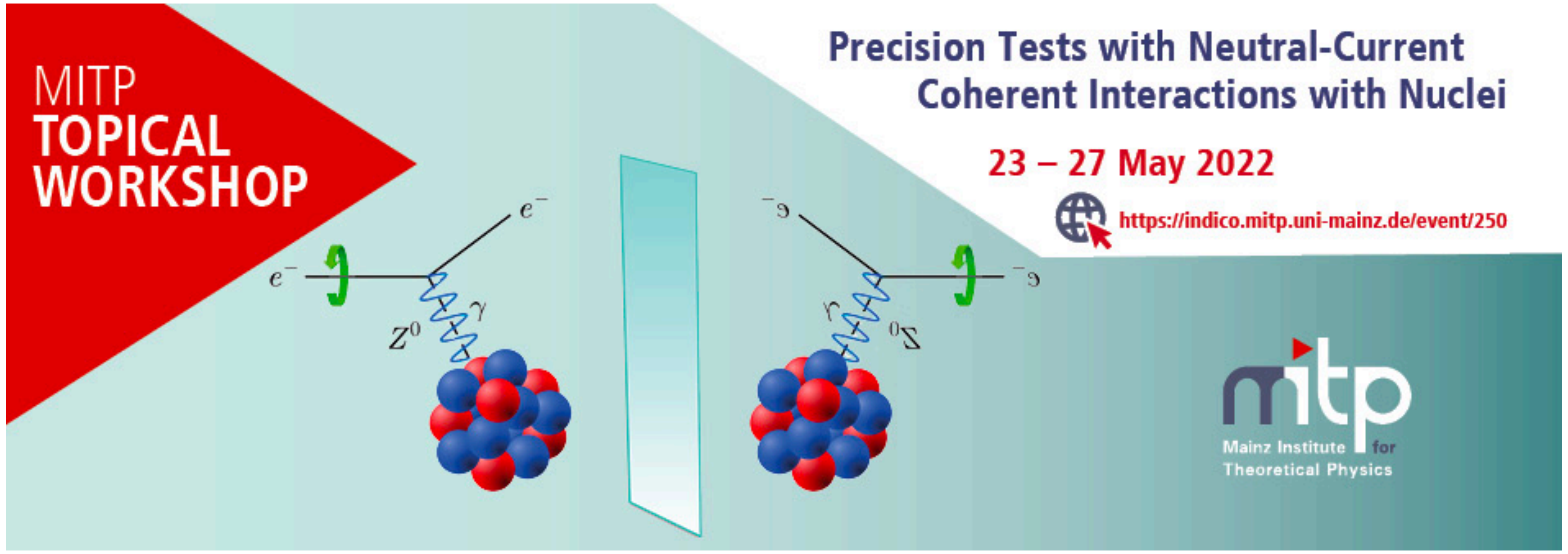

Constraints on dimension-6 SMEFT operators

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Overview

- Motivation
- Introduction to SMEFT
- P2(A_{RL})
- SoLID(A_{RL})
- LHC(Drell-Yan)(A_{FB})

Motivation

- Constrain the linear combination of dim.6 SMEFT Operators that contributes for P2,SoLID and LHC(Drell-Yan process)
- Look how P2, SoLID and LHC(Drell-Yan) can improve the current bounds on SMEFT coefficients

Introduction

Standard Model Effective Field Theory: low-energy limit of UV-complete theories at high energies

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM}^{(4)} + \frac{1}{\Lambda_L}\sum_k c_k^{(5)}\mathscr{O}_k^{(5)} + \frac{1}{\Lambda^2}\sum_k c_k^{(6)}\mathscr{O}_k^{(6)} + \frac{1}{\Lambda_L^3}\sum_k c_k^{(7)}\mathscr{O}_k^{(7)} + \frac{1}{\Lambda^4}\sum_k c_k^{(8)}\mathscr{O}_k^{(8)} + \ldots$$

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Effects of BSM physics are encoded in the higher dim. Operators

B-L - (Baryon number - Lepton number)

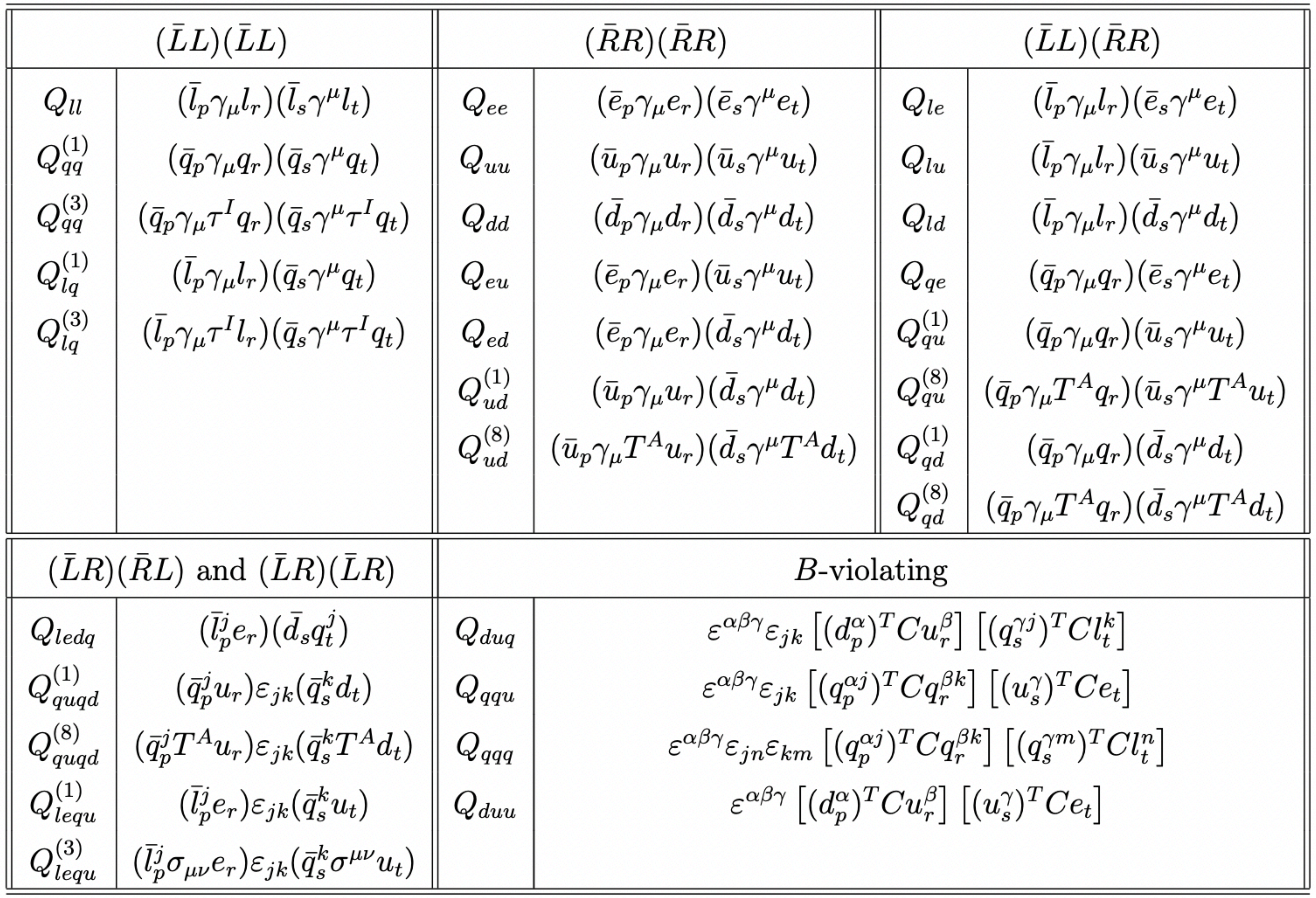
$$v << \underbrace{\Lambda}_{\swarrow} << \underbrace{\Lambda_L}_{\searrow}$$

B-L conserving
new physics scale

B-L violating
new physics scale
$\Lambda_L \sim \mathscr{O}(10^{15} GeV)$

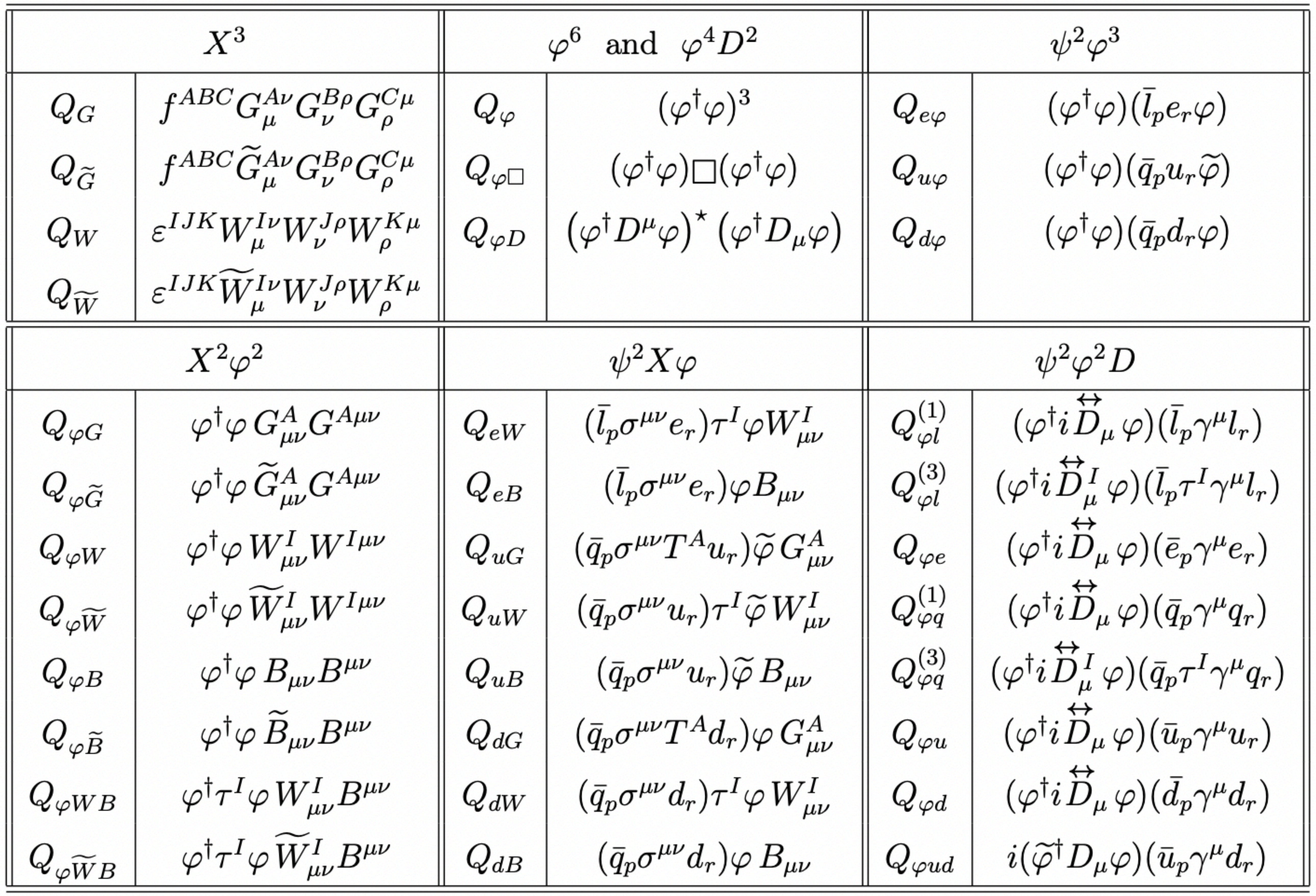
Dimension 6 SMEFT Operators

arXiv:1008.4884
B. Grzadkowski, M. Iskrzyński, M. Misiak and J. Rosiek



$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		



X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$$D_\mu = \partial_\mu - ig_L T^I W_\mu^I - ig_Y Y B_\mu - ig_s C^A G_\mu^A$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi = i\varphi^\dagger(D_\mu\varphi) - i(D_\mu\varphi)^\dagger\varphi$$

$$\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi = i\varphi^\dagger\tau^I(D_\mu\varphi) - i(D_\mu\varphi)^\dagger\tau^I\varphi$$

- 59 non redundant operators at dim.6 with flavour universality
- More than 2000 operators without any flavour assumption

Dimension 6 SMEFT Operators

arXiv:1008.4884

B. Grzadkowski, M. Iskrzyński, M. Misiak and J. Rosiek

Four fermion operators

$(\bar{L}L)(\bar{L}L)$				$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	[illegible]	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
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$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
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$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
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$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu} u_t)$		

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$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r\widetilde\varphi)$
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$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

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$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\,\widetilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

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Four fermion operators

Correction to fermion-Z vertex

$(\bar{L}L)(\bar{L}L)$				$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}		Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
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$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$
$Q_{\widetilde{G}}$	$f^{ABC}\widetilde{G}_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$			
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\,\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{u}_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\,\varphi)(\bar{d}_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$$D_\mu = \partial_\mu - ig_L T^I W_\mu^I - ig_Y Y B_\mu - ig_s C^A G_\mu^A$$
$$\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi = i\varphi^\dagger(D_\mu\varphi) - i(D_\mu\varphi)^\dagger\varphi$$
$$\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi = i\varphi^\dagger\tau^I(D_\mu\varphi) - i(D_\mu\varphi)^\dagger\tau^I\varphi$$

- 59 non redundant operators at dim.6 with flavour universality
- More than 2000 operators without any flavour assumption

Dimension 6 SMEFT Operators

arXiv:1008.4884
B. Grzadkowski, M. Iskrzyński, M. Misiak and J. Rosiek

$(\bar LL)(\bar LL)$		Four fermion operators		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	Q_{ee}	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	Q_{le}	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	Q_{uu}	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	Q_{lu}	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	Q_{ld}	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	Q_{eu}	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	Q_{qe}	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^TCu_r^\beta\right]\left[(q_s^{\gamma j})^TCl_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^TCq_r^{\beta k}\right]\left[(u_s^\gamma)^TCe_t\right]$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^TCq_r^{\beta k}\right]\left[(q_s^{\gamma m})^TCl_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^TCu_r^\beta\right]\left[(u_s^\gamma)^TCe_t\right]$
$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$		

X^3		φ^6 and φ^4D^2		$\psi^2\varphi^3$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r\varphi)$
$Q_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$Q_{\varphi\Box}$	Correction to M_Z	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r\widetilde\varphi)$
Q_W	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star\left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r\varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2X\varphi$		Correction to fermion-Z vertex	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar l_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\,\widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar l_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar e_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\,\widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar q_p\gamma^\mu q_r)$
$Q_{\varphi B}$	Correction to kinetic term($Z_{\mu\nu}Z^{\mu\nu}$)	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$		Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar u_p\gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar d_p\gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\,\widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p\gamma^\mu d_r)$

$$D_\mu = \partial_\mu - ig_LT^IW_\mu^I - ig_YYB_\mu - ig_sC^AG_\mu^A$$
$$\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi = i\varphi^\dagger(D_\mu\varphi) - i(D_\mu\varphi)^\dagger\varphi$$
$$\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi = i\varphi^\dagger\tau^I(D_\mu\varphi) - i(D_\mu\varphi)^\dagger\tau^I\varphi$$

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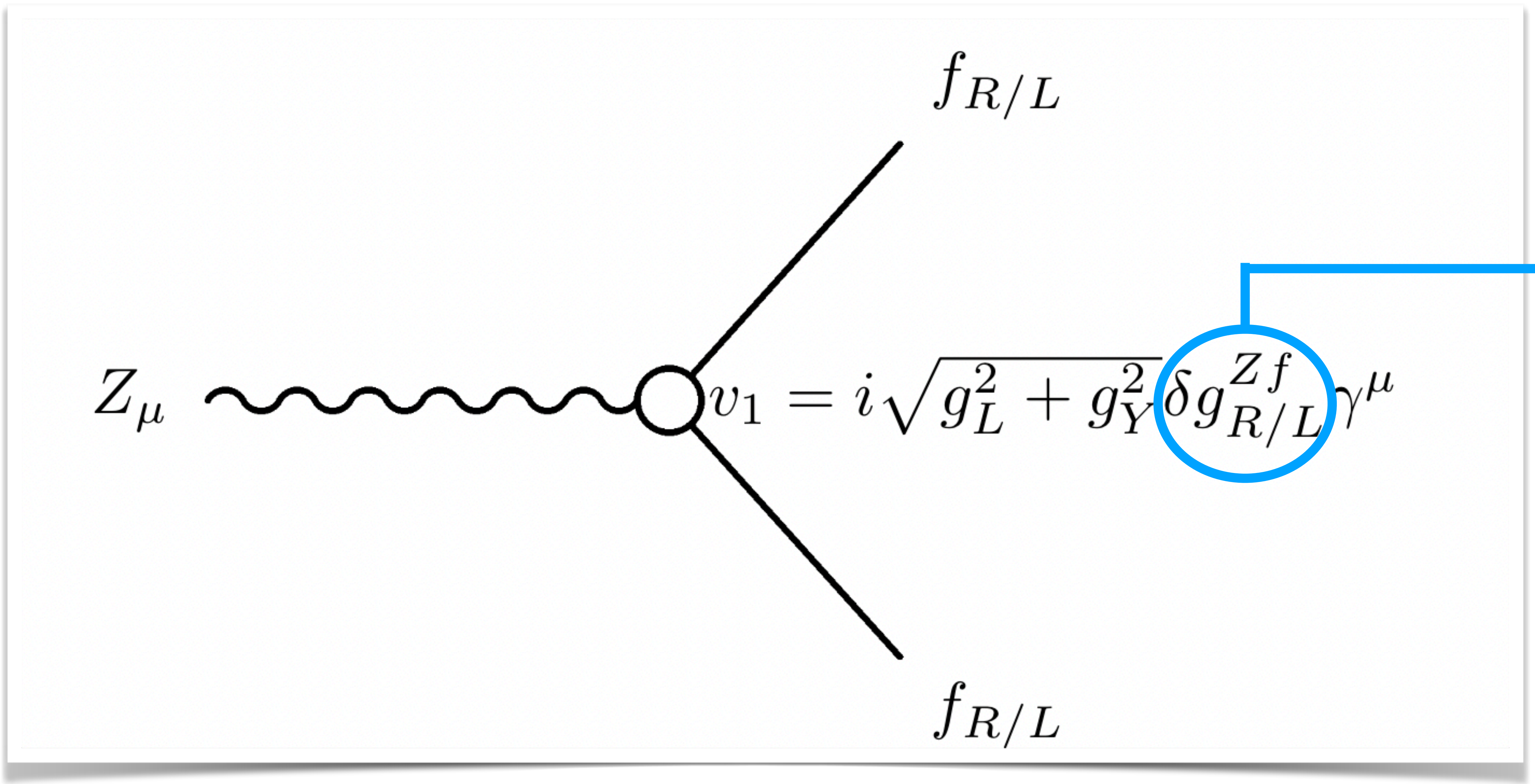
- More than 2000 operators without any flavour assumption

Correction to Z vertex from Dimension 6 SMEFT operators

Example: $\frac{C_{\varphi l}^{(1)}}{\Lambda^2}(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r) = \frac{C_{\varphi l}^{(1)}}{\Lambda^2}(-\frac{1}{2}\sqrt{g_L^2+g_Y^2}(h+v)^2 Z_\mu)(\bar{\nu}_{pL}\gamma^\mu\nu_{rL}+\bar{e}_{pL}\gamma^\mu e_{rL})$



$$\delta g_L^{Zd} = (-C_{\varphi q}^{(1)} - C_{\varphi q}^{(3)})\frac{v^2}{2\Lambda^2}$$

$$\delta g_L^{Zu} = (-C_{\varphi q}^{(1)} + C_{\varphi q}^{(3)})\frac{v^2}{2\Lambda^2}$$

$$\delta g_L^{Ze} = (-C_{\varphi l}^{(1)} - C_{\varphi l}^{(3)})\frac{v^2}{2\Lambda^2}$$

$$\delta g_L^{Z\nu} = (-C_{\varphi l}^{(1)} + C_{\varphi l}^{(3)})\frac{v^2}{2\Lambda^2}$$

$$\delta g_R^{Ze} = (-C_{\varphi e})\frac{v^2}{2\Lambda^2}$$

$$\delta g_R^{Zu} = (-C_{\varphi u})\frac{v^2}{2\Lambda^2}$$

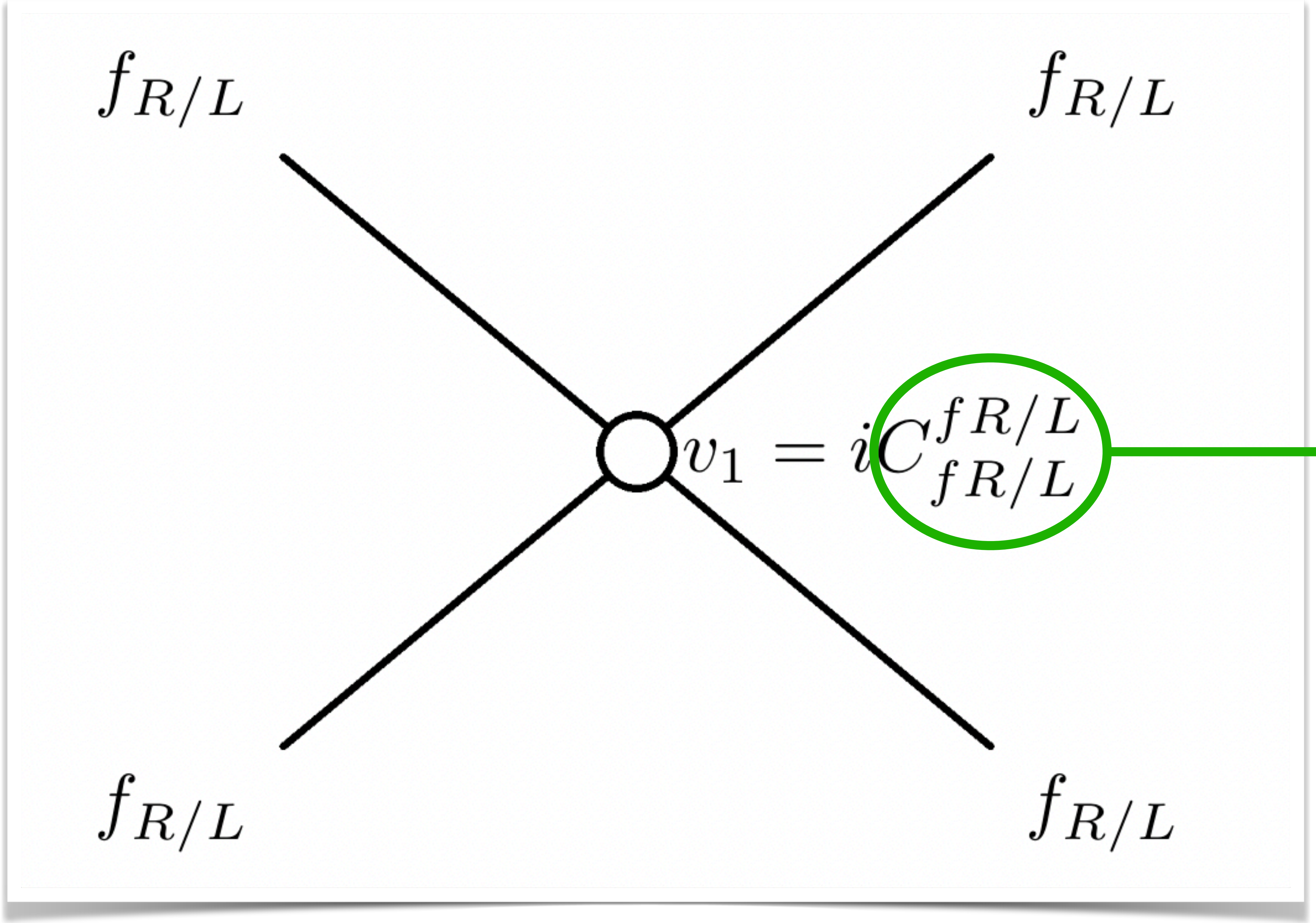
$$\delta g_R^{Zd} = (-C_{\varphi u})\frac{v^2}{2\Lambda^2}$$

$$\delta g_L^{Wq} = (C_{\varphi q}^{(3)})\frac{v^2}{\Lambda^2}$$

$$\delta g_L^{We} = (C_{\varphi l}^{(3)})\frac{v^2}{\Lambda^2}$$

Four fermion Dimension 6 SMEFT operators

Example: $$\frac{C_{lq}^{(1)}}{\Lambda^2}(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t) = \frac{C_{lq}^{(1)}}{\Lambda^2}(\bar{\nu}_{pL}\gamma_\mu \nu_{rL})(\bar{u}_{sL}\gamma^\mu u_{tL}) + \frac{C_{lq}^{(1)}}{\Lambda^2}(\bar{\nu}_{pL}\gamma_\mu \nu_{rL})(\bar{d}_{sL}\gamma^\mu d_{tL}) + \frac{C_{lq}^{(1)}}{\Lambda^2}(\bar{e}_{pL}\gamma_\mu e_{rL})(\bar{u}_{sL}\gamma^\mu u_{tL}) + \frac{C_{lq}^{(1)}}{\Lambda^2}(\bar{e}_{pL}\gamma_\mu e_{rL})(\bar{d}_{sL}\gamma^\mu d_{tL})$$



$$C^{eL}_{uL} = C^{\nu L}_{dL} = \frac{C^{(1)}_{lq} - C^{(3)}_{lq}}{\Lambda^2} \qquad C^{eR}_{dR} = \frac{C_{ed}}{\Lambda^2}$$

$$C^{\nu L}_{uL} = C^{eL}_{dL} = \frac{C^{(1)}_{lq} + C^{(3)}_{lq}}{\Lambda^2} \qquad C^{\nu eL}_{udL} = 2\frac{C^{(3)}_{lq}}{\Lambda^2}$$

$$C^{eL}_{uR} = C^{\nu L}_{uR} = \frac{C_{lu}}{\Lambda^2} \qquad C^{eR}_{uR} = \frac{C_{eu}}{\Lambda^2}$$

$$C^{eR}_{uL} = C^{eR}_{dL} = \frac{C_{qe}}{\Lambda^2} \qquad C^{eL}_{dR} = C^{\nu L}_{dR} = \frac{C_{ld}}{\Lambda^2}$$

P2(Electron-Proton Elastic Scattering)

arXiv:1802.04759v2

$$A_{RL}^{Exp.} = \underset{A_{RL}^{SM}}{\underset{\Big\downarrow}{\boxed{\frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}}}} + \underset{\delta A_{RL}}{\underset{\Big\downarrow}{\boxed{\frac{d\delta\sigma_R - d\delta\sigma_L}{d\sigma_R + d\sigma_L}}}}$$

$$\boxed{A_{RL}^{Exp.} = \lim_{Q^2 \to 0} \left(\frac{-Q^2 G_F}{4\pi\alpha_{em}\sqrt{2}} \right) \left[Q_W(p) + 2\delta Q_W(p) \right]}$$

P2(Electron-Proton Elastic Scattering)

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$$A_{RL}^{Exp.} = \underbrace{\boxed{\frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}}}_{A_{RL}^{SM}} + \underbrace{\boxed{\frac{d\delta\sigma_R - d\delta\sigma_L}{d\sigma_R + d\sigma_L}}}_{\delta A_{RL}}$$

$$\boxed{A_{RL}^{Exp.} = \lim_{Q^2 \to 0} \left(\frac{-Q^2 G_F}{4\pi\alpha_{em}\sqrt{2}} \right) \left[\underbrace{Q_W(p)} + 2\delta Q_W(p) \right]}$$

Proton’s weak charge,

$$Q_W(p) = (2\hat{g}_V^u + \hat{g}_V^d) = (1 - 4\sin^2\theta_W)$$

P2(Electron-Proton Elastic Scattering)

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Proton’s weak charge,

$$Q_W(p) = (2\hat{g}_V^u + \hat{g}_V^d) = (1 - 4\sin^2\theta_W)$$

Correction to Proton’s weak charge from Dim.6 SMEFT operators,

$$\delta Q_W(p) = \underbrace{(2\delta\hat{g}_V^{Zu} + \delta\hat{g}_V^{Zd})}_{\text{Quark-Z vertex correction}} + \underbrace{Q_W(p)\delta\hat{g}_A^{Ze}}_{\text{electron-Z vertex correction}} + \underbrace{\frac{v^2}{2}(2C_{uV}^{eA} + C_{dV}^{eA})}_{\text{4 fermion}}$$

P2(Electron-Proton Elastic Scattering)

arXiv:1802.04759v2

$$A_{RL}^{Exp.} = \underset{\displaystyle A_{RL}^{SM}}{\underset{\Big\downarrow}{\boxed{\frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}}}} + \underset{\displaystyle \delta A_{RL}}{\underset{\Big\downarrow}{\boxed{\frac{d\delta\sigma_R - d\delta\sigma_L}{d\sigma_R + d\sigma_L}}}}$$

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Convention:

$$\boxed{\begin{aligned} C_{uV}^{eA} &= C_{uV}^{eR} - C_{uV}^{eL} = C_{uR}^{eR} + C_{uL}^{eR} - C_{uR}^{eL} - C_{uL}^{eL} \\ C_{dV}^{eA} &= C_{dV}^{eR} - C_{dV}^{eL} = C_{dR}^{eR} + C_{dL}^{eR} - C_{dR}^{eL} - C_{dL}^{eL} \\ \delta\hat{g}_V^{Zu} &= \delta\hat{g}_R^{Zu} + \delta\hat{g}_L^{Zu} \\ \delta\hat{g}_V^{Zd} &= \delta\hat{g}_R^{Zd} + \delta\hat{g}_L^{Zd} \\ \delta\hat{g}_A^{Ze} &= \delta\hat{g}_R^{Ze} - \delta\hat{g}_L^{Ze} \end{aligned}}$$

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Correction to Proton's weak charge from Dim.6 SMEFT operators,

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SoLID(Electron- Deuteron Deep Inelastic Scattering)

$$\boxed{A_{RL} = -\left(\frac{G_F Q^2}{4\sqrt{2}\alpha\pi}\right)\left[\frac{4\sum_q Q^q(C_{1q}+\delta C_{1q})(f_q(x)+f_{\bar{q}}(x))}{\sum_q (Q^q)^2(f_q(x)+f_{\bar{q}}(x))}Y_1 + \frac{4\sum_q Q^q(C_{2q}+\delta C_{2q})(f_q(x)-f_{\bar{q}}(x))}{\sum_q (Q^q)^2(f_q(x)+f_{\bar{q}}(x))}Y_2\right]}$$

C_{1q}, C_{2q} - SM coefficients

$\delta C_{1q}, \delta C_{2q}$ - SMEFT coefficients

$f_q(x), f_{\bar{q}}(x)$ - Quark, anti-quark PDF

arXiv:2104.03979v1

Radja Boughezal, Frank Petriello and Daniel Wiegand

In Center of Mass (treating the electron and proton as massless)

$$Y_1 = 1, Y_2 = \frac{1-(1-y)^2}{1+(1-y)^2}$$

$$y = \frac{2P\,.\,q}{s} = \frac{\hat{s}+\hat{u}}{\hat{s}}$$

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SoLID(Electron- Deuteron Deep Inelastic Scattering)

$$C_{1q} = \hat{g}^e_A \hat{g}^q_V \qquad \delta C_{1q} = \hat{g}^e_A \delta\hat{g}^q_V + \delta\hat{g}^e_A \hat{g}^q_V + C^{eA}_{qV}\frac{v^2}{4} \qquad C_{2q} = \hat{g}^e_V \hat{g}^q_A \qquad \delta C_{2q} = \hat{g}^e_V \delta\hat{g}^q_A + \delta\hat{g}^e_V \hat{g}^q_A + C^{eV}_{qA}\frac{v^2}{4}$$

$$\boxed{A_{RL} = -\left(\frac{G_F Q^2}{4\sqrt{2}\alpha\pi}\right)\left[\frac{4\sum_q Q^q(\overbrace{C_{1q}} + \overbrace{\delta C_{1q}})(f_q(x) + f_{\bar{q}}(x))}{\sum_q (Q^q)^2(f_q(x) + f_{\bar{q}}(x))}Y_1 + \frac{4\sum_q Q^q(\overbrace{C_{2q}} + \overbrace{\delta C_{2q}})(f_q(x) - f_{\bar{q}}(x))}{\sum_q (Q^q)^2(f_q(x) + f_{\bar{q}}(x))}Y_2\right]}$$

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$$\boxed{A_{RL} = -\left(\frac{G_F Q^2}{4\sqrt{2}\alpha\pi}\right)\left[\frac{4\sum_q Q^q(\overbrace{C_{1q}}^{C_{1q} = \hat{g}^e_A \hat{g}^q_V} + \overbrace{\delta C_{1q}}^{\delta C_{1q} = \hat{g}^e_A \delta\hat{g}^q_V + \delta\hat{g}^e_A \hat{g}^q_V + C^{eA}_{qV}\frac{v^2}{4}})(f_q(x) + f_{\bar{q}}(x))}{\sum_q (Q^q)^2(f_q(x) + f_{\bar{q}}(x))}Y_1 + \frac{4\sum_q Q^q(\overbrace{C_{2q}}^{C_{2q} = \hat{g}^e_V \hat{g}^q_A} + \overbrace{\delta C_{2q}}^{\delta C_{2q} = \hat{g}^e_V \delta\hat{g}^q_A + \delta\hat{g}^e_V \hat{g}^q_A + C^{eV}_{qA}\frac{v^2}{4}})(f_q(x) - f_{\bar{q}}(x))}{\sum_q (Q^q)^2(f_q(x) + f_{\bar{q}}(x))}Y_2\right]}$$

C_{1q}, C_{2q} - SM coefficients

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$f_q(x), f_{\bar{q}}(x)$ - Quark, anti-quark PDF

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Radja Boughezal, Frank Petriello and Daniel Wiegand

Convention:

$$C^{eA}_{qV} = C^{eR}_{qV} - C^{eL}_{qV} = C^{eR}_{qR} + C^{eR}_{qL} - C^{eL}_{qR} - C^{eL}_{qL}$$

$$C^{eV}_{qA} = C^{eR}_{qA} + C^{eL}_{qA} = C^{eR}_{qR} - C^{eR}_{qL} + C^{eL}_{qR} - C^{eL}_{qL}$$

$$\delta\hat{g}^{Zq}_V = \delta\hat{g}^{Zq}_R + \delta\hat{g}^{Zq}_L$$

$$\delta\hat{g}^{Zq}_A = \delta\hat{g}^{Zq}_R - \delta\hat{g}^{Zq}_L$$

$$\delta\hat{g}^{Ze}_V = \delta\hat{g}^{Ze}_R + \delta\hat{g}^{Ze}_L$$

$$\delta\hat{g}^{Ze}_A = \delta\hat{g}^{Ze}_R - \delta\hat{g}^{Ze}_L$$

In Center of Mass (treating the electron and proton as massless)

$$Y_1 = 1, Y_2 = \frac{1-(1-y)^2}{1+(1-y)^2}$$

$$y = \frac{2P\,.\,q}{s} = \frac{\hat{s}+\hat{u}}{\hat{s}}$$

LHC(Drell-Yan Process)

SM contribution for asymmetry

SMEFT contribution for asymmetry

$$\sigma(Y,\hat{s}) = \sigma^{SM}(Y,\hat{s}) + \delta\sigma(Y,\hat{s})$$

arXiv:1110.2682v2
The CMS Collaboration

$$\boxed{\sigma(Y,\hat{s}) = \sum_q \int d\hat{s}dYd\cos\theta\left(\frac{\alpha_{em}^2\pi}{6s}\right)\left((X_{even}+\delta X_{even})(1+\cos^2\theta)+\underbrace{D_{q\bar{q}}(Y,\hat{s})}(X_{odd}+\delta X_{odd})2\cos\theta\right)\underbrace{F_{q\bar{q}}(Y,\hat{s})}}$$

$$\overbrace{F_{q\bar{q}}(Y,\hat{s}) = f_q(x_1)f_{\bar{q}}(x_2) + f_q(x_2)f_{\bar{q}}(x_1)}$$

$$\overbrace{D_{q\bar{q}}(Y,\hat{s}) = \frac{f_q(x_1)f_{\bar{q}}(x_2) - f_q(x_2)f_{\bar{q}}(x_1)}{F_{q\bar{q}}(Y,\hat{s})}}$$

M- dilepton invariant mass
Y-rapidity
S- Center of Mass Energy

$$x_1 = \sqrt{\frac{\hat{s}}{s}}e^{Y}\ , x_2 = \sqrt{\frac{\hat{s}}{s}}e^{-Y}$$

$$Y = \frac{1}{2}(lnx_1 - lnx_2)$$

$$\hat{s}= M^2=x_1x_2s$$

Forward Backward Asymmetry in LHC Drell-Yan

$$X_{even} = \frac{Q_l^2 Q_q^2}{\hat{s}} + \frac{2Q^l Q^q}{c_W^2 s_W^2} \frac{1}{(\hat{s} - M_z^2)} \frac{\hat{g}_V^e \hat{g}_V^q}{4} + \frac{1}{c_W^4 c_W^4} \frac{\hat{s}}{(\hat{s} - M_z^2)^2} \frac{(\hat{g}_V^{e2} + \hat{g}_A^{e2})(\hat{g}_V^{q2} + \hat{g}_A^{q2})}{16}$$

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$c_W = cos\theta_w$

M_z=91.1876 GeV

$$A_{FB}^{Exp.} = \underset{\substack{\Big\downarrow \\ A_{FB}^{SM}}}{\boxed{\frac{\sigma_F(Y, \hat{s}) - \sigma_B(Y, \hat{s})}{\sigma_F(Y, \hat{s}) + \sigma_B(Y, \hat{s})}}} + \underset{\substack{\Big\downarrow \\ \delta A_{FB}}}{\boxed{\frac{\delta\sigma_F(Y, \hat{s}) - \delta\sigma_B(Y, \hat{s})}{\sigma_F(Y, \hat{s}) + \sigma_B(Y, \hat{s})}}}$$

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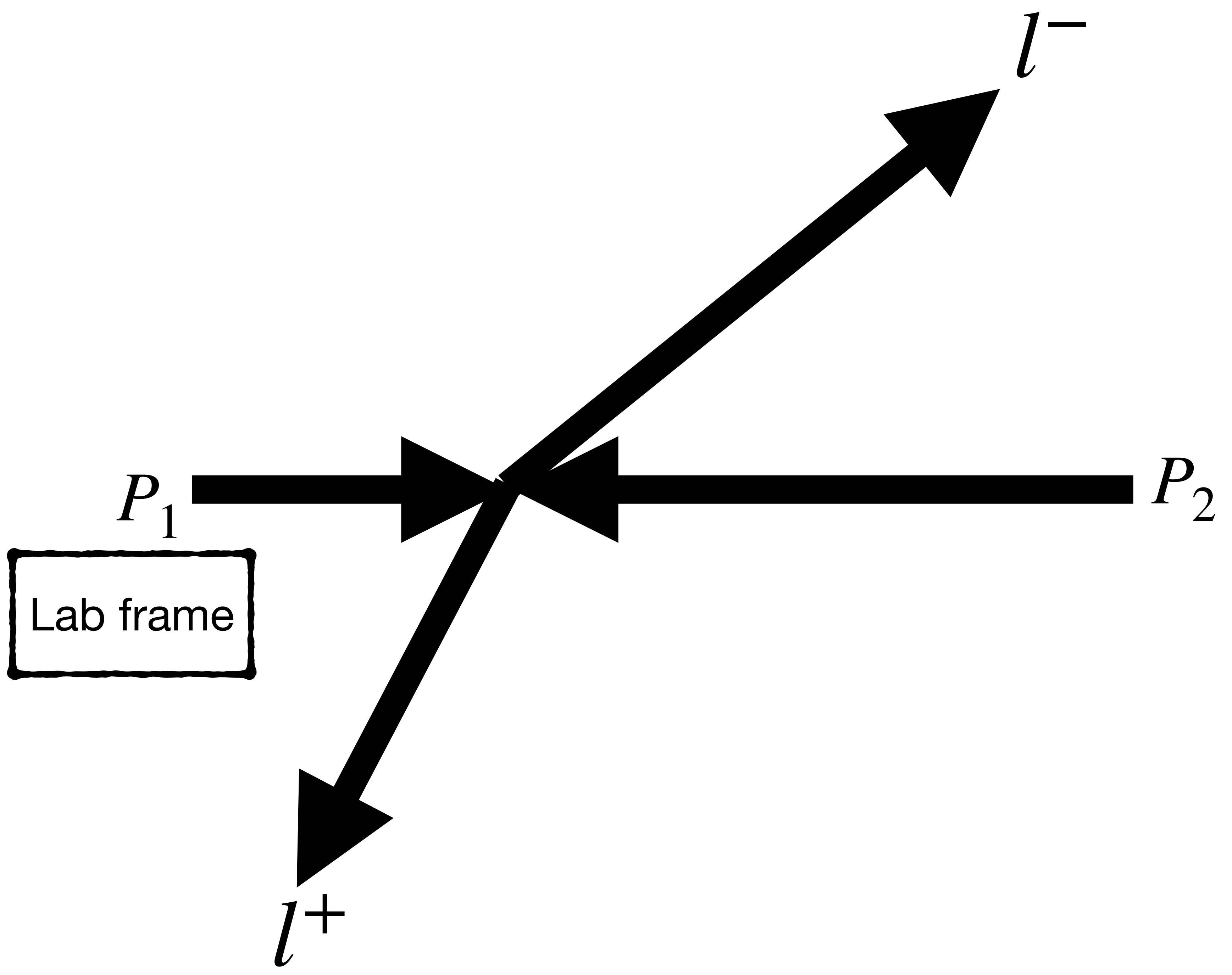

Forward Backward Asymmetry in LHC Drell-Yan

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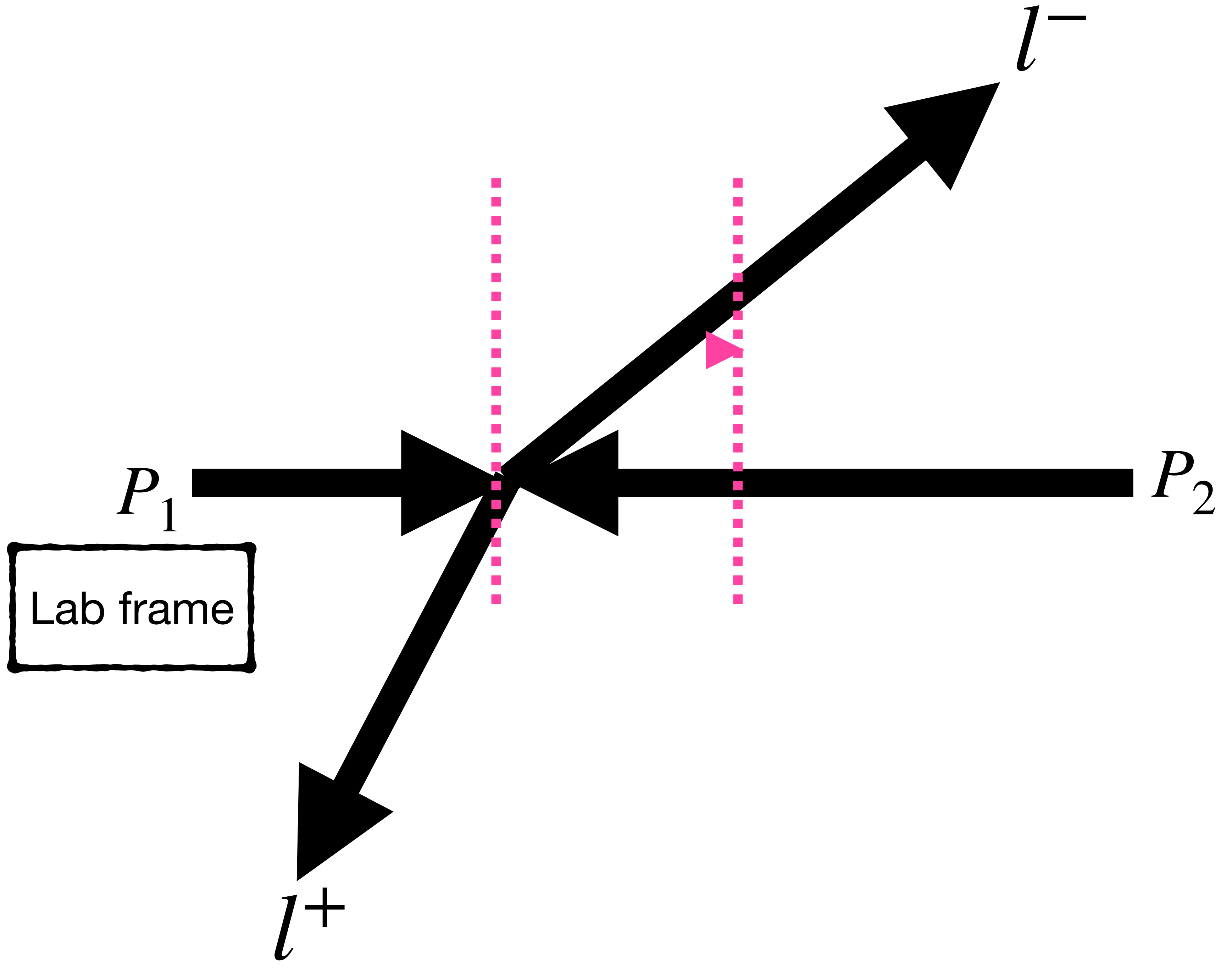

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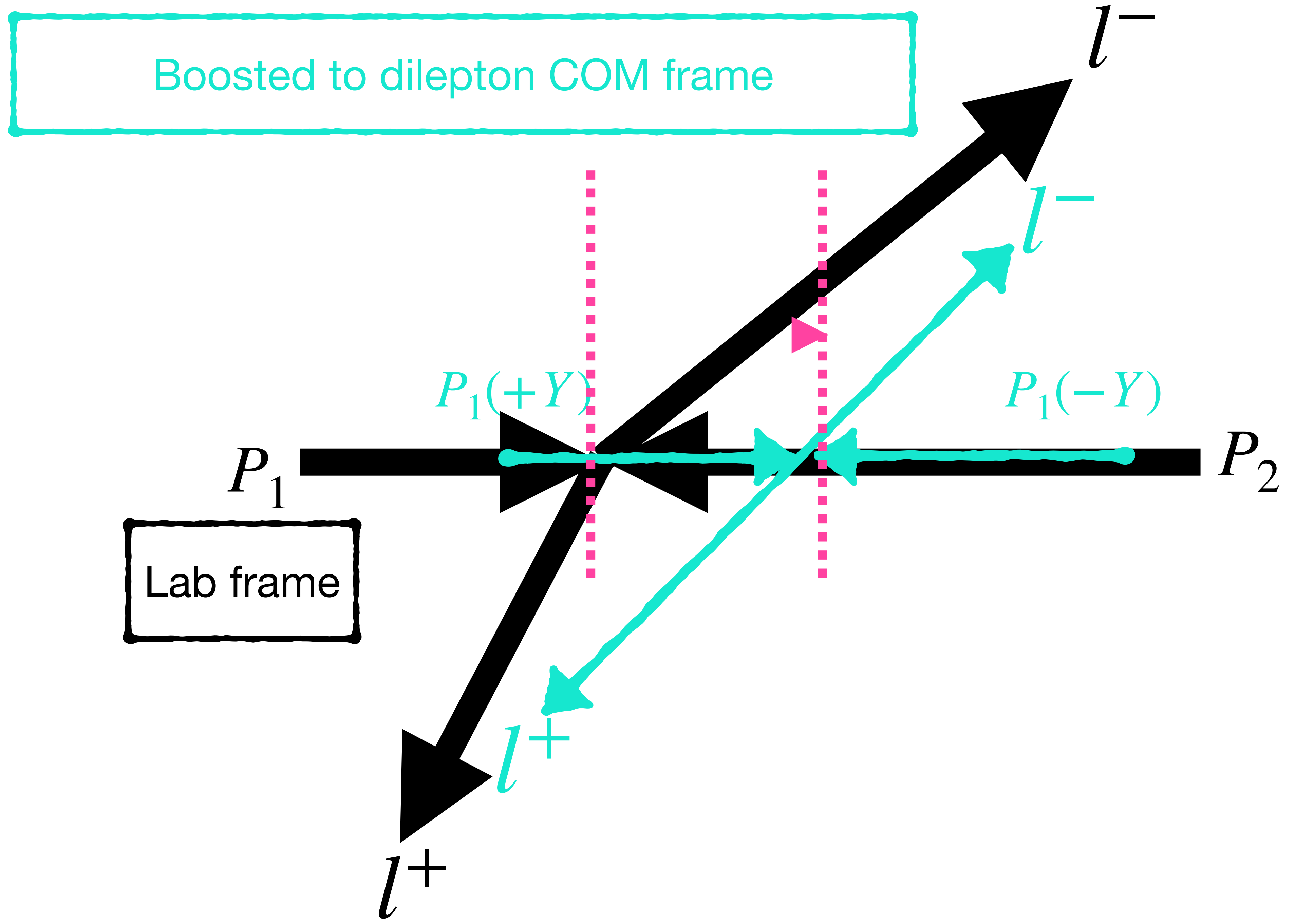

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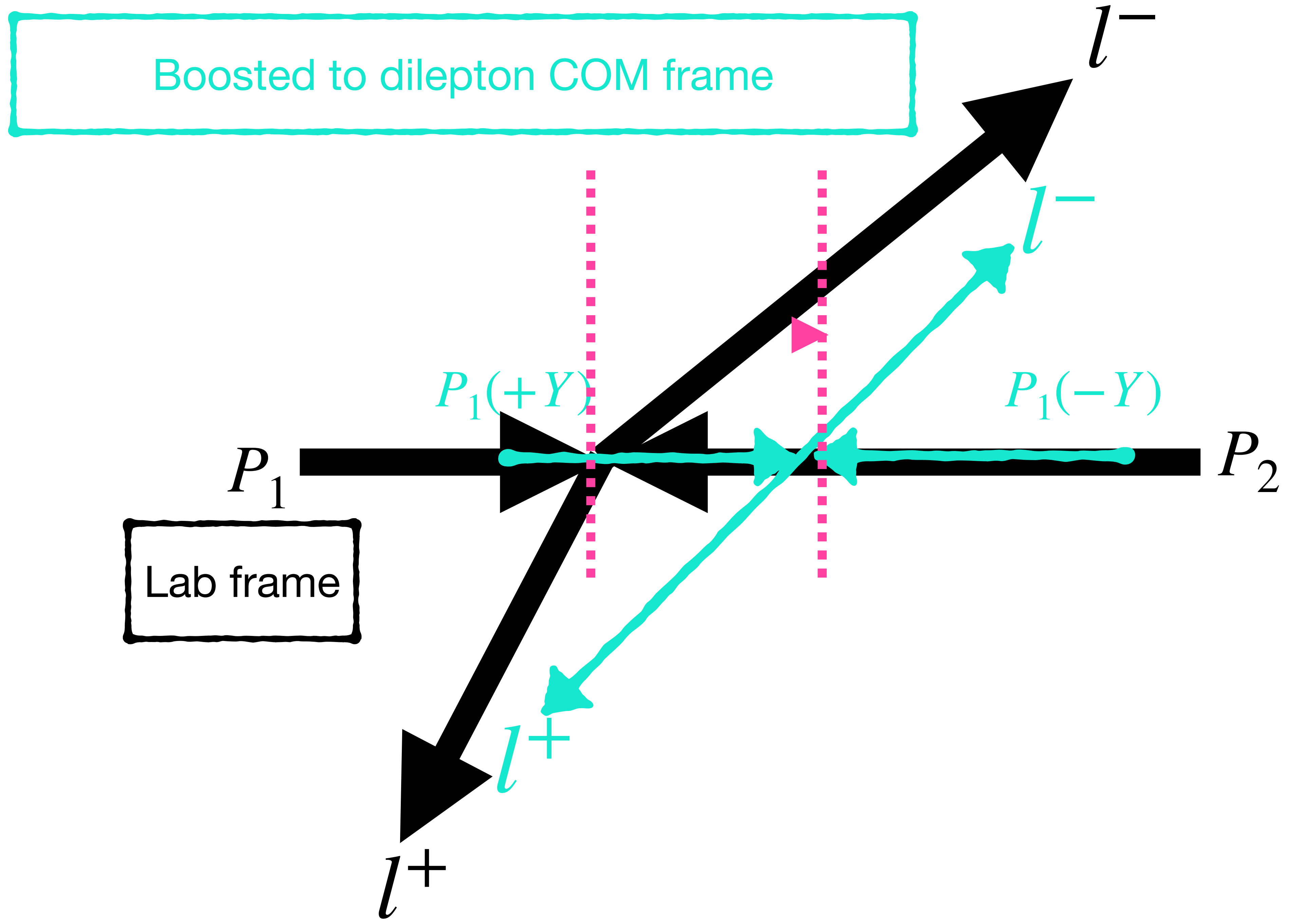
Forward scattering - lepton and boost are direction same
Backward scattering- lepton and boost direction are opposite



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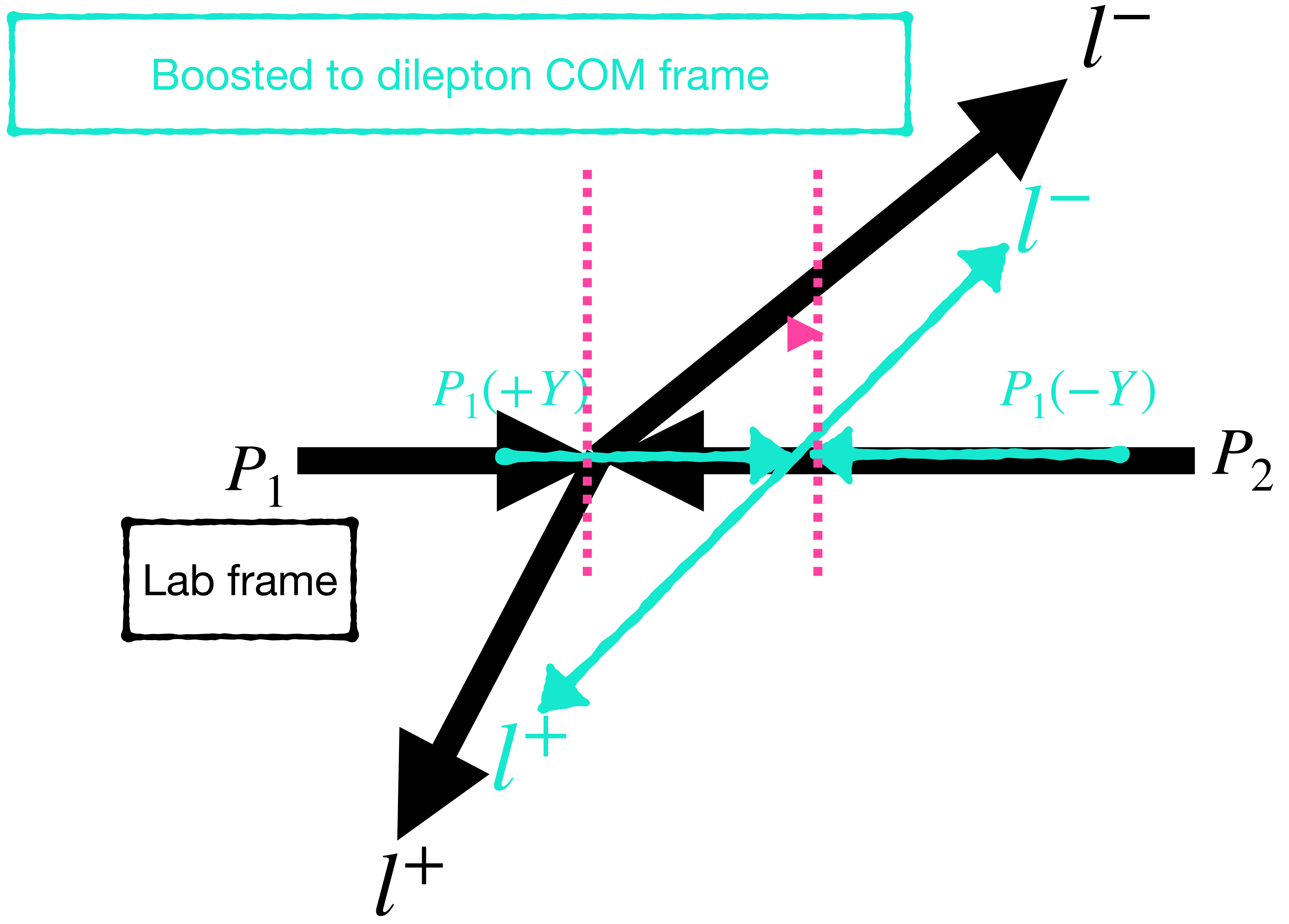

Forward scattering - lepton and boost are direction same
Backward scattering- lepton and boost direction are opposite

X_{odd} leads to forward backward asymmetry

Standard Model prediction

A_{FB} at leading order for different PDFs

Y	CT18NNLO	MSTW2008nnlo)	MSTW2008lo
0.0-0.8	0.0144(0.0%)	0.0147(2.0%)	0.0134(7.0%)
0.8-1.6	0.0493(4.6%)	0.0493(4.6%)	0.0441(6.8%)
1.6-2.5	0.0998(7.5%)	0.0978(5.3%)	0.0887(4.4%)
2.5-3.6	0.1476(0.8%)	0.1481(1.0%)	0.1400(4.3%)

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A_{FB} at NNLO in QCD

Y	Experimental	SM Prediction
0.0-0.8	0.0195±0.0015	0.0144±0.0007
0.8-1.6	0.0448±0.0016	0.0471±0.0017
1.6-2.5	0.0923±0.0026	0.0928±0.0021
2.5-3.6	0.1445±0.0046	0.1464±0.0021

Reference: ATLAS, Report number: ATLAS-CONF-2018-037 (2018).

Future Work

- Simplify the linear combination of dim.6 SMEFT operators for A_{FB} from LHC
- Look at the correlations in systematic errors of all the linear combinations

Backup slides

$$A_{RL}^{Exp.} = A_{RL}^{SM} + \delta A_{RL} = \underbrace{\boxed{\frac{d\sigma_R - d\sigma_L}{d\sigma_R + d\sigma_L}}}_{A_{RL}^{SM}} + \underbrace{\boxed{\frac{d\delta\sigma_R - d\delta\sigma_L}{d\sigma_R + d\sigma_L}}}_{\delta A_{RL}} - \underbrace{\boxed{A_{RL}^{SM}\frac{d\delta\sigma_R + d\delta\sigma_L}{d\sigma_R + d\sigma_L}}}_{\text{smaller that } \delta A_{RL}} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

Backup slides

$$\delta X_{even} = \underbrace{(\frac{2Q^lQ^q}{C_W^2S_W^2})\frac{1}{(\hat{s}-M_z^2)}\frac{\delta\hat{g}_V^e\hat{g}_V^q+\hat{g}_V^e\delta\hat{g}_V^q}{4}}_{\begin{array}{c}\downarrow\\ \gamma-\delta Z\\ \text{interference}\end{array}} \underbrace{+(\frac{2}{C_W^4S_W^4})\frac{\hat{s}}{(\hat{s}-M_z^2)^2}\frac{(\hat{g}_V^e\delta\hat{g}_V^e+\hat{g}_A^e\delta\hat{g}_A^e)(\hat{g}_V^{q2}+\hat{g}_A^{q2})+(\hat{g}_V^{e2}+\hat{g}_A^{e2})(\hat{g}_V^q\delta\hat{g}_V^q+\hat{g}_A^q\delta\hat{g}_A^q)}{16}}_{\begin{array}{c}\downarrow\\ \text{Z}-\delta Z\\ \text{interference}\end{array}} + \underbrace{\frac{2Q_lQ_q}{\alpha4\pi}\frac{C_{qV}^{eV}}{4}}_{\begin{array}{c}\downarrow\\ \gamma\text{-4}\\ \text{interference}\end{array}} + \underbrace{\frac{2}{C_W^2S_W^2}\frac{1}{\alpha4\pi}\frac{\hat{s}}{(\hat{s}-M_z^2)}\frac{\hat{g}_V^q(\hat{g}_V^eC_{qV}^{eV}+\hat{g}_A^eC_{qV}^{eA})+\hat{g}_A^q(\hat{g}_V^eC_{qA}^{eV}+\hat{g}_A^eC_{qA}^{eA})}{16}}_{\begin{array}{c}\downarrow\\ \text{Z-4}\\ \text{interference}\end{array}}$$

$$\delta X_{odd} = \overbrace{(\frac{2Q^lQ^q}{C_W^2S_W^2})\frac{1}{(\hat{s}-M_z^2)}\frac{\delta\hat{g}_A^e\hat{g}_A^q+\hat{g}_A^e\delta\hat{g}_A^q}{4}}^{\uparrow} \overbrace{+(\frac{2}{C_W^4S_W^4})\frac{\hat{s}}{(\hat{s}-M_z^2)^2}\frac{2\hat{g}_V^q\hat{g}_A^q(\delta\hat{g}_V^e\hat{g}_A^e+\hat{g}_V^e\delta\hat{g}_A^e)+2\hat{g}_V^e\hat{g}_A^e(\delta\hat{g}_V^q\hat{g}_A^q+\hat{g}_V^q\delta\hat{g}_A^q)}{16}}^{\uparrow} + \overbrace{\frac{2Q_lQ_q}{\alpha4\pi}\frac{C_{qA}^{eA}}{4}}^{\uparrow} + \overbrace{\frac{2}{C_W^2S_W^2}\frac{1}{\alpha4\pi}\frac{\hat{s}}{(\hat{s}-M_z^2)}\frac{\hat{g}_V^q(\hat{g}_V^eC_{qA}^{eA}+\hat{g}_A^eC_{qA}^{eV})+\hat{g}_A^q(\hat{g}_V^eC_{qV}^{eA}+\hat{g}_A^eC_{qV}^{eV})}{16}}^{\uparrow}$$