W-top-bottom couplings

Wouter Dekens
HL/HE-LHC meeting

In collaboration with
S. Alioli, V. Cirigliano, E. Mereghetti, J. de Vries

arXiv:1703.04751; 1605.04311; 1603.03049

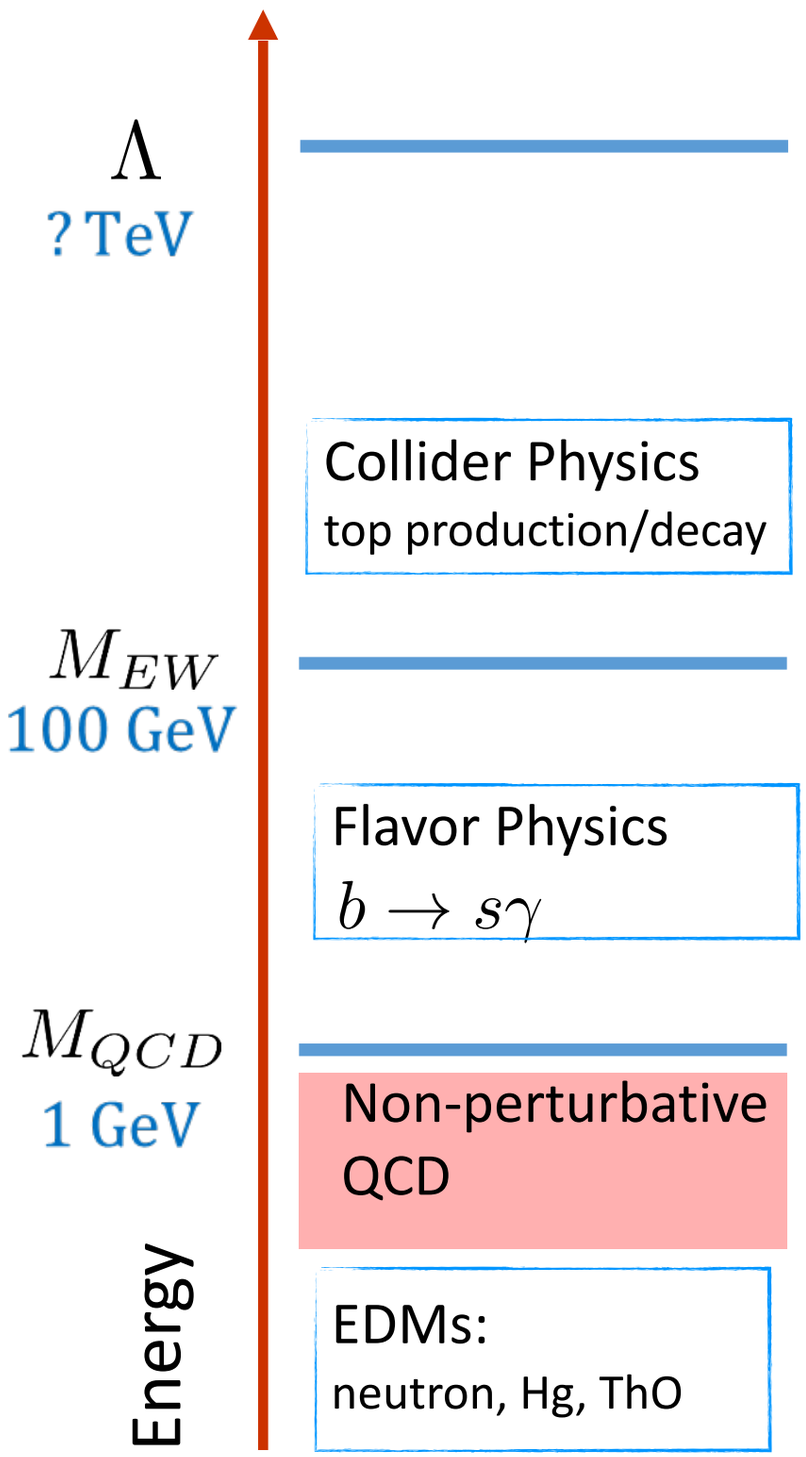
Los Alamos
NATIONAL LABORATORY
EST. 1943

Outline

CPV BSM physics:
SUSY, 2HDM, compositeness…

Effective Field Theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c^{(5)}}{\Lambda} O^{(5)} + \frac{c^{(6)}}{\Lambda^2} O^{(6)} + \dots$$



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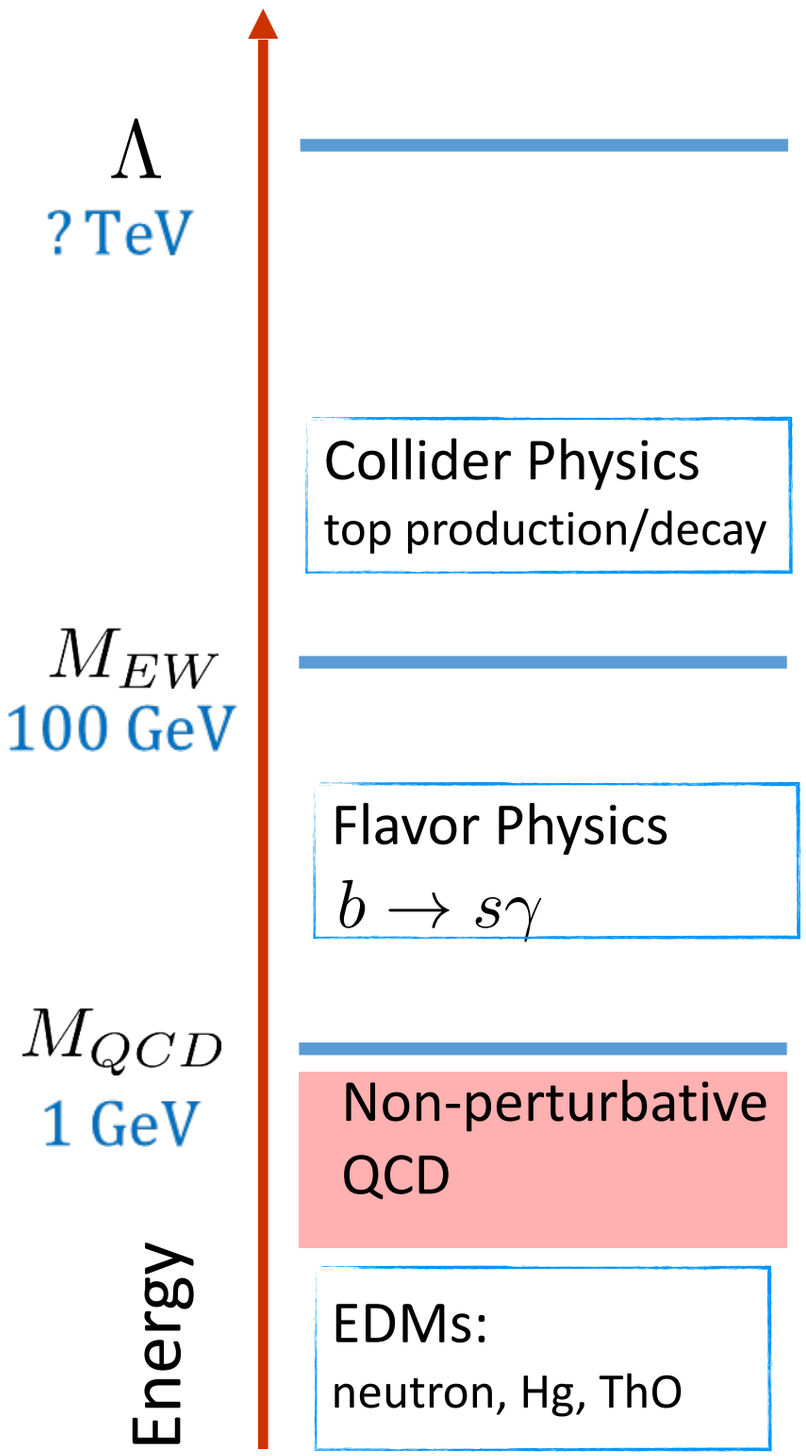
RG evolution



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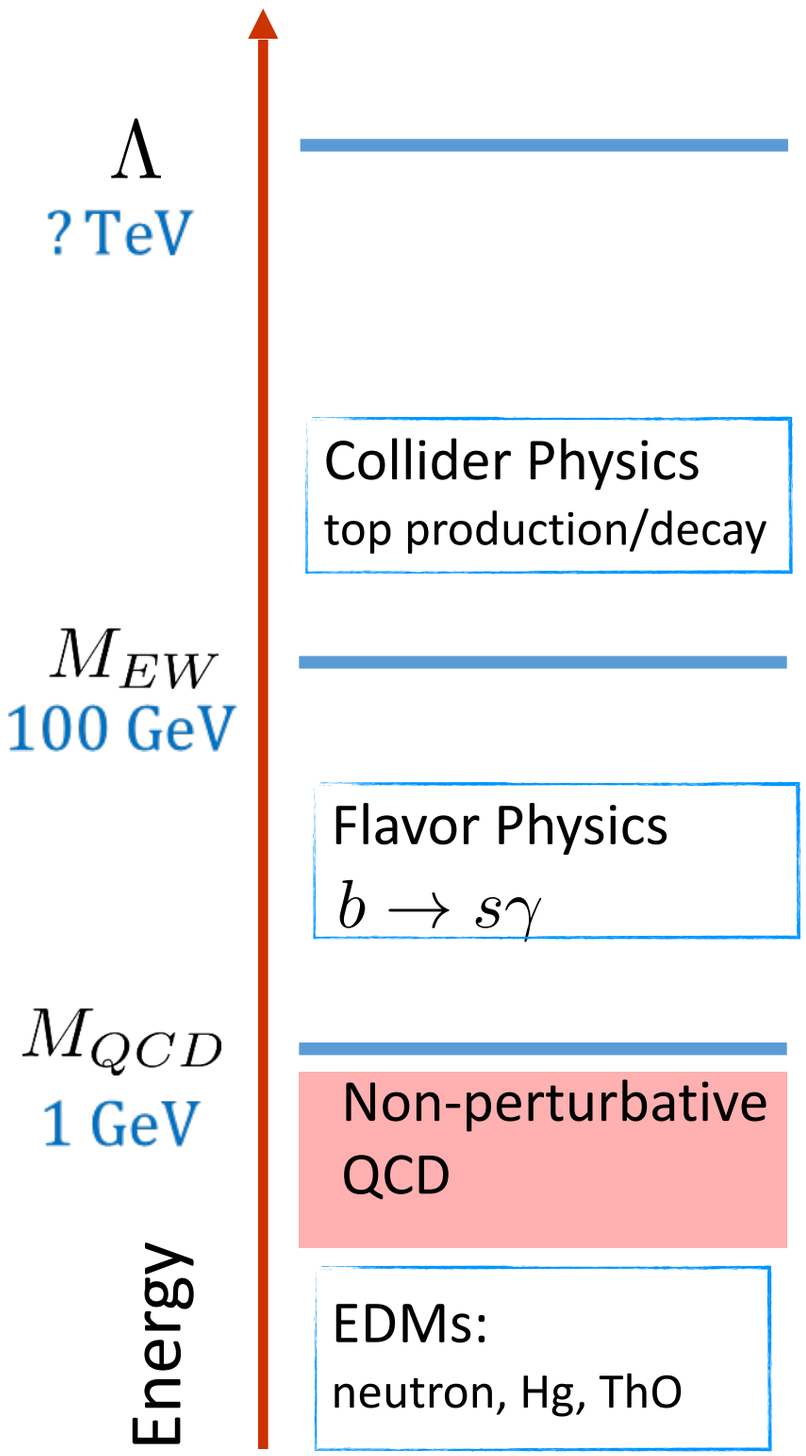

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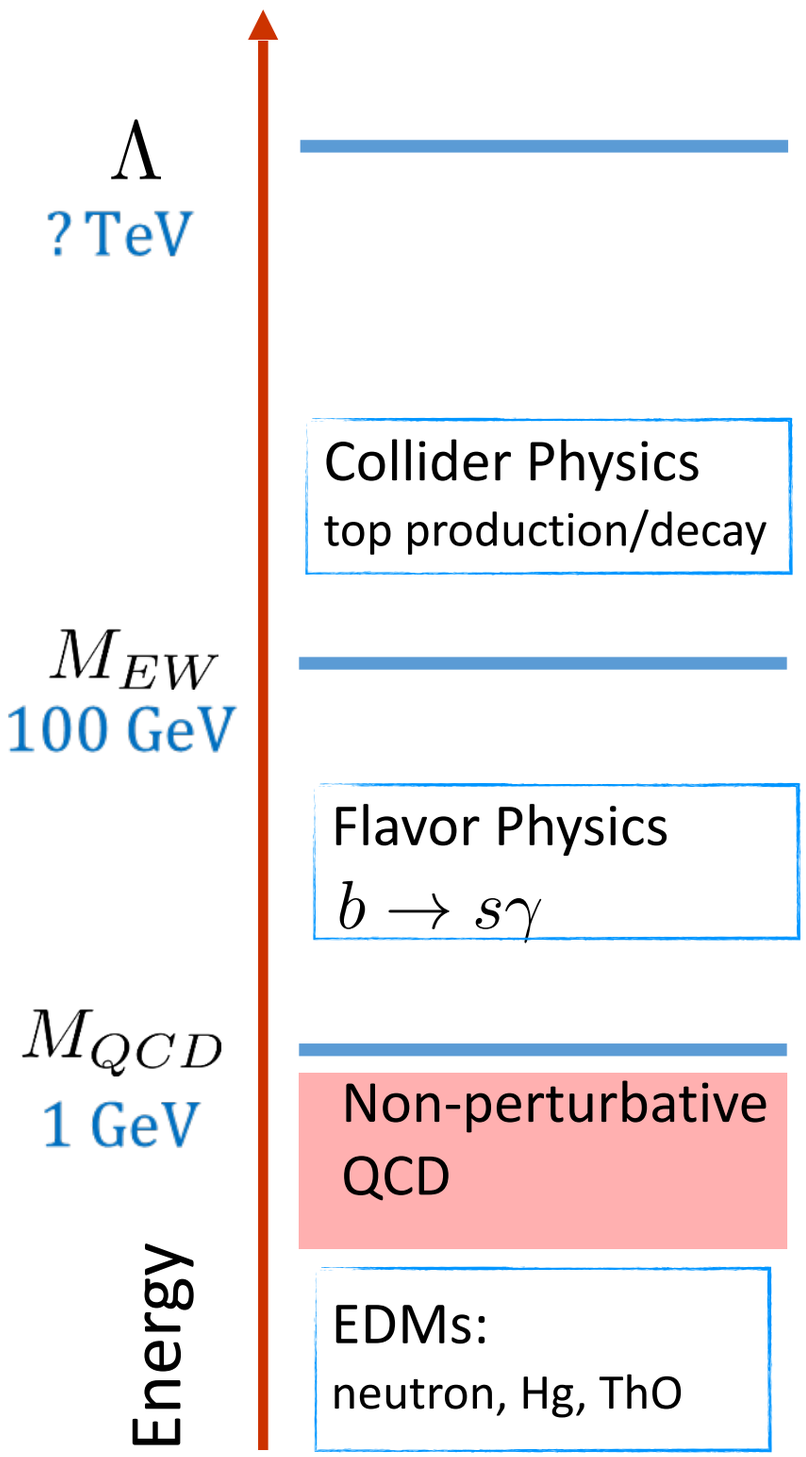

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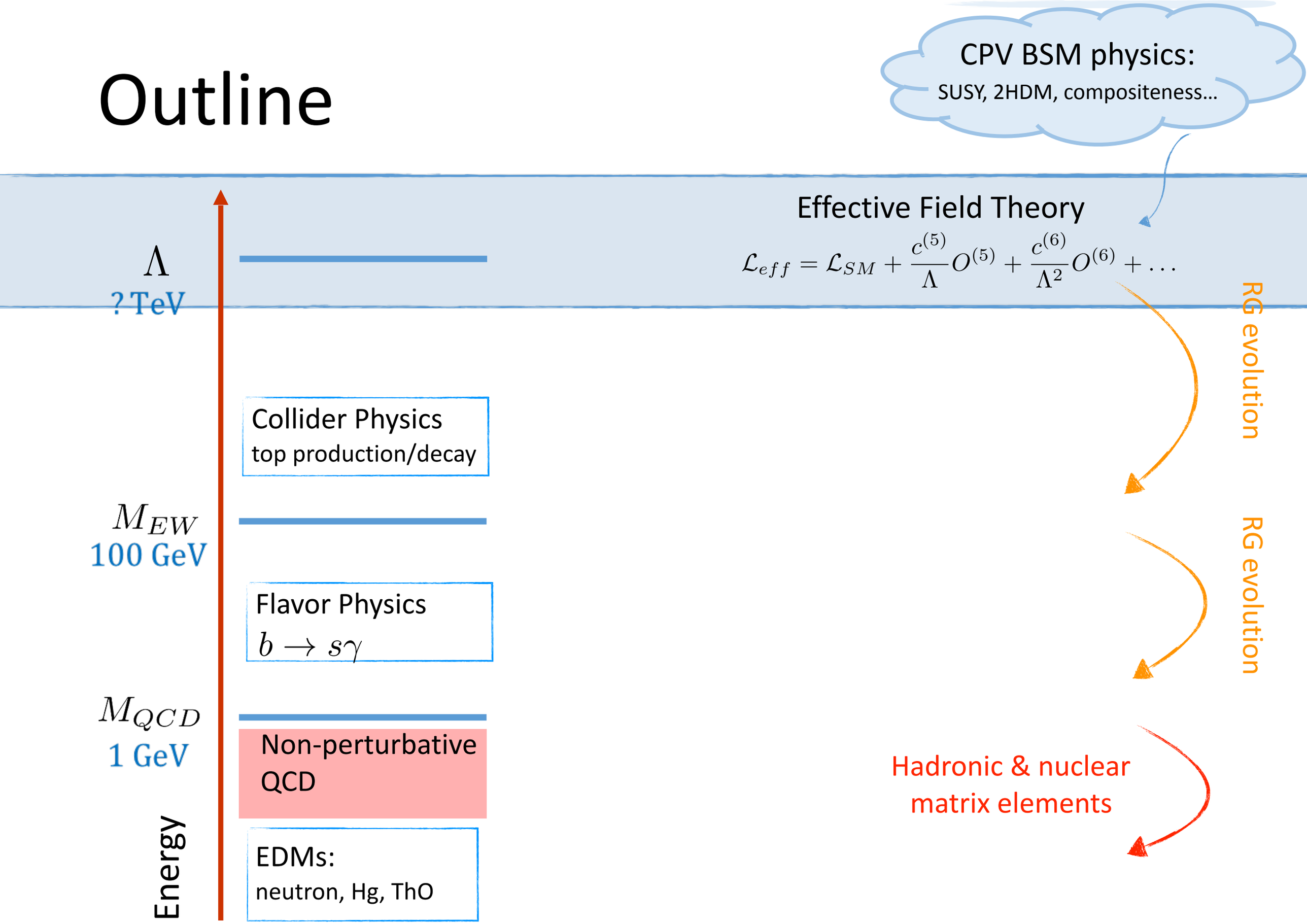
RG evolution

RG evolution

Hadronic & nuclear matrix elements

Outline


CPV BSM physics:
SUSY, 2HDM, compositeness…
Effective Field Theory
$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c^{(5)}}{\Lambda} O^{(5)} + \frac{c^{(6)}}{\Lambda^2} O^{(6)} + \dots$
Λ
? TeV
Collider Physics
top production/decay
M_{EW}
100 GeV
Flavor Physics
$b \to s\gamma$
M_{QCD}
1 GeV
Non-perturbative QCD
EDMs:
neutron, Hg, ThO
Energy
RG evolution
RG evolution
Hadronic & nuclear matrix elements

The SM Effective Field Theory

Describing BSM physics

Also see yesterday's talk by C. Murphy

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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Dimension-six operators

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

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

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

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

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

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

The SM Effective Field Theory

Describing BSM physics

Also see yesterday's talk by C. Murphy

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

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

$(\bar{L}L)(\bar{R}R)$
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$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

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

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

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Describing BSM physics

Also see yesterday's talk by C. Murphy

Dimension five operators

- One term, generates Majorana neutrino masses

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

Focus on Wtb couplings

- These are the largest in some BSM scenarios
  - Light stop SUSY
  - Compositeness
- Just 5 operators left
  - Manageable

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

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

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

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

Kaplan NP B, '91; Carena, Nardini, Quiros, Wagner, NP B, '09

Wtb couplings

- Left-handed vector coupling
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Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q^{(3)}_{\varphi l}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
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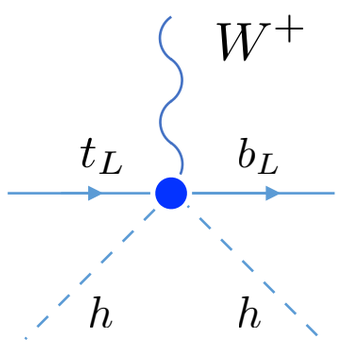

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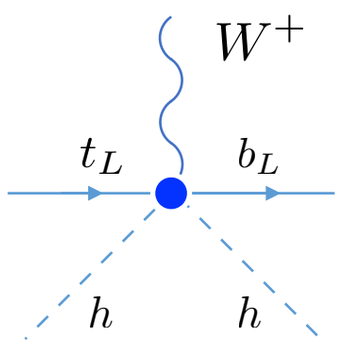
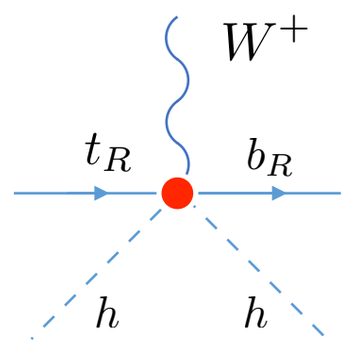


δ_{LL}



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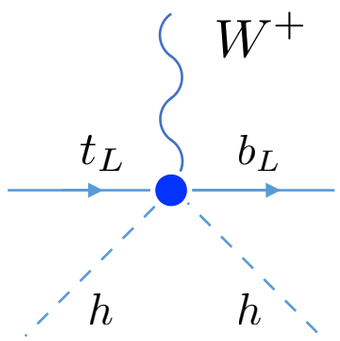
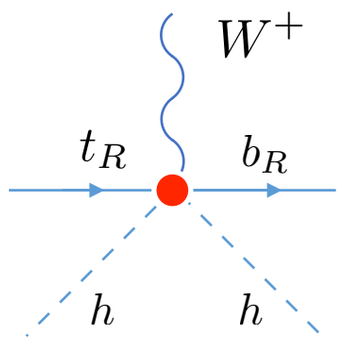
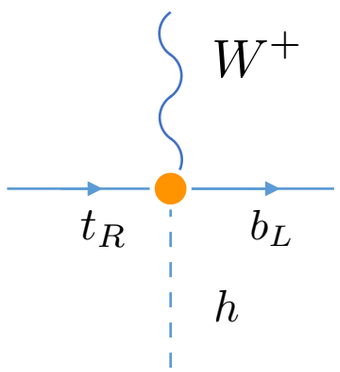


δ_{LL}



ξ_{tb}



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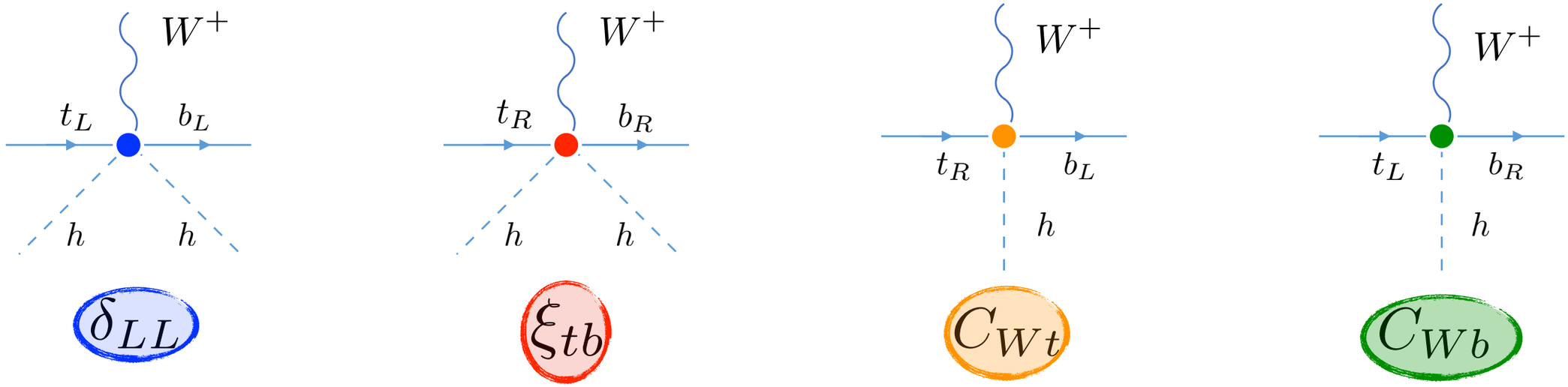

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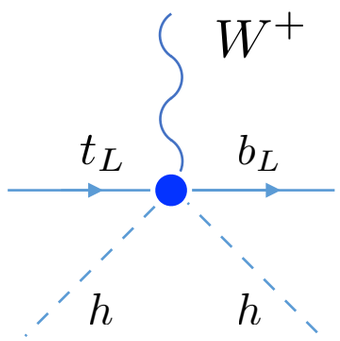
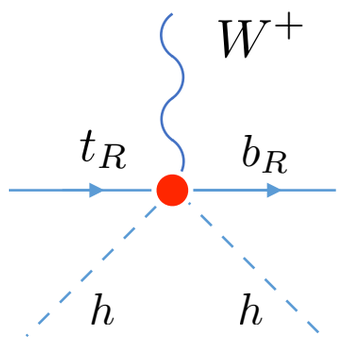
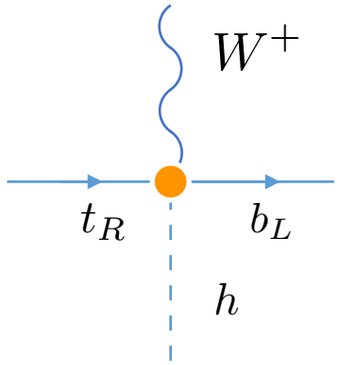


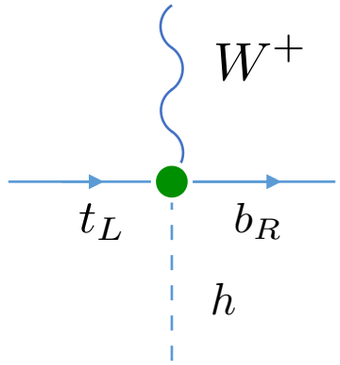
δ_{LL}



ξ_{tb}



C_{Wt}



C_{Wb}

- All couplings scale as

$$\delta_{LL},\ \xi_{tb},\ C_{Wt},\ C_{Wb} \propto \mathcal{O}(v^2/\Lambda^2)$$

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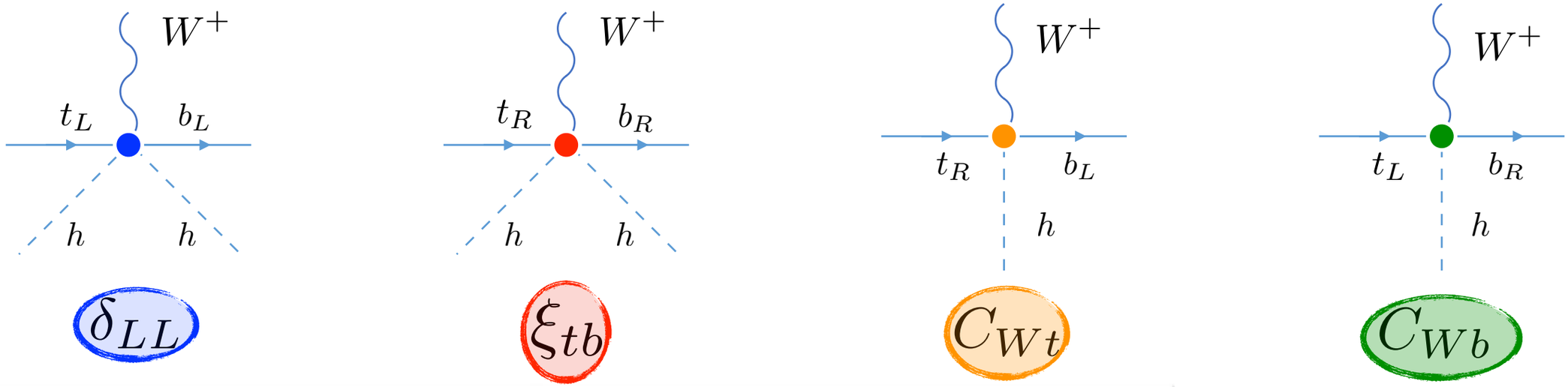


- All couplings scale as

$$\delta_{LL},\ \xi_{tb},\ C_{Wt},\ C_{Wb} \propto \mathcal{O}(v^2/\Lambda^2)$$

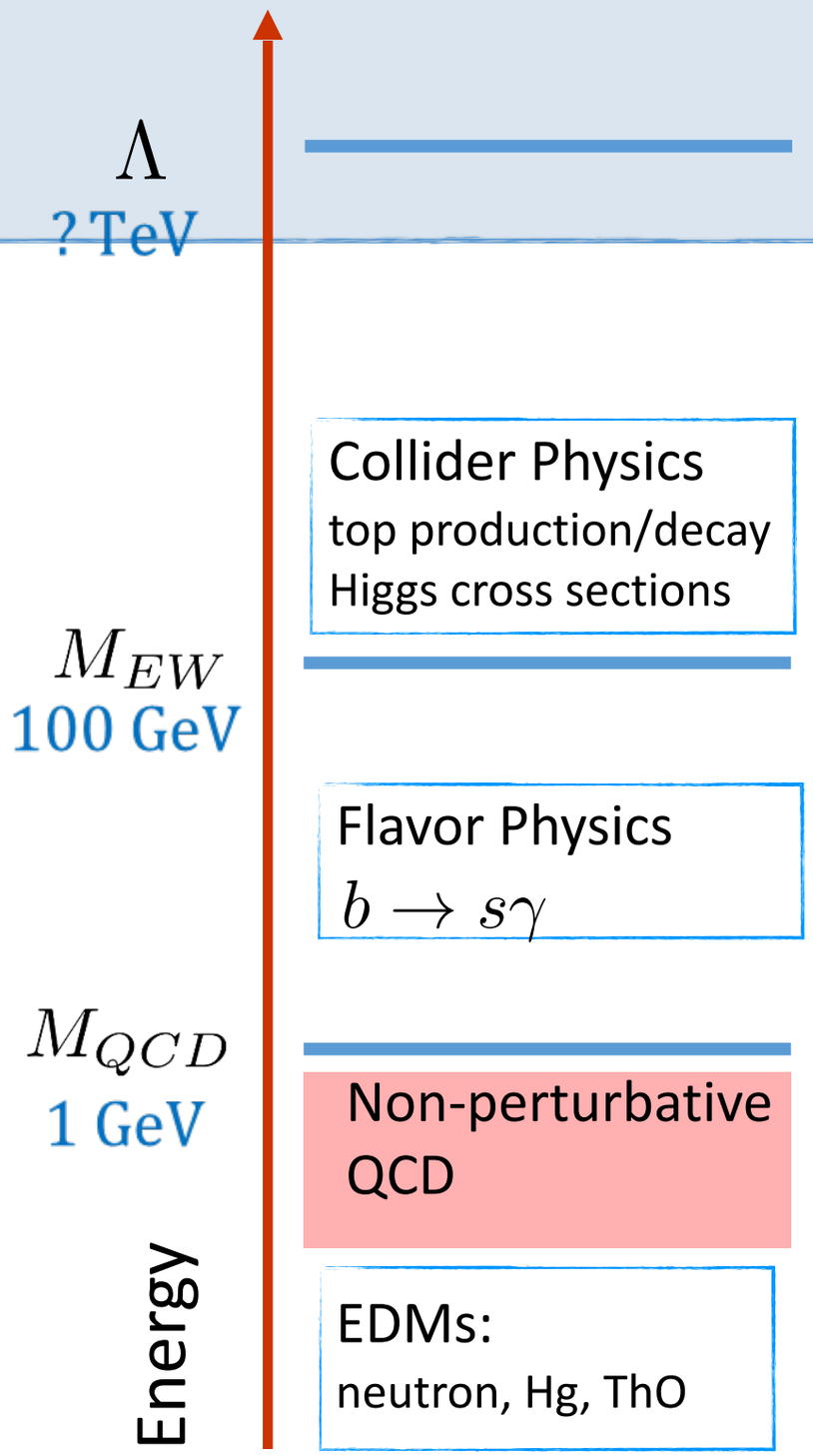
- Real parts are CP-even, imaginary parts CP-odd
  - δ_{LL} is purely real (assuming no FCNCs)

Outline

CPV BSM physics:
SUSY, 2HDM, compositeness…

Effective Field Theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c^{(5)}}{\Lambda} O^{(5)} + \frac{c^{(6)}}{\Lambda^2} O^{(6)} + \dots$$



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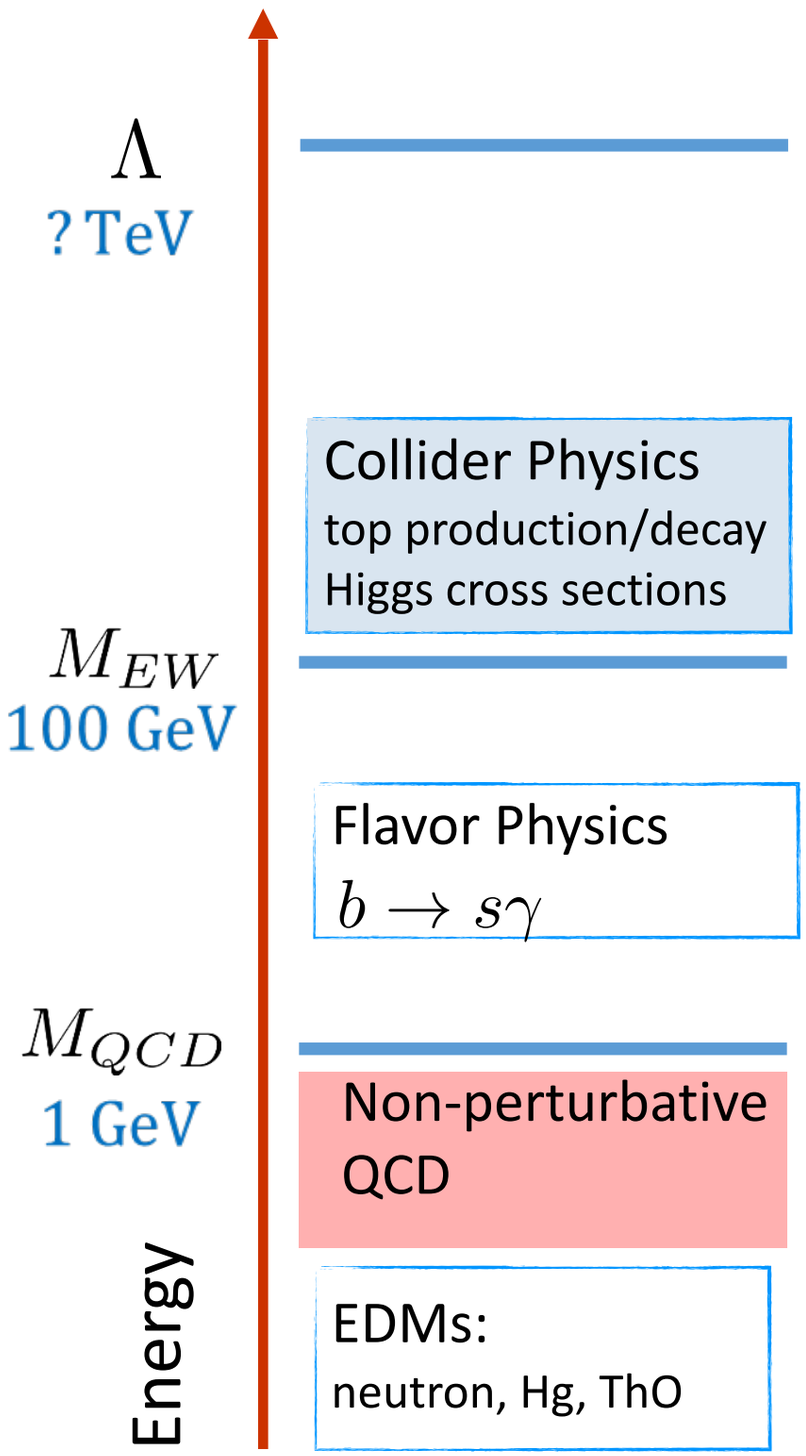
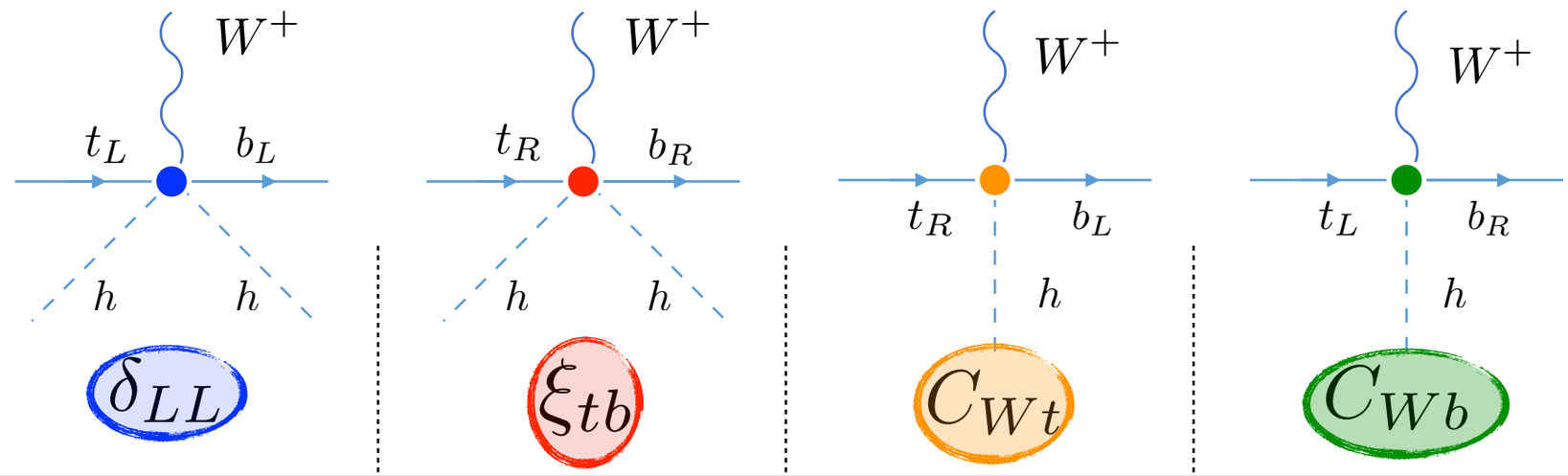
RG evolution

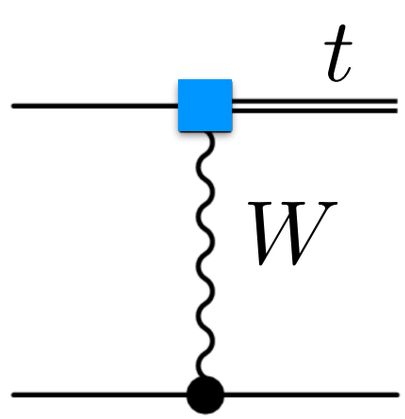


Direct collider observables



	δ_{LL}	ξ_{tb}	C_{Wt}	C_{Wb}
t	✓	✓	✓	
$t \to W^+ b$ W-boson helicity fractions	✓	✓	✓	

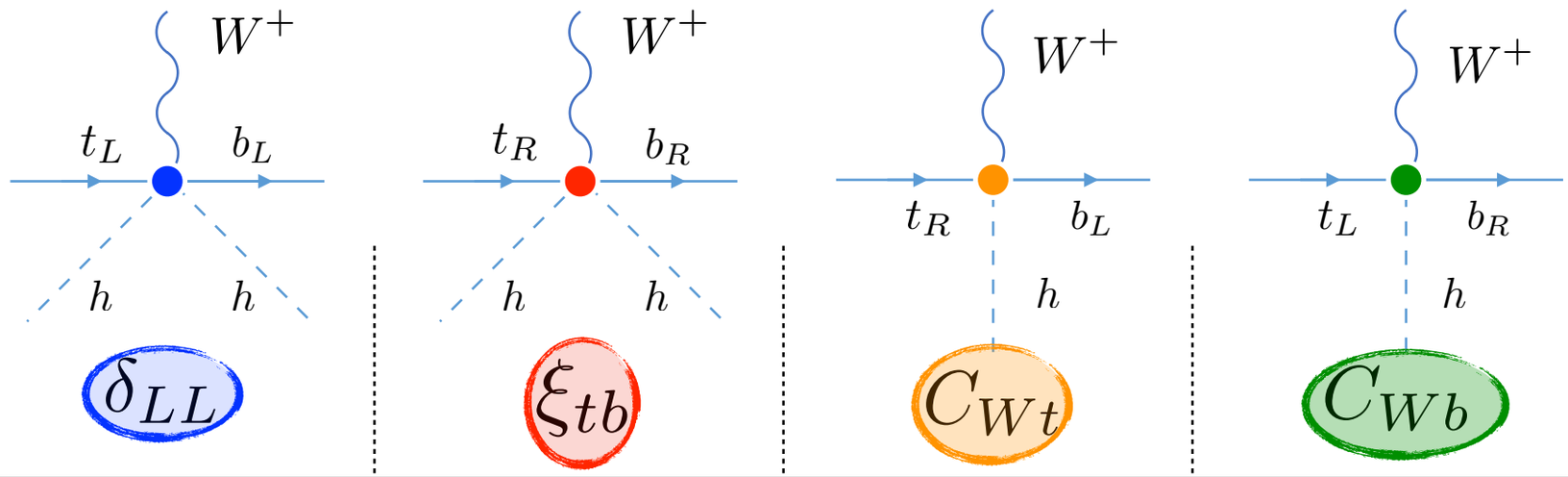
$\delta_{LL}\ \xi_{tb}\ C_{Wt}$



- SM known to NNLO in QCD
- Computed BSM to NLO in QCD

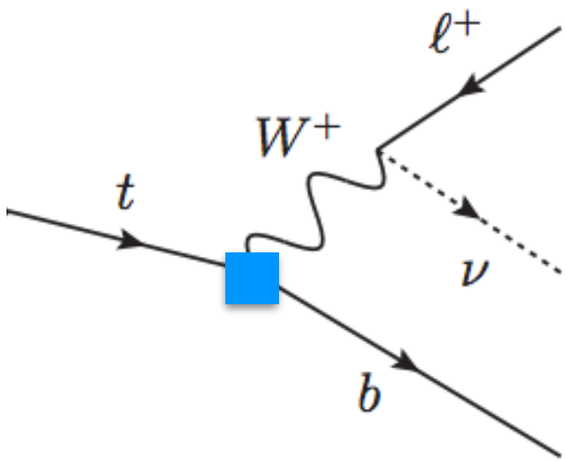
Brucherseifer, Caola and Melnikov, ‘14

Direct collider observables



	δ_{LL}	ξ_{tb}	C_{Wt}	C_{Wb}
t	✓	✓	✓	
$t \to W^+ b$ W-boson helicity fractions	✓	✓	✓	

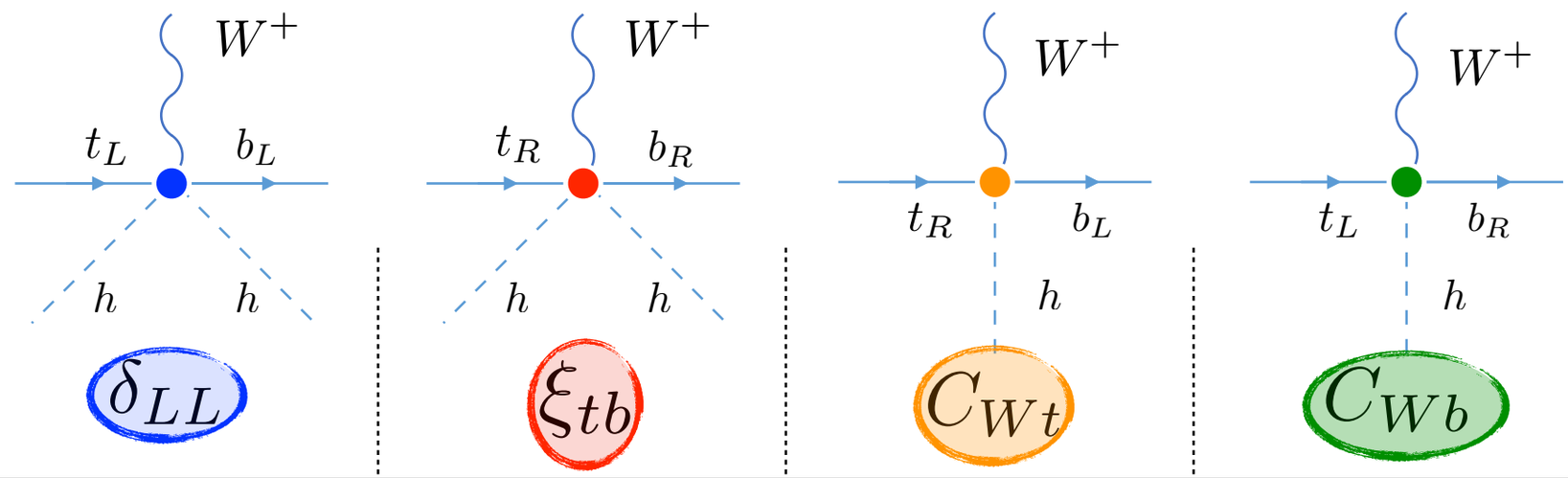
$\delta_{LL}\ \xi_{tb}\ C_{Wt}$



- Known to NLO in QCD

Drobnak, Fajfer, Kamenik, '10

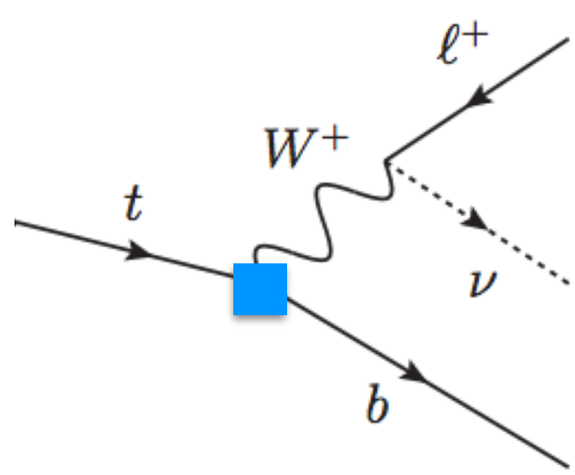
Direct collider observables



	δ_{LL}	ξ_{tb}	C_{Wt}	C_{Wb}
t	✓	✓	✓	
$t \to W^+ b$	✓	✓	✓	
W-boson helicity fractions	✓	✓	✓	

Suppressed by m_b

$\delta_{LL}\ \xi_{tb}\ C_{Wt}$



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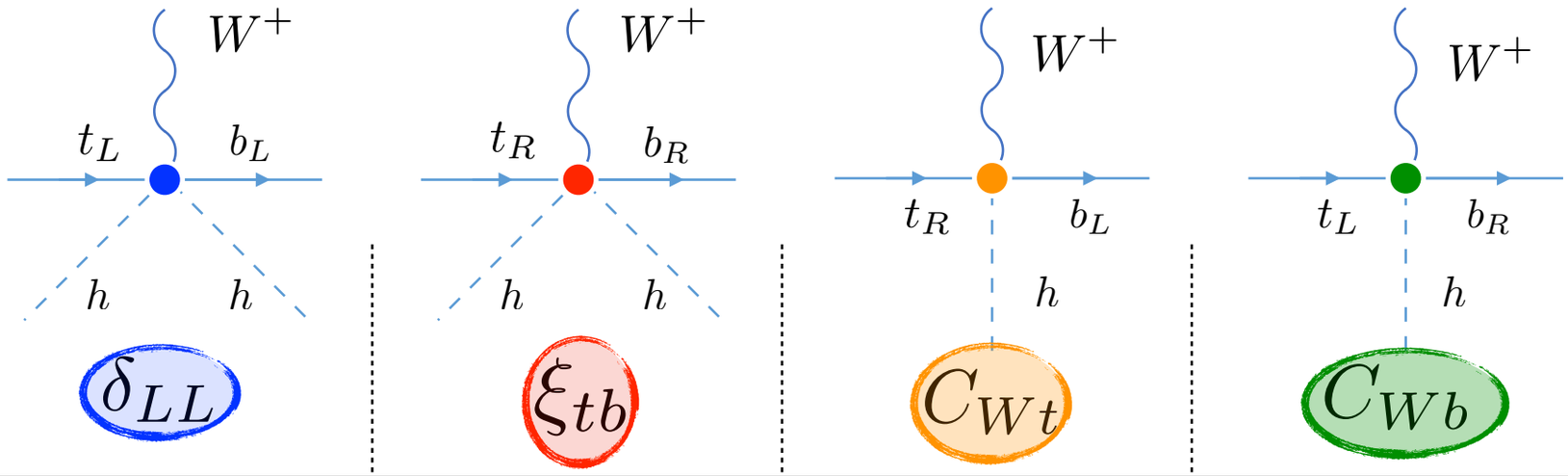


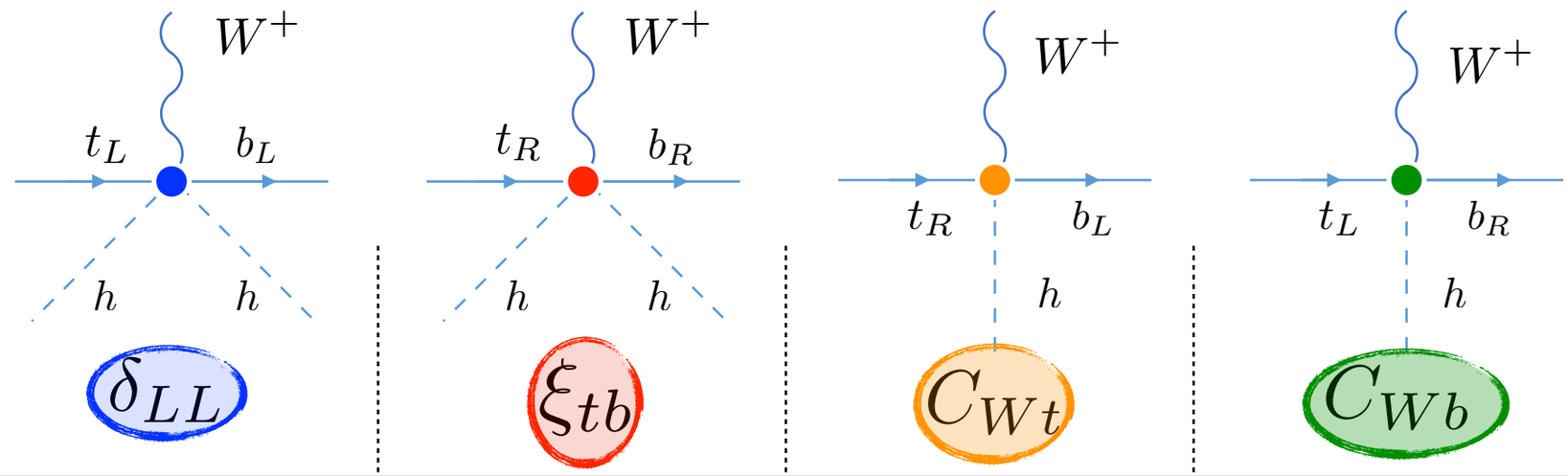
	δ_{LL}	ξ_{tb}	C_{Wt}	C_{Wb}
t	✓	✓	✓	
$t \to W^+ b$ W-boson helicity fractions	✓	✓	✓	

- Most of these observables are sensitive to the real parts / absolute values of couplings
- However, $\delta^-(t \to Wb)$ is sensitive to Im(C_{Wt})
  - $\delta^-(t \to Wb)$ is the phase between longitudinally- and tranversely-polarized W bosons

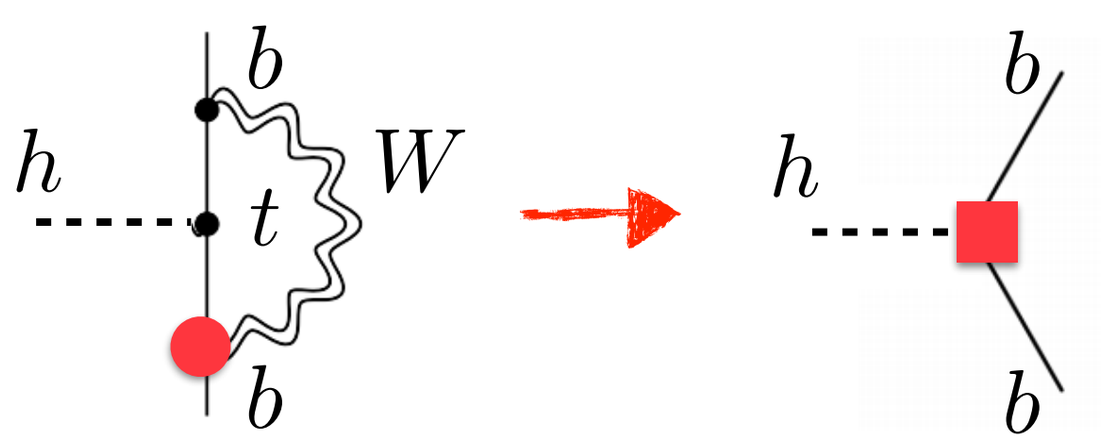
Drobnak, Fajfer, Kamenik, '10

Boudreau, Escobar, Mueller, Sapp, Su, '13

Indirect collider observables

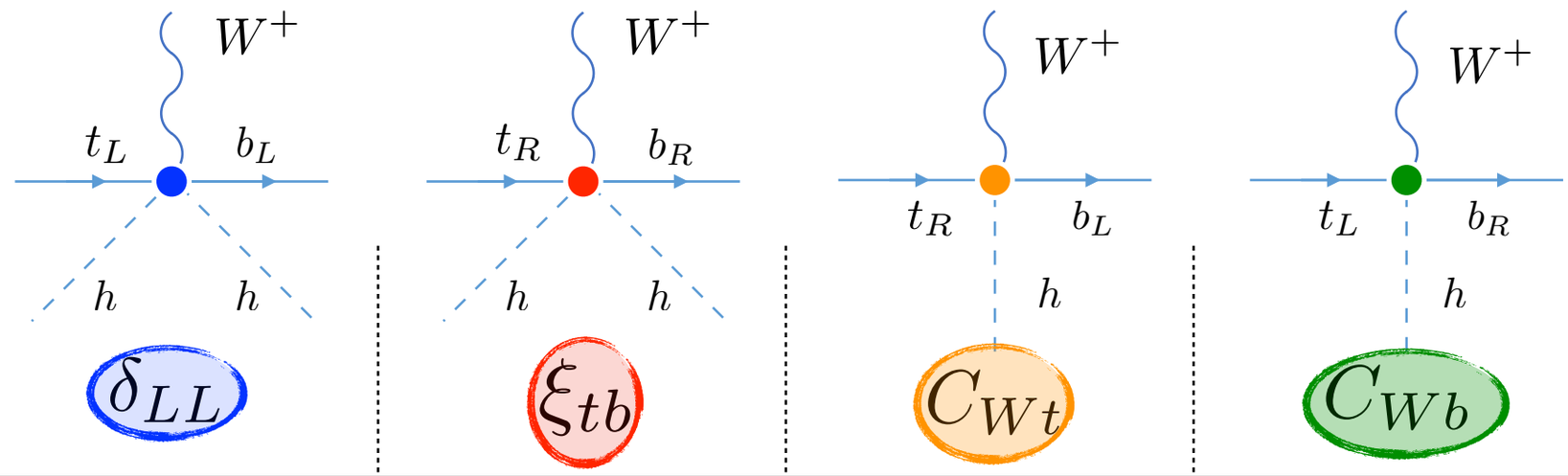


	δ_{LL}	ξ_{tb}	C_{Wt}	C_{Wb}
$h \to \bar{b}b$ Higgs signal strengths		✓		
S parameter			✓	



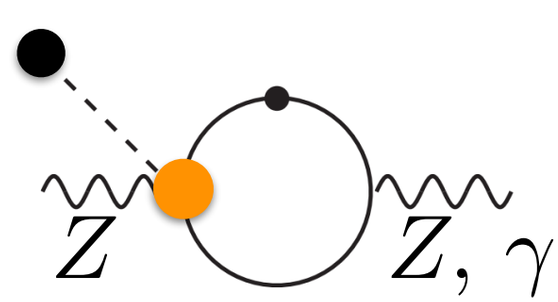
$$y_b^{\text{induced}} \sim m_t/m_b \xi_{tb}$$

Indirect collider observables



	δ_{LL}	ξ_{tb}	C_{Wt}	C_{Wb}
$h \to \bar{b}b$ Higgs signal strengths		✓		
S parameter			✓	

C_{Wt}



$$S \sim y_t^2 (v^2 C_{Wt})$$

Zhang, Willenbrock '10; Greiner, Willenbrock, Zhang '11

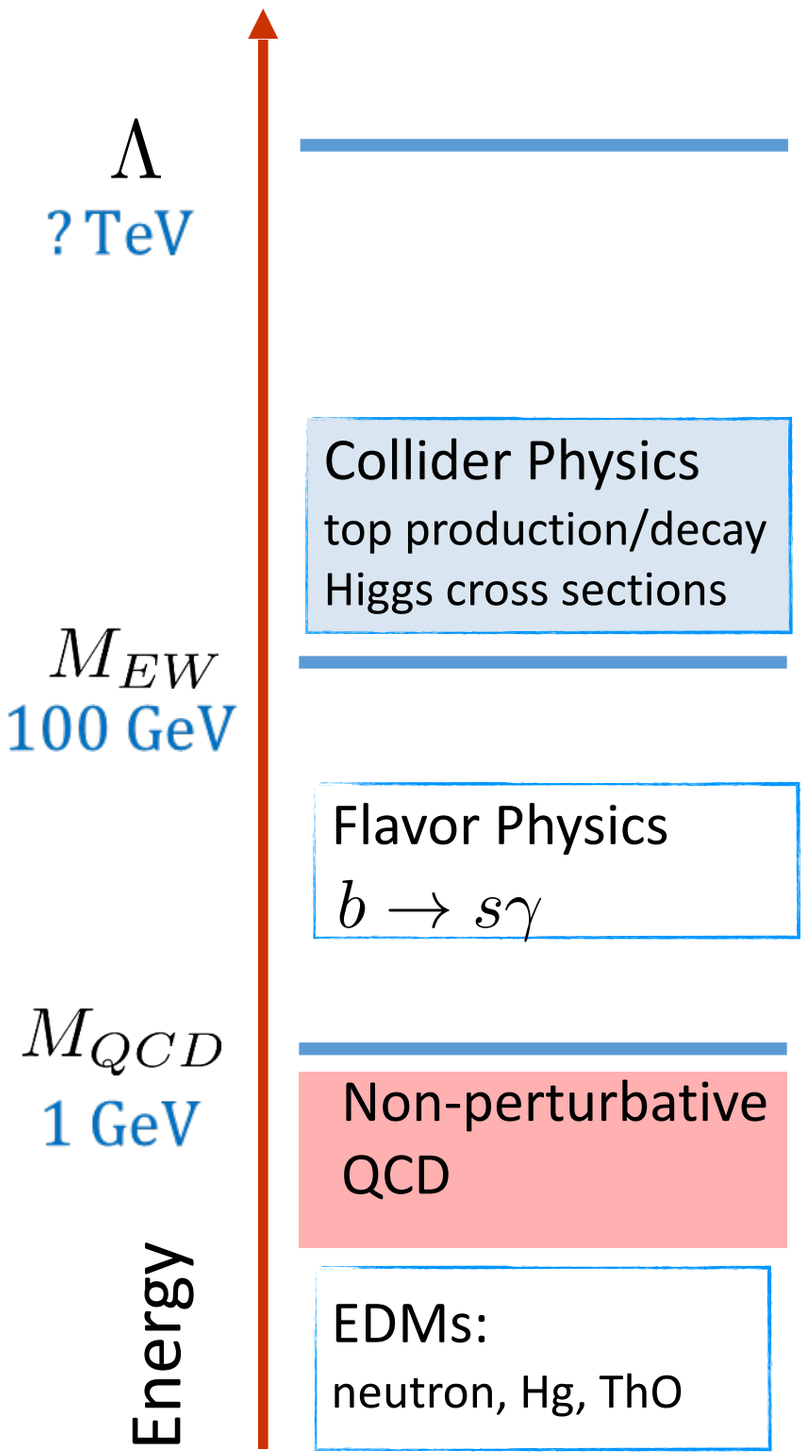
Outline

CPV BSM physics:
SUSY, 2HDM, compositeness…

Effective Field Theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c^{(5)}}{\Lambda} O^{(5)} + \frac{c^{(6)}}{\Lambda^2} O^{(6)} + \dots$$

RG evolution



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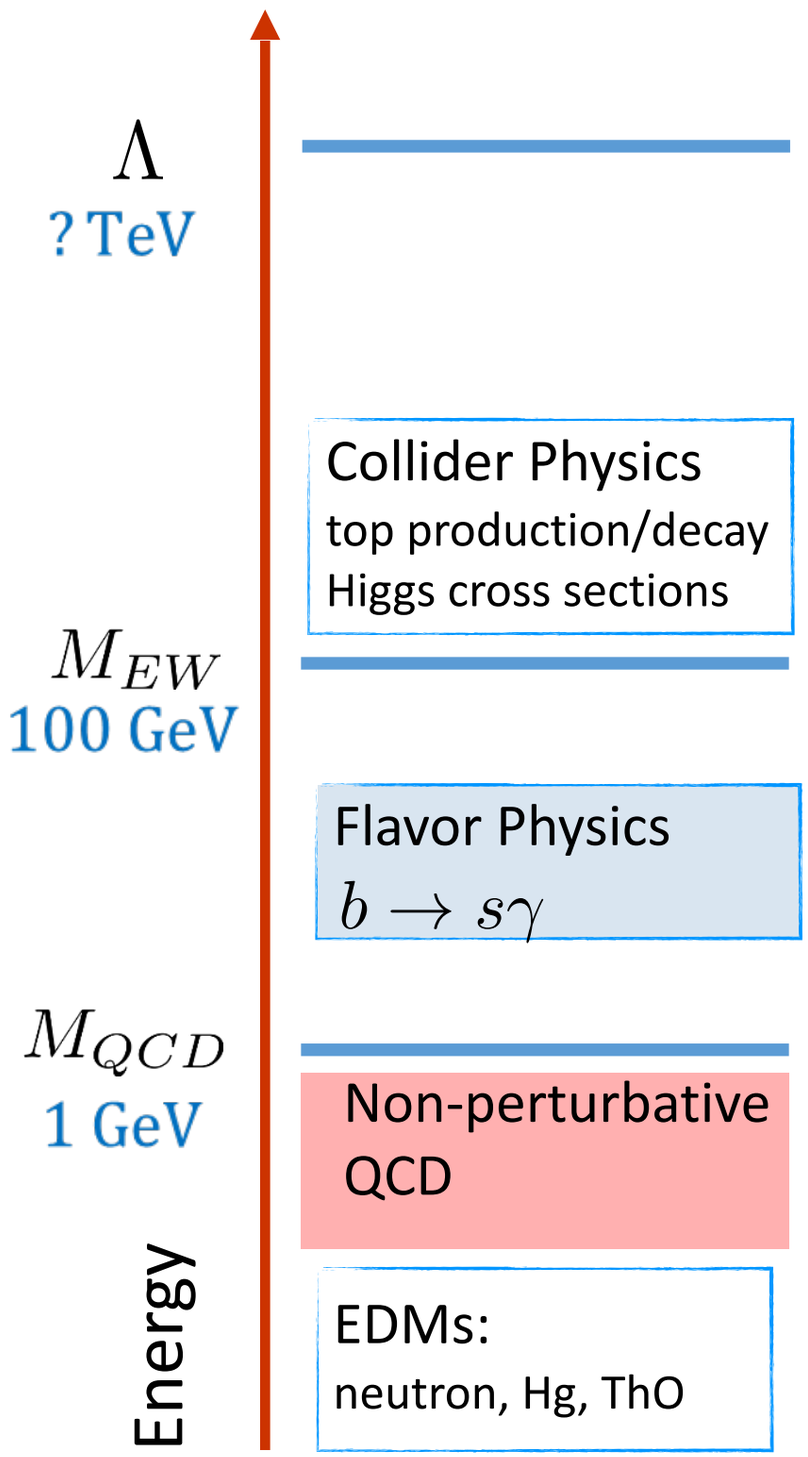
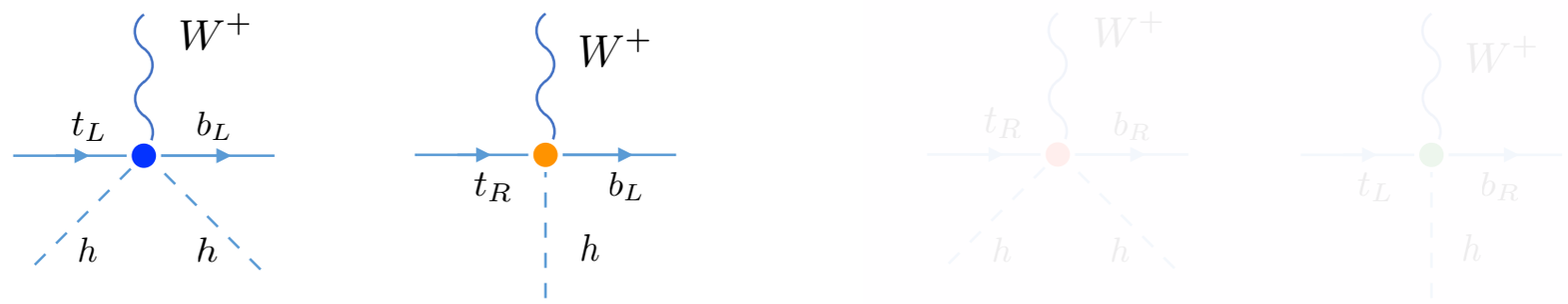
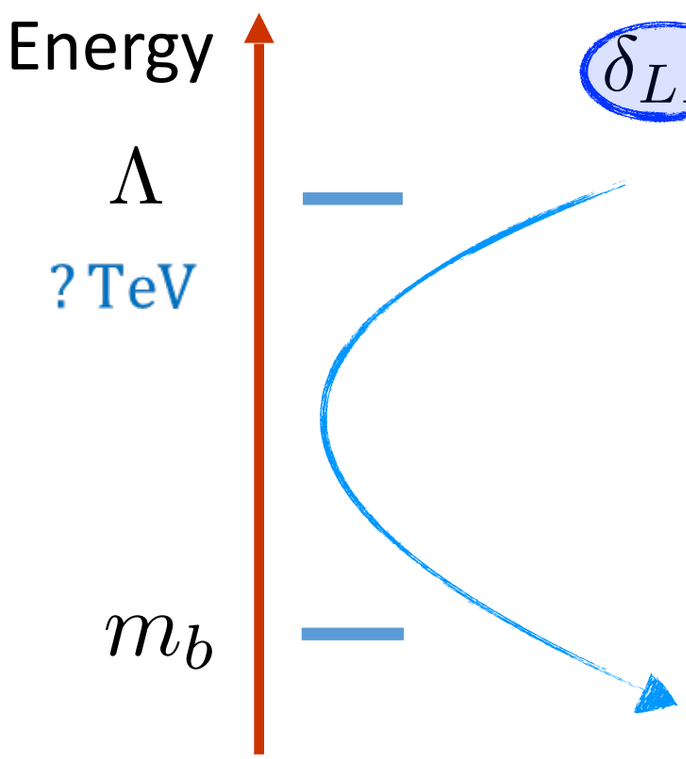


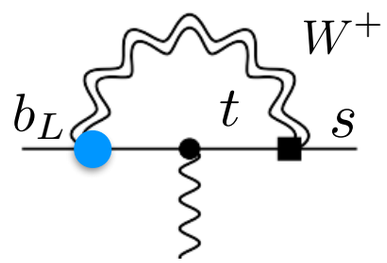
Flavor physics

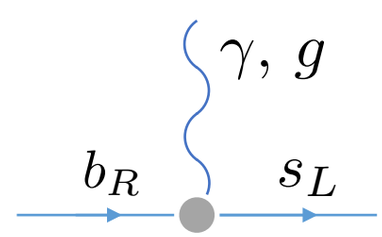
$b \to s\gamma$



δ_{LL} C_{Wt} ξ_{tb} C_{Wb}







$C_7,\ C_8$

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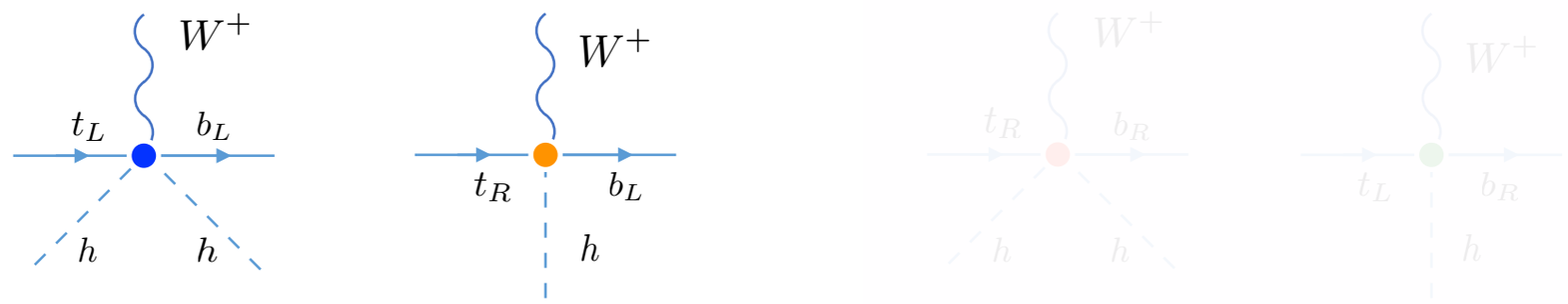
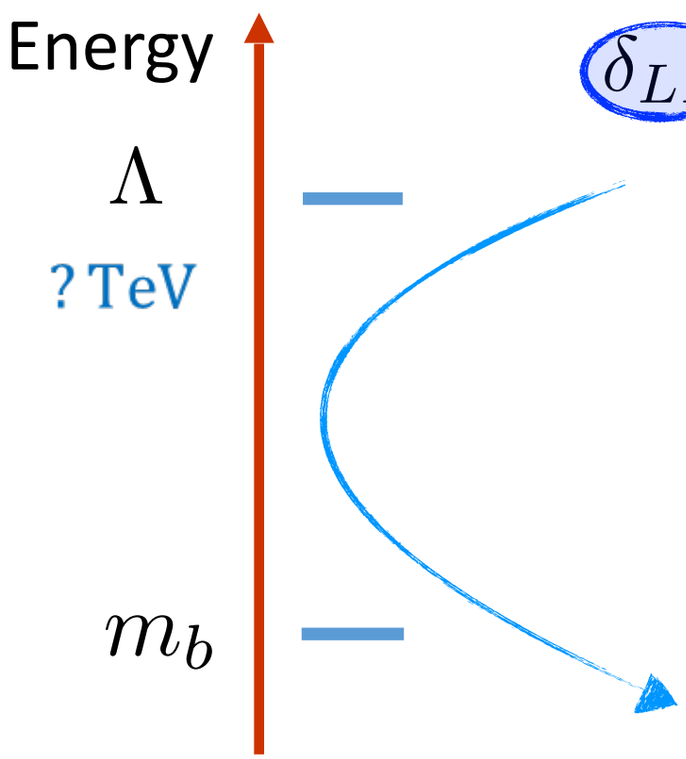
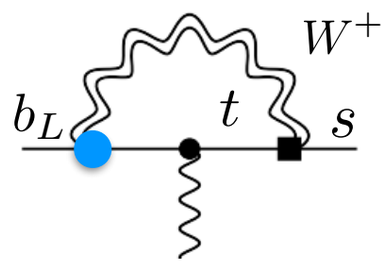
$b \to s\gamma$

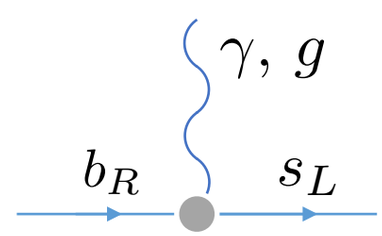


δ_{LL} C_{Wt} ξ_{tb} C_{Wb}





$\sim m_b$



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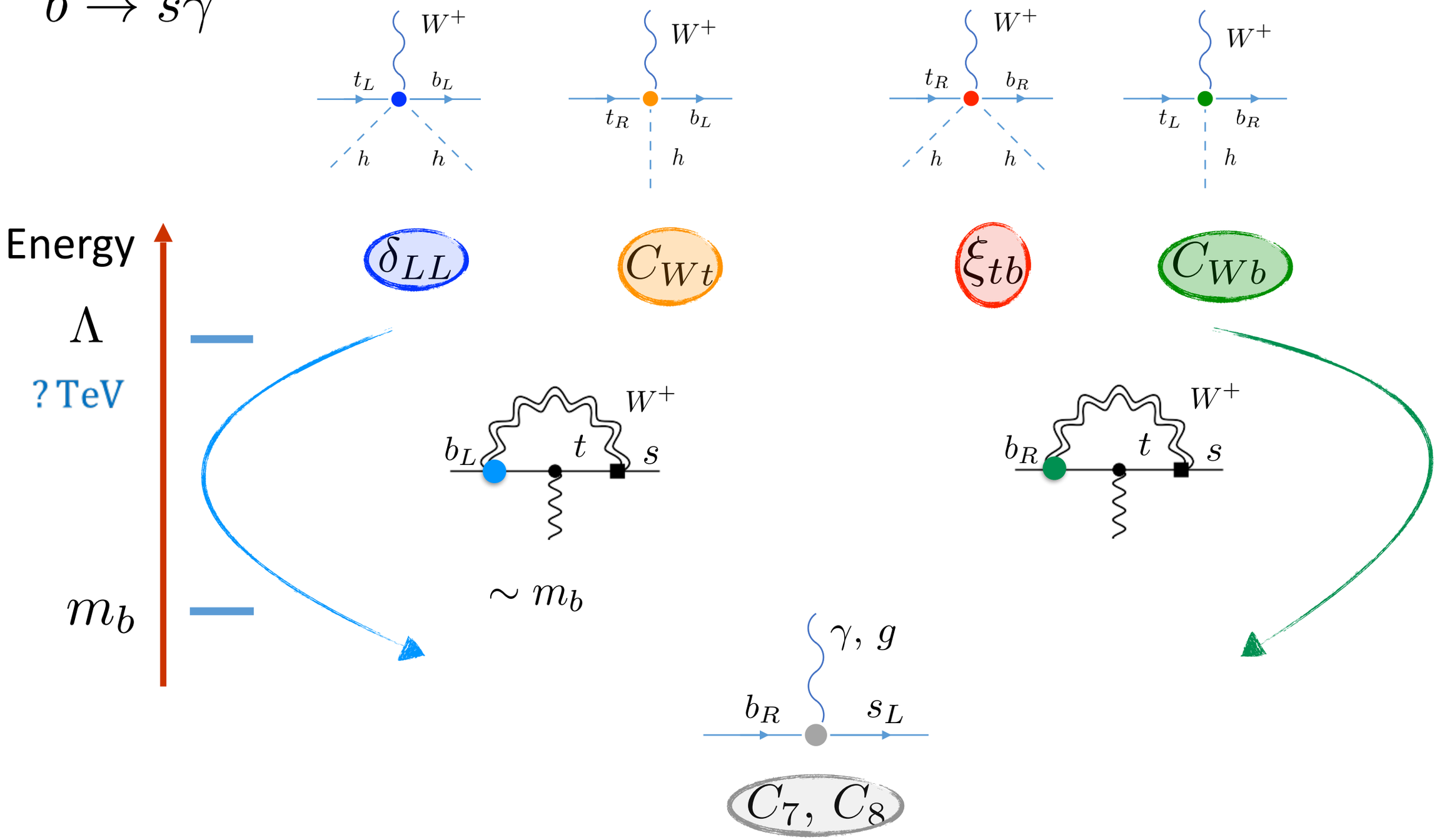

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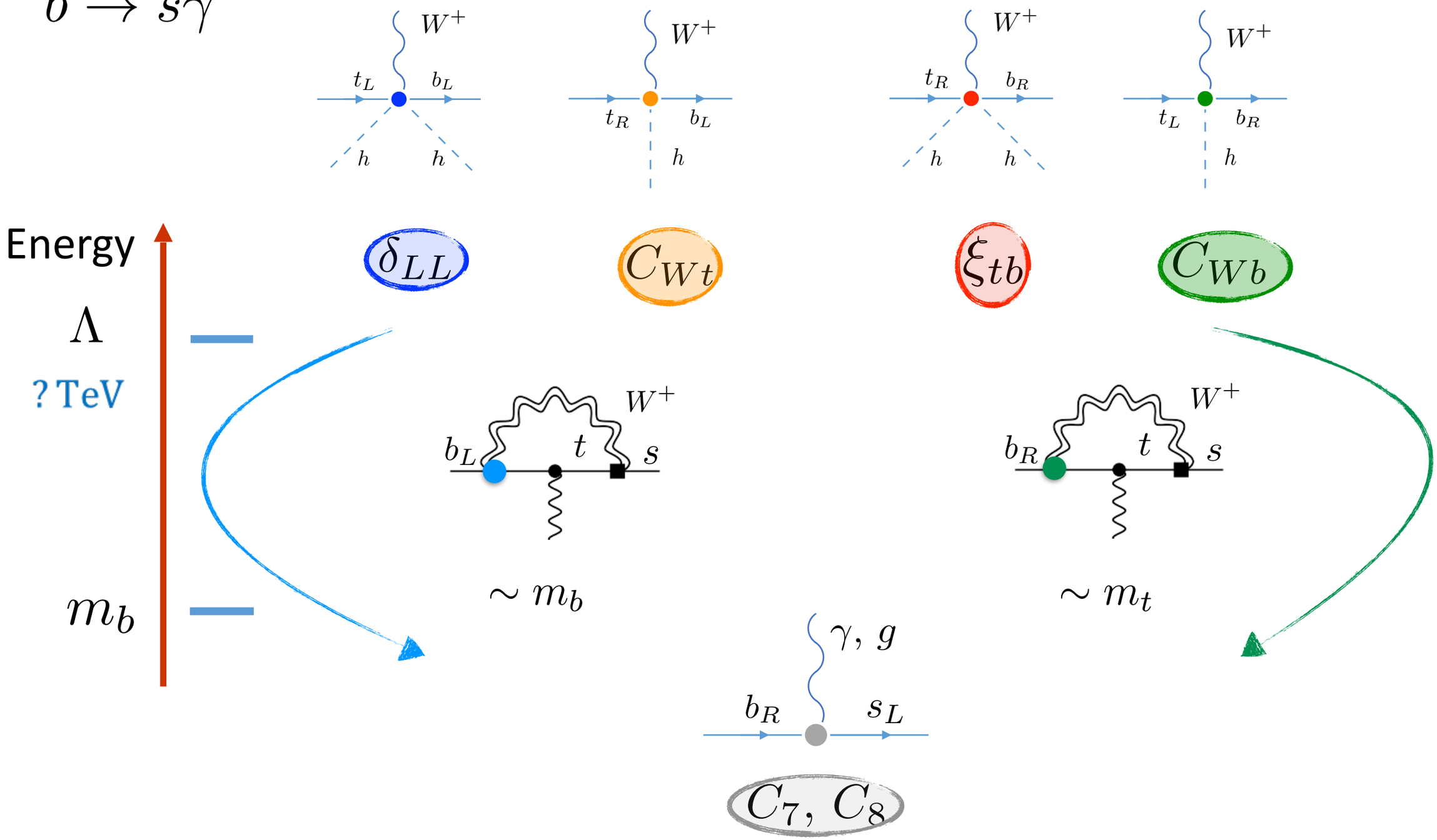

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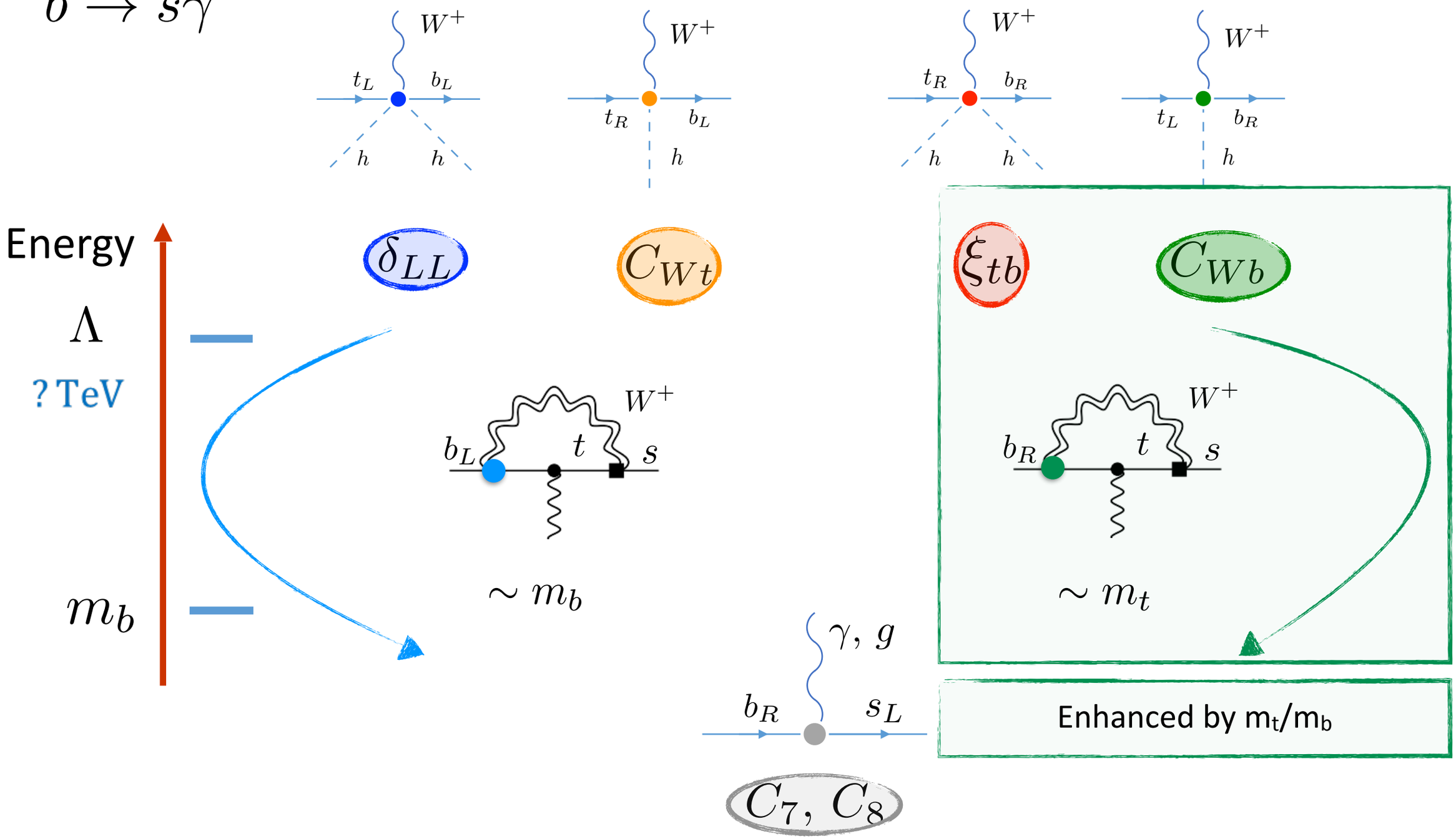
$b \to s\gamma$



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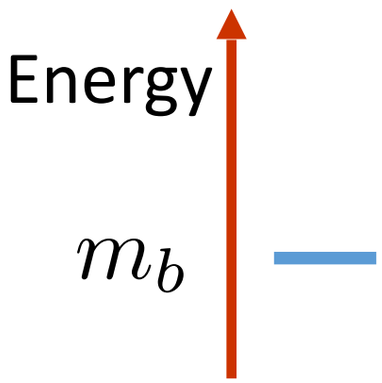

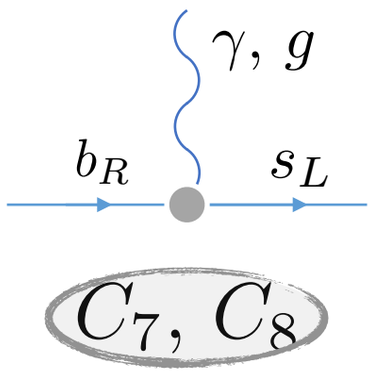

- Real parts contribute mainly to the branching ratio

Misiak et al, ’07; Lunghi & Matias, ’07; Kagan & Neubert, ‘99

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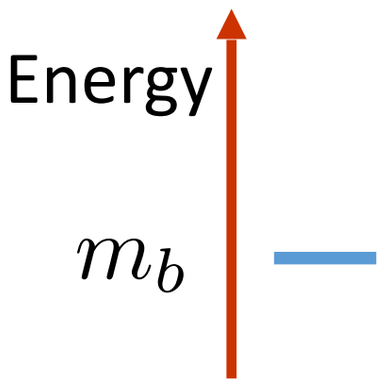
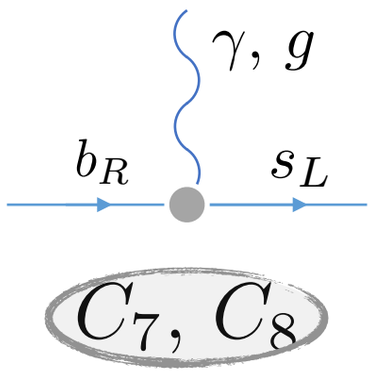
$b \to s\gamma$





- Real parts contribute mainly to the branching ratio

- Imaginary parts mainly contribute to the CP asymmetry

$$A_{CP} \equiv \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}$$

Misiak et al, ’07; Lunghi & Matias, ’07; Kagan & Neubert, ‘99

Benzke, Lee, Neubert, Paz, ‘11

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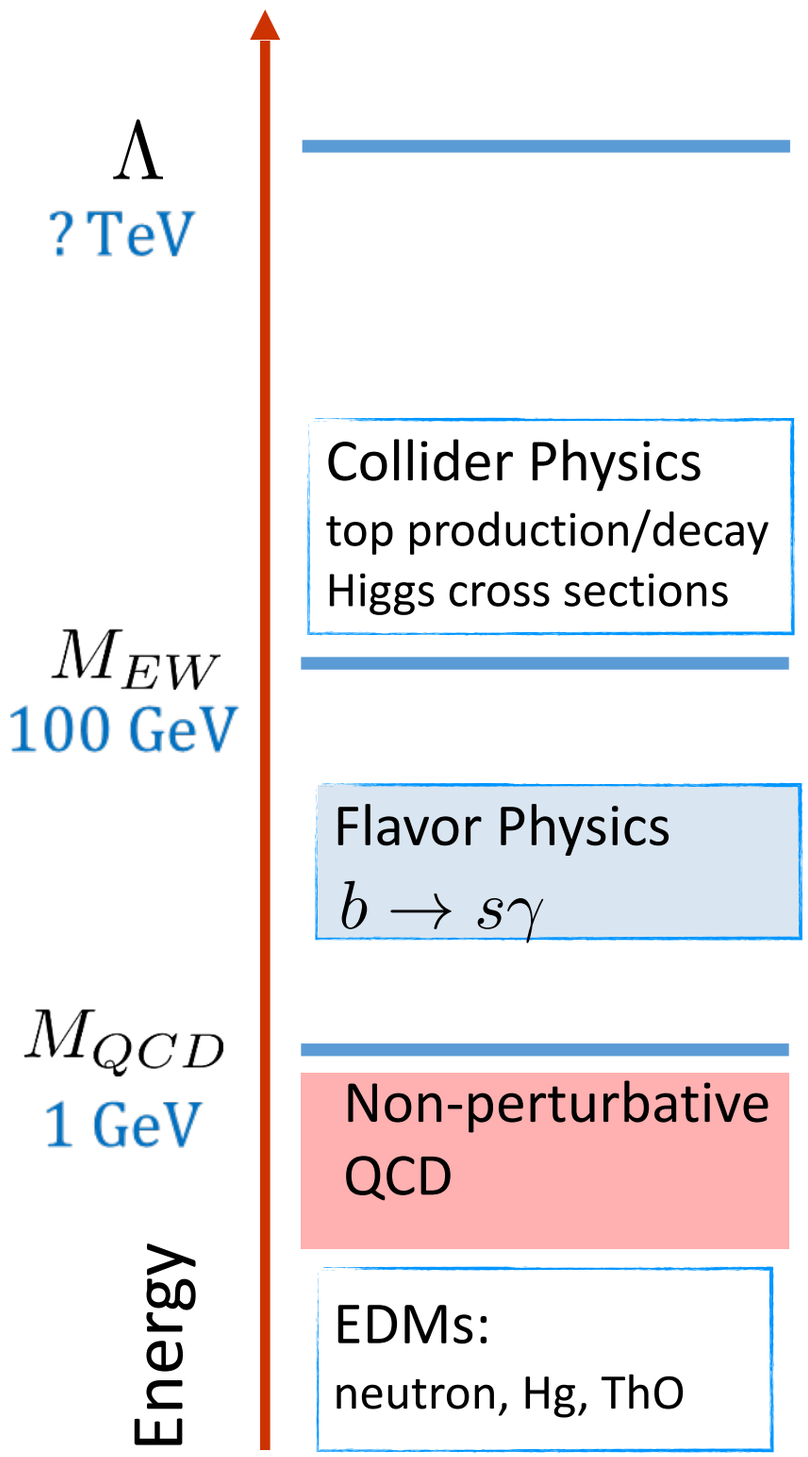

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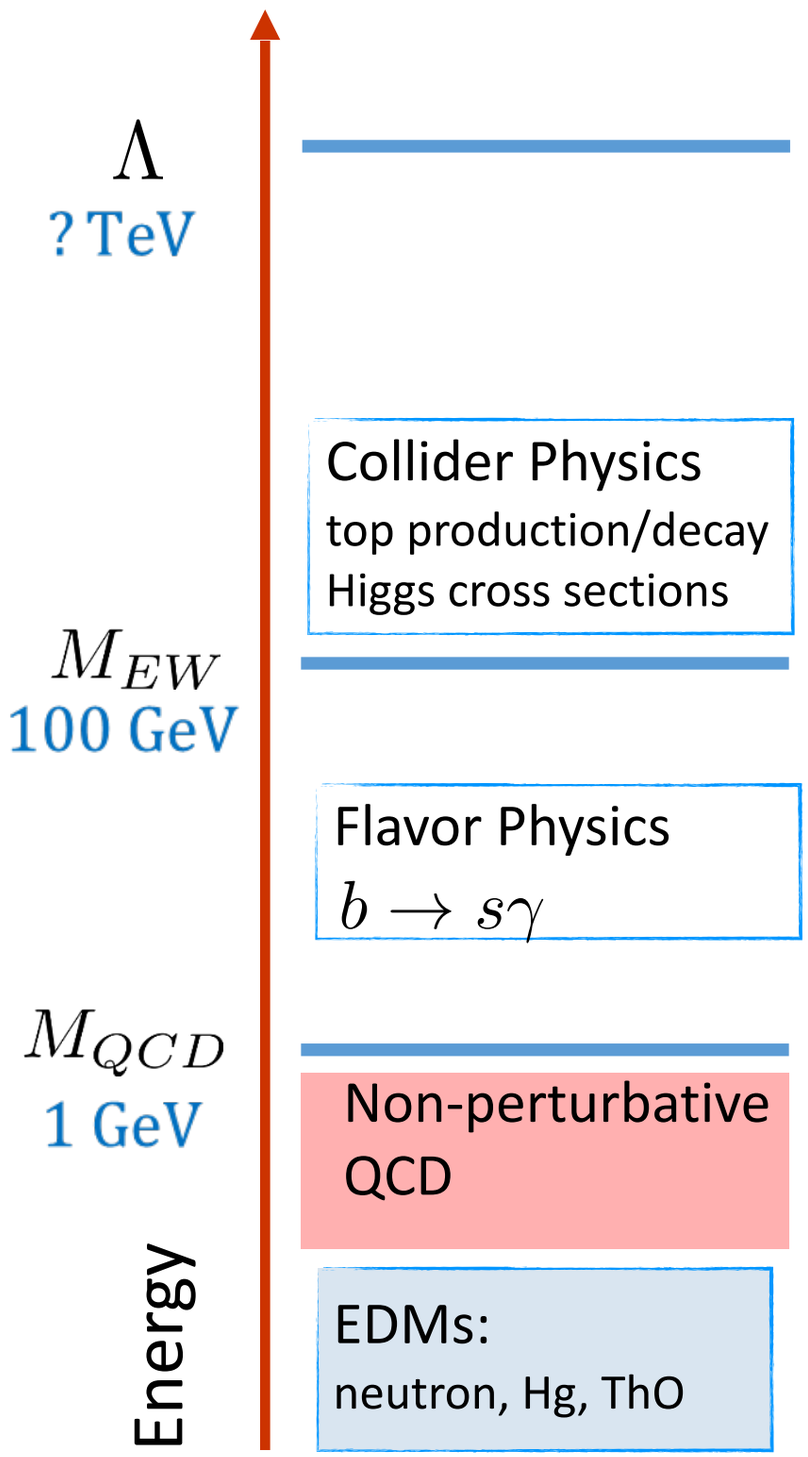
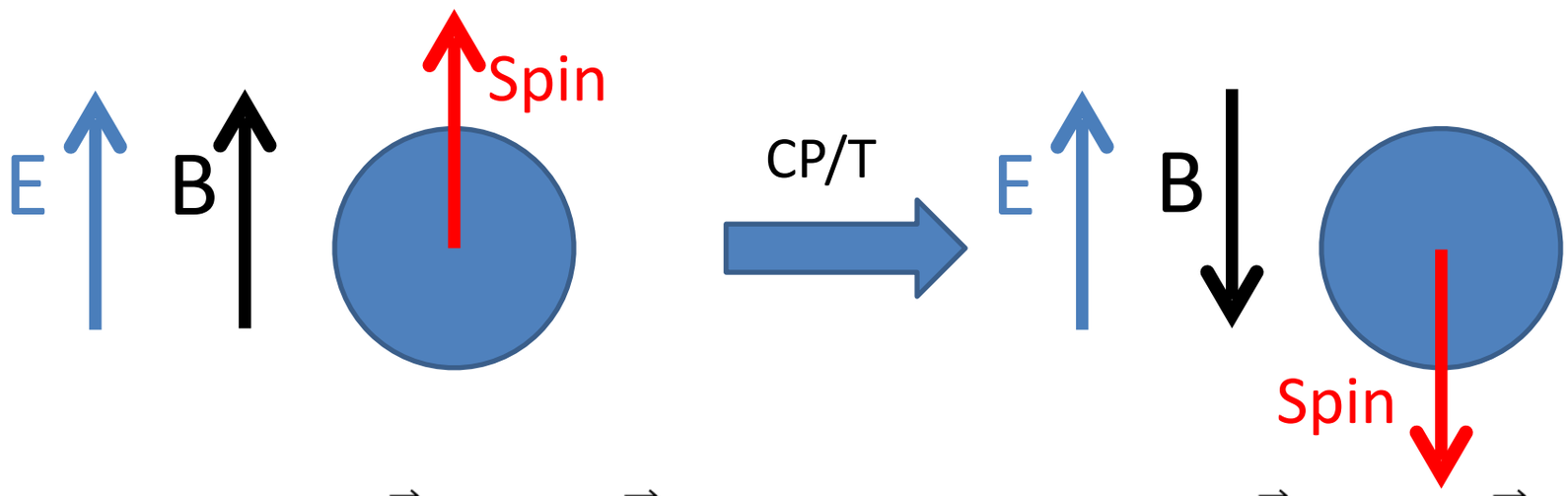


RG evolution

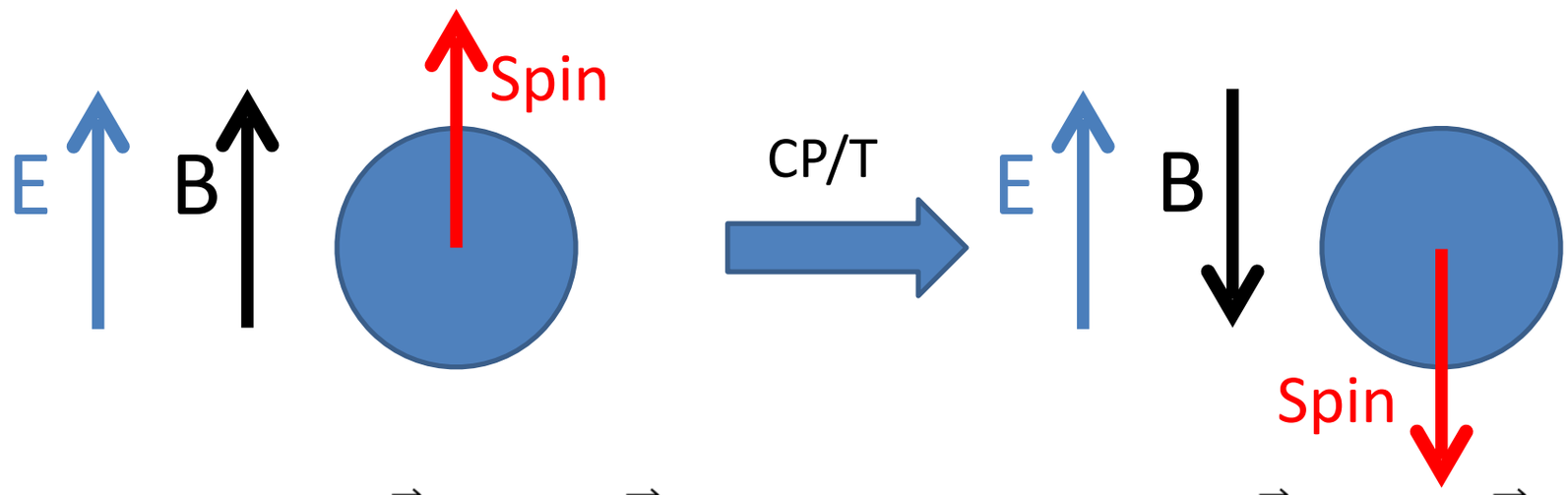
Electric Dipole Moments



$$H = -\,d\,\vec{\sigma}\cdot\vec{E} - \mu\,\vec{\sigma}\cdot\vec{B}$$

$$H = +\,d\,\vec{\sigma}\cdot\vec{E} - \mu\,\vec{\sigma}\cdot\vec{B}$$

Electric Dipole Moments



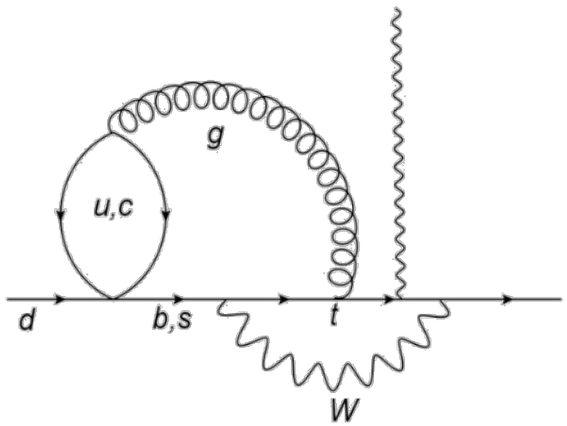
$$H = -\,d\,\vec{\sigma}\cdot\vec{E} - \mu\,\vec{\sigma}\cdot\vec{B} \qquad H = +\,d\,\vec{\sigma}\cdot\vec{E} - \mu\,\vec{\sigma}\cdot\vec{B}$$

Current limits

Limits (e cm)	neutron	mercury	ThO
Current	2.9×10^{-26} Baker et al, '06	7.4×10^{-30} Graner et al, '16	8.7×10^{-29} ACME collaboration, '14
Expected	10^{-28}		5.0×10^{-30}

Electric Dipole Moments

- Negligible SM contribution
  - E.g. $d_n^{\mathrm{SM}} \sim 10^{-31} - 10^{-33}\, e\,\mathrm{cm}$



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Khriplovich, Zhitnitsky; '82; McKellar et al. '87; Engel, Ramsey-Musolf, van Kolck, '13

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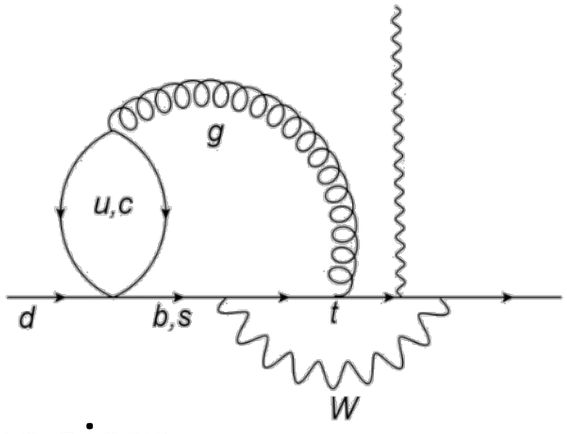

- At least when assuming a Peccei-Quinn mechanism

$$\propto \theta \epsilon^{\alpha\beta\mu\nu} G^a_{\mu\nu} G^a_{\alpha\beta}$$

Current limits

Limits (e cm)	neutron	mercury	ThO
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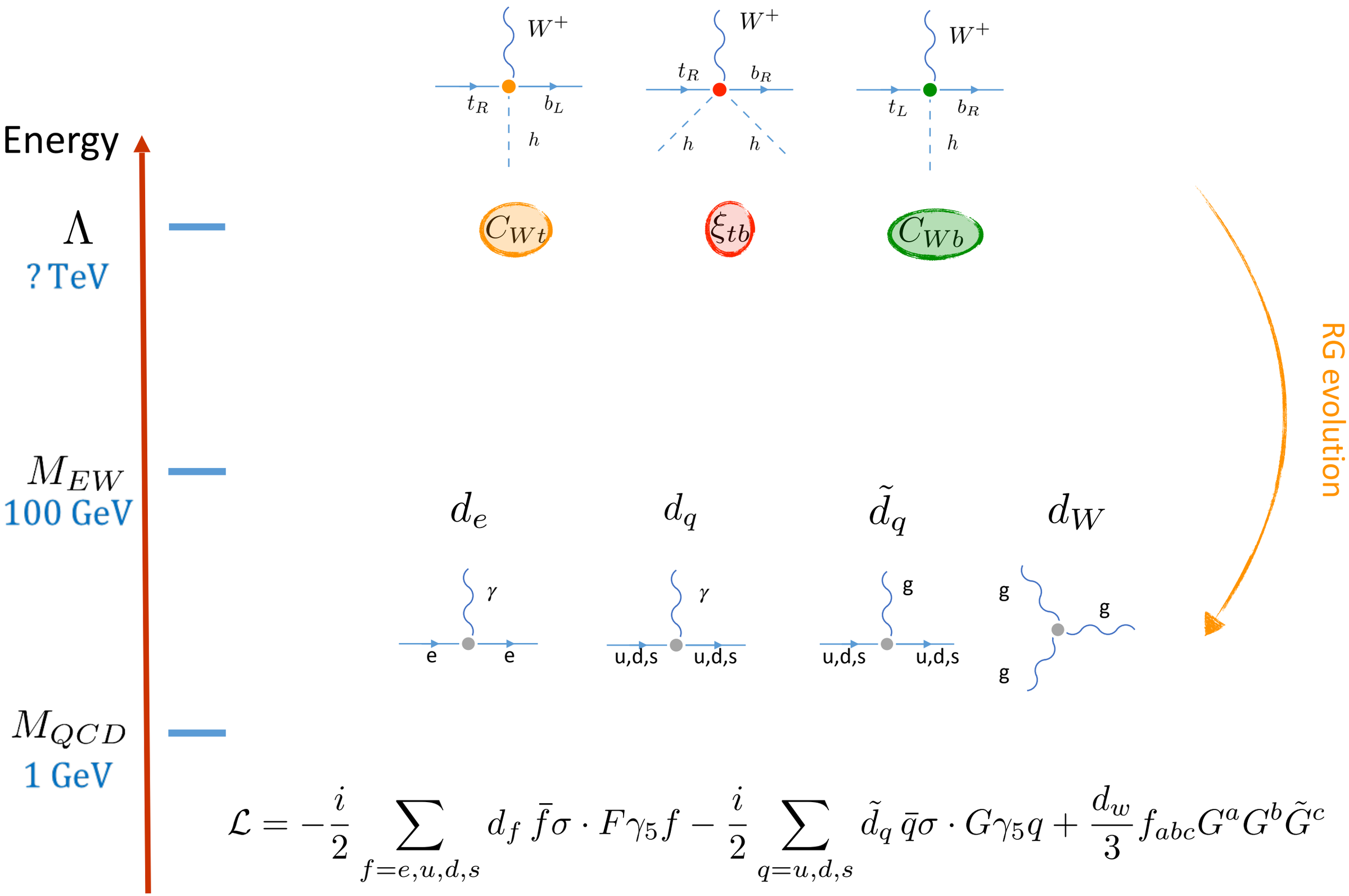
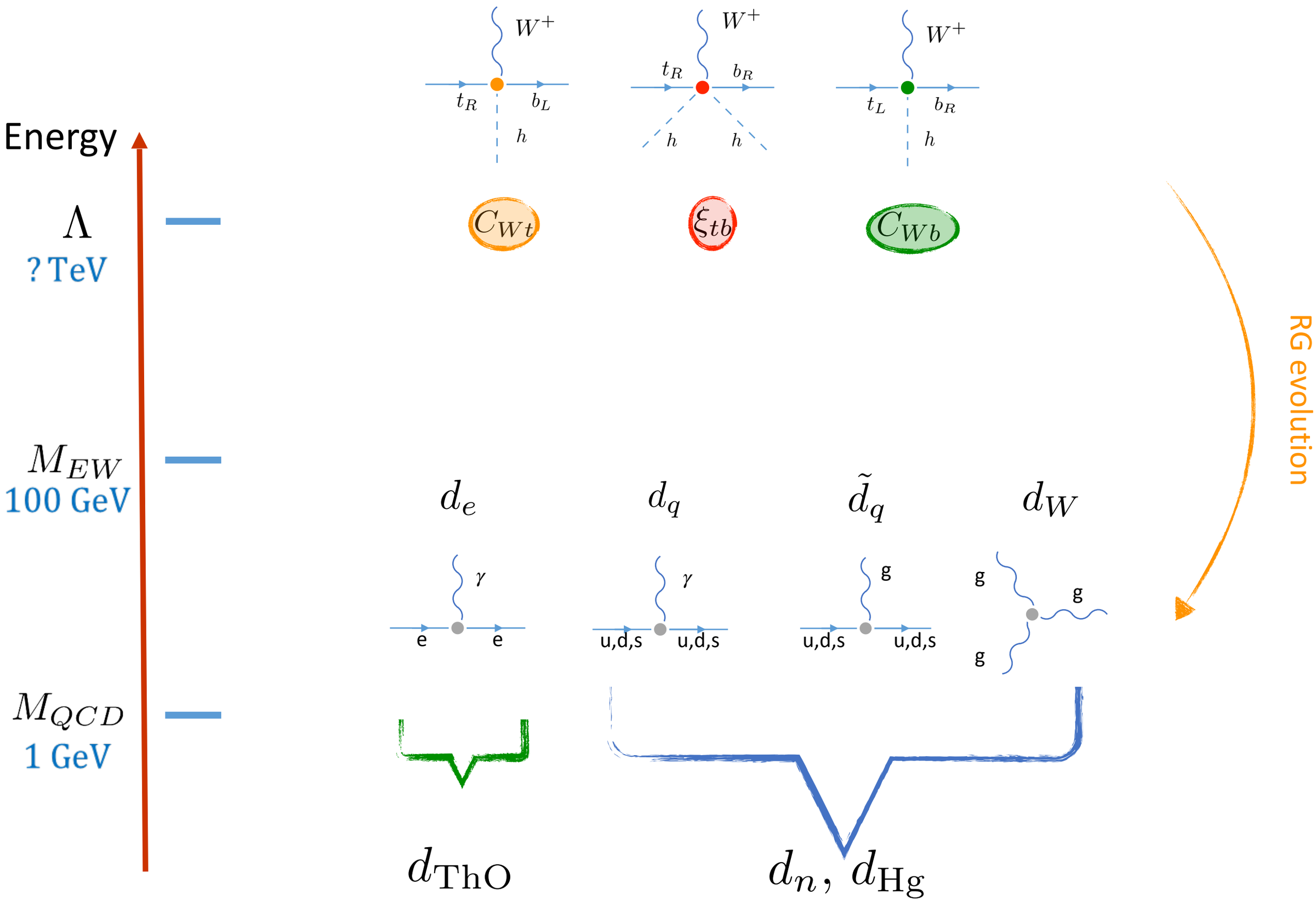
Connection to low-energy Lagrangian



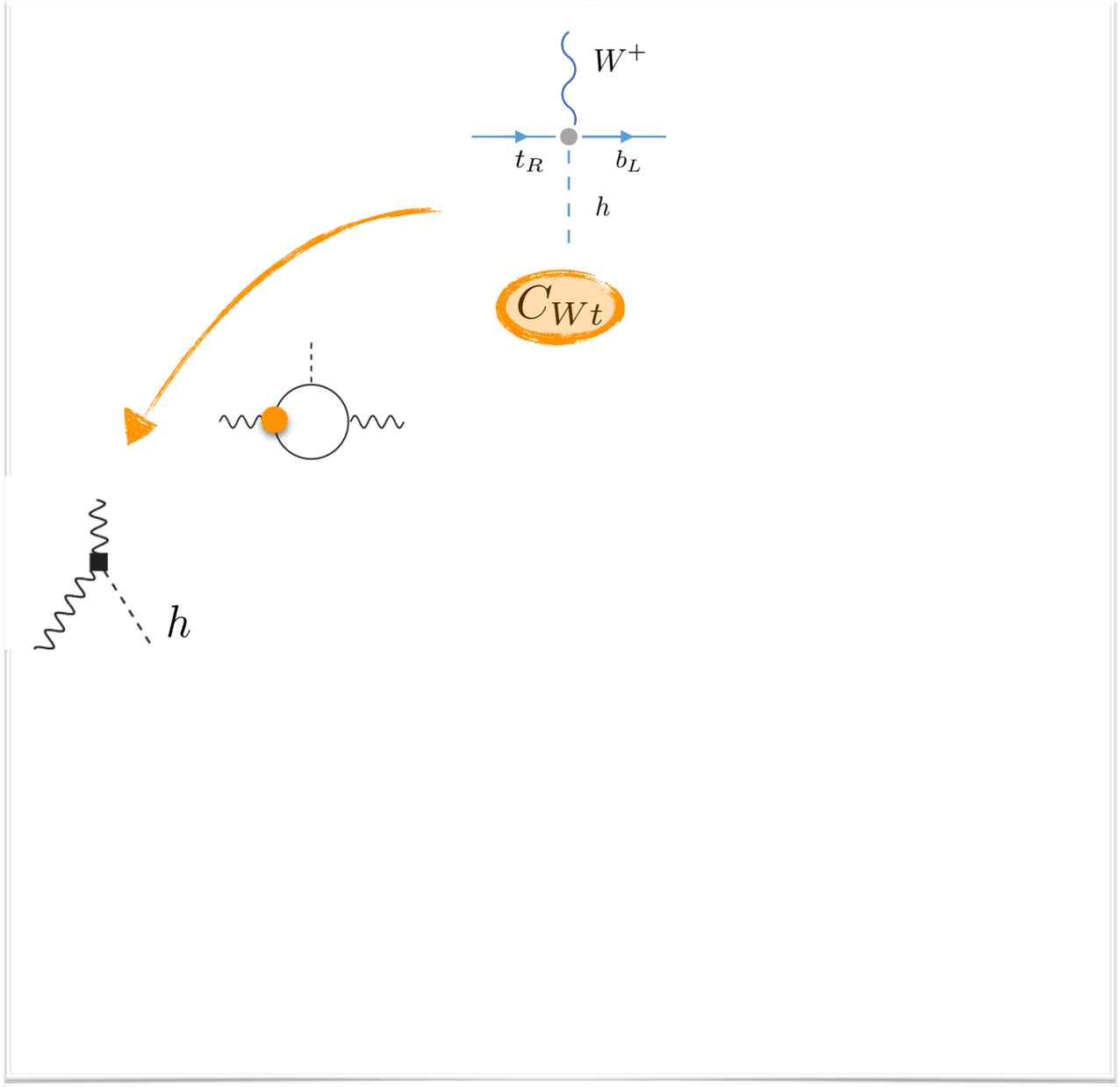
$$\mathcal{L} = -\frac{i}{2}\sum_{f=e,u,d,s} d_f\, \bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s} \tilde{d}_q\, \bar{q}\sigma\cdot G\gamma_5 q + \frac{d_w}{3} f_{abc} G^a G^b \tilde{G}^c$$

Connection to low-energy Lagrangian



Connection to low-energy Lagrangian

Two-loop contribution



Cirigliano, de Vries, Mereghetti, WD, ’16; Ramsey-Musolf, Fuyuto, ‘17

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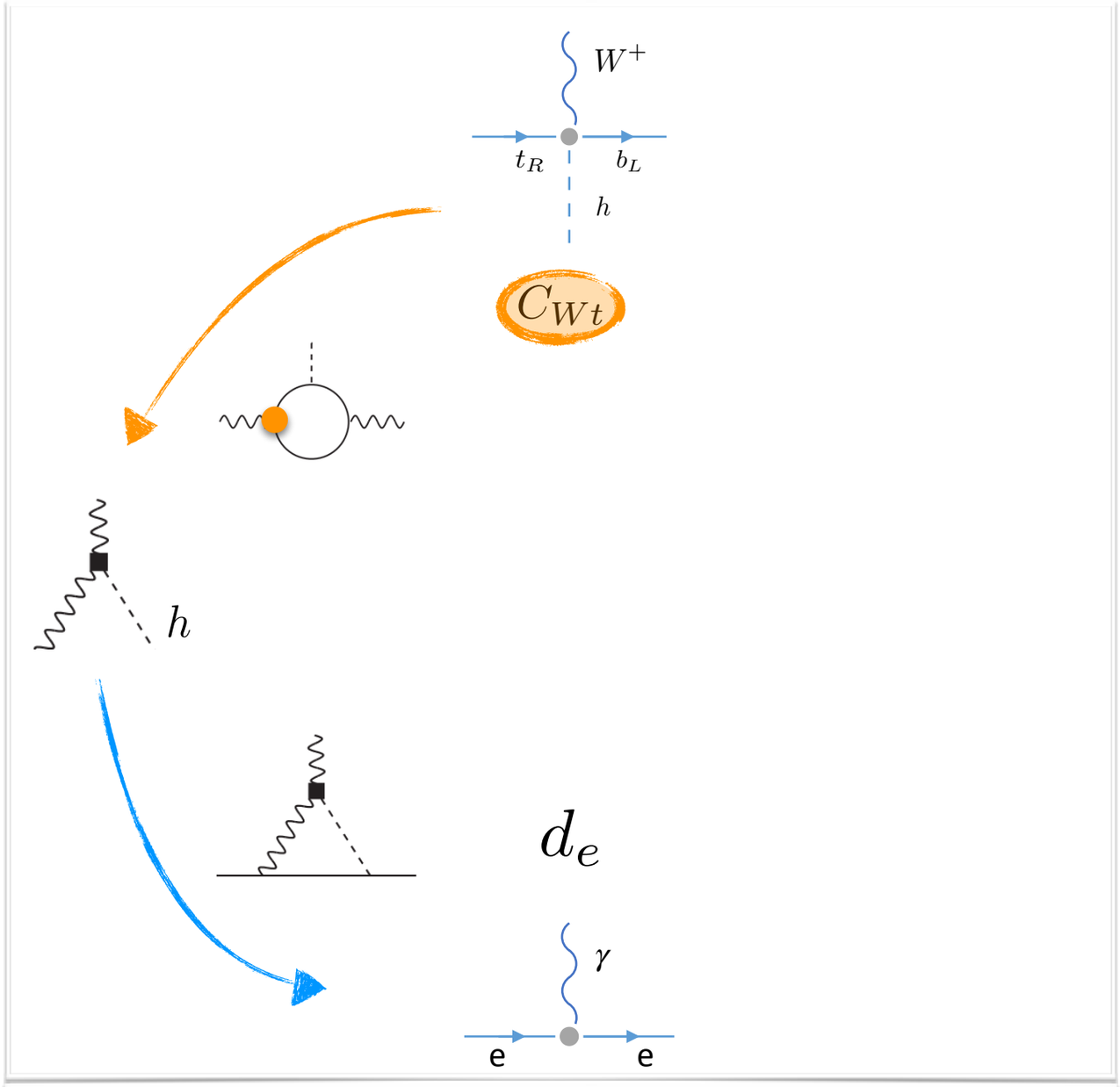

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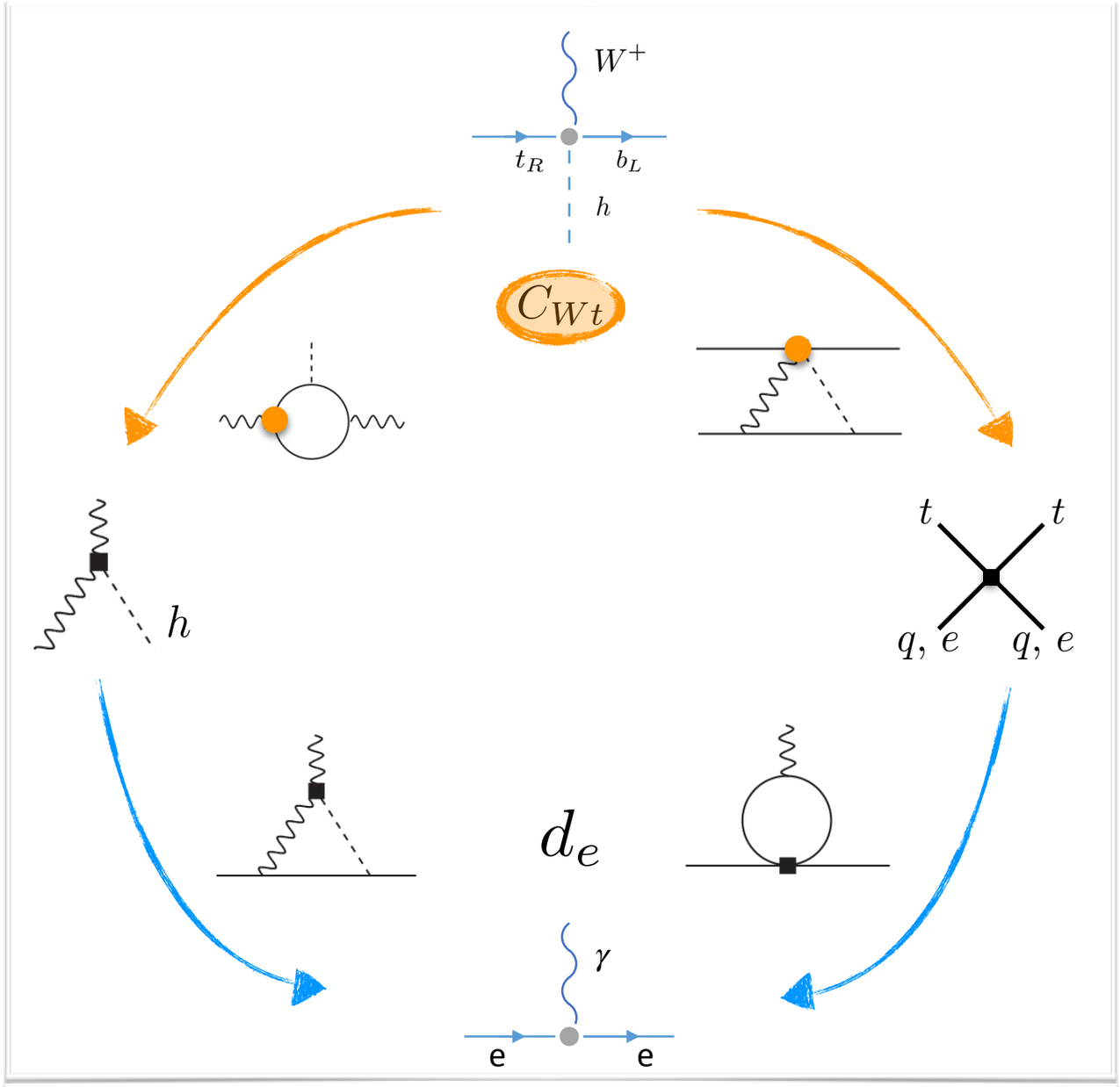

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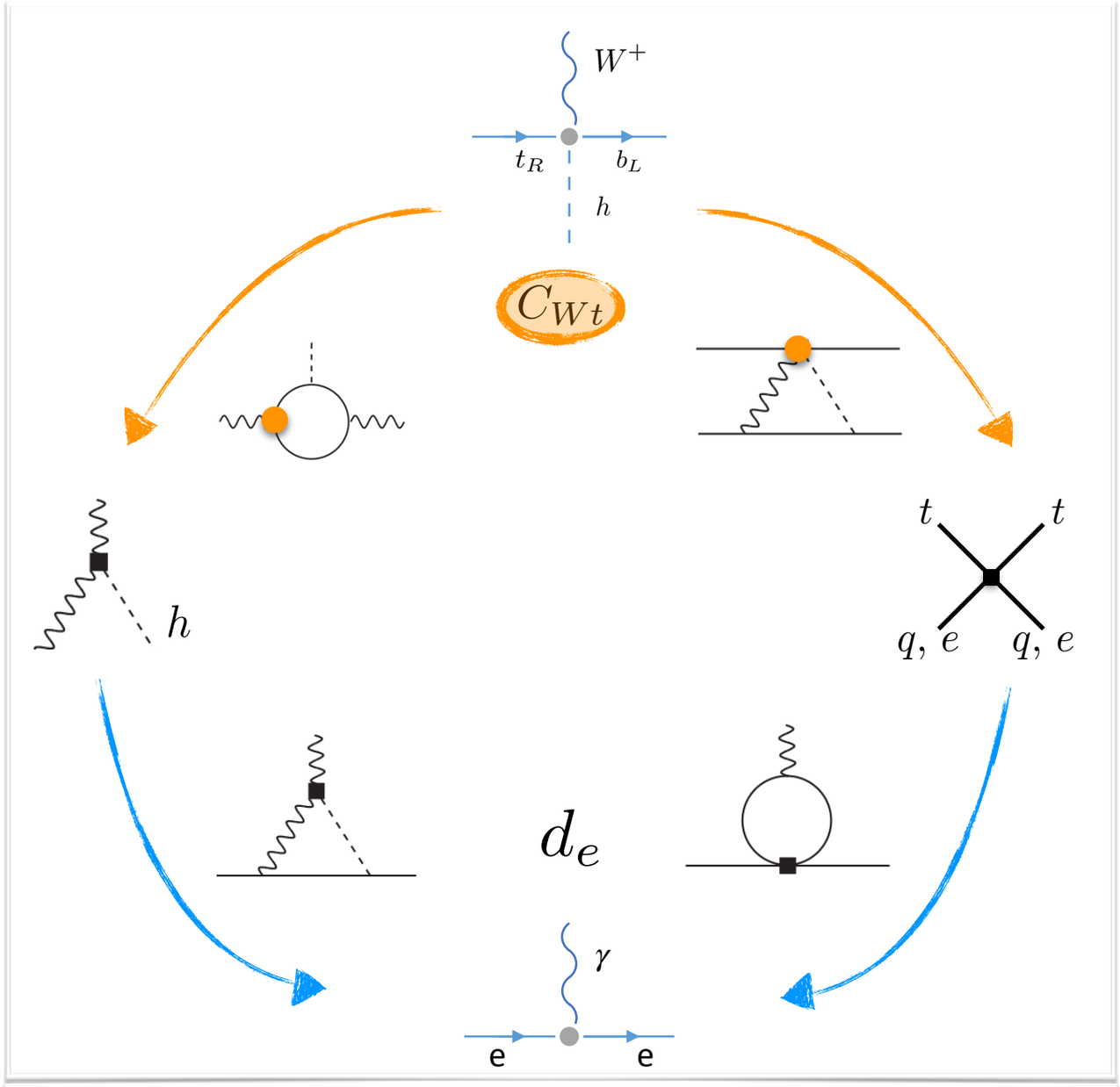
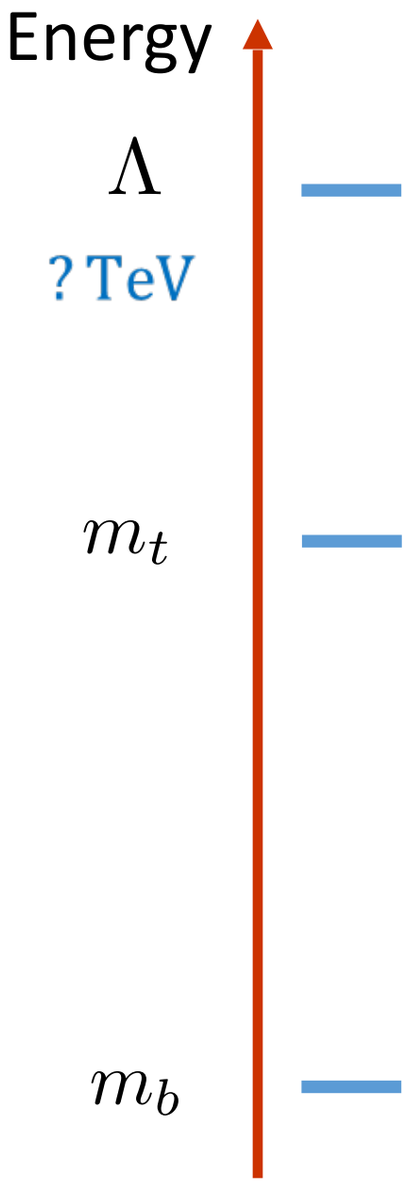
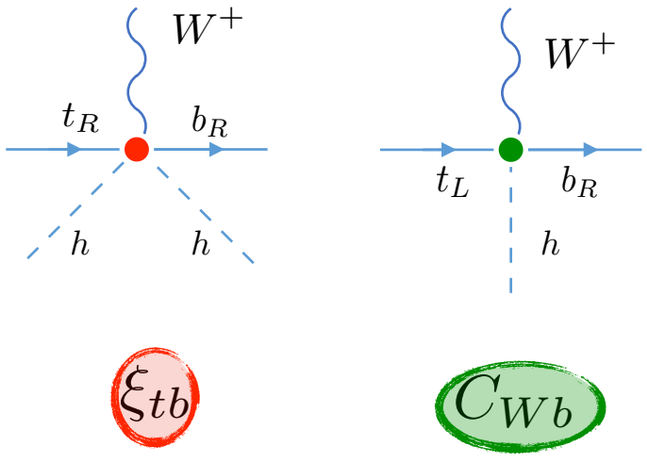


$$d_e \sim \frac{m_e}{v^2}\frac{\alpha}{4\pi}\frac{1}{(4\pi)^2}C_{Wt}$$

Cirigliano, de Vries, Mereghetti, WD, ’16; Ramsey-Musolf, Fuyuto, ‘17

Connection to low-energy Lagrangian





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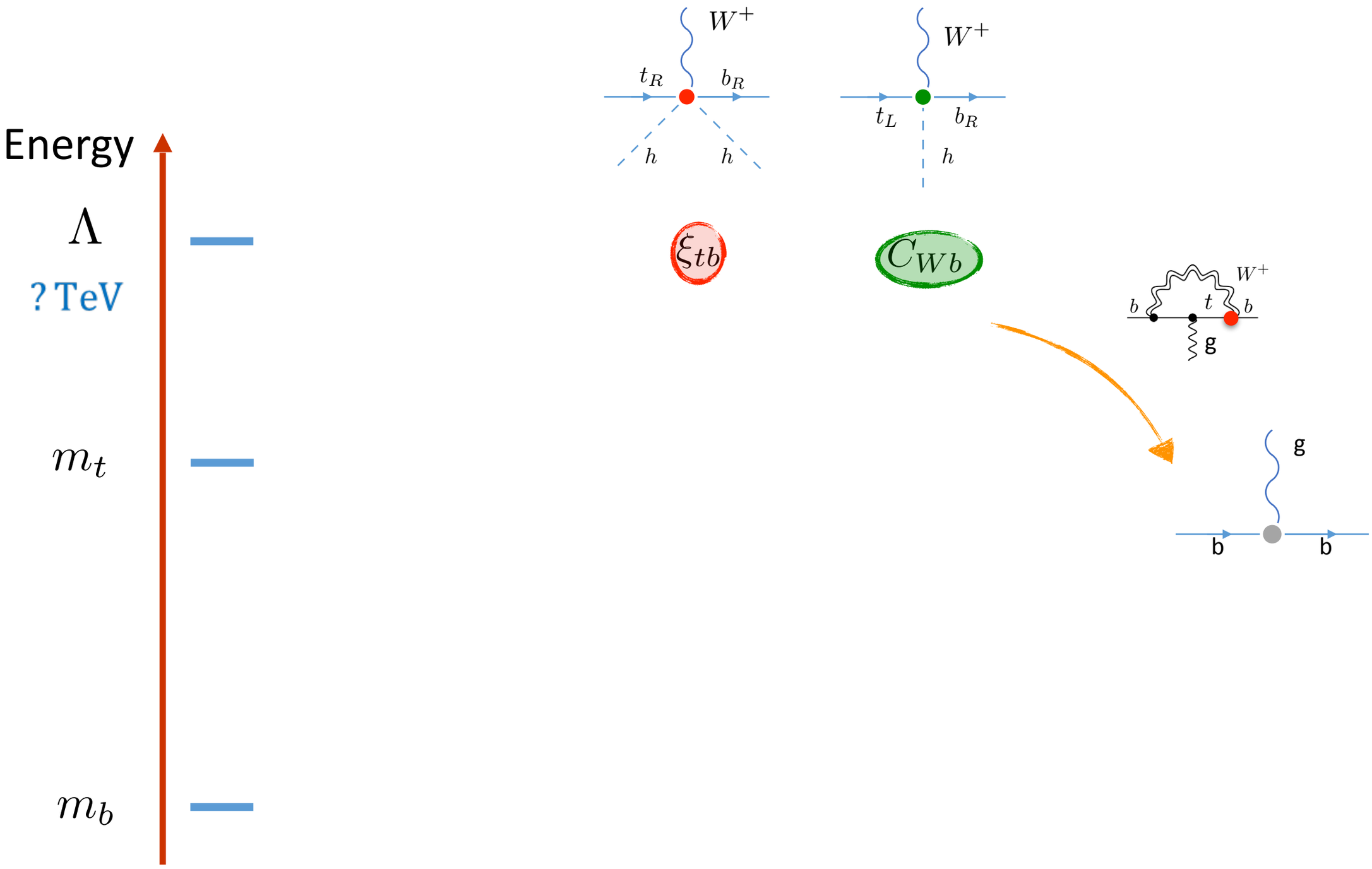
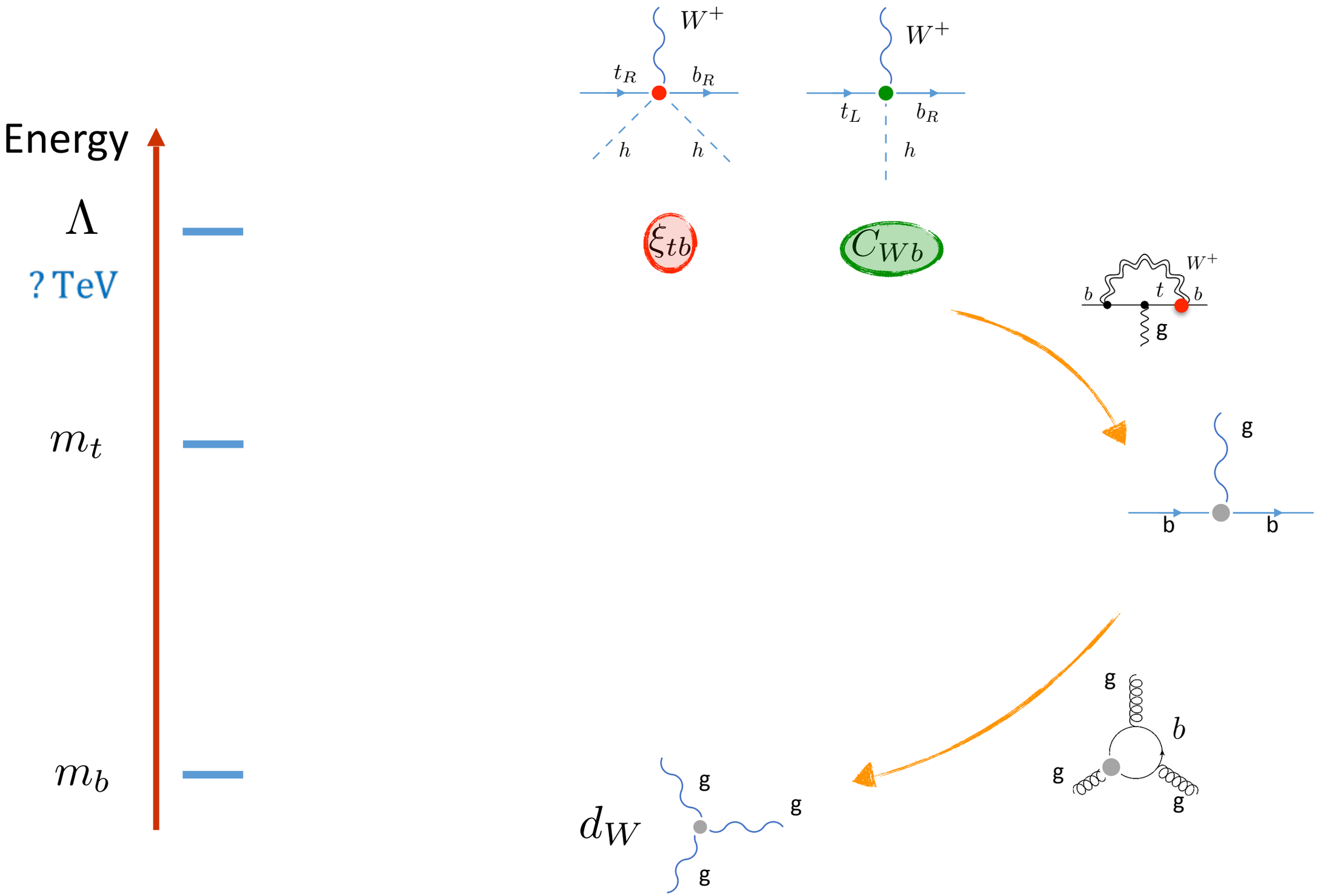
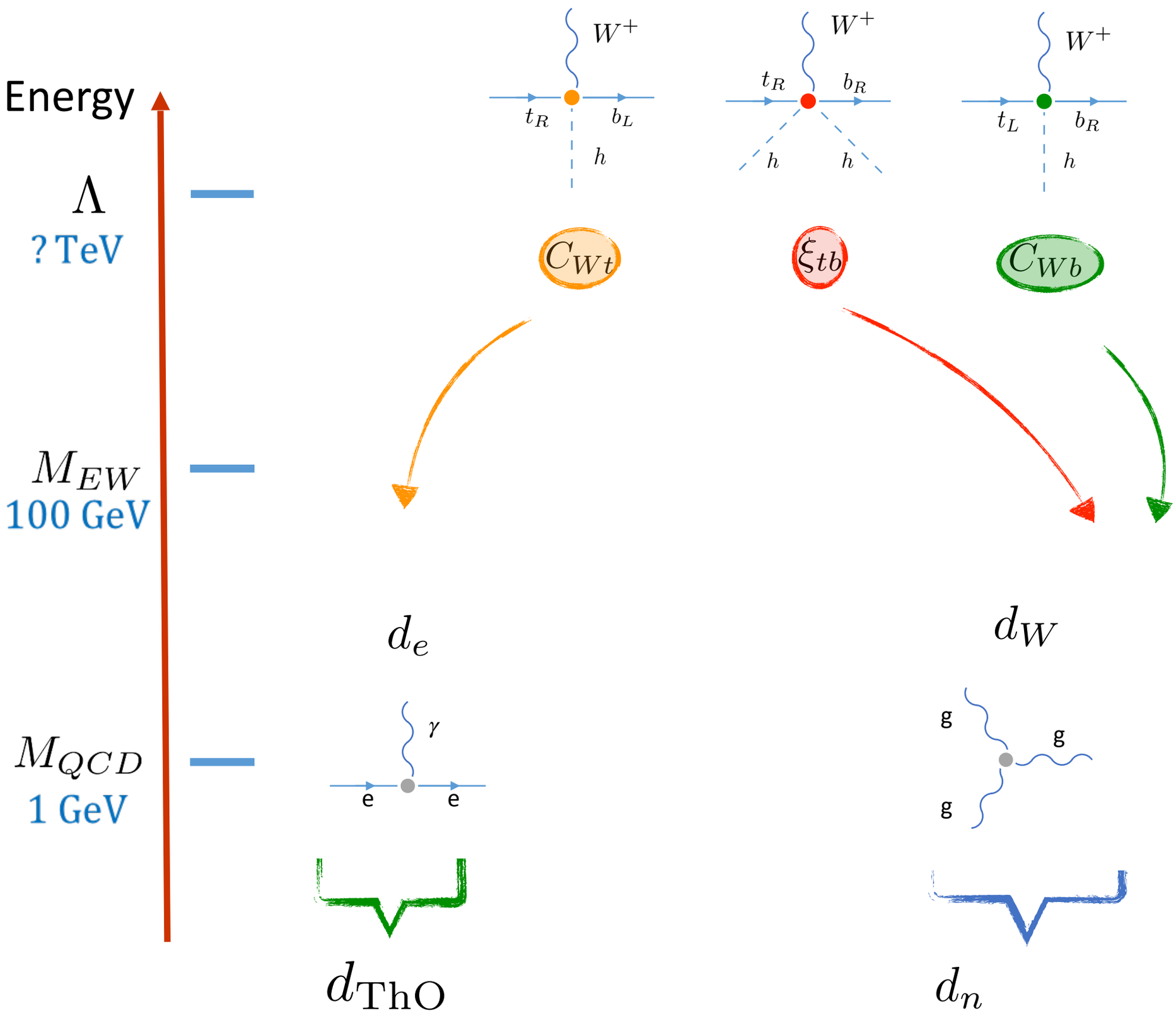


Connection to low-energy Lagrangian

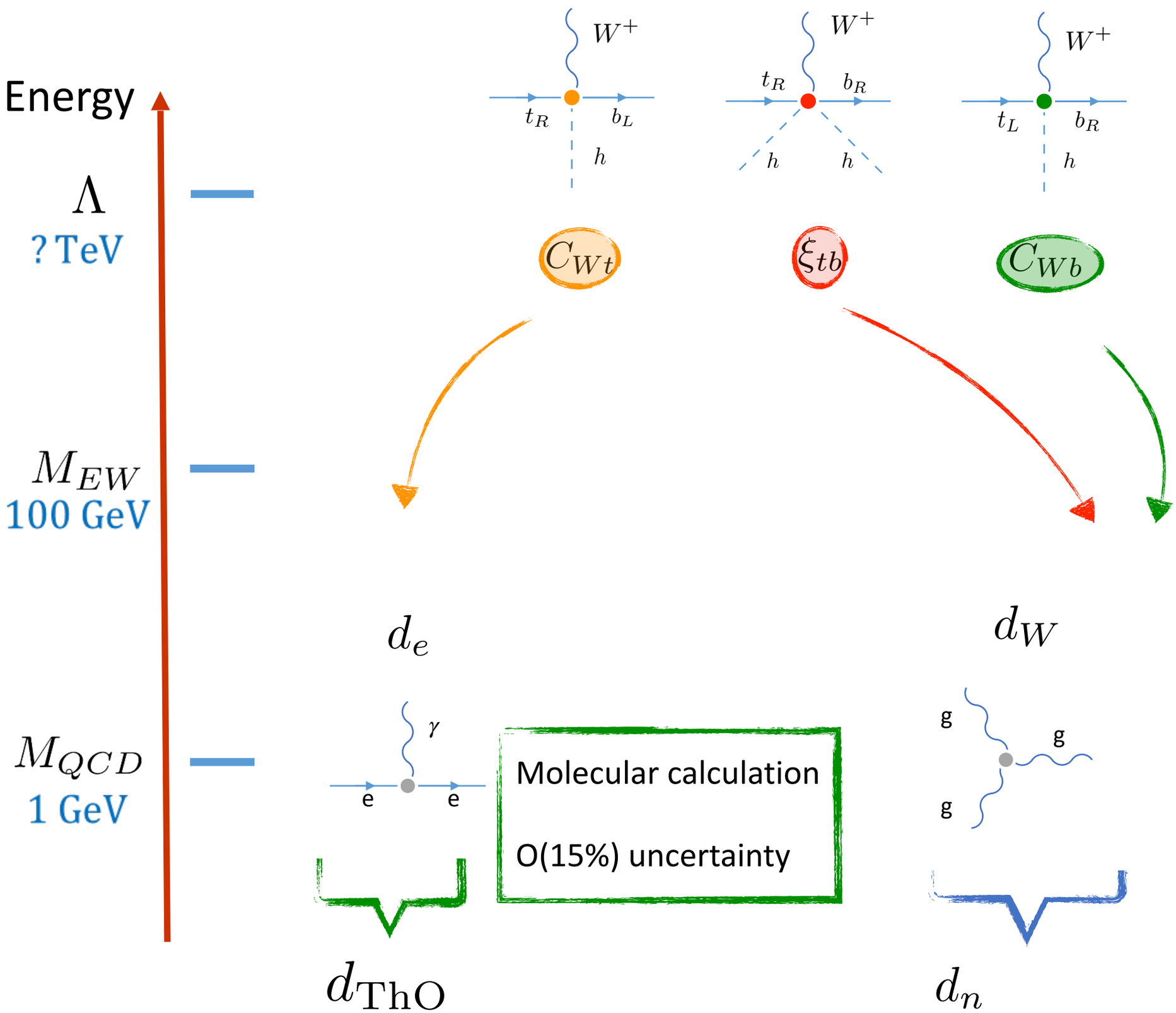


Braaten, Li, Yuan PRL, ’90; Boyd, Gupta, Trivedi, Wise, PLB, ‘90

Connection to low-energy Lagrangian

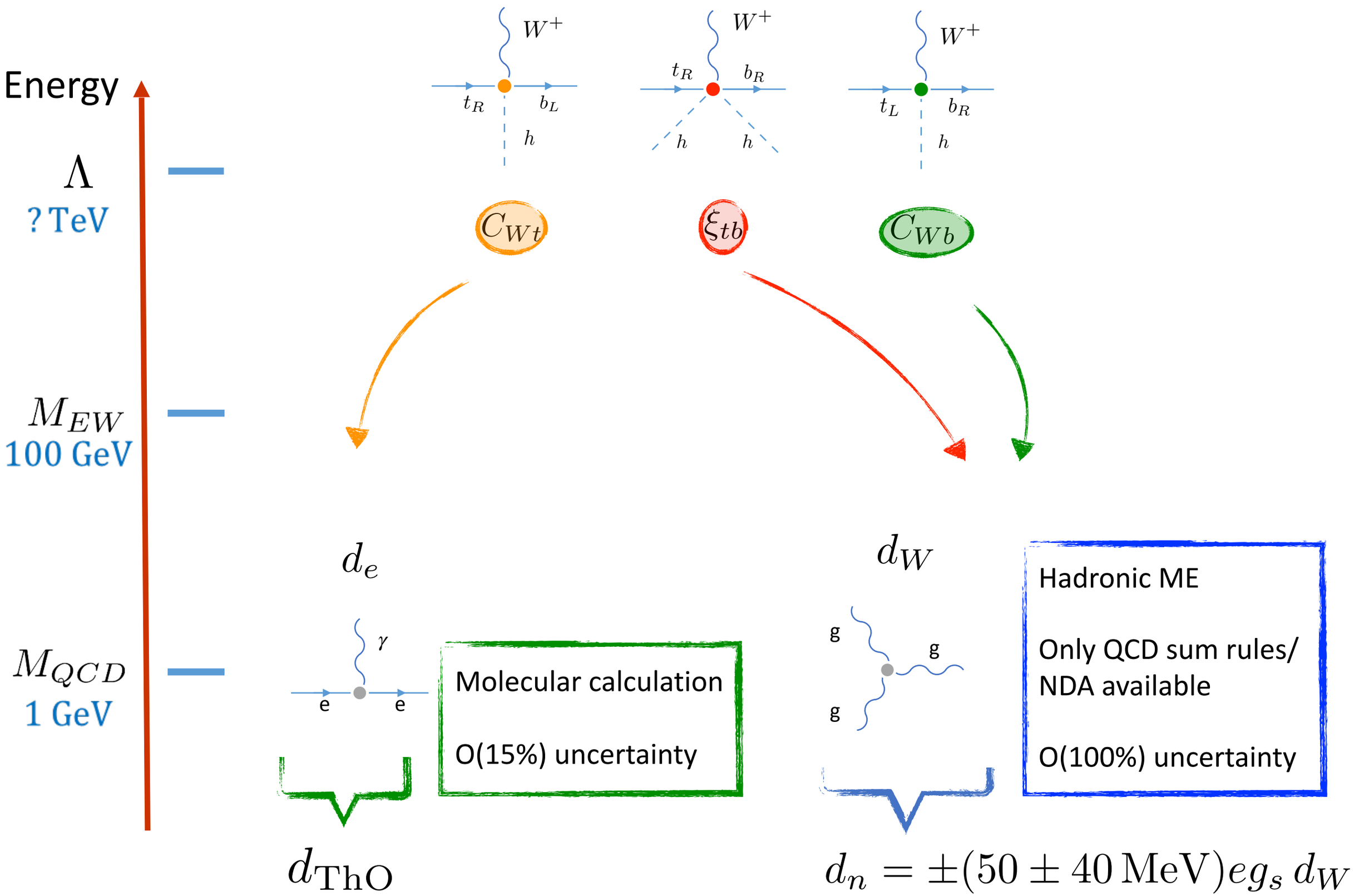


Connection to low-energy Lagrangian



Skripnikov et al, '13; Fleig et al, '14

Connection to low-energy Lagrangian



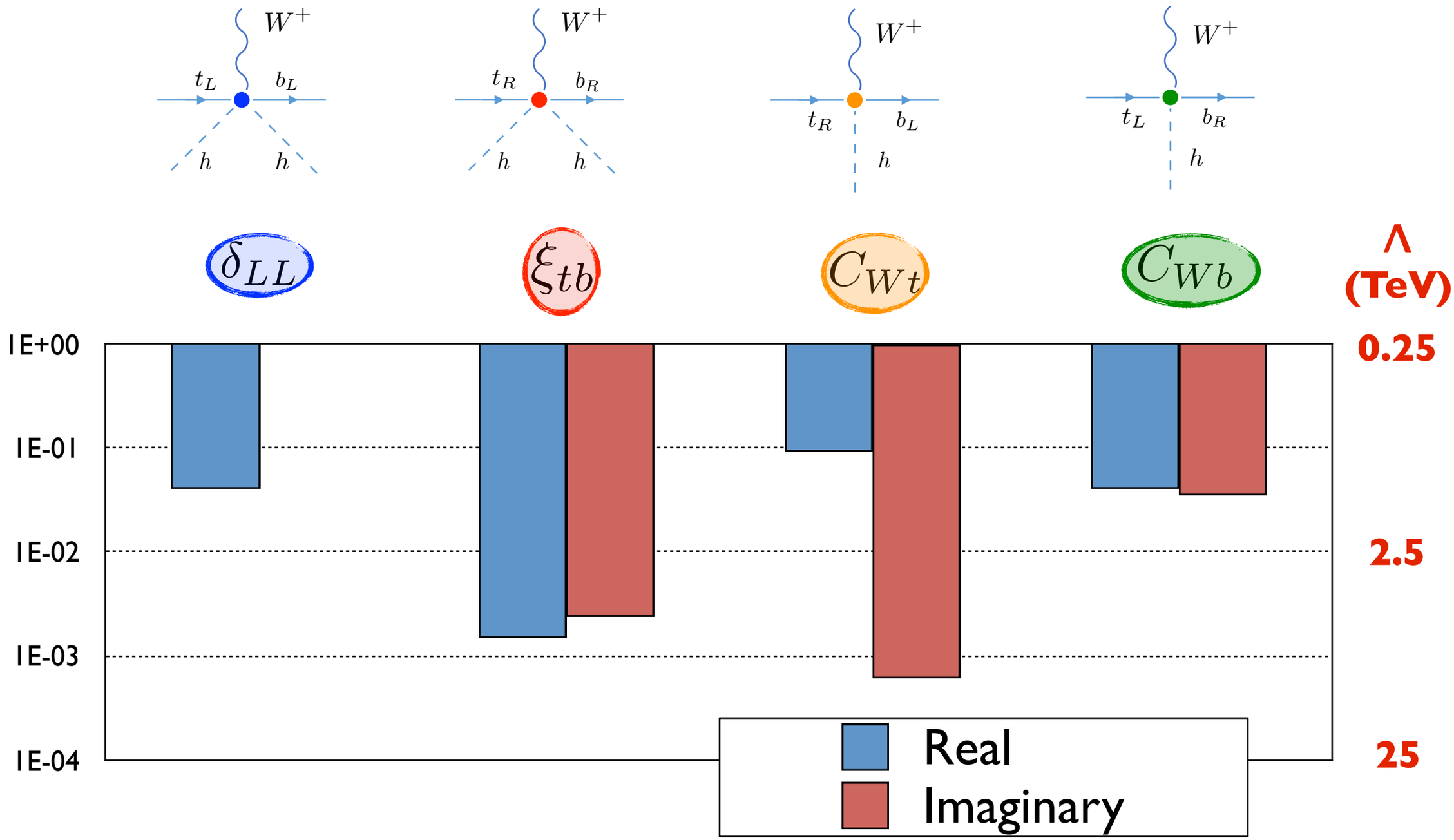
Skripnikov et al, '13; Fleig et al, '14

Demir, Pospelov, Ritz, '03; de Vries et al, '10

Results

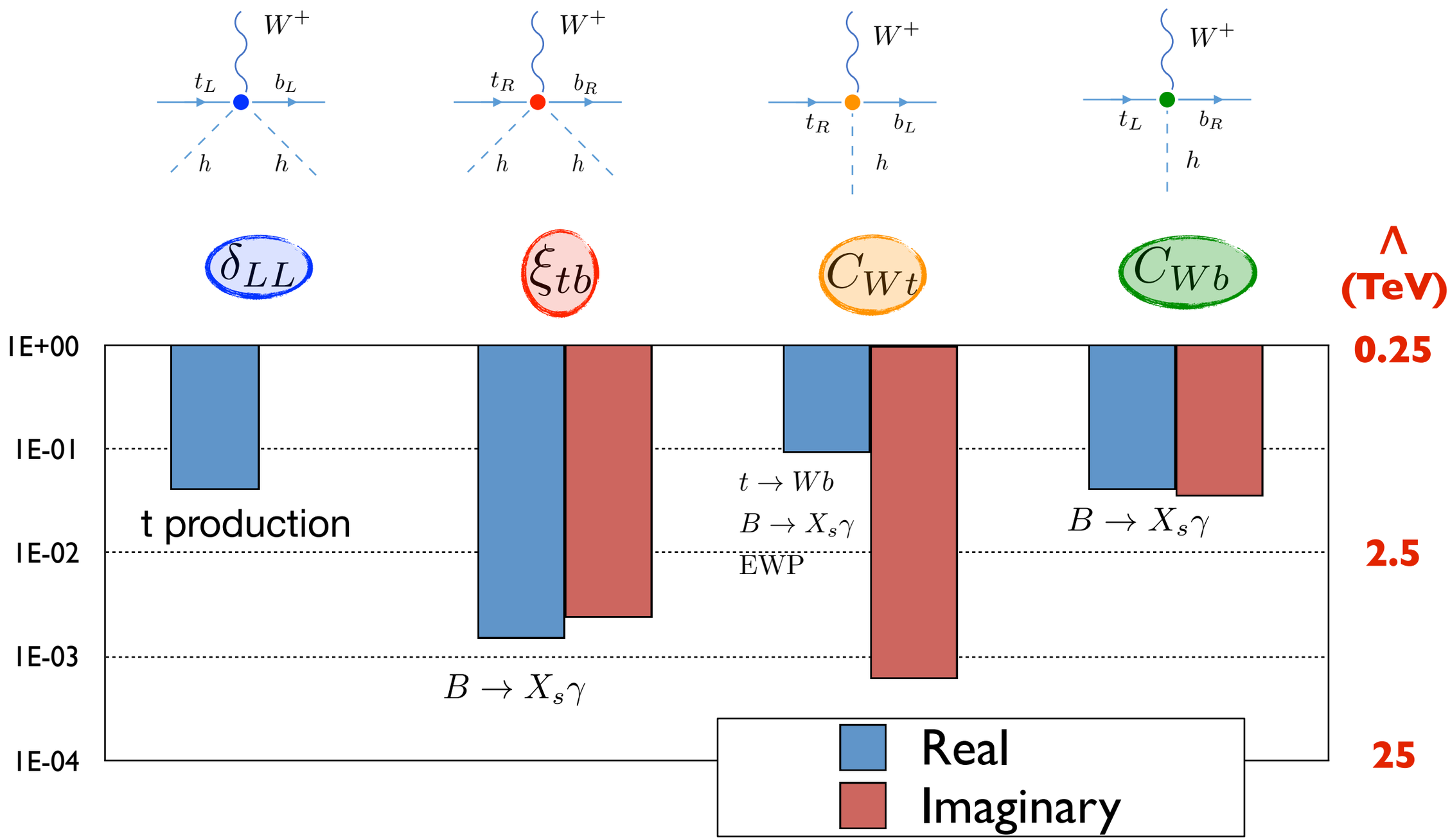
Constraints

One coupling at a time



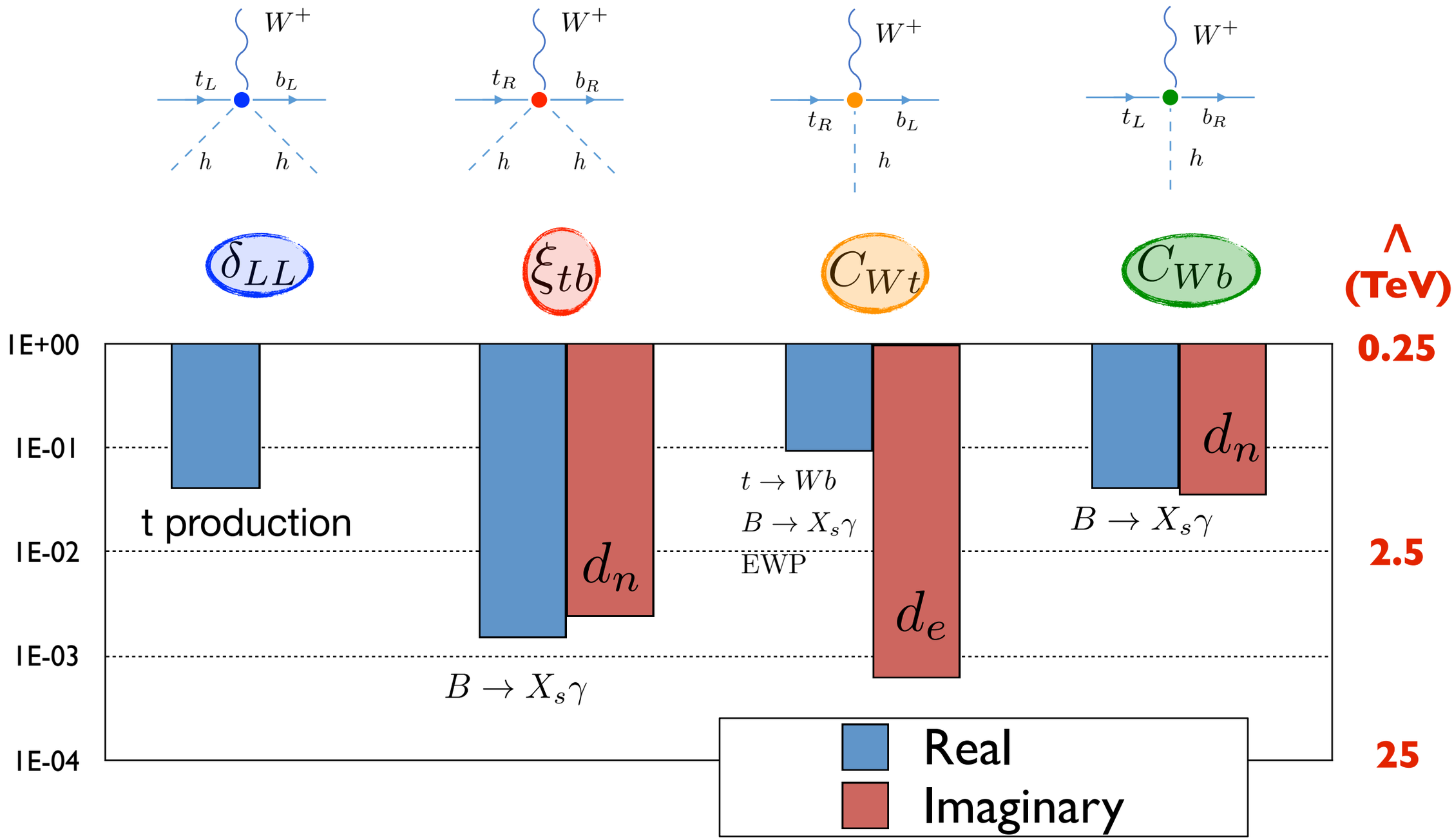
Constraints

One coupling at a time



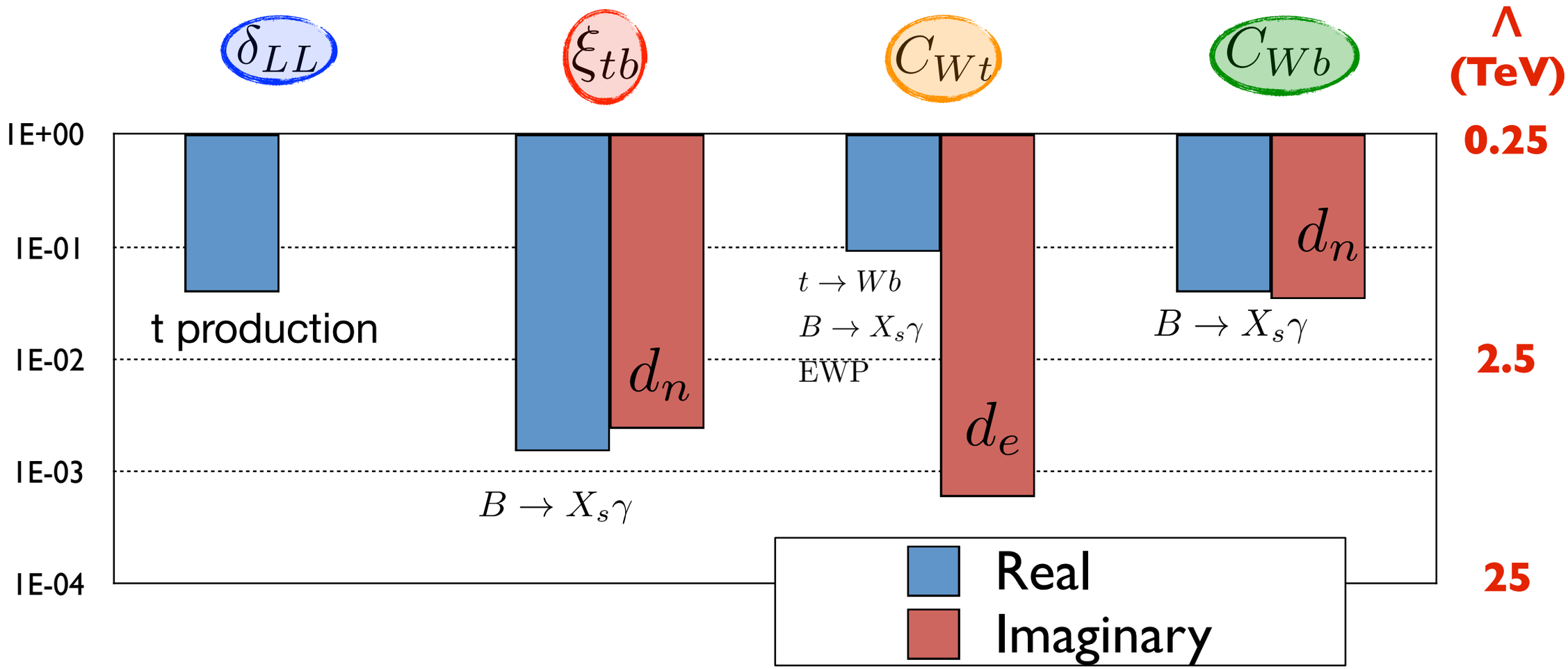
Constraints

One coupling at a time



Constraints

One coupling at a time

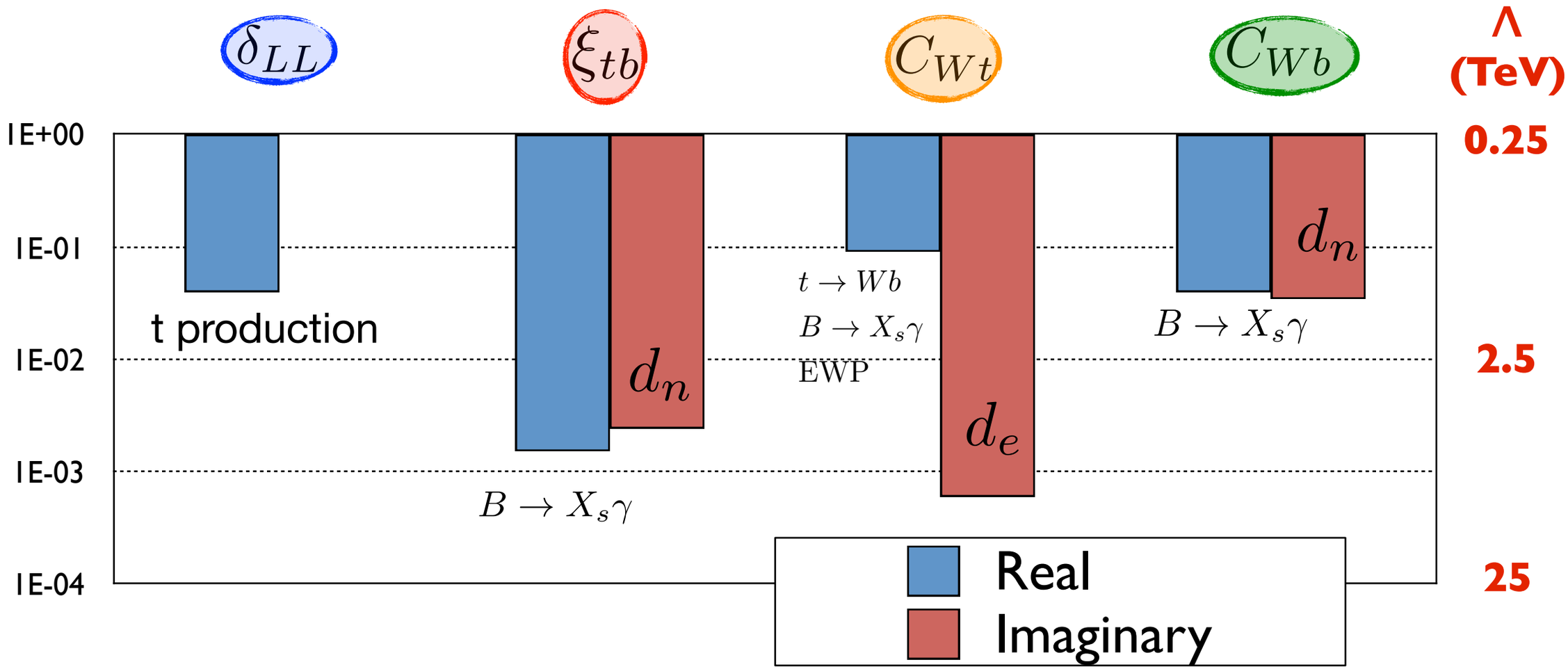


- Top production and $t \to Wb$ already dominant/important for δ_{LL} & C_{Wt} couplings
  - Top cross section uncertainty improves by factor of ~2 at the HL-LHC

Schoenrock, Drueke, Gonzalez, Schwienhorst, '10;

Constraints

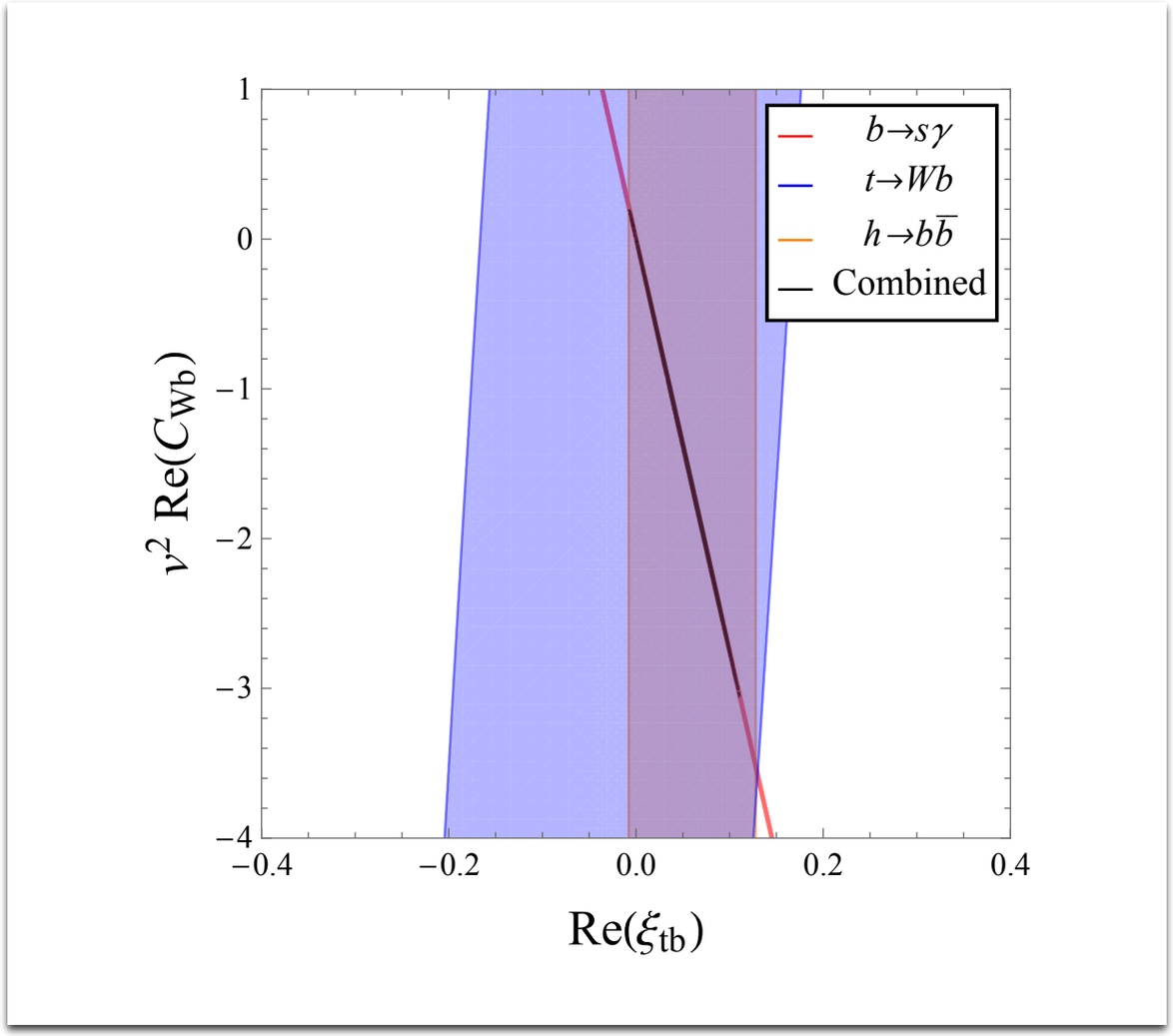
One coupling at a time



- Top production and $t \to Wb$ already dominant/important for δ_{LL} & C_{Wt} couplings
  - Top cross section uncertainty improves by factor of ~2 at the HL-LHC
- Additional measurement become competitive at the HL-LHC
  - $pp \to ttZ$ could probe $C_{Wt} < O(0.1)$

Constraints

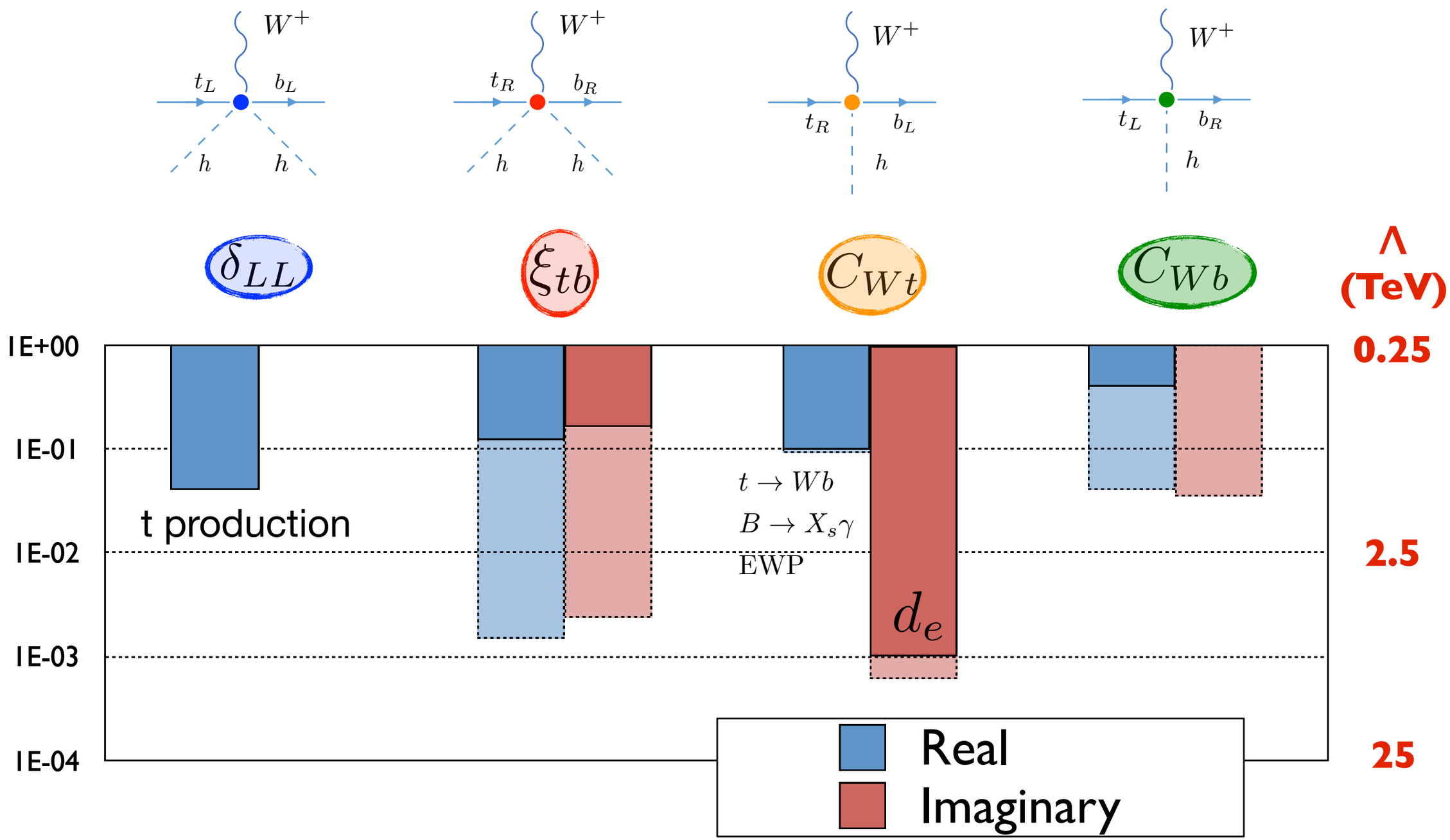
Two couplings at a time



- Indirect probes can be very stringent, but affected by cancellations:
  - E.g. significant cancellations are possible between C_{Wb} and ξ_{tb}
  - Similar cancellations for the imaginary parts

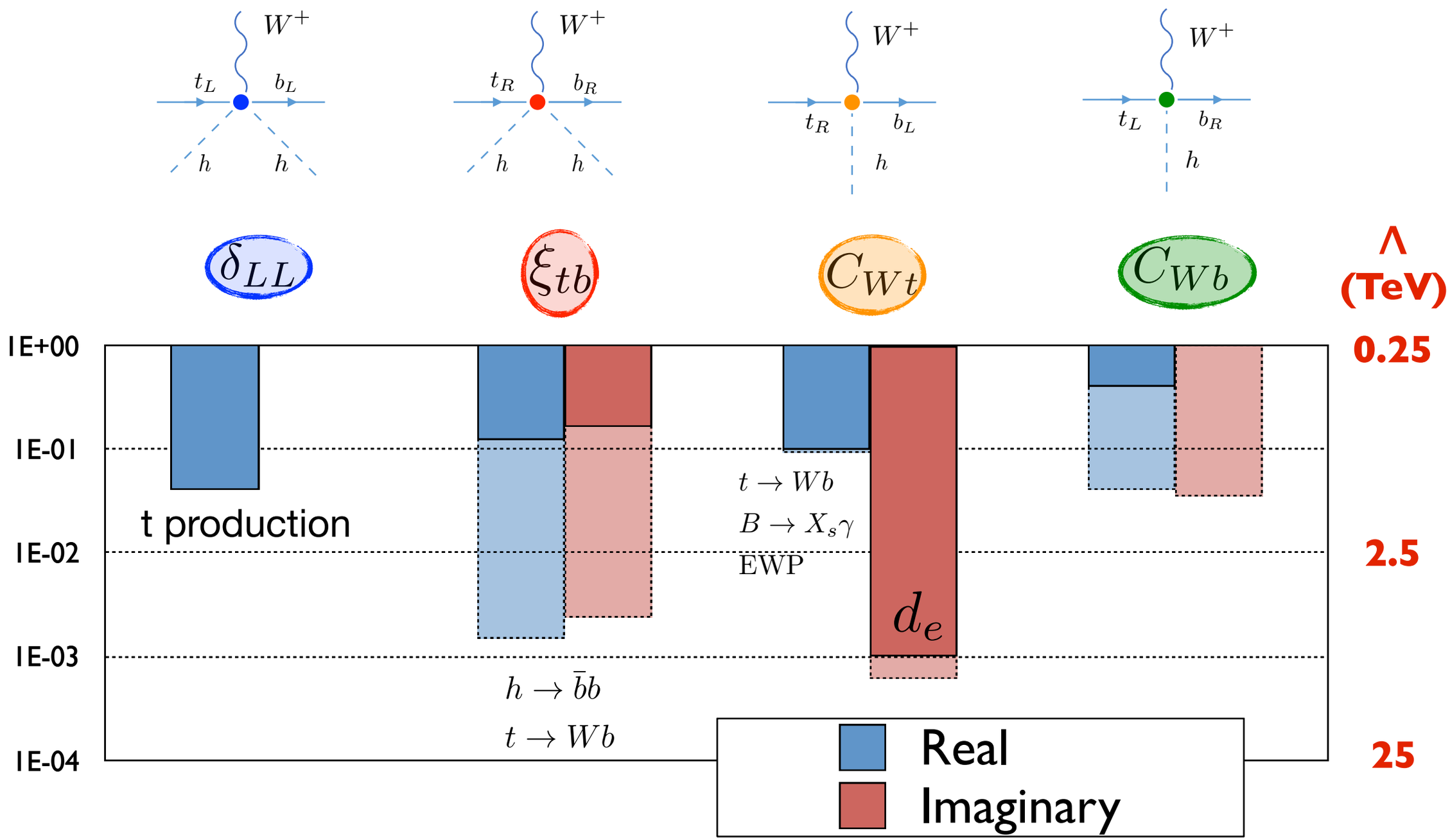
Constraints

Global fit



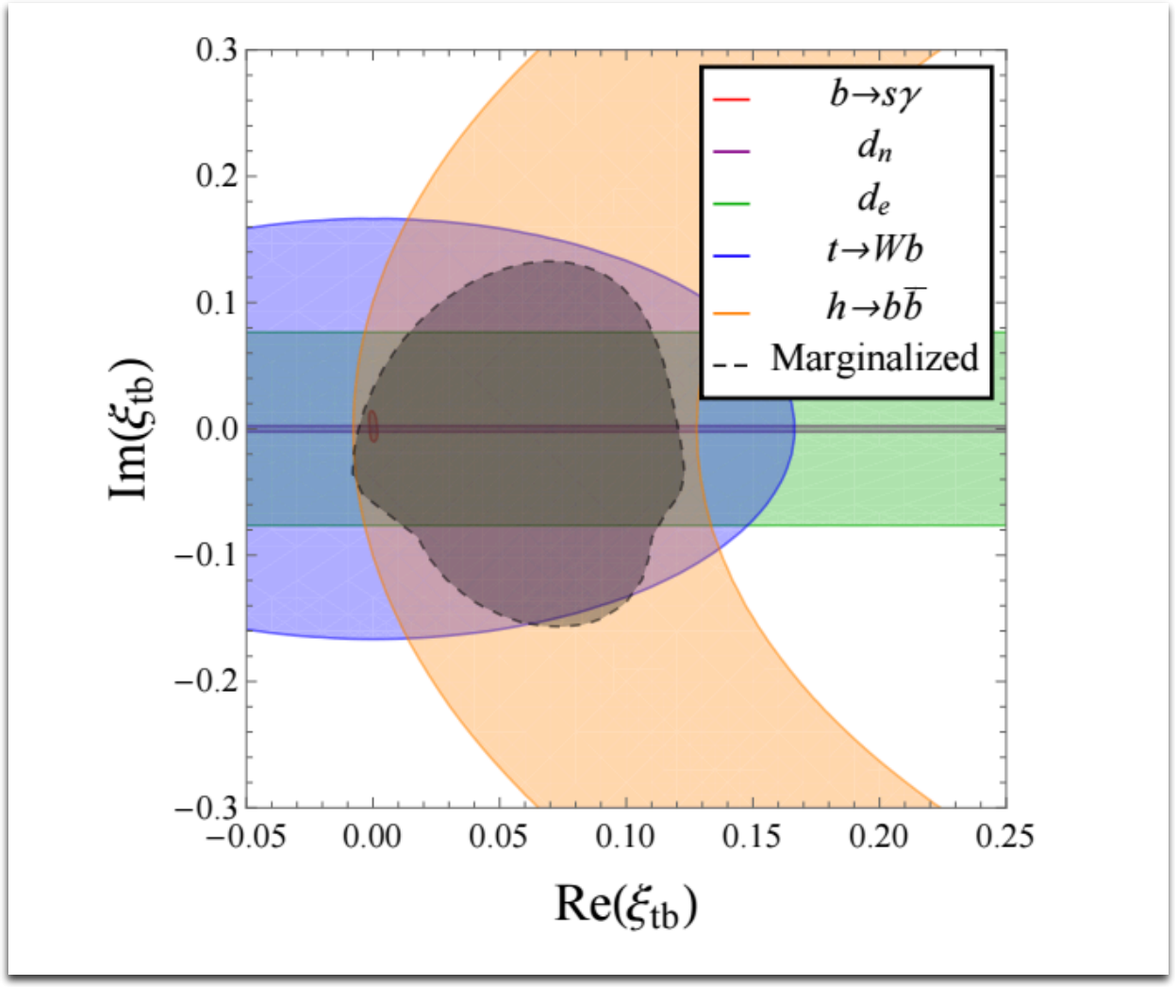
Constraints

Global fit



Constraints

Global fit



- Indirect constraints on ξ_{tb} are significantly weakened
  - Global constraints set by helicity fractions ($t \to Wb$) and Higgs signal strengths ($'h \to bb'$)
- HL-LHC should shrink the allowed region
  - E.g. by measuring $h \to \gamma\gamma$, WW to 5%

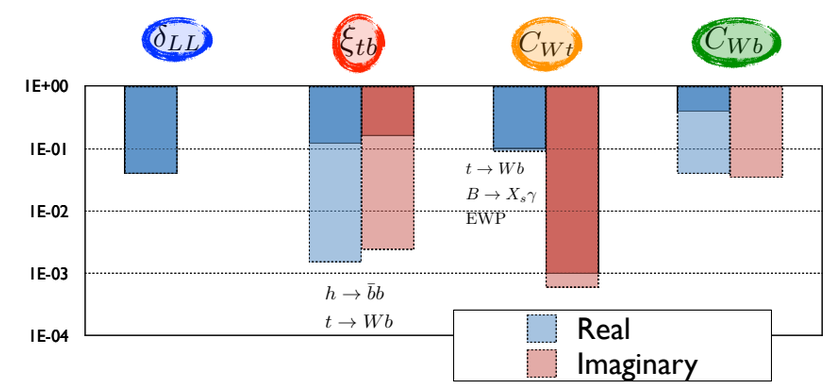
S. Braibant's talk on Wednesday

Summary

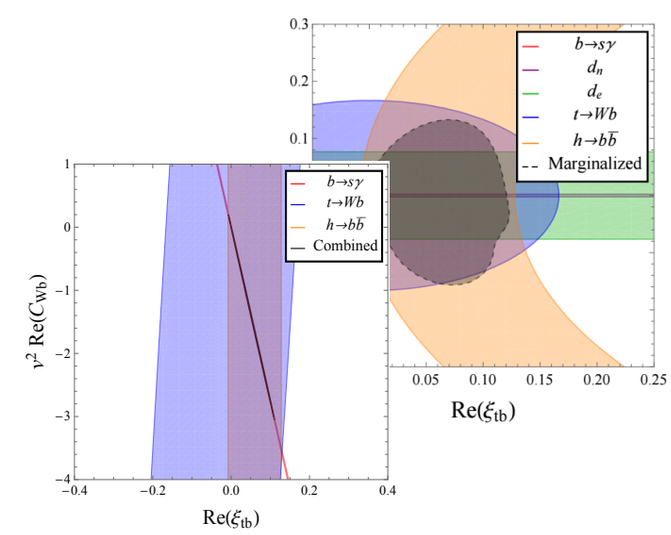
The EFT framework

- Study the Wtb couplings in a model independent fashion
- Systematically take into account high- and low-energy probes

- Interplay between direct and indirect probes
  - E.g.
  - δ_{LL} strongly constrained by top production
  - ξ_{tb} stringently bound by $B \to X_s \gamma$



- Indirect probes can be very stringent, but affected by cancellations
- Bounds are often set by high-energy probes in a global setting



Thank you for your attention!

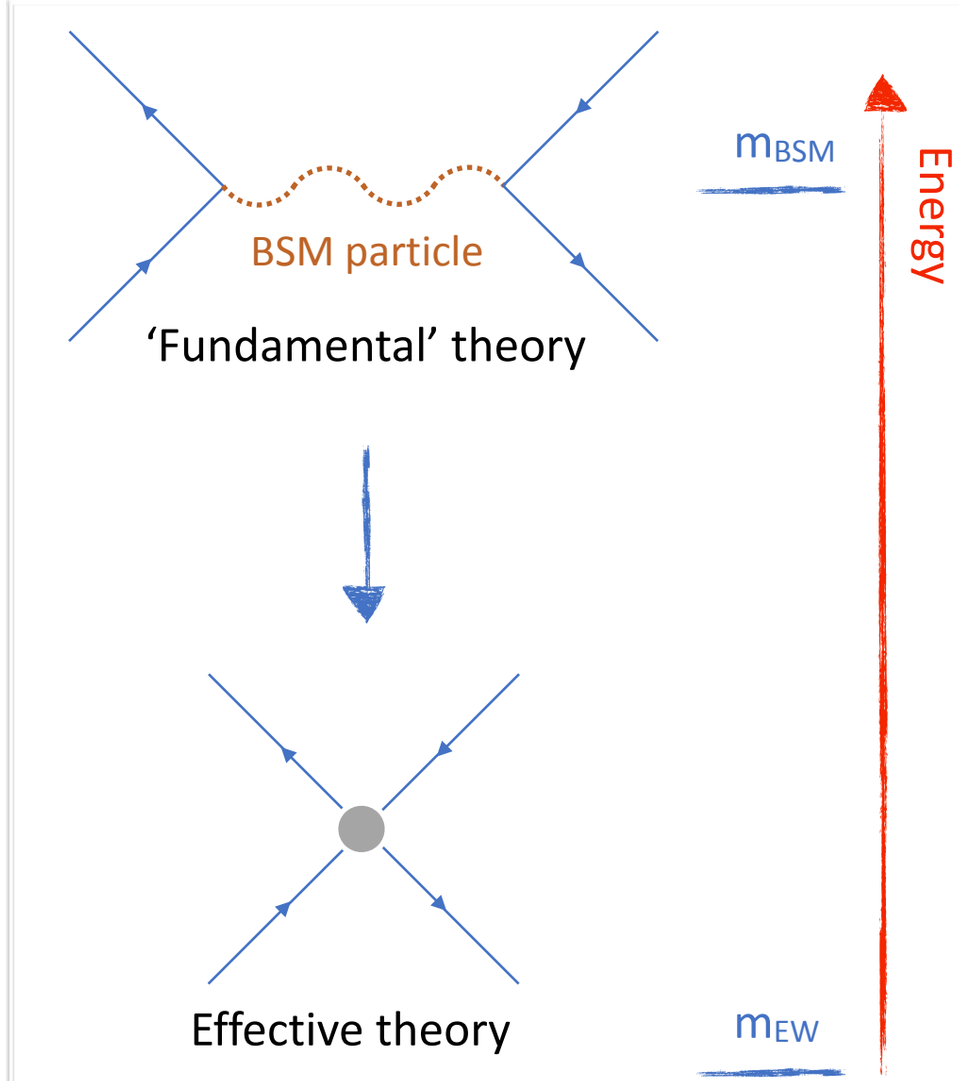
Backup slides

The SM Effective Field Theory

Describing BSM physics

Assumptions

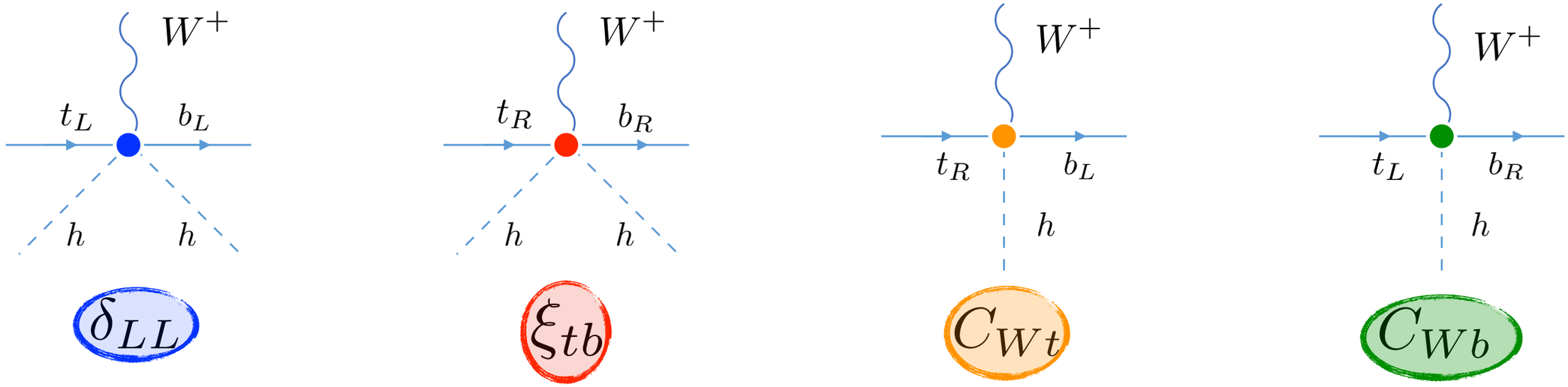
- No new light degrees of freedom
- BSM physics appears above the electroweak scale, $m_{EW} << m_{BSM}$
- SM gauge group SU(3)xSU(2)xU(1) is linearly realized (elementary scalar SU(2) doublet)



Wtb couplings

- Left-handed vector coupling
  - Correction to V_{tb}
- Right-handed vector coupling
- Dipole operator (right-handed top)
- Dipole operator (right-handed bottom)

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



Related to often used notation:

$$V_L = V^*_{tb}(1+\delta_{LL}) \qquad V_R = \xi^*_{tb} \qquad g_R = g\, y_t C_{Wt} \qquad g_L = g\, y_b C^*_{Wb}$$

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 $A_{CP}(b \to s\gamma)$

CKMFitter Group, Charles et al, ‘05

Running results

$\Lambda = 1\,\text{TeV}$	$c_\gamma(\Lambda)$	$c_g(\Lambda)$	$c_{Wt}(\Lambda)$	$c_{Wb}(\Lambda)$	$c_Y(\Lambda)$
$c_\gamma(m_t^+)$	0.86	0.13	$-9.2 \cdot 10^{-3}$	$-7.7 \cdot 10^{-6}$	–
$c_g(m_t^+)$	$2.8 \cdot 10^{-3}$	0.87	-0.021	$-1.2 \cdot 10^{-8}$	–
$c_{Wt}(m_t^+)$	$-5.4 \cdot 10^{-5}$	-0.033	0.86	–	–
$c_{Wb}(m_t^+)$	–	–	–	0.86	–
$c_Y(m_t^+)$	$-3.2 \cdot 10^{-4}$	-0.20	$2.4 \cdot 10^{-3}$	–	1
$C_{\varphi G}(m_t^+)$	$2.6 \cdot 10^{-5}$	$1.6 \cdot 10^{-2}$	$-2.0 \cdot 10^{-4}$	$-7.7 \cdot 10^{-11}$	–
$C_{\varphi\gamma}(m_t^+)$	$-4.2 \cdot 10^{-4}$	$-3.1 \cdot 10^{-5}$	$2.1 \cdot 10^{-6}$	$1.8 \cdot 10^{-9}$	–
$C_{\varphi WB}(m_t^+)$	$1.6 \cdot 10^{-2}$	$1.5 \cdot 10^{-3}$	$-1.6 \cdot 10^{-2}$	$5.5 \cdot 10^{-6}$	–

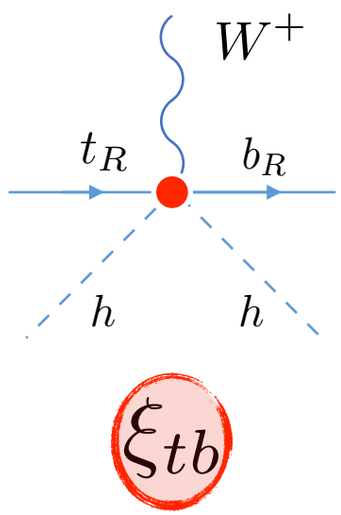
Running results

$\Lambda = 1\,\text{TeV}$	$\tilde{c}_{Wt}(\Lambda)$	$\tilde{c}_{Wb}(\Lambda)$
$\tilde{c}_{\gamma}^{(e)}(\Lambda_\chi)$	$-4.4 \cdot 10^{-4}$	$2.3 \cdot 10^{-8}$
$\tilde{c}_{\gamma}^{(u)}(\Lambda_\chi)$	$-1.2 \cdot 10^{-4}$	$-2.9 \cdot 10^{-6}$
$\tilde{c}_{g}^{(u)}(\Lambda_\chi)$	$-1.9 \cdot 10^{-5}$	$-1.7 \cdot 10^{-5}$
$\tilde{c}_{\gamma}^{(d)}(\Lambda_\chi)$	$-9.1 \cdot 10^{-4}$	$-2.9 \cdot 10^{-6}$
$\tilde{c}_{g}^{(d)}(\Lambda_\chi)$	$-2.4 \cdot 10^{-5}$	$-1.7 \cdot 10^{-5}$
$\tilde{c}_{\gamma}^{(s)}(\Lambda_\chi)$	$-9.5 \cdot 10^{-4}$	$-2.9 \cdot 10^{-6}$
$\tilde{c}_{g}^{(s)}(\Lambda_\chi)$	$-2.4 \cdot 10^{-5}$	$-1.7 \cdot 10^{-5}$
$C_{\tilde{G}}(\Lambda_\chi)$	$2.2 \cdot 10^{-5}$	$7.8 \cdot 10^{-5}$

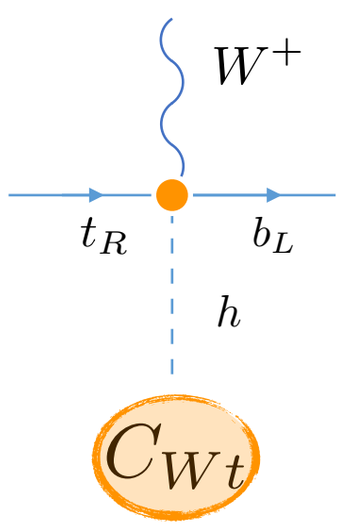
	$V_{tb}^{*}\xi_{tb}$
$\tilde{c}_{\gamma l}^{ee}$	6.8×10^{-6}
$\tilde{c}_{\gamma u}^{uu}$	$-1.5 \cdot 10^{-5}$
$\tilde{c}_{gu}^{uu}$	$-2.0 \cdot 10^{-4}$
$\tilde{c}_{\gamma d}^{dd}$	$-1.5 \cdot 10^{-5}$
$\tilde{c}_{gd}^{dd}$	$-2.0 \cdot 10^{-4}$
$\tilde{c}_{\gamma d}^{ss}$	$-1.5 \cdot 10^{-5}$
$\tilde{c}_{gd}^{ss}$	$-2.0 \cdot 10^{-4}$
$v^2 C_{\tilde{G}}$	$2.2 \cdot 10^{-3}$

Direct collider observables

Single top



$\sqrt{S}$ (TeV)		SM	$\lvert\xi_{tb}\rvert^2$
7	σ_t (pb)	$41.9^{+1.8}_{-0.9}$	36.0 ± 1.2
	$\sigma_{\bar{t}}$ (pb)	$22.7^{+0.9}_{-1.0}$	24.0 ± 0.8
8	σ_t (pb)	$56.4^{+2.4}_{-1.1}$	48 ± 1.6
	$\sigma_{\bar{t}}$ (pb)	$30.7^{+1.1}_{-1.3}$	32 ± 1.0
13	σ_t (pb)	136 ± 5	126 ± 12
	$\sigma_{\bar{t}}$ (pb)	$81.0^{+4.1}_{-3.6}$	88 ± 2.4



$$\frac{\sigma_t(7\text{ TeV})}{\text{pb}} = (41.9 \pm 1.8) - (9.4 \pm 0.3)\, v^2 c_{Wt} + (15.6 \pm 0.2)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right),$$

$$\frac{\sigma_{\bar{t}}(7\text{ TeV})}{\text{pb}} = (22.7 \pm 1.0) - (0.3 \pm 0.1)\, v^2 c_{Wt} + (5.5 \pm 0.2)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right),$$

$$\frac{\sigma_t(8\text{ TeV})}{\text{pb}} = (56.4 \pm 2.4) - (11.7 \pm 0.3)\, v^2 c_{Wt} + (21.0 \pm 0.5)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right)$$

$$\frac{\sigma_{\bar{t}}(8\text{ TeV})}{\text{pb}} = (30.7 \pm 1.3) - (0.5 \pm 0.2)\, v^2 c_{Wt} + (7.7 \pm 0.2)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right),$$

$$\frac{\sigma_t(13\text{ TeV})}{\text{pb}} = (136 \pm 5.4) - (26.2 \pm 0.4)\, v^2 c_{Wt} + (57.0 \pm 1.0)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right)$$

$$\frac{\sigma_{\bar{t}}(13\text{ TeV})}{\text{pb}} = (81.0 \pm 4.1) - (2.6 \pm 0.4)\, v^2 c_{Wt} + (24.7 \pm 1.0)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right).$$

Direct collider observables

Helicity fractions

$$F_0 = \frac{1 - 4y_t^2 x^2 (v^2 c_{Wt}) + 4x^4 y_t^4 \left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right)}{(1+2x^2) - 12 y_t^2 x^2 (v^2 c_{Wt}) + 4x^2(2+x^2) y_t^4 \left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right)}$$

$$F_L = \frac{2x^2 \left(1 - 4y_t^2 (v^2 c_{Wt}) + 4y_t^4 \left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right)\right)}{(1+2x^2) - 12 y_t^2 x^2 (v^2 c_{Wt}) + 4x^2(2+x^2) y_t^4 \left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right)}.$$

$$\delta_- = V_{tb}^2 \arg\left((x - g_R)(1 - x g_R)^*\right), \qquad \text{with} \quad g_R = 2\frac{m_W}{v} y_t (v^2 c_{Wt} + i\, v^2 \tilde{c}_{Wt}).$$

Drobnak, Fajfer, Kamenik, ‘10

Indirect collider observables

Hbb

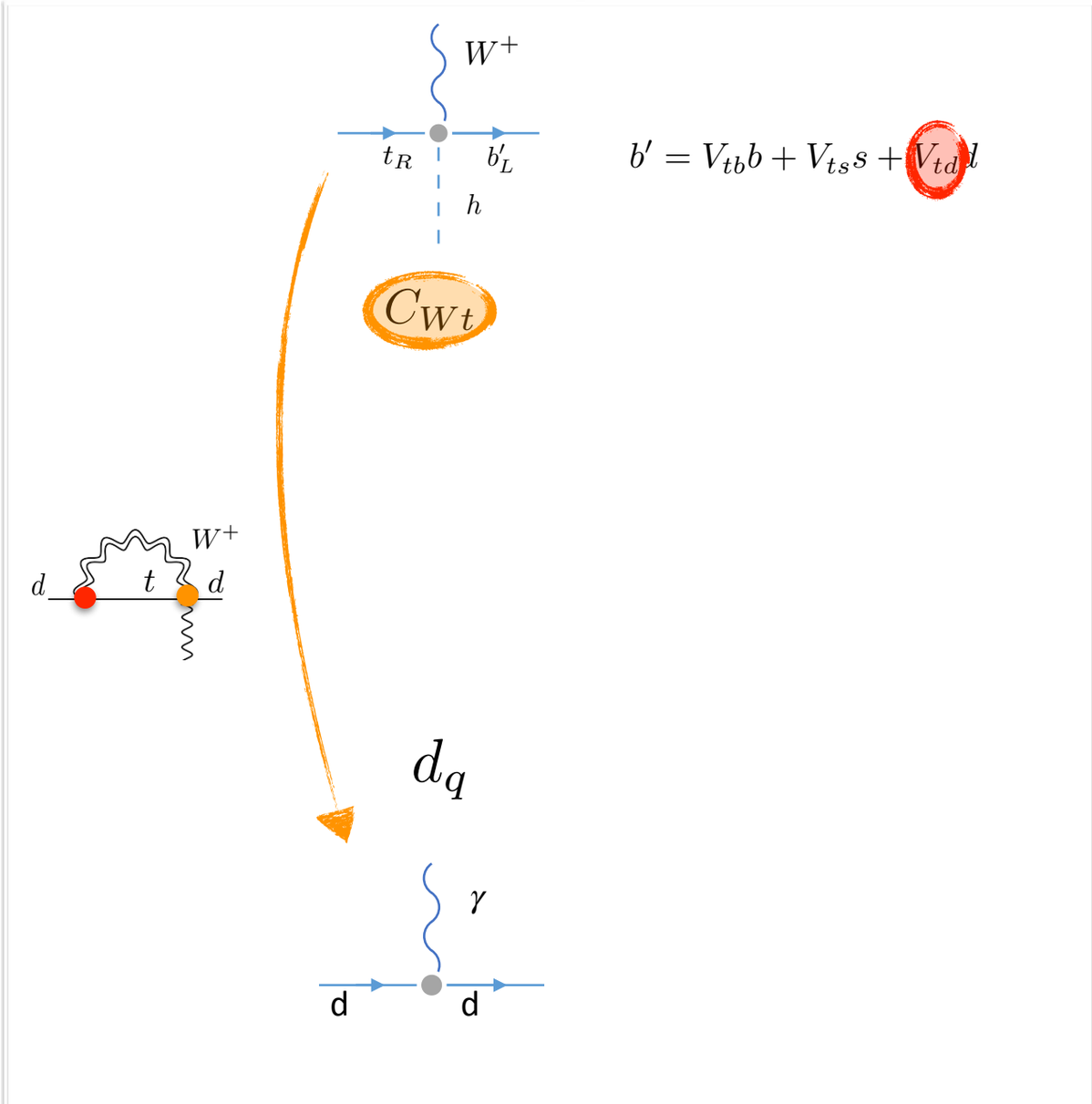
$$
\begin{aligned}
y_b^{(\mathrm{eff})} &= y_b(\mu) - \frac{g^2}{(4\pi)^2}\frac{m_t}{v}\frac{\xi_{tb}V_{tb}^*}{2}\Bigg[(x_h+3x_t-9)\log\frac{\mu^2}{m_W^2} - 3\frac{x_t(x_t-3)}{x_t-1}\log x_t + x_t\beta_t\log\left(\frac{\beta_t-1}{\beta_t+1}\right) \\
&\quad +(x_h-2)\beta_w\log\left(\frac{\beta_W-1}{\beta_W+1}\right) + (2x_h+x_t(x_t-7))f_1(x_h,x_t) \\
&\quad -(4+(2-x_h)x_t)f_2(x_h,x_t) + (-5+2x_h+4x_t)\,,\Bigg], \qquad (23)
\end{aligned}
$$

$$
\begin{aligned}
\frac{dm_b}{d\ln\mu} &= \gamma_m\frac{\alpha_s}{4\pi}m_b + \frac{g^2}{(4\pi)^2}m_t(x_t-3)V_{tb}^*\xi_{tb}\,, \\
\frac{dy_b}{d\ln\mu} &= \gamma_m\frac{\alpha_s}{4\pi}y_b + \frac{g^2}{(4\pi)^2}\frac{m_t}{v}(x_h+3x_t-9)V_{tb}^*\xi_{tb}\,,
\end{aligned}
$$

$$
\begin{aligned}
f_1(x_h,x_t) &= \int_0^1 dz\frac{1}{1-x_t+x_hz}\log\left(\frac{x_t-x_h(1-z)z}{1+(x_t-1)z}\right)\,, \\
f_2(x_h,x_t) &= \int_0^1 dz\frac{1}{-1+x_t+x_hz}\log\left(\frac{1-x_h(1-z)z}{x_t+z(1-x_t)}\right)\,.
\end{aligned}
$$

1 loop vs 2 loop

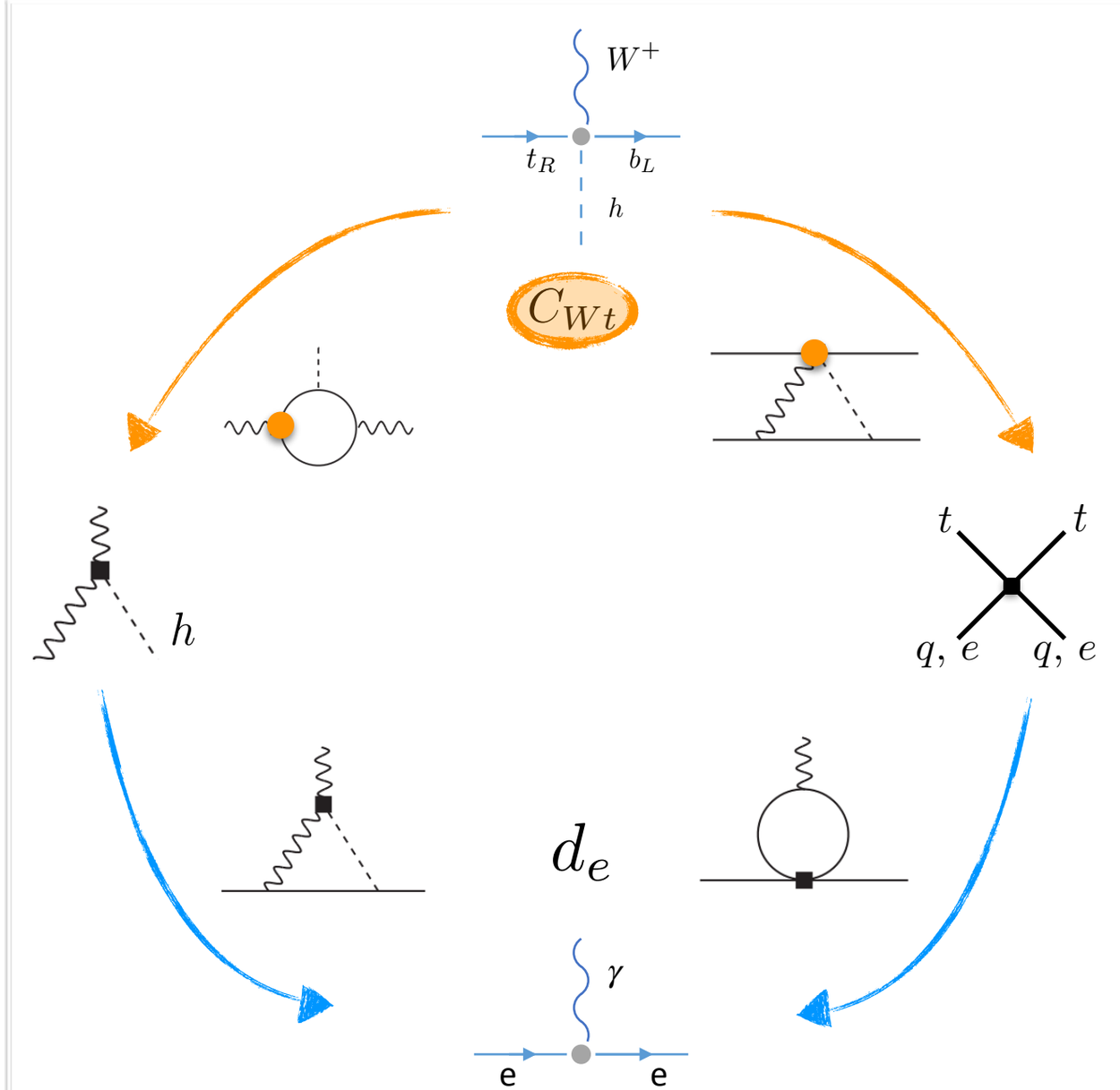
One-loop contribution



$$d_q \sim \frac{m_q}{v^2}\frac{\alpha}{4\pi}|V_{td}|^2 C_{Wt}$$

Cordero-Cid, Hernandez, Tavares-Velasco, and Toscano, '08

Two-loop contribution



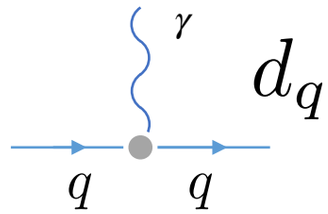
$$d_e \sim \frac{m_e}{v^2}\frac{\alpha}{4\pi}\frac{1}{(4\pi)^2}C_{Wt}$$

$\sim 10^2$ [One-loop contribution]

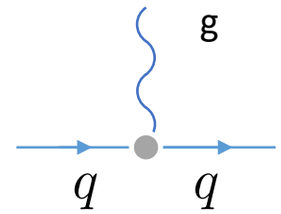
Cirigliano, de Vries, Mereghetti, WD, '16; Ramsey-Musolf, Fuyuto, '17

Connection to EDMs

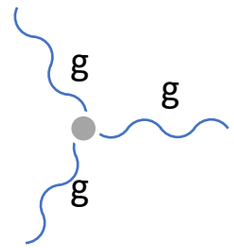
Hadronic EDMs



d_q



$\tilde{d}_q$



d_W

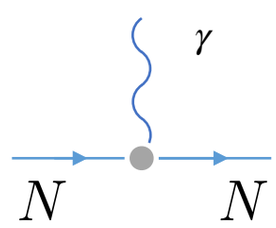
Energy

M_{QCD}
1 GeV

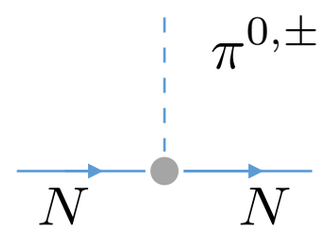
d.of.: Quarks, Gluons, photons

Chiral Perturbation Theory
d.of.: Nucleons, pions, photons

Hadronic Matrix Elements



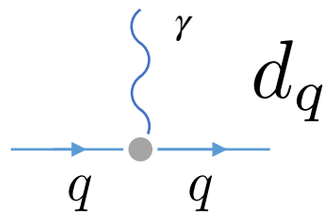
$d_{n,p}$



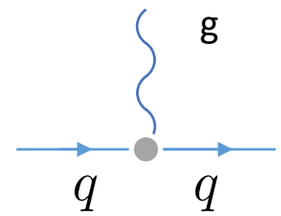
$\bar{g}_{0,1}$

Connection to EDMs

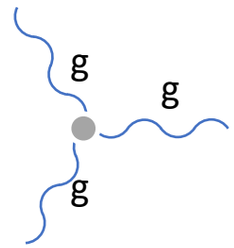
Hadronic EDMs



d_q



$\tilde{d}_q$



d_W

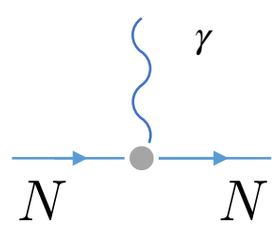
Energy

M_{QCD}
1 GeV

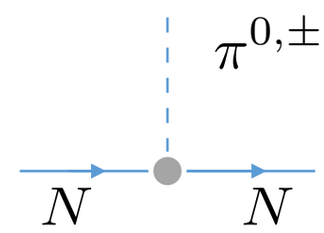
d.of.: Quarks, Gluons, photons

Chiral Perturbation Theory
d.of.: Nucleons, pions, photons

Hadronic Matrix Elements



$d_{n,p}$



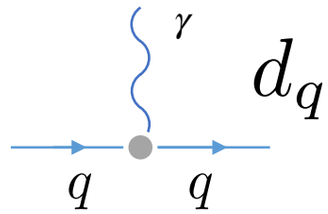
$\bar{g}_{0,1}$

- Hadronic EDMs

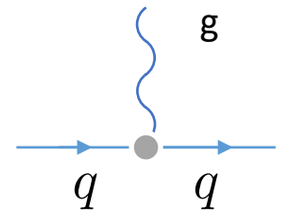
e fm	d_n	$d_{p,D}$
current limit	$3.0 \cdot 10^{-13}$	x
expected limit	$1.0 \cdot 10^{-15}$	$1.0 \cdot 10^{-16}$

Connection to EDMs

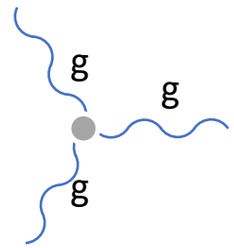
Hadronic EDMs



d_q



$\tilde{d}_q$



d_W

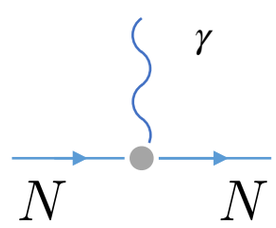
Energy

M_{QCD}
1 GeV

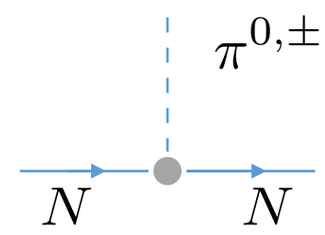
d.of.: Quarks, Gluons, photons

Chiral Perturbation Theory
d.of.: Nucleons, pions, photons

Hadronic Matrix Elements



$d_{n,p}$



$\bar{g}_{0,1}$

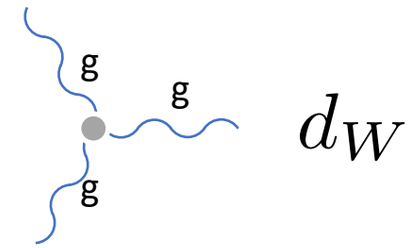
+nuclear calculations

- Hadronic EDMs

e fm	d_n	$d_{p,D}$	d_{Hg}	d_{Xe}	d_{Ra}
current limit	$3.0 \cdot 10^{-13}$	x	$6.2 \cdot 10^{-17}$	$5.5 \cdot 10^{-14}$	$1.2 \cdot 10^{-10}$
expected limit	$1.0 \cdot 10^{-15}$	$1.0 \cdot 10^{-16}$	$6.2 \cdot 10^{-17}$	$5.0 \cdot 10^{-16}$	$1.0 \cdot 10^{-14}$

Connection to EDMs

Hadronic EDMs



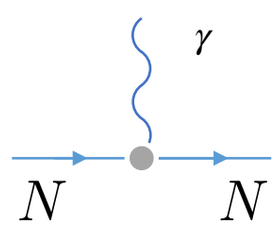
Energy

M_{QCD}
1 GeV

d.of.: Quarks, Gluons, photons

Chiral Perturbation Theory
d.of.: Nucleons, pions, photons

Hadronic Matrix Elements



$d_{n,p}$

$\bar{g}_{0,1}$

$$d_n = \pm(50 \pm 40\,\mathrm{MeV})eg_s\, d_W$$

- Matrix element from NDA/QCD sum rules
  - O(100%) uncertainty

Demir, Pospelov, Ritz, ’03; de Vries et al, ‘10