

# Symmetry breaking beyond the SM

Wouter Dekens

Based on work with  
V. Cirigliano, A. Crivellin, J. de Vries,  
E. Mereghetti, M. Hoferichter



# Beyond the SM

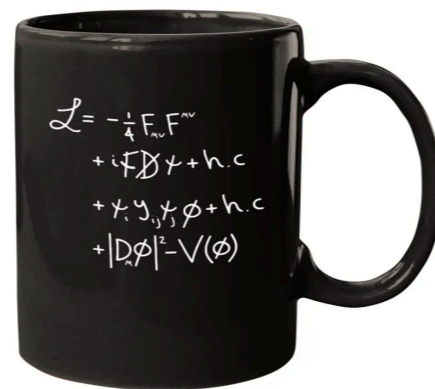
The Standard Model does not explain:

# Beyond the SM

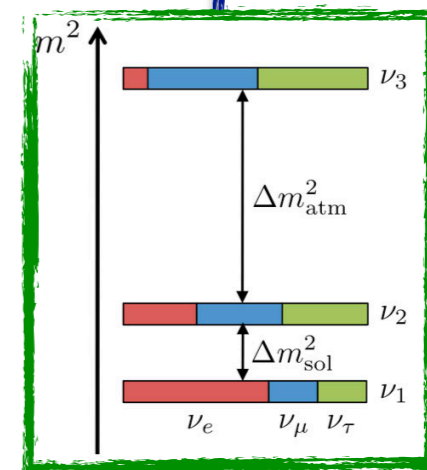
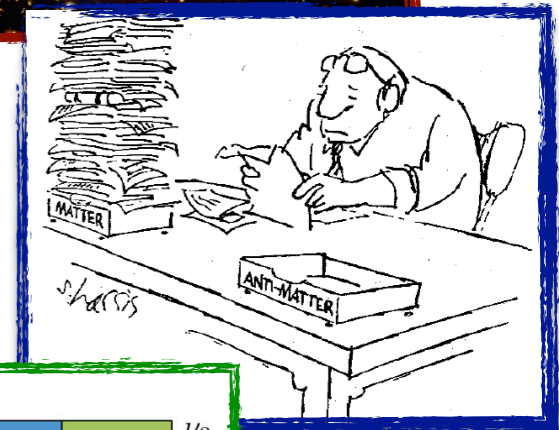
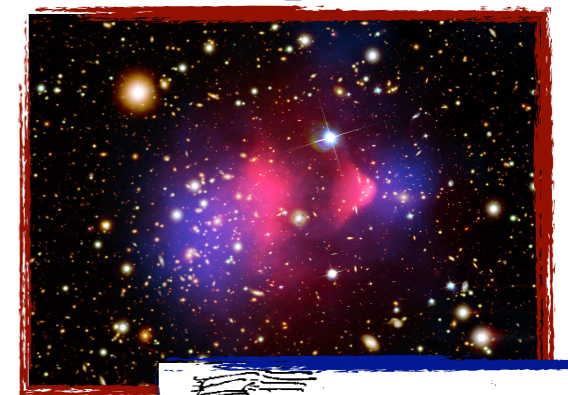
The Standard Model does not explain:

## Open problems:

- Dark Matter
- Baryon Asymmetry
- Neutrino masses



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Credit: JUNO Collaboration

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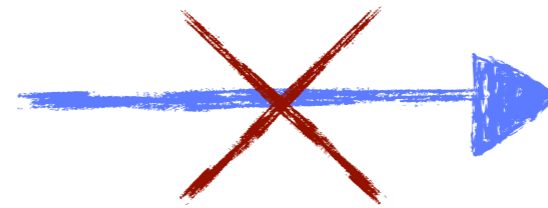
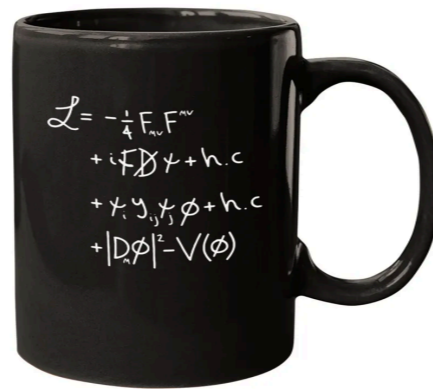
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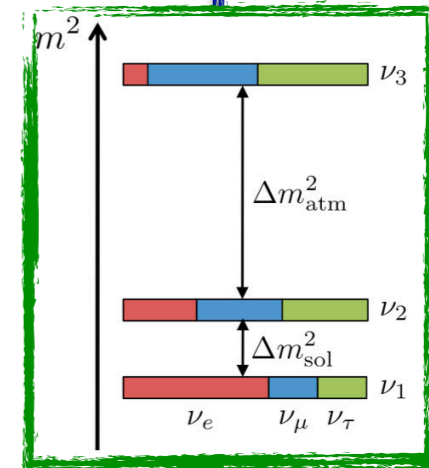
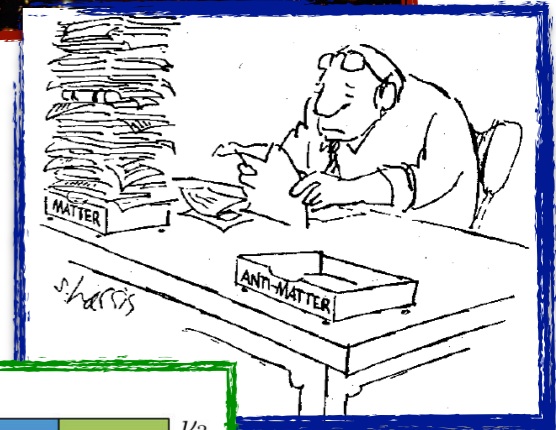
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## Theoretical questions:

- Strong CP problem
- Hierarchy problem
- Flavor structure....



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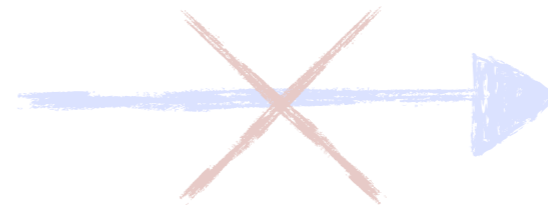
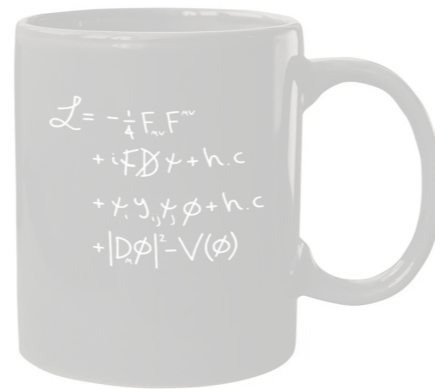
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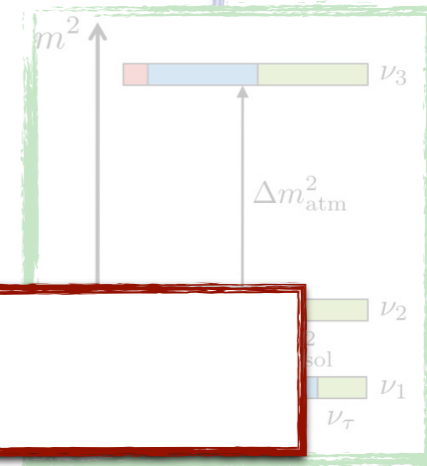


## Where to find the needed BSM?

## Theoretical questions

- Strong CP problem
- Hierarchy problem
- Flavor structure....

- Search directly at the energy frontier; LHC



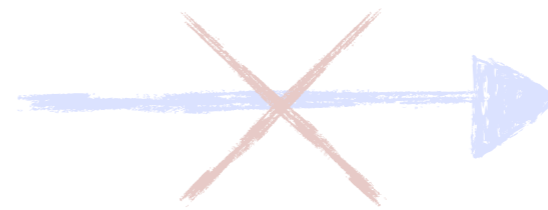
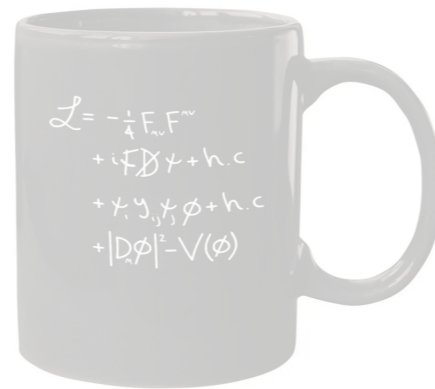
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## Theoretical questions

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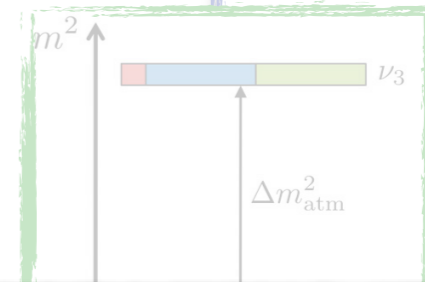
## Where to find the needed BSM?

- Search directly at the energy frontier; LHC

Several problems require symmetry-breaking BSM

⇒ search for symmetry-violating processes:

- CP violation; EDMs
- Parity violation; atomic parity, PV electron scattering...

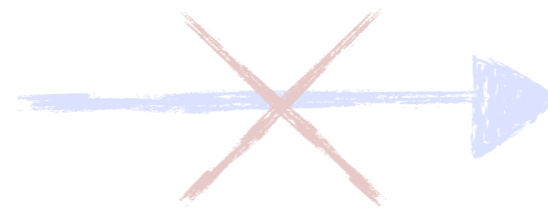
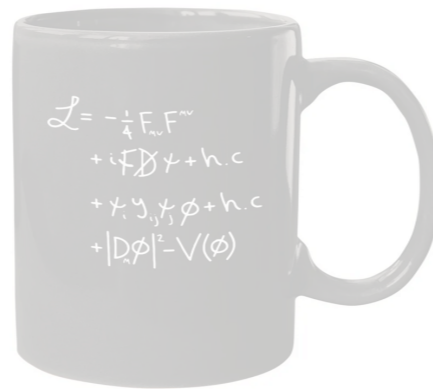


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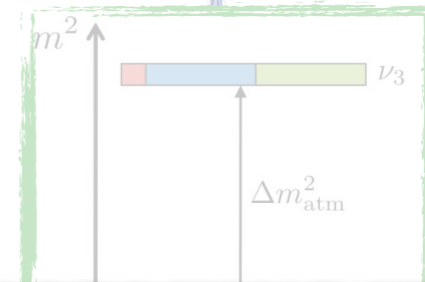
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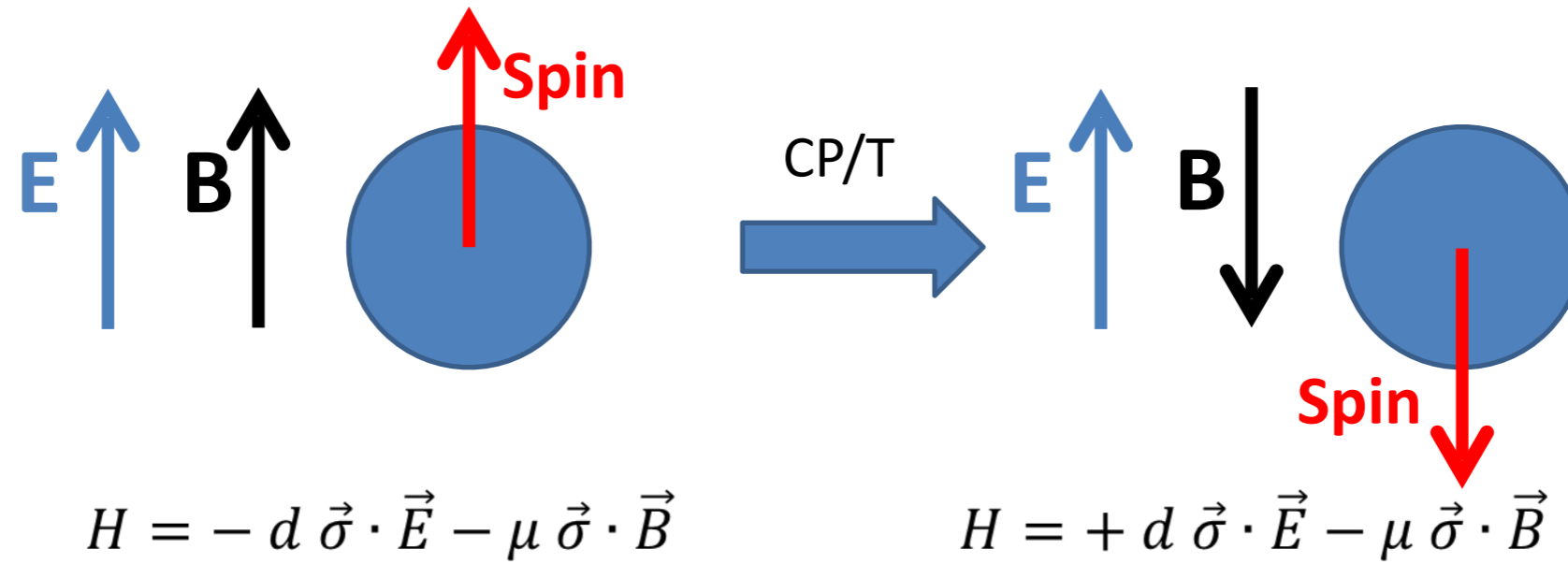
- CP violation; EDMs **Most of this talk**
- Parity violation; atomic parity, PV electron scattering...



## Theoretical questions

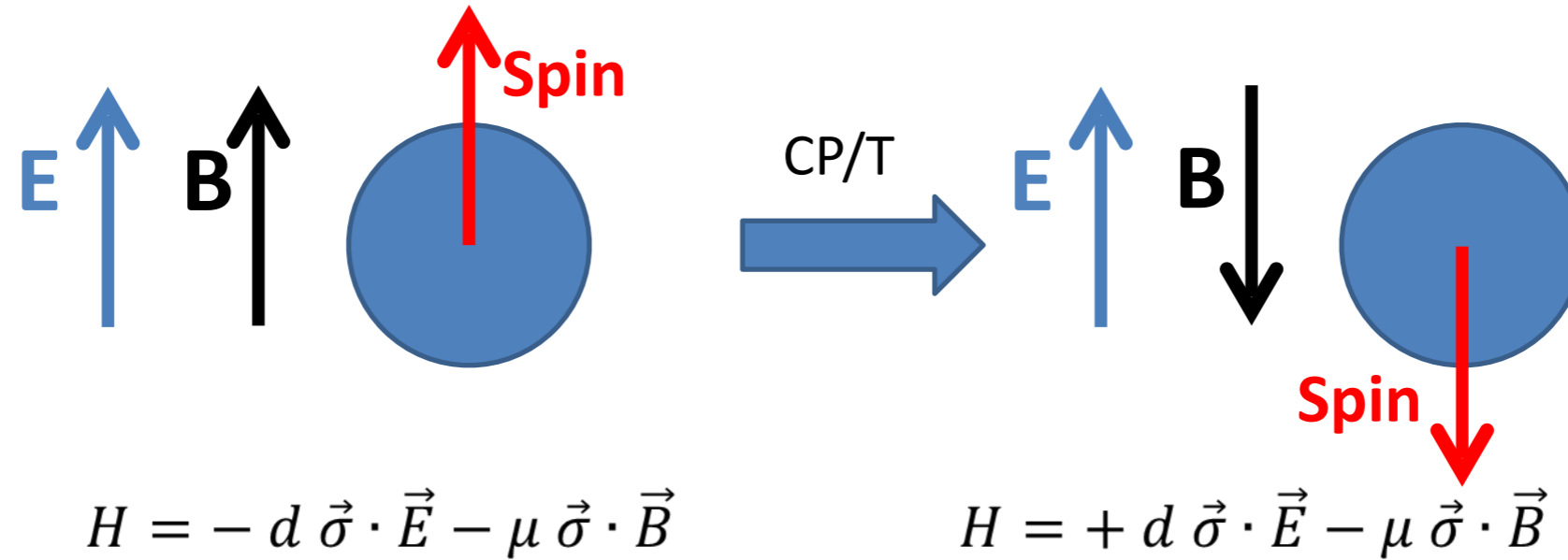
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# Electric Dipole Moments



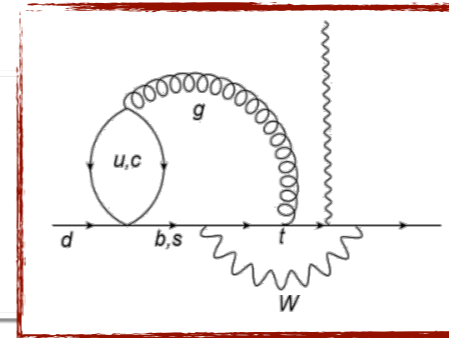


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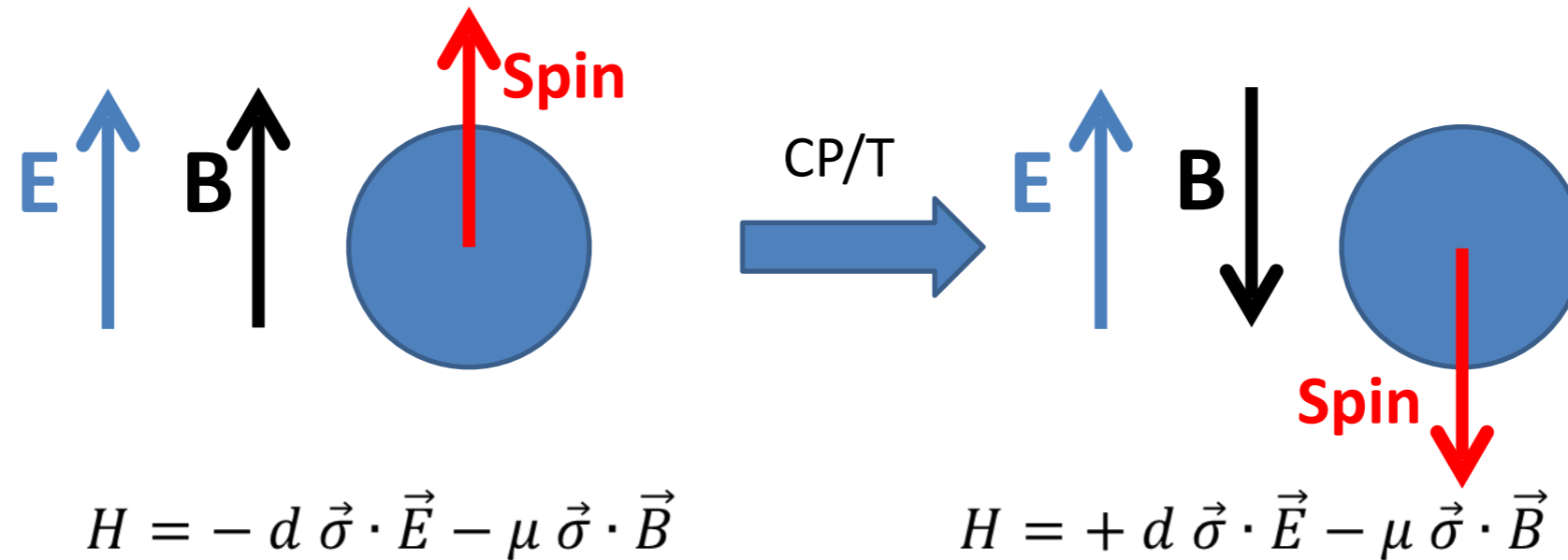


## SM contributions

- Phase in the CKM matrix
- Loop suppressed, leads to small EDMs

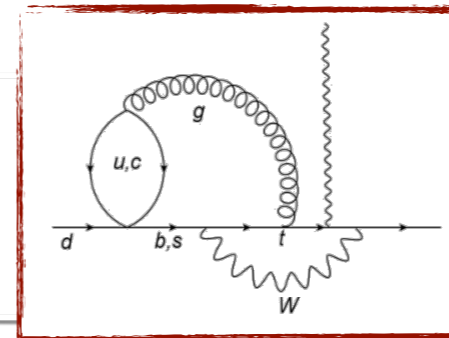


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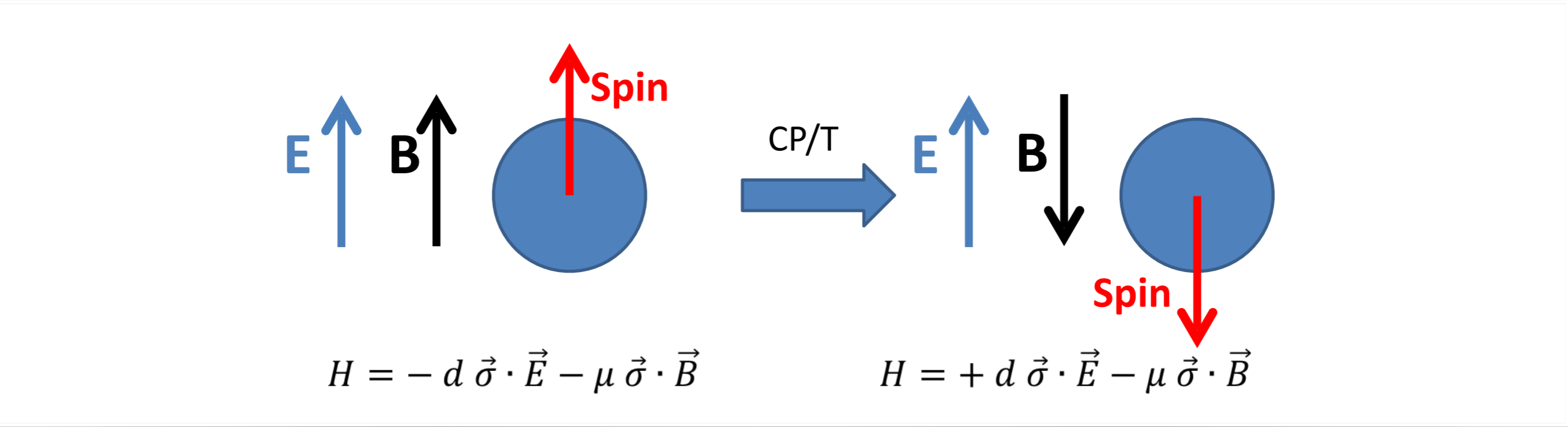
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- QCD theta term,  $L_\theta = \theta \frac{\alpha_s}{8\pi} G_{\mu\nu} \tilde{G}^{\mu\nu}$
- Allowed by all QCD symmetries
- Bound to be  $\theta \lesssim 10^{-10}$ , (strong CP problem)

# Electric Dipole Moments

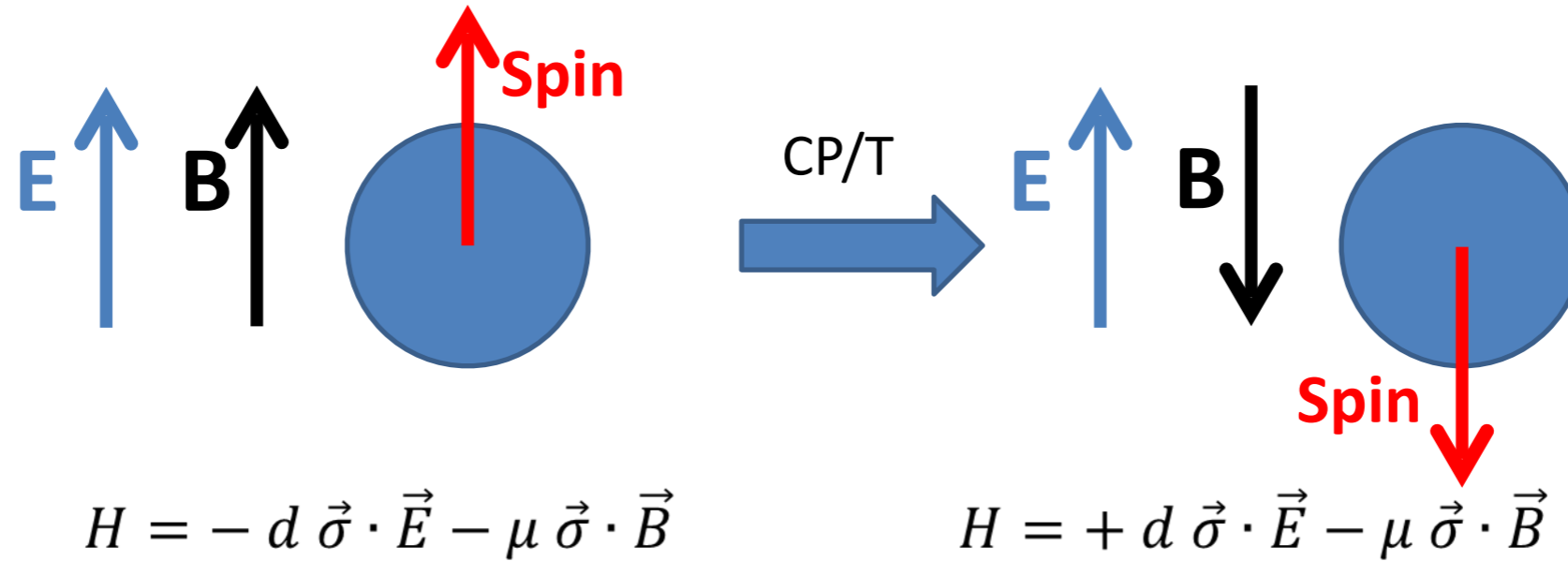


## Current limits

Limits (e cm)	Nucleons: neutron	Diamagnetic systems: mercury	Paramagnetic systems: HfF
Current	1.8x10 <sup>-26</sup> <i>Baker et al. '20</i>	6.2x10 <sup>-30</sup> <i>Graner et al. '17</i>	4.1x10 <sup>-30</sup> <i>Roussv et al. '22</i>
SM background (CKM matrix)	<10 <sup>-31</sup>	<10 <sup>-34</sup>	10 <sup>-35</sup>

Chupp *et al.* '17; Ema *et al.* '22;  
Arrowsmith-Kron *et al.* '23

# Electric Dipole Moments



## Current limits

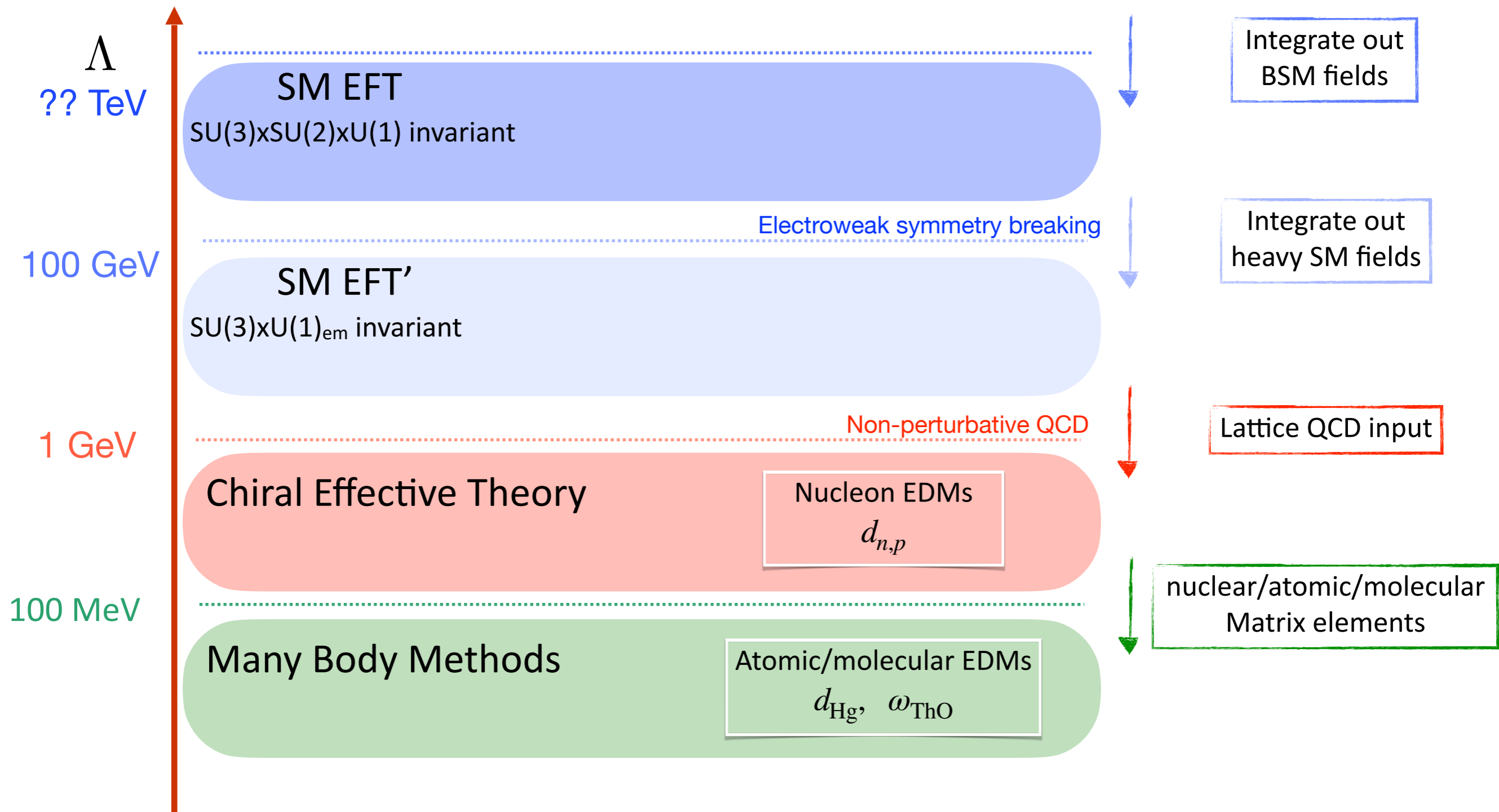
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SM background (CKM matrix)	$<10^{-31}$	$<10^{-34}$	$10^{-35}$

## Radioactive molecules

- Can have enhanced sensitivity compared to mercury,  $10^{2-6}$ 
  - Octupole deformation + large electric field in molecule

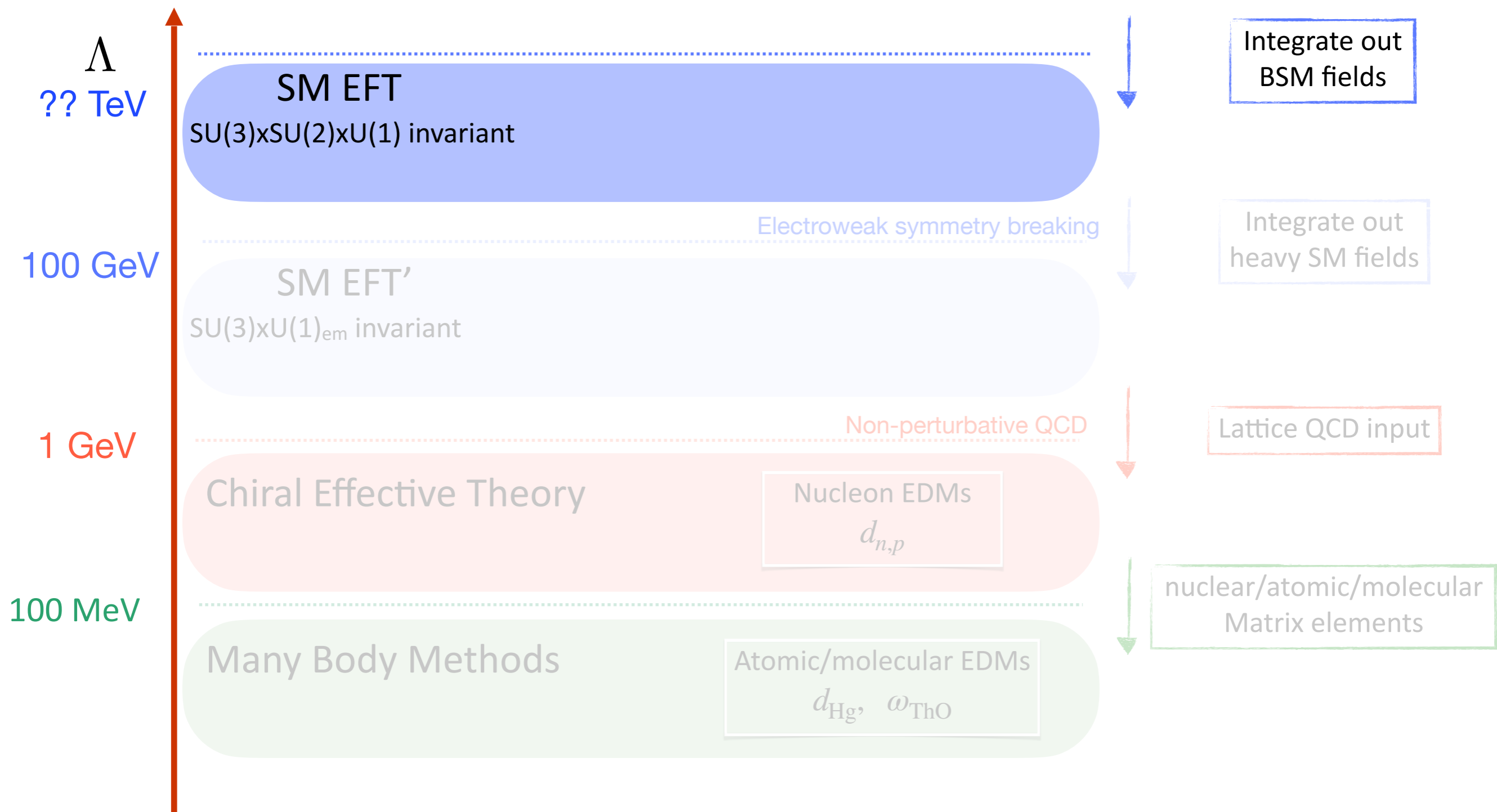
# Outline

CP-violating BSM physics



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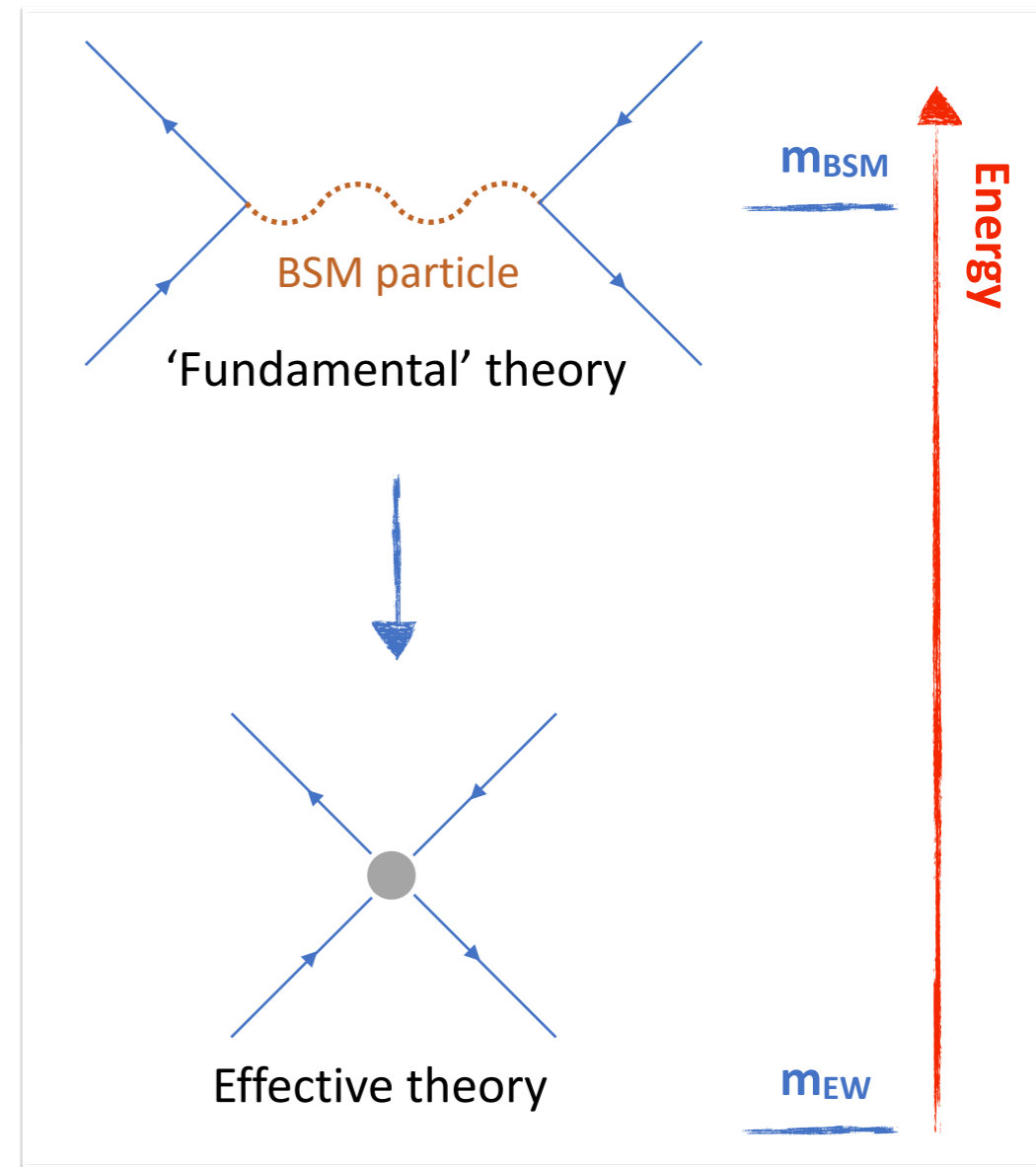


# The SM Effective Field Theory

## Describing BSM physics

### Assumptions

- BSM physics is heavy  $m_{EW} \ll m_{BSM}$
- No new light degrees of freedom
- SM gauge group is linearly realized



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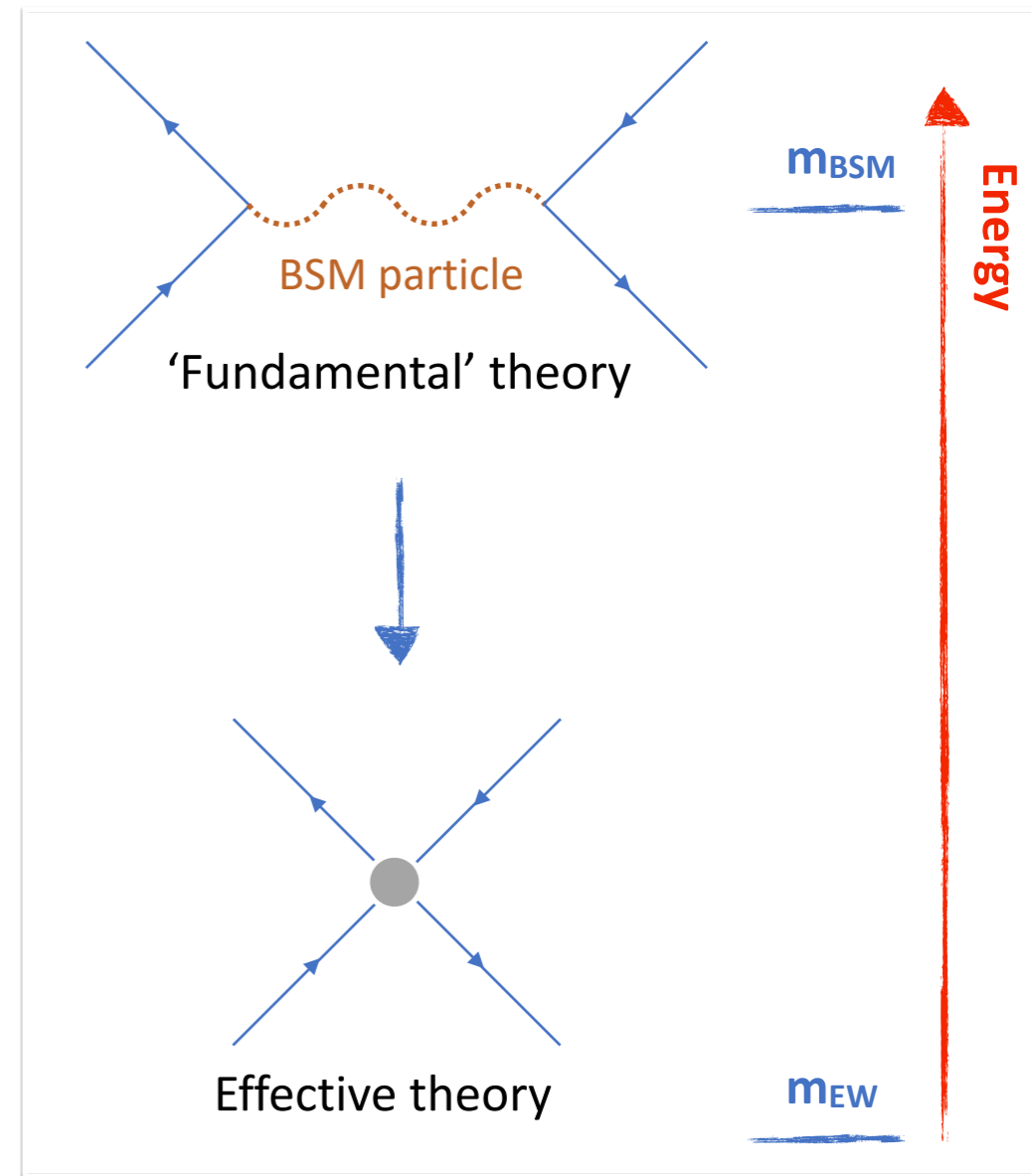
- No new light degrees of freedom

### Light new particles not covered:

E.g.  $Z'$ , light DM, axions...

- Could give (C)PV signals

- SM gauge group is linearly realized





# SM EFT

## SM EFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{C_i^{(5)}}{\Lambda} \mathcal{O}_i^{(5)} + \frac{C_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$

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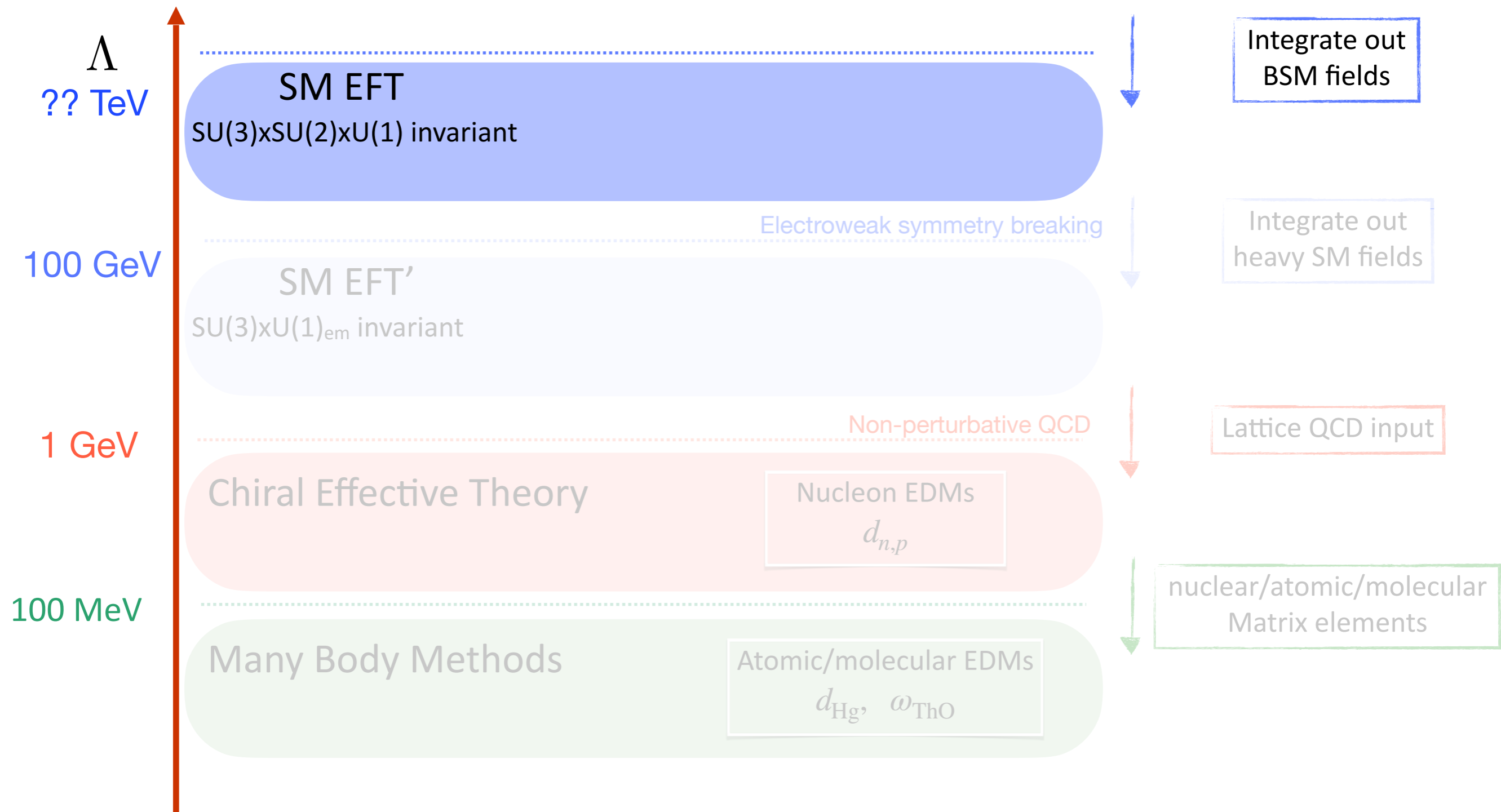
- 2499 operators at dimension six
- Several classes of CP-odd interactions

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$	
$Q_{ll}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$Q_{ee}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{uu}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_{dd}$	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{eu}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_{ed}$	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		$B$ -violet	
$Q_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s^k q_t^j)$	$Q_{duq}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(d_p^\alpha)_j (d_r^\beta)_k (u_t^\gamma)]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	$Q_{quq}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} [(q_p^\alpha)_j (q_r^\beta)_k (q_t^\gamma)]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	$Q_{qqq}^{(1)}$	$\varepsilon^{\alpha\beta\gamma} \varepsilon_{jk} \varepsilon_{mn} [(q_p^\alpha)_j (q_r^\beta)_k (q_t^\gamma)_m (q_t^\gamma)_n]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$	$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn}$
$Q_{legu}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$	$Q_{duu}$	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$

$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \varphi)$
$Q_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{WB}}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\varphi^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$

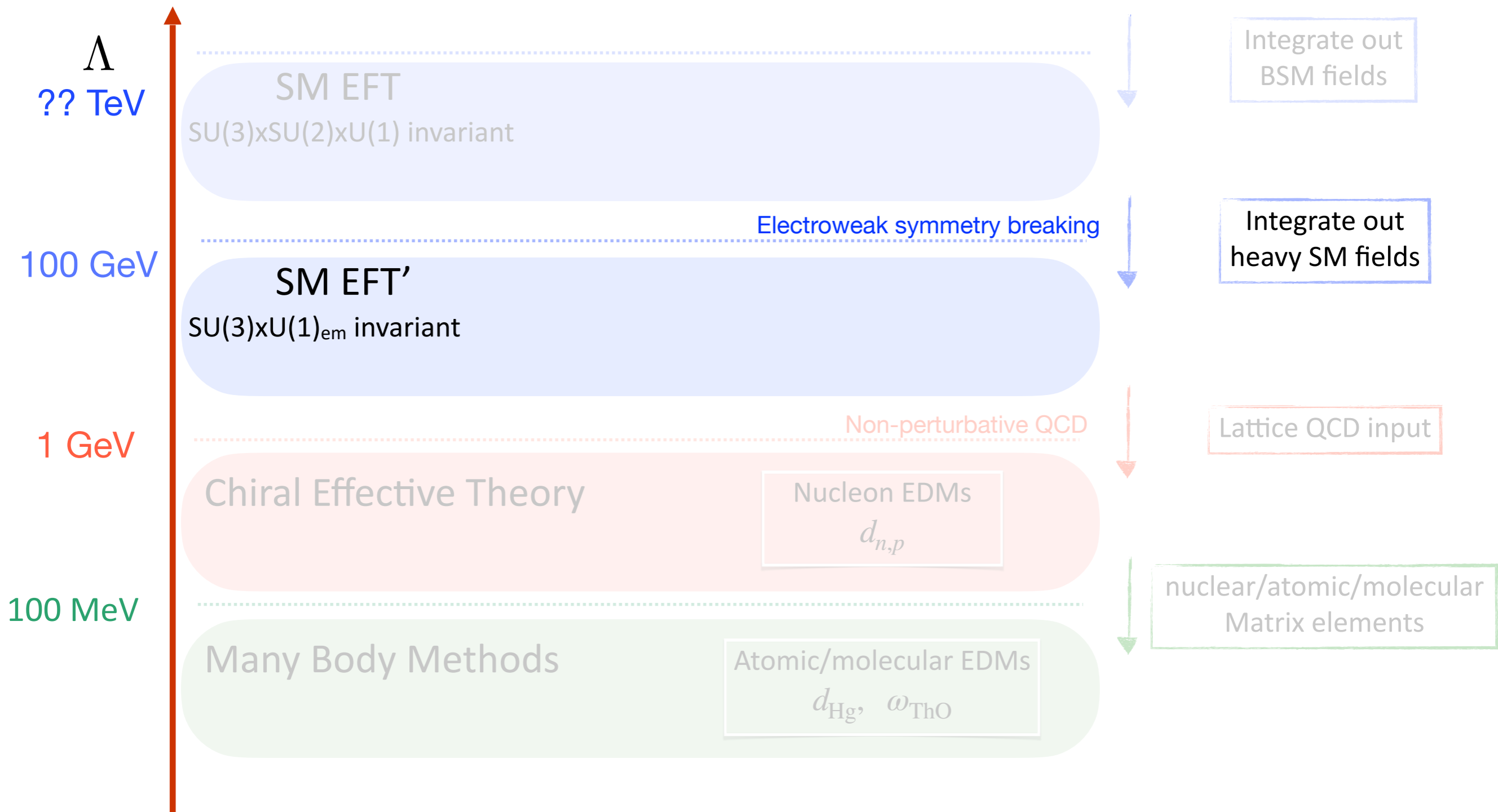
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# CPV below the weak scale

$\Lambda$

**SM EFT**  
SU(3)xSU(2)xU(1) invariant

$(\bar{L}L)(\bar{L}L)$		$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_{ll}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$Q_G$	$f^{ABC} G_\mu^A G_\nu^B G_\rho^C G_\mu^\nu$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma^\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^A \tilde{G}_\nu^B \tilde{G}_\rho^C \tilde{G}_\mu^\nu$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \varphi)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma^\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_W$	$\varepsilon^{IJK} W_\mu^I W_\nu^J W_\rho^K W_\mu^\nu$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^I \tilde{W}_\nu^J \tilde{W}_\rho^K \tilde{W}_\mu^\nu$				
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$						
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{leq}^{(1)}$	$(\bar{l}_p e_r)(\bar{d}_s q_t^\dagger)$	$Q_{\varphi G}$	$\varphi^\dagger \varphi G_\mu^A G^{\mu\nu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{leq}^{(8)}$	$(\bar{q}_p^\dagger u_r) \varepsilon_{jk} (\bar{q}_s^\dagger d_t)$	$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_\mu^A G^{\mu\nu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{leq}^{(3)}$	$(\bar{q}_p^\dagger T^A u_r) \varepsilon_{jk} (\bar{q}_s^\dagger T^A d_t)$	$Q_{\varphi W}$	$\varphi^\dagger \varphi W_\mu^I W^{\mu\nu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu e_r)$
$Q_{leq}^{(3)}$	$(\bar{l}_p e_r) \varepsilon_{jk} (\bar{q}_s^\dagger u_t)$	$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_\mu^I W^{\mu\nu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{leq}^{(3)}$	$(\bar{l}_p^\dagger \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^\dagger \sigma^{\mu\nu} u_t)$	$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \varphi B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu u_r)$
		$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu d_r)$
		$Q_{\varphi \tilde{WB}}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi d}^{(3)}$	$i(\varphi^\dagger D_\mu \varphi)(\bar{q}_p \gamma^\mu d_r)$
		$Q_{\varphi\varphi\varphi}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^\alpha)^\dagger T C q_r^\beta] [(q_s^m)^\dagger T C l_t^\gamma]$				
		$Q_{duu}$	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^\dagger T C u_r^\beta] [(u_s^\gamma)^\dagger T C e_t]$				

$m_W$

**SM EFT'**  
SU(3)xU(1)<sub>em</sub> invariant

$(\bar{L}L)(\bar{L}L)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R) + \text{H.c.}$	
$\mathcal{O}_{V_{ud}^{LL}}$	$(\bar{u}_L \gamma^\mu u_L)(\bar{d}_L \gamma_\mu d_L)$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{u}_L \gamma^\mu u_L)(\bar{d}_R \gamma_\mu d_R)$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{u}_L e_R)(\bar{u}_L u_R)$
$\mathcal{O}_{V_{ud}^{LL}}$	$(\bar{u}_L \gamma^\mu u_L)(\bar{d}_L \gamma_\mu d_L)$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{u}_L \gamma^\mu u_L)(\bar{d}_R \gamma_\mu d_R)$	$\mathcal{O}_{T_{ud}^{RR}}$	$(\bar{e}_L \sigma^{\mu\nu} e_R)(\bar{u}_L \sigma_{\mu\nu} u_R)$
$\mathcal{O}_{V_{ud}^{LL}}$	$(\bar{e}_L \gamma^\mu e_L)(\bar{u}_L \gamma_\mu u_L)$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{e}_L \gamma^\mu e_L)(\bar{u}_R \gamma_\mu u_R)$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{e}_L e_R)(\bar{d}_L d_R)$
$\mathcal{O}_{V_{ud}^{LL}}$	$(\bar{e}_L \gamma^\mu e_L)(\bar{d}_L \gamma_\mu d_L)$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{e}_L \gamma^\mu e_L)(\bar{d}_R \gamma_\mu d_R)$	$\mathcal{O}_{T_{ud}^{RR}}$	$(\bar{e}_L \sigma^{\mu\nu} e_R)(\bar{d}_L \sigma_{\mu\nu} d_R)$
$\mathcal{O}_{V_{udsu}^{LL}}$	$(\bar{u}_L \gamma^\mu u_L)(\bar{d}_L \gamma_\mu d_L) + \text{H.c.}$	$\mathcal{O}_{V_{udsu}^{LR}}$	$(\bar{u}_L \gamma^\mu u_L)(\bar{e}_R \gamma_\mu e_R)$	$\mathcal{O}_{S_{udsu}^{RR}}$	$(\bar{u}_L e_R)(\bar{d}_L u_R)$
		$\mathcal{O}_{V_{udsu}^{LR}}$	$(\bar{d}_L \gamma^\mu d_L)(\bar{e}_R \gamma_\mu e_R)$	$\mathcal{O}_{T_{udsu}^{RR}}$	$(\bar{u}_L \sigma^{\mu\nu} e_R)(\bar{d}_L \sigma_{\mu\nu} u_R)$
		$\mathcal{O}_{V_{udsu}^{LR}}$	$(\bar{u}_L \gamma^\mu e_L)(\bar{d}_R \gamma_\mu u_R) + \text{H.c.}$	$\mathcal{O}_{S_{udsu}^{RR}}$	$(\bar{u}_L u_R)(\bar{u}_L u_R)$
		$\mathcal{O}_{V_{udsu}^{LR}}$	$(\bar{u}_L \gamma^\mu u_L)(\bar{u}_R \gamma_\mu u_R)$	$\mathcal{O}_{S_{udsu}^{RR}}$	$(\bar{u}_L T^A u_R)(\bar{u}_L T^A u_R)$
$\mathcal{O}_{u\gamma}$	$\bar{u}_L \sigma^{\mu\nu} u_R F_{\mu\nu}$	$\mathcal{O}_{V_{uu}^{LR}}$	$(\bar{u}_L \gamma^\mu T^A u_L)(\bar{u}_R \gamma_\mu T^A u_R)$	$\mathcal{O}_{S_{uu}^{RR}}$	$(\bar{u}_L u_R)(\bar{d}_L d_R)$
$\mathcal{O}_{d\gamma}$	$\bar{d}_L \sigma^{\mu\nu} d_R F_{\mu\nu}$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{u}_L \gamma^\mu u_L)(\bar{d}_R \gamma_\mu d_R)$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{u}_L T^A u_R)(\bar{d}_L T^A d_R)$
$\mathcal{O}_{uG}$	$\bar{u}_L \sigma^{\mu\nu} T^A u_R G_{\mu\nu}^A$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{u}_L \gamma^\mu T^A u_L)(\bar{d}_R \gamma_\mu d_R)$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{u}_L T^A u_R)(\bar{d}_L T^A d_R)$
$\mathcal{O}_{dG}$	$\bar{d}_L \sigma^{\mu\nu} T^A d_R G_{\mu\nu}^A$	$\mathcal{O}_{V_{du}^{LR}}$	$(\bar{d}_L \gamma^\mu d_L)(\bar{u}_R \gamma_\mu u_R)$	$\mathcal{O}_{S_{du}^{RR}}$	$(\bar{d}_L d_R)(\bar{d}_L d_R)$
		$\mathcal{O}_{V_{du}^{LR}}$	$(\bar{d}_L \gamma^\mu T^A d_L)(\bar{u}_R \gamma_\mu T^A u_R)$	$\mathcal{O}_{S_{du}^{RR}}$	$(\bar{d}_L T^A d_R)(\bar{d}_L T^A d_R)$
		$\mathcal{O}_{V_{dd}^{LR}}$	$(\bar{d}_L \gamma^\mu d_L)(\bar{d}_R \gamma_\mu d_R)$	$\mathcal{O}_{S_{duu}^{RR}}$	$(\bar{u}_L d_R)(\bar{d}_L u_R)$
		$\mathcal{O}_{V_{dd}^{LR}}$	$(\bar{d}_L \gamma^\mu T^A d_L)(\bar{d}_R \gamma_\mu T^A d_R)$	$\mathcal{O}_{S_{duu}^{RR}}$	$(\bar{u}_L T^A d_R)(\bar{d}_L T^A u_R)$
		$\mathcal{O}_{V_{uddu}^{LR}}$	$(\bar{u}_L \gamma^\mu d_L)(\bar{d}_R \gamma_\mu u_R) + \text{H.c.}$		
		$\mathcal{O}_{V_{uddu}^{LR}}$	$(\bar{u}_L \gamma^\mu T^A d_L)(\bar{d}_R \gamma_\mu T^A u_R) + \text{H.c.}$		
				$(\bar{L}R)(\bar{R}L) + \text{H.c.}$	
				$\mathcal{O}_{S_{eu}^{RL}}$	$(\bar{e}_L e_R)(\bar{u}_R u_L)$
				$\mathcal{O}_{S_{ed}^{RL}}$	$(\bar{e}_L e_R)(\bar{d}_R d_L)$
				$\mathcal{O}_{S_{vedu}^{RL}}$	$(\bar{v}_L e_R)(\bar{d}_R u_L)$

$\Lambda_\chi$

# CPV below the weak scale

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SM EFT  
SU(3)xSU(2)xU(1) invariant

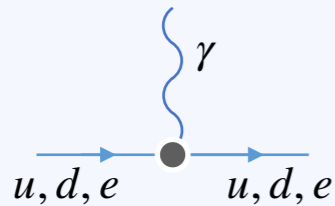
$(\bar{L}L)(\bar{L}L)$		$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_{ll}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$Q_G$	$f^{ABC} G_\mu^{Av} G_\nu^{B\mu} G_\rho^{C\nu}$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma^\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{Av} G_\nu^{B\mu} G_\rho^{C\nu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \varphi)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma^\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_W$	$\varepsilon^{IJK} W_\mu^I W_\nu^J W_\rho^K$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^I W_\nu^J W_\rho^K$				
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
		$Q_{\varphi G}$	$\varphi^\dagger \varphi G_\mu^A G^{A\mu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
		$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_\mu^A G^{A\mu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
		$Q_{\varphi W}$	$\varphi^\dagger \varphi W_\mu^I W^{I\mu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu e_r)$
		$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_\mu^I W^{I\mu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
		$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \varphi B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu u_r)$
		$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_\mu^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu d_r)$
		$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_\mu^I B^{\mu\nu}$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi d}$	$i(\varphi^\dagger D_\mu \varphi)(\bar{q}_p \gamma^\mu d_r)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		$Q_{\varphi\varphi}^{(3)}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I \varepsilon)_{jk}(\tau^I \varepsilon)_{mn} [(q_p^\alpha)^T C q_r^\beta] [(q_s^\gamma)^T C l_t^\delta]$				
$Q_{leq}^{(1)}$	$(\bar{l}_p e_r)(\bar{d}_s q_t^\dagger)$	$Q_{duu}$	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t^\delta]$				
$Q_{leq}^{(8)}$	$(\bar{l}_p^j u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$						
$Q_{leq}^{(3)}$	$(\bar{l}_p^j T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$						
$Q_{lecu}^{(1)}$	$(\bar{l}_p e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$						
$Q_{lecu}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$						

$m_W$

SM EFT'  
SU(3)xU(1)<sub>em</sub> invariant

$(\bar{L}L)(\bar{L}L)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R) + \text{H.c.}$	
$\mathcal{O}_{V_{ud}^{LL}}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{u}_{Ls} \gamma_\mu u_{Lt})$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{u}_{Rs} \gamma_\mu u_{Rt})$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{V_{ud}^{LL}}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{d}_{Ls} \gamma_\mu d_{Lt})$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt})$	$\mathcal{O}_{T_{ud}^{RR}}$	$(\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{u}_{Ls} \sigma_{\mu\nu} u_{Rt})$
$\mathcal{O}_{V_{ud}^{LL}}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{u}_{Ls} \gamma_\mu u_{Lt})$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{u}_{Rs} \gamma_\mu u_{Rt})$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{V_{ud}^{LL}}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Ls} \gamma_\mu d_{Lt})$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt})$	$\mathcal{O}_{T_{ud}^{RR}}$	$(\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls} \sigma_{\mu\nu} d_{Rt})$
$\mathcal{O}_{V_{vedu}^{LL}}$	$(\bar{v}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Ls} \gamma_\mu u_{Lt}) + \text{H.c.}$	$\mathcal{O}_{V_{vedu}^{LR}}$	$(\bar{v}_{Lp} \gamma^\mu e_{Lr})(\bar{e}_{Rs} \gamma_\mu e_{Rt})$	$\mathcal{O}_{S_{vedu}^{RR}}$	$(\bar{v}_{Lp} e_{Rr})(\bar{d}_{Ls} u_{Rt})$
$(\bar{L}R)X + \text{H.c.}$		$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{v}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Rs} \gamma_\mu u_{Rt}) + \text{H.c.}$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{v}_{Lp} u_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{u\gamma}$	$\bar{u}_{Lp} \sigma^{\mu\nu} u_{Rr} F_{\mu\nu}$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{u}_{Rs} \gamma_\mu u_{Rt})$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{u}_{Ls} T^A u_{Rt})$
$\mathcal{O}_{d\gamma}$	$\bar{d}_{Lp} \sigma^{\mu\nu} d_{Rr} F_{\mu\nu}$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{u}_{Lp} \gamma^\mu T^A u_{Lr})(\bar{u}_{Rs} \gamma_\mu T^A u_{Rt})$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{u}_{Lp} u_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{uG}$	$\bar{u}_{Lp} \sigma^{\mu\nu} T^A u_{Rr} G_{\mu\nu}^A$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt})$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{d}_{Ls} T^A d_{Rt})$
$\mathcal{O}_{dG}$	$\bar{d}_{Lp} \sigma^{\mu\nu} T^A d_{Rr} G_{\mu\nu}^A$	$\mathcal{O}_{V_{ud}^{LR}}$	$(\bar{u}_{Lp} \gamma^\mu T^A u_{Lr})(\bar{d}_{Rs} \gamma_\mu T^A d_{Rt})$	$\mathcal{O}_{S_{ud}^{RR}}$	$(\bar{d}_{Lp} d_{Rr})(\bar{d}_{Ls} d_{Rt})$
$X^3$		$\mathcal{O}_{du}^{V1,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{u}_{Rs} \gamma_\mu u_{Rt})$	$\mathcal{O}_{S_{du}^{RR}}$	$(\bar{d}_{Lp} T^A d_{Rr})(\bar{d}_{Ls} T^A d_{Rt})$
$\mathcal{O}_G$	$f^{ABC} G_\mu^{Av} G_\nu^{B\mu} G_\rho^{C\nu}$	$\mathcal{O}_{dd}^{V1,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt})$	$\mathcal{O}_{S_{du}^{RR}}$	$(\bar{u}_{Lp} d_{Rr})(\bar{d}_{Ls} u_{Rt})$
$\mathcal{O}_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{Av} G_\nu^{B\mu} G_\rho^{C\nu}$	$\mathcal{O}_{dd}^{V1,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{d}_{Rs} \gamma_\mu u_{Rt}) + \text{H.c.}$	$\mathcal{O}_{S_{du}^{RR}}$	$(\bar{u}_{Lp} T^A d_{Rr})(\bar{d}_{Ls} T^A u_{Rt})$
		$\mathcal{O}_{duu}^{V1,LR}$	$(\bar{u}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{d}_{Rs} \gamma_\mu T^A u_{Rt}) + \text{H.c.}$	$(\bar{L}R)(\bar{R}L) + \text{H.c.}$	
		$\mathcal{O}_{duu}^{V1,LR}$	$(\bar{u}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{d}_{Rs} \gamma_\mu T^A u_{Rt}) + \text{H.c.}$	$\mathcal{O}_{S_{du}^{RL}}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Rs} u_{Lt})$
				$\mathcal{O}_{S_{du}^{RL}}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Rs} d_{Lt})$
				$\mathcal{O}_{S_{vedu}^{RL}}$	$(\bar{v}_{Lp} e_{Rr})(\bar{d}_{Rs} u_{Lt})$

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Fermion  
EDMs

# CPV below the weak scale

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**SM EFT**  
SU(3)xSU(2)xU(1) invariant

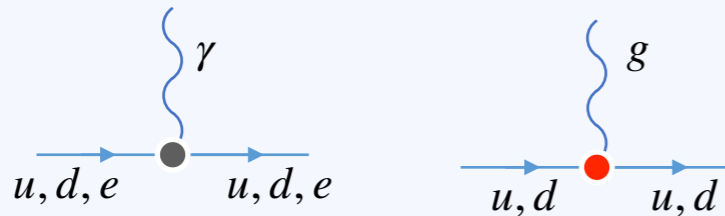
$(\bar{L}L)(\bar{L}L)$		$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_{ll}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$Q_G$	$f^{ABC} G_\mu^A G_\nu^B G_\rho^C G_\sigma^\mu$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma^\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^A G_\nu^B G_\rho^C G_\sigma^\mu$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \varphi)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma^\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_W$	$\varepsilon^{IJK} W_\mu^I W_\nu^J W_\rho^K W_\sigma^\mu$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^I W_\nu^J W_\rho^K W_\sigma^\mu$				
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
		$Q_{\varphi G}$	$\varphi^\dagger \varphi G_\mu^A G_\nu^B G_\rho^C G_\sigma^\mu$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
		$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_\mu^A G_\nu^B G_\rho^C G_\sigma^\mu$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
		$Q_{\varphi W}$	$\varphi^\dagger \varphi W_\mu^I W_\nu^J W_\rho^K W_\sigma^\mu$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu e_r)$
		$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_\mu^I W_\nu^J W_\rho^K W_\sigma^\mu$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
		$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \varphi B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_\mu^A B_\nu^B B_\rho^C B_\sigma^\mu$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu u_r)$
		$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_\mu^I B_\nu^J B_\rho^K B_\sigma^\mu$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu d_r)$
		$Q_{\varphi \tilde{WB}}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_\mu^I B_\nu^J B_\rho^K B_\sigma^\mu$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi d}$	$i(\varphi^\dagger D_\mu \varphi)(\bar{q}_p \gamma^\mu d_r)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		$Q_{\varphi\varphi}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^\alpha)^T C q_r^\beta] [(q_s^\gamma)^T C l_t^\delta]$				
$Q_{leqr}^{(1)}$	$(\bar{l}_p e_r)(\bar{d}_s q_t^\dagger)$	$Q_{duu}$	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t^\delta]$				
$Q_{quqd}^{(1)}$	$(\bar{q}_p^i u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$						
$Q_{quqd}^{(8)}$	$(\bar{q}_p^i T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$						
$Q_{lequ}^{(1)}$	$(\bar{l}_p e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$						
$Q_{lequ}^{(3)}$	$(\bar{l}_p \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$						

$m_W$

**SM EFT'**  
SU(3)xU(1)<sub>em</sub> invariant

$(\bar{L}L)(\bar{L}L)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R) + \text{H.c.}$	
$\mathcal{O}_{u\gamma}^{V,LL}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{u}_{Ls} \gamma_\mu u_{Lt})$	$\mathcal{O}_{e\gamma}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{u}_{Rs} \gamma_\mu u_{Rt})$	$\mathcal{O}_{eu}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{vd}^{V,LL}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{d}_{Ls} \gamma_\mu d_{Lt})$	$\mathcal{O}_{vd}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt})$	$\mathcal{O}_{ed}^{T,RR}$	$(\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{u}_{Ls} \sigma_{\mu\nu} u_{Rt})$
$\mathcal{O}_{eu}^{V,LL}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{u}_{Ls} \gamma_\mu u_{Lt})$	$\mathcal{O}_{ed}^{V,LR}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{u}_{Rs} \gamma_\mu u_{Rt})$	$\mathcal{O}_{ed}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{ed}^{V,LL}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Ls} \gamma_\mu d_{Lt})$	$\mathcal{O}_{ed}^{V,LR}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt})$	$\mathcal{O}_{ed}^{T,RR}$	$(\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls} \sigma_{\mu\nu} d_{Rt})$
$\mathcal{O}_{vedu}^{V,LL}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{d}_{Ls} \gamma_\mu u_{Lt}) + \text{H.c.}$	$\mathcal{O}_{vu}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{e}_{Rs} \gamma_\mu e_{Rt})$	$\mathcal{O}_{ed}^{S,RR}$	$(\bar{v}_{Lp} e_{Rr})(\bar{d}_{Ls} u_{Rt})$
$(\bar{L}R)X + \text{H.c.}$		$\mathcal{O}_{vu}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{e}_{Rs} \gamma_\mu e_{Rt})$	$\mathcal{O}_{vu}^{T,RR}$	$(\bar{v}_{Lp} \sigma^{\mu\nu} v_{Rr})(\bar{d}_{Ls} \sigma_{\mu\nu} u_{Rt})$
$\mathcal{O}_{u\gamma}$	$\bar{u}_{Lp} \sigma^{\mu\nu} u_{Rr} F_{\mu\nu}$	$\mathcal{O}_{vu}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt}) + \text{H.c.}$	$\mathcal{O}_{vu}^{S,RR}$	$(\bar{v}_{Lp} u_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{d\gamma}$	$\bar{d}_{Lp} \sigma^{\mu\nu} d_{Rr} F_{\mu\nu}$	$\mathcal{O}_{vu}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{u}_{Rs} \gamma_\mu u_{Rt})$	$\mathcal{O}_{vu}^{S,RR}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{uG}$	$\bar{u}_{Lp} \sigma^{\mu\nu} T^A u_{Rr} G_{\mu\nu}^A$	$\mathcal{O}_{vu}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt})$	$\mathcal{O}_{vu}^{S,RR}$	$(\bar{u}_{Lp} u_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{dG}$	$\bar{d}_{Lp} \sigma^{\mu\nu} T^A d_{Rr} G_{\mu\nu}^A$	$\mathcal{O}_{vu}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{u}_{Rs} \gamma_\mu u_{Rt})$	$\mathcal{O}_{vu}^{S,RR}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{d}_{Ls} d_{Rt})$
$X^3$		$\mathcal{O}_{du}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{u}_{Rs} \gamma_\mu u_{Rt})$	$\mathcal{O}_{du}^{S,RR}$	$(\bar{d}_{Lp} d_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_G$	$f^{ABC} G_\mu^A G_\nu^B G_\rho^C G_\sigma^\mu$	$\mathcal{O}_{du}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{u}_{Rs} \gamma_\mu u_{Rt})$	$\mathcal{O}_{du}^{S,RR}$	$(\bar{d}_{Lp} T^A d_{Rr})(\bar{d}_{Ls} T^A d_{Rt})$
$\mathcal{O}_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^A G_\nu^B G_\rho^C G_\sigma^\mu$	$\mathcal{O}_{dd}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt})$	$\mathcal{O}_{dd}^{S,RR}$	$(\bar{d}_{Lp} d_{Rr})(\bar{d}_{Ls} u_{Rt})$
		$\mathcal{O}_{dd}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt})$	$\mathcal{O}_{dd}^{S,RR}$	$(\bar{u}_{Lp} d_{Rr})(\bar{d}_{Ls} u_{Rt})$
		$\mathcal{O}_{dd}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{d}_{Rs} \gamma_\mu d_{Rt}) + \text{H.c.}$	$\mathcal{O}_{dd}^{S,RR}$	$(\bar{u}_{Lp} T^A d_{Rr})(\bar{d}_{Ls} T^A u_{Rt})$
		$\mathcal{O}_{ddu}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{d}_{Rs} \gamma_\mu T^A u_{Rt}) + \text{H.c.}$	$\mathcal{O}_{ddu}^{S,RR}$	$(\bar{v}_{Lp} e_{Rr})(\bar{d}_{Ls} u_{Lt})$
		$\mathcal{O}_{ddu}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{d}_{Rs} \gamma_\mu T^A u_{Rt}) + \text{H.c.}$	$\mathcal{O}_{vedu}^{S,RL}$	$(\bar{v}_{Lp} e_{Rr})(\bar{d}_{Rb} d_{Lt})$
		$\mathcal{O}_{ddu}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{d}_{Rs} \gamma_\mu T^A u_{Rt}) + \text{H.c.}$	$\mathcal{O}_{vedu}^{S,RL}$	$(\bar{v}_{Lp} e_{Rr})(\bar{d}_{Rb} u_{Lt})$

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Fermion EDMs

Quark color EDM



# CPV below the weak scale

$\Lambda$

**SM EFT**  
SU(3)xSU(2)xU(1) invariant

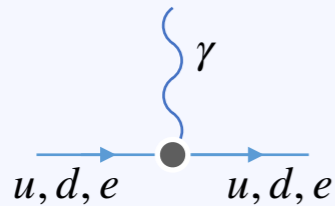
$(\bar{L}L)(\bar{L}L)$		$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_{ll}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$Q_G$	$f^{ABC} G_\mu^{Av} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma^\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{Av} \tilde{G}_\nu^{B\rho} \tilde{G}_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \varphi)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma^\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_W$	$\varepsilon^{IJK} W_\mu^I W_\nu^J W_\rho^K$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^\dagger (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{ll}^{(1)}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^I \tilde{W}_\nu^J \tilde{W}_\rho^K$				
$Q_{ll}^{(3)}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
		$Q_{\varphi G}$	$\varphi^\dagger \varphi G_\mu^A G^{A\mu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
		$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_\mu^A \tilde{G}^{A\mu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
		$Q_{\varphi W}$	$\varphi^\dagger \varphi W_\mu^I W^{I\mu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu e_r)$
		$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_\mu^I \tilde{W}^{I\mu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
		$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \varphi B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} \tilde{B}^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu u_r)$
		$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_\mu^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu d_r)$
		$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_\mu^I B^{\mu\nu}$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi d}$	$i(\varphi^\dagger D_\mu \varphi)(\bar{q}_p \gamma^\mu d_r)$
		$Q_{\varphi \tilde{WB}}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_\mu^I \tilde{B}^{\mu\nu}$				
		$Q_{\varphi \varphi \varphi}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^\alpha)^T C q_r^{\beta k}] [(q_s^m)^T C l_t^\alpha]$				
		$Q_{\varphi \varphi \varphi}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t^\alpha]$				

$m_W$

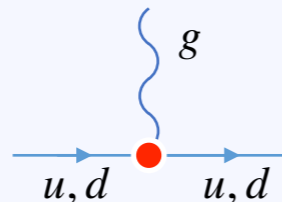
**SM EFT'**  
SU(3)xU(1)<sub>em</sub> invariant

$(\bar{L}L)(\bar{L}L)$		$(\bar{L}L)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R) + \text{H.c.}$	
$\mathcal{O}_{u\gamma}^{V,LL}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{u}_{Ls} \gamma_\mu u_{Lt})$	$\mathcal{O}_{u\gamma}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{u}_{Rr} \gamma_\mu u_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{u\gamma}^{V,LL}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{d}_{Ls} \gamma_\mu d_{Lt})$	$\mathcal{O}_{u\gamma}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu v_{Lr})(\bar{d}_{Rr} \gamma_\mu d_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{u}_{Ls} \sigma_{\mu\nu} u_{Rt})$
$\mathcal{O}_{u\gamma}^{V,LL}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{u}_{Ls} \gamma_\mu u_{Lt})$	$\mathcal{O}_{e\gamma}^{V,LR}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{u}_{Rr} \gamma_\mu u_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{u\gamma}^{V,LL}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Ls} \gamma_\mu d_{Lt})$	$\mathcal{O}_{e\gamma}^{V,LR}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Rr} \gamma_\mu d_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls} \sigma_{\mu\nu} d_{Rt})$
$\mathcal{O}_{vedu}^{V,LL}$	$(\bar{v}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Ls} \gamma_\mu u_{Lt}) + \text{H.c.}$	$\mathcal{O}_{vedu}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu e_{Lr})(\bar{e}_{Rr} \gamma_\mu e_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{v}_{Lp} e_{Rr})(\bar{d}_{Ls} u_{Rt})$
		$\mathcal{O}_{vedu}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{e}_{Rr} \gamma_\mu e_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{v}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls} \sigma_{\mu\nu} u_{Rt})$
		$\mathcal{O}_{vu}^{V,LR}$	$(\bar{v}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Rr} \gamma_\mu u_{Rt}) + \text{H.c.}$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{u}_{Lp} u_{Rr})(\bar{u}_{Ls} u_{Rt})$
		$\mathcal{O}_{vu}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{u}_{Rr} \gamma_\mu u_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{u}_{Ls} T^A u_{Rt})$
		$\mathcal{O}_{vu}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu T^A u_{Lr})(\bar{u}_{Rr} \gamma_\mu T^A u_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{u}_{Lp} u_{Rr})(\bar{d}_{Ls} d_{Rt})$
		$\mathcal{O}_{ud}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{d}_{Rr} \gamma_\mu d_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{d}_{Ls} T^A d_{Rt})$
		$\mathcal{O}_{ud}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu T^A u_{Lr})(\bar{d}_{Rr} \gamma_\mu T^A d_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{d}_{Lp} d_{Rr})(\bar{d}_{Ls} d_{Rt})$
		$\mathcal{O}_{du}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{u}_{Rr} \gamma_\mu u_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{d}_{Lp} T^A d_{Rr})(\bar{d}_{Ls} T^A d_{Rt})$
		$\mathcal{O}_{du}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{u}_{Rr} \gamma_\mu T^A u_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{u}_{Lp} d_{Rr})(\bar{d}_{Ls} u_{Rt})$
		$\mathcal{O}_{dd}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{d}_{Rr} \gamma_\mu d_{Rt})$	$\mathcal{O}_{e\gamma}^{S,RR}$	$(\bar{u}_{Lp} T^A d_{Rr})(\bar{d}_{Ls} T^A u_{Rt})$
		$\mathcal{O}_{dd}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{d}_{Rr} \gamma_\mu T^A d_{Rt})$		
		$\mathcal{O}_{ddu}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu d_{Lr})(\bar{d}_{Rr} \gamma_\mu u_{Rt}) + \text{H.c.}$		
		$\mathcal{O}_{ddu}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{d}_{Rr} \gamma_\mu T^A u_{Rt}) + \text{H.c.}$		
				<b><math>(\bar{L}R)(\bar{R}L) + \text{H.c.}</math></b>	
		$\mathcal{O}_{eu}^{S,RL}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Rr} u_{Lt})$	$\mathcal{O}_{e\gamma}^{S,RL}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Rr} d_{Lt})$
		$\mathcal{O}_{ed}^{S,RL}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Rr} d_{Lt})$	$\mathcal{O}_{e\gamma}^{S,RL}$	$(\bar{v}_{Lp} e_{Rr})(\bar{d}_{Rr} u_{Lt})$
		$\mathcal{O}_{vedu}^{S,RL}$	$(\bar{v}_{Lp} e_{Rr})(\bar{d}_{Rr} u_{Lt})$		

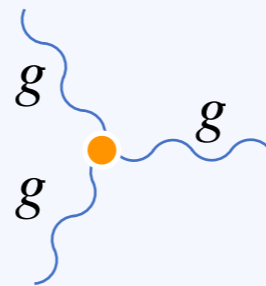
$\Lambda_\chi$



Fermion EDMs



Quark color EDM



Gluon color EDM

# CPV below the weak scale

$\Lambda$

SM EFT  
 SU(3)xSU(2)xU(1) invariant

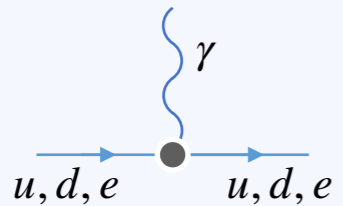
$(\bar{L}L)(\bar{L}L)$		$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_{ll}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	$Q_G$	$f^{ABC} G_\mu^A G_\nu^B G_\rho^C G_\sigma^A$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma^\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_G$	$f^{ABC} \tilde{G}_\mu^A G_\nu^B G_\rho^C G_\sigma^A$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \varphi)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma^\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	$Q_W$	$\varepsilon^{IJK} W_\mu^I W_\nu^J W_\rho^K W_\sigma^A$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma^\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	$Q_{\bar{W}}$	$\varepsilon^{IJK} \bar{W}_\mu^I W_\nu^J W_\rho^K W_\sigma^A$				
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma^\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$						
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{leq}$	$(\bar{l}_p e_r)(\bar{d}_s q_t^I)$	$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{\mu\nu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger \vec{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^i u_r) \varepsilon_{jk} (\bar{q}_s^k d_t)$	$Q_{\varphi G}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{\mu\nu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \vec{D}_\mu \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^i T^A u_r) \varepsilon_{jk} (\bar{q}_s^k T^A d_t)$	$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{\mu\nu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \vec{D}_\mu \varphi)(\bar{q}_p \gamma^\mu e_r)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p e_r) \varepsilon_{jk} (\bar{q}_s^k u_t)$	$Q_{\varphi B}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \vec{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p \sigma_{\mu\nu} e_r) \varepsilon_{jk} (\bar{q}_s^k \sigma^{\mu\nu} u_t)$	$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \varphi B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \vec{D}_\mu \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
		$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{qu}$	$(\varphi^\dagger i \vec{D}_\mu \varphi)(\bar{q}_p \gamma^\mu u_r)$
		$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{qd}$	$(\varphi^\dagger i \vec{D}_\mu \varphi)(\bar{q}_p \gamma^\mu d_r)$
		$Q_{qqq}^{(3)}$	$\varepsilon^{\alpha\beta\gamma} (\tau^I \varepsilon)_{jk} (\tau^I \varepsilon)_{mn} [(q_p^\alpha)^T C q_r^\beta] [(q_s^m)^T C l_t^\gamma]$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{qud}$	$i(\varphi^\dagger D_\mu \varphi)(\bar{q}_p \gamma^\mu d_r)$
		$Q_{duu}$	$\varepsilon^{\alpha\beta\gamma} [(d_p^\alpha)^T C u_r^\beta] [(u_s^\gamma)^T C e_t]$				

$m_W$

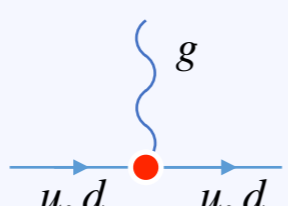
SM EFT'  
 SU(3)xU(1)<sub>em</sub> invariant

$(\bar{L}L)(\bar{L}L)$		$(\bar{L}R)(\bar{R}R)$		$(\bar{L}R)(\bar{L}R) + \text{H.c.}$	
$\mathcal{O}_{uL}^{V,LL}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{u}_{Ls} \gamma^\mu u_{Lt})$	$\mathcal{O}_{uL}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{u}_{Rr} \gamma^\mu u_{Rt})$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Ls} u_{Rt})$
$\mathcal{O}_{uL}^{V,LL}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{d}_{Ls} \gamma^\mu d_{Lt})$	$\mathcal{O}_{uL}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{d}_{Rr} \gamma^\mu d_{Rt})$	$\mathcal{O}_{eL}^{T,RR}$	$(\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{u}_{Ls} \sigma_{\mu\nu} u_{Rt})$
$\mathcal{O}_{uL}^{V,LL}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{u}_{Ls} \gamma^\mu u_{Lt})$	$\mathcal{O}_{uL}^{V,LR}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{u}_{Rr} \gamma^\mu u_{Rt})$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Ls} d_{Rt})$
$\mathcal{O}_{uL}^{V,LL}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Ls} \gamma^\mu d_{Lt})$	$\mathcal{O}_{uL}^{V,LR}$	$(\bar{e}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Rr} \gamma^\mu d_{Rt})$	$\mathcal{O}_{eL}^{T,RR}$	$(\bar{e}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls} \sigma_{\mu\nu} d_{Rt})$
$\mathcal{O}_{uL}^{V,LL}$	$(\bar{u}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Ls} \gamma^\mu u_{Lt}) + \text{H.c.}$	$\mathcal{O}_{uL}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{e}_{Rr} \gamma^\mu e_{Rt})$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{u}_{Lp} e_{Rr})(\bar{d}_{Ls} u_{Rt})$
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{e}_{Rr} \gamma^\mu e_{Rt})$	$\mathcal{O}_{eL}^{T,RR}$	$(\bar{u}_{Lp} \sigma^{\mu\nu} e_{Rr})(\bar{d}_{Ls} \sigma_{\mu\nu} u_{Rt})$
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu e_{Lr})(\bar{d}_{Rr} \gamma^\mu u_{Rt}) + \text{H.c.}$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{u}_{Lp} u_{Rr})(\bar{u}_{Ls} u_{Rt})$
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{u}_{Rr} \gamma^\mu u_{Rt})$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{u}_{Ls} T^A u_{Rt})$
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu T^A u_{Lr})(\bar{u}_{Rr} \gamma^\mu T^A u_{Rt})$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{u}_{Lp} u_{Rr})(\bar{d}_{Ls} d_{Rt})$
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu u_{Lr})(\bar{d}_{Rr} \gamma^\mu d_{Rt})$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{u}_{Lp} T^A u_{Rr})(\bar{d}_{Ls} T^A d_{Rt})$
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu T^A u_{Lr})(\bar{d}_{Rr} \gamma^\mu T^A d_{Rt})$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{d}_{Lp} d_{Rr})(\bar{d}_{Ls} d_{Rt})$
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{u}_{Rr} \gamma^\mu u_{Rt})$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{d}_{Lp} T^A d_{Rr})(\bar{d}_{Ls} T^A d_{Rt})$
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{u}_{Rr} \gamma^\mu T^A u_{Rt})$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{u}_{Lp} d_{Rr})(\bar{d}_{Ls} u_{Rt})$
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu d_{Lr})(\bar{d}_{Rr} \gamma^\mu d_{Rt})$	$\mathcal{O}_{eL}^{S,RR}$	$(\bar{u}_{Lp} T^A d_{Rr})(\bar{d}_{Ls} T^A u_{Rt})$
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{d}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{d}_{Rr} \gamma^\mu T^A d_{Rt})$		
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu d_{Lr})(\bar{d}_{Rr} \gamma^\mu u_{Rt}) + \text{H.c.}$		
		$\mathcal{O}_{uL}^{V,LR}$	$(\bar{u}_{Lp} \gamma^\mu T^A d_{Lr})(\bar{d}_{Rr} \gamma^\mu T^A u_{Rt}) + \text{H.c.}$		
$(\bar{L}R)X + \text{H.c.}$		$X^3$		$(\bar{L}R)(\bar{R}L) + \text{H.c.}$	
$\mathcal{O}_{u\gamma}$	$\bar{u}_{Lp} \sigma^{\mu\nu} u_{Rr} F_{\mu\nu}$	$\mathcal{O}_G$	$f^{ABC} G_\mu^A G_\nu^B G_\rho^C G_\sigma^A$	$\mathcal{O}_{eL}^{S,RL}$	$(\bar{e}_{Lp} e_{Rr})(\bar{u}_{Rr} u_{Lt})$
$\mathcal{O}_{d\gamma}$	$\bar{d}_{Lp} \sigma^{\mu\nu} d_{Rr} F_{\mu\nu}$	$\mathcal{O}_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^A G_\nu^B G_\rho^C G_\sigma^A$	$\mathcal{O}_{eL}^{S,RL}$	$(\bar{e}_{Lp} e_{Rr})(\bar{d}_{Rr} d_{Lt})$
$\mathcal{O}_{uG}$	$\bar{u}_{Lp} \sigma^{\mu\nu} T^A u_{Rr} G_{\mu\nu}^A$			$\mathcal{O}_{eL}^{S,RL}$	$(\bar{v}_{Lp} e_{Rr})(\bar{d}_{Rr} u_{Lt})$
$\mathcal{O}_{dG}$	$\bar{d}_{Lp} \sigma^{\mu\nu} T^A d_{Rr} G_{\mu\nu}^A$				

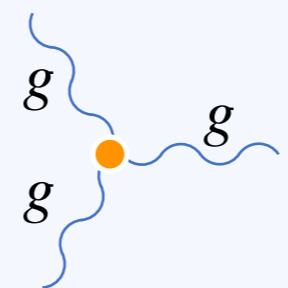
$\Lambda_\chi$



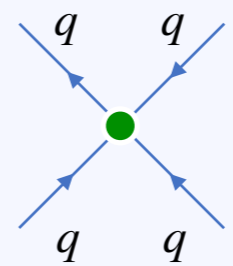
Fermion EDMs



Quark color EDM



Gluon color EDM

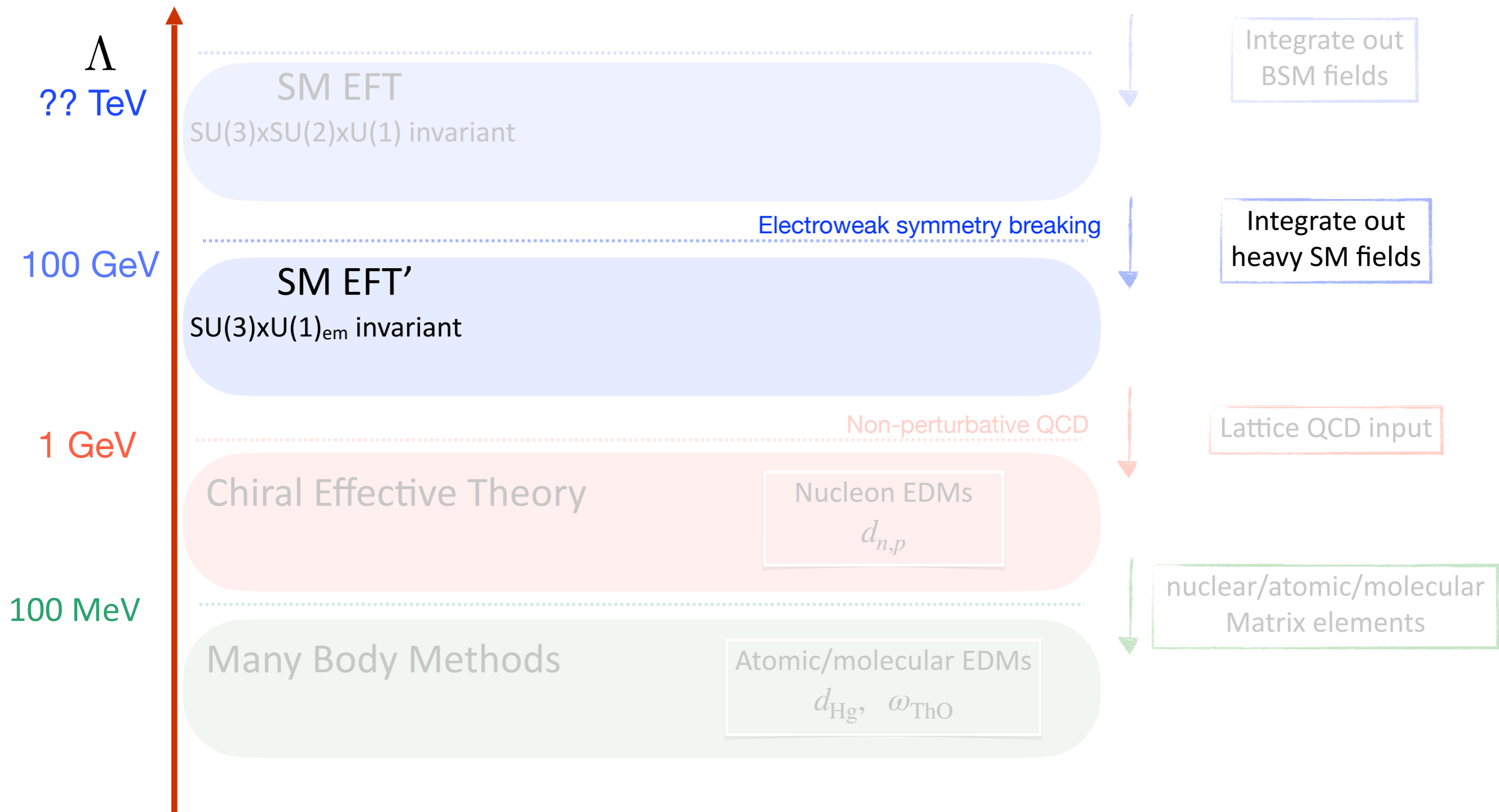


Four-fermion (Hadronic)



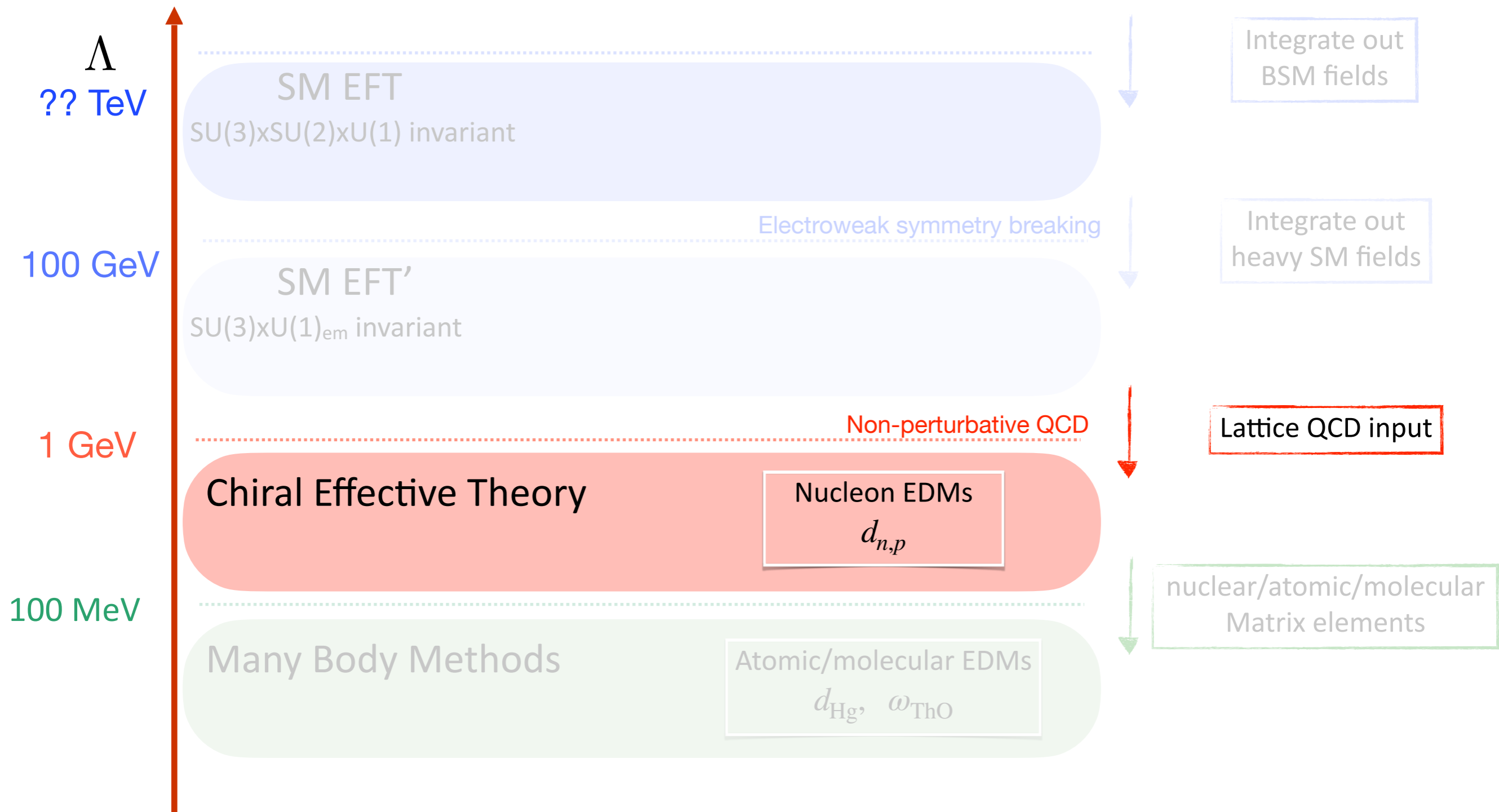
# Outline

CP-violating BSM physics

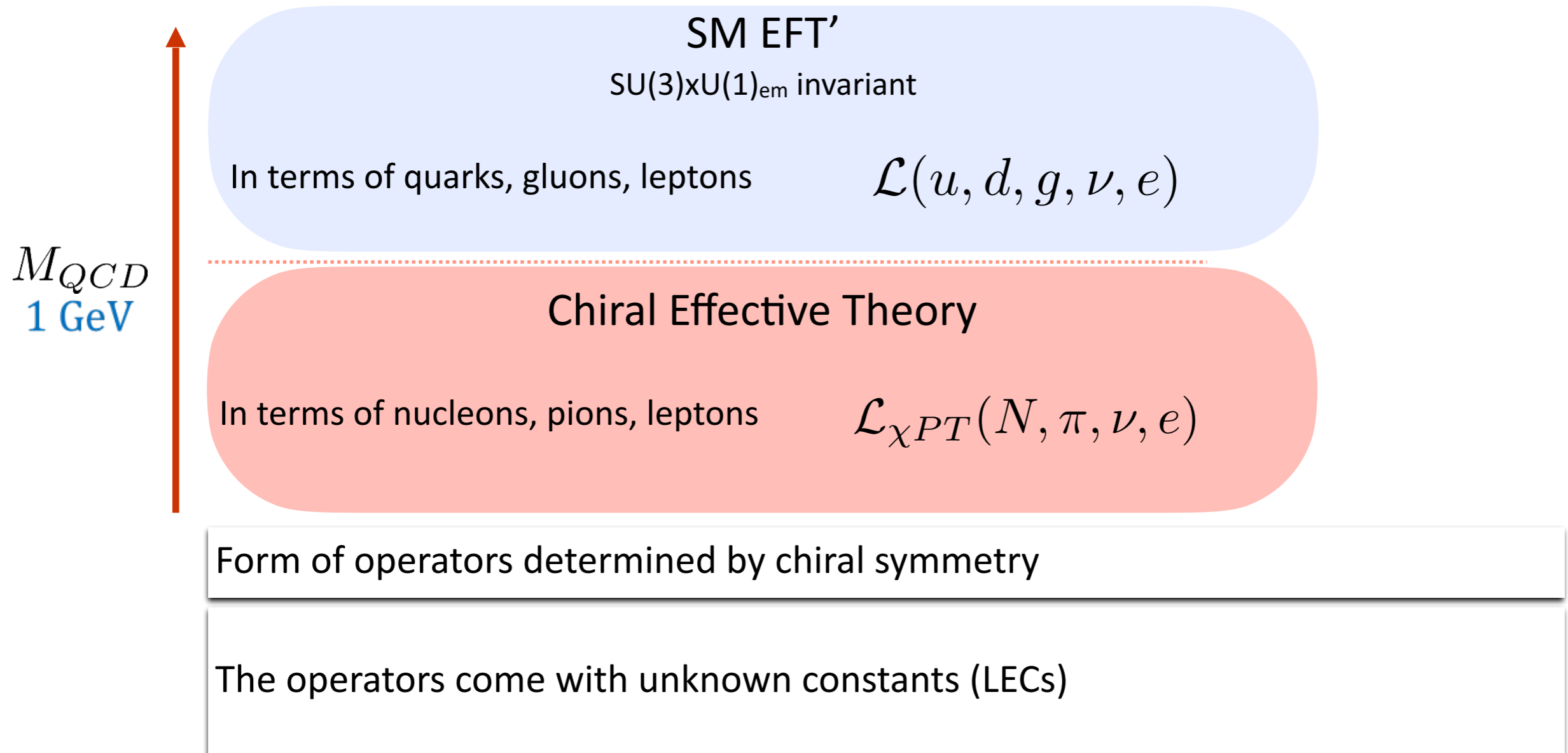


# Outline

CP-violating BSM physics



# Matching to Chiral EFT

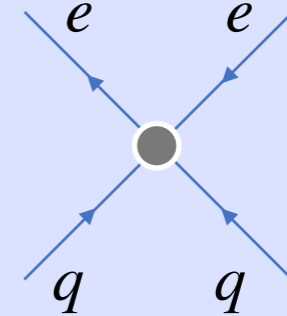
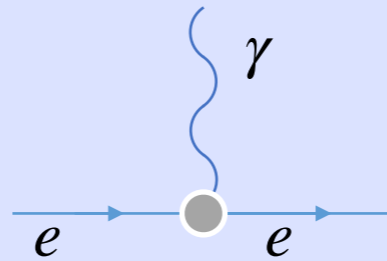


# Matching to Chiral EFT

(Semi)leptonic interactions

SM EFT'

SU(3)xU(1) invariant



1 GeV

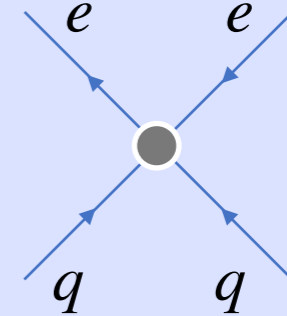
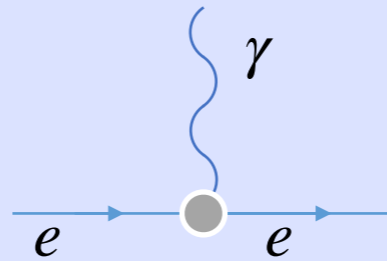
Chiral Effective Theory

# Matching to Chiral EFT

(Semi)leptonic interactions

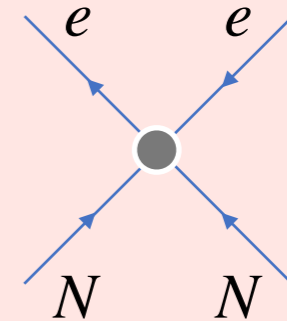
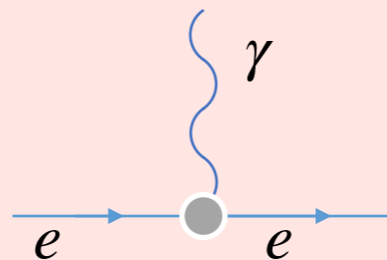
SM EFT'

SU(3)xU(1) invariant



Hadronic matrix elements

Chiral Effective Theory



1 GeV

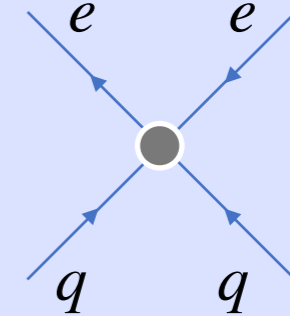
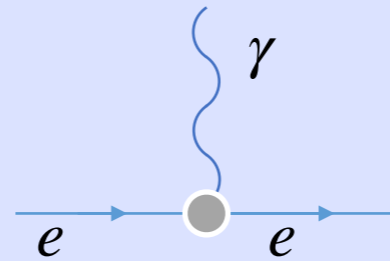


# Matching to Chiral EFT

(Semi)leptonic interactions

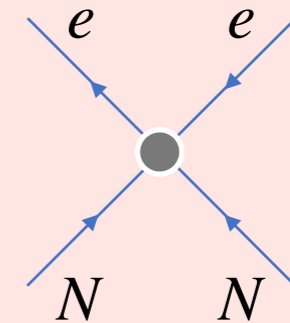
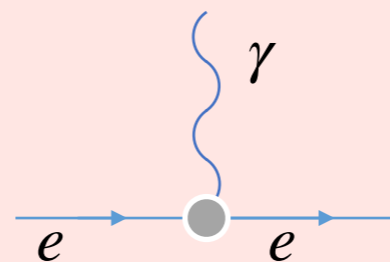
SM EFT'

SU(3)xU(1) invariant



Hadronic matrix elements

Chiral Effective Theory

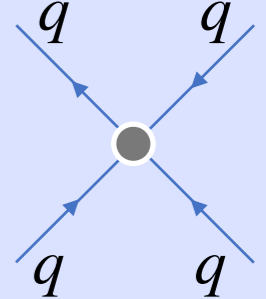
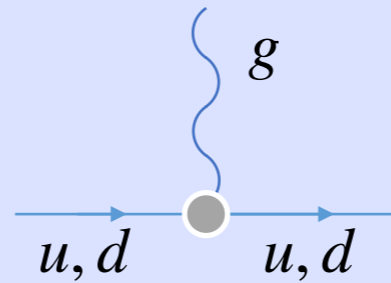
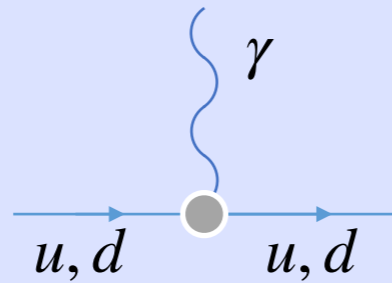


- Needed hadronic matrix elements known from Lattice QCD
- Percent-level uncertainties

# Matching to Chiral EFT

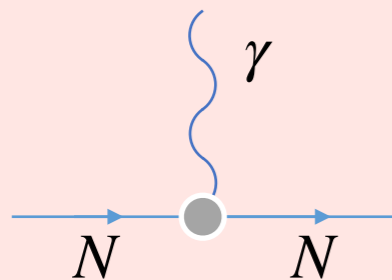
SM EFT'

SU(3)xU(1) invariant



Hadronic matrix elements

Chiral Effective Theory

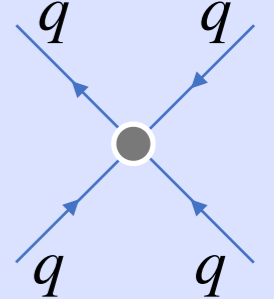
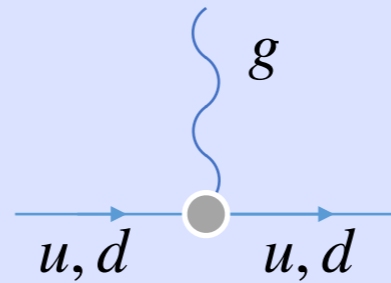
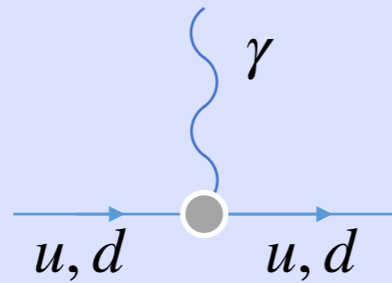


1 GeV

# Matching to Chiral EFT

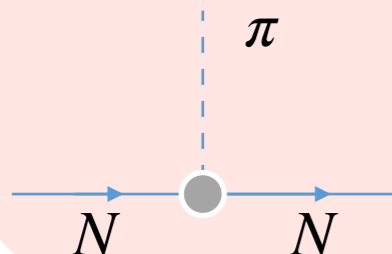
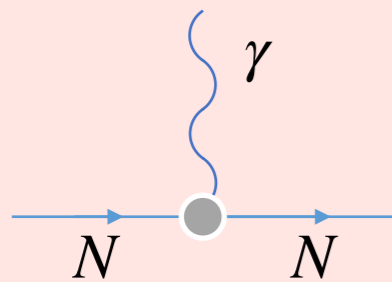
SM EFT'

SU(3)xU(1) invariant



Hadronic matrix elements

Chiral Effective Theory



1 GeV

# Matching to Chiral EFT

Uncertainties:

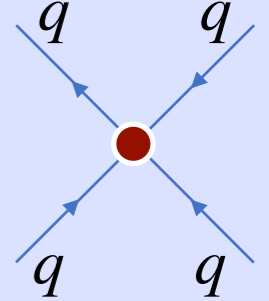
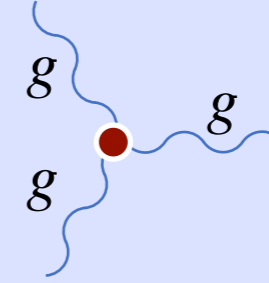
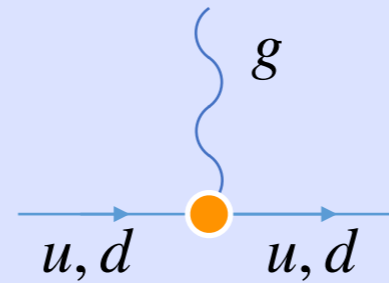
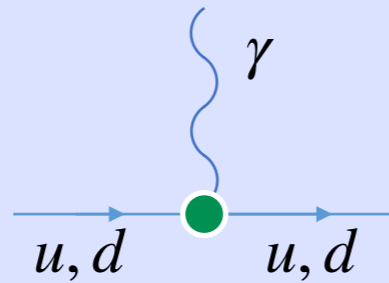
LQCD  
 $\mathcal{O}(\text{few } \%)$

NDA/sum rules  
 $\mathcal{O}(50\%)$

NDA/sum rules  
 $\mathcal{O}(100\%)$

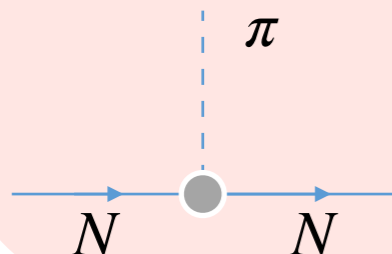
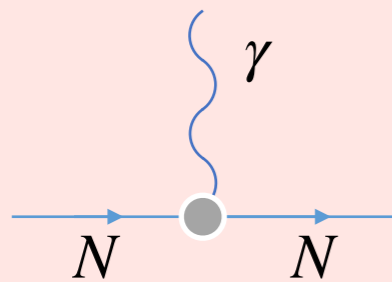
SM EFT'

SU(3)xU(1) invariant



Hadronic matrix elements

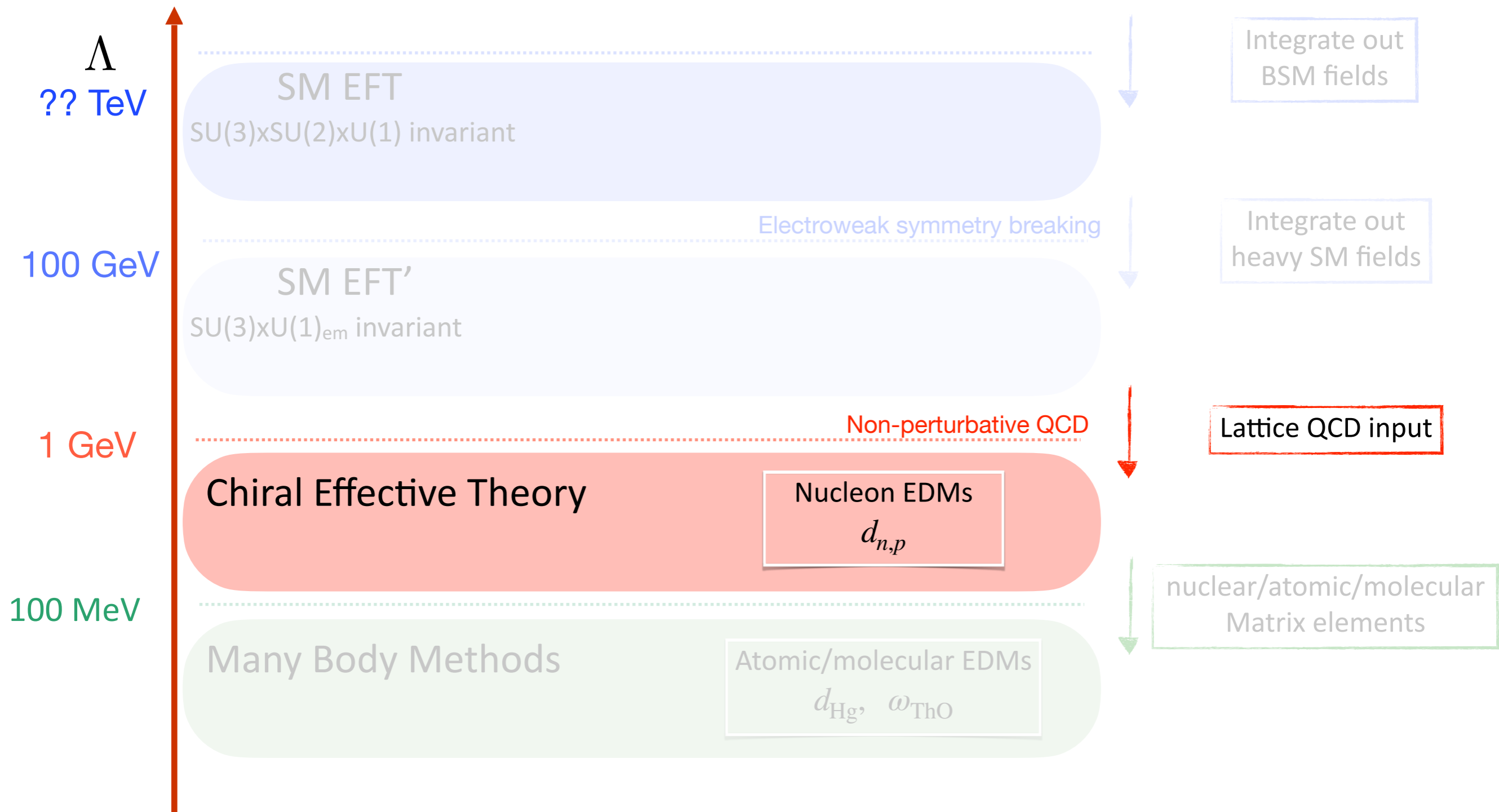
Chiral Effective Theory



1 GeV

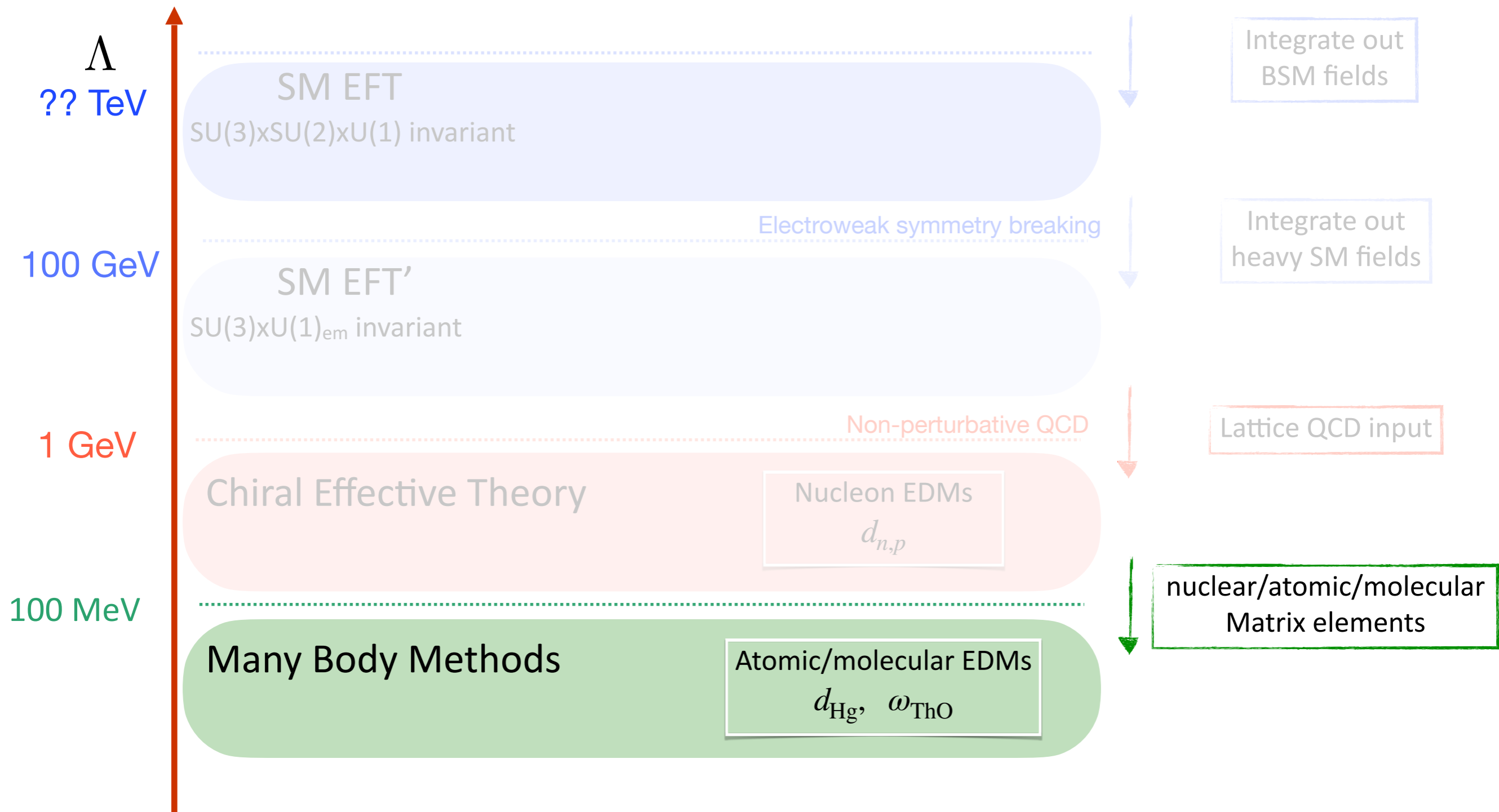
# Outline

CP-violating BSM physics



# Outline

CP-violating BSM physics



# Atomic/molecular EDMs

## Diamagnetic atoms



$$d_{\text{Atom}} = AS \sim A \left[ \alpha_n d_n + \alpha_p d_p + a_0 \bar{g}_0 + a_1 \bar{g}_1 \right]$$

# Atomic/molecular EDMs

## Diamagnetic atoms

Schiff moment



$$d_{\text{Atom}} = AS \sim A \left[ \alpha_n d_n + \alpha_p d_p + a_0 \bar{g}_0 + a_1 \bar{g}_1 \right]$$

- Atomic screening factor
- Known to  $\mathcal{O}(30\%)$



# Atomic/molecular EDMs

## Diamagnetic atoms

Schiff moment



$$d_{\text{Atom}} = AS \sim A \left[ \alpha_n d_n + \alpha_p d_p + a_0 \bar{g}_0 + a_1 \bar{g}_1 \right]$$

- Atomic screening factor
- Known to  $\mathcal{O}(30\%)$

- Nucleon-EDMs
- Known to  $\mathcal{O}(30\%)$  (for Hg)

# Atomic/molecular EDMs

## Diamagnetic atoms

Schiff moment



$$d_{\text{Atom}} = AS \sim A \left[ \alpha_n d_n + \alpha_p d_p + a_0 \bar{g}_0 + a_1 \bar{g}_1 \right]$$

- Atomic screening factor
- Known to  $\mathcal{O}(30\%)$

- Nucleon-EDMs
- Known to  $\mathcal{O}(30\%)$  (for Hg)

- Pion-Nucleon couplings
- Large uncertainties  $\mathcal{O}(100\%)$

# Atomic/molecular EDMs

## Diamagnetic atoms

Schiff moment



$$d_{\text{Atom}} = AS \sim A \left[ \alpha_n d_n + \alpha_n d_p + a_0 \bar{g}_0 + a_1 \bar{g}_1 \right]$$

- Atomic screening factor
  - Known to  $\mathcal{O}(30\%)$

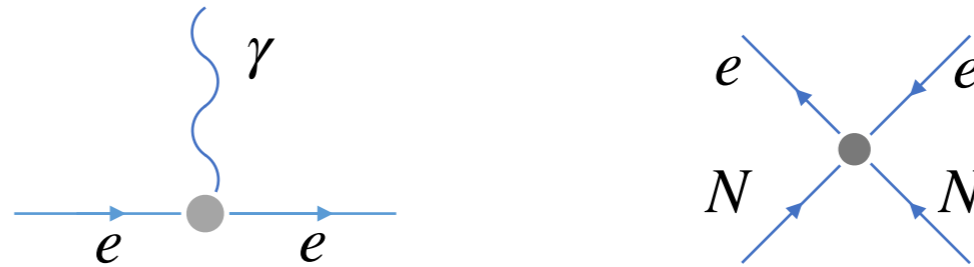
- Nucleon-EDMs
  - Known to  $\mathcal{O}(30\%)$  (for Hg)

- Pion-Nucleon couplings
  - Large uncertainties  $\mathcal{O}(100\%)$
  - Better controlled & **enhanced** in octupole deformed nuclei

- E.g.  $\frac{a_{0,1}(\text{Ra})}{a_{0,1}(\text{Hg})} \sim 10^2$

# Atomic/molecular EDMs

## Paramagnetic molecules



$$\omega_{\text{HfF}} = E_{\text{eff}} d_e + W_S C_S$$

Both types of matrix elements known to  $\mathcal{O}(\text{few } \%)$

# Atomic/molecular EDMs

## Radioactive molecules



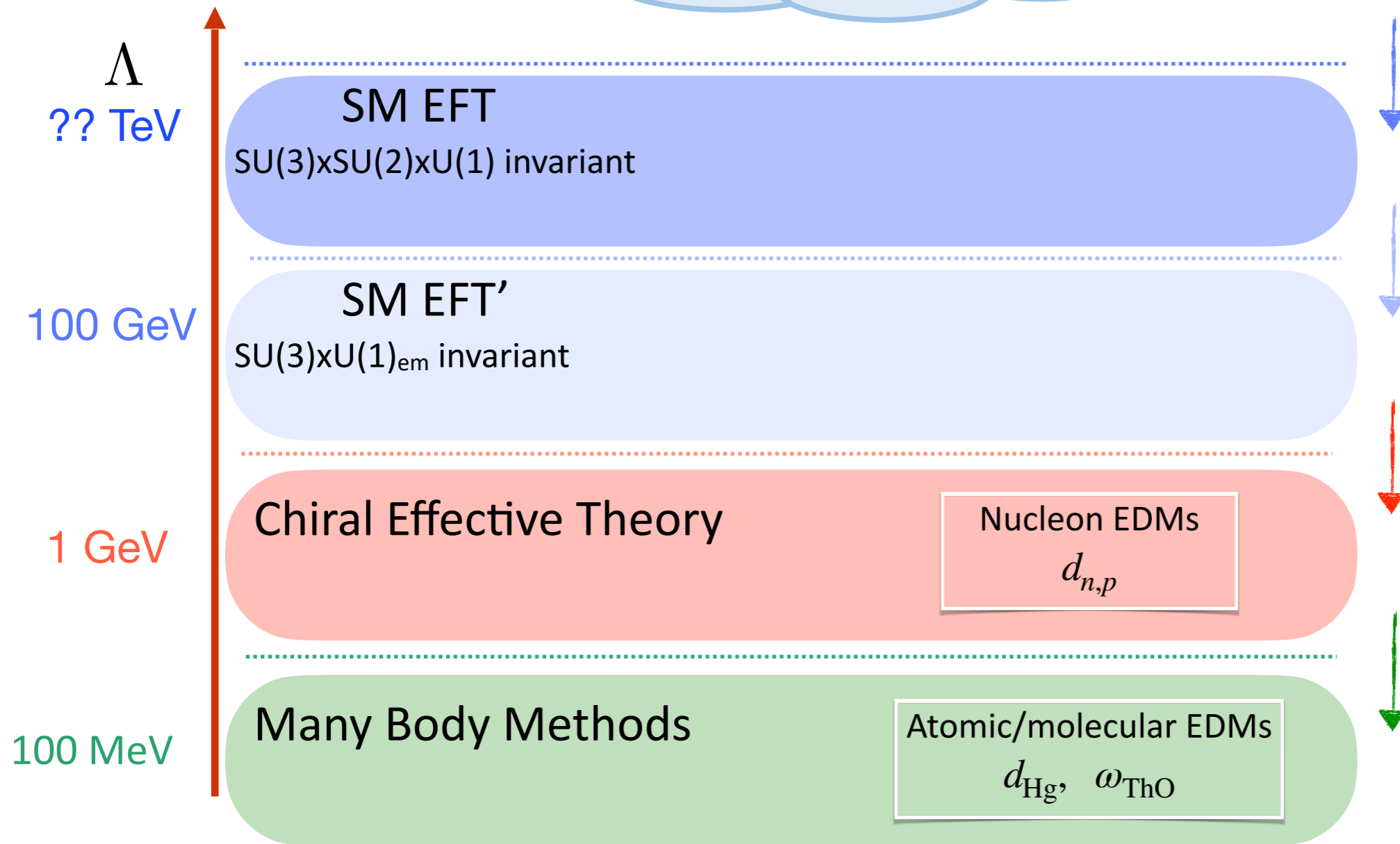
$$W_{\mathcal{P},\mathcal{T},a} = d_e W_{d,a}^m + d_{sr,n} W_{m,a} + d_{sr,n} R_{vol} W_{S,a} + S_{coll} W_{S,a} + k_s W_{s,a}^m + k_T W_{T,a} + k_p W_{p,a},$$

Molecule	$W_d^m / \frac{10^{20} \text{ Hz h}}{e \text{ cm}}$	$W_s^m / (h \text{ Hz})$	$W_T / (h \text{ kHz})$	$W_p / (h \text{ Hz})$	$W_m / \frac{10^{17} \text{ Hz h}}{e \text{ cm}}$	$W_S / \frac{\text{MHz h}}{e \text{ fm}^3}$
RaSH <sup>+</sup>	31.9	82.9	-3.91	-15.3	-1.68	-1.95
RaOCH <sub>3</sub> <sup>+</sup>	34.9	93.5	-4.45	-17.5	-1.88	-2.23
RaCH <sub>3</sub> <sup>+</sup>	39.0	98.5	-4.62	-18.1	-1.91	-2.24
RaCN <sup>+</sup>	32.5	86.4	-4.10	-16.1	-1.82	-2.06
RaNC <sup>+</sup>	32.0	86.1	-4.10	-16.1	-1.82	-2.08

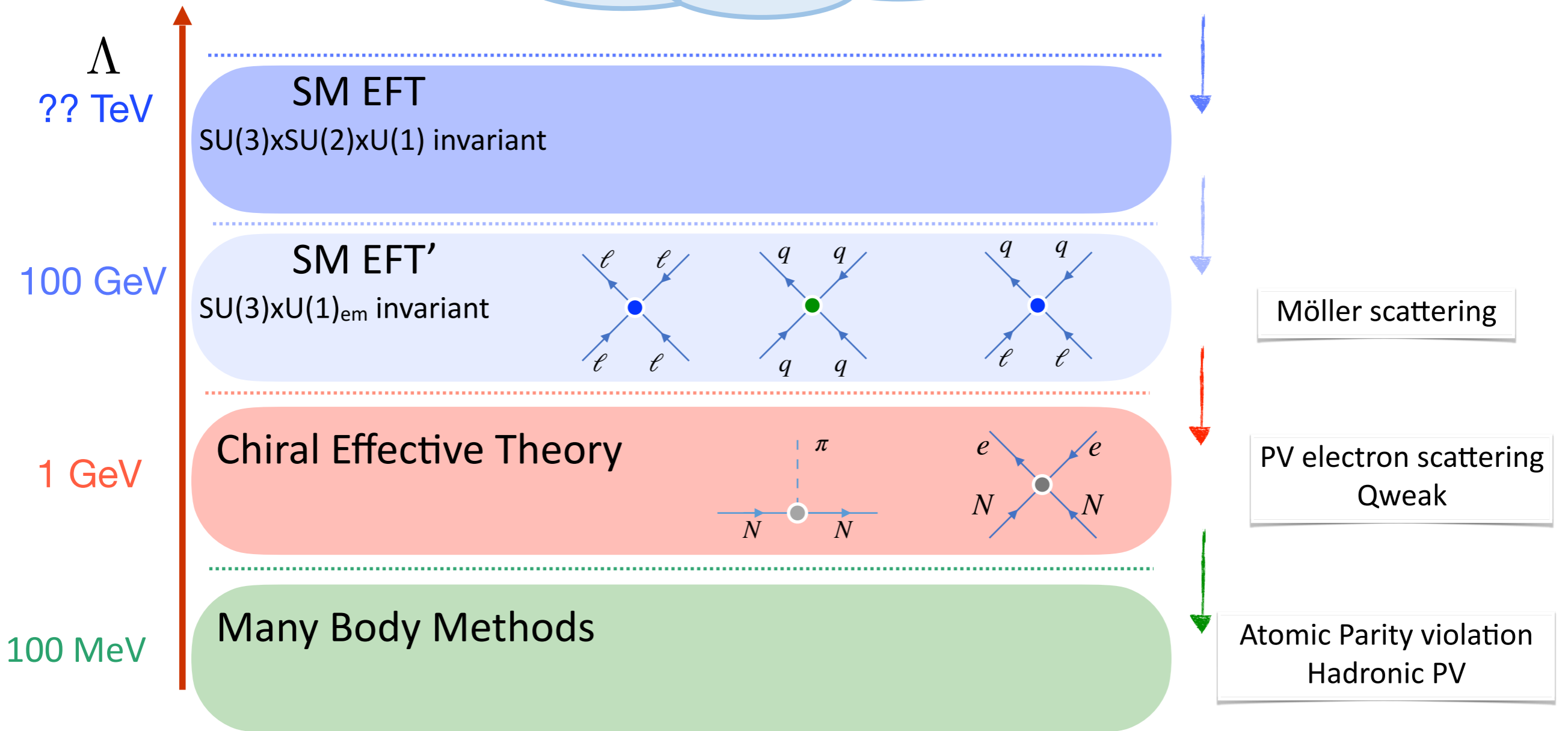
Gaul *et al.* '23

# Outline

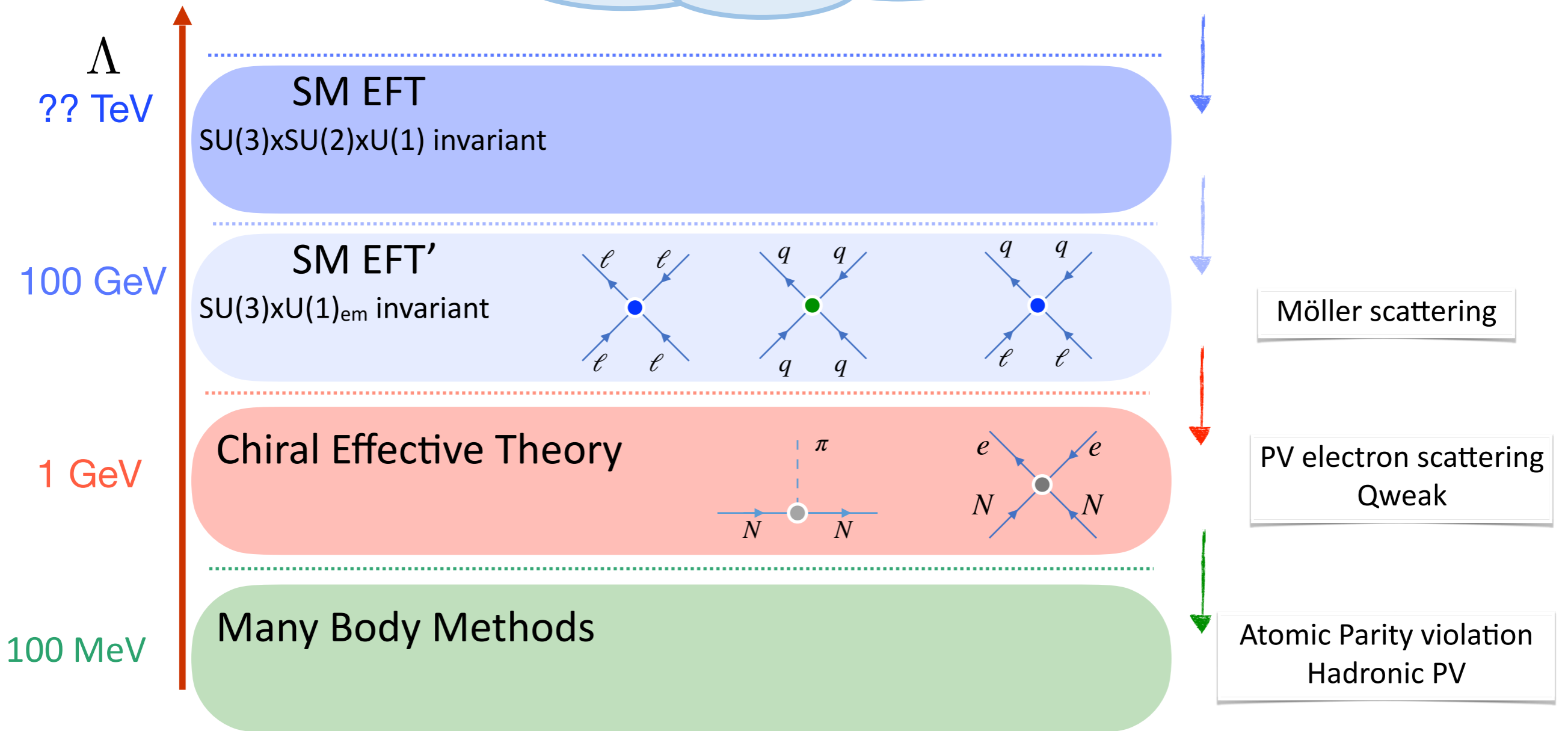
CP-violating BSM physics



# Outline



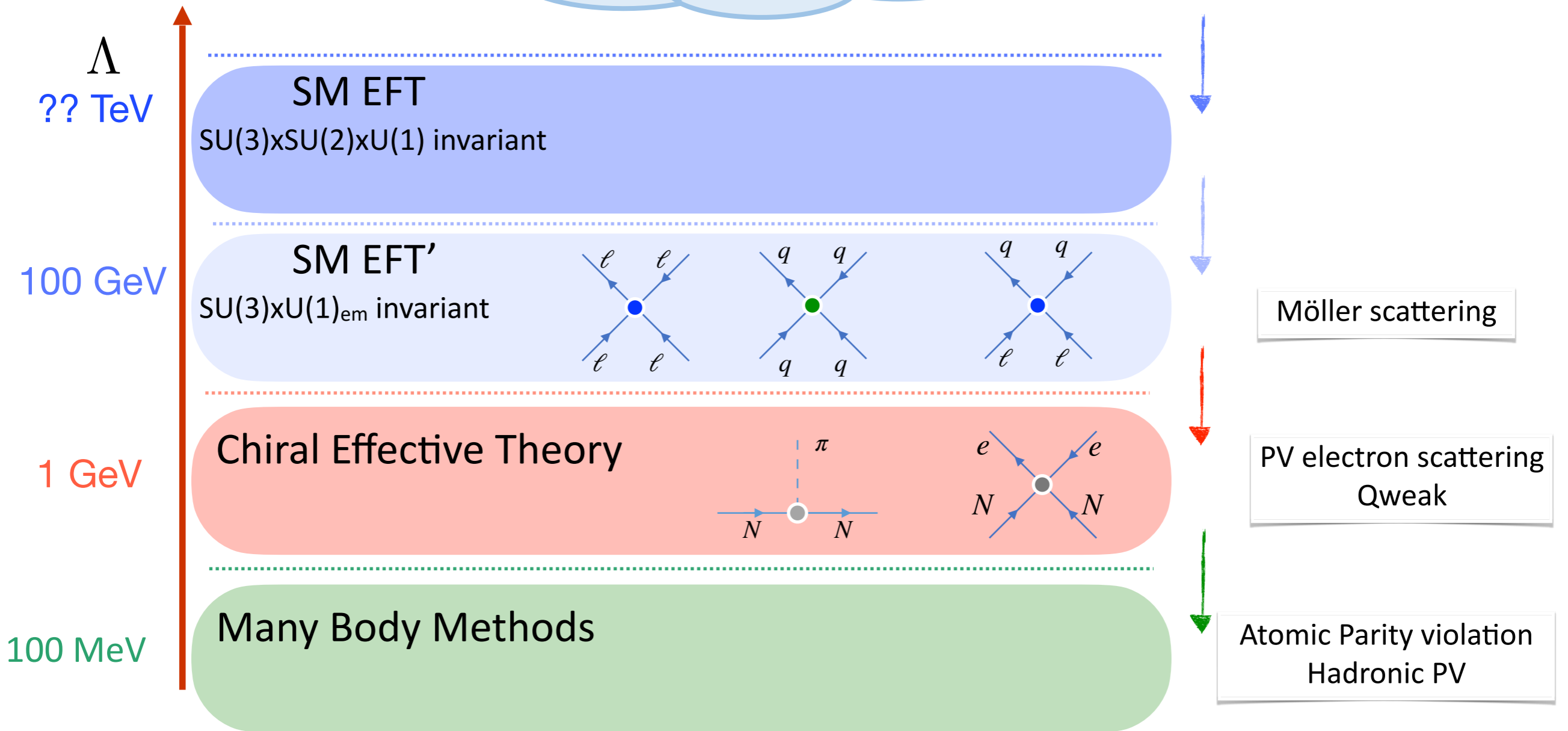
# Outline



- Can similarly treat Parity-violating physics
  - Construct (hadronic) interactions in the same way
  - Again require hadronic/nuclear matrix elements



# Outline



- Can similarly treat Parity-violating physics
  - Construct (hadronic) interactions in the same way
  - Again require hadronic/nuclear matrix elements

- Nonzero SM background
  - Currently these observables probe BSM scales  $\Lambda \sim \text{several TeV}$

# Phenomenology

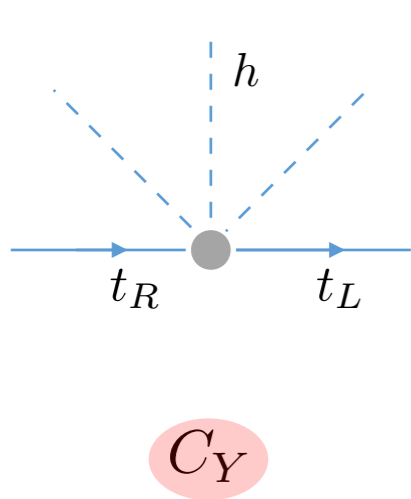
CPV top-Higgs interactions

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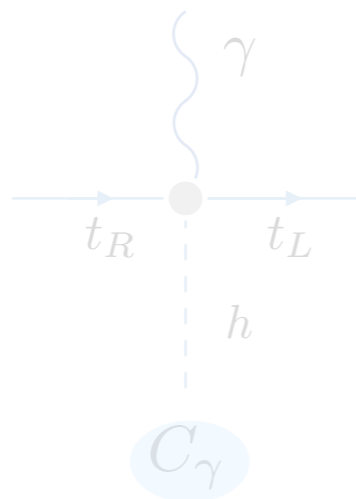
# The top-Higgs couplings

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  - Focus on top-Higgs interactions

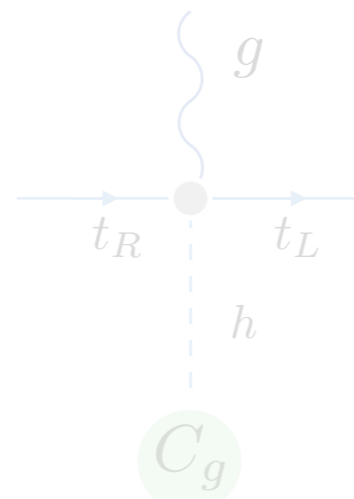
$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
$Q_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$



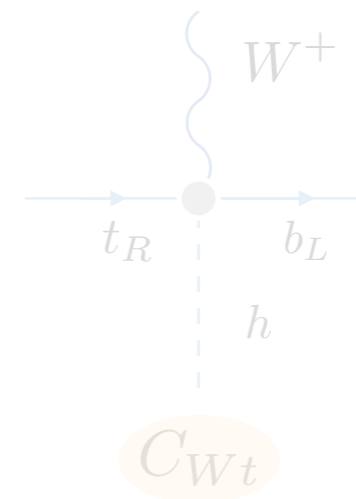
CPV  $t$  Yukawa



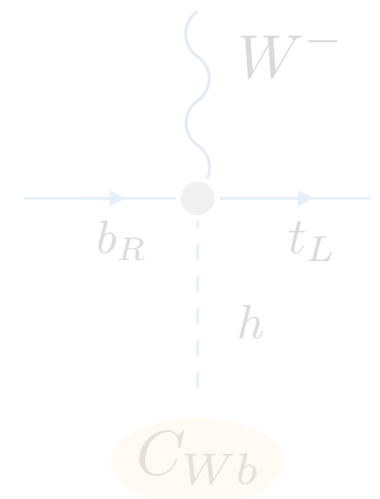
$t$  EDM



$t$  CEDM



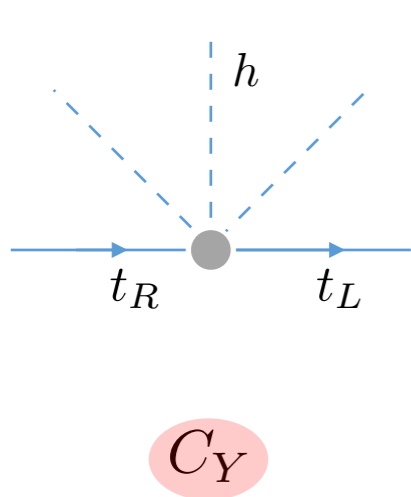
$t$  weak-EDMs



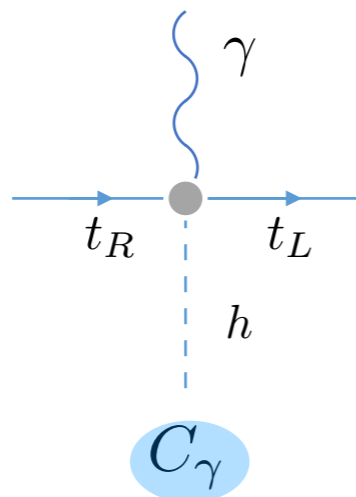
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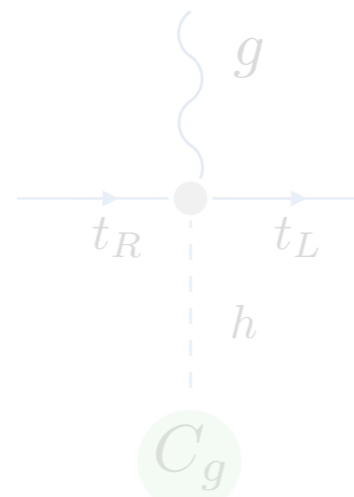
$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
$Q_{\tilde{G}}$	$f^{ABC} \tilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger \varphi)\Box(\varphi^\dagger \varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p u_r \tilde{\varphi})$
$Q_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$



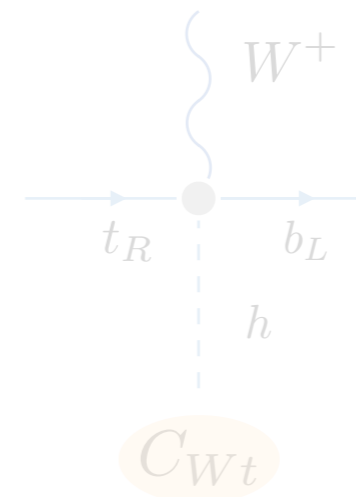
CPV  $t$  Yukawa



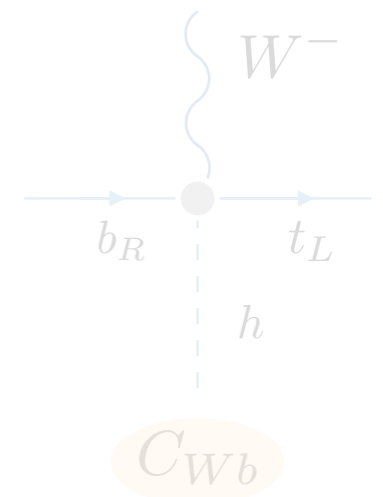
$t$  EDM



$t$  CEDM



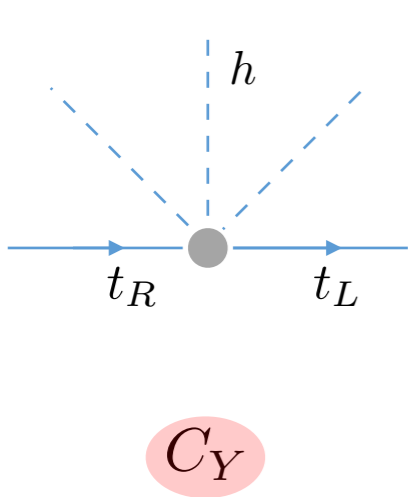
$t$  weak-EDMs



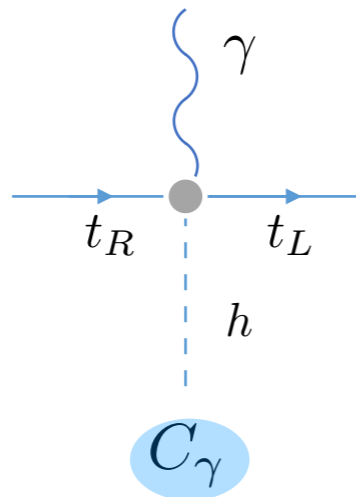
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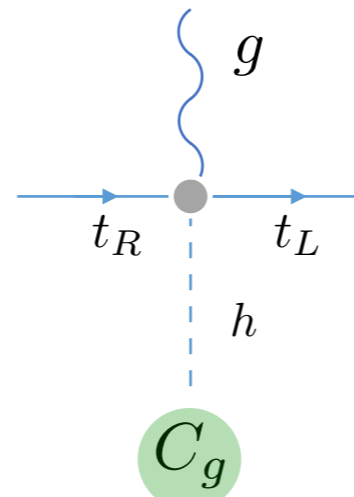
$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
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$Q_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
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$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$



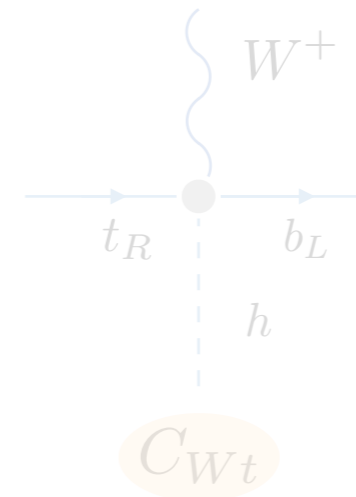
CPV  $t$  Yukawa



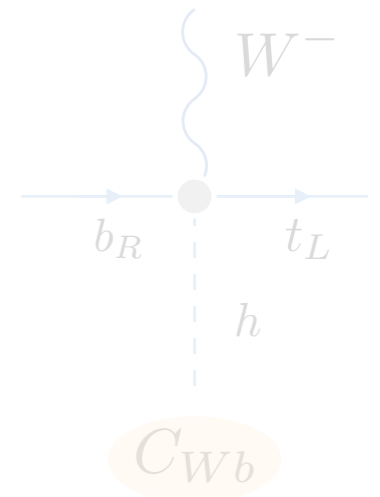
$t$  EDM



$t$  CEDM



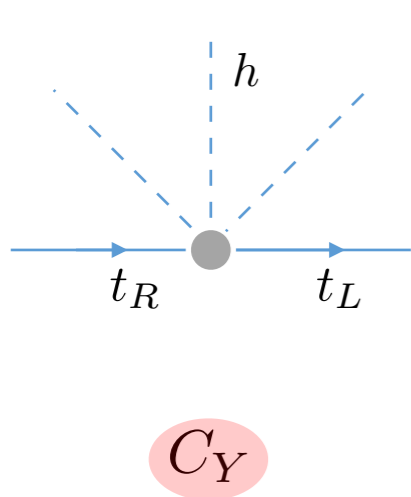
$t$  weak-EDMs



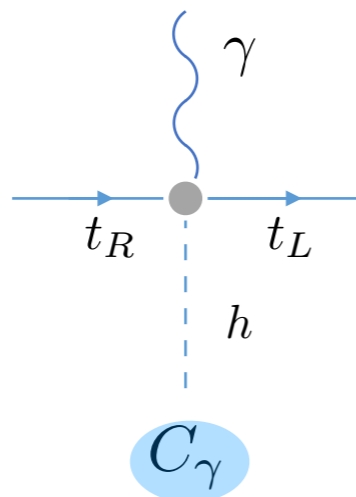
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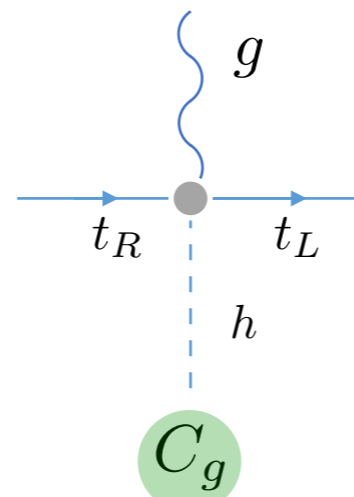
$X^3$		$\varphi^6$ and $\varphi^4 D^2$		$\psi^2 \varphi^3$	
$Q_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_\varphi$	$(\varphi^\dagger \varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger \varphi)(\bar{l}_p e_r \varphi)$
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$Q_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu \varphi)^* (\varphi^\dagger D_\mu \varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger \varphi)(\bar{q}_p d_r \varphi)$
$Q_{\tilde{W}}$	$\varepsilon^{IJK} \tilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2 \varphi^2$		$\psi^2 X \varphi$		$\psi^2 \varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eW}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{l}_p \gamma^\mu l_r)$
$Q_{\varphi \tilde{G}}$	$\varphi^\dagger \varphi \tilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$Q_{eB}$	$(\bar{l}_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{l}_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \tilde{\varphi} G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{e}_p \gamma^\mu e_r)$
$Q_{\varphi \tilde{W}}$	$\varphi^\dagger \varphi \tilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$Q_{uW}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \tilde{\varphi} W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{q}_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi B_{\mu\nu} B^{\mu\nu}$	$Q_{uB}$	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tilde{\varphi} B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar{q}_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi \tilde{B}}$	$\varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$Q_{dG}$	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) \varphi G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{u}_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi W_{\mu\nu}^I B^{\mu\nu}$	$Q_{dW}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{d}_p \gamma^\mu d_r)$
$Q_{\varphi \tilde{W}B}$	$\varphi^\dagger \tau^I \varphi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$Q_{dB}$	$(\bar{q}_p \sigma^{\mu\nu} d_r) \varphi B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{u}_p \gamma^\mu d_r)$



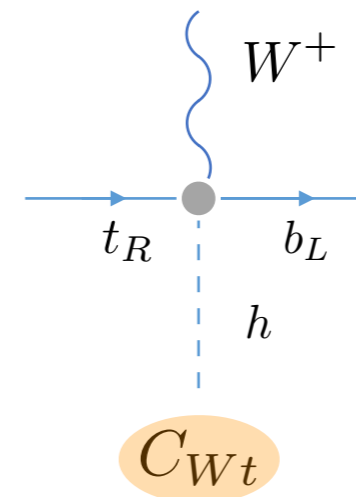
CPV  $t$  Yukawa



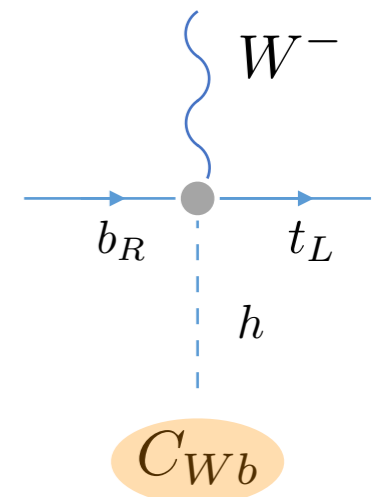
$t$  EDM



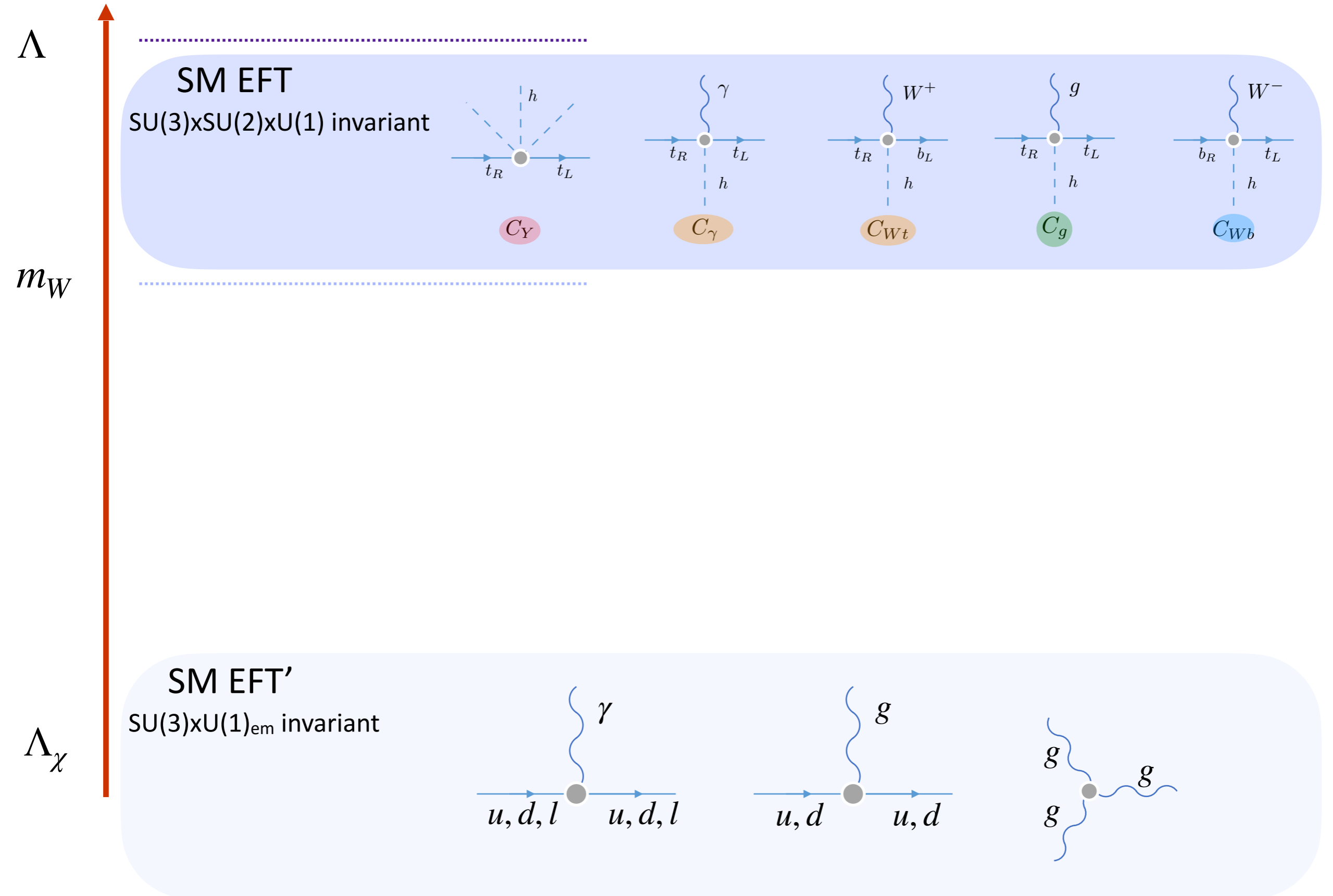
$t$  CEDM



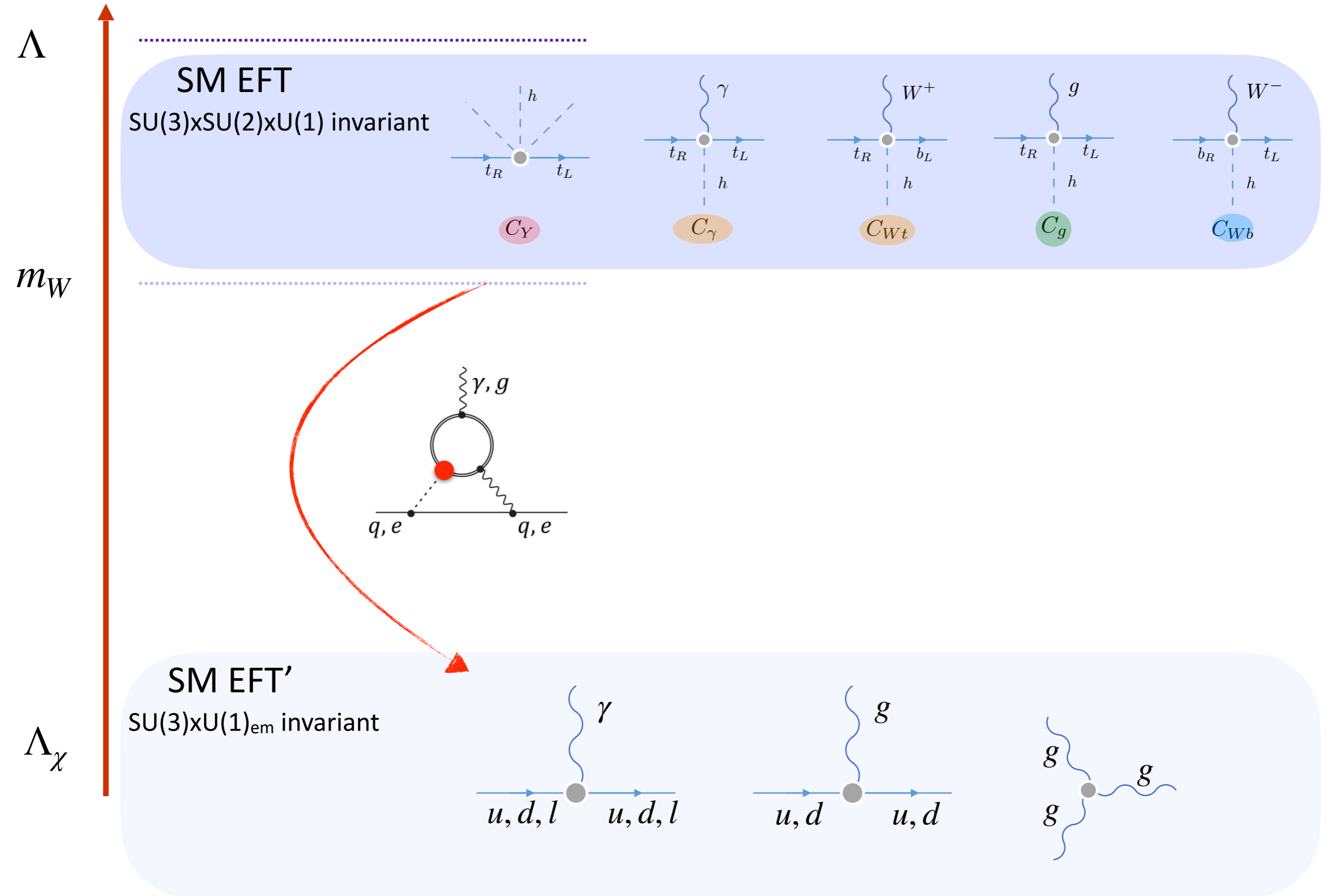
$t$  weak-EDMs



# Below the weak scale

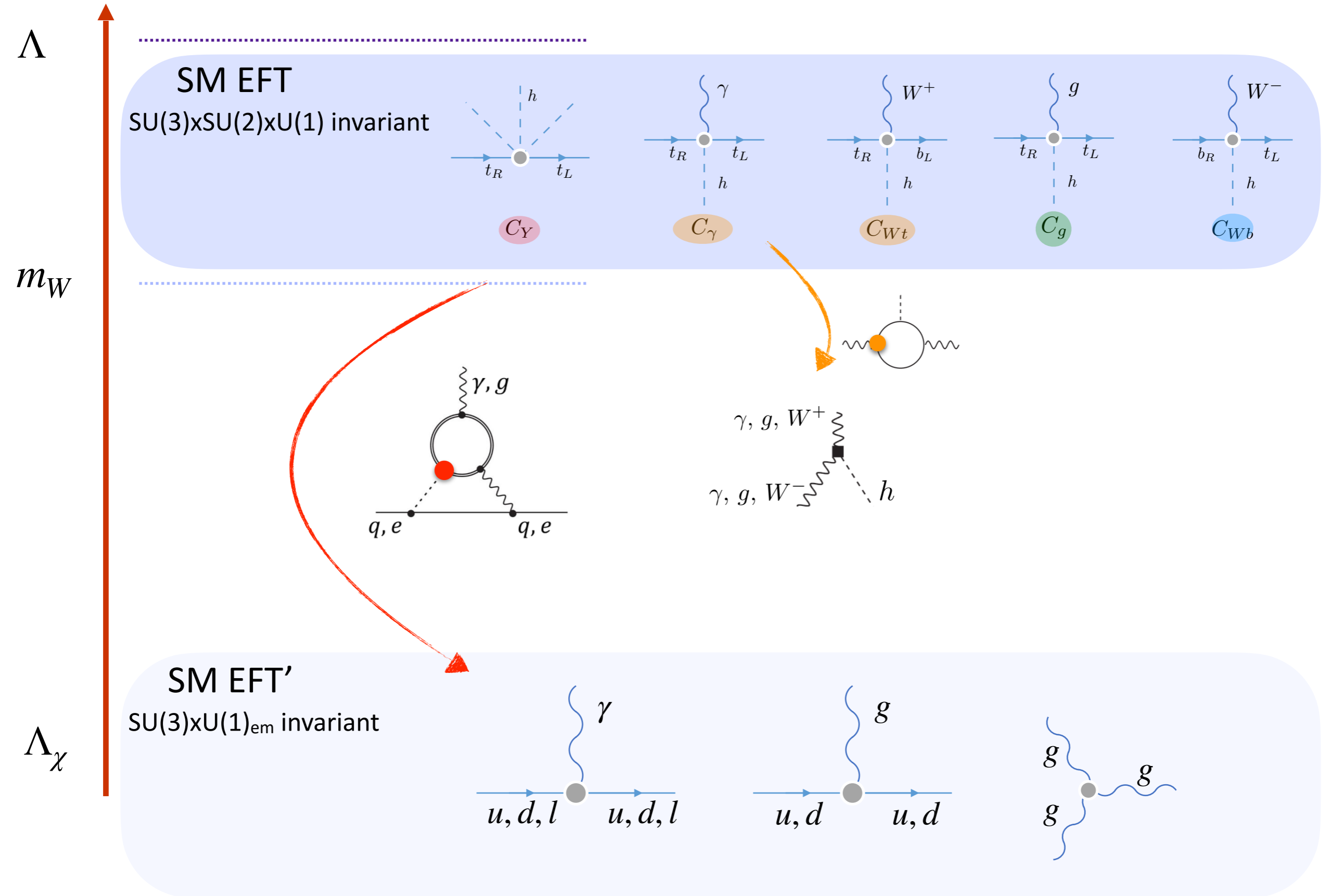


# Below the weak scale

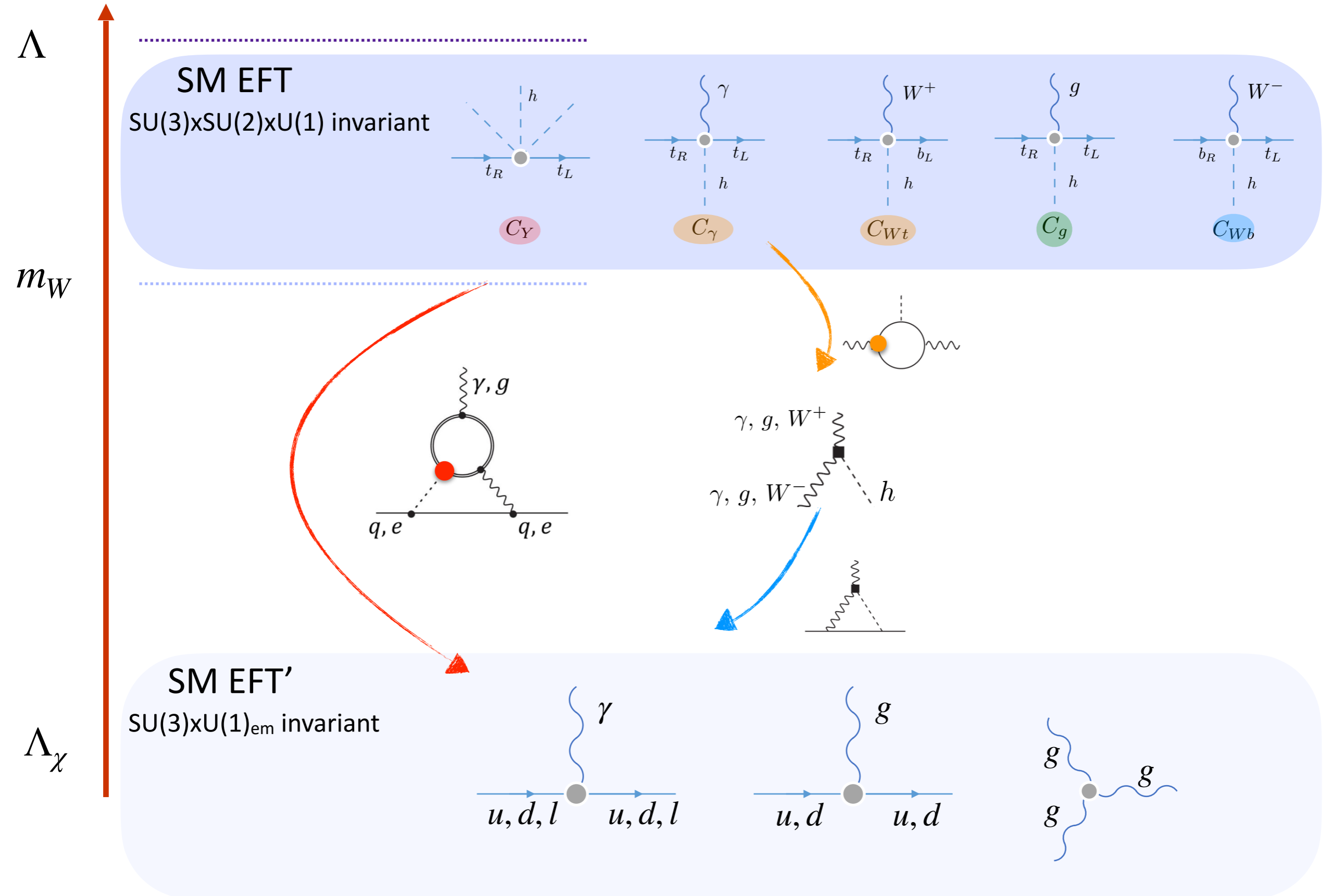




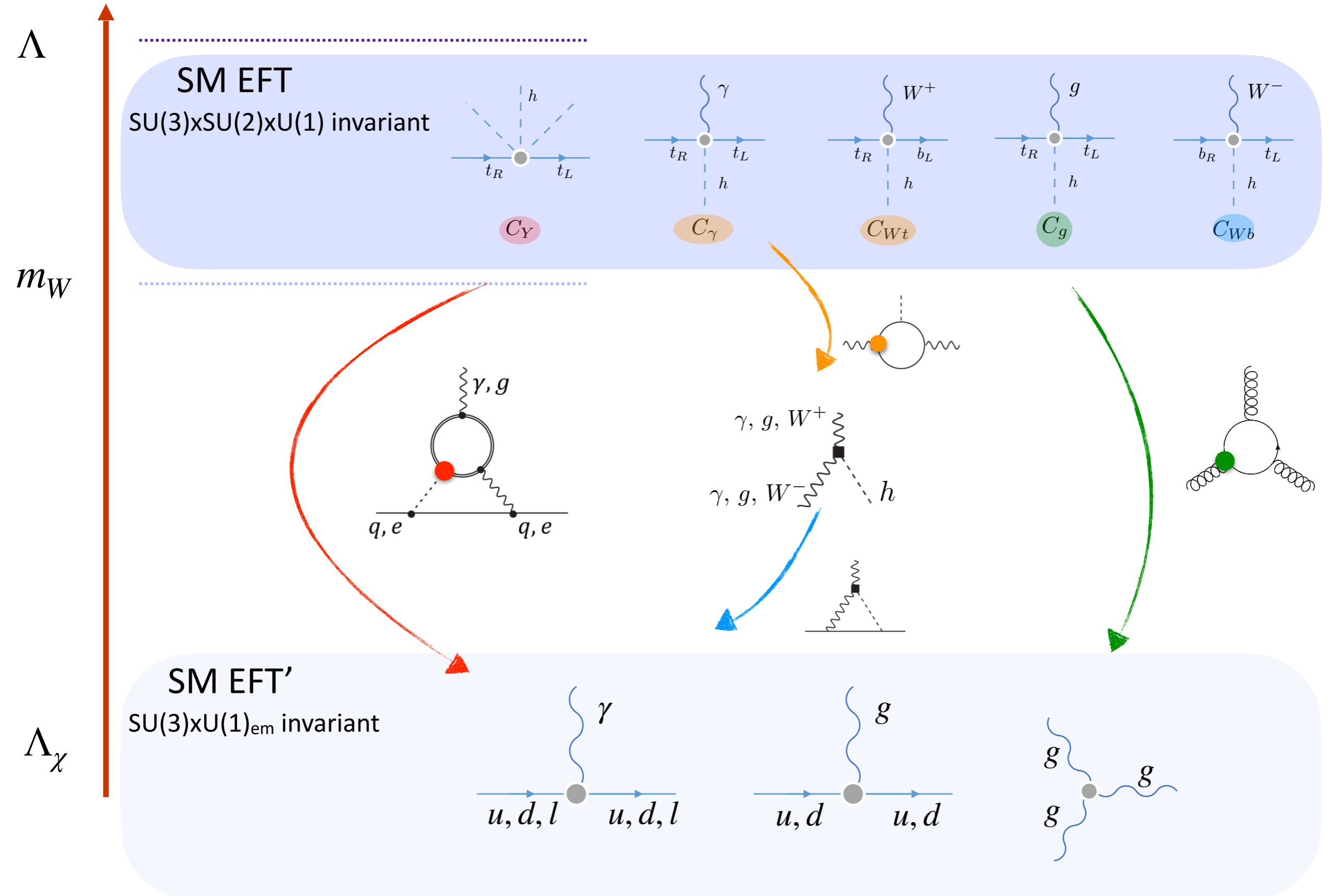
# Below the weak scale



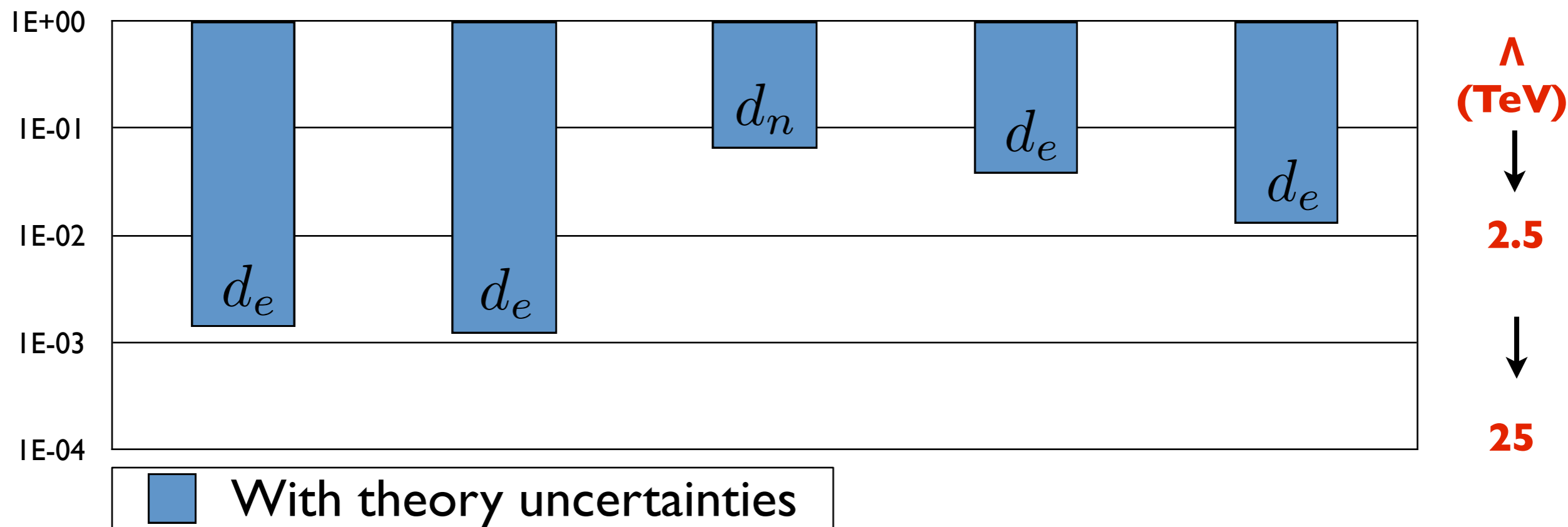
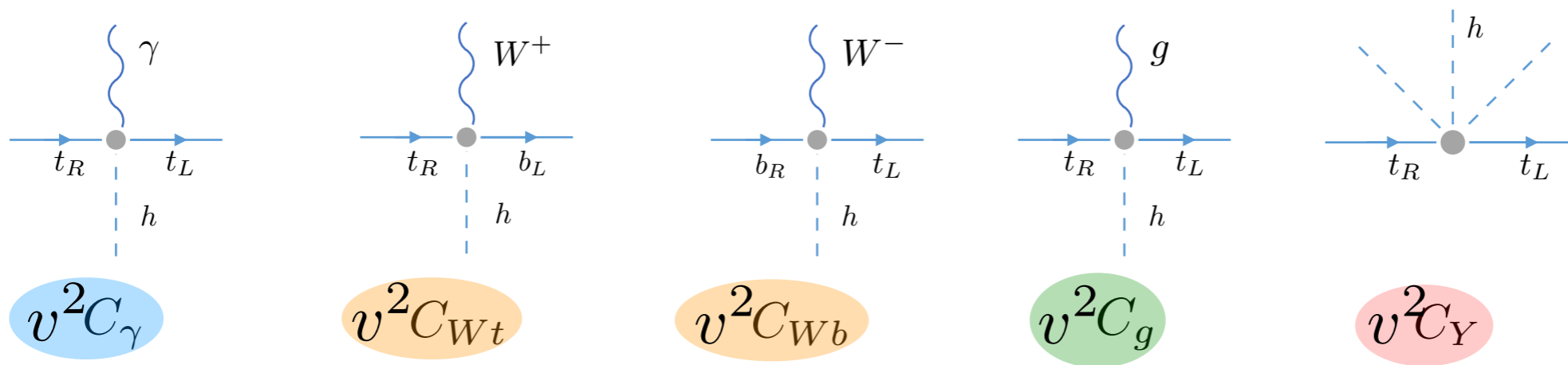
# Below the weak scale



# Below the weak scale



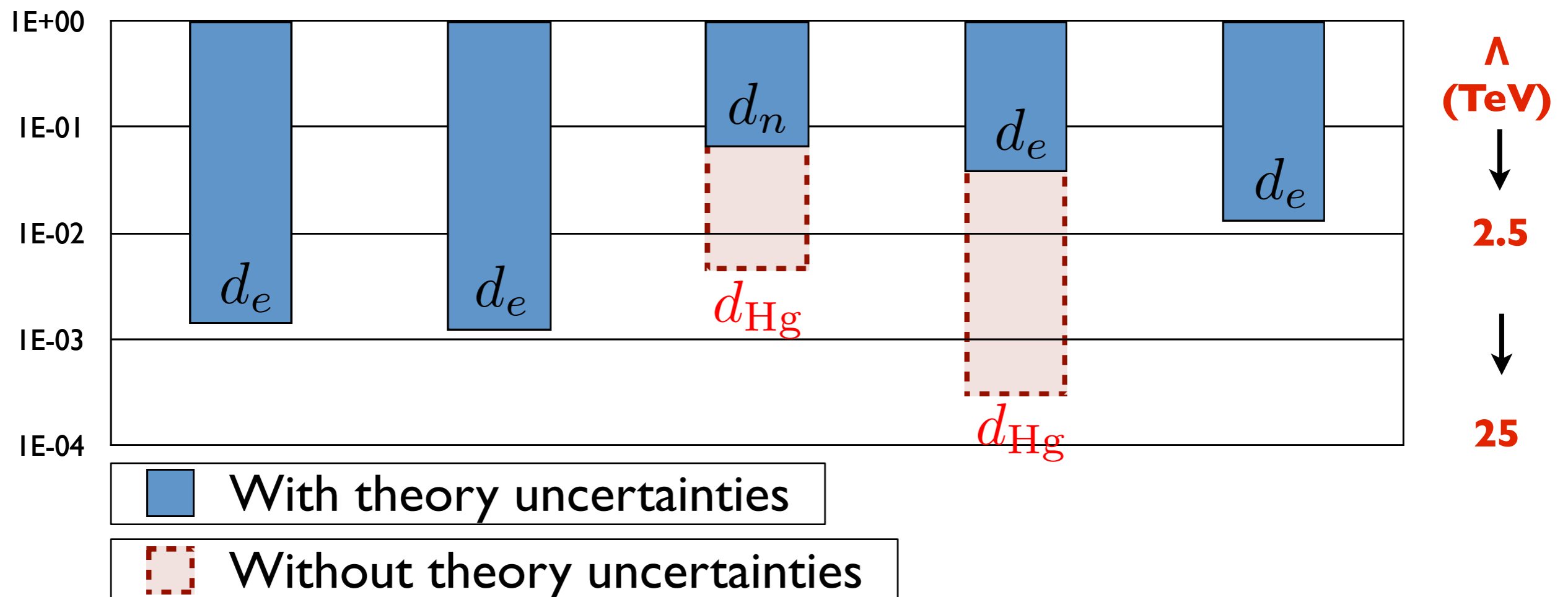
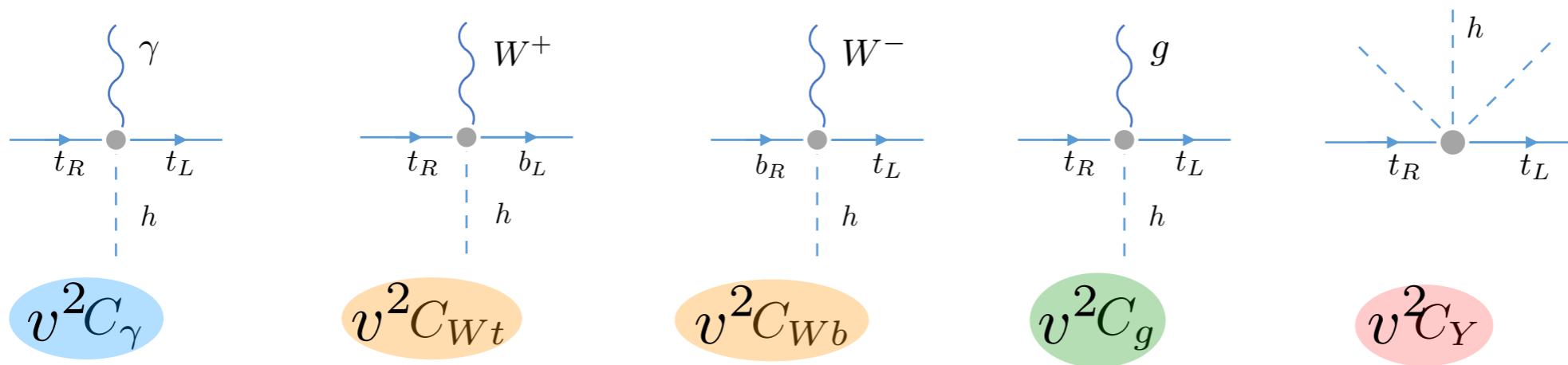
# Single coupling constraints



- Even though loop-generated, EDMs probe  $\Lambda \gtrsim 10$  TeV
- More sensitive than LHC reach for most couplings

# Single coupling constraints

Impact of theoretical uncertainties



- Hadronic/Nuclear uncertainties weaken the constraints from hadronic systems
  - Nucleon & mercury EDMs

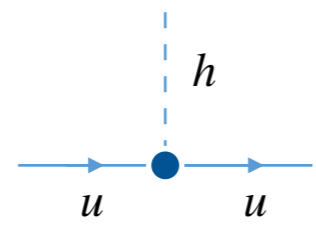
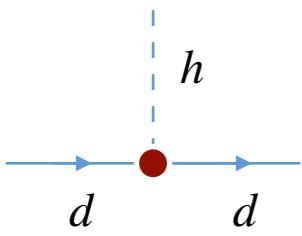
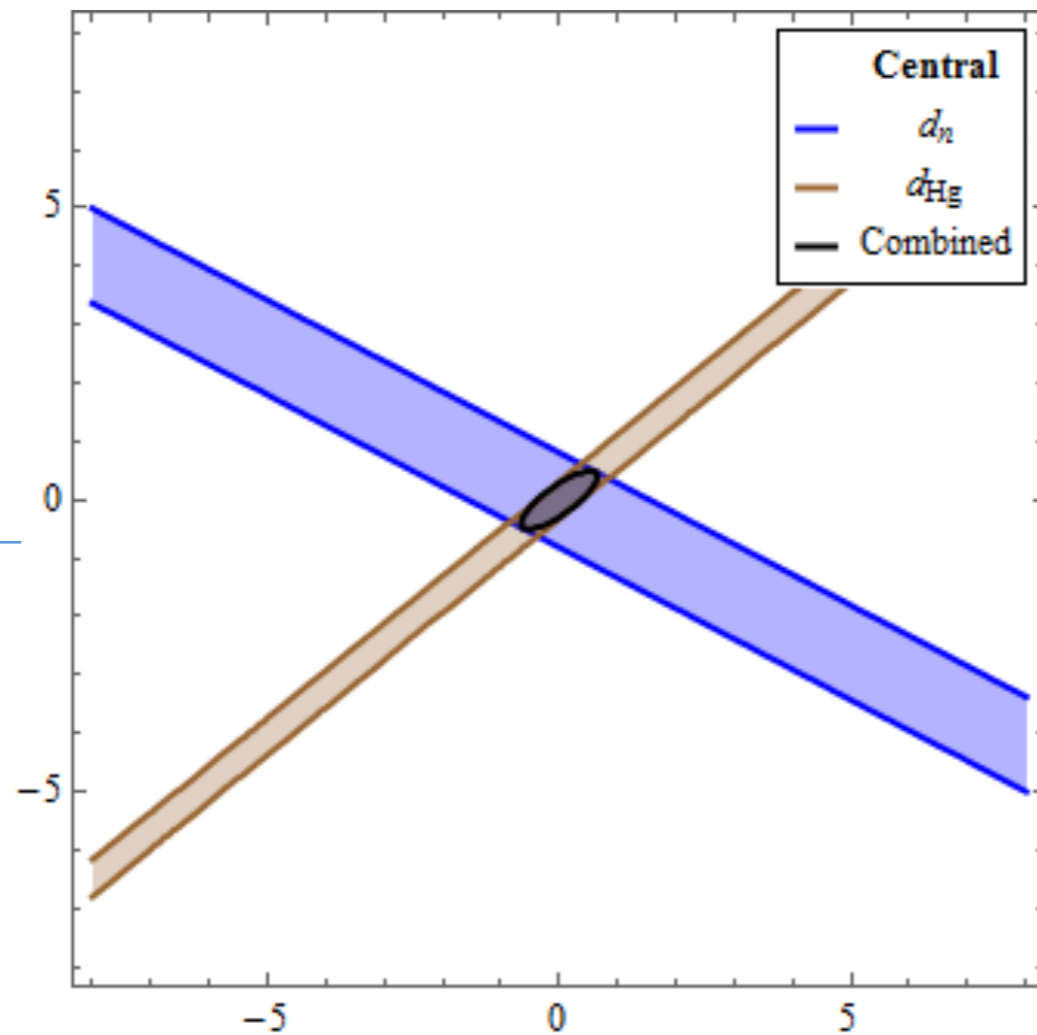
# Phenomenology

CPV Yukawa interactions of light quarks

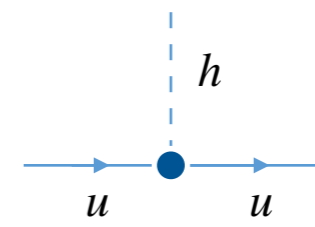
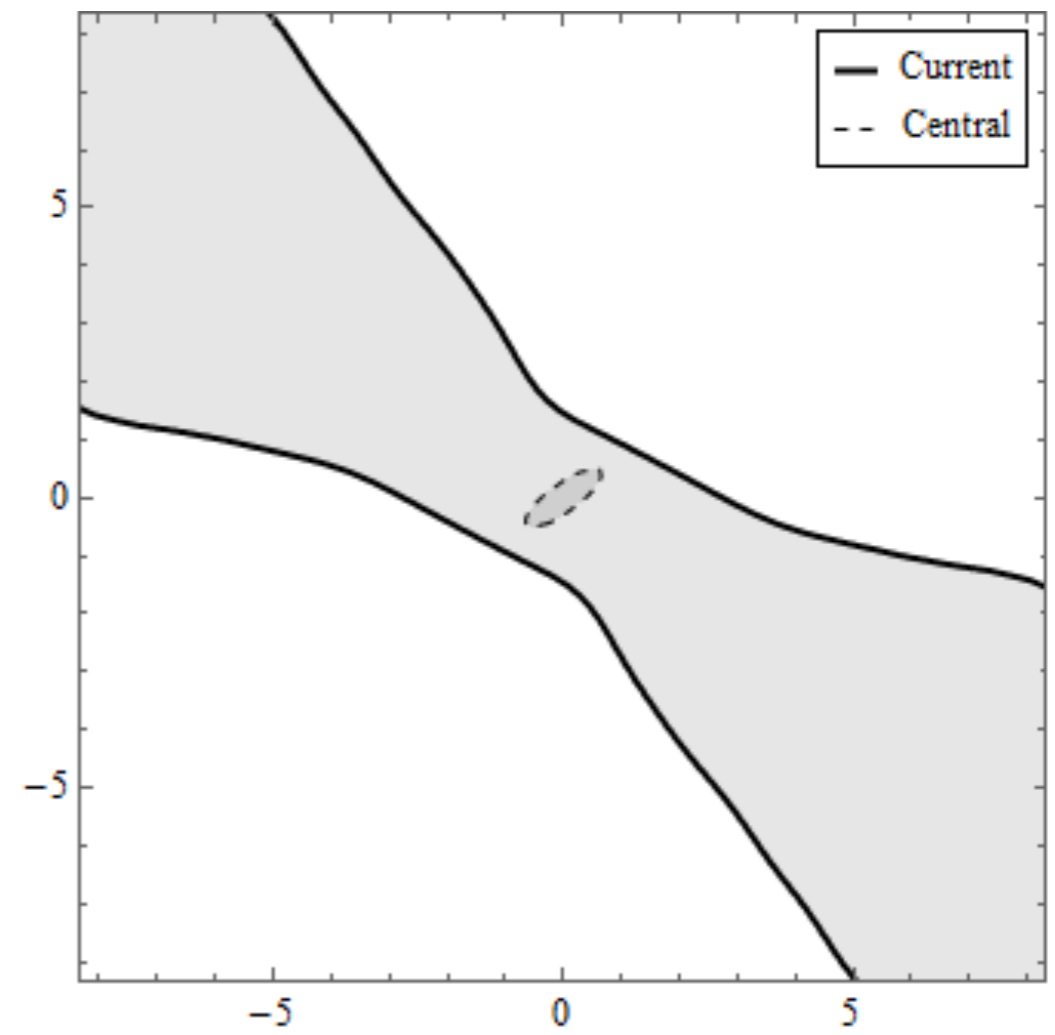
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# Two-coupling analysis

**Without** theory uncertainties



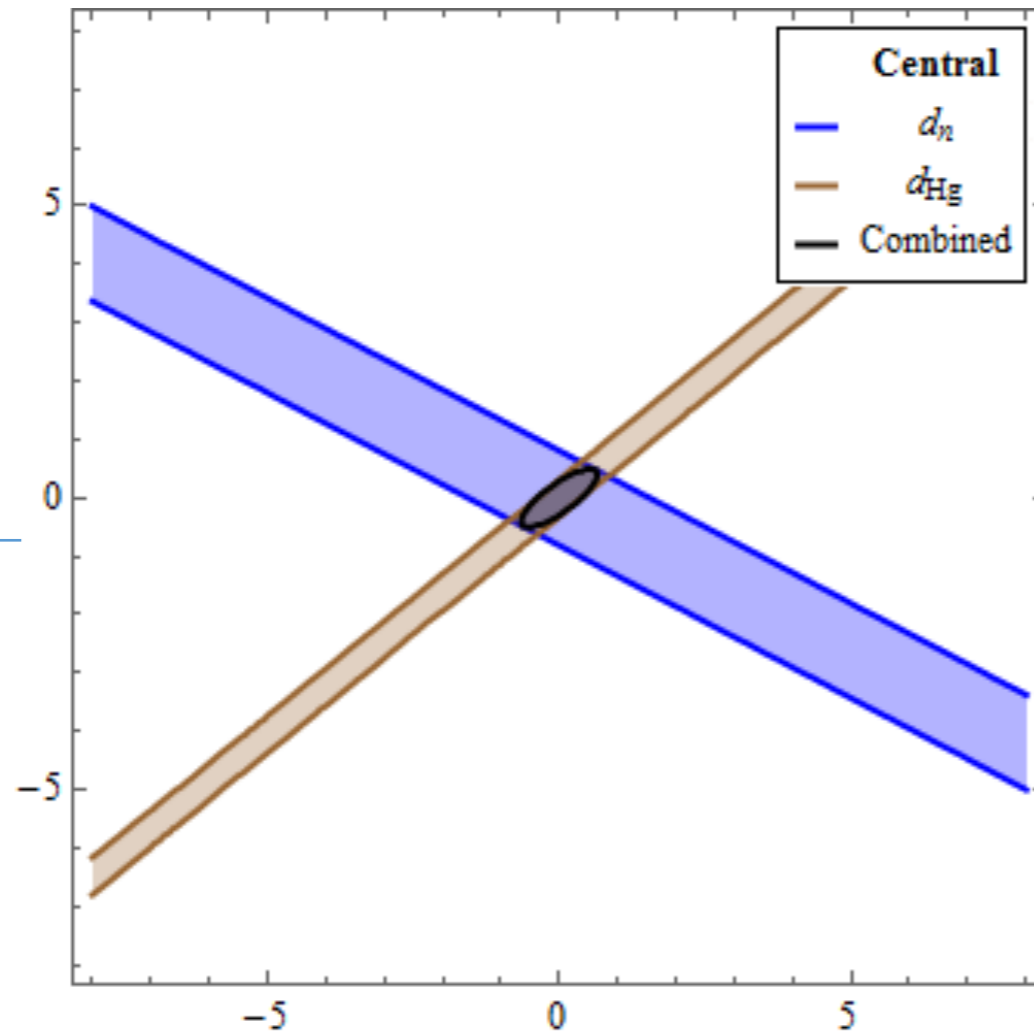
**With** theory uncertainties



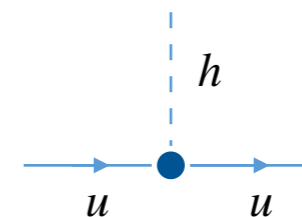
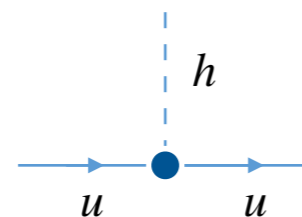
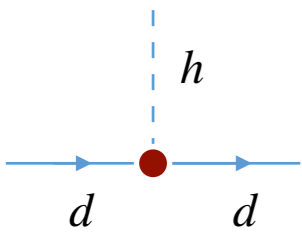
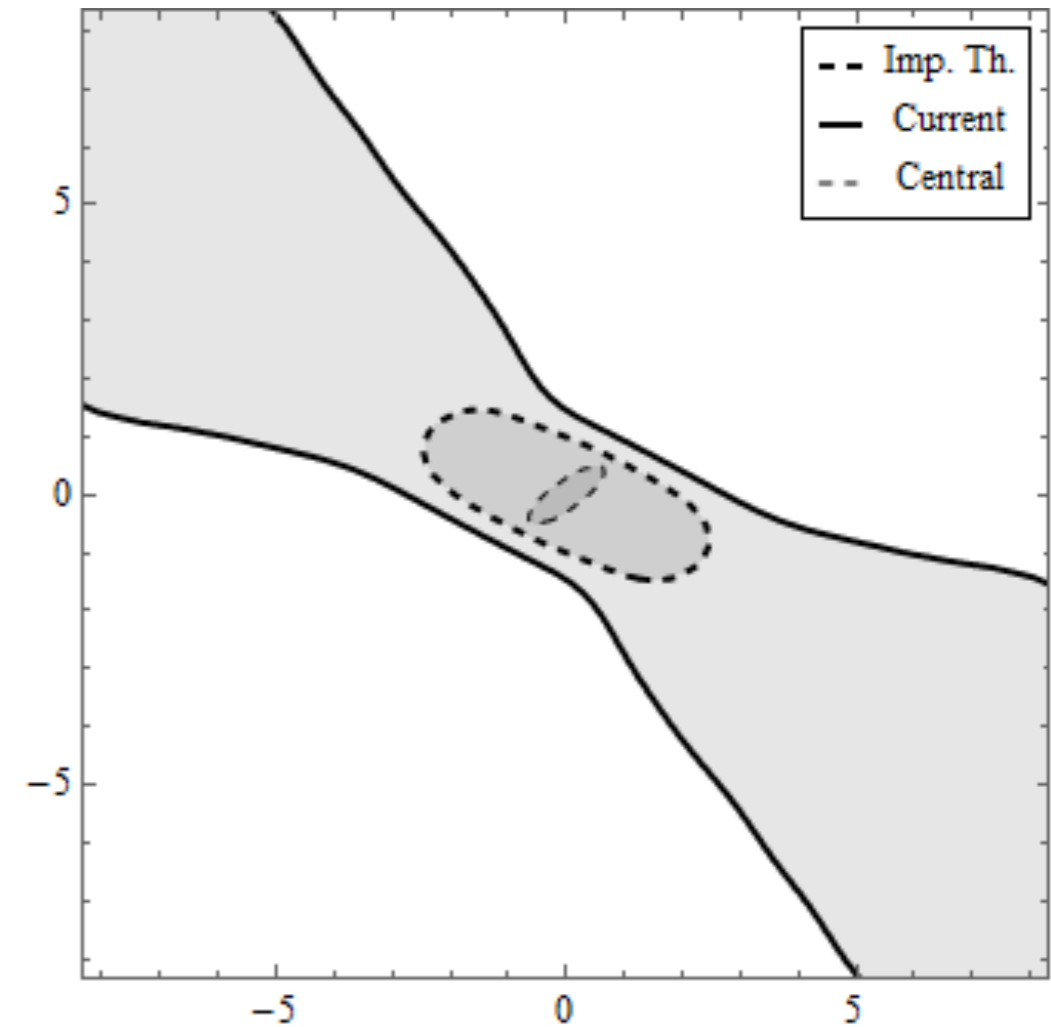
- Uncertainties significantly weaken the constraints

# Two-coupling analysis

**Without** theory uncertainties



**With** theory uncertainties

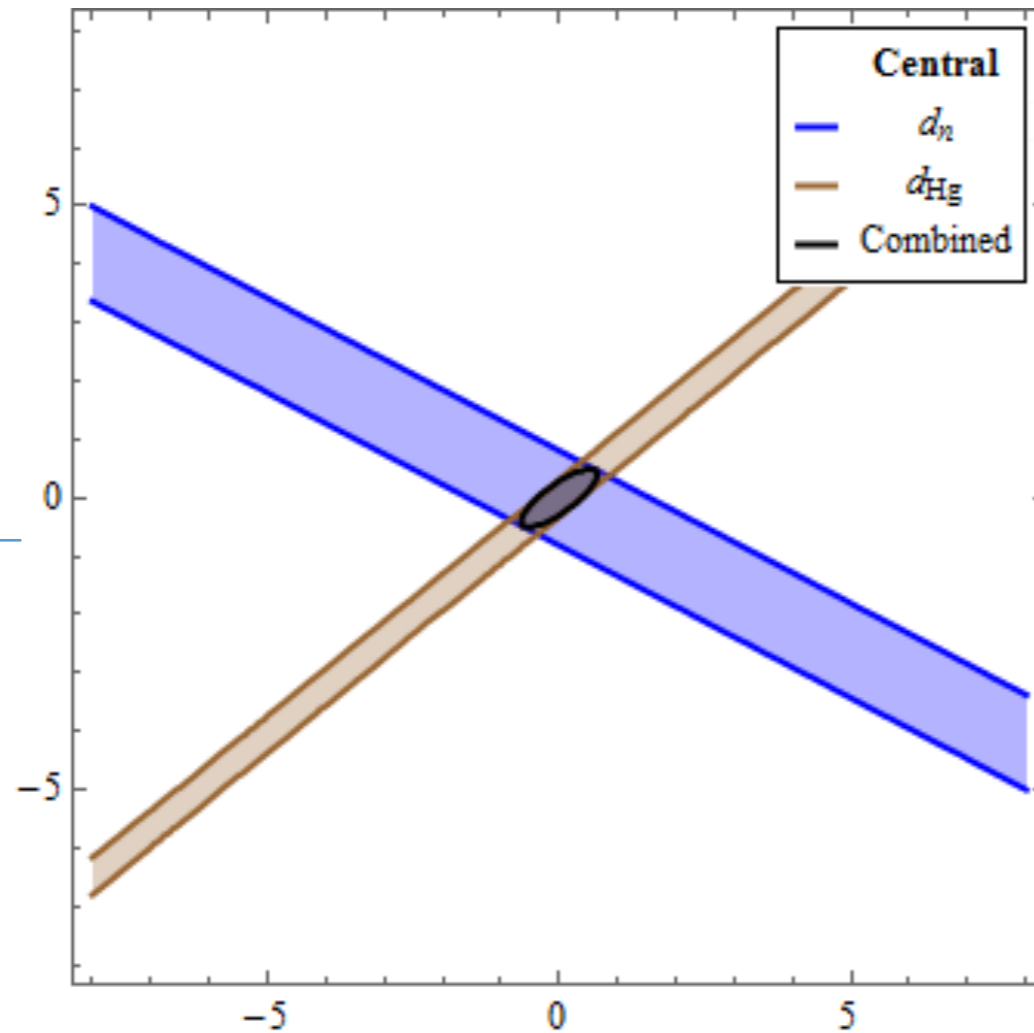


- Uncertainties significantly weaken the constraints
- Can be mitigated by
  - Improved theory: 50%(25%) uncertainty on nuclear(hadronic) matrix elements

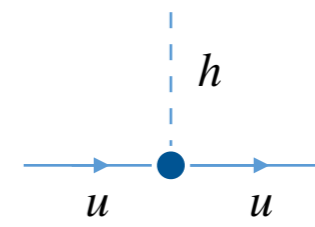
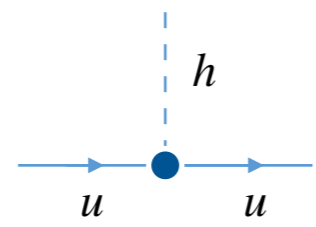
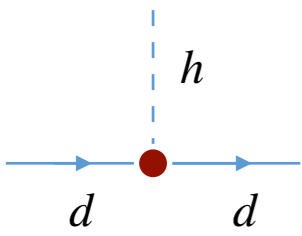
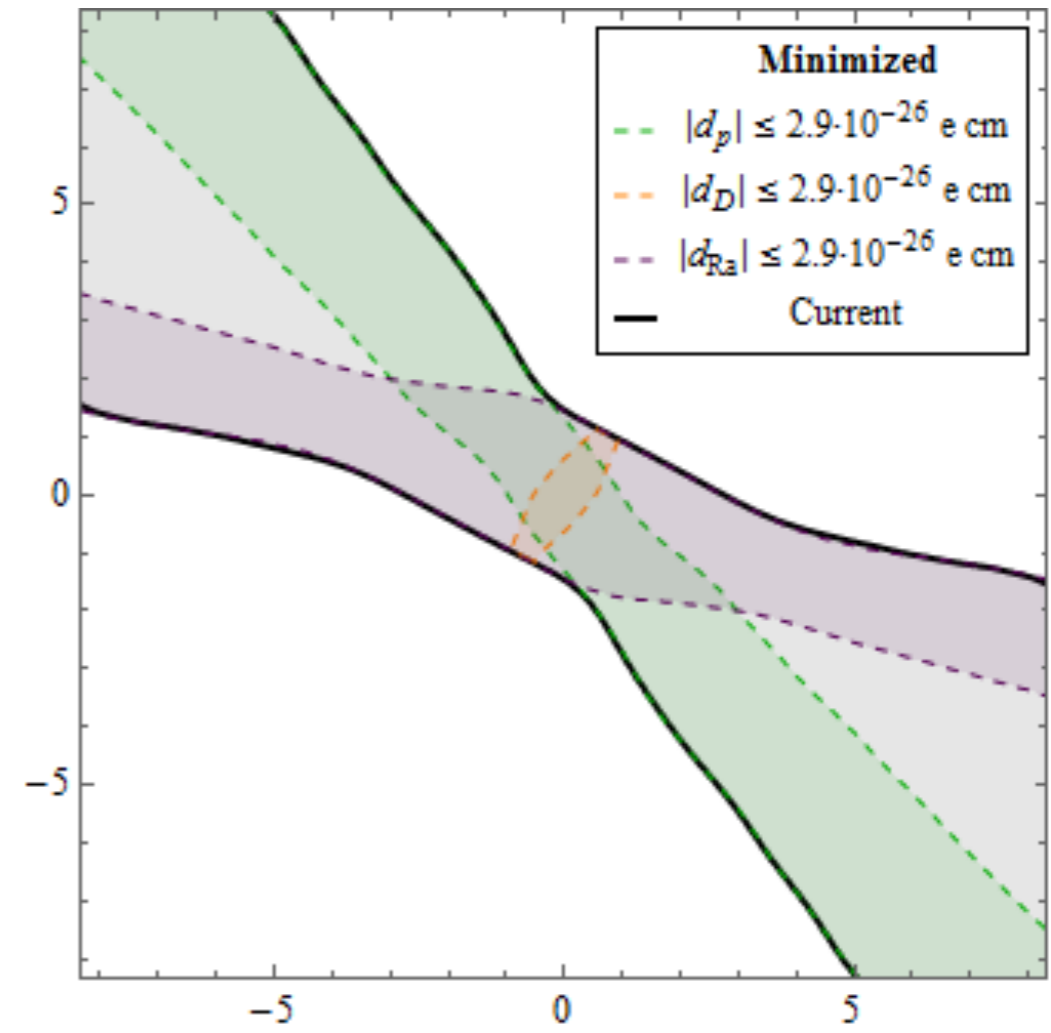


# Two-coupling analysis

**Without** theory uncertainties



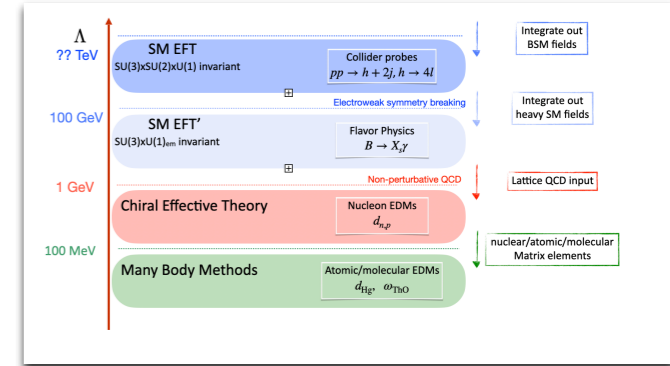
**With** theory uncertainties



- Uncertainties significantly weaken the constraints
- Can be mitigated by
  - Improved theory: 50%(25%) uncertainty on nuclear(hadronic) matrix elements
  - Additional measurements, e.g.  $d_p$ ,  $d_D$ ,  $d_{Ra}$  at current  $d_n$  sensitivity

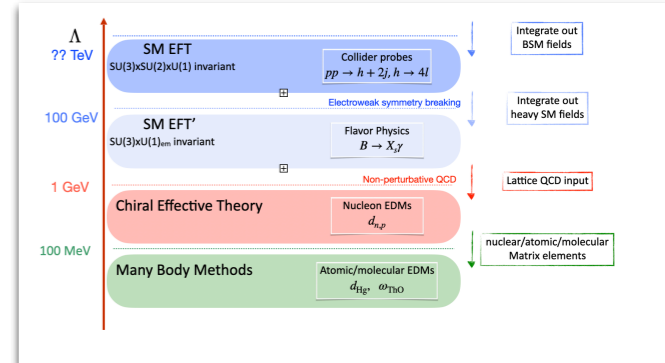
# Summary

- EFTs can systematically describe symmetry-breaking BSM
- Incorporating high- and low-energy probes in one framework



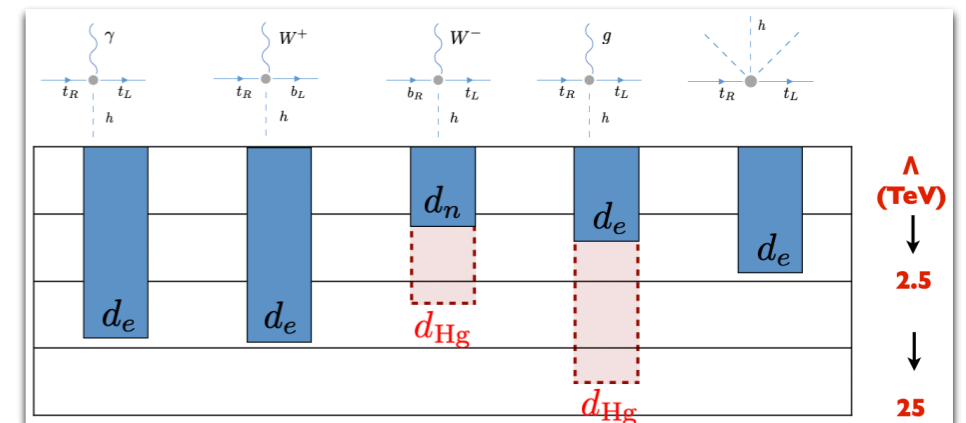
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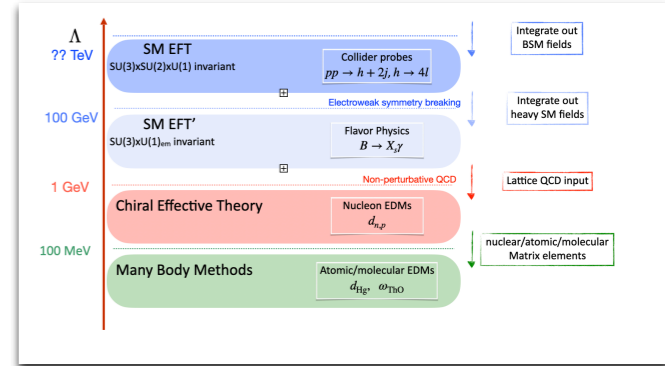
- CPV interactions already stringently constrained

- EDMs probe
  - $\Lambda \gtrsim 100 \text{ TeV}$  for tree-level BSM
  - $\Lambda \gtrsim 10 \text{ TeV}$  for loop-level BSM



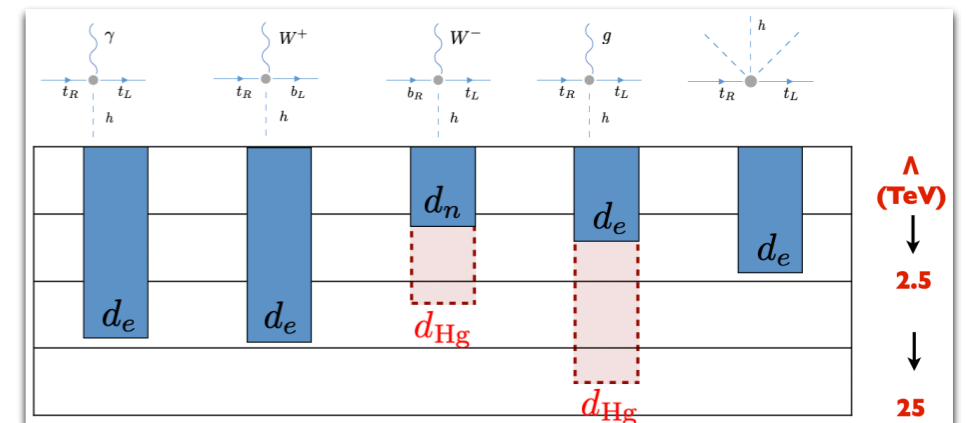
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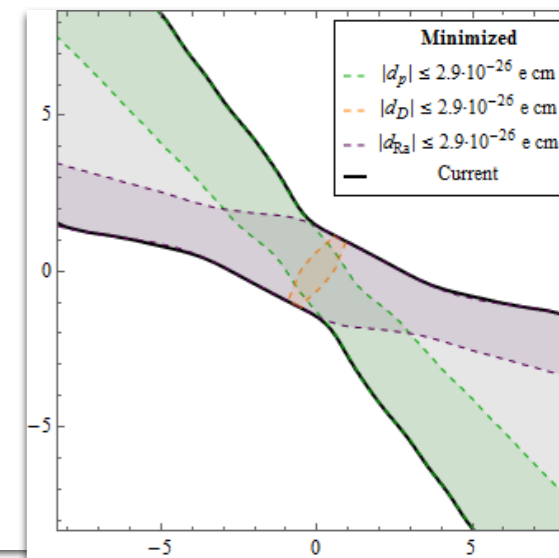


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  - $\Lambda \gtrsim 10 \text{ TeV}$  for loop-level BSM



- Hadronic & nuclear uncertainties
  - Neutron & mercury constraints significantly affected
- Can be mitigated by
  - Improved theory determinations of matrix elements
  - Additional measurements



# Backup slides

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# Theory error treatment

- **'Rfit'**: Vary matrix elements within their allowed ranges; choose values giving the smallest Chi-square (pick the weakest bound)
  - Hadronic/nuclear EDM uncertainties
  - Long-distance uncertainties in  $A_{CP}(b \rightarrow s\gamma)$

# Electric Dipole Moments

## Summary

Limits (e cm)	ThO	neutron	mercury
Bound	$1.1 \times 10^{-29}$	$3.0 \times 10^{-26}$	$6.2 \times 10^{-30}$
Theory uncertainty	Molecular ME $\mathcal{O}(\text{few } \%)$	Hadronic MEs $\mathcal{O}(50\%)$	Hadronic/Nuclear MEs $\mathcal{O}(100\%)$

- In terms of quark-level operators at  $\mu \simeq \text{GeV}$

$$\omega_{\text{ThO}} = (120.6 \pm 4.9)(\text{mrad/s}) \left( \frac{d_e}{10^{-27} \text{ e cm}} \right)$$

# Electric Dipole Moments

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- In terms of quark-level operators at  $\mu \simeq \text{GeV}$

$$d_n = -0.204(11) d_u + 0.784(28) d_d - 0.0028(17) d_s - 0.55(28) e \tilde{d}_u - 1.10(55) e \tilde{d}_d + 50(40) \text{ MeV } e g_s C_{\tilde{G}},$$

$\mathcal{O}(50\%)$  hadronic uncertainties



# Electric Dipole Moments

## Summary

Limits (e cm)	ThO	neutron	mercury
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- In terms of nucleon-level operators:

$$d_{\text{Hg}} = -2.1(5) \cdot 10^{-4} \left[ 1.9(1)d_n + 0.20(6)d_p + \left( 0.13_{-0.07}^{+0.50} \bar{g}_0 + 0.25_{-0.63}^{+0.89} \bar{g}_1 \right) e \text{ fm} \right]$$

$\mathcal{O}(100\%)$  nuclear uncertainties

# Electric Dipole Moments

## Summary

Limits (e cm)	ThO	neutron	mercury
Bound	$1.1 \times 10^{-29}$	$3.0 \times 10^{-26}$	$6.2 \times 10^{-30}$
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$$d_n = -0.204(11) d_u + 0.784(28) d_d - 0.0028(17) d_s - 0.55(28) e \tilde{d}_u - 1.10(55) e \tilde{d}_d + 50(40) \text{ MeV } e g_s C_{\tilde{G}},$$

$$d_p = 0.784(28) d_u - 0.204(11) d_d - 0.0028(17) d_s + 1.30(65) e \tilde{d}_u + 0.6(3) e \tilde{d}_d - 50(40) \text{ MeV } e g_s C_{\tilde{G}},$$

$$\bar{g}_0 = 5(10) (m_u \tilde{C}_g^{(u)} + m_d \tilde{C}_g^{(d)}) \text{ fm}^{-1},$$

$$\bar{g}_1 = 20_{-10}^{+40} (m_u \tilde{C}_g^{(u)} - m_d \tilde{C}_g^{(d)}) \text{ fm}^{-1}.$$

$\mathcal{O}(50\%)$  hadronic uncertainties

# Projected limits

## Global Higgs-gauge analysis

Assuming

- Low energy: Improved nuclear/hadronic MEs
- HL-LHC 3000 fb<sup>-1</sup>

Bernlochner et al. PLB '19

- Low-energy allows
  - Large couplings in global case
  - Only very specific combinations

