CP-violating Higgs couplings
Interplay with low-energy observables

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Outline

CP-violating BSM physics

Λ
?? TeV

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

Collider probes
$pp \to h + 2j, h \to 4l$

Integrate out BSM fields

Electroweak symmetry breaking

100 GeV

SM EFT'
SU(3)xU(1)$_{em}$ invariant

Flavor Physics
$B \to X_s\gamma$

Integrate out heavy SM fields

Non-perturbative QCD

1 GeV

Chiral Effective Theory

Nucleon EDMs
$d_{n,p}$

Lattice QCD input

100 MeV

Many Body Methods

Atomic/molecular EDMs
$d_{\rm Hg}, \quad \omega_{\rm ThO}$

nuclear/atomic/molecular Matrix elements

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The SM Effective Field Theory

Describing BSM physics

Dimension five operators

- One term, generates Majorana neutrino masses

$$\frac{g}{M_T}(\bar{L}^c\tilde{\phi}^*)(\tilde{\phi}^\dagger L)$$

Weinberg ’79;

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$$\frac{g}{M_T}(\bar{L}^c\tilde{\phi}^*)(\tilde{\phi}^\dagger L)$$

Dimension-six operators

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

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

$(\bar{L}L)(\bar{R}R)$
$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

		$Q^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
		$Q^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$Q^{(1)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$Q^{(3)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$

Weinberg ’79; Buchmuller & Wyler ’86, Grzadkowski et al 2010

The SM Effective Field Theory

Describing BSM physics

Dimension five operators

- One term, generates Majorana neutrino masses

$$\frac{g}{M_T}(\bar{L}^c\tilde{\phi}^*)(\tilde{\phi}^\dagger L)$$

Dimension-six operators

- 59 of them
- (2499 including all flavor structures)

have to make some choice of operators…

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

$(\bar{L}L)(\bar{R}R)$
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		$Q^{(1)}_{ud}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
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$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$Q^{(1)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$Q^{(3)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$

Weinberg ’79; Buchmuller & Wyler ’86, Grzadkowski et al 2010

The SM Effective Field Theory

Describing BSM physics

Dimension five operators

- One term, generates Majorana neutrino masses

$$\frac{g}{M_T}(\bar{L}^c\tilde{\phi}^*)(\tilde{\phi}^\dagger L)$$

Focus on bosonic operators

- Captures `Universal theories'
  - BSM fields couple to SM currents
- Manageable number of operators:
  - 4 Higgs-gauge couplings
  - 2 triple-gauge interactions

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

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

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}^j_p e_r)(\bar{d}_s q^j_t)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(q^{\gamma j}_s)^T C l^k_t\right]$
$Q^{(1)}_{quqd}$	$(\bar{q}^j_p u_r)\varepsilon_{jk}(\bar{q}^k_s d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(u^\gamma_s)^T C e_t\right]$
$Q^{(8)}_{quqd}$	$(\bar{q}^j_p T^A u_r)\varepsilon_{jk}(\bar{q}^k_s T^A d_t)$	$Q^{(1)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\varepsilon_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$Q^{(1)}_{lequ}$	$(\bar{l}^j_p e_r)\varepsilon_{jk}(\bar{q}^k_s u_t)$	$Q^{(3)}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}(\tau^I\varepsilon)_{jk}(\tau^I\varepsilon)_{mn}\left[(q^{\alpha j}_p)^T C q^{\beta k}_r\right]\left[(q^{\gamma m}_s)^T C l^n_t\right]$
$Q^{(3)}_{lequ}$	$(\bar{l}^j_p\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}^k_s\sigma^{\mu\nu}u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d^\alpha_p)^T C u^\beta_r\right]\left[(u^\gamma_s)^T C e_t\right]$

Weinberg '79; Buchmuller & Wyler '86, Grzadkowski et al 2010

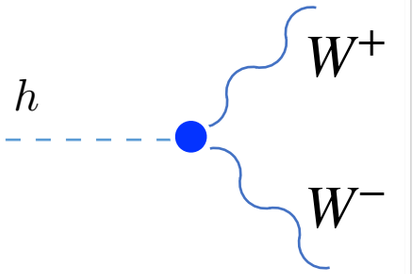
Barbieri et al '04; Wells & Zhang '15

Higgs-gauge couplings

$$\mathcal{L} = -g^2 C_{\varphi\tilde{W}}\, \varphi^\dagger\varphi\, \tilde{W}^i_{\mu\nu} W_i^{\mu\nu} - g'^2 C_{\varphi\tilde{B}}\, \varphi^\dagger\varphi\, \tilde{B}_{\mu\nu} B^{\mu\nu}$$
$$- g g' C_{\varphi\tilde{W}B}\, \varphi^\dagger\tau^i\varphi\, \tilde{W}^i_{\mu\nu} B^{\mu\nu} - g_s^2 C_{\varphi\tilde{G}}\, \varphi^\dagger\varphi G^a_{\mu\nu}\tilde{G}_a^{\mu\nu}$$
$$+ \frac{C_{\tilde{G}}}{3}\, g_s f_{abc} \tilde{G}^a_{\mu\nu} G_b^{\nu\rho} G_\rho^{c\,\mu} + \frac{C_{\tilde{W}}}{3}\, g \epsilon_{ijk} \tilde{W}^i_{\mu\nu} W_j^{\nu\rho} W_\rho^{k\,\mu}$$

Higgs-gauge

$C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$

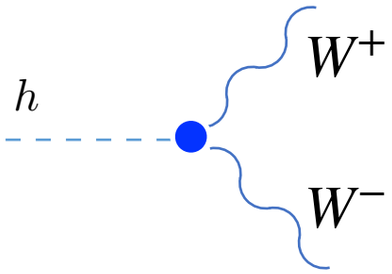


Higgs-gauge couplings

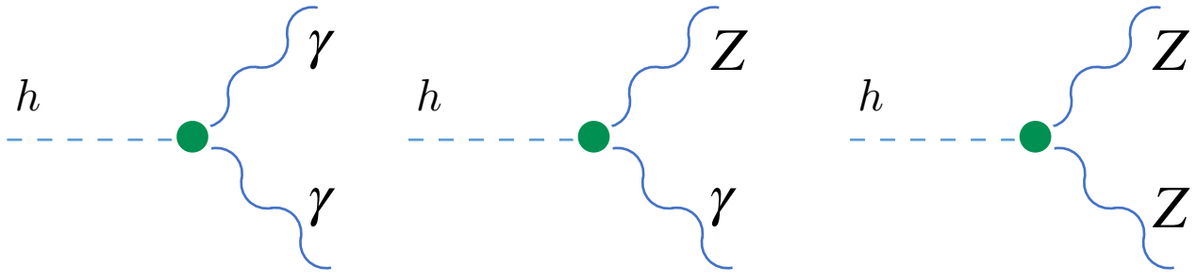
$$\mathcal{L} = -g^2 C_{\varphi\tilde{W}} \varphi^\dagger \varphi \tilde{W}^i_{\mu\nu} W_i^{\mu\nu} - g'^2 C_{\varphi\tilde{B}} \varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$$
$$- g g' C_{\varphi\tilde{W}B} \varphi^\dagger \tau^i \varphi \tilde{W}^i_{\mu\nu} B^{\mu\nu} - g_s^2 C_{\varphi\tilde{G}} \varphi^\dagger \varphi G^a_{\mu\nu} \tilde{G}_a^{\mu\nu}$$
$$+ \frac{C_{\tilde{G}}}{3} g_s f_{abc} \tilde{G}^a_{\mu\nu} G_b^{\nu\rho} G_\rho^{c\,\mu} + \frac{C_{\tilde{W}}}{3} g \epsilon_{ijk} \tilde{W}^i_{\mu\nu} W_j^{\nu\rho} W_\rho^{k\,\mu}$$

Higgs-gauge

$C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$



$C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{B}}$, $C_{\varphi\tilde{W}B}$

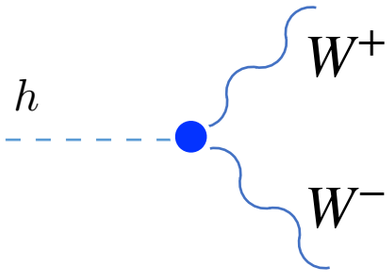


Higgs-gauge couplings

$$\mathcal{L} = -g^2 C_{\varphi\tilde{W}} \varphi^\dagger \varphi \tilde{W}^i_{\mu\nu} W_i^{\mu\nu} - g'^2 C_{\varphi\tilde{B}} \varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$$
$$- g g' C_{\varphi\tilde{W}B} \varphi^\dagger \tau^i \varphi \tilde{W}^i_{\mu\nu} B^{\mu\nu} - g_s^2 C_{\varphi\tilde{G}} \varphi^\dagger \varphi G^a_{\mu\nu} \tilde{G}_a^{\mu\nu}$$
$$+ \frac{C_{\tilde{G}}}{3} g_s f_{abc} \tilde{G}^a_{\mu\nu} G_b^{\nu\rho} G_\rho^{c\,\mu} + \frac{C_{\tilde{W}}}{3} g \epsilon_{ijk} \tilde{W}^i_{\mu\nu} W_j^{\nu\rho} W_\rho^{k\,\mu}$$

Higgs-gauge

$C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$



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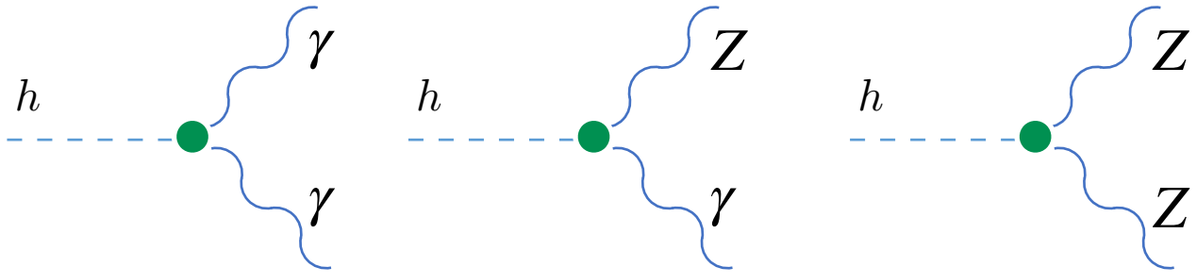
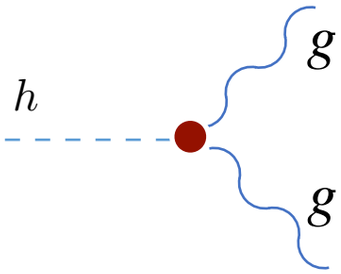


$C_{\varphi\tilde{G}}$



Higgs-gauge couplings

$$\mathcal{L} = -g^2 C_{\varphi\tilde{W}} \varphi^\dagger \varphi \tilde{W}^i_{\mu\nu} W_i^{\mu\nu} - g'^2 C_{\varphi\tilde{B}} \varphi^\dagger \varphi \tilde{B}_{\mu\nu} B^{\mu\nu}$$
$$- g g' C_{\varphi\tilde{W}B} \varphi^\dagger \tau^i \varphi \tilde{W}^i_{\mu\nu} B^{\mu\nu} - g_s^2 C_{\varphi\tilde{G}} \varphi^\dagger \varphi G^a_{\mu\nu} \tilde{G}_a^{\mu\nu}$$
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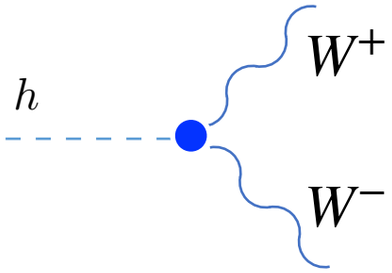
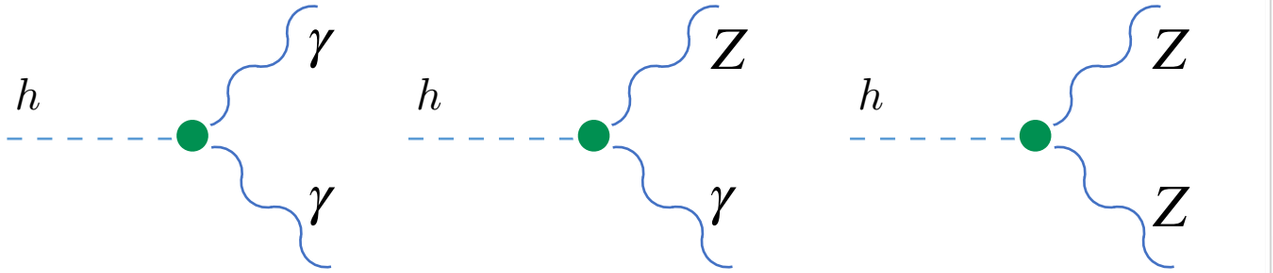
Higgs-gauge

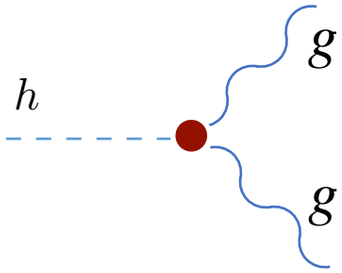
$C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{W}B}$



$C_{\varphi\tilde{W}}$, $C_{\varphi\tilde{B}}$, $C_{\varphi\tilde{W}B}$

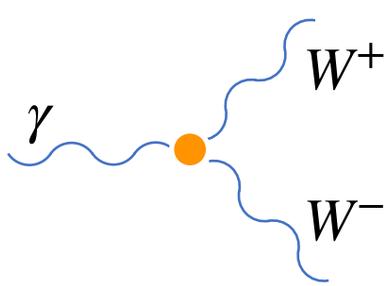


$C_{\varphi\tilde{G}}$

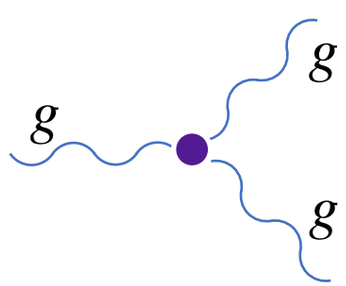


Triple-gauge

$C_{\tilde{W}}$, $C_{\varphi\tilde{W}B}$



$C_{\tilde{G}}$



Higgs-gauge couplings

Collider observables

	(Higgs) Cross sections	Asymmetries/angular Distributions	$h \to 4l$ $pp \to hZ, hW$	$pp \to h + 2j$ $e^+e^- \to W^+W^-$
Higgs-gauge	$\mathcal{O}(v^4/\Lambda^4)$		$\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(v^2/\Lambda^2)$
Triple-gauge	$\mathcal{O}(v^4/\Lambda^4)$			$\mathcal{O}(v^2/\Lambda^2)$

Ferreira et al. ’17; Soni & Xu ’93; Bernlochner et al. PLB ’19; Gritsan et al. ’21; Davis et al. ’21

Outline

CP-violating BSM physics

Λ
?? TeV

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

Collider probes
$pp \to h + 2j, h \to 4l$

Integrate out BSM fields

Electroweak symmetry breaking

100 GeV

SM EFT'
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Flavor Physics
$B \to X_s\gamma$

Integrate out heavy SM fields

Non-perturbative QCD

1 GeV

Chiral Effective Theory

Nucleon EDMs
$d_{n,p}$

Lattice QCD input

100 MeV

Many Body Methods

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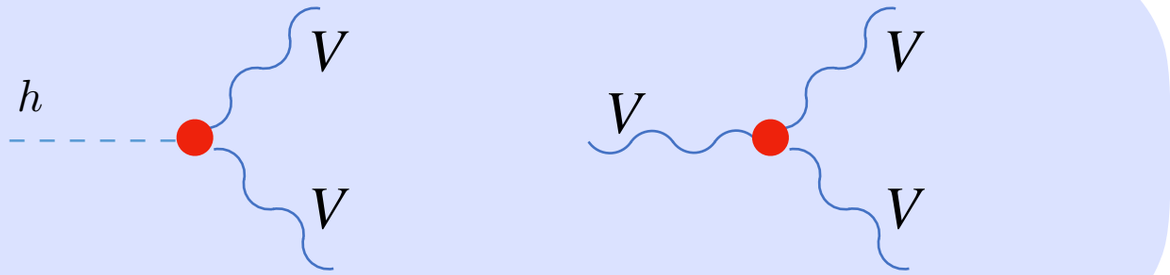
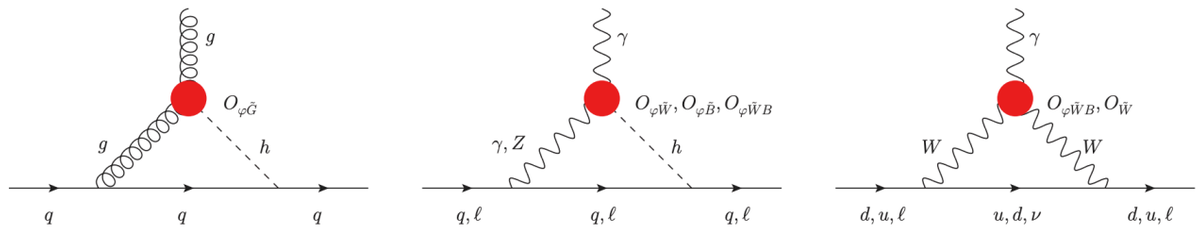
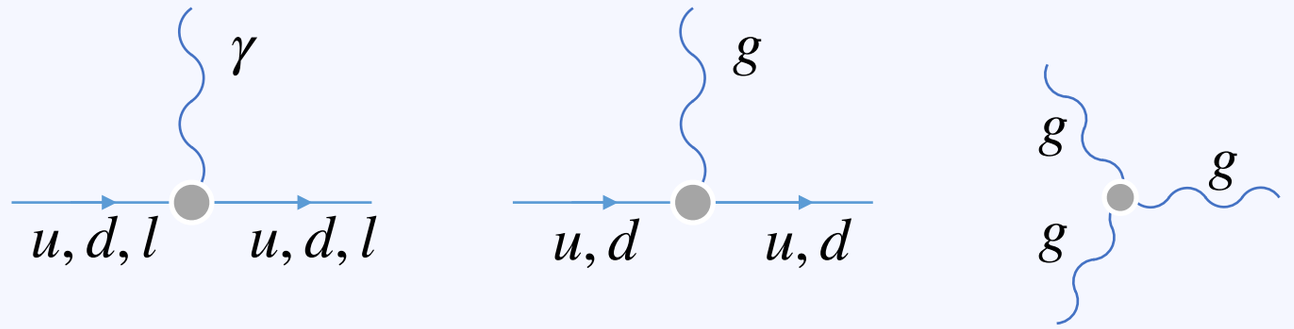


m_W



SM EFT’

SU(3)xU(1)$_{em}$ invariant



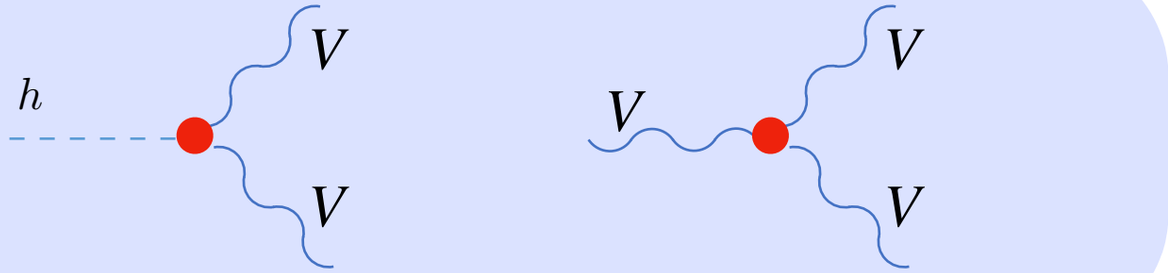
m_b

Below $\mu = m_W$

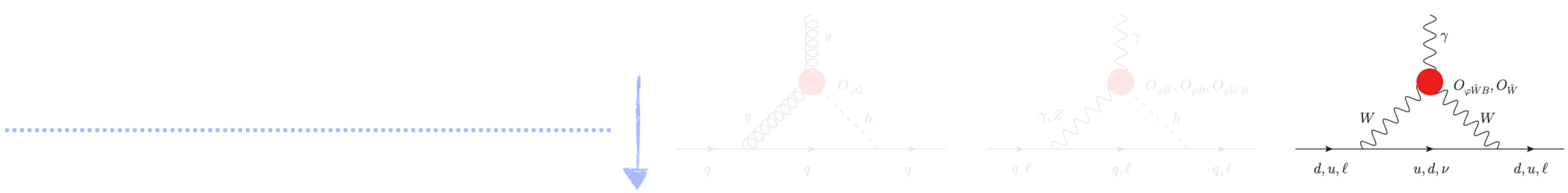
$B \to X_s \gamma$

SM EFT

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



m_W



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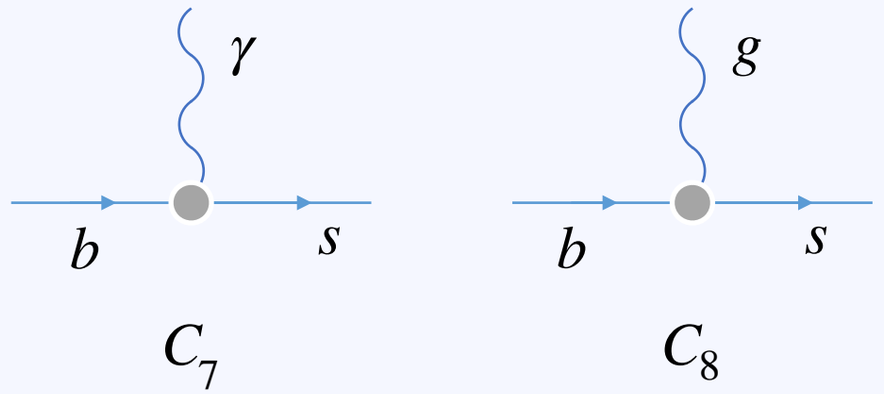

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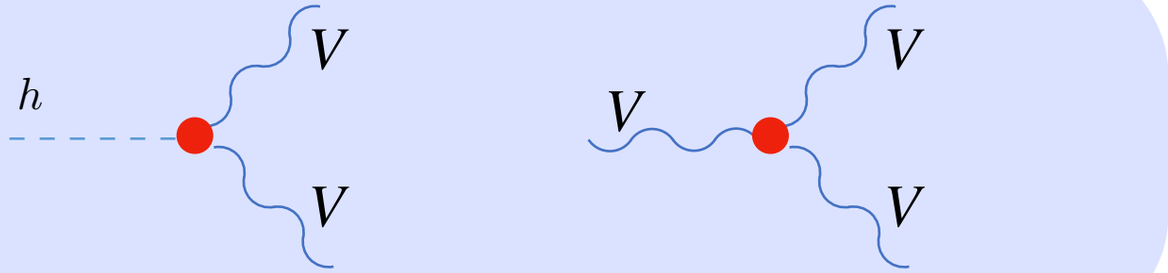
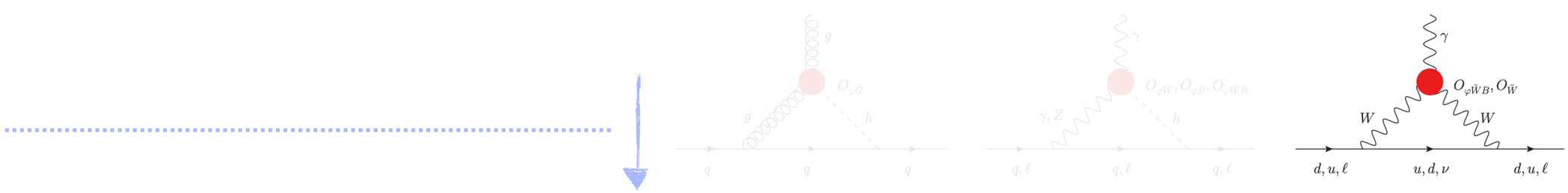


m_W



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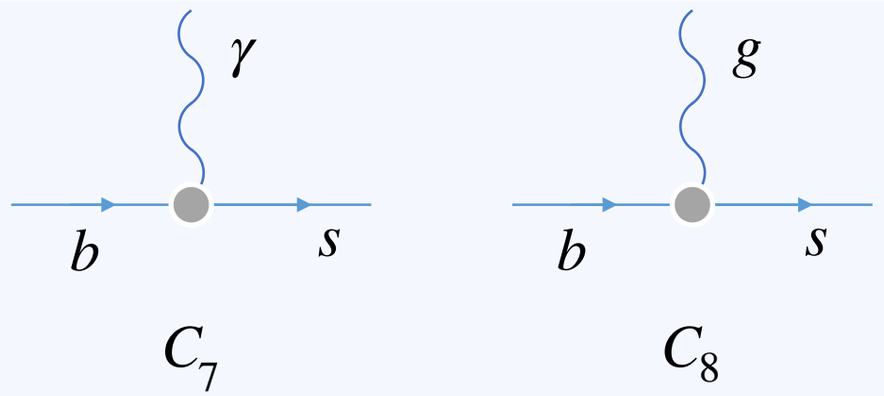

m_b

Rare B decays

$$A_{CP}(B \to X_s\gamma) \sim \mathrm{Im}\left(C_{7,8}^{\mathrm{NP}}\right) \sim A_{CP}^{SM}(1 + v^2 C_{\varphi\tilde{W}B,\tilde{W}})$$

No large enhancement w.r.t. SM

Benzke, Lee, Neubert, Paz, '11

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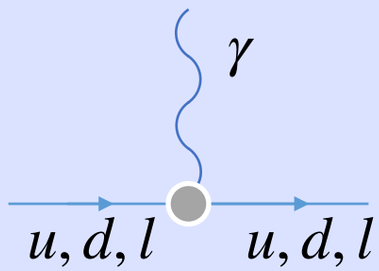
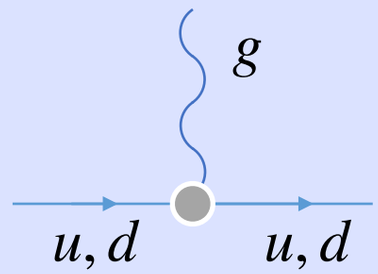
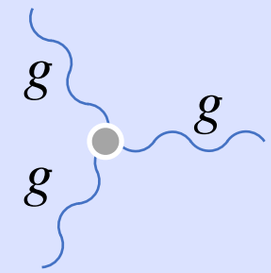


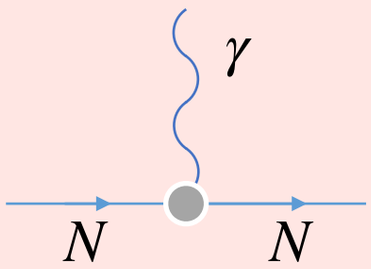




1 GeV

Hadronic matrix elements

Chiral Effective Theory

Nucleon EDMs		✓ LQCD $\mathcal{O}$(few %)	✓ NDA/sum rules $\mathcal{O}$(50%)	✓ NDA/sum rules $\mathcal{O}$(100%)

Gupta et al. '18; Demir, Pospelov, Ritz, '03; de Vries et al, '10; Haisch & Hala '19; Yamanaka '21

Below $\mu = m_W$

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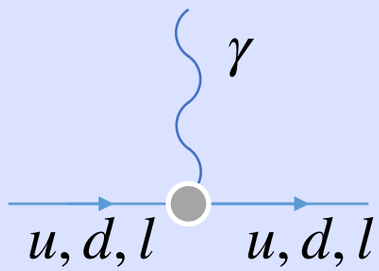

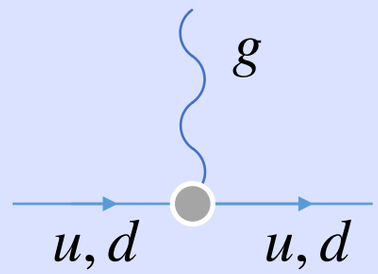

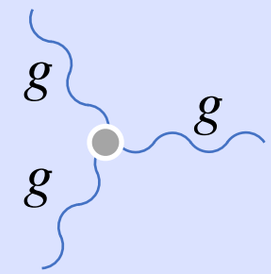

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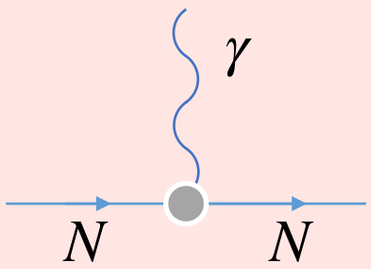
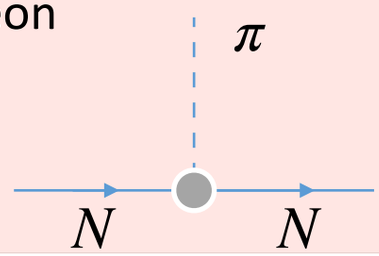
Hadronic matrix elements

Chiral Effective Theory

Nucleon EDMs		✓ LQCD $\mathcal{O}$(few %)	✓ NDA/sum rules $\mathcal{O}$(50%)	✓ NDA/sum rules $\mathcal{O}$(100%)
pion-nucleon couplings		✗	✓ NDA/sum rules $\mathcal{O}$(50%)	✗

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1 GeV

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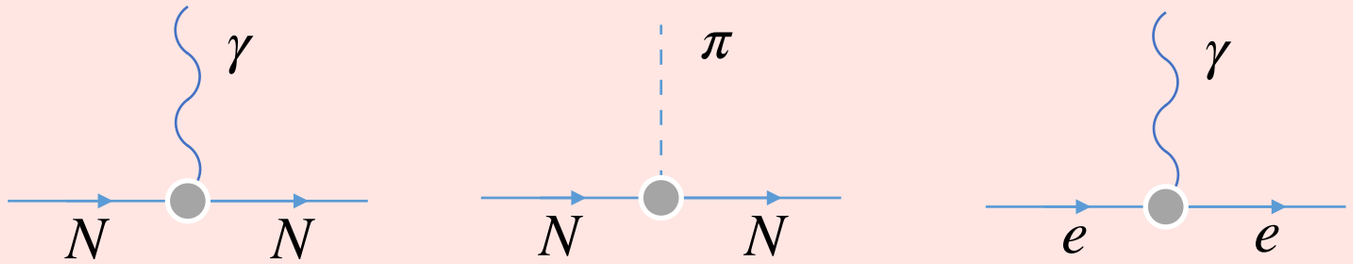


nuclear/atomic/molecular Matrix elements

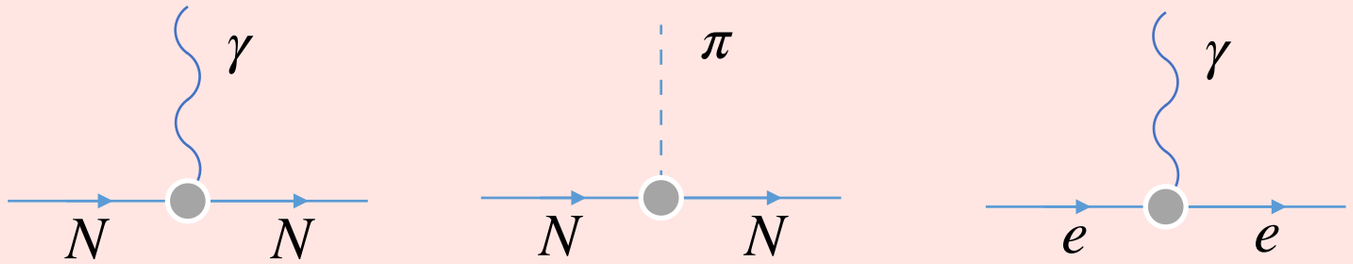
Mercury EDM	✓	✓	✗
d_{Hg}	$\mathcal{O}(\text{few }\%)$	$\mathcal{O}(100\%)$	

de Jesus, Engel, ’05; Ban, Dobaczewski, Engel, Shukla, ’10;

Atomic/molecular EDMs

1 GeV

Chiral Effective Theory



nuclear/atomic/molecular Matrix elements

	✓	✓	✗
Mercury EDM d_{Hg}	$\mathcal{O}(\text{few }\%)$	$\mathcal{O}(100\%)$	
CPV in ThO ω_{ThO}	✗	✗	✓ $\mathcal{O}(\text{few }\%)$

de Jesus, Engel, ’05; Ban, Dobaczewski, Engel, Shukla, ’10; Skripnikov et al. ’13; Fleig & Nayak ‘14

Electric Dipole Moments

Current limits

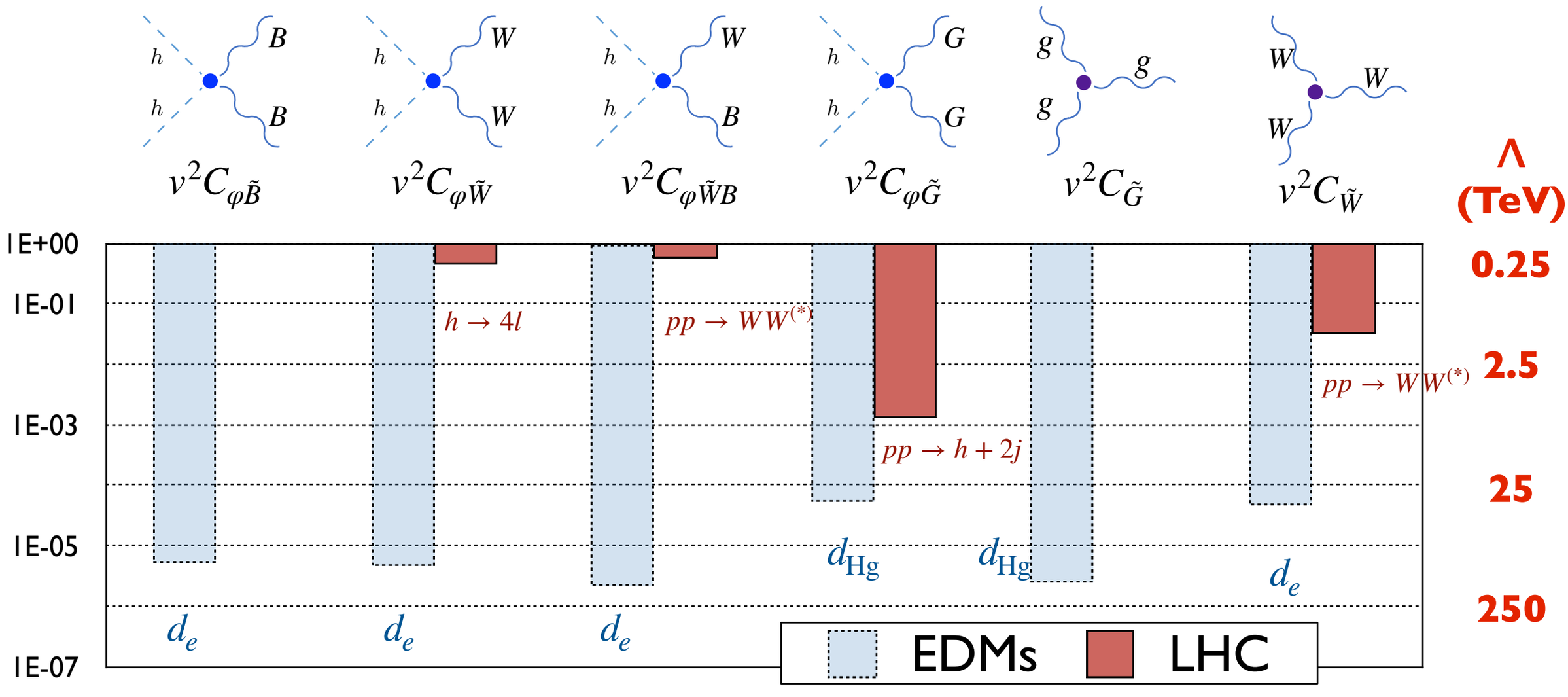
Limits (e cm)	neutron	mercury	ThO
Current	3.0×10^{-26} Baker *et al*, '06	6.2×10^{-30} Graner *et al, '*17	1.1×10^{-29} ACME collaboration, '18
Expected	10^{-28}		5.0×10^{-30}
Theory uncertainty	$\mathcal{O}(50\%)$	$\mathcal{O}(100\%)$	$\mathcal{O}(\text{few }\%)$

Phenomenology

Current constraints

One coupling at a time

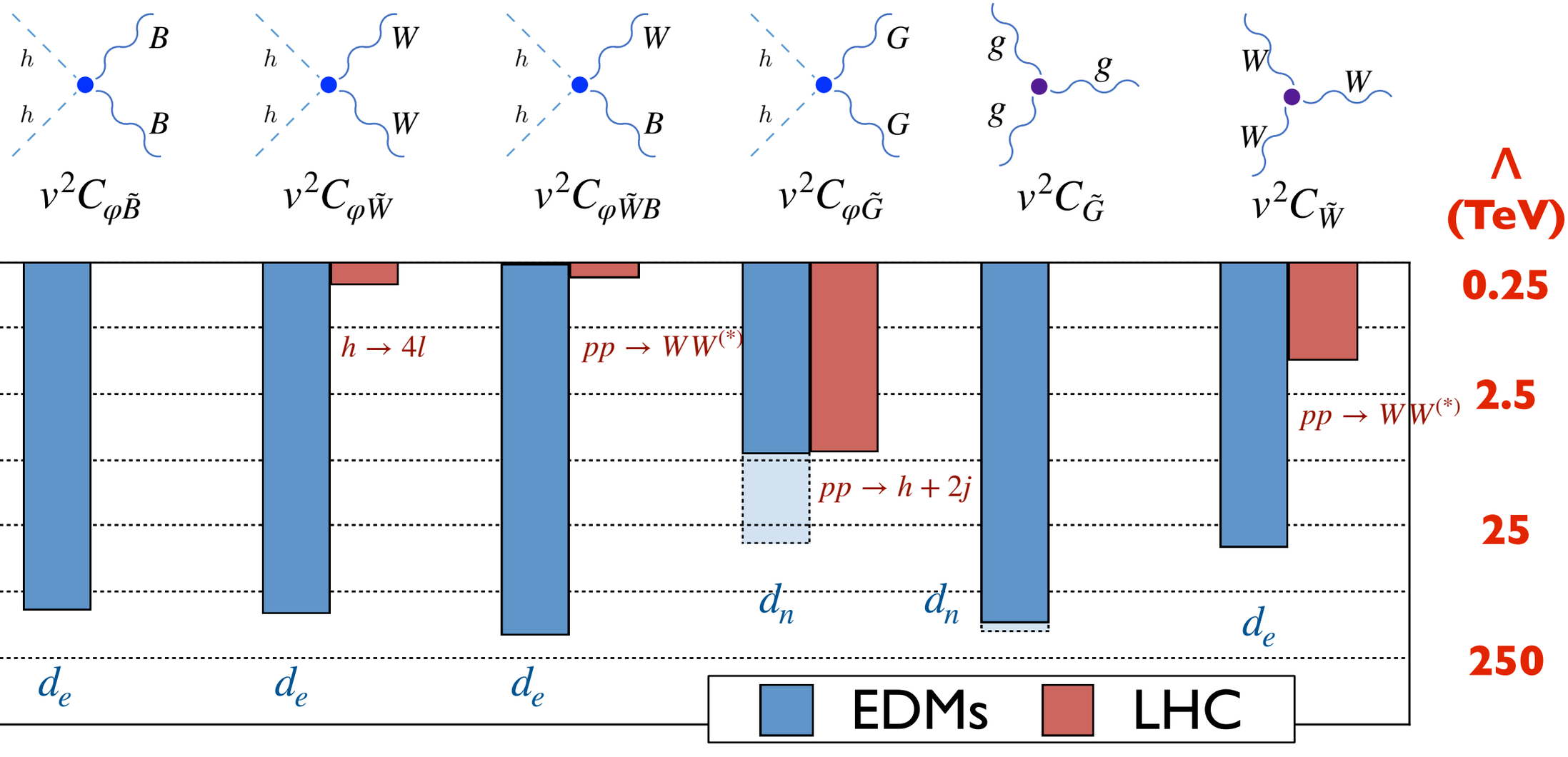
Neglecting nuclear/hadronic uncertainties



Current constraints

One coupling at a time

Conservative nuclear/hadronic uncertainties



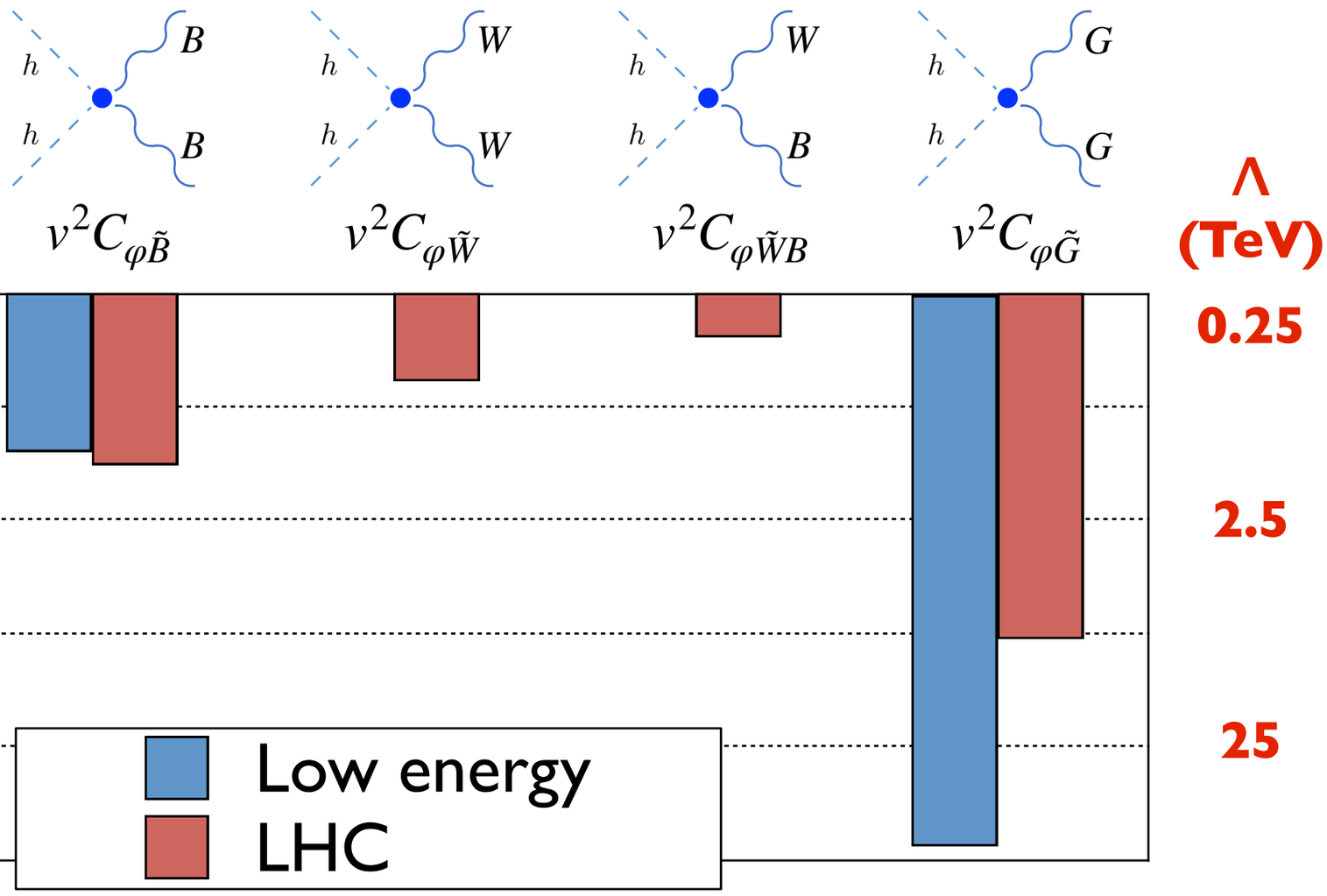
Projected limits

Global Higgs-gauge analysis

Assuming

- Low energy: Improved nuclear/hadronic MEs
- $pp \to h + 2j$, HL-LHC 3000 fb^{-1}

Bernlochner et al. PLB ’19



Λ (TeV)

0.25

2.5

25

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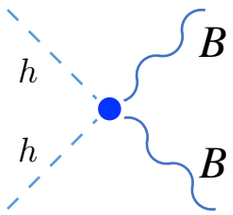
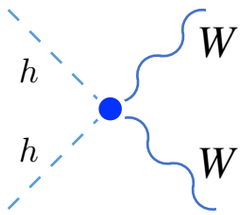
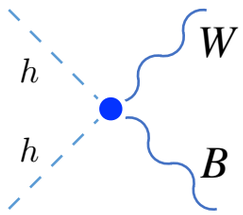


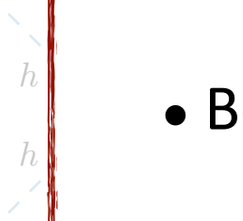
$v^2 C_{\varphi\tilde{B}}$



$v^2 C_{\varphi\tilde{W}}$

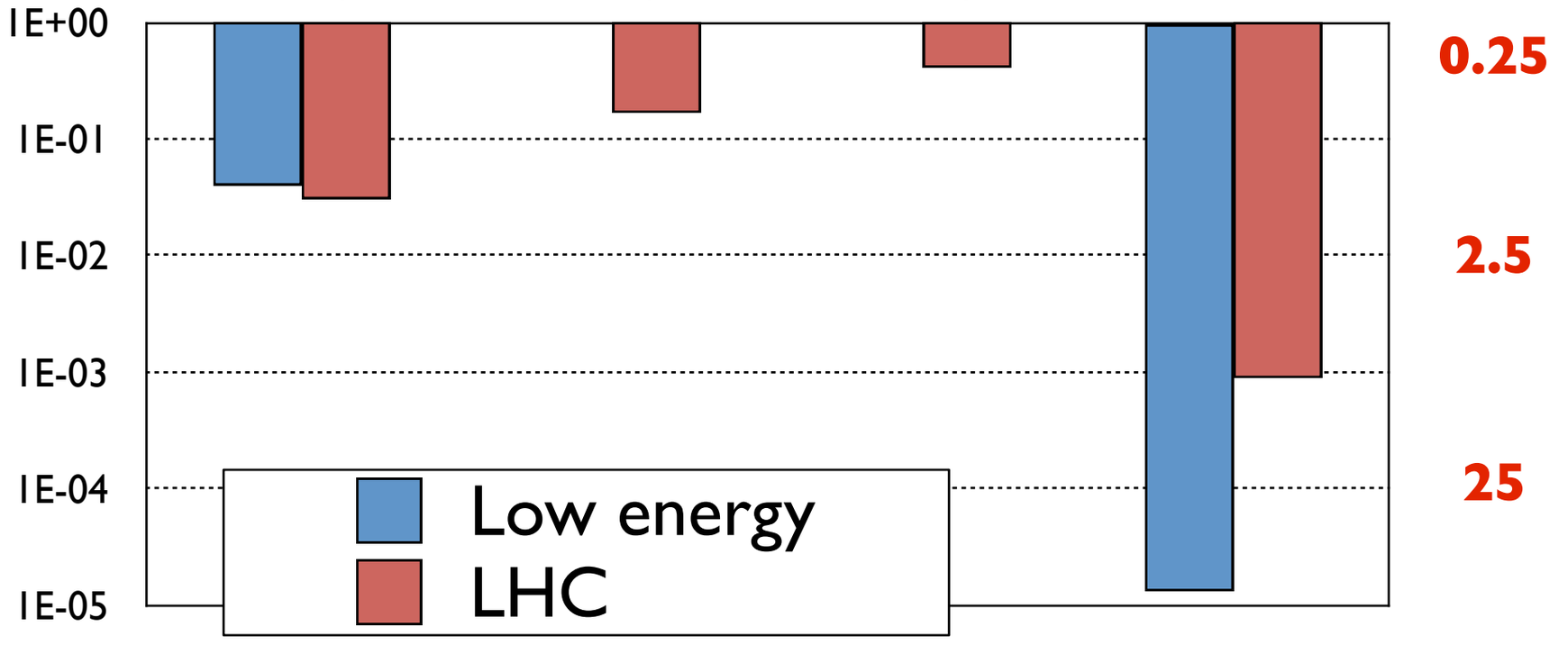


$v^2 C_{\varphi\tilde{W}B}$



$v^2 C_{\varphi\tilde{G}}$

(TeV)



0.25

2.5

25

- Low-energy weakens in global setting
  - EDMs leave a free direction

    $\sim 0.17\, C_{\varphi\tilde{B}} + 0.86\, C_{\varphi\tilde{W}} + 0.48\, C_{\varphi\tilde{W}B}$
  - Bound by weaker $B \to X_s\gamma$, LEP

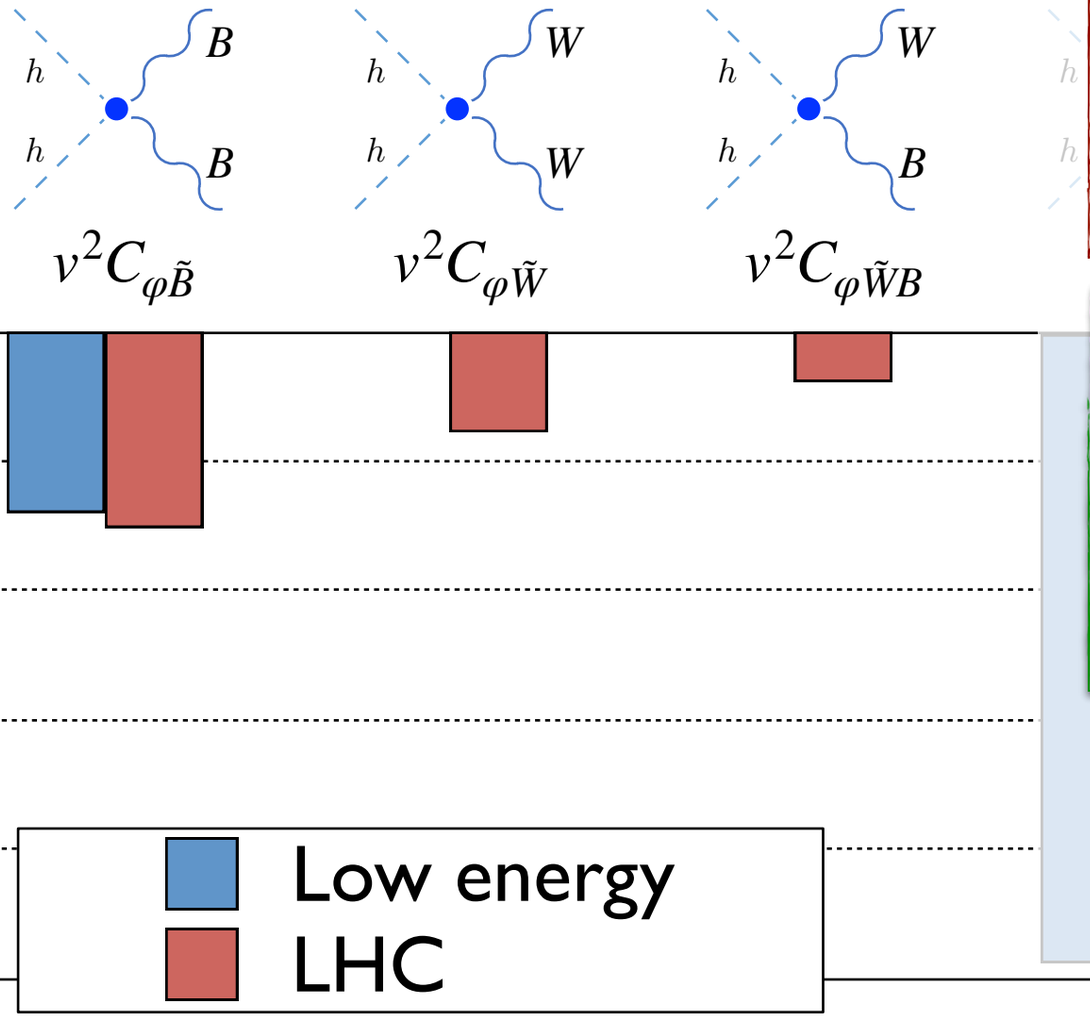
Projected limits

Global Higgs-gauge analysis

Assuming

- Low energy: Improved nuclear/hadronic MEs
- $pp \to h + 2j$, HL-LHC 3000 fb^{-1}

Bernlochner et al. PLB '19



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- High energy
  - HL-LHC very competitive
  - Probes all couplings

Projected limits

Global Higgs-gauge analysis

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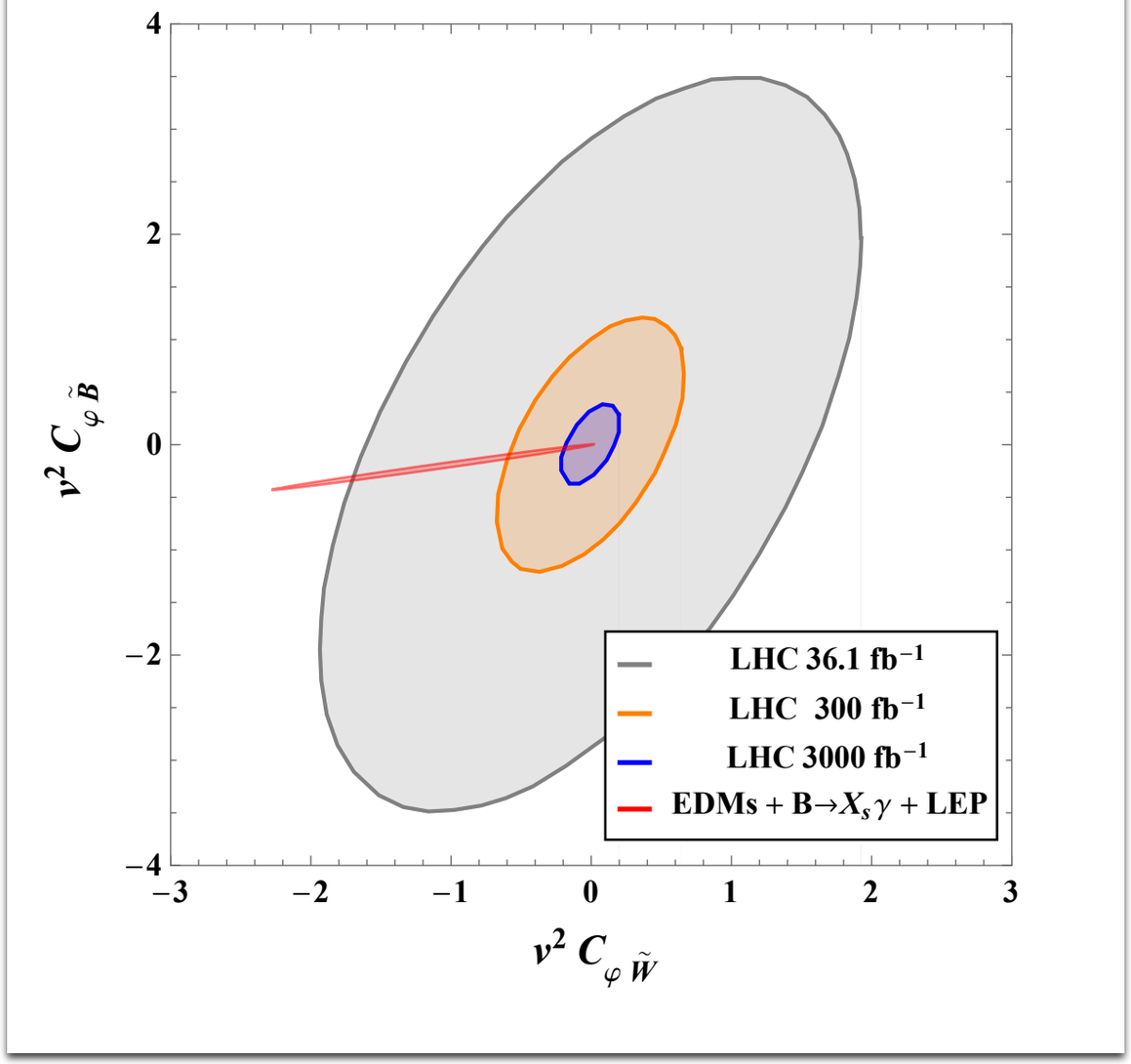
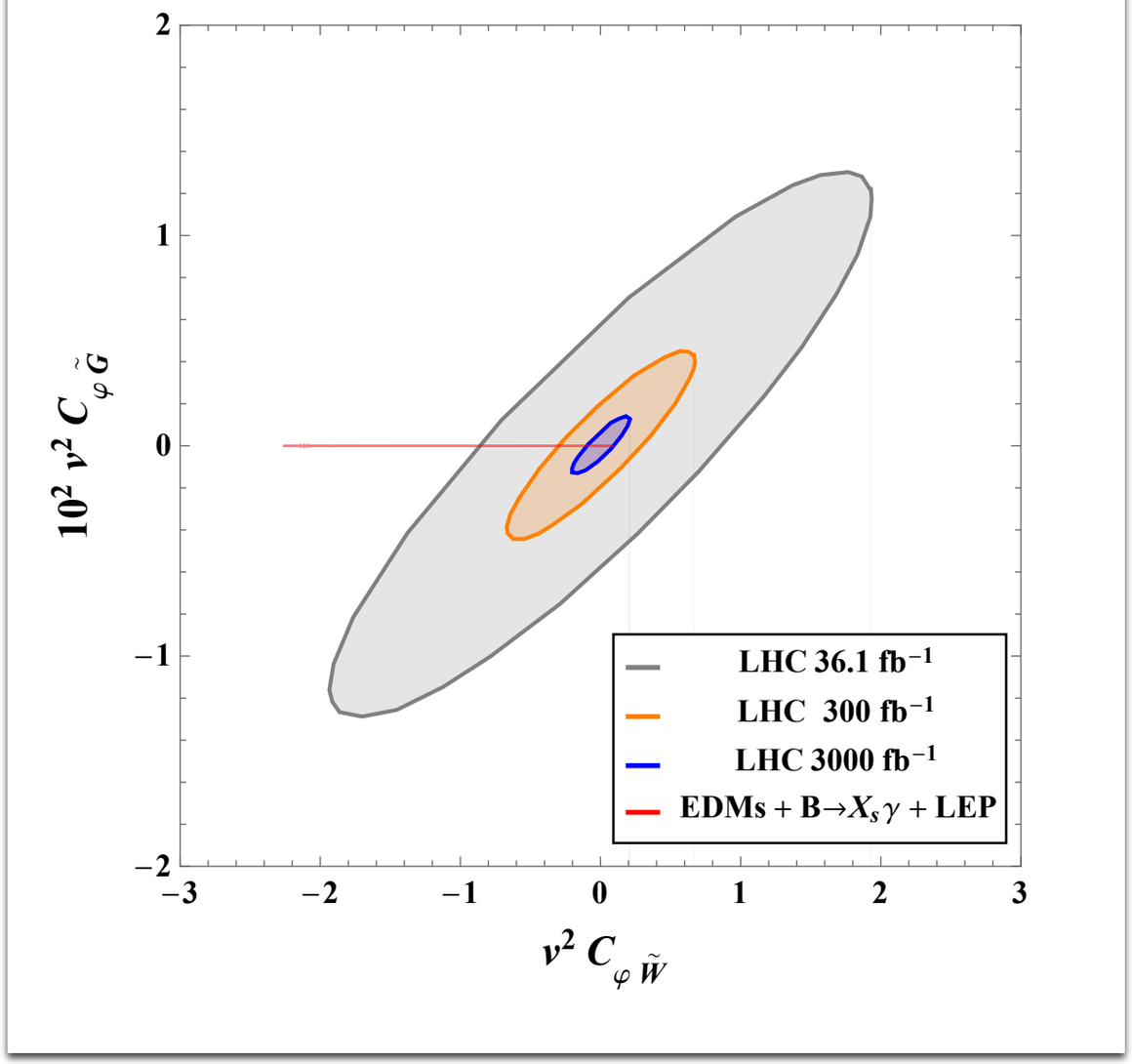
Bernlochner et al. PLB ’19





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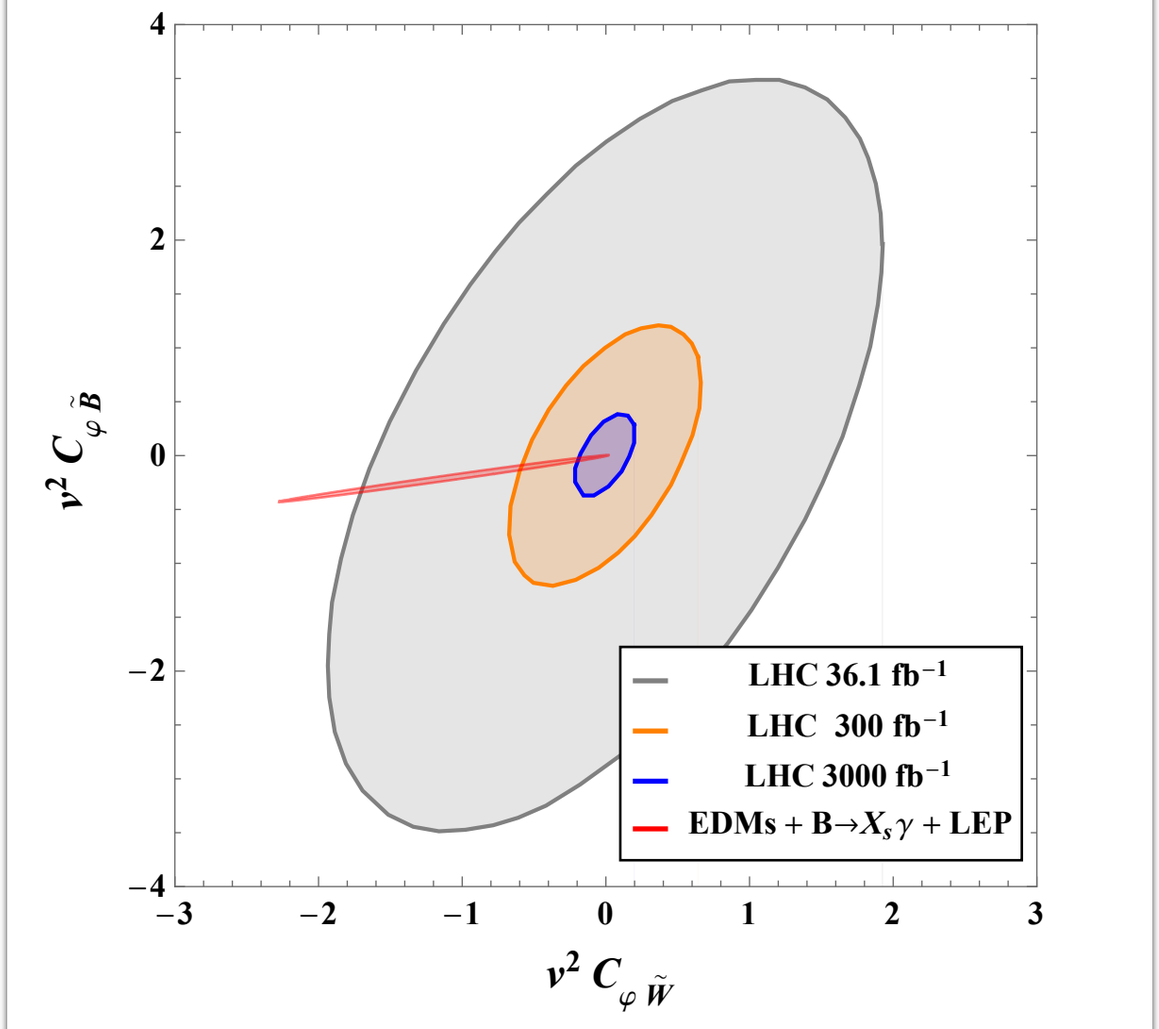
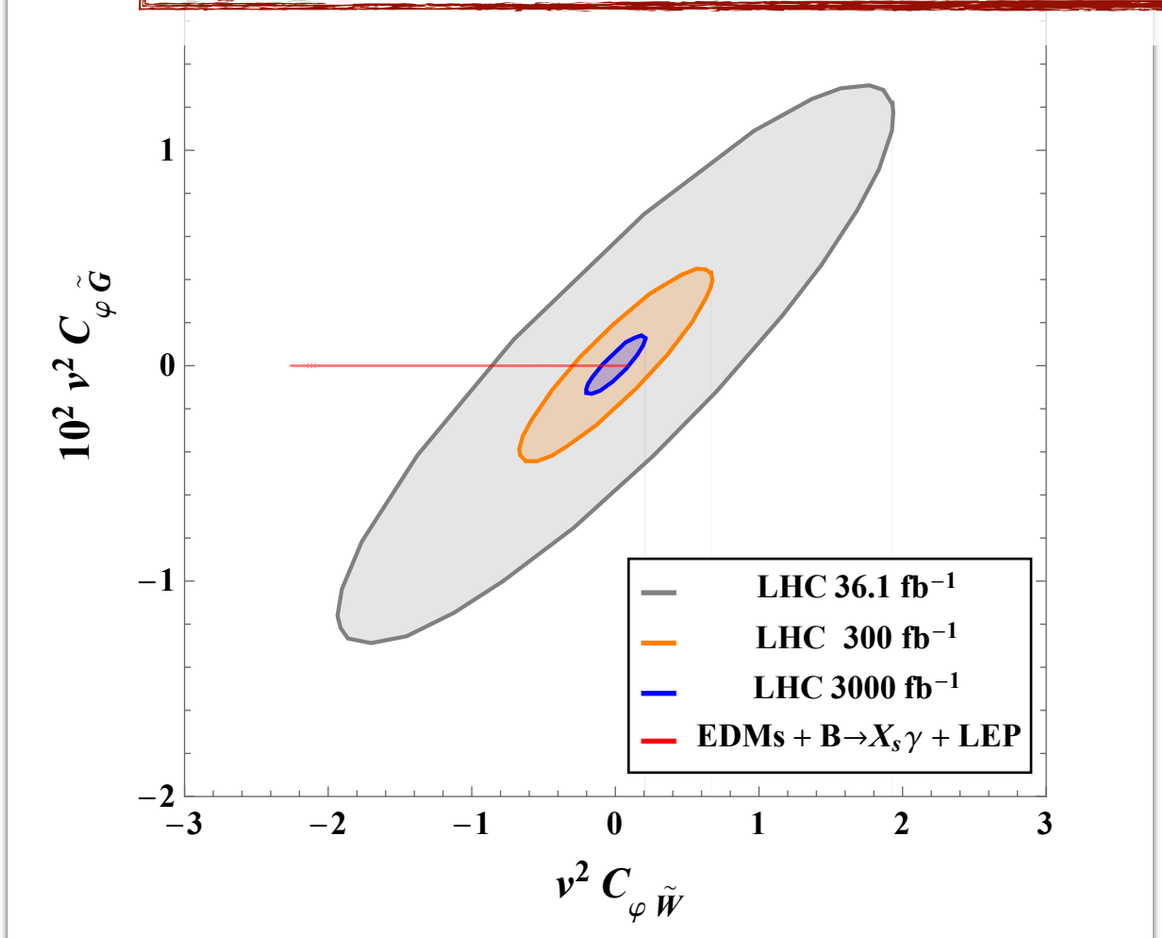
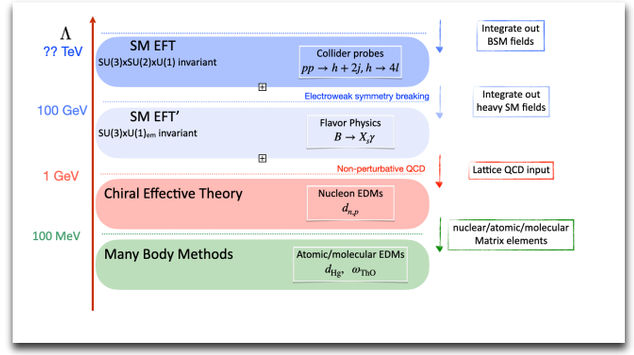


- Low-energy allows
  - Large couplings in global case
  - Only very specific combinations



Summary

- EFTs allow one to systematically describe bosonic CPV couplings
- Incorporating high- and low-energy probes in one framework



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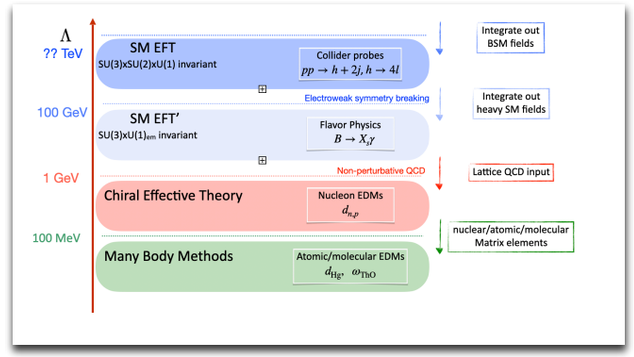
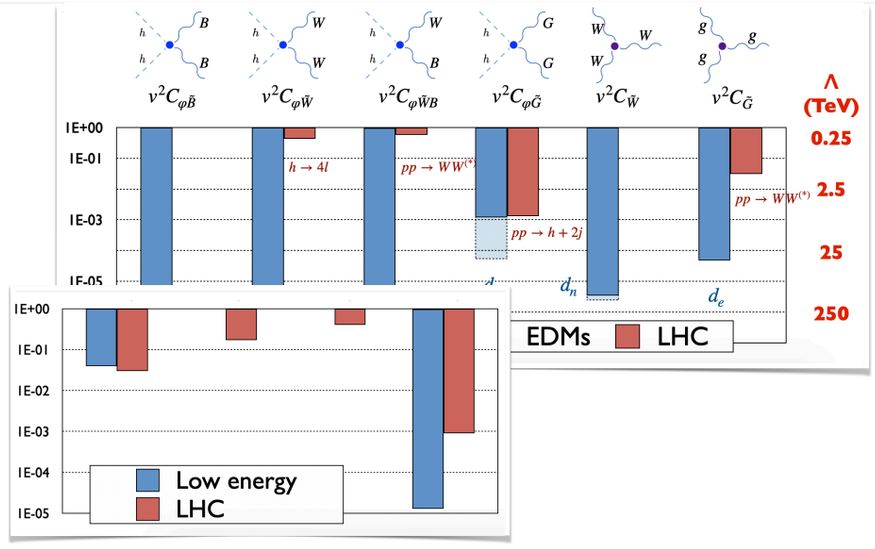


- Interplay between high- and low-energy probes
  - Low-energy probes leave little room for CPV at the LHC
- LHC becomes complementary in a global analysis



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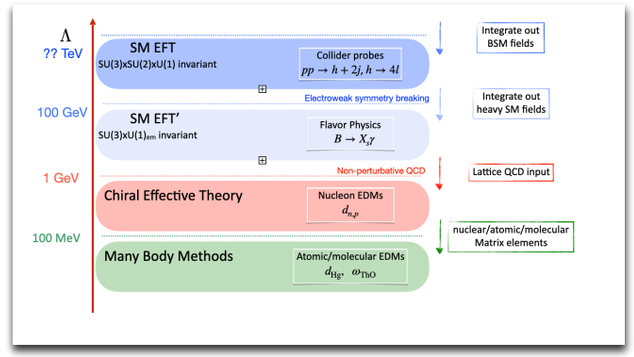

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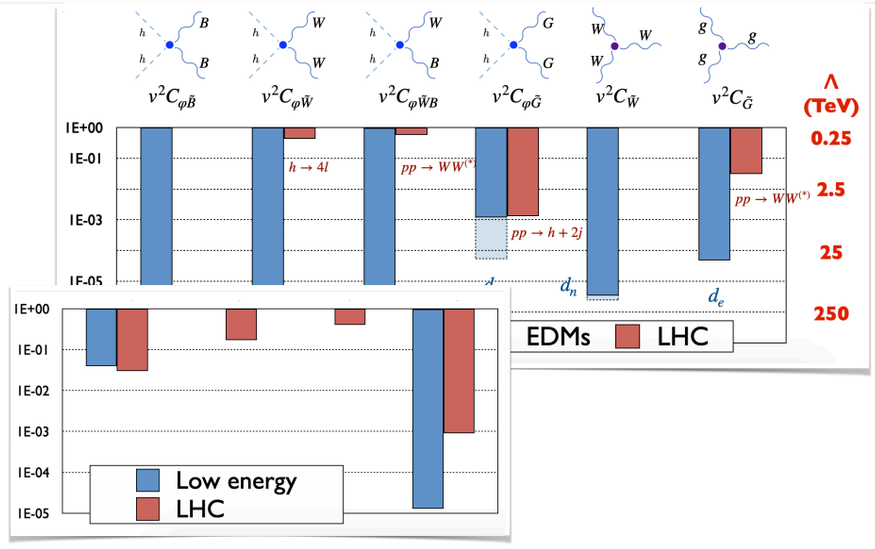
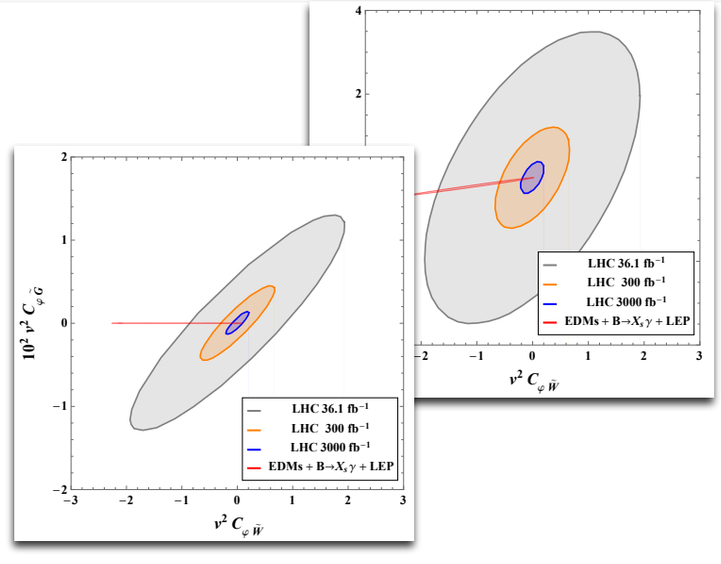


- Low-energy probes only allow specific combinations of couplings
- Nonzero signal of $C_{\varphi\tilde{X}}$ requires nonzero values of other couplings
  - Associated signals in different observables



Thank you for your attention!