gamma_5\} = 0$$

Without γ^5

$$\mathbf{Tr}[\gamma_{\mu 1}\gamma_{\mu 2}\dots\gamma_{\mu_{2n-1}}] = 0$$

$$\mathbf{Tr}[\gamma_{\mu 1}\gamma_{\mu 2}\dots\gamma_{\mu_{2n}}] = 4\sum_\sigma (-1)^{sgn(\sigma)}\, g_{\mu_{i_1}\mu_{j_1}} g_{\mu_{i_2}\mu_{j_2}}\dots g_{\mu_{i_n}\mu_{j_n}}$$

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Kreimer: example

AVV

Anomaly

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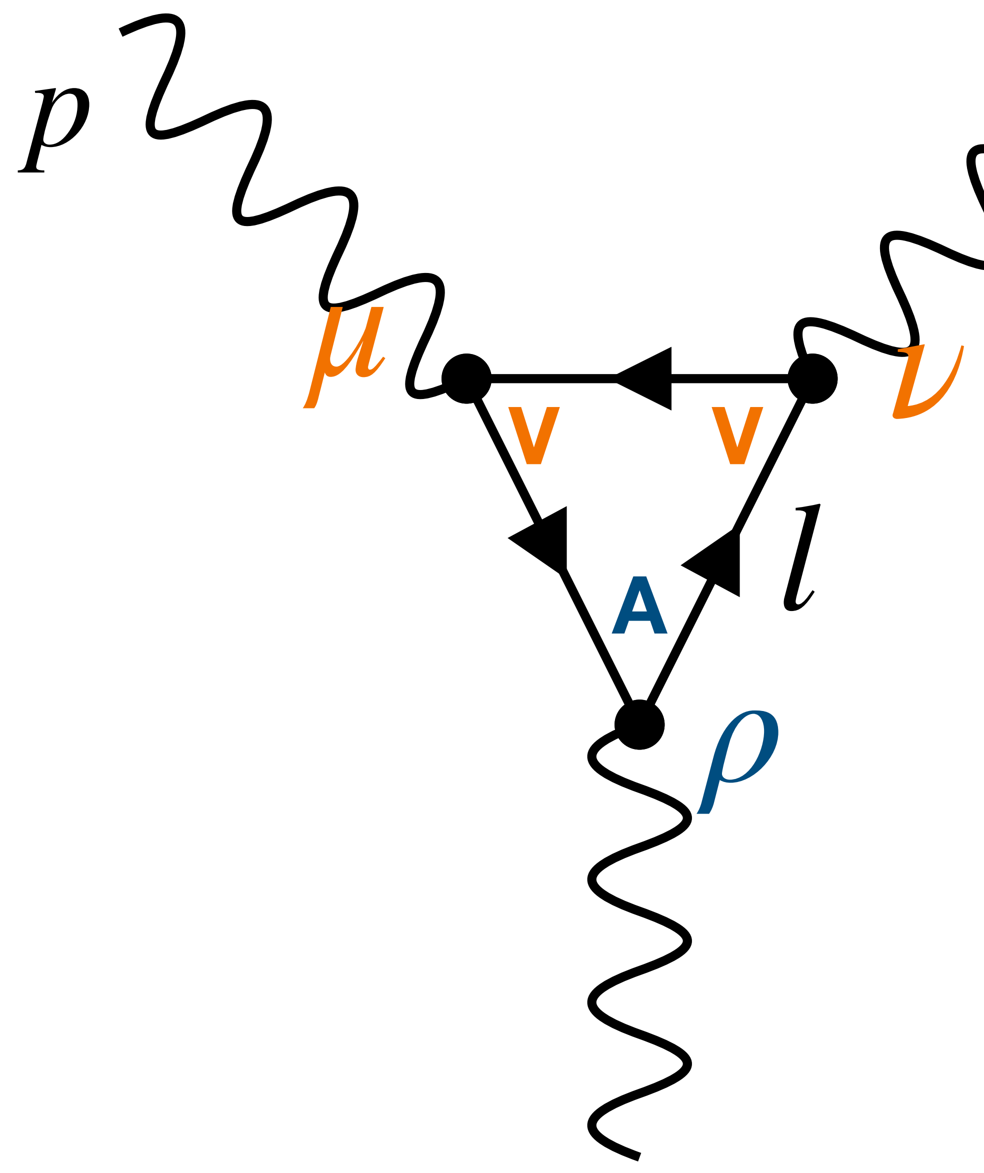

$$+\begin{Bmatrix} \mu \leftrightarrow \nu \\ p \leftrightarrow q \end{Bmatrix} \sim \textbf{Tr}[\gamma^5 . \gamma^\rho . (\gamma \cdot l) . \gamma^\mu . (\gamma \cdot (l+p)) . \gamma^\nu . (\gamma \cdot (l+p+q))] + \textbf{Tr}[\gamma^5 . \gamma^\rho . (\gamma \cdot l) . \gamma^\nu . (\gamma \cdot (l+q)) . \gamma^\mu . (\gamma \cdot (l+p+q))]$$

Assuming a single flavor

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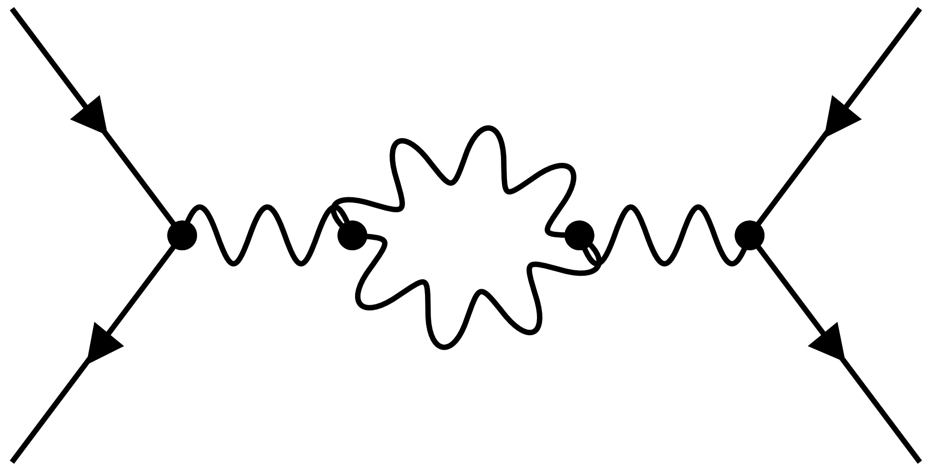

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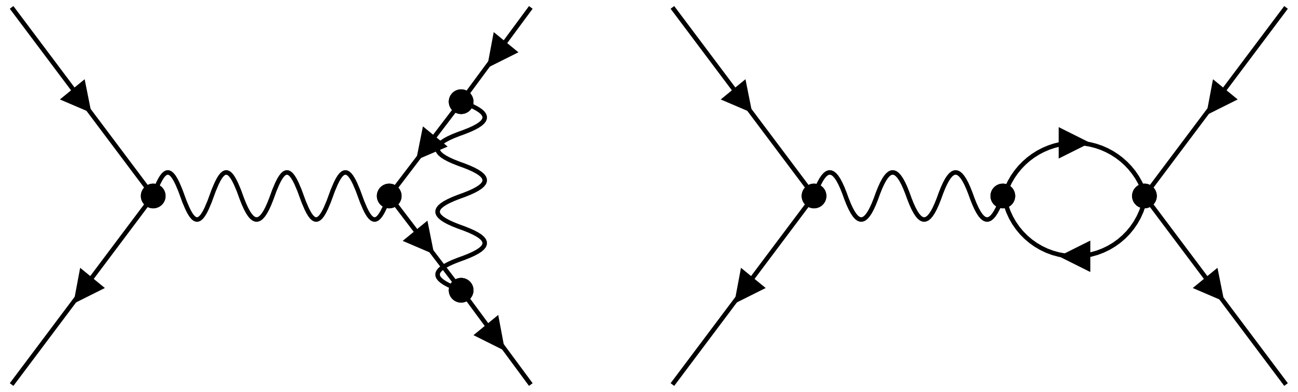

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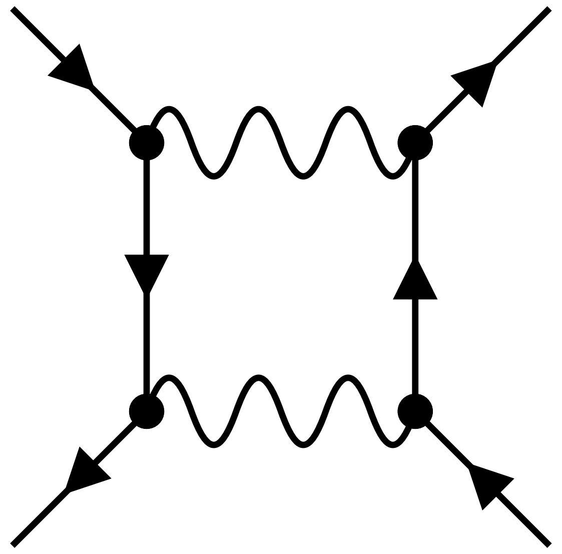

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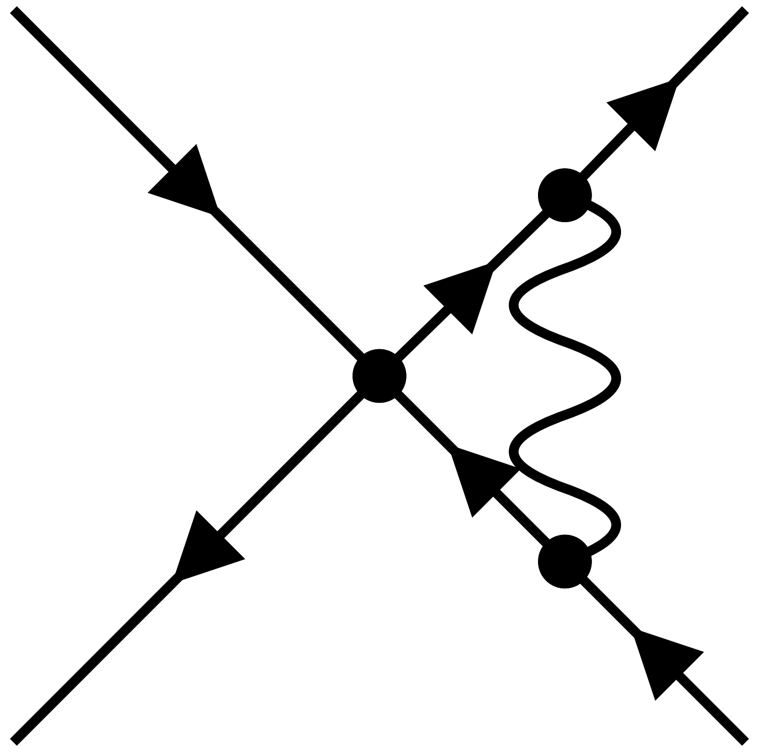

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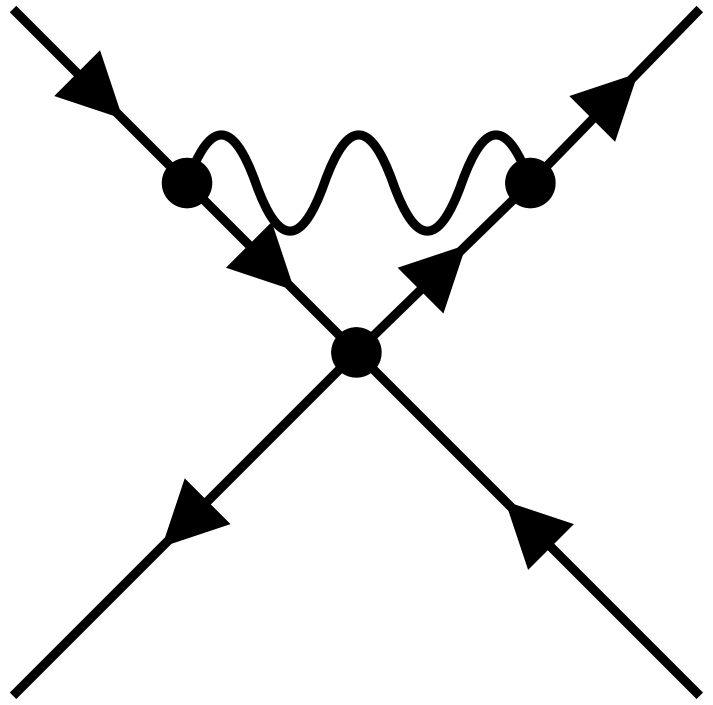

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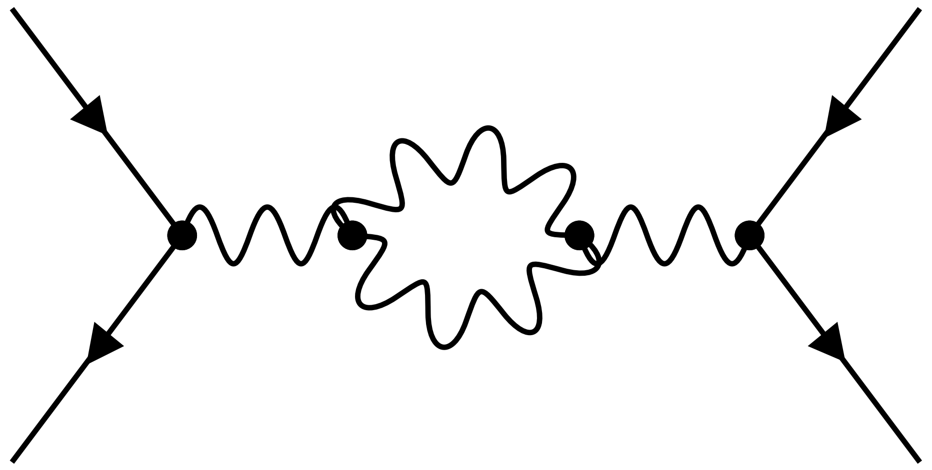

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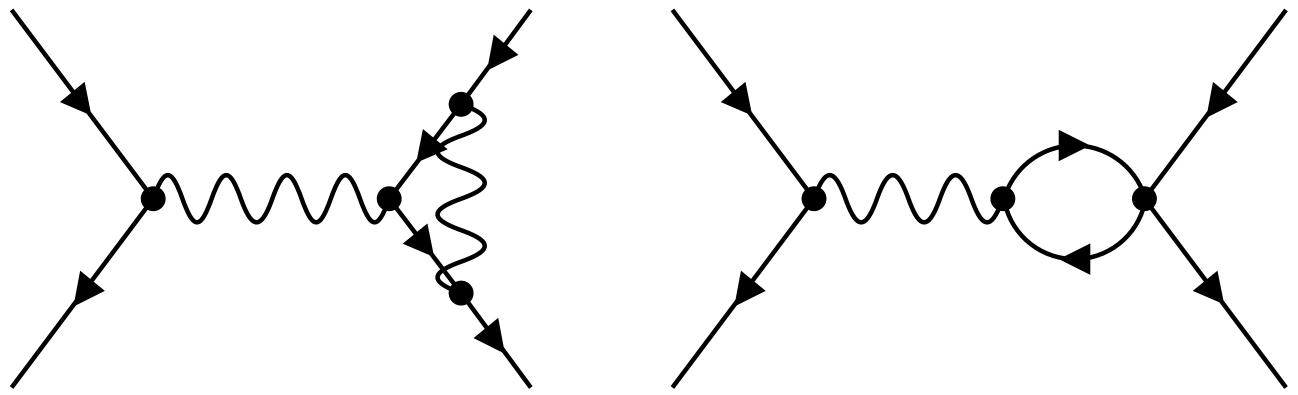

NDR

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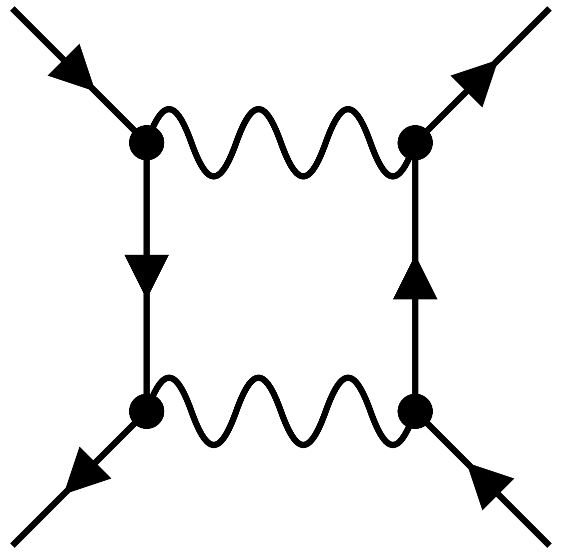

Kreimer

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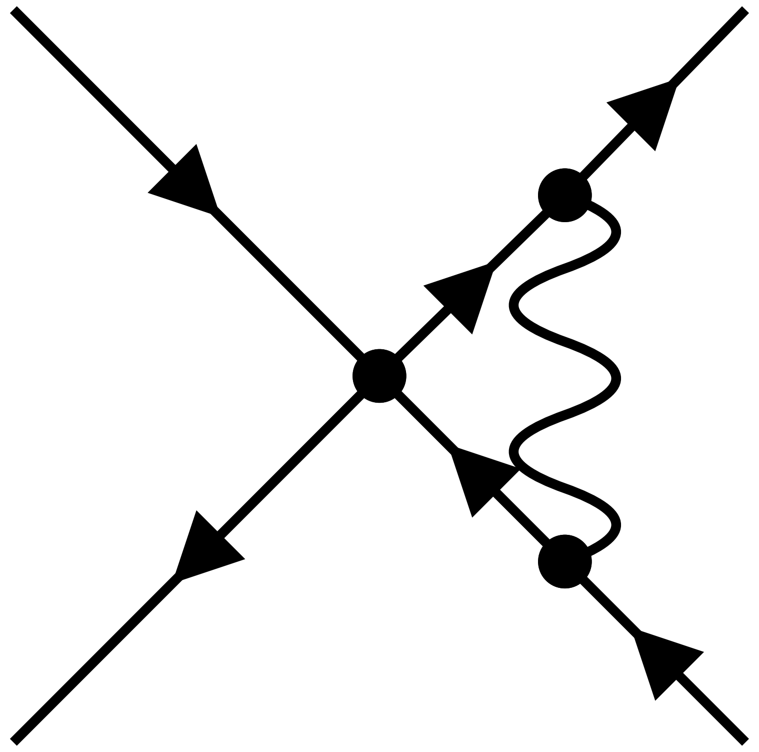

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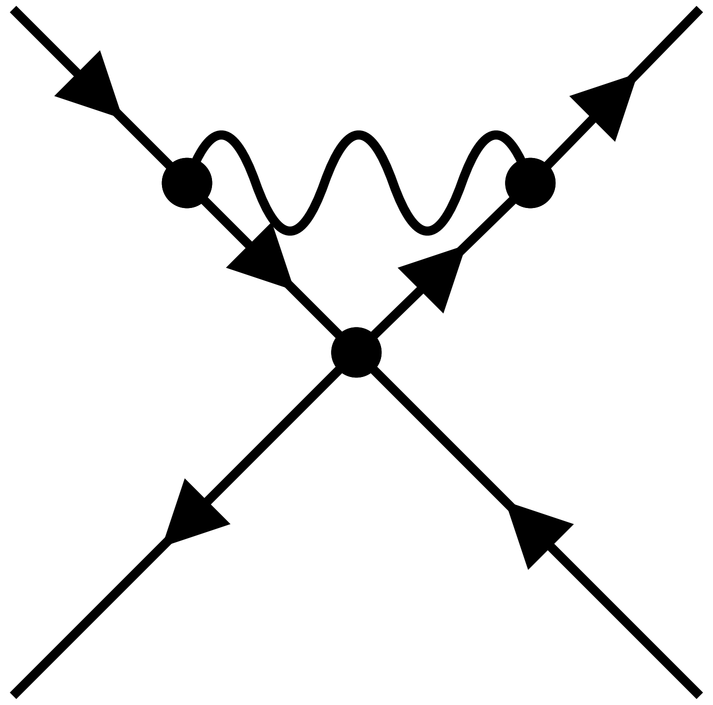

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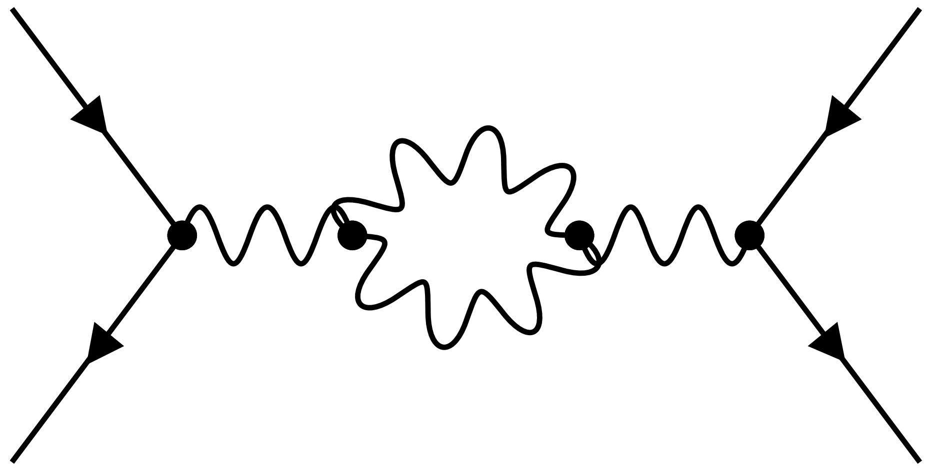

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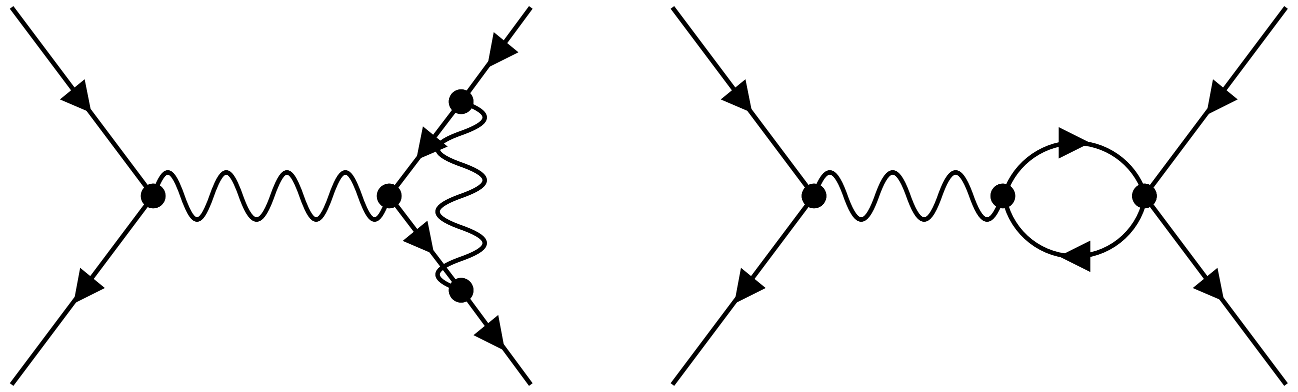

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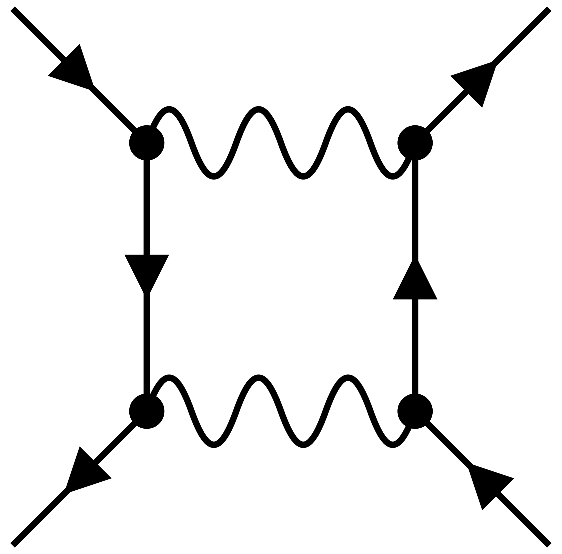

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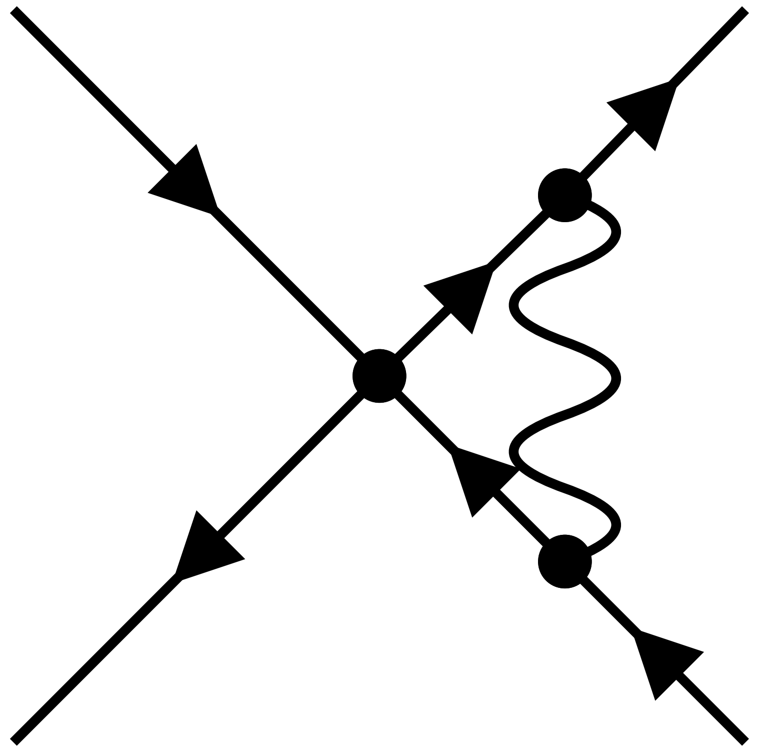

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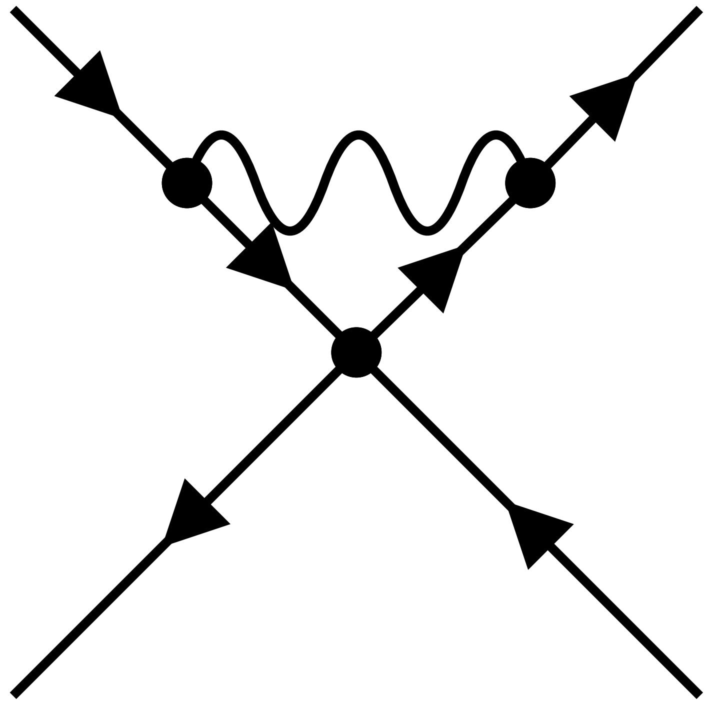
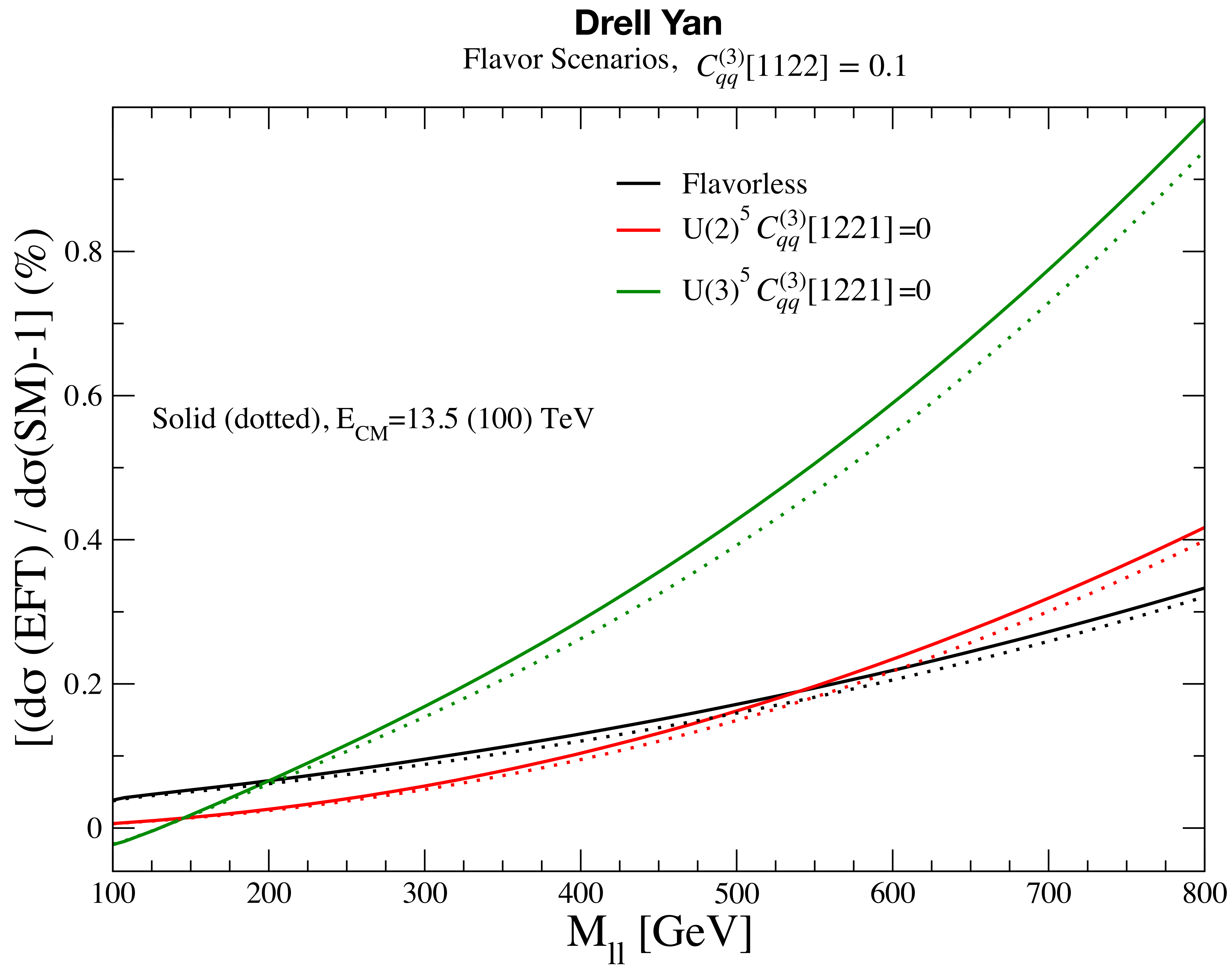


Kreimer

Phenomenology

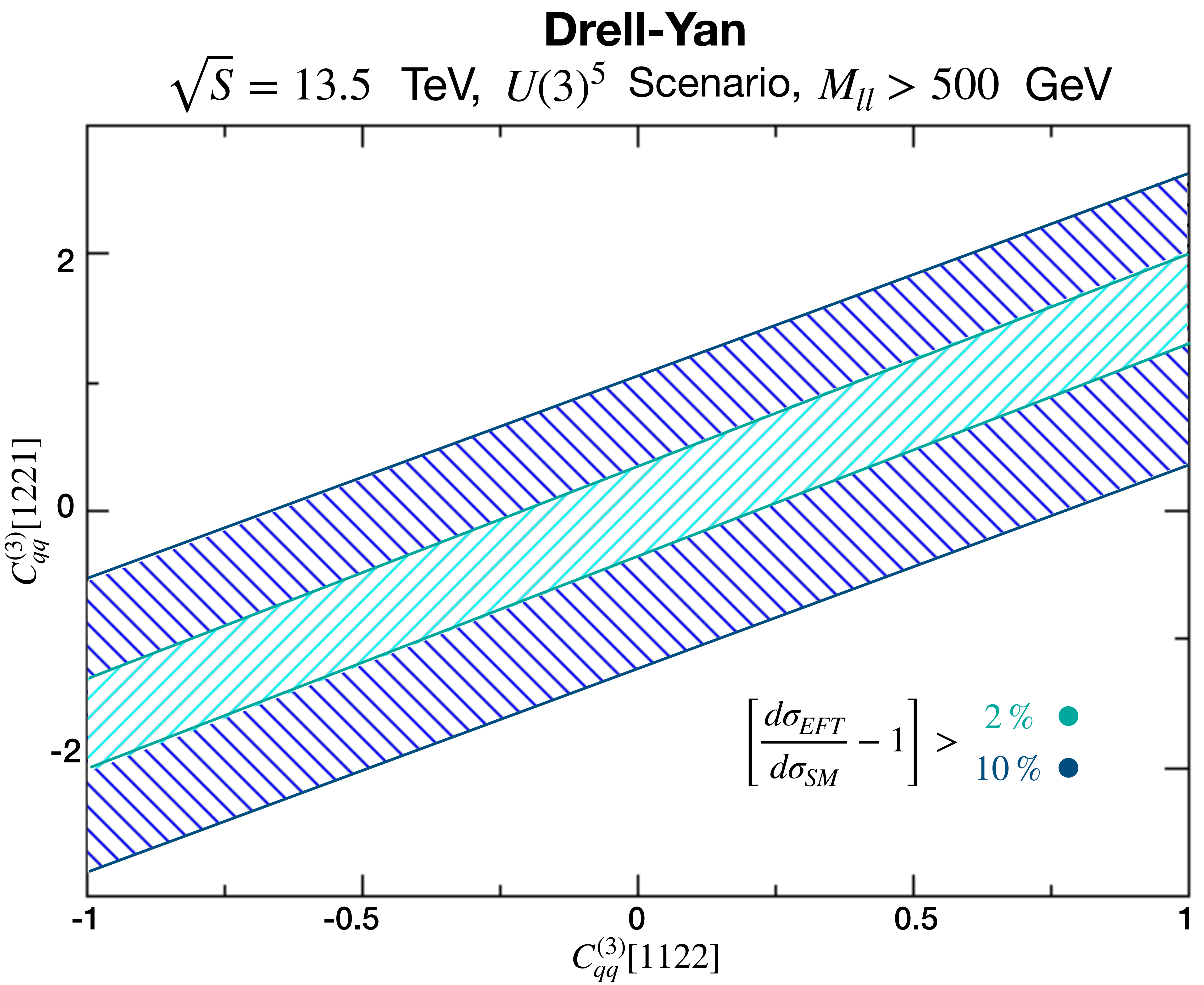


- **We notice that in all the flavor scenarios, the SMEFT 4-fermion contribution grows with the dilepton energy, with reaching 0.9% in $U(3)^5$ while the flavorless and the $U(2)^5$scenarios remain below 0.4%.**

We are plotting the percentage difference between the SMEFT and SM differential cross sections as a function of dilepton mass

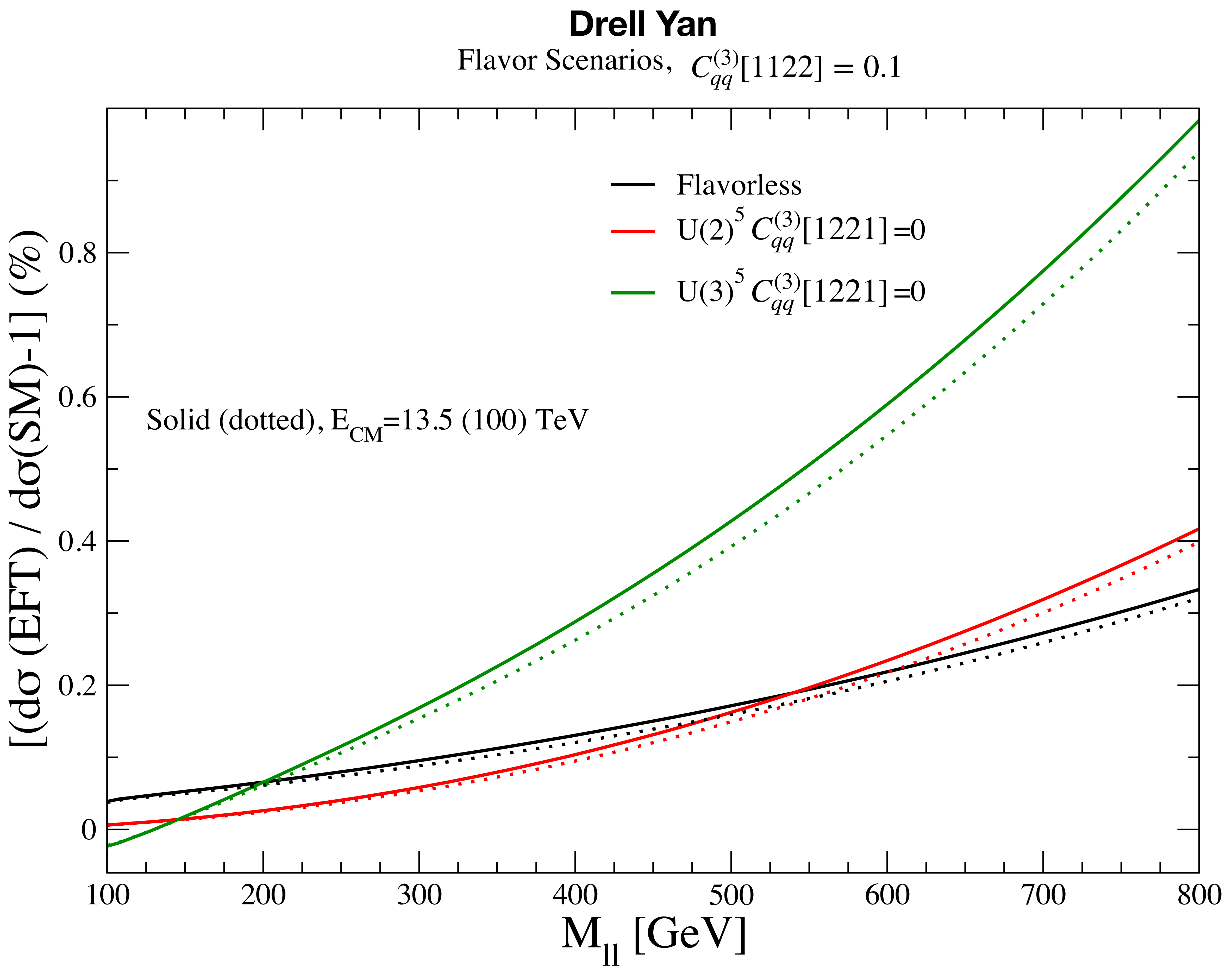
Phenomenology

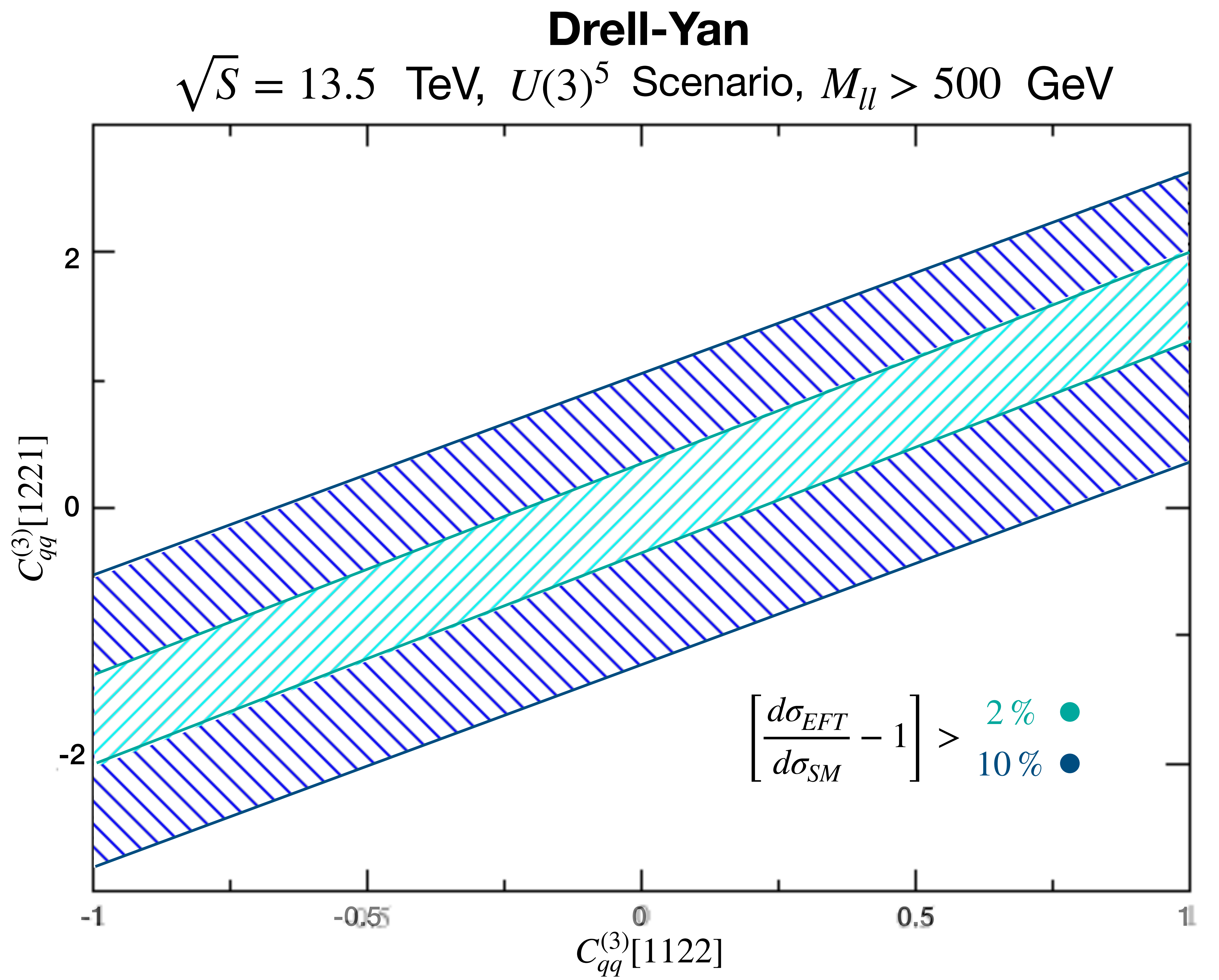
Currently the DY relative uncertainty for muon dilepton mass $M_{ll} > 500\ GeV$ is $\gtrsim 19\%$.
We can assume that the precision will increase at future colliders.



We notice that, due to the linear approximation, we can not set bounds on the SMEFT coefficients, since the area of the allowed values is delimited by two straight parallel lines. Nevertheless, it is meaningful to point out that the two parameters show a strong correlation.

Consideration





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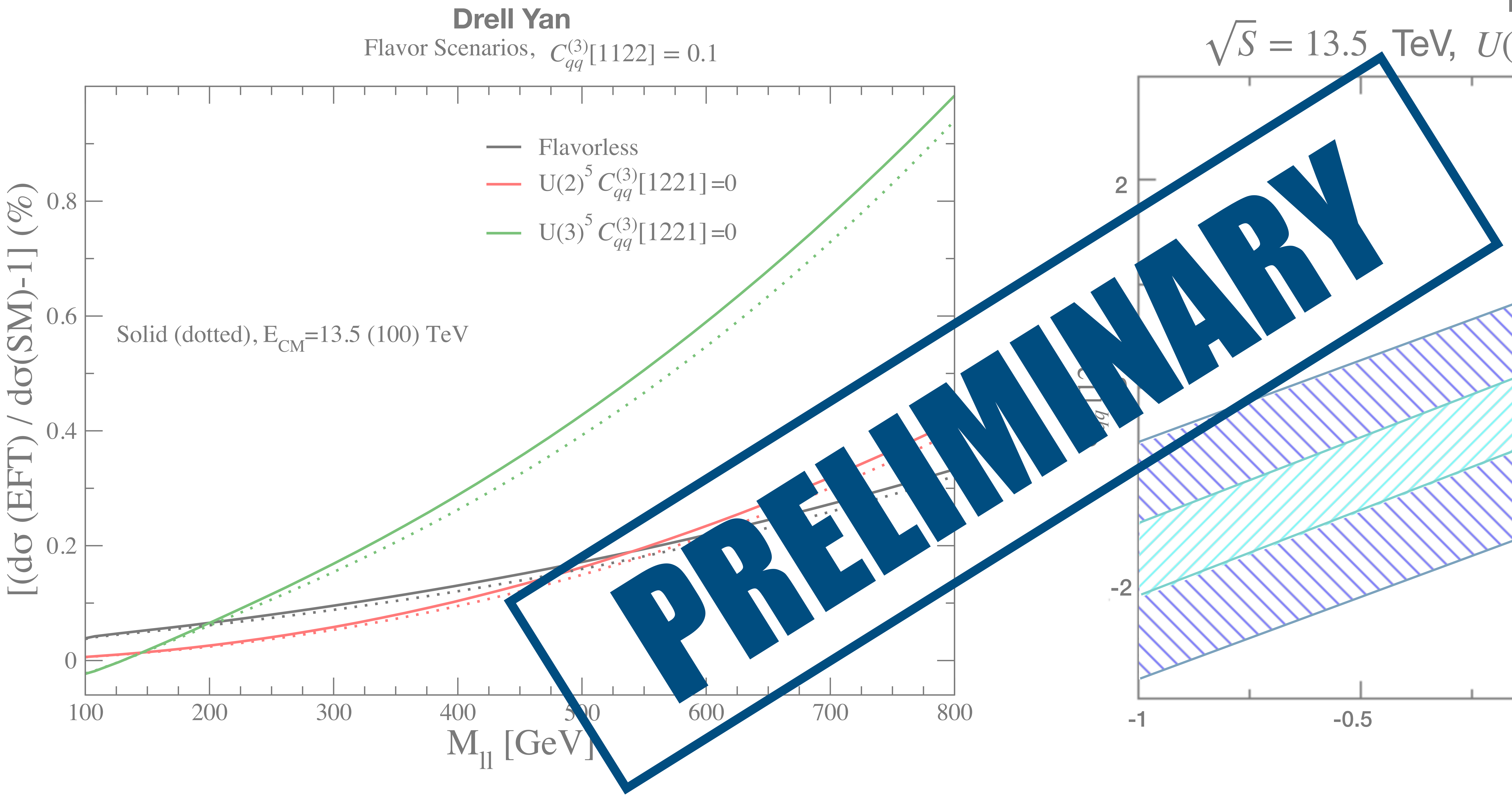

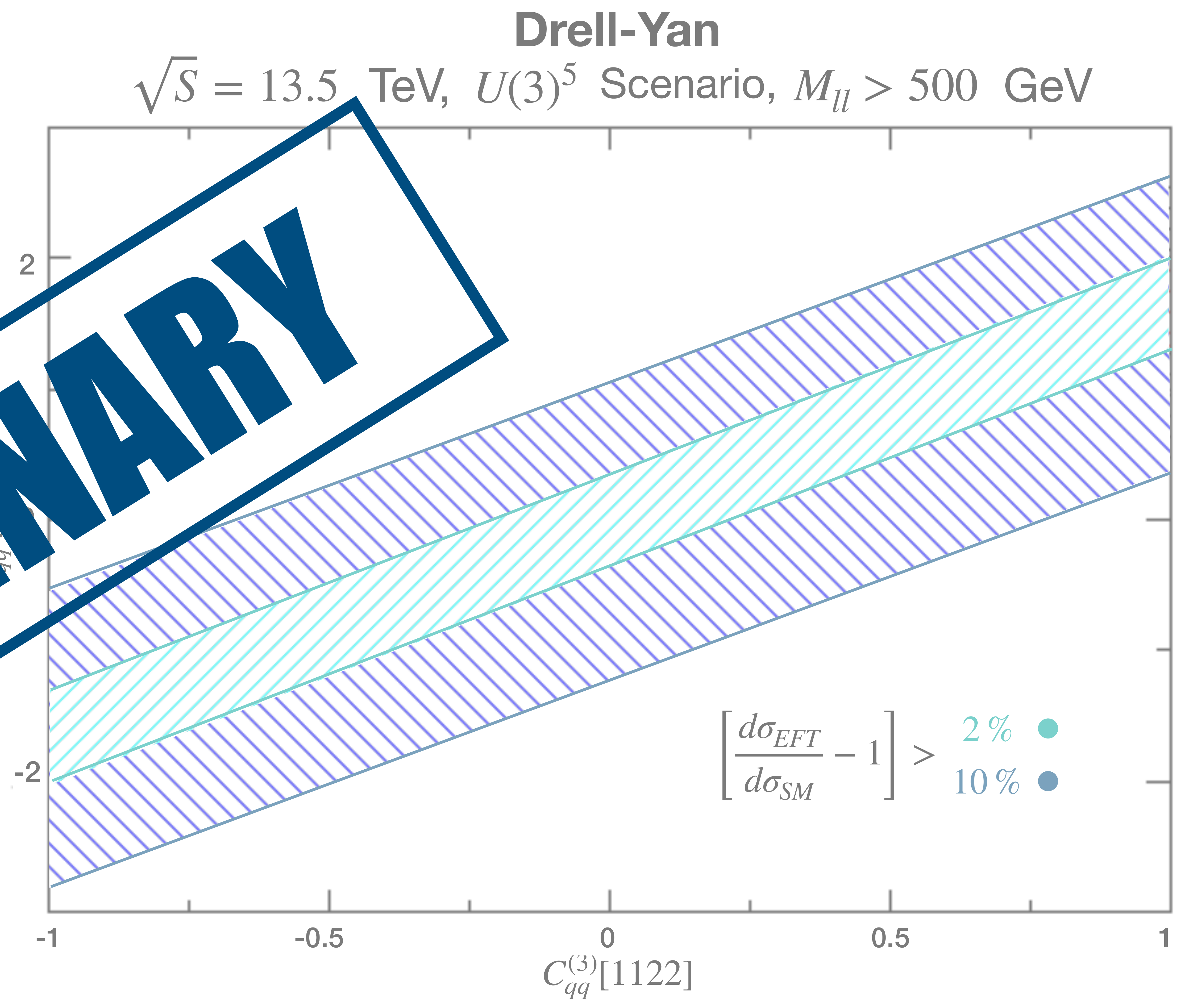

- **The constraints on the 4-fermion operators derived from this analysis appear to be less stringent than those obtained, for example, from the EWPOs. We expect that the bounds resulting through the DY process can be used to strengthen those from other sources.**

Conclusions

- ***We have computed the neutral Drell Yan scattering including all dimension-6 operators in the SMEFT framework, providing NLO QCD and electroweak contributions.***

- ***Using the Kreimer scheme, we discussed how to calculate all the virtual contributions including 4 fermions at NLO.***

- ***With these results we presented an initial phenomenological study for one of the operators, discussing different flavor scenarios and the correlation between the coefficients.***

Thank you very much!