Dimension Six Terms in the Standard Model Lagrangian

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Unification in the LHC era
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Effective theories

Example

Standard Model $\rightarrow$ *Extension*

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But how does *Extension* correct *Standard Model* interactions in low-energy processes?

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Situation:
maximal momentum of particles $k \ll \Lambda$ scale of masses of heavy fields
$\rightarrow$ no explicit presence of heavy fields in the theory

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But how does *Extension* correct *Standard Model* interactions in low-energy processes?

Situation:
maximal momentum of particles $k \ll \Lambda$ scale of masses of heavy fields
$\to$ no explicit presence of heavy fields in the theory
$\to$ Appelquist-Carazzone decoupling theorem

$$\mathcal{L} = \mathcal{L}_{SM}^{(4)} + \frac{1}{\Lambda}\sum_i c_i^{(5)}\mathcal{O}_i^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)}\mathcal{O}_i^{(6)} + O(\frac{1}{\Lambda^3})$$

Significance of effective theories

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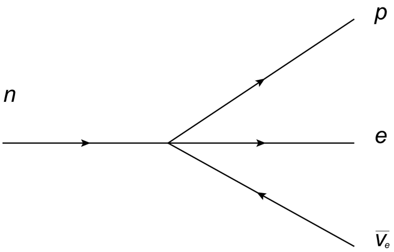

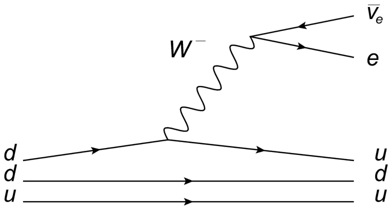

Significance of effective theories

When the underlying theory is not yet known:

- experimental constraints on coefficients give bounds for the couplings of broader theory
- clues for construction of the broader theory

When the underlying theory is known (e.g. it is SM) - effective theories give us calculational tools, that i.a. extend the validity of perturbation theory.

Classifications of effective operators

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What are the operators $\mathcal{O}_i^{(5)}$ and $\mathcal{O}_i^{(6)}$?

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Constraints:

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- Dependencies through EOM (H. D. Politzer, 1980)

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$\rightarrow$ but in fact only 59 operators are independent.

SM - gauge group representations structure

Field	representation (dimension)		hypercharge
	SU(3)	SU(2)	U(1)
G_μ	8	1	0
W_μ	1	3	0
B_μ	1	1	0
q	3	2	$\frac{1}{6}$
u	3	1	$\frac{2}{3}$
d	3	1	$-\frac{1}{3}$
l	1	2	$-\frac{1}{2}$
e	1	1	-1
φ	1	2	$\frac{1}{2}$

Mass-dimension of fundamental objects in units $\hbar = c = 1$

Type	vector V_μ	tensor $X_{\mu\nu}$	spinor Ψ	skalar φ
Dimension	$(GeV)^1$	$(GeV)^2$	$(GeV)^{\frac{3}{2}}$	$(GeV)^1$
Object	D_μ	$W_{\mu\nu}, G_{\mu\nu}, B_{\mu\nu}$	q, l, u, d, e	φ

- for SU(3)

$$G^A_{\mu\nu} = \partial_\mu G^B_\nu - \partial_\nu G^C_\mu - g_s f^{ABC} G^B_\mu G^C_\nu$$

- for SU(2)

$$W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu - g \varepsilon^{IJK} W^J_\mu W^K_\nu$$

- for U(1)

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

Reasoning scheme

1. Description in terms of matter fields (φ, ψ), field strength tensors $X_{\mu\nu}$ and covariant derivatives D_μ. Dimensional analysis.
2. Gauge and Lorentz symmetry.
3. Reduction of the set of operators using algebraic properties and SM EOM:

Reasoning scheme

1. Description in terms of matter fields (φ, ψ), field strength tensors $X_{\mu\nu}$ and covariant derivatives D_μ. Dimensional analysis.
   e.g. dim-6 expressions containing both fermionic and bosonic fields: $\psi\psi XD$, $\psi\psi X\varphi$, $\psi\psi\varphi\varphi\varphi$, $\psi\psi\varphi\varphi D$, $\psi\psi\varphi DD$, $\psi\psi DDD$
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   e.g. $\boxed{\psi\psi\varphi DD}$:
   many possible choices of ψ - the only singlet in $\hat{2}_{SU(2)} \otimes \hat{2}_{SU(2)}$
   hypercharge conservation

$$(q^\dagger \varepsilon \varphi^*)u, \quad (q^\dagger \varphi)d, \quad (l^\dagger \varphi)e, \quad + h.c.$$

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   Lorentz structure contains 2 singlets:

$$(0, \tfrac{1}{2}) \otimes (0, \tfrac{1}{2}) \otimes (\tfrac{1}{2}, \tfrac{1}{2}) \otimes (\tfrac{1}{2}, \tfrac{1}{2}) = (0,0) \oplus (0,0) \oplus (1,0) \oplus (2,0) \oplus (1,1) \oplus (0,1) \oplus (1,1) \oplus (2,1)$$

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   $$(q^\dagger \varepsilon \varphi^*)u, \ \ (q^\dagger \varphi)d, \ \ (l^\dagger \varphi)e, \quad + h.c.$$

   2 independent Lorentz invariants (for each):

   $$\bar{\psi}_L \psi_R \varphi D_\mu D^\mu \quad \bar{\psi}_L \sigma_{\mu\nu} \psi_R \varphi D^\mu D^\nu$$

3. Reduction of the set of operators using algebraic properties and SM EOM:

Reasoning scheme

1. Description in terms of matter fields (φ, ψ), field strength tensors $X_{\mu\nu}$ and covariant derivatives D_μ. Dimensional analysis.
2. Gauge and Lorentz symmetry.
3. Reduction of the set of operators using algebraic properties and SM EOM:
   We have (omitting full div) the following operators:

$$(\bar{\psi}_L \sigma_{\mu\nu} \psi_R)(D^\mu D^\nu \varphi) \tag{1}$$

$$(\bar{\psi}_L \sigma_{\mu\nu} D^\mu D^\nu \psi_R)\varphi \tag{2}$$

$$(\bar{\psi}_L \sigma_{\mu\nu} D^\mu \psi_R)(D^\nu \varphi) \tag{3}$$

$$(\bar{\psi}_L D_\mu D^\mu \psi_R)\varphi \tag{4}$$

$$(\bar{\psi}_L D_\mu \psi_R)(D^\mu \varphi) \tag{5}$$

$$(\bar{\psi}_L \psi_R)(D_\mu D^\mu \varphi) \tag{6}$$

Reasoning scheme

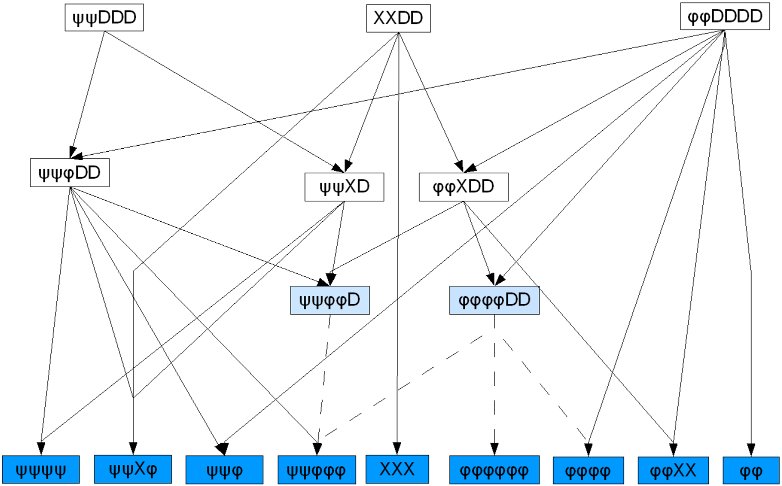
1. Description in terms of matter fields (φ, ψ), field strength tensors $X_{\mu\nu}$ and covariant derivatives D_μ. Dimensional analysis.
2. Gauge and Lorentz symmetry.
3. Reduction of the set of operators using algebraic properties and SM EOM:
   Using EOM for φ:

$$-(D_\mu D^\mu \varphi) + m^2\varphi - \lambda\varphi(\varphi^\dagger\varphi) - \Gamma_e^\dagger l\bar{e} + \Gamma_u \varepsilon \bar{q} u - \Gamma_d^\dagger q\bar{d} = 0$$

   we get

$$(\bar{\psi}_L\psi_R)(D_\mu D^\mu\varphi) = \boxed{\psi\psi\varphi} + \boxed{\psi\psi\varphi\varphi\varphi} + \boxed{\psi\psi\psi\psi}$$

Reduction scheme



Bosonic invariant operators

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

Bosonic invariant operators

$X^2\varphi^2$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$

Invariant operators with 2 fermions

$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$

(φ^2 singlet)(SM Yukawa couplings of φ)

Invariant operators with 2 fermions

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

Fermionic operators

General structure:

$$(\bar{\psi}_1 \gamma_\mu \psi_1)(\bar{\psi}_2 \gamma^\mu \psi_2) \quad (\bar{\psi}_1 \gamma_\mu T^\alpha \psi_1)(\bar{\psi}_2 \gamma^\mu T^\alpha \psi_2)$$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

Fermionic operators

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

Redundant operators

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$$(\bar{\psi}_R D_\mu \psi_L)(D^\mu \varphi)$$
$$[(D_\mu \bar{\psi}_R)\psi_L](D^\mu \varphi)$$

$$(\bar{\psi}\gamma_\mu D_\nu \psi)X^{\mu\nu}$$

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$$(\bar{l}_{p_1}\gamma_\mu T^I l_{p_2})(\bar{l}_{p_3}\gamma^\mu T^I l_{p_4})$$

$$T^I_{ij}T^I_{kl} = \frac{1}{2}\delta_{il}\delta_{kj} - \frac{1}{2N}\delta_{ij}\delta_{kl}$$

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The absent one: $(\bar{q}e)\varepsilon(\bar{l}u)^T$

Independence of listed operators

How do we know that these operators are finally independent?

Main arguments:

- field content
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Why $(\bar{q}e)\varepsilon(\bar{l}u)^T$ must be on the list?

- completeness of classification
- field content

Lepton/baryon nr violating invariant operators

$$(l^T \tilde{\varphi}^*)(\tilde{\varphi}^\dagger l)$$

B-violating	
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_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$

list already given by L.F. Abbott and M. B. Wise (1980), which simplified those given by S. Weinberg (1976) and F. Wilczek and A. Zee (1979)

The importance of classification

How to discover new physics?

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Recent papers with redundant operators:

- J. A. Aguilar-Saavedra, "Single top quark production at LHC with anomalous Wtb couplings", Nucl. Phys. B804 (2008) 160;
- K. Agashe, R. Contino, "Composite Higgs-mediated flavor-changing neutral current", Phys. Rev. D 80, 075016 (2009);
- S. Kanemura, K. Tsumura, "Effects of the anomalous Higgs couplings on the Higgs boson production at the Large Hadron Collider ", Eur. Phys. J. C63 (2009) 11;

The published results

- Bohdan Grzadkowski, Mikołaj Misiak, Janusz Rosiek, MI
  "Dimension-Six Terms in the Standard Model Lagrangian"
  JHEP 1010:085,2010
- J. A. Aguilar-Saavedra
  "Effective four-fermion operators in top physics: a roadmap"
  Nucl.Phys.B843:638-672,2011

Questions

Example: reduction of $(\bar{\psi} D_\mu \psi)(D^\mu \varphi)$

$$(\bar{\psi} D_\mu \psi)(D^\mu \varphi) = (\bar{\psi} D_\nu \eta^{\nu\mu} \psi)(D_\mu \varphi) = (\bar{\psi} D_\nu \tfrac{1}{2}\{\gamma^\nu, \gamma^\mu\} \psi)(D_\mu \varphi)$$

$$= \tfrac{1}{2}(\bar{\psi} D_\nu \gamma^\nu \gamma^\mu \psi)(D_\mu \varphi) + \tfrac{1}{2}(\bar{\psi} \gamma^\mu \underline{\not{D} \psi})(D_\mu \varphi)$$

$$= \boxed{\psi\psi\varphi\varphi D} + \tfrac{1}{2} D_\nu [(\bar{\psi} \gamma^\nu \gamma^\mu \psi)(D_\mu \varphi)] - \tfrac{1}{2}(\underline{\bar{\psi} \overleftarrow{\not{D}}} \gamma^\mu \psi)(D_\mu \varphi) +$$
$$- \tfrac{1}{2}(\bar{\psi} \gamma^\nu \gamma^\mu \psi)(D_\nu D_\mu \varphi)$$

but

$$(\bar{\psi} \gamma^\nu \gamma^\mu \psi)(D_\nu D_\mu \varphi) = (\bar{\psi}(-i)\sigma^{\nu\mu} \psi)(\sum_k X^k_{\nu\mu} \varphi) + (\bar{\psi} \psi)(\underline{D^\mu D_\mu \varphi})$$

so

$$(\bar{\psi}_L D_\mu \psi_R)(D^\mu \varphi) = \boxed{\psi\psi\varphi\varphi D} + \boxed{\psi\psi X \varphi} + \boxed{\psi\psi\varphi} + \boxed{\psi\psi\varphi\varphi\varphi} + \boxed{\psi\psi\psi\psi}$$

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$$(\bar\psi D_\mu\psi)(D^\mu\varphi) = (\bar\psi D_\nu \eta^{\nu\mu}\psi)(D_\mu\varphi) = (\bar\psi D_\nu \tfrac{1}{2}\{\gamma^\nu,\gamma^\mu\}\psi)(D_\mu\varphi)$$

$$= \tfrac{1}{2}(\bar\psi D_\nu\gamma^\nu\gamma^\mu\psi)(D_\mu\varphi) + \tfrac{1}{2}(\bar\psi\gamma^\mu \underline{\not{D}\psi})(D_\mu\varphi)$$

$$= \boxed{\psi\psi\varphi\varphi D} + \tfrac{1}{2} D_\nu[(\bar\psi\gamma^\nu\gamma^\mu\psi)(D_\mu\varphi)] - \tfrac{1}{2}(\underline{\bar\psi \overleftarrow{\not{D}}}\gamma^\mu\psi)(D_\mu\varphi) +$$
$$- \tfrac{1}{2}(\bar\psi\gamma^\nu\gamma^\mu\psi)(D_\nu D_\mu\varphi)$$

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so

$$(\bar\psi_L D_\mu\psi_R)(D^\mu\varphi) = \boxed{\psi\psi\varphi\varphi D} + \boxed{\psi\psi X\varphi} + \boxed{\psi\psi\varphi} + \boxed{\psi\psi\varphi\varphi\varphi} + \boxed{\psi\psi\psi\psi}$$

Example: reduction of $(\bar\psi D_\mu \psi)(D^\mu \varphi)$

$$(\bar\psi D_\mu \psi)(D^\mu \varphi) = (\bar\psi D_\nu \eta^{\nu\mu} \psi)(D_\mu \varphi) = (\bar\psi D_\nu \tfrac{1}{2}\{\gamma^\nu, \gamma^\mu\} \psi)(D_\mu \varphi)$$

$$= \tfrac{1}{2}(\bar\psi D_\nu \gamma^\nu \gamma^\mu \psi)(D_\mu \varphi) + \tfrac{1}{2}(\bar\psi \gamma^\mu \underline{\not{D}\psi})(D_\mu \varphi)$$

$$= \boxed{\psi\psi\varphi\varphi D} + \tfrac{1}{2} D_\nu[(\bar\psi \gamma^\nu \gamma^\mu \psi)(D_\mu \varphi)] - \tfrac{1}{2}(\underline{\bar\psi \overleftarrow{\not{D}}}\gamma^\mu \psi)(D_\mu \varphi) +$$
$$- \tfrac{1}{2}(\bar\psi \gamma^\nu \gamma^\mu \psi)(D_\nu D_\mu \varphi)$$

but

$$(\bar\psi \gamma^\nu \gamma^\mu \psi)(D_\nu D_\mu \varphi) = (\bar\psi (-i)\sigma^{\nu\mu} \psi)(\sum_k X^k_{\nu\mu} \varphi) + (\bar\psi \psi)(\underline{D^\mu D_\mu \varphi})$$

so

$$(\bar\psi_L D_\mu \psi_R)(D^\mu \varphi) = \boxed{\psi\psi\varphi\varphi D} + \boxed{\psi\psi X \varphi} + \boxed{\psi\psi\varphi} + \boxed{\psi\psi\varphi\varphi\varphi} + \boxed{\psi\psi\psi\psi}$$

Example: reduction of $(\bar{\psi} D_\mu \psi)(D^\mu \varphi)$

$$(\bar{\psi} D_\mu \psi)(D^\mu \varphi) = (\bar{\psi} D_\nu \eta^{\nu\mu} \psi)(D_\mu \varphi) = (\bar{\psi} D_\nu \tfrac{1}{2}\{\gamma^\nu, \gamma^\mu\} \psi)(D_\mu \varphi)$$

$$= \tfrac{1}{2}(\bar{\psi} D_\nu \gamma^\nu \gamma^\mu \psi)(D_\mu \varphi) + \tfrac{1}{2}(\bar{\psi} \gamma^\mu \underline{\not{D} \psi})(D_\mu \varphi)$$

$$= \boxed{\psi\psi\varphi\varphi D} + \tfrac{1}{2} D_\nu[(\bar{\psi} \gamma^\nu \gamma^\mu \psi)(D_\mu \varphi)] - \tfrac{1}{2}(\underline{\bar{\psi}\, \overleftarrow{\not{D}}} \gamma^\mu \psi)(D_\mu \varphi) + - \tfrac{1}{2}(\bar{\psi} \gamma^\nu \gamma^\mu \psi)(D_\nu D_\mu \varphi)$$

but

$$(\bar{\psi} \gamma^\nu \gamma^\mu \psi)(D_\nu D_\mu \varphi) = (\bar{\psi}(-i)\sigma^{\nu\mu} \psi)(\sum_k X^k_{\nu\mu} \varphi) + (\bar{\psi}\psi)(\underline{D^\mu D_\mu \varphi})$$

so

$$(\bar{\psi}_L D_\mu \psi_R)(D^\mu \varphi) = \boxed{\psi\psi\varphi\varphi D} + \boxed{\psi\psi X \varphi} + \boxed{\psi\psi\varphi} + \boxed{\psi\psi\varphi\varphi\varphi} + \boxed{\psi\psi\psi\psi}$$

Example: reduction of $(\bar\psi D_\mu \psi)(D^\mu \varphi)$

$$(\bar\psi D_\mu \psi)(D^\mu \varphi) = (\bar\psi D_\nu \eta^{\nu\mu} \psi)(D_\mu \varphi) = (\bar\psi D_\nu \tfrac{1}{2}\{\gamma^\nu, \gamma^\mu\}\psi)(D_\mu \varphi)$$

$$= \tfrac{1}{2}(\bar\psi D_\nu \gamma^\nu \gamma^\mu \psi)(D_\mu \varphi) + \tfrac{1}{2}(\bar\psi \gamma^\mu \underline{\not{D}\psi})(D_\mu \varphi)$$

$$= \boxed{\psi\psi\varphi\varphi D} + \tfrac{1}{2} D_\nu[(\bar\psi \gamma^\nu \gamma^\mu \psi)(D_\mu \varphi)] - \tfrac{1}{2}(\underline{\bar\psi \overleftarrow{\not{D}}} \gamma^\mu \psi)(D_\mu \varphi) +$$

$$- \tfrac{1}{2}(\bar\psi \gamma^\nu \gamma^\mu \psi)(D_\nu D_\mu \varphi)$$

but

$$(\bar\psi \gamma^\nu \gamma^\mu \psi)(D_\nu D_\mu \varphi) = (\bar\psi (-i) \sigma^{\nu\mu} \psi)(\sum_k X^k_{\nu\mu} \varphi) + (\bar\psi \psi)(\underline{D^\mu D_\mu \varphi})$$

so

$$(\bar\psi_L D_\mu \psi_R)(D^\mu \varphi) = \boxed{\psi\psi\varphi\varphi D} + \boxed{\psi\psi X \varphi} + \boxed{\psi\psi\varphi} + \boxed{\psi\psi\varphi\varphi\varphi} + \boxed{\psi\psi\psi\psi}$$