Low-energy constraints on top-Higgs couplings

Based on:

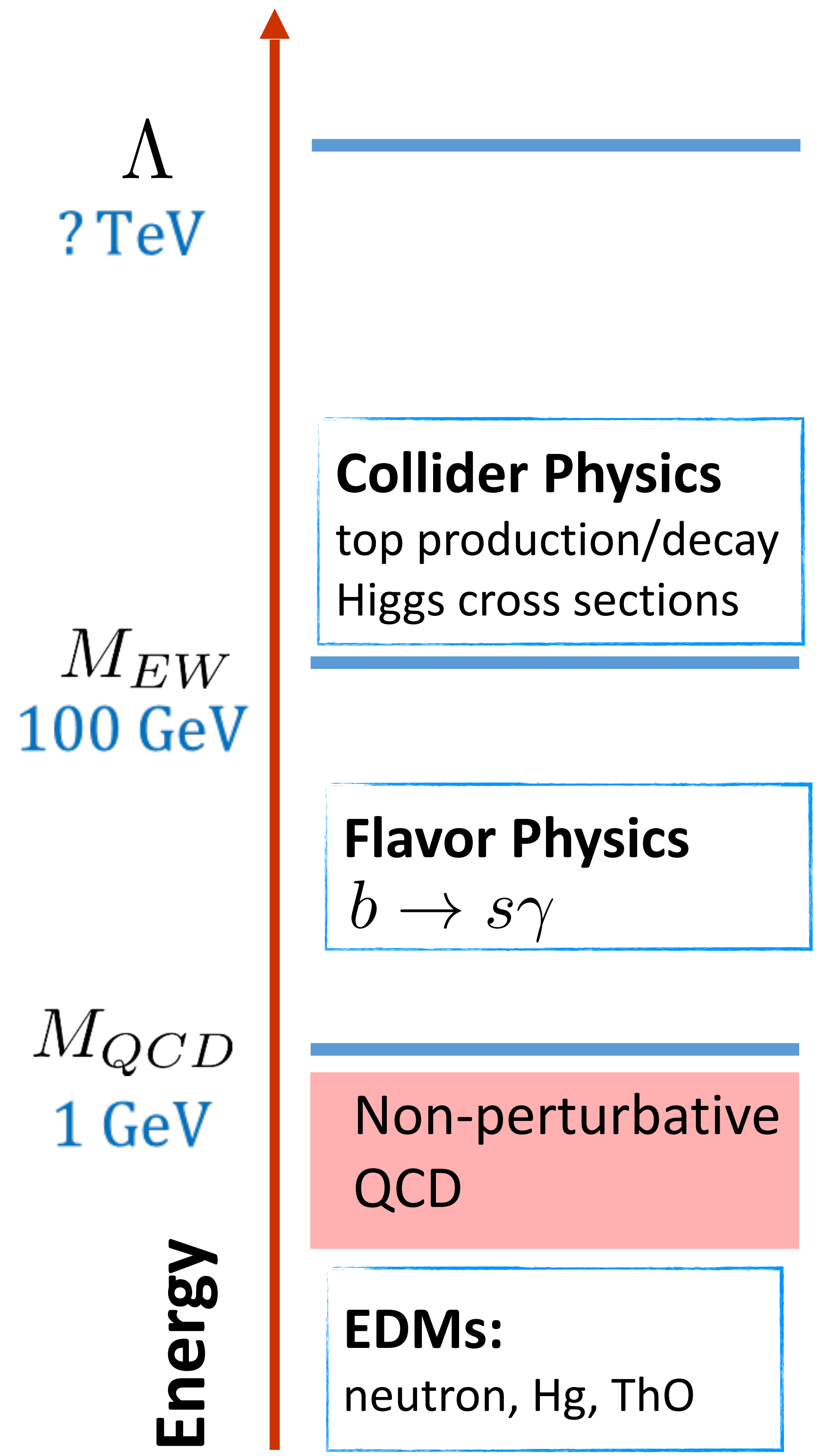
arXiv:1605.04311, 1603.03049,
with V. Cirigliano, E. Mereghetti, J. de Vries

New Mexico CONSORTIUM

Los Alamos NATIONAL LABORATORY EST. 1943

CPV BSM physics:
SUSY, 2HDM, compositeness...

Outline



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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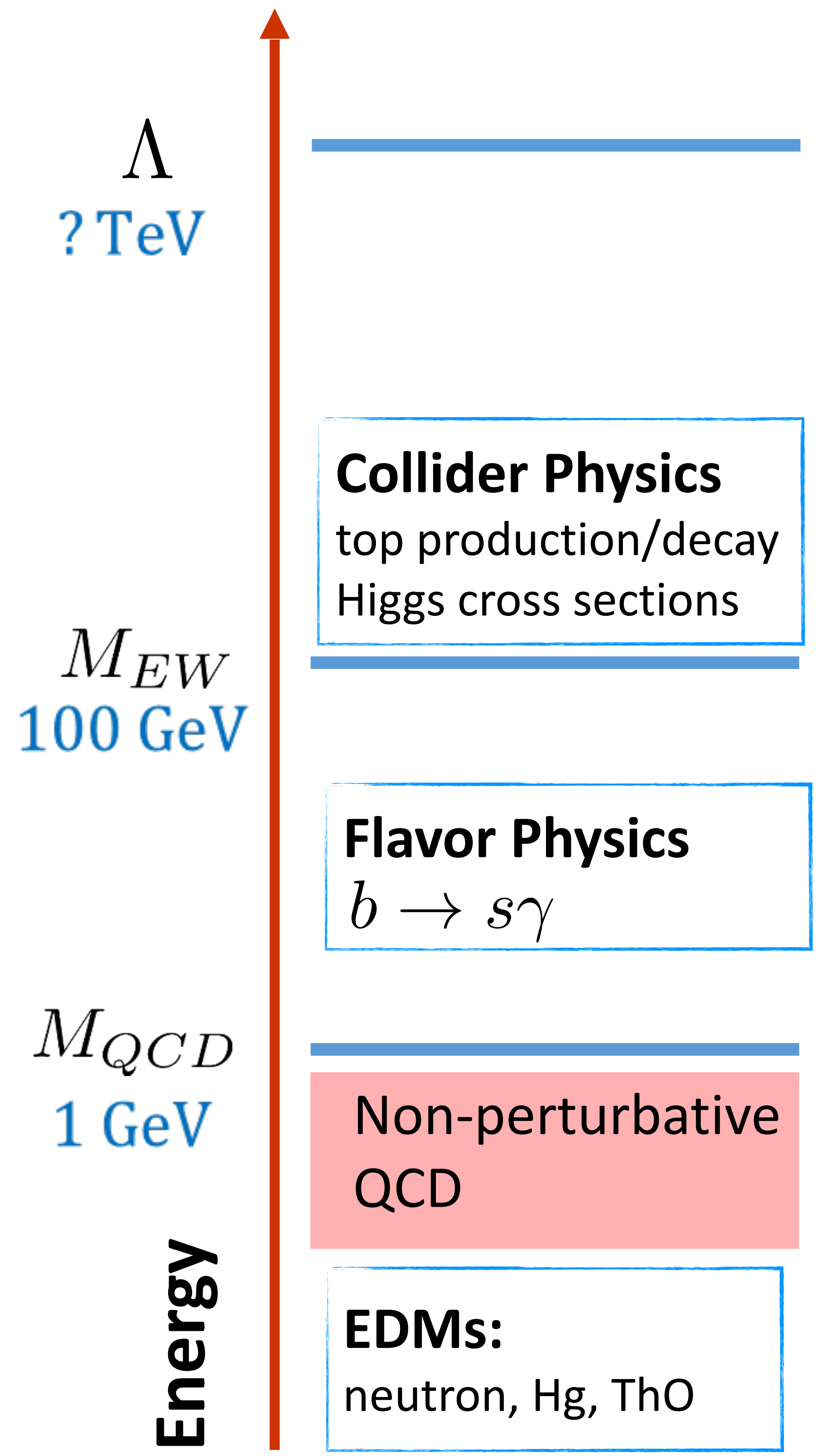
RG evolution



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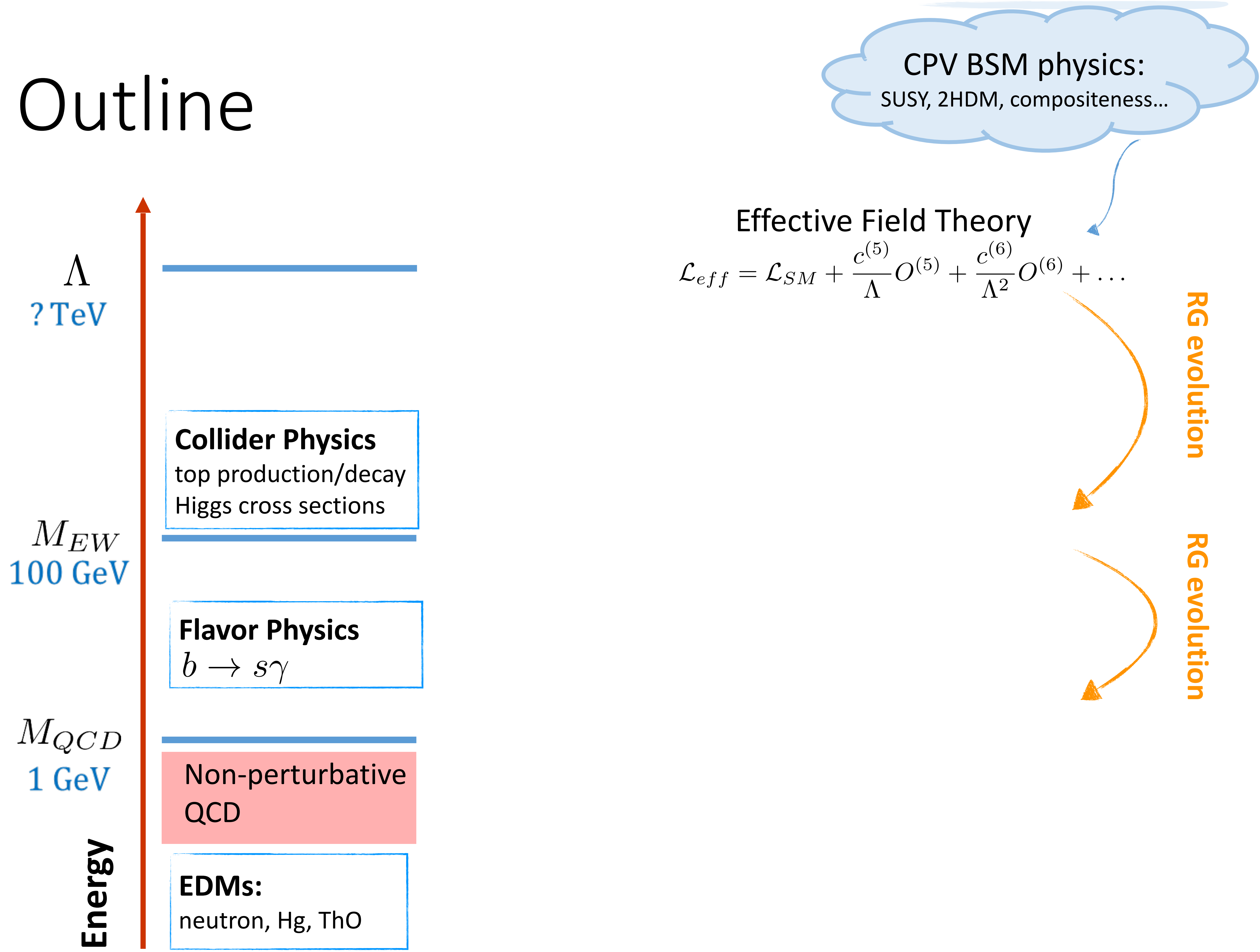
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? TeV
Collider Physics
top production/decay
Higgs cross sections
M_{EW}
100 GeV
Flavor Physics
$b \to s\gamma$
M_{QCD}
1 GeV
Non-perturbative QCD
EDMs:
neutron, Hg, ThO
Energy

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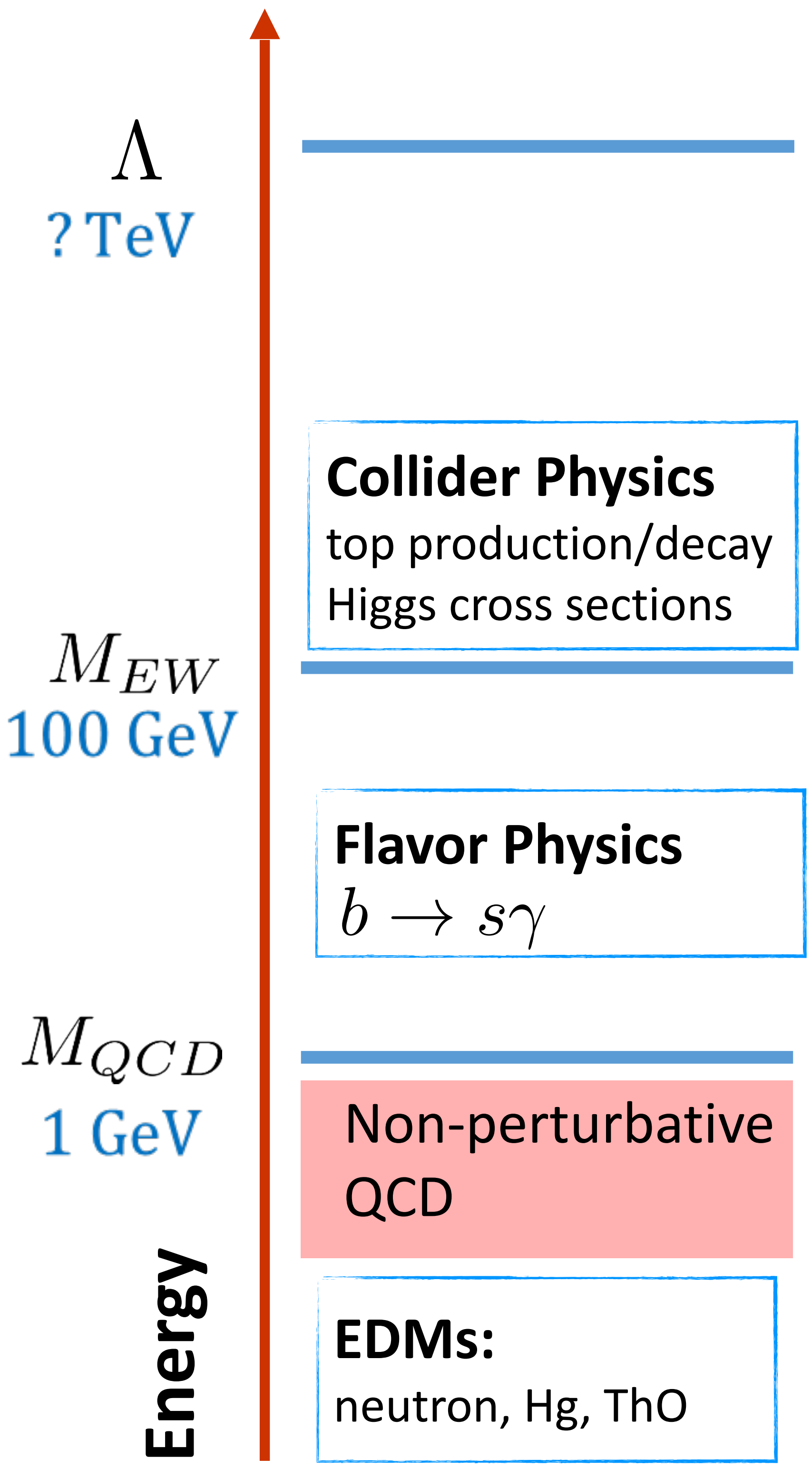

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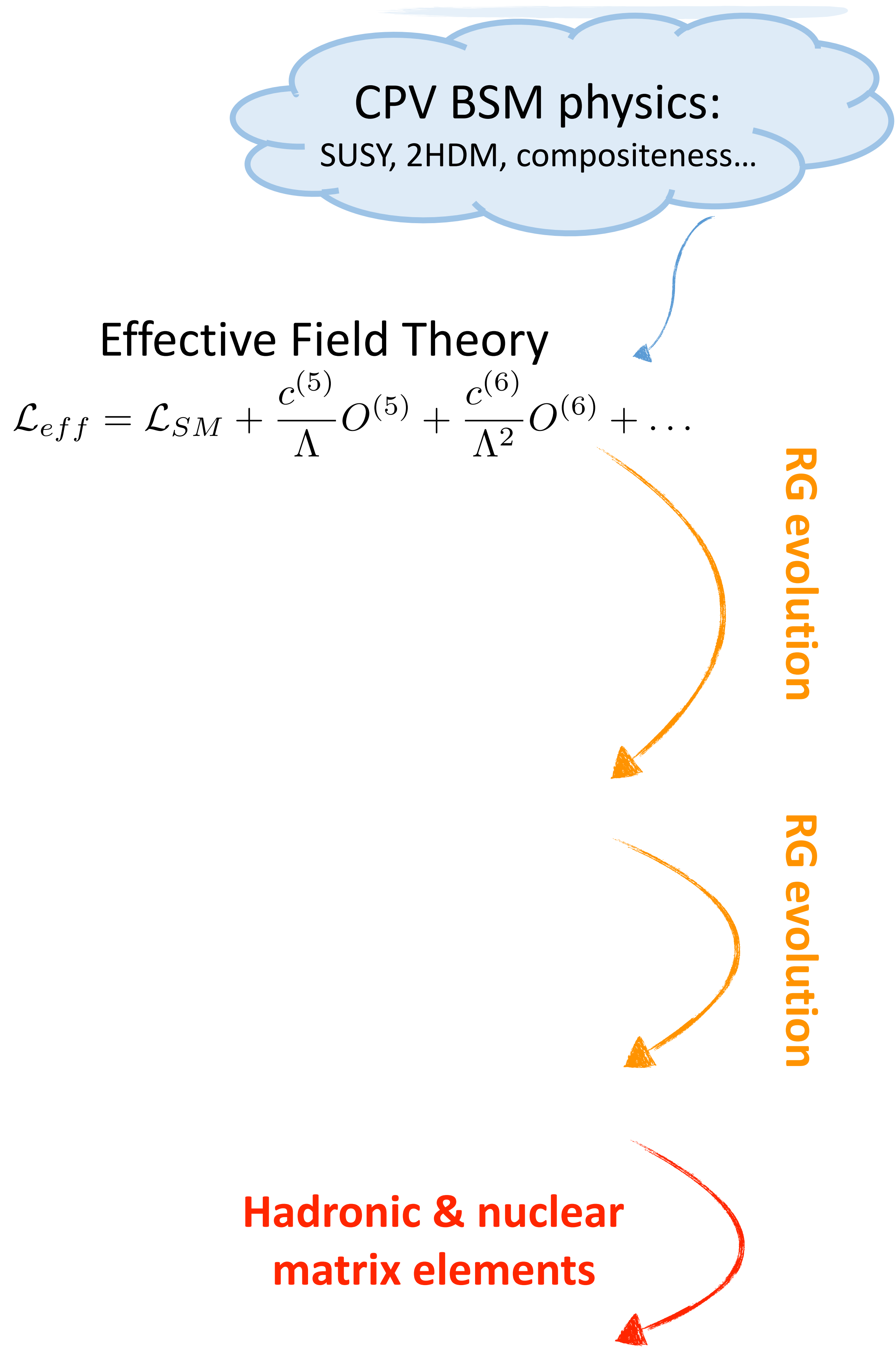

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Hadronic & nuclear matrix elements

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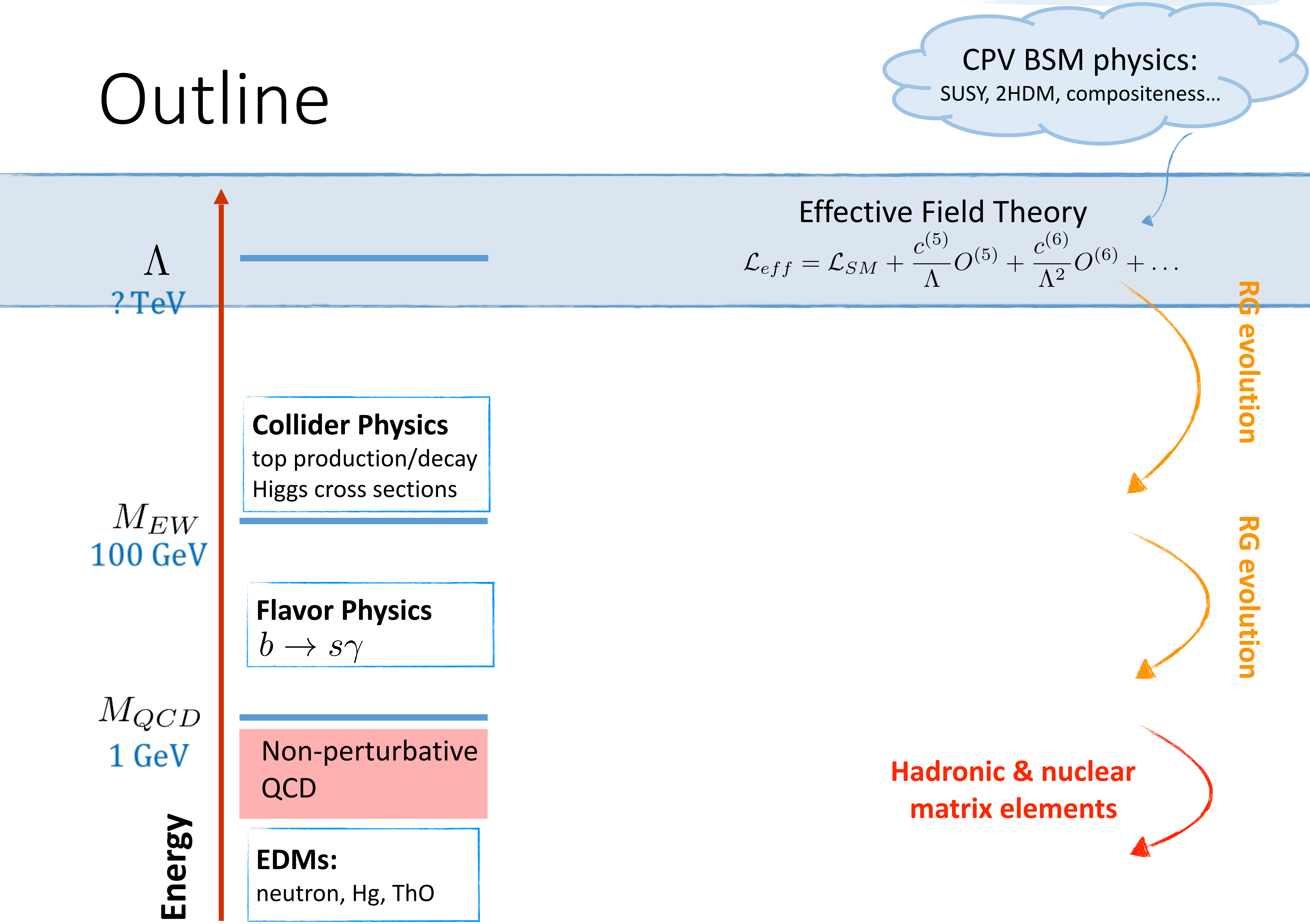

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Why the top-Higgs sector?

- The top quark has the largest couplings to the Higgs & EWSB sector
  - Might be most sensitive to BSM physics (e.g. in compositeness/light stop SUSY)

- CP-violating top-Higgs couplings are relevant for Baryogenesis

Kaplan NP B, ’91; Carena, Nardini, Quiros, Wagner, NP B, ’09; Kobakhidze, Wu, Yue, JHEP, ‘16

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- Frequently studied,

Atwood et al. '92; Choudhury et al, '12
Baumgart et al, '13; Bernreuther et al, '15, '15
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Cordero-Cid et al, '08; Brod et al, '13;
Kamenik, 'et al, 12; Gorbahn, 'et al, 14;

- Frequently studied, but less so in context of low-energy constraints (EDMs)

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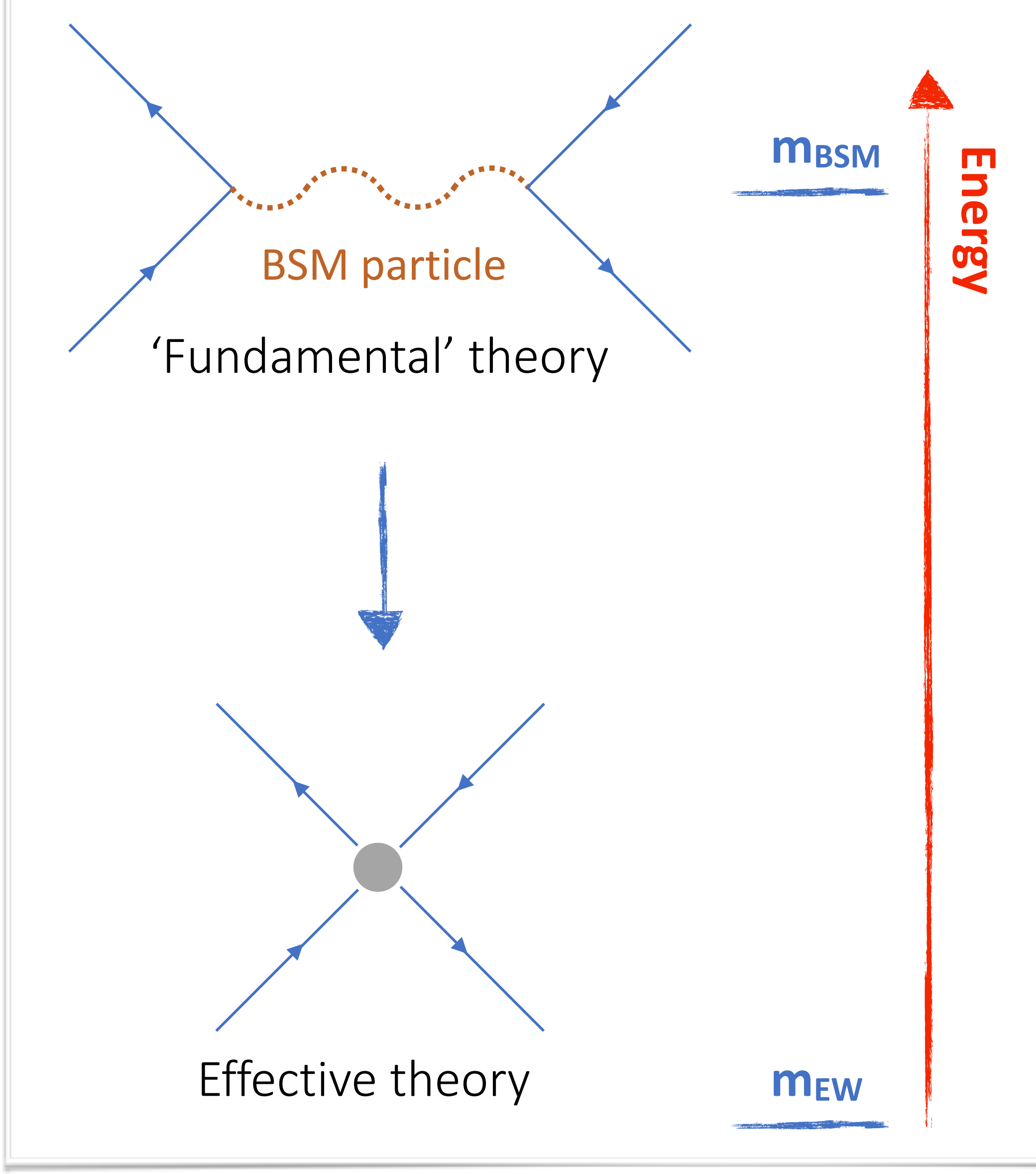
Effective Field Theory

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)



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;

Effective Field Theory

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

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	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK}\widetilde{W}_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$	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}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
					$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

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

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

Effective Field Theory

Describing BSM physics

Focus on the top-Higgs sector

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

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
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				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	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

Effective Field Theory

Describing BSM physics

Focus on the top-Higgs sector

- Operators involving a top and a Higgs, which are
  - Have no flavor-changing neutral currents
- ->Just 5 chirality-flipping* operators left

*1 additional chirality-conserving operator exists, future work…

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	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
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$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	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

Effective Field Theory

Describing BSM physics

Focus on the top-Higgs sector **Manageable**

- Operators involving a top and a Higgs, which are
  - Have no flavor-changing neutral currents
- ->Just 5 chirality-flipping* operators left

*1 additional chirality-conserving operator exists, future work…

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}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
					$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

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

- Non-standard Yukawa coupling
- Top electric dipole moment
- Top gluonic dipole
- 2 top weak dipoles

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

$\psi^2 X\varphi$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$

Lagrangian (mass basis): $\mathcal{L}^6_Y = -C_Y m_t \bar{t}_L t_R \left(vh + \frac{3}{2}h^2 + \frac{1}{2}\frac{h^3}{v} \right)$

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Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$
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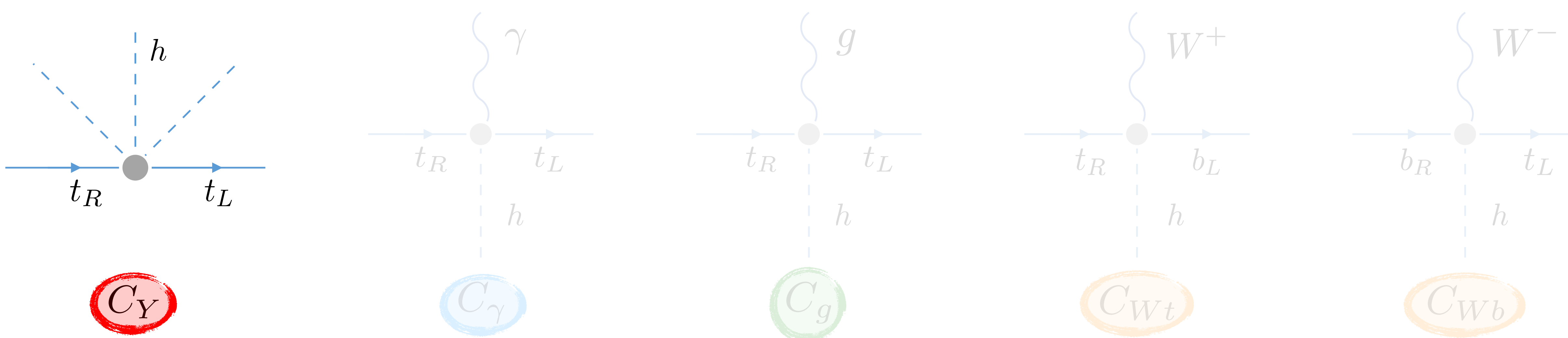
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$



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Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W^I_{\mu\nu}$
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Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$
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Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W^I_{\mu\nu}$
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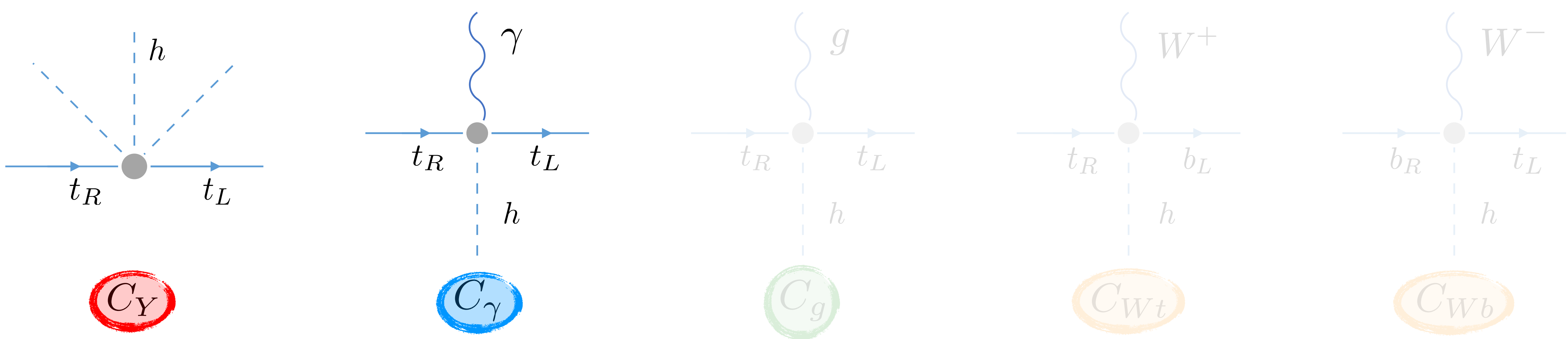

Lagrangian (mass basis): $\mathcal{L}^6_\gamma = -C_\gamma \frac{eQ_t}{2} m_t\, \bar{t}_L \sigma_{\mu\nu}\left(F^{\mu\nu} - \tan\theta_W Z^{\mu\nu}\right)t_R\left(1+\frac{h}{v}\right)$

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$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
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$\psi^2 X\varphi$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$
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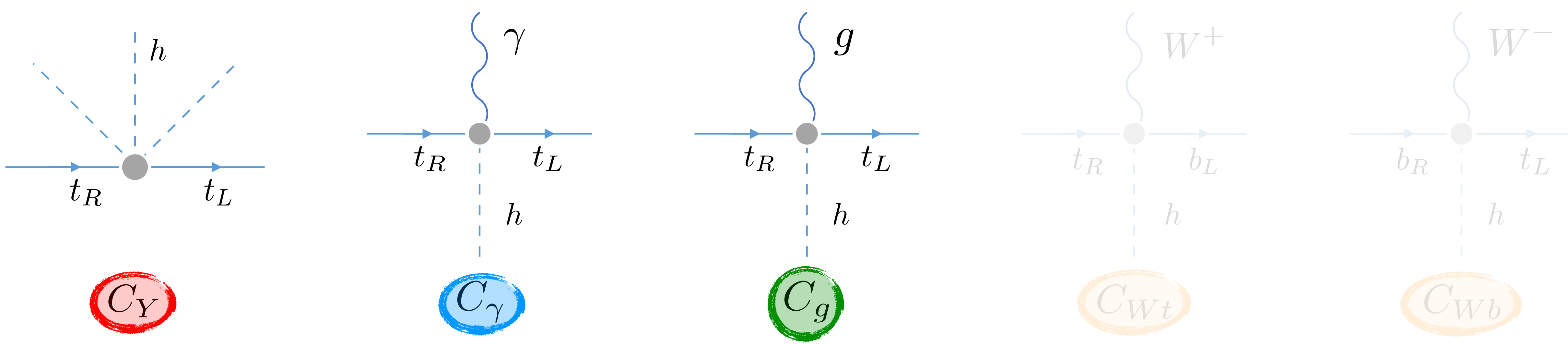

Lagrangian (mass basis): $\mathcal{L}_g^6 = -C_g \frac{g_s}{2} m_t \bar t_L \sigma_{\mu\nu} G^{\mu\nu} t_R \left(1+\frac{h}{v}\right)$

The top-Higgs couplings

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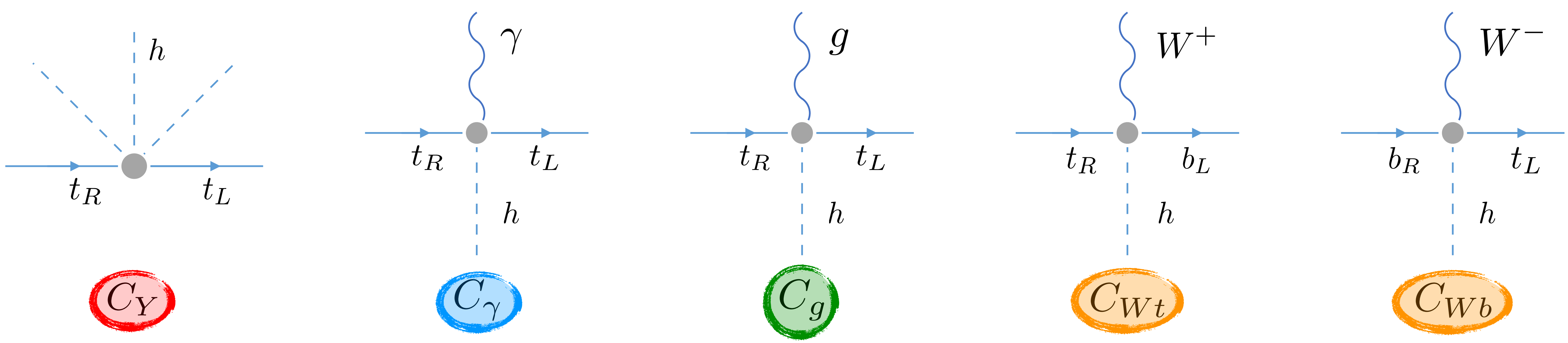
$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$

$\psi^2 X\varphi$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{\varphi}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{\varphi}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{\varphi}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$

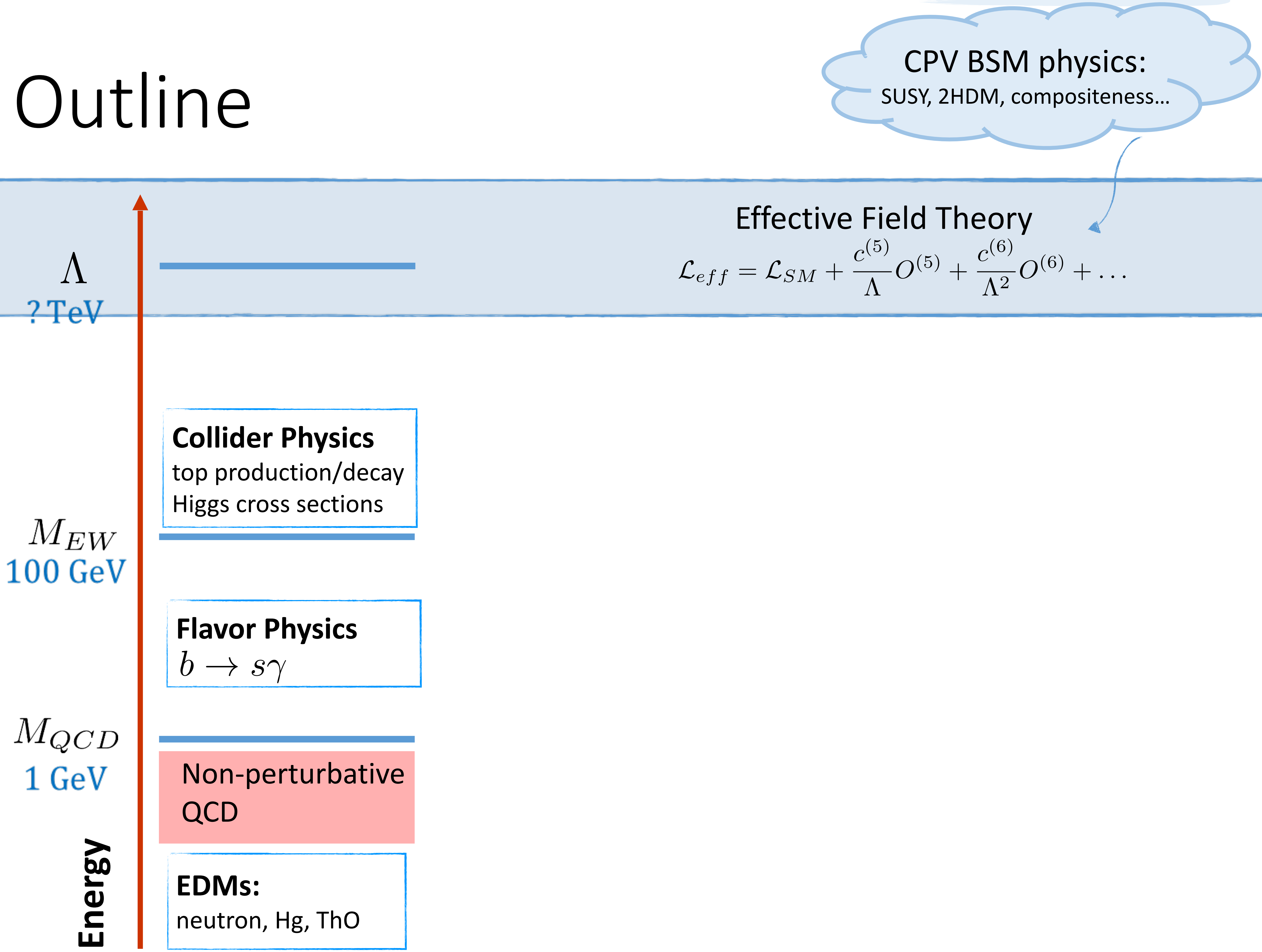


Lagrangian (mass basis):

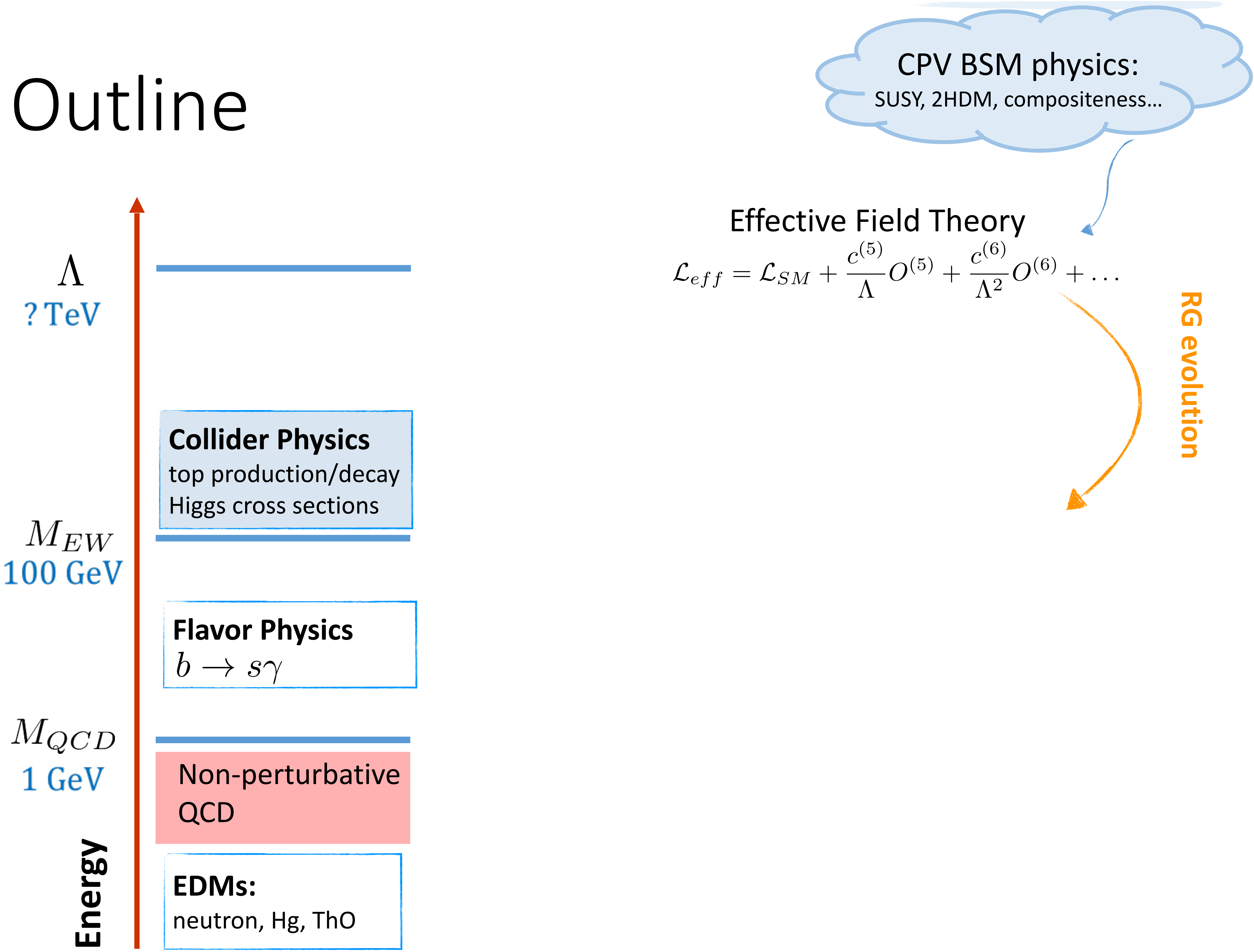
$$\mathcal{L}^6_{Wt} = -C_{Wt}\, g m_t \left[\frac{1}{\sqrt{2}}\bar{b}_L\sigma^{\mu\nu}W^+_{\mu\nu}t_R + \bar{t}_L\sigma^{\mu\nu}t_R\left(\frac{1}{2\cos\theta_W}Z_{\mu\nu} + igW^-_\mu W^+_\nu\right)\right]\left(1+\frac{h}{v}\right)$$

$$\mathcal{L}^6_{Wb} = -C_{Wb}\, g m_b \left[\frac{1}{\sqrt{2}}\bar{t}_L\sigma^{\mu\nu}W^+_{\mu\nu}b_R - \bar{b}_L\sigma^{\mu\nu}b_R\left(\frac{1}{2\cos\theta_W}Z_{\mu\nu} + igW^-_\mu W^+_\nu\right)\right]\left(1+\frac{h}{v}\right)$$

Outline


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

Outline



CPV BSM physics:
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RG evolution
Λ
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Energy
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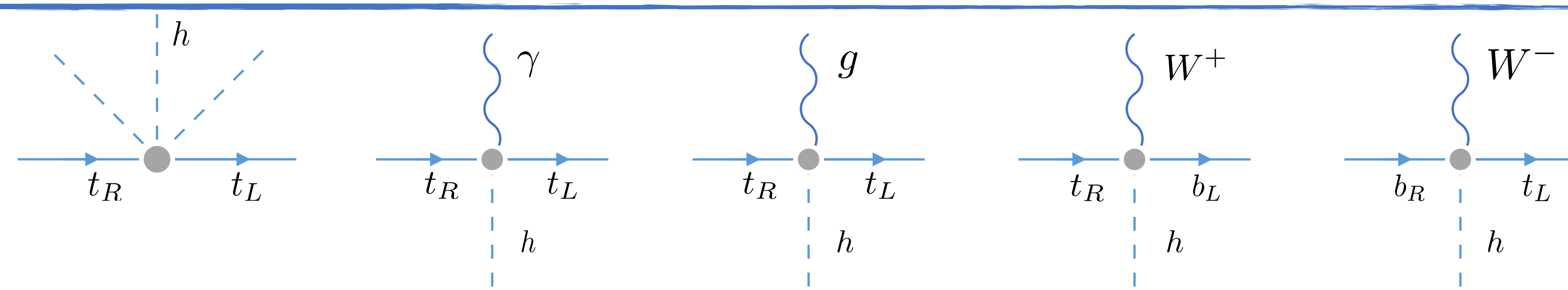
Direct collider observables

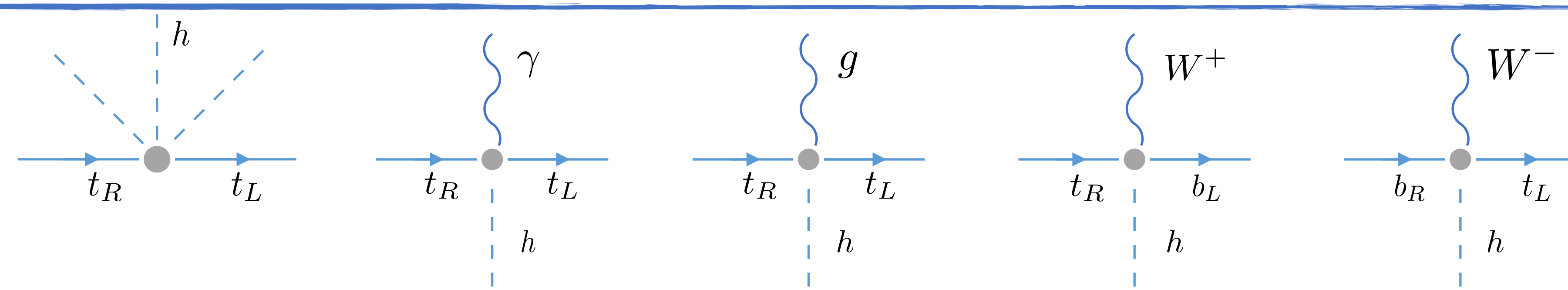
Real couplings



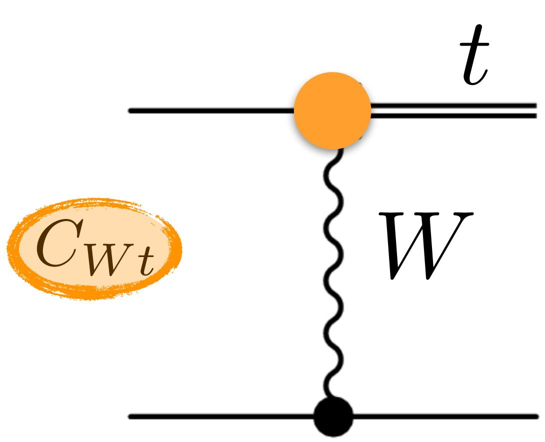
	C_Y	C_γ	C_g	C_{Wt}	C_{Wb}
t					
$t\bar{t}$					
$t\bar{t}h$					
$t \to W^+ b$					

Direct collider observables

Real couplings



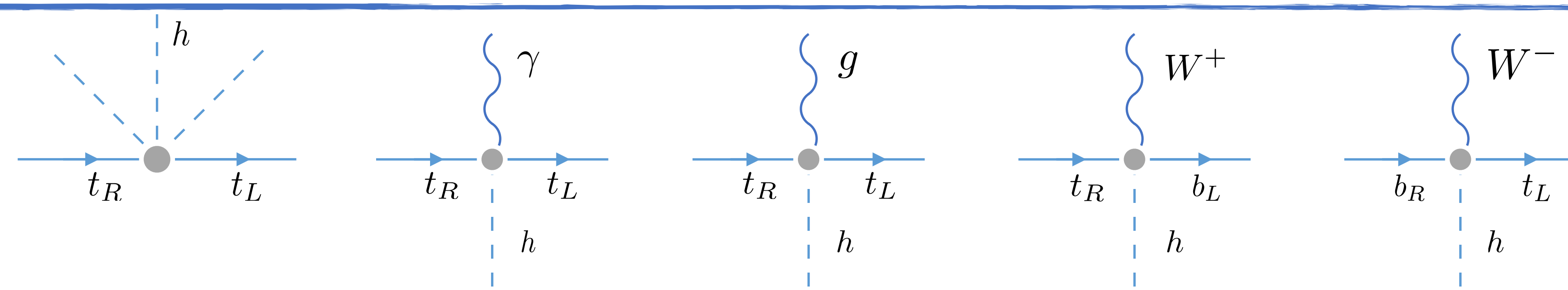
	C_Y	C_γ	C_g	C_{Wt}	C_{Wb}
t				✓	
$t\bar{t}$					
$t\bar{t}h$					
$t \to W^+ b$					



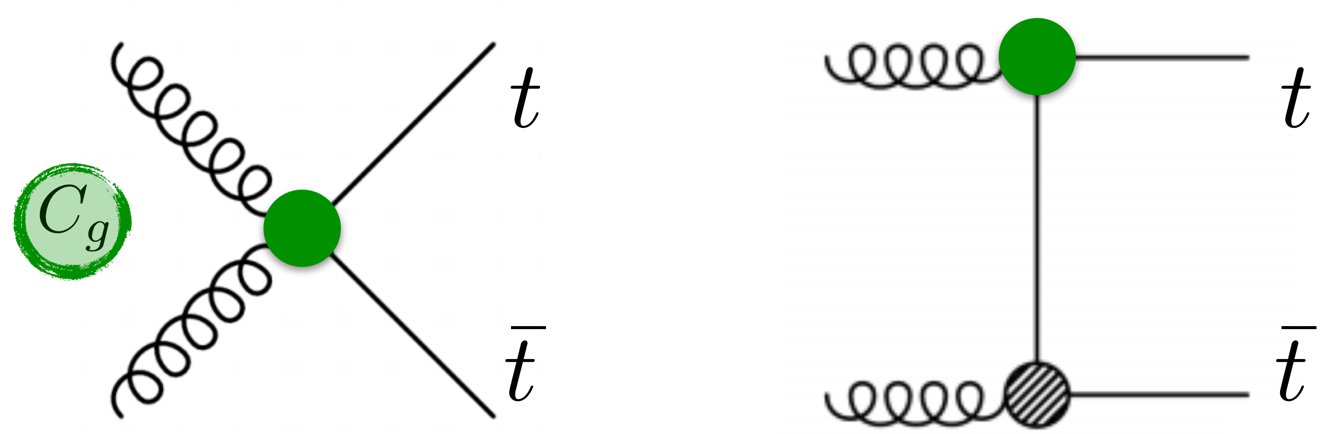
- The C_{Wb} coupling is suppressed by m_b

Direct collider observables

Real couplings



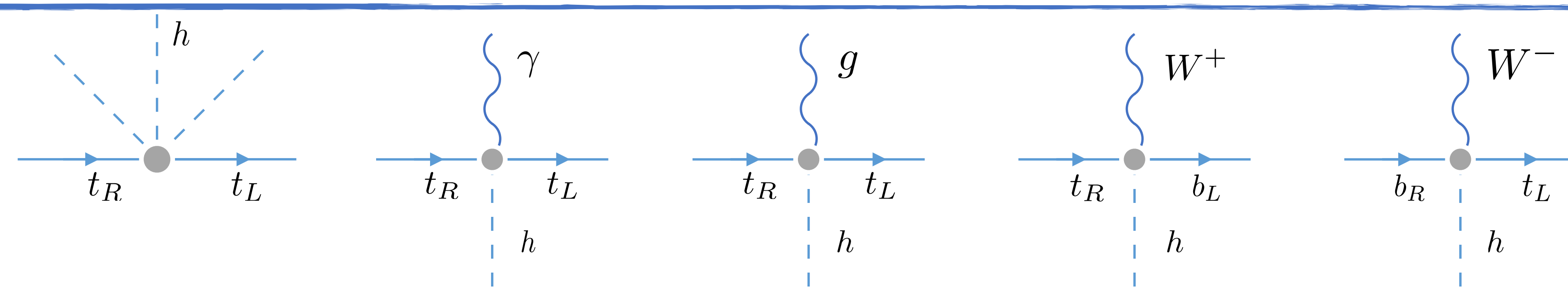
	C_Y	C_γ	C_g	C_{Wt}	C_{Wb}
t				✓	
$t\bar{t}$			✓		
$t\bar{t}h$					
$t \to W^+ b$					



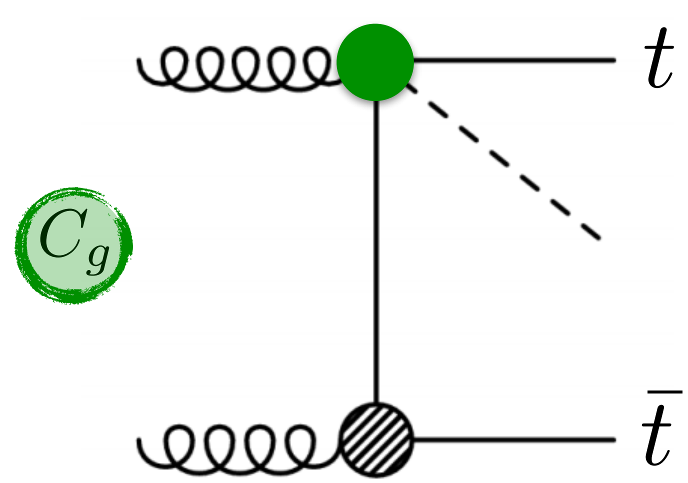
Atwood, et al '95; Haberl et al, '96

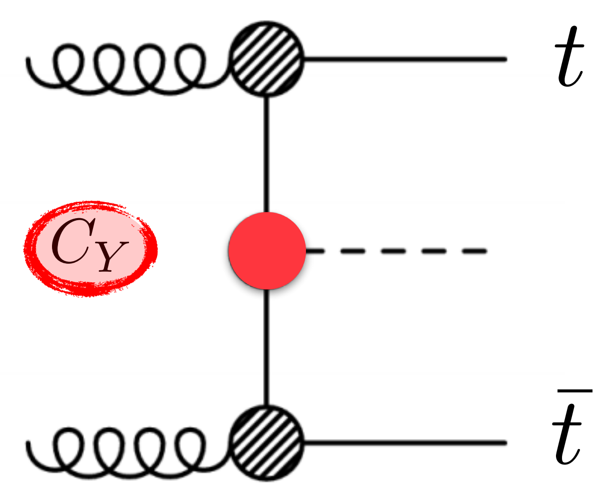
Direct collider observables

Real couplings



	C_Y	C_γ	C_g	C_{Wt}	C_{Wb}
t				✓	
$t\bar{t}$			✓		
$t\bar{t}h$	✓		✓		
$t \to W^+ b$					

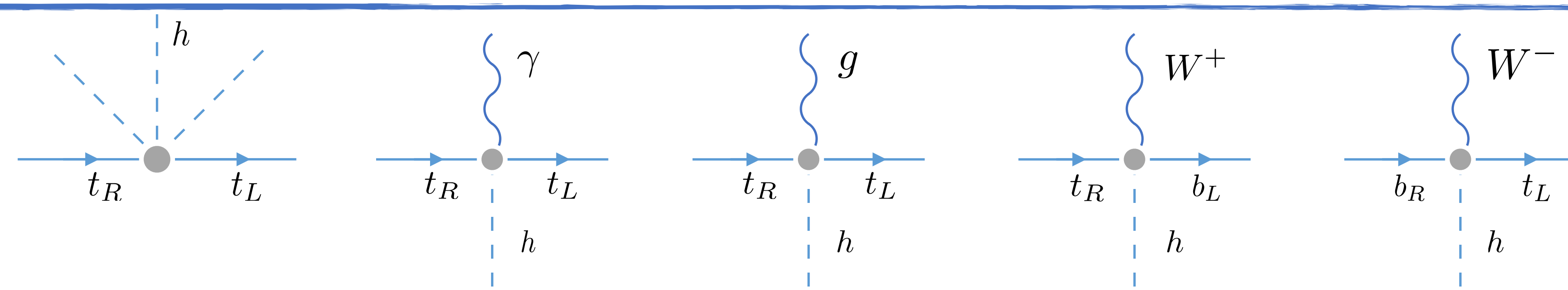




Frederix, et al ’11; Degrande et al, ’13;Hayreter et al, ‘13

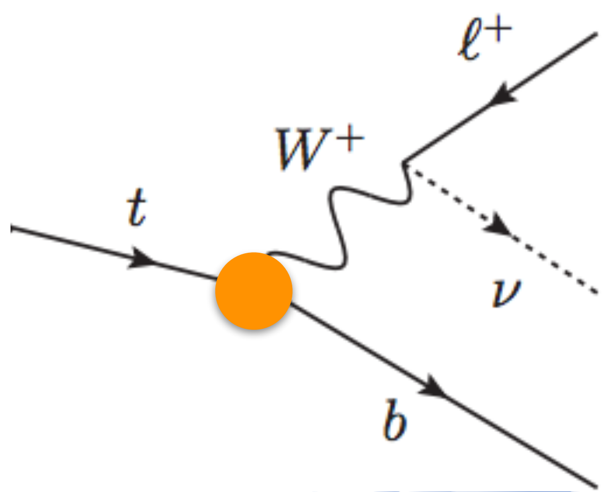
Direct collider observables

Real couplings



	C_Y	C_γ	C_g	C_{Wt}	C_{Wb}
t				✓	
$t\bar{t}$			✓		
$t\bar{t}h$	✓		✓		
$t \to W^+ b$				✓	

C_{Wt}

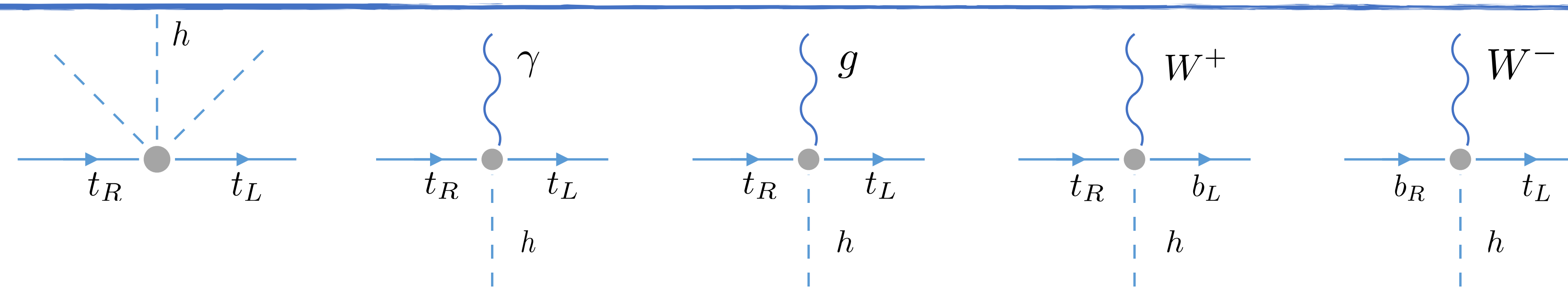


- The C_{Wb} coupling is suppressed by m_b

Drobnak, Fajfer, Kamenik, '10

Direct collider observables

Imaginary couplings



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t					
$t\bar{t}$					
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$t \to W^+ b$				✓	

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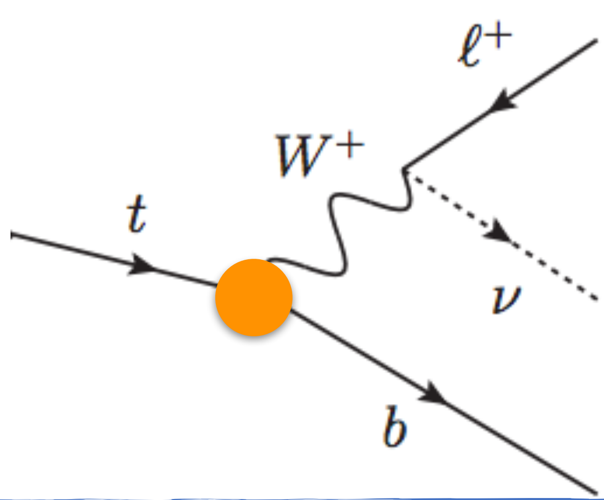

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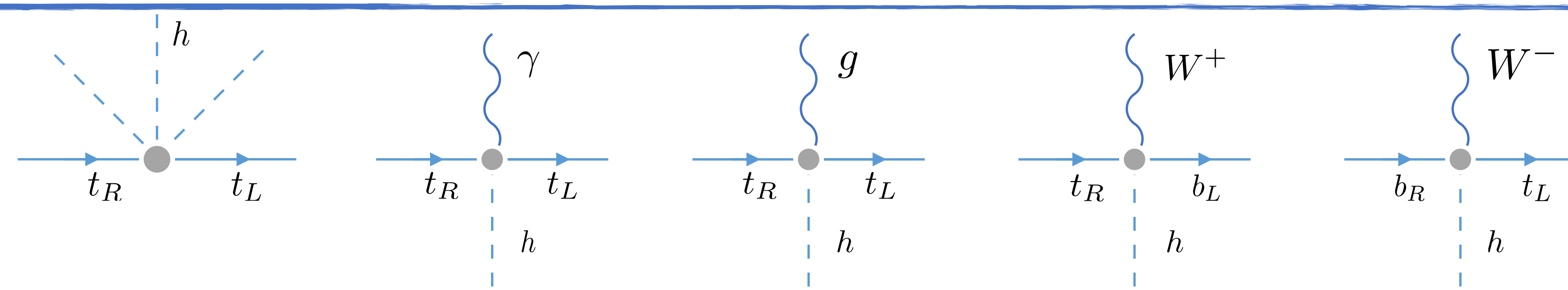
Boudreau, et al, ‘13

Direct collider observables

Imaginary couplings



		C_Y	C_γ	C_g	C_{Wt}	C_{Wb}
CP-even (X-sections)	t					
	$t\bar{t}$					
	$t\bar{t}h$					
Helicity fractions	$t \to W^+ b$				✓	

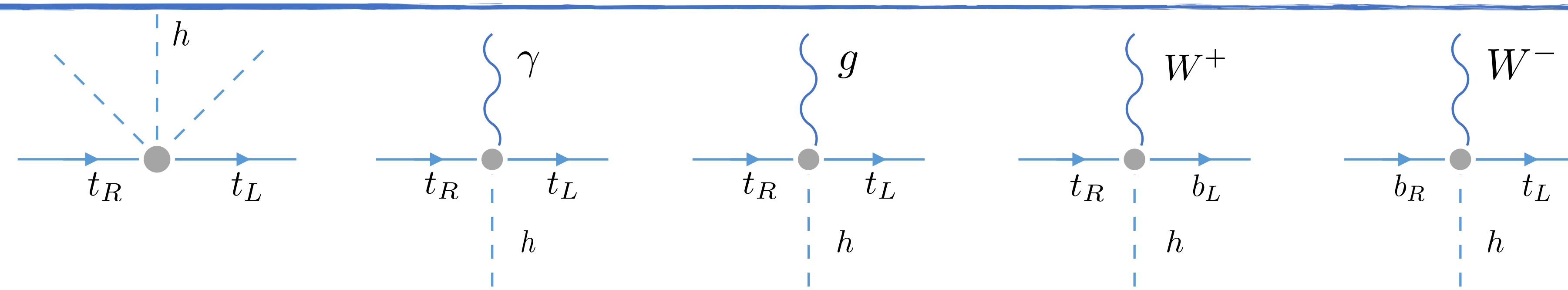
$\delta^-(t \to W^+ b)$

- Most sensitive collider observables are CP-even
  - Not sensitive to the imaginary couplings at the dim-6 level, $\mathcal{O}(1/\Lambda^2)$
- Most other CP-odd collider observables are not yet competitive (more later)

Boudreau, et al, '13

Indirect collider observables

Just real couplings



	C_Y	C_γ	C_g	C_{Wt}	C_{Wb}
$gg \to h$					
$h \to \gamma\gamma$					
S parameter					

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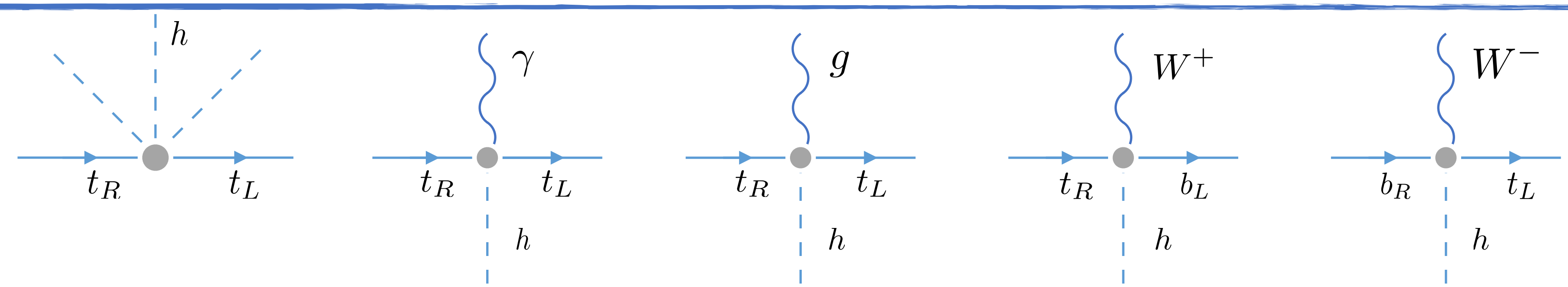

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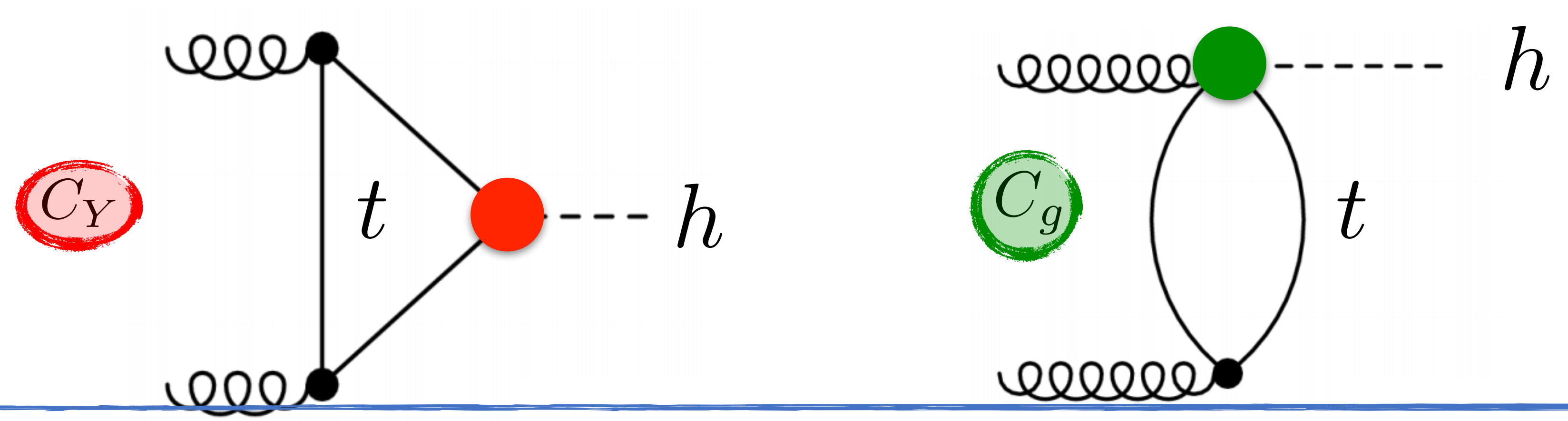

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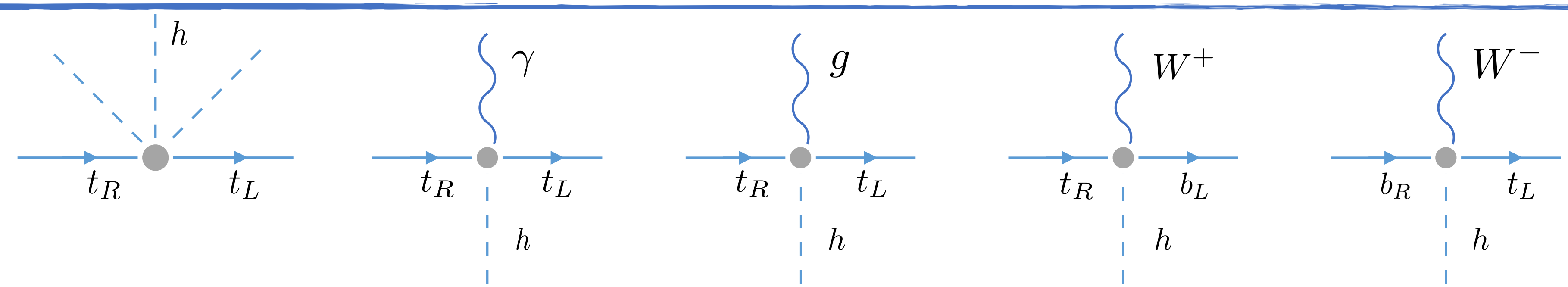

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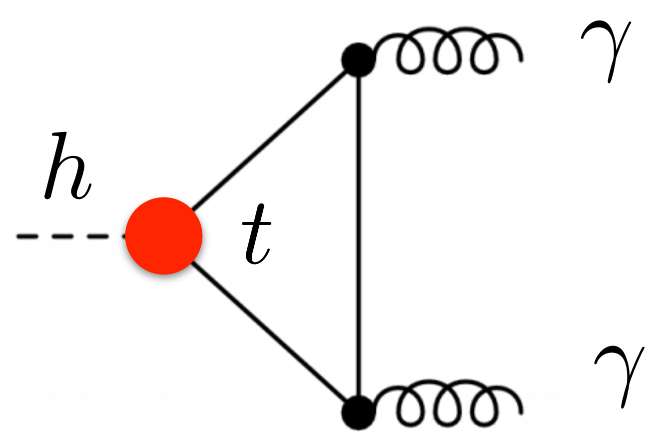
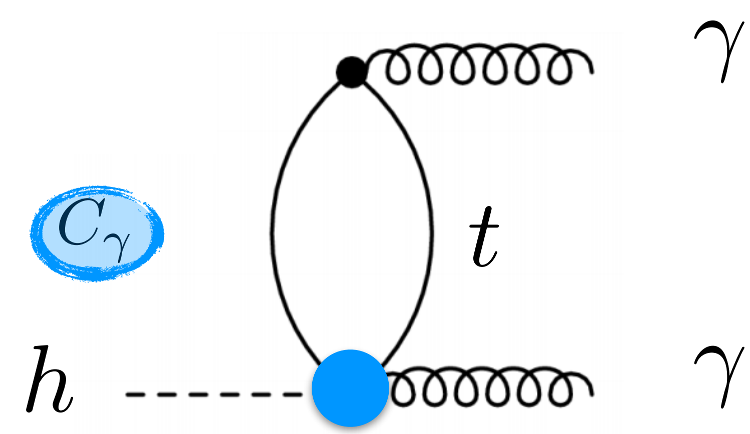
C_Y



C_γ



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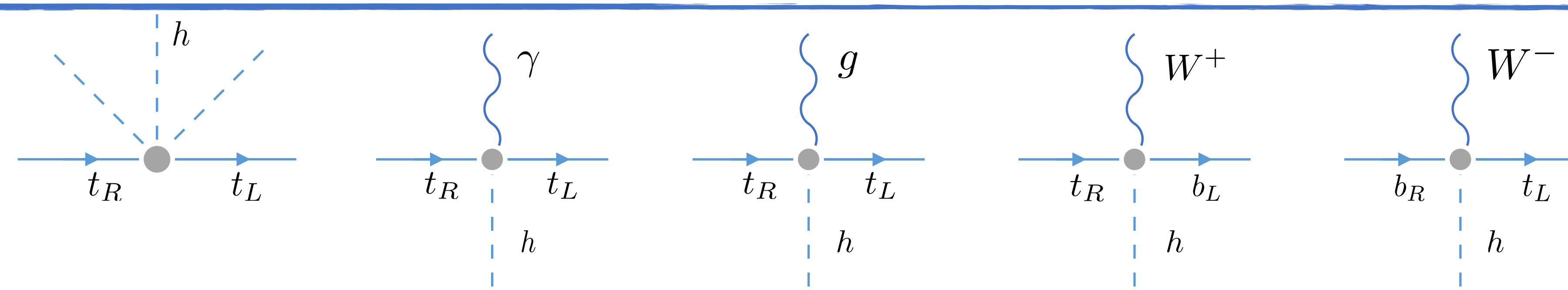

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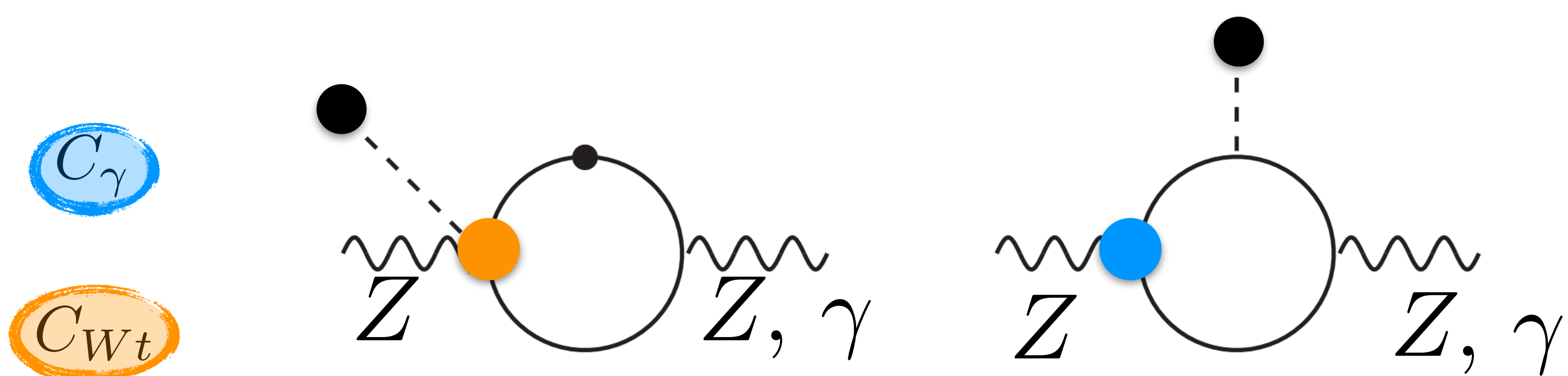

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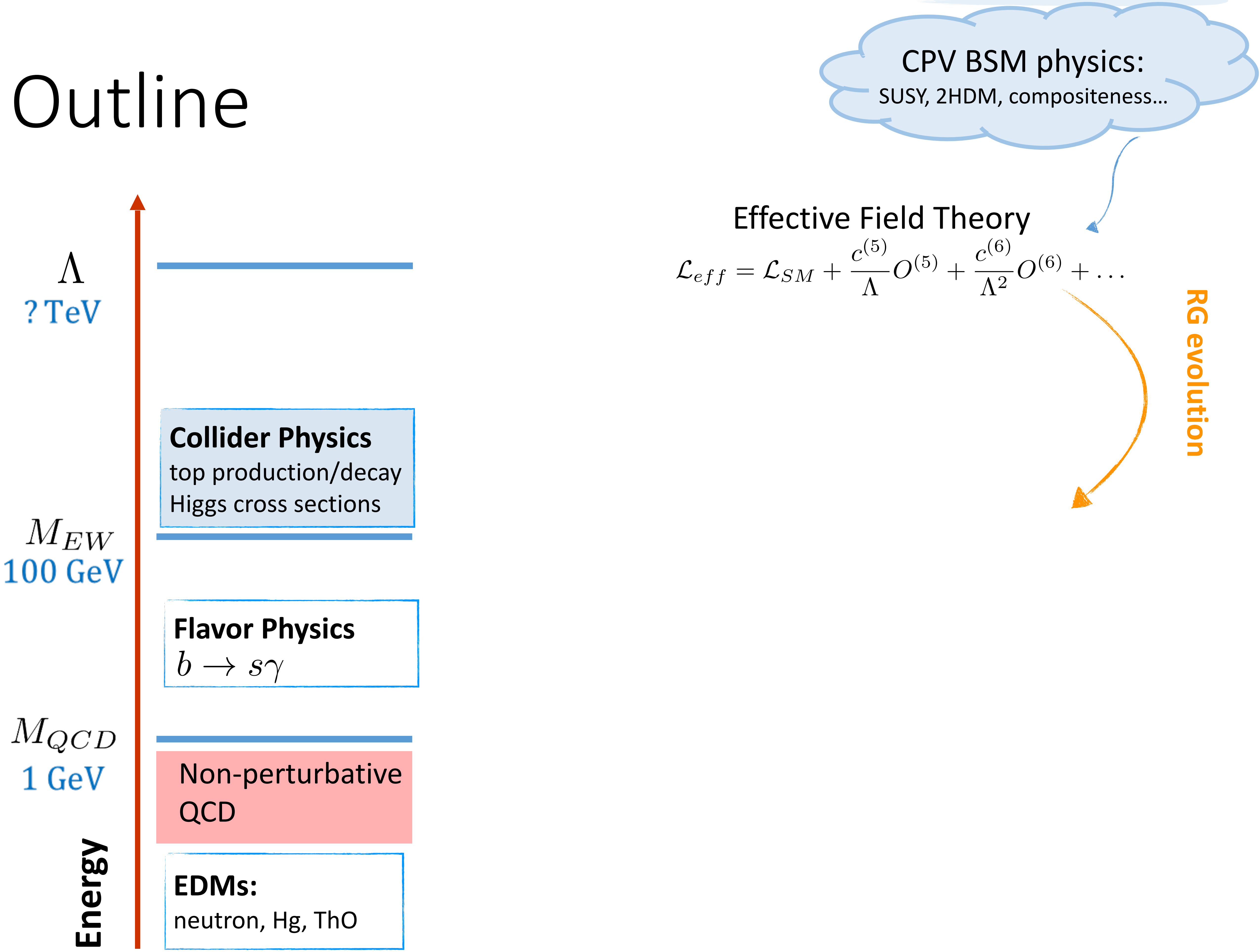
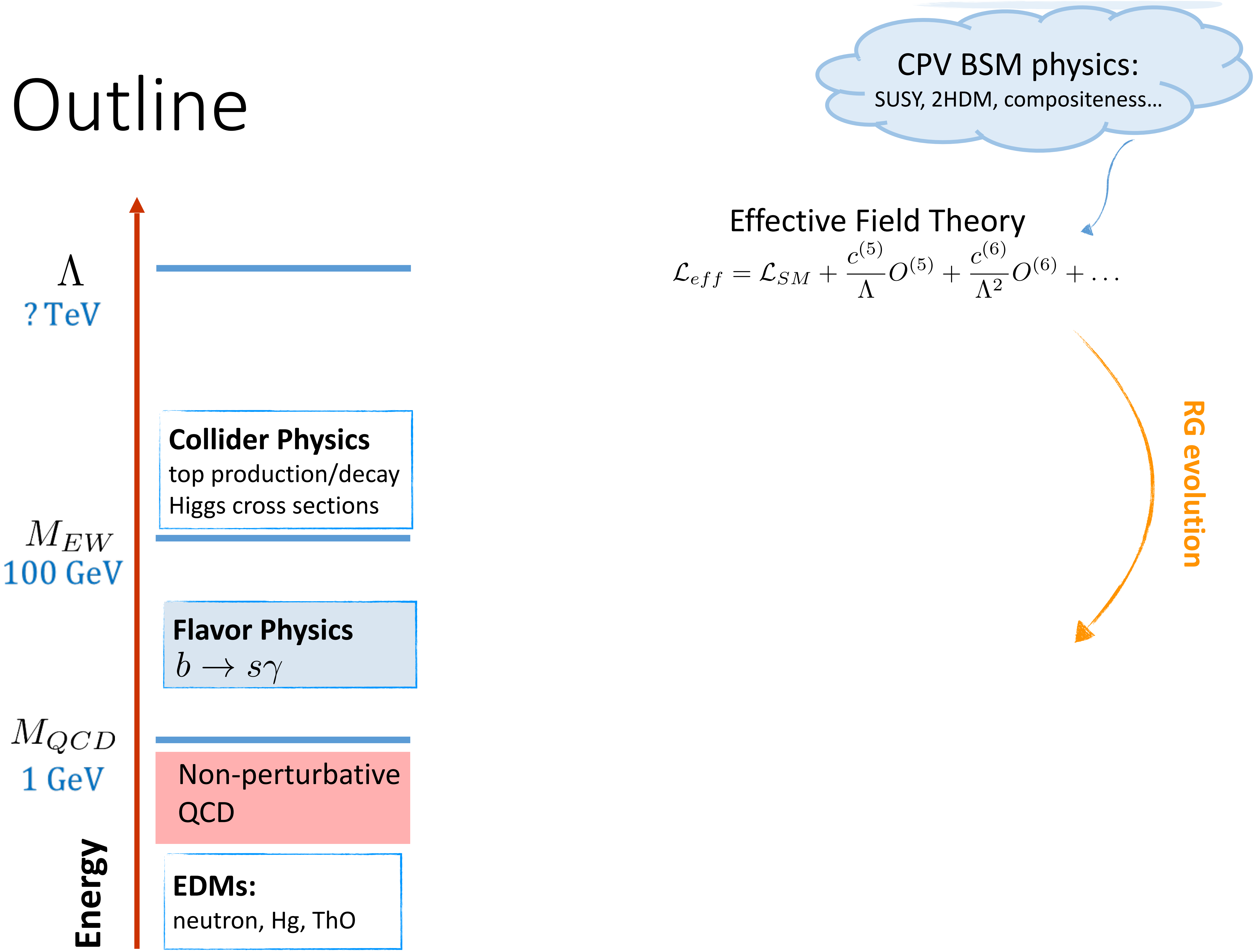
Outline


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

Outline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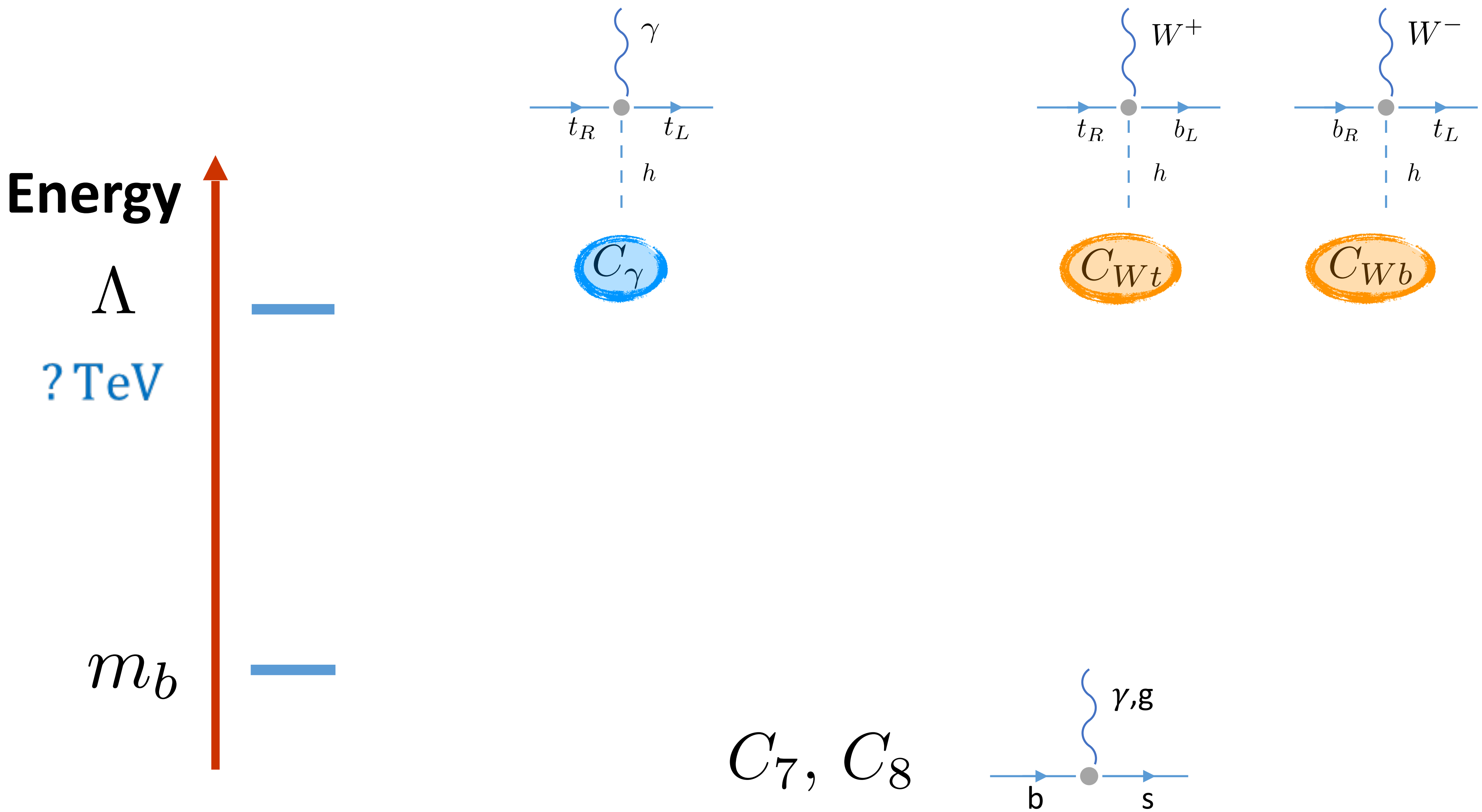

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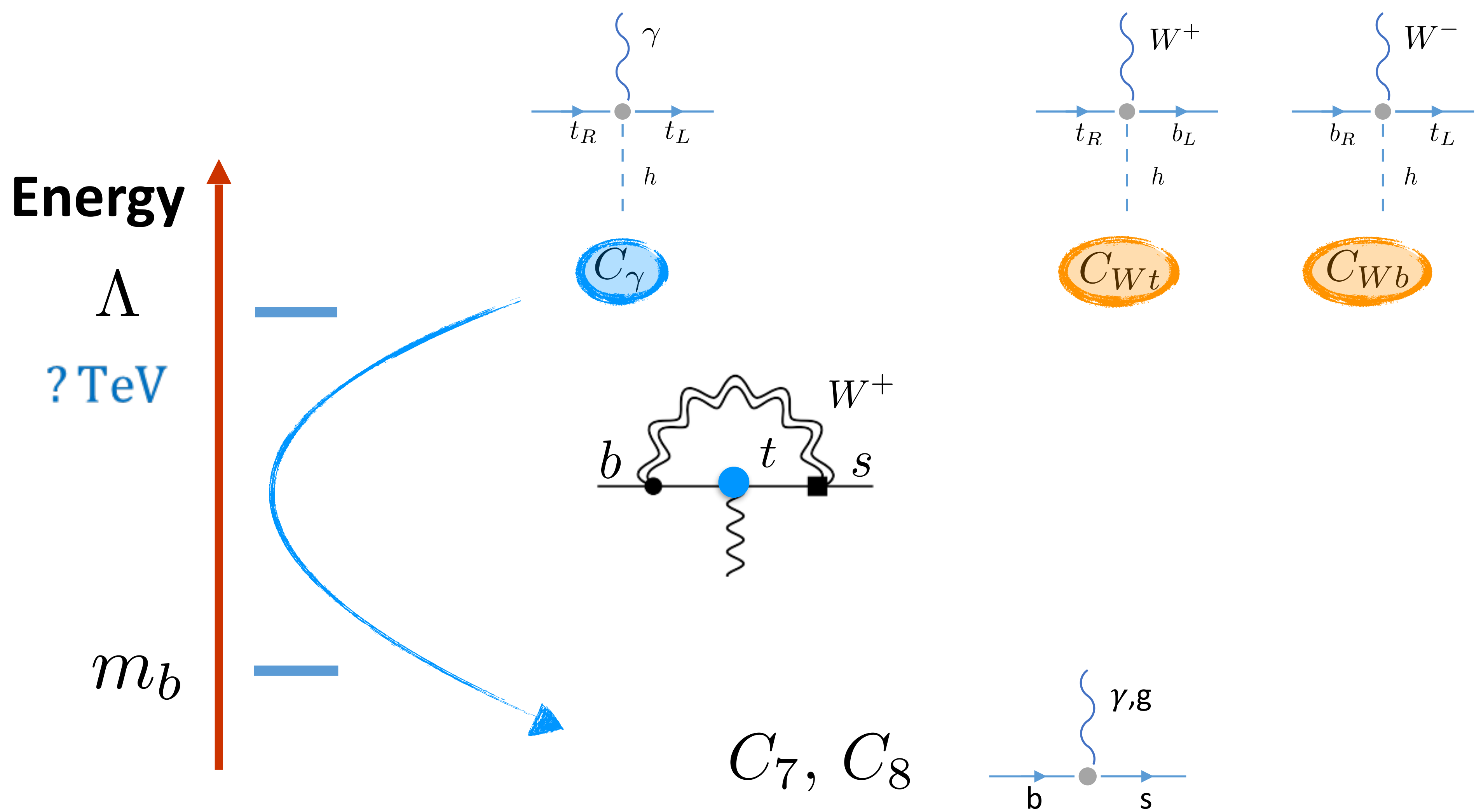

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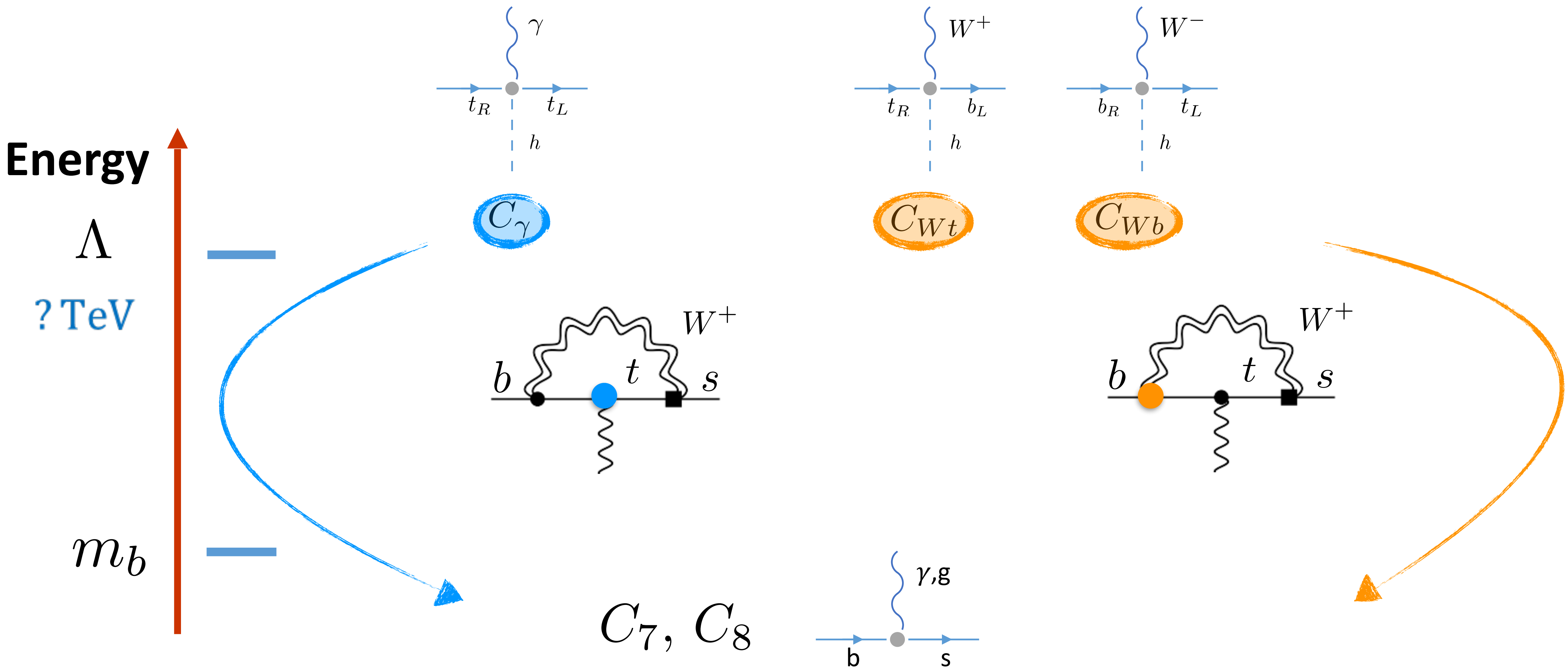

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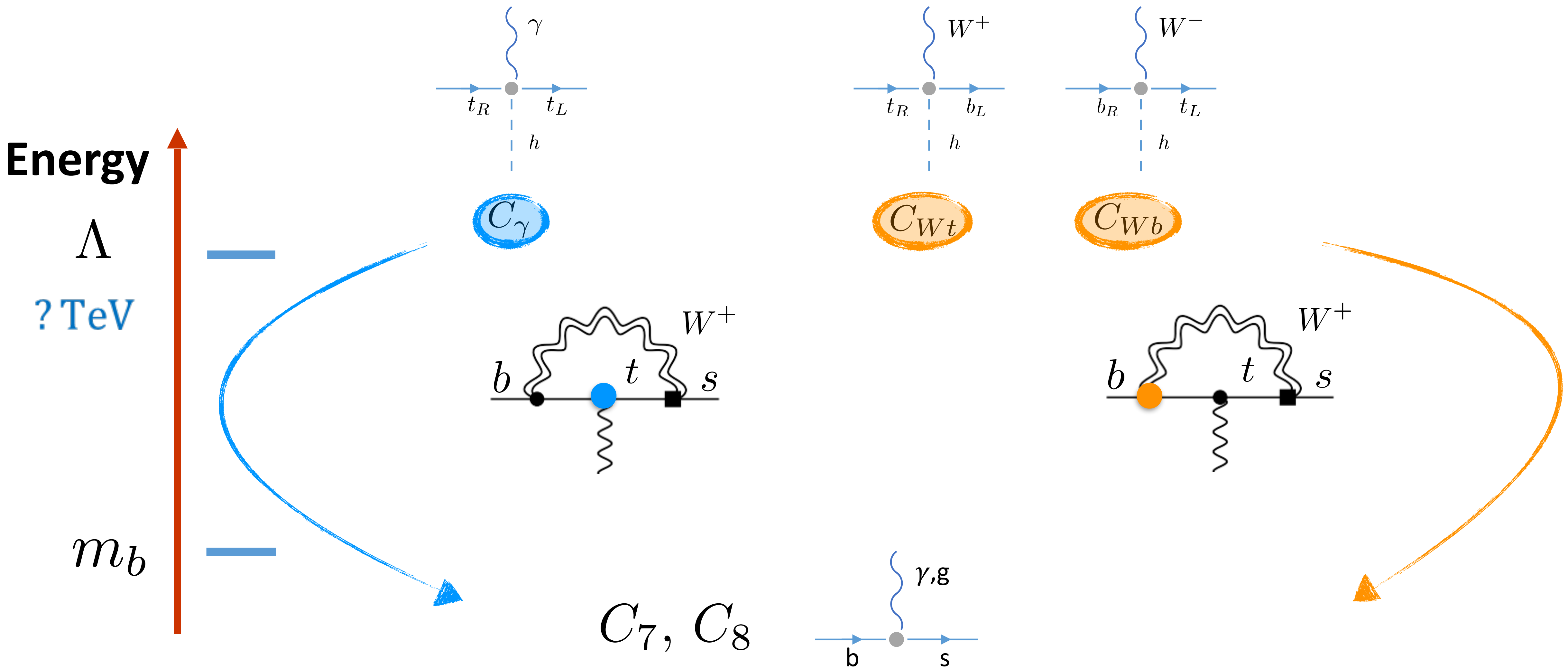

- Real parts contribute mainly to the branching ratio
- Imaginary parts mainly contribute to the CP asymmetry $A_{CP} \equiv \frac{\Gamma(\bar{B} \to X_s\gamma) - \Gamma(B \to X_{\bar{s}}\gamma)}{\Gamma(\bar{B} \to X_s\gamma) + \Gamma(B \to X_{\bar{s}}\gamma)}$

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

Benzke, Lee, Neubert, Paz, '11

Outline

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SUSY, 2HDM, compositeness...

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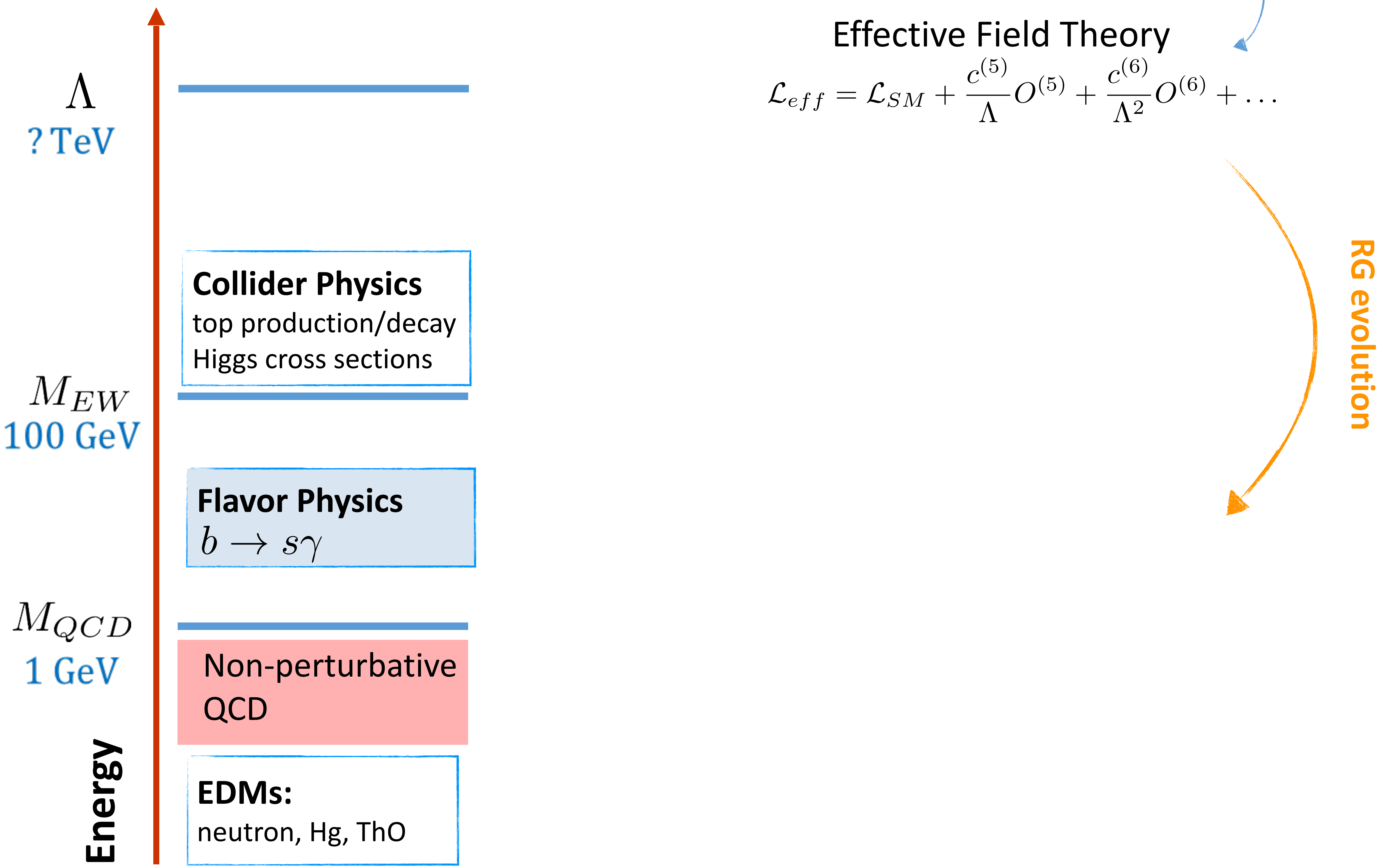
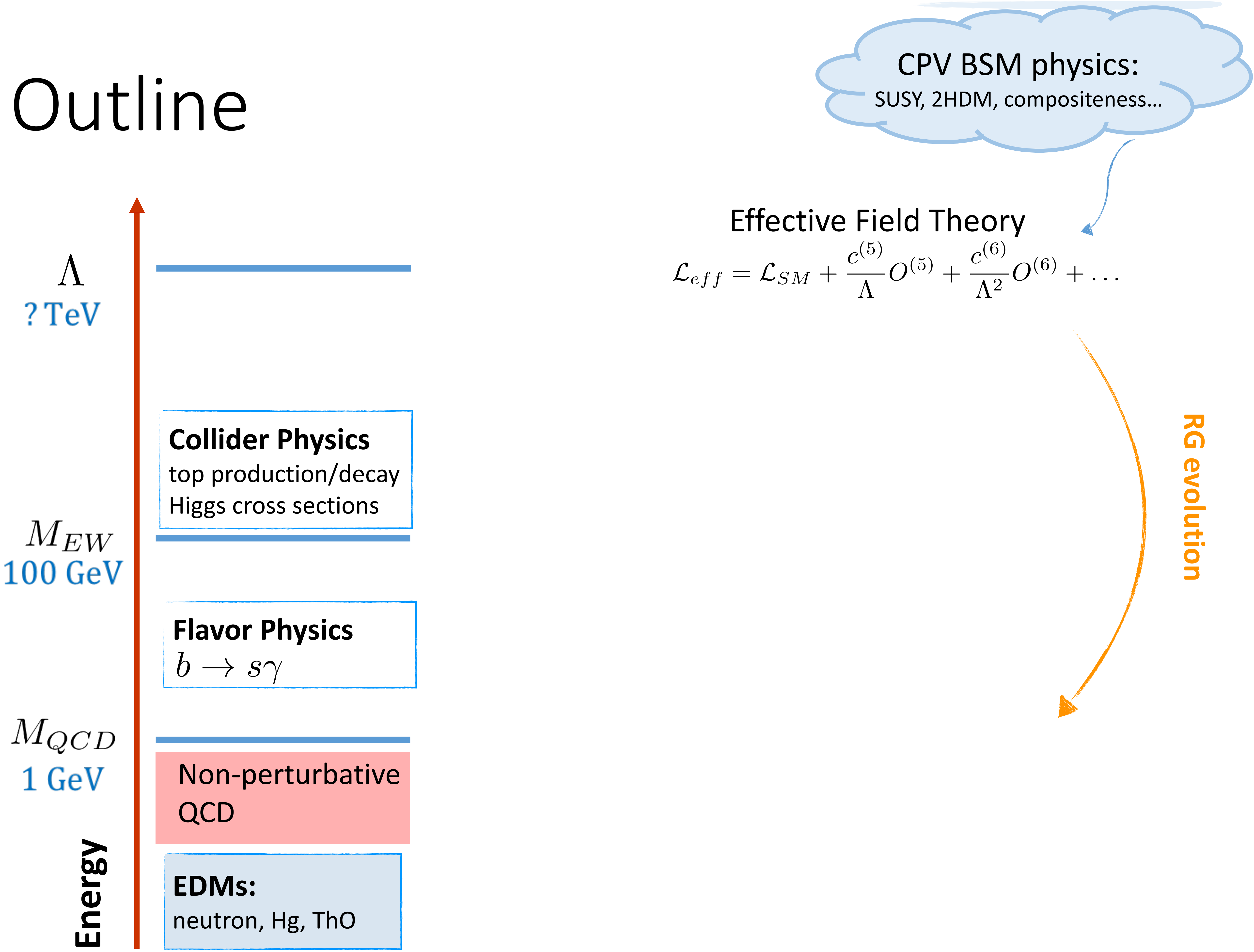


Outline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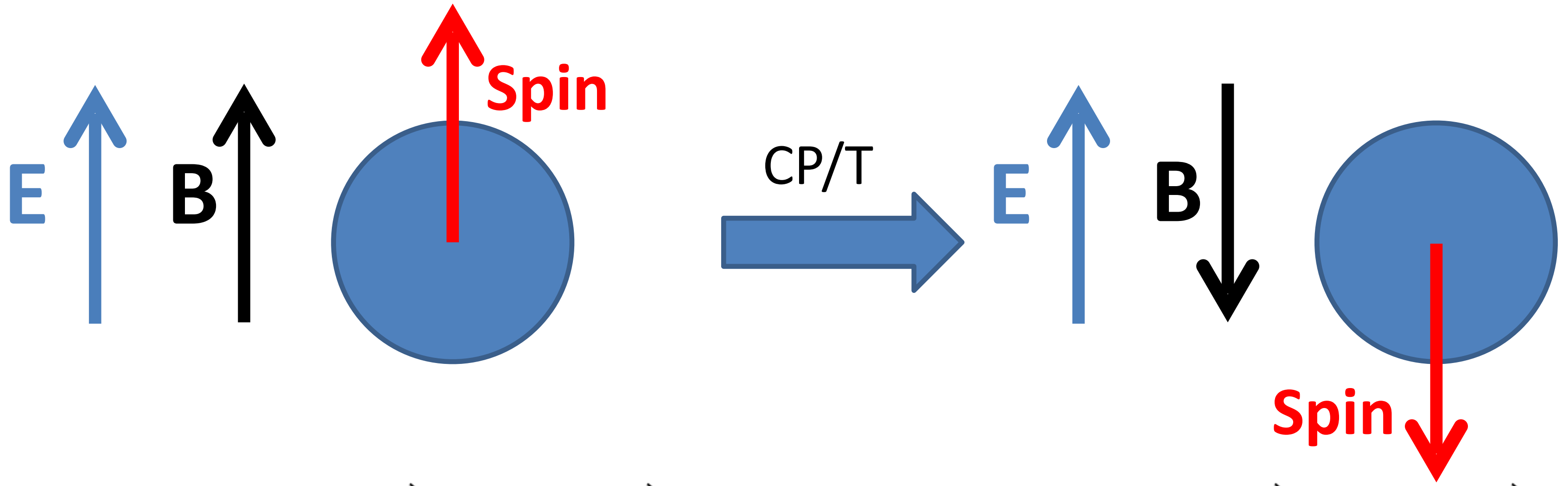
Observables

Electric Dipole Moments



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

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

Observables

Electric Dipole Moments

Most stringent 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}	Recent factor 4 improvement	5.0×10^{-30}

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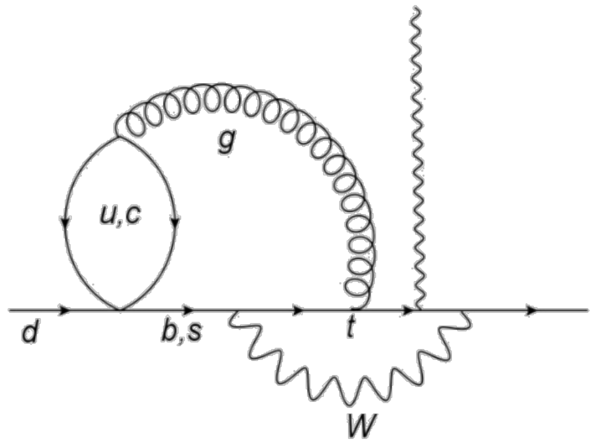
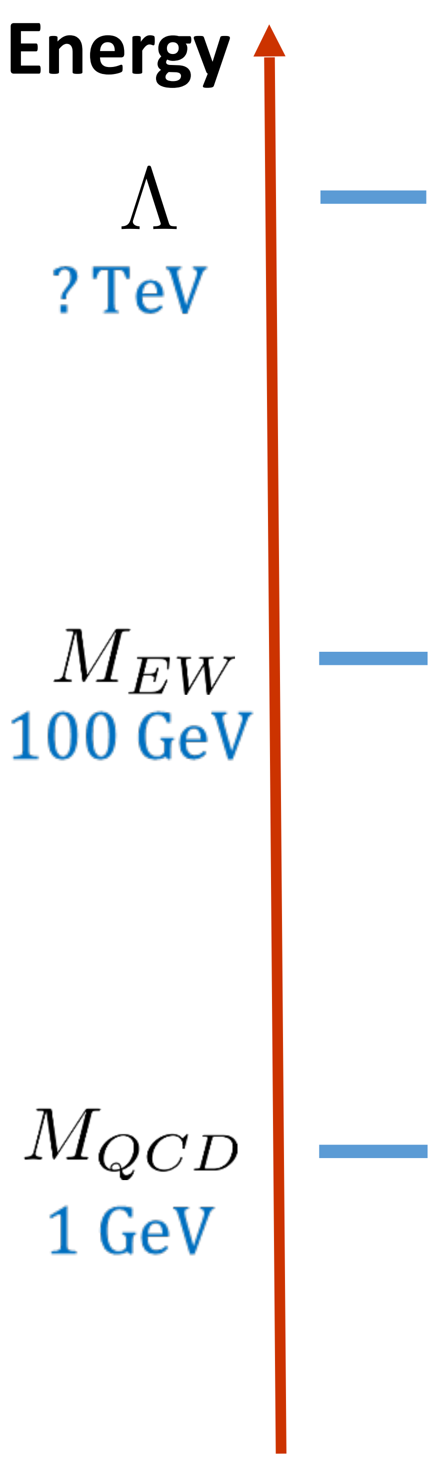
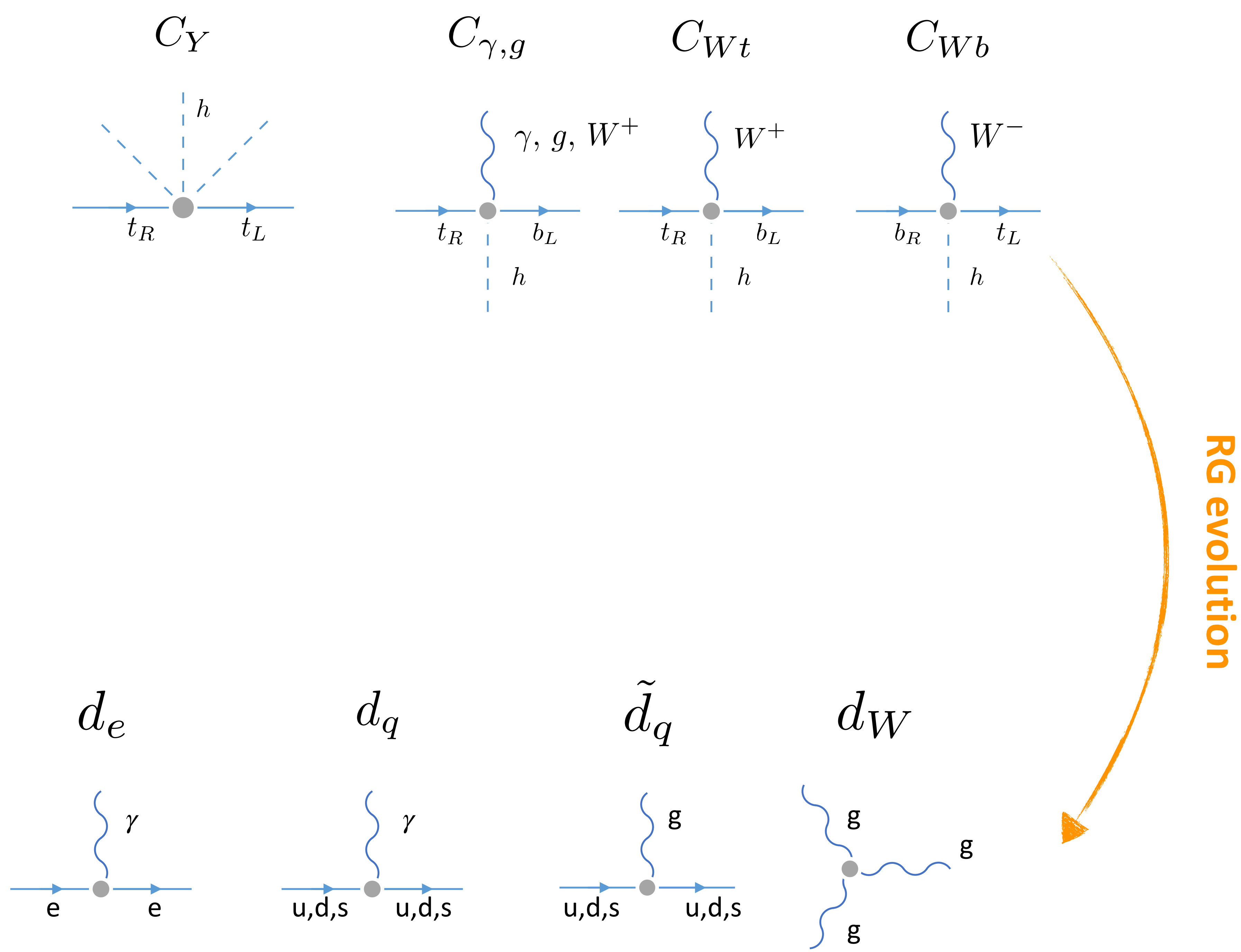
SM background



- The electroweak (CKM) contribution is negligible
- Unknown contribution from the QCD theta term, $\propto \theta \epsilon^{\alpha\beta\mu\nu} G^a_{\mu\nu} G^a_{\alpha\beta}$
  - Will assume a Peccei-Quinn mechanism in this talk

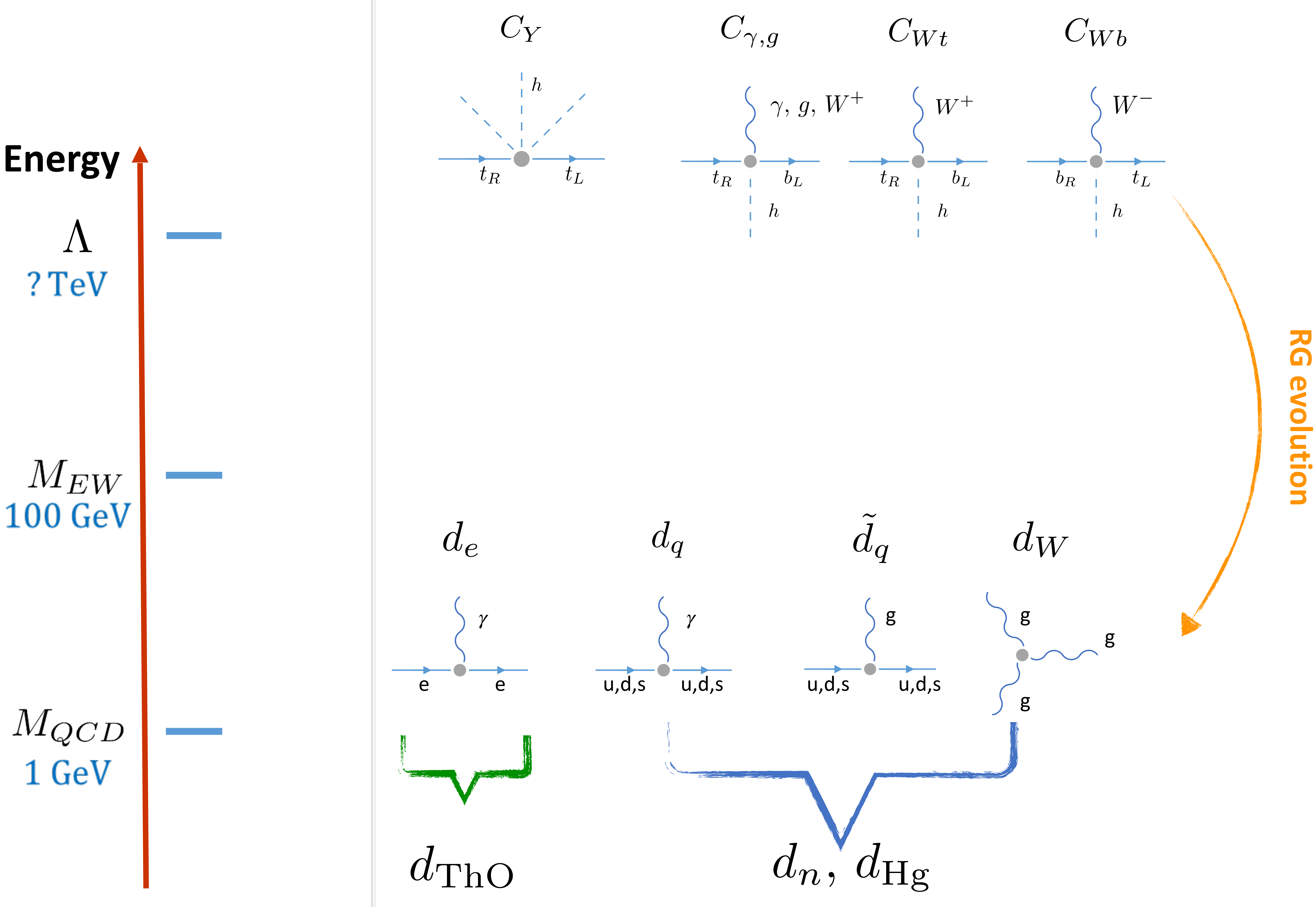
Connection to low-energy Lagrangian





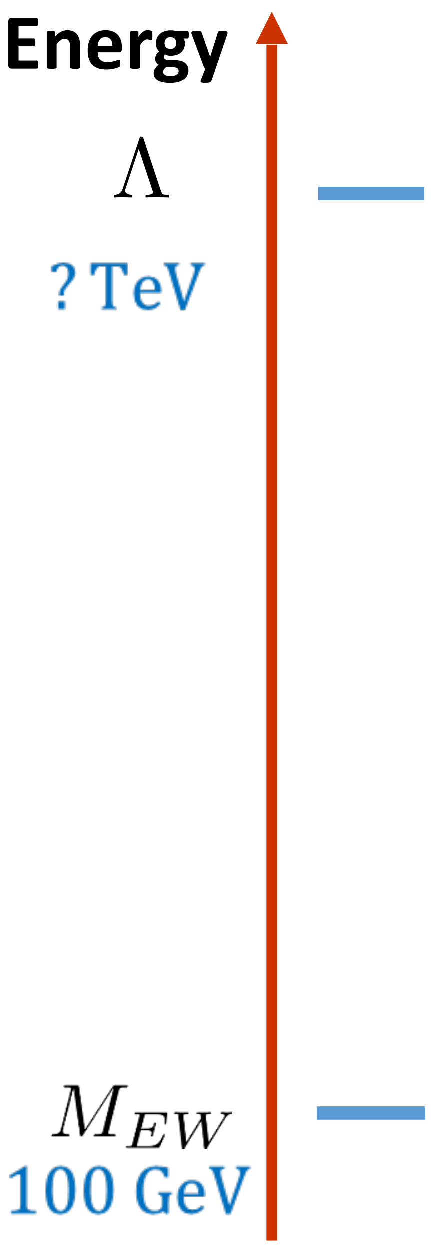
$$\mathcal{L}_6 = -\frac{i}{2}\sum_{f=e,u,d,s}\bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s}\bar{q}\sigma\cdot G\gamma_5 q + \frac{d_W}{3} f_{abc}G^a G^b \tilde{G}^c$$

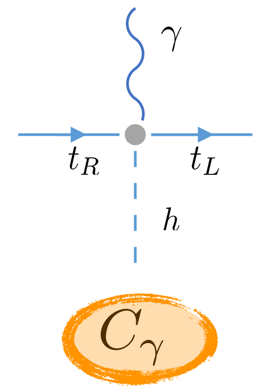
Connection to low-energy Lagrangian

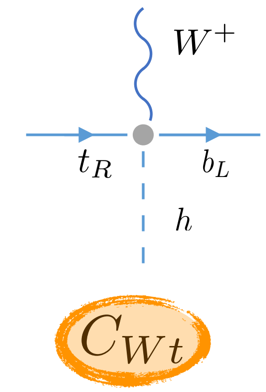


Mixing onto 1-GeV Lagrangian

Direct contribution (one-loop)







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

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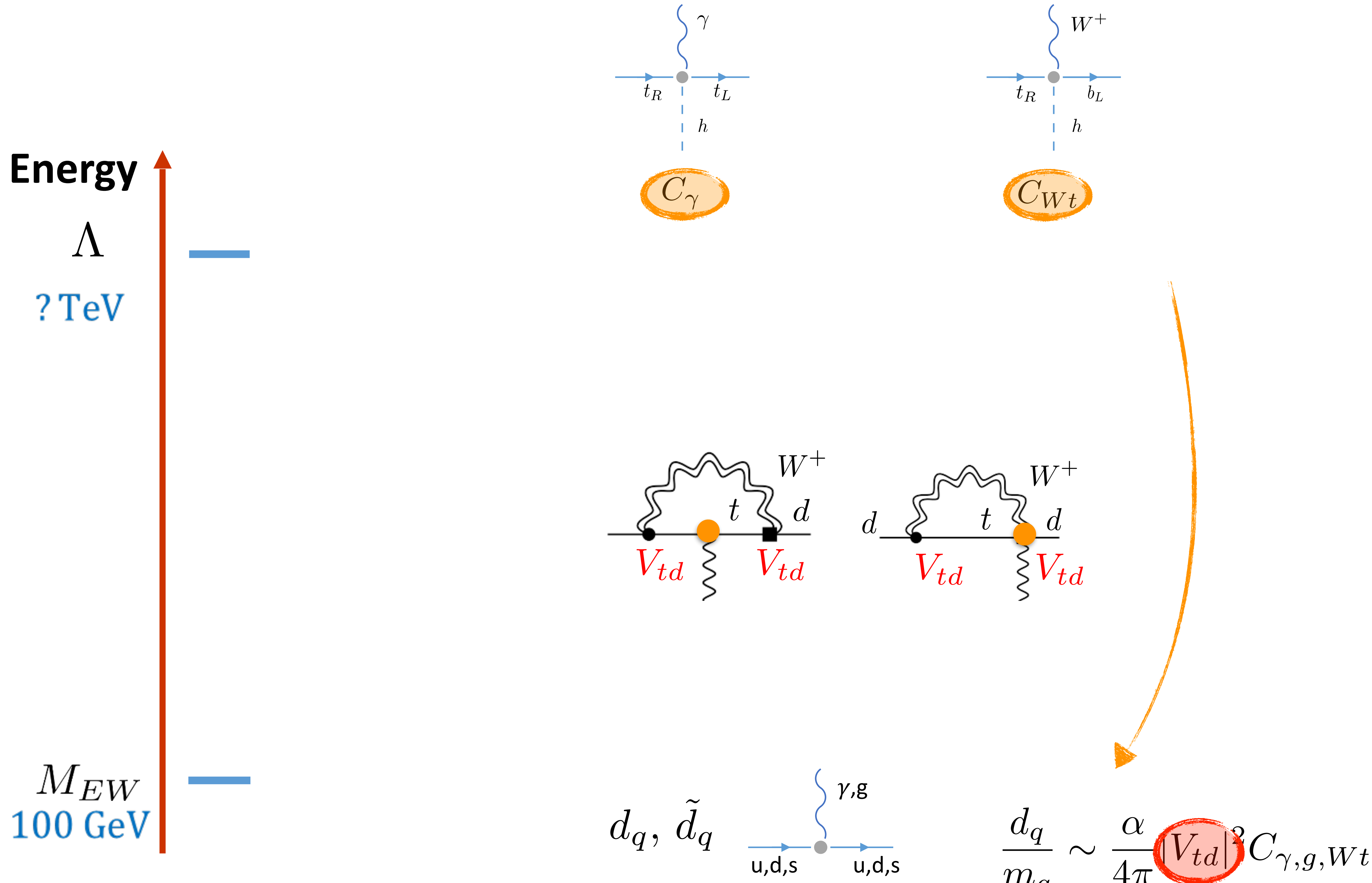

$$\frac{d_q}{m_q} \sim \frac{\alpha}{4\pi} |V_{td}|^2 C_{\gamma,g,Wt}$$

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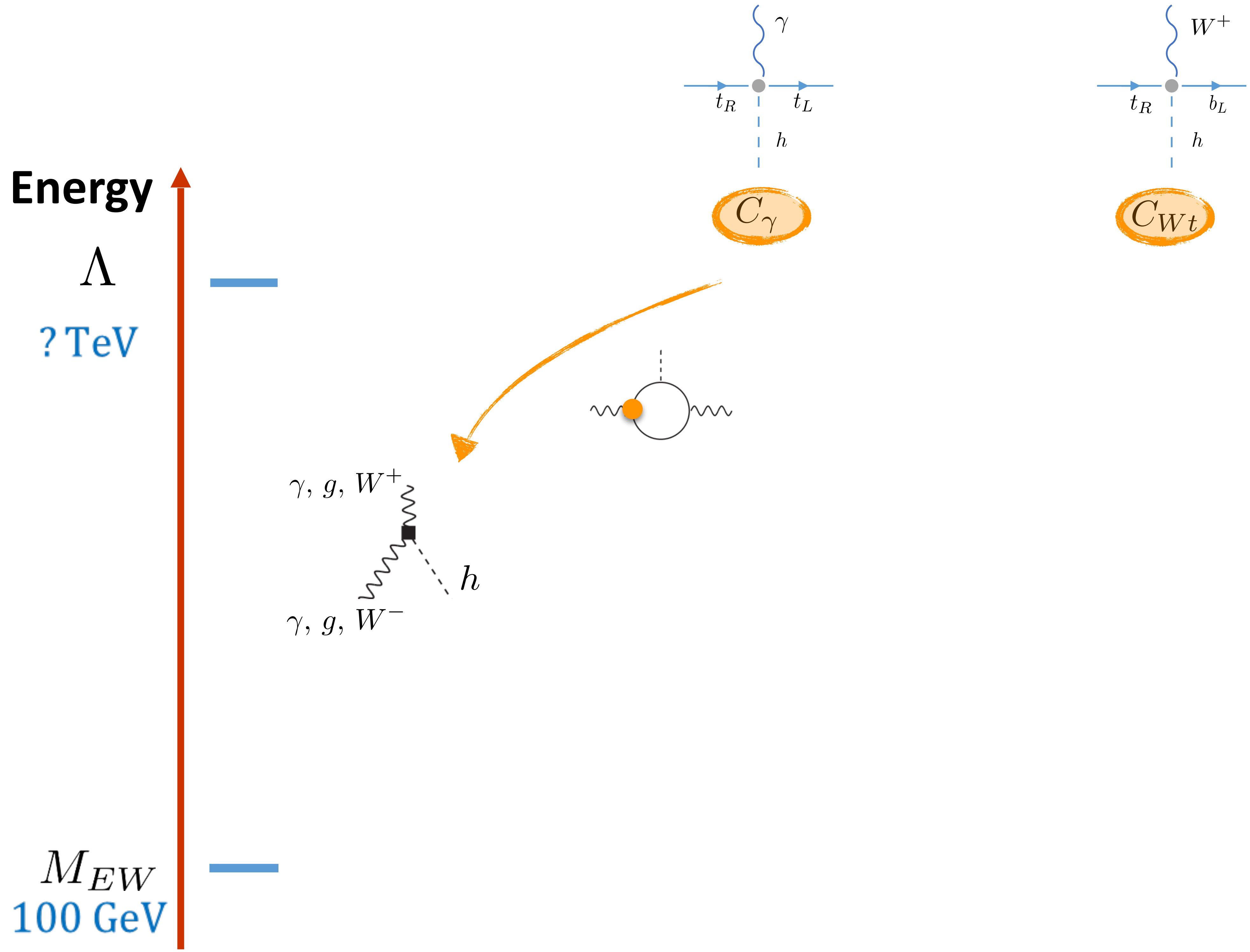
Mixing onto 1-GeV Lagrangian

Two-step mechanism



Cirigliano, de Vries, Mereghetti, WD, '16

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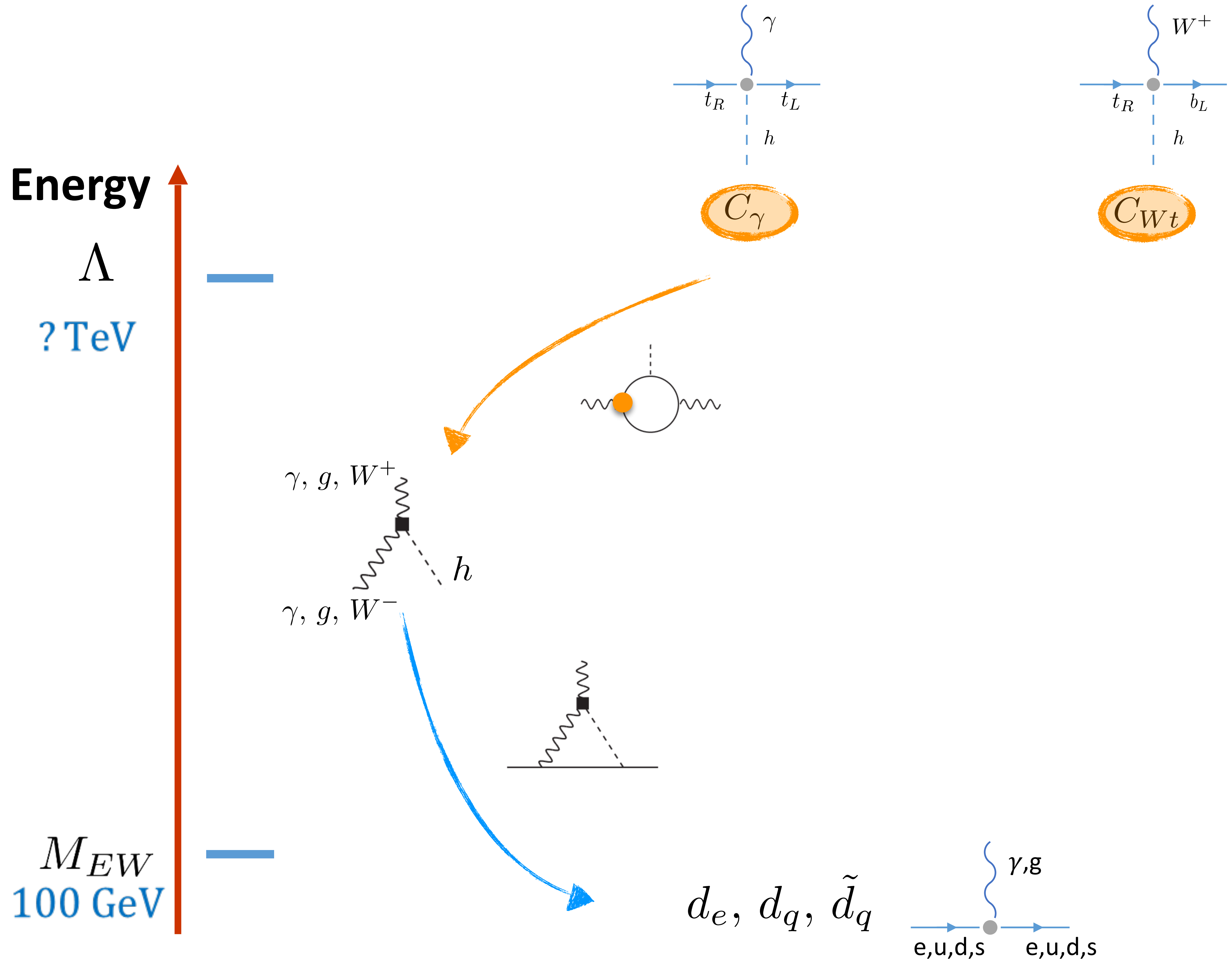

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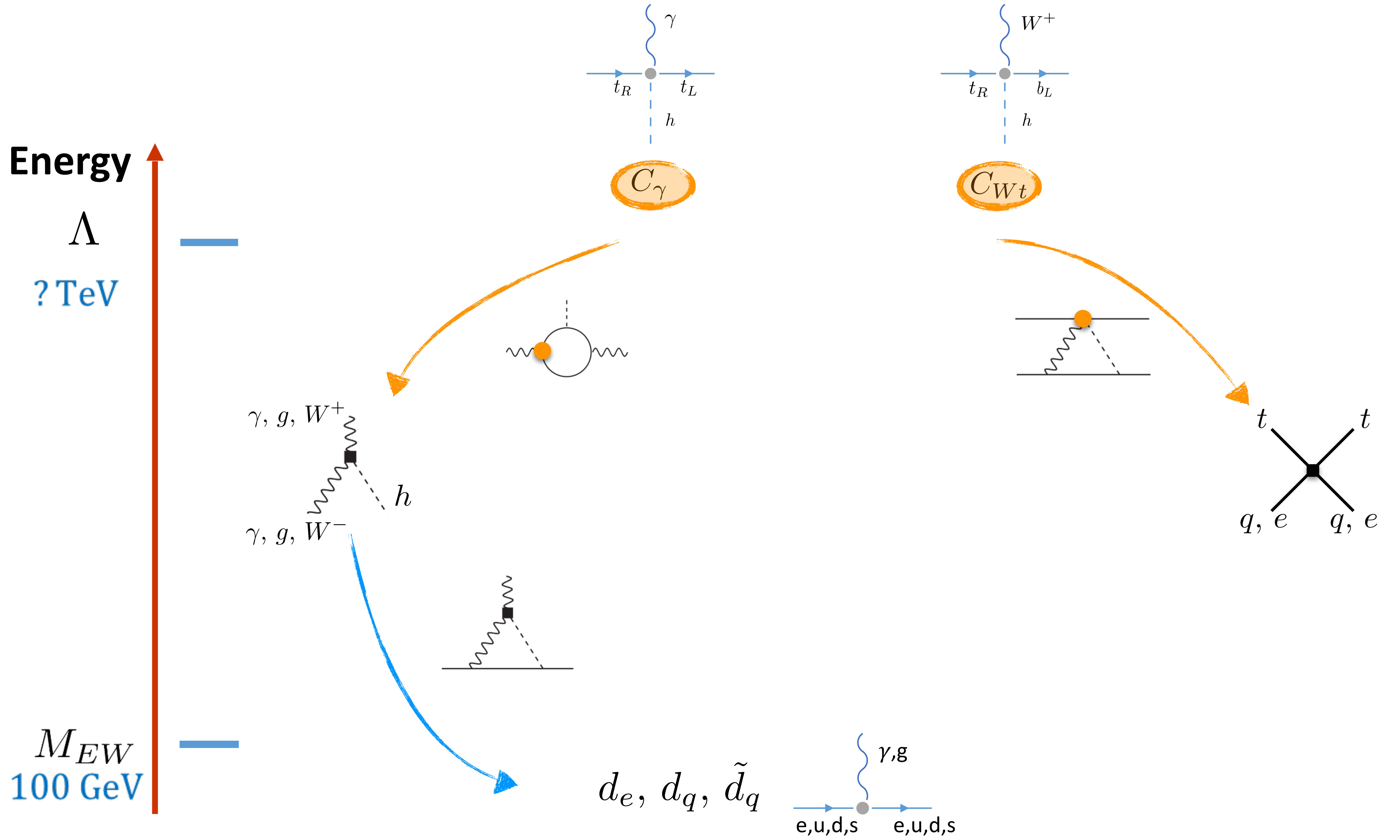

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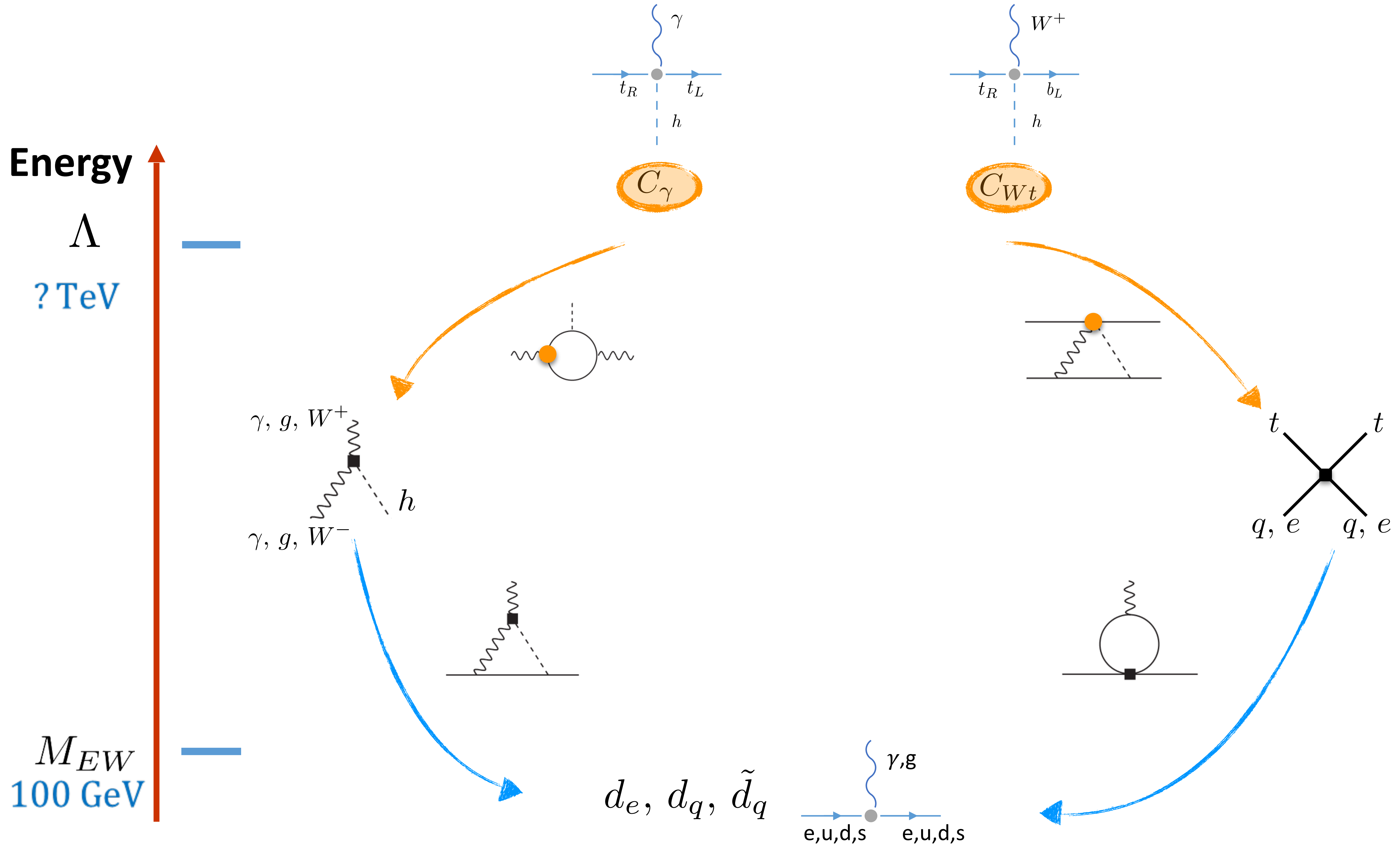

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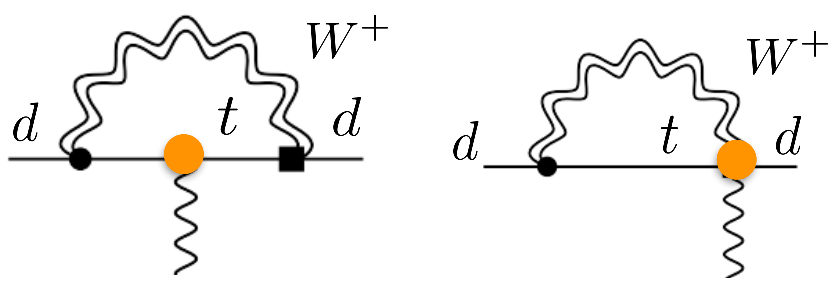
Mixing onto 1-GeV Lagrangian

Two-step vs direct contributions

- Direct contribution (one-loop) $\frac{d_q}{m_q} \sim \frac{\alpha}{4\pi}|V_{td}|^2 C_{\gamma,g,Wt}$



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  - **Enhanced**
  - Induces an electron EDM (expt. limit a factor $\sim 10^2$ more stringent than d_n)

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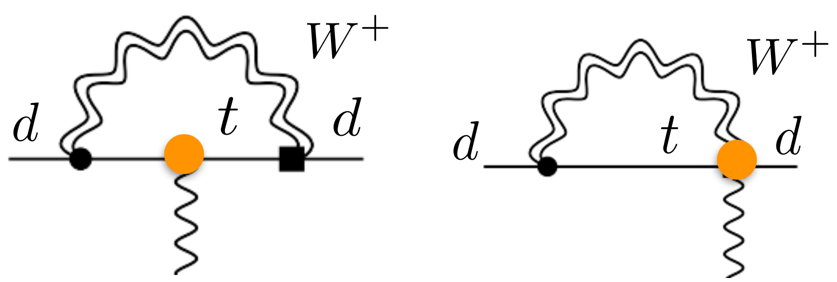

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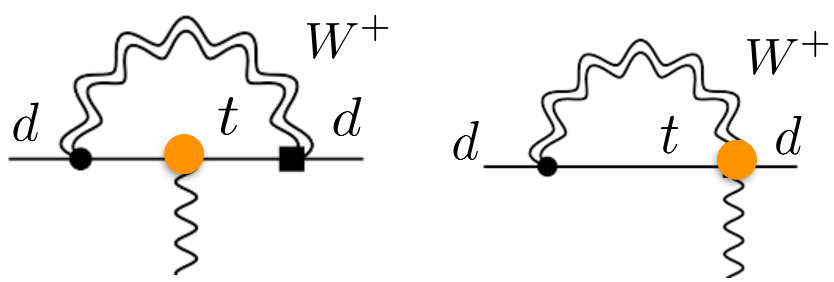

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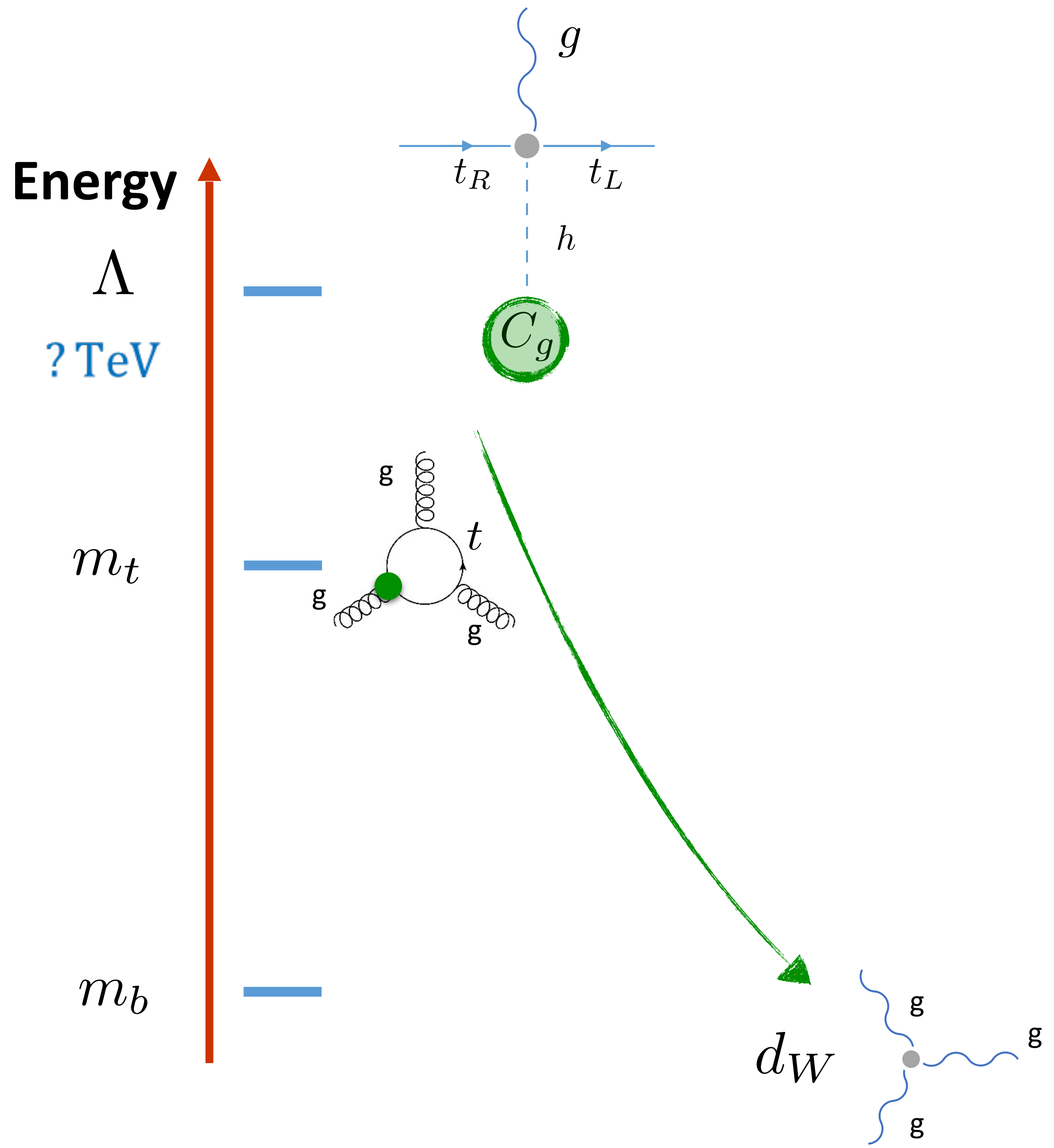
Other (threshold) contributions are relevant

Contribution to 1-GeV Lagrangian

Threshold contributions



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

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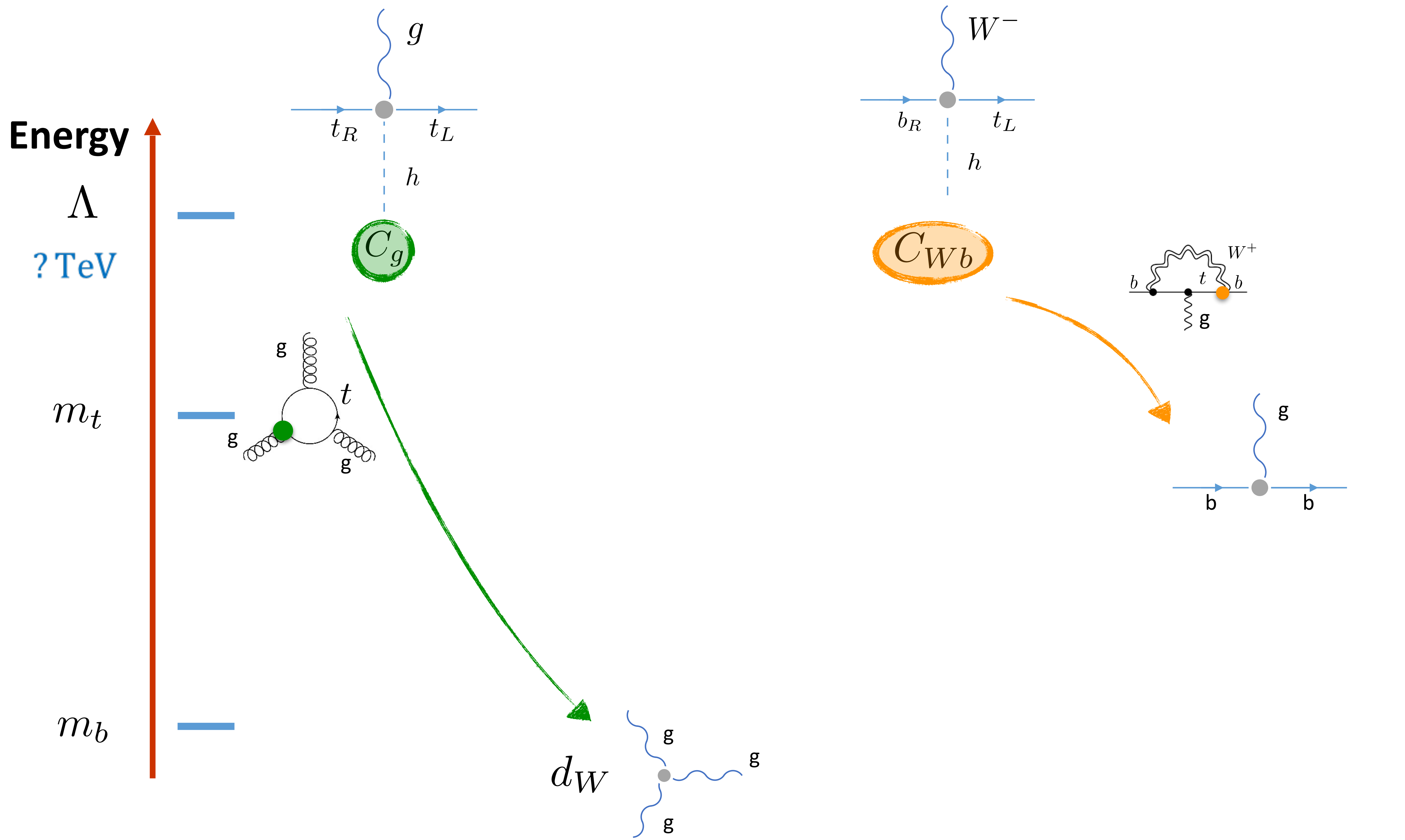

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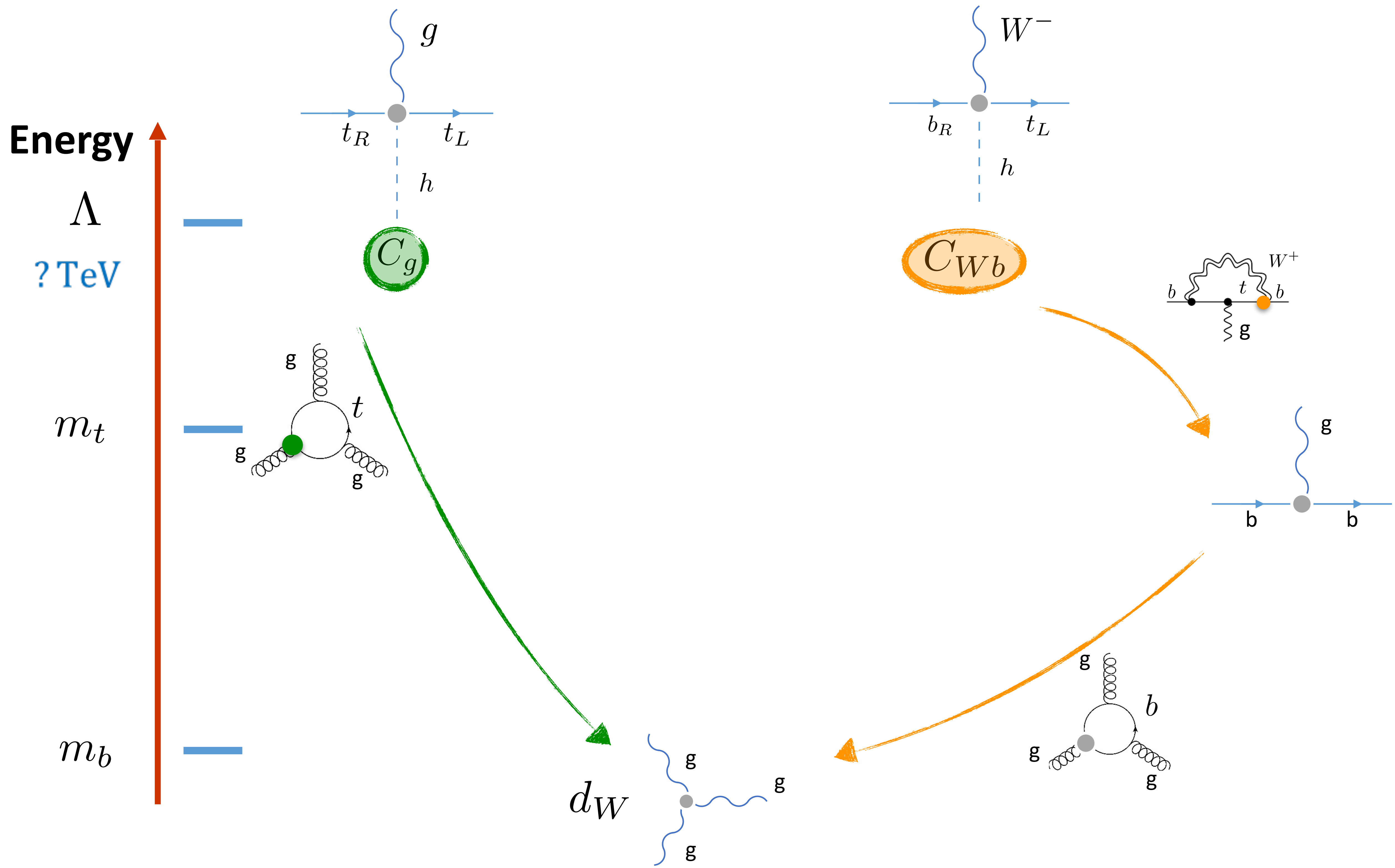

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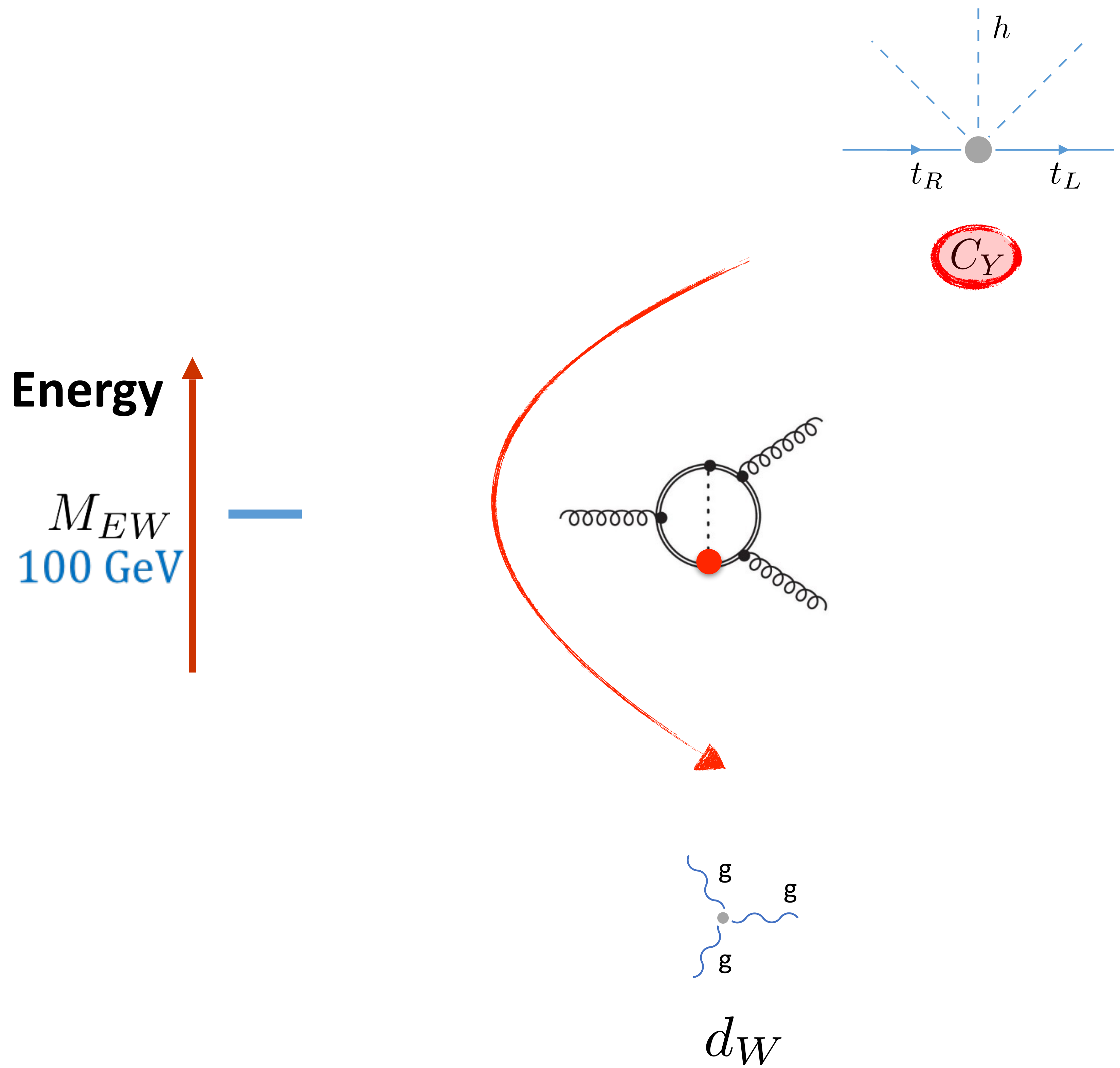

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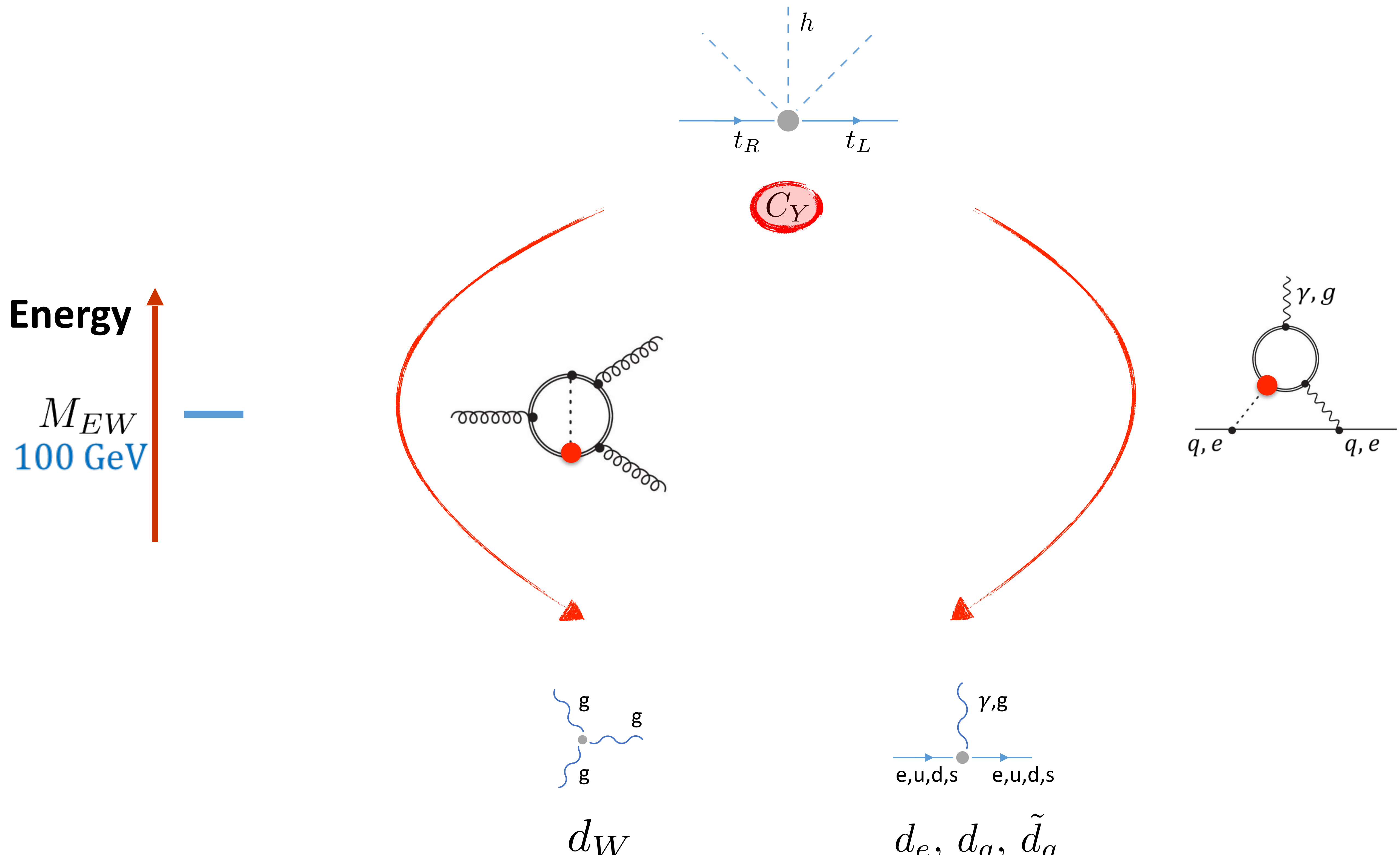

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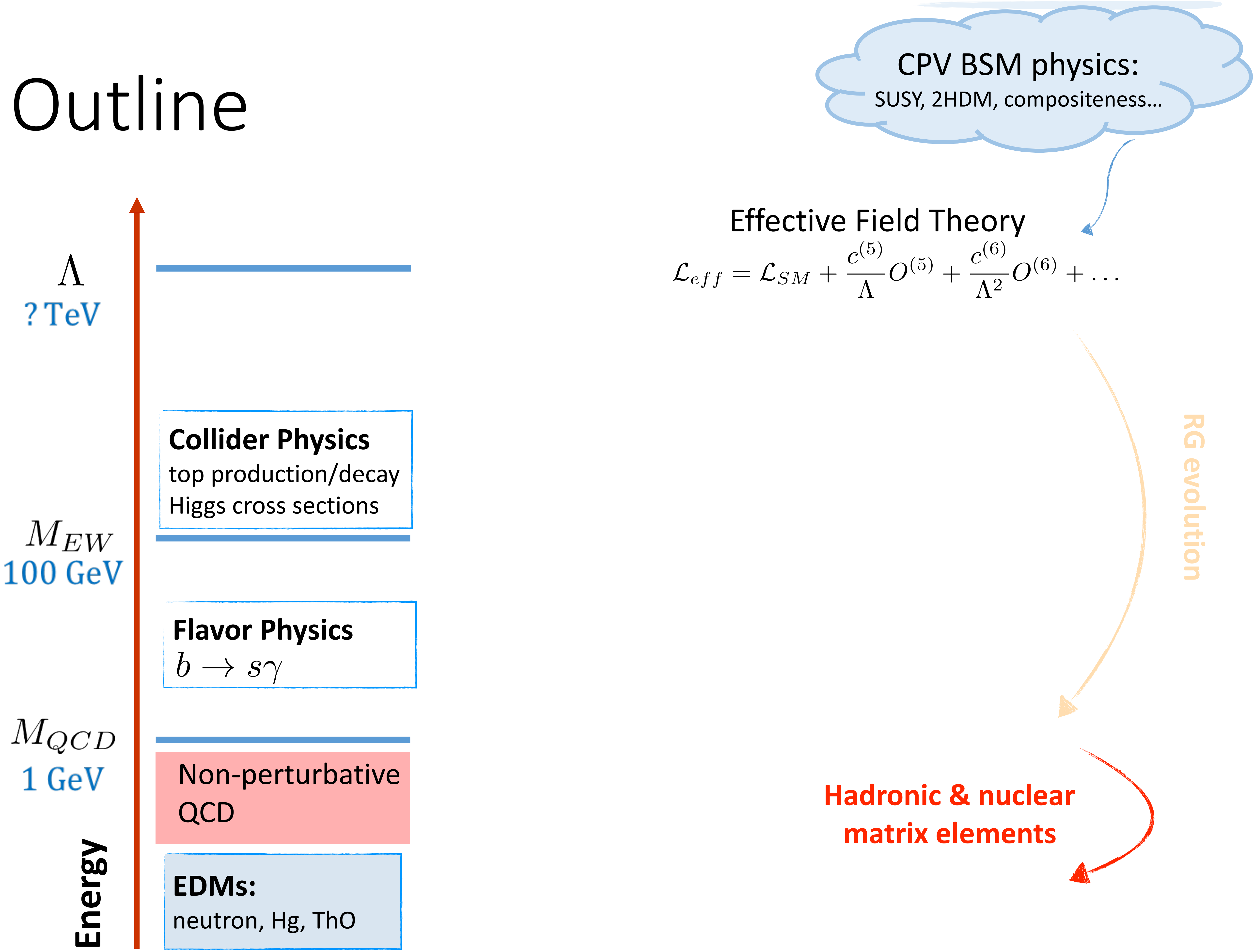
Energy

Outline


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

Below 1 GeV

ThO measurement

- Effectively a constraint on the electron EDM in our case $d_e \leq 8.7 \times 10^{-29} e\,\mathrm{cm}$

- Uncertainties estimated to be at the 15% level

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

Below 1 GeV

ThO measurement

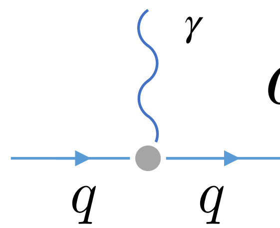
- Effectively a constraint on the electron EDM in our case $d_e \leq 8.7 \times 10^{-29} e\,\mathrm{cm}$

- Uncertainties estimated to be at the 15% level

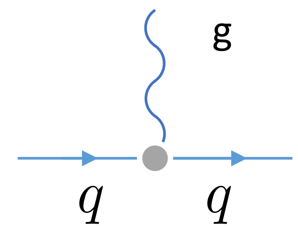
- Uncertainties are well under control in this case
- Much more important for hadronic EDMs

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

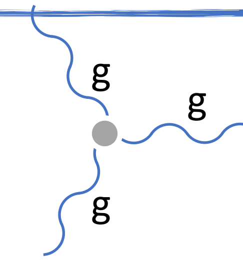
Below 1 GeV



d_q



$\tilde{d}_q$



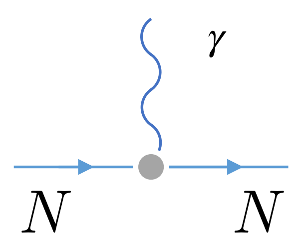
d_W

Energy

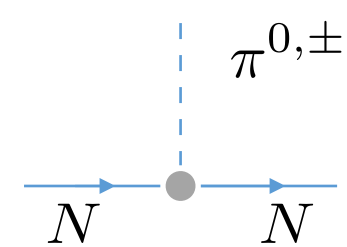
M_{QCD}
1 GeV

d.of.: Quarks, Gluons, photons

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

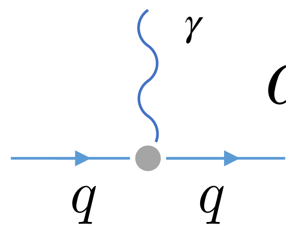


$d_{n,p}$

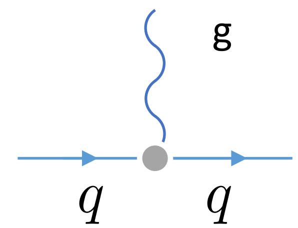


$\bar{g}_{0,1}$

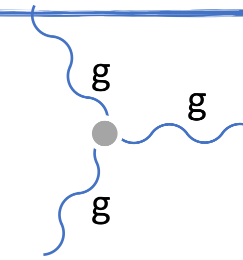
Below 1 GeV



d_q



$\tilde{d}_q$



d_W

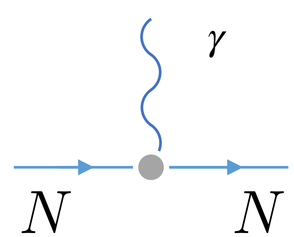
Energy

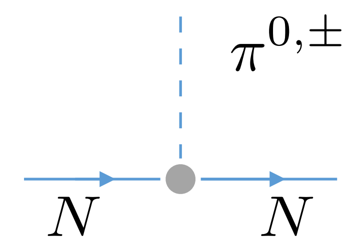
M_{QCD}
1 GeV

d.of.: Quarks, Gluons, photons

Hadronic Matrix Elements

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

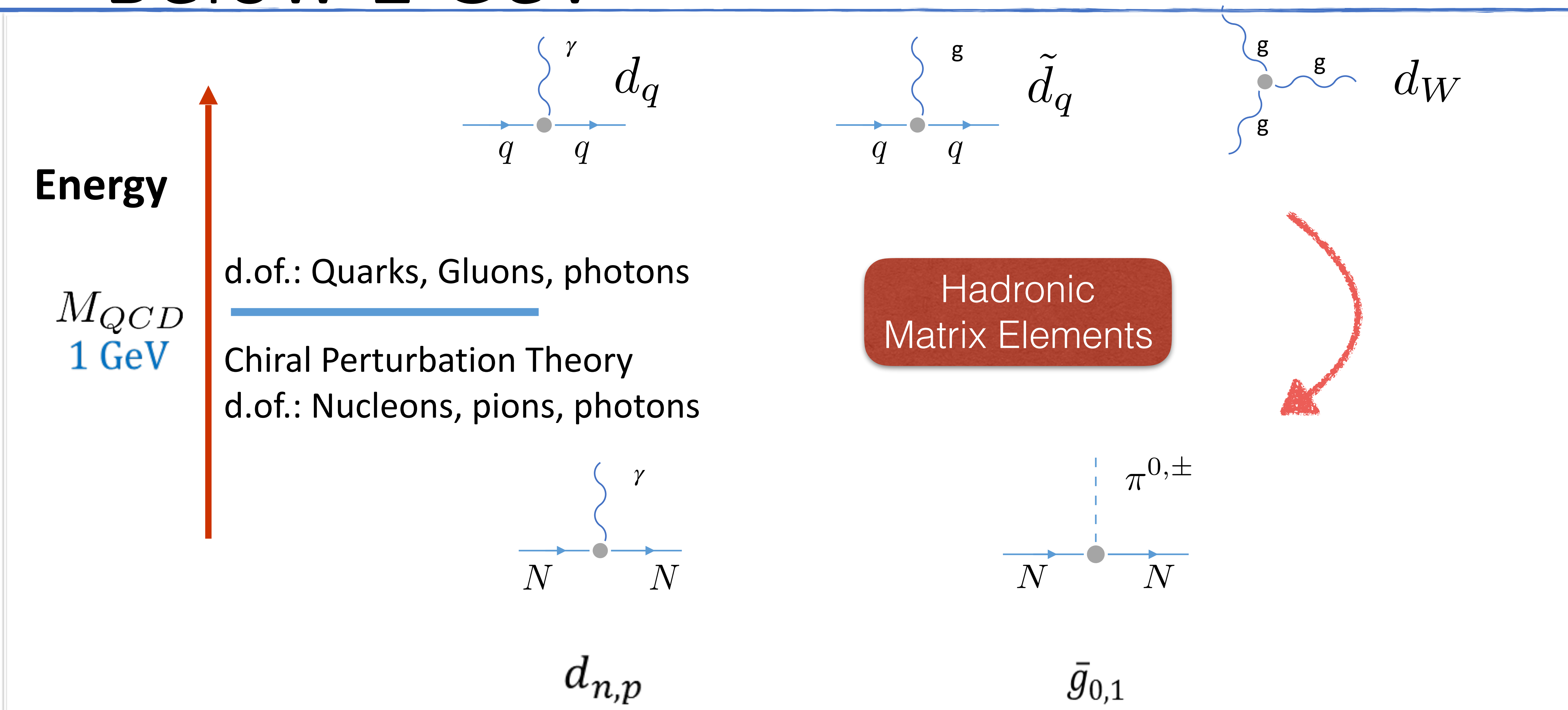




$d_{n,p}$

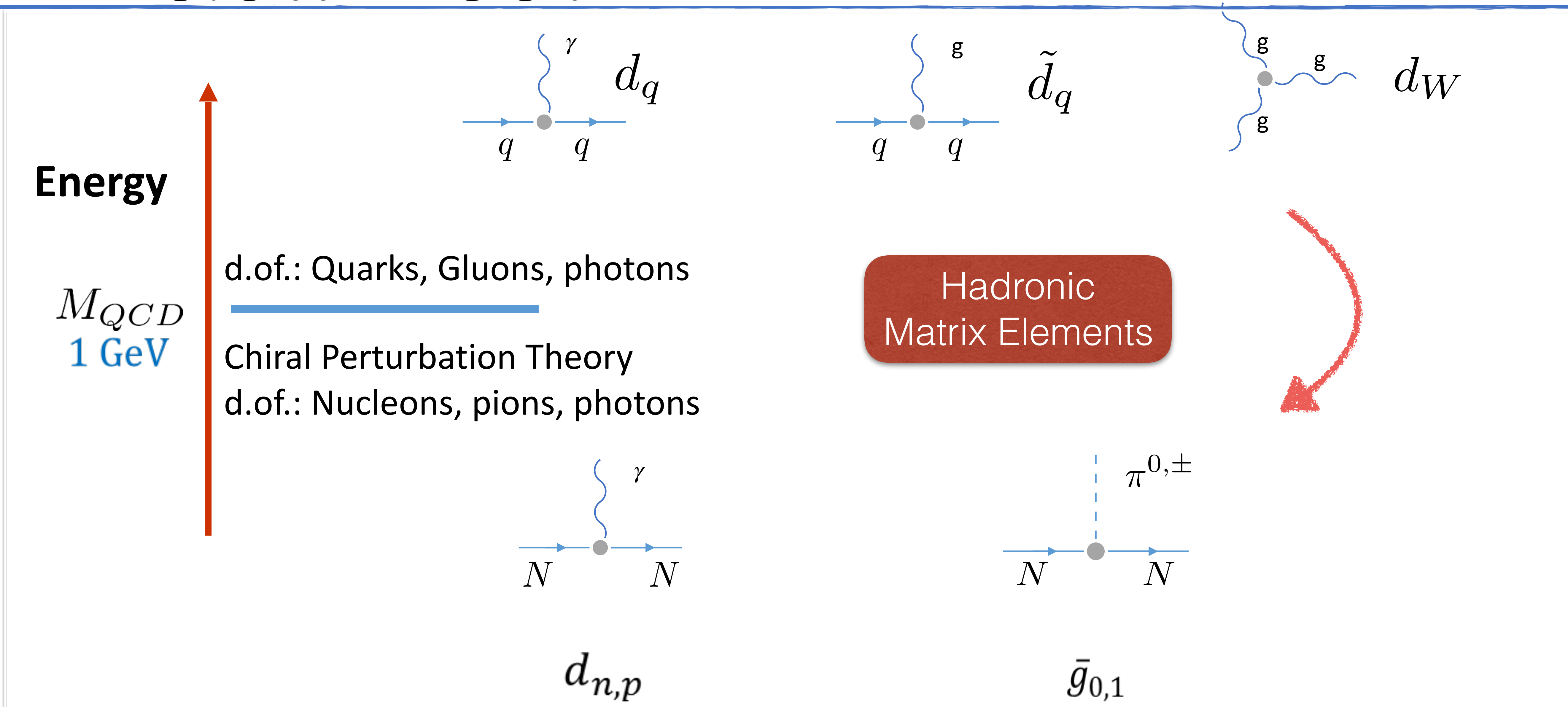
$\bar{g}_{0,1}$

Below 1 GeV



Uncertainties: $d_{n,p} = d_{n,p}(d_q,\ \tilde{d}_q,\ d_W)$ $\qquad \bar{g}_{0,1} = \bar{g}_{0,1}(\tilde{d}_q)$

Below 1 GeV

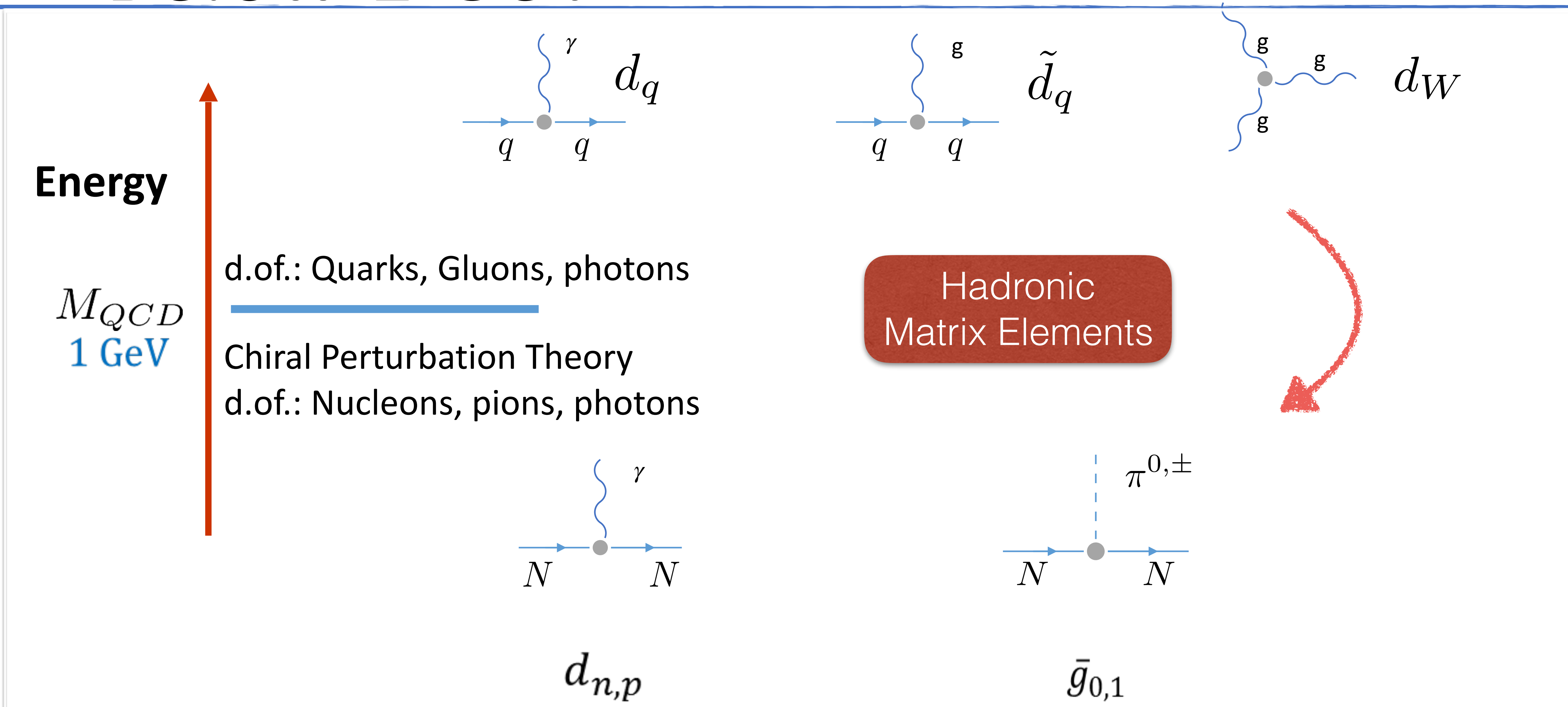


Uncertainties: $d_{n,p} = d_{n,p}(d_q,\, \tilde{d}_q,\, d_W)$ $\bar{g}_{0,1} = \bar{g}_{0,1}(\tilde{d}_q)$

- Lattice-QCD: 10%

T. Bhattacharya *et al*, '15

Below 1 GeV



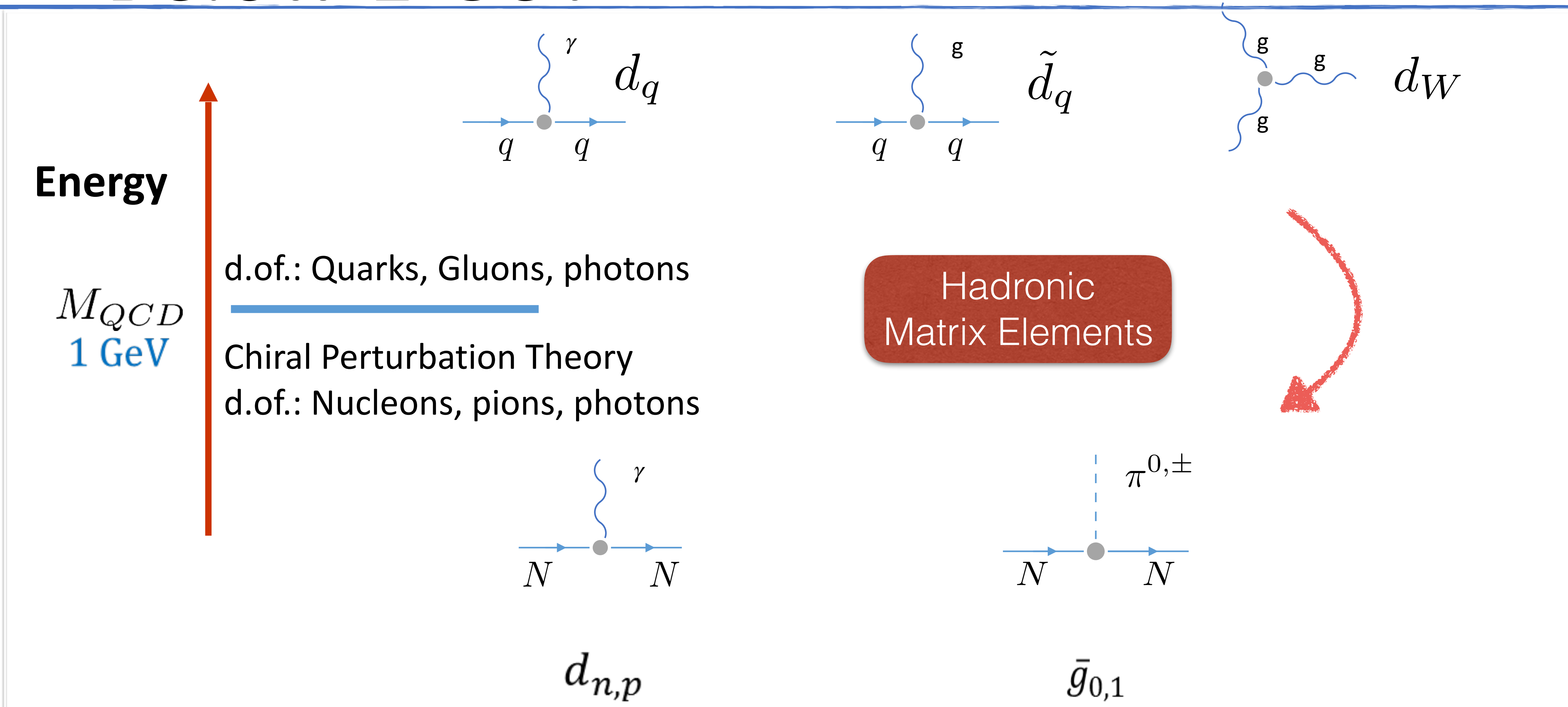
Uncertainties: $d_{n,p} = d_{n,p}(d_q,\, \tilde{d}_q,\, d_W)$ $\bar{g}_{0,1} = \bar{g}_{0,1}(\tilde{d}_q)$

- QCD sum rules: 10% **50%** **100%**

M. Pospelov & A. Ritz, '05, Hisano et al. '12

M. Pospelov, Annals Phys, '02

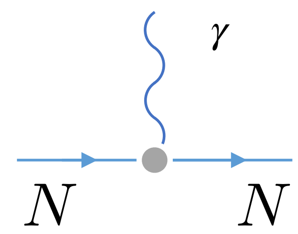
Below 1 GeV



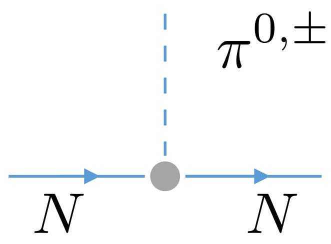
Uncertainties: $d_{n,p} = d_{n,p}(d_q,\ \tilde{d}_q,\ d_W)$ $\quad \bar{g}_{0,1} = \bar{g}_{0,1}(\tilde{d}_q)$

- NDA/QCD sum rules: 10% 50% **100%** 100%

Below 1 GeV



$d_{n,p}$

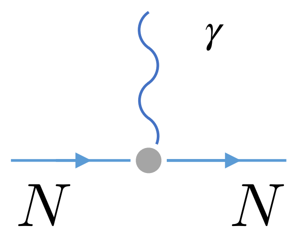


$\bar{g}_{0,1}$

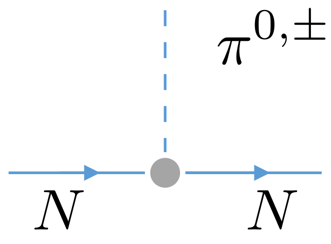
Nuclear Matrix Elements

Nuclear EDMs

Below 1 GeV



$d_{n,p}$



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

Nuclear Matrix Elements

Uncertainties in the mercury EDM:

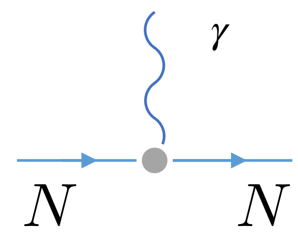
- Atomic screening

$$d_{\mathrm{Hg}} = -(2.8 \pm 0.6) \cdot 10^{-4} \left[(1.9 \pm 0.1) d_n + (0.20 \pm 0.06) d_p + \left(0.13^{+0.5}_{-0.07}\, \bar{g}_0 + 0.25^{+0.89}_{-0.63}\, \bar{g}_1 \right) e\,\mathrm{fm} \right]$$

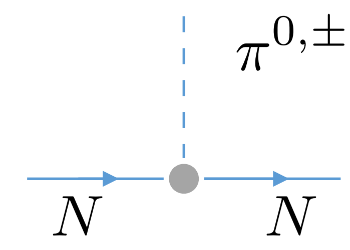
<30%

Dzuba, Flambaum, ’09, ’12; Singh, Sahoo, ’15;

Below 1 GeV



$d_{n,p}$



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

Nuclear Matrix Elements

Uncertainties in the mercury EDM:

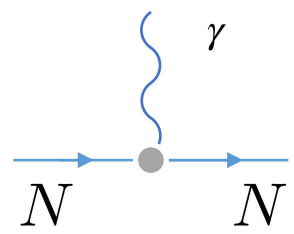
- Single nucleon contribution:

$$d_{\mathrm{Hg}} = -(2.8 \pm 0.6) \cdot 10^{-4} \left[(1.9 \pm 0.1) d_n + (0.20 \pm 0.06) d_p + \left(0.13^{+0.5}_{-0.07}\, \bar{g}_0 + 0.25^{+0.89}_{-0.63}\, \bar{g}_1 \right) e\,\mathrm{fm} \right]$$

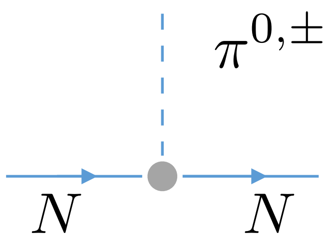
<30%   <30%

Dzuba, Flambaum, '09, '12; Singh, Sahoo, '15;   Dmitriev & Sen'kov, '03

Below 1 GeV



$d_{n,p}$



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

Nuclear Matrix Elements

Uncertainties in the mercury EDM:

- Pion-nucleon contribution:

$$d_{\rm Hg} = -(2.8 \pm 0.6) \cdot 10^{-4} \left[(1.9 \pm 0.1) d_n + (0.20 \pm 0.06) d_p + \left(0.13^{+0.5}_{-0.07}\, \bar{g}_0 + 0.25^{+0.89}_{-0.63}\, \bar{g}_1 \right) e\,{\rm fm} \right]$$

<30% | <30% | **>100%**

Dzuba, Flambaum, '09, '12; Singh, Sahoo, '15; Dmitriev & Sen'kov, '03 de Jesus, Engel, '05; Ban, Dobaczewski, Engel, Shukla, '10;

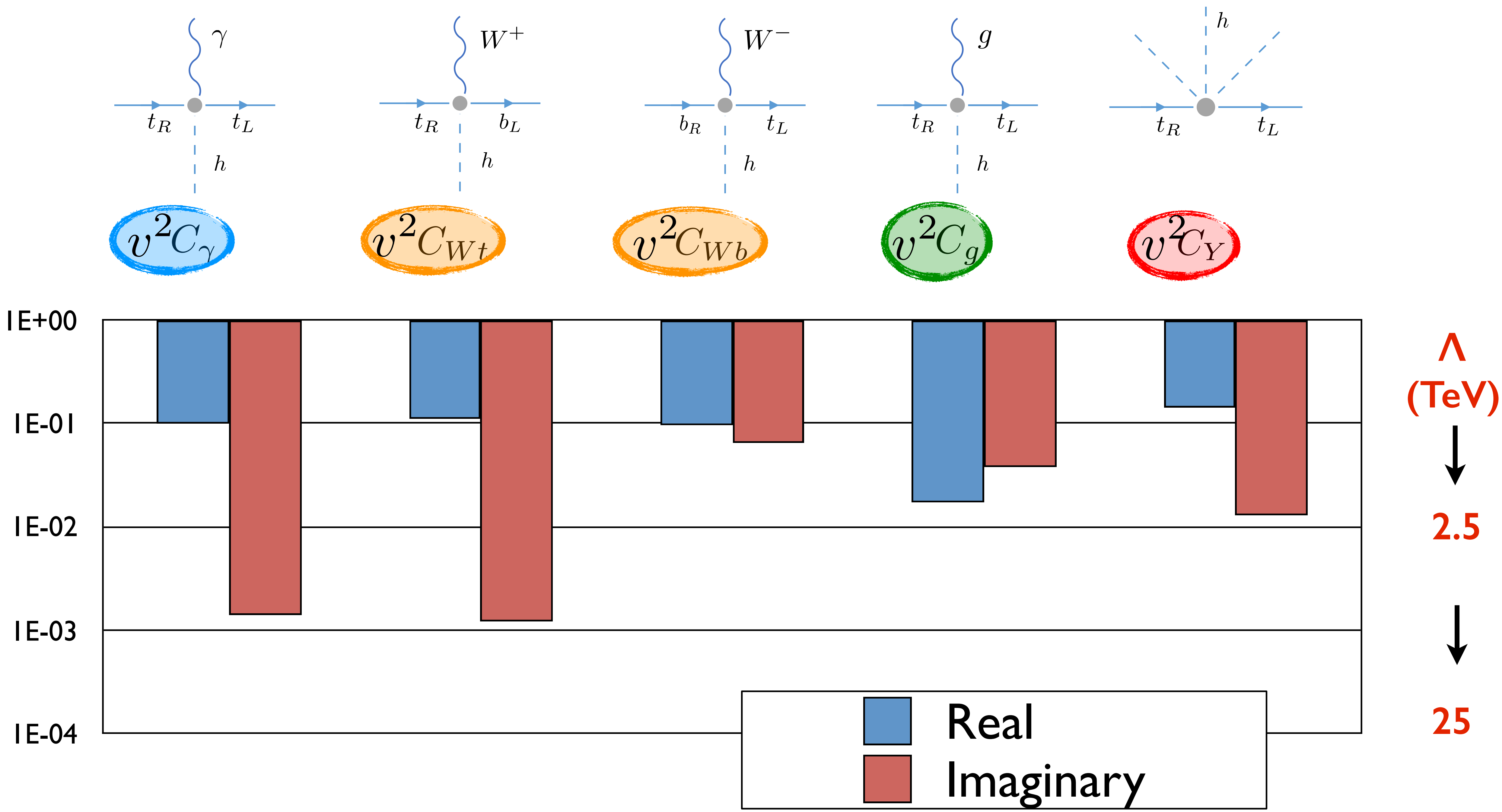
Theory error treatment

- **'Rfit':** Vary matrix elements within their allowed ranges; choose values giving the smallest Chi-square (pick the weakest bound)

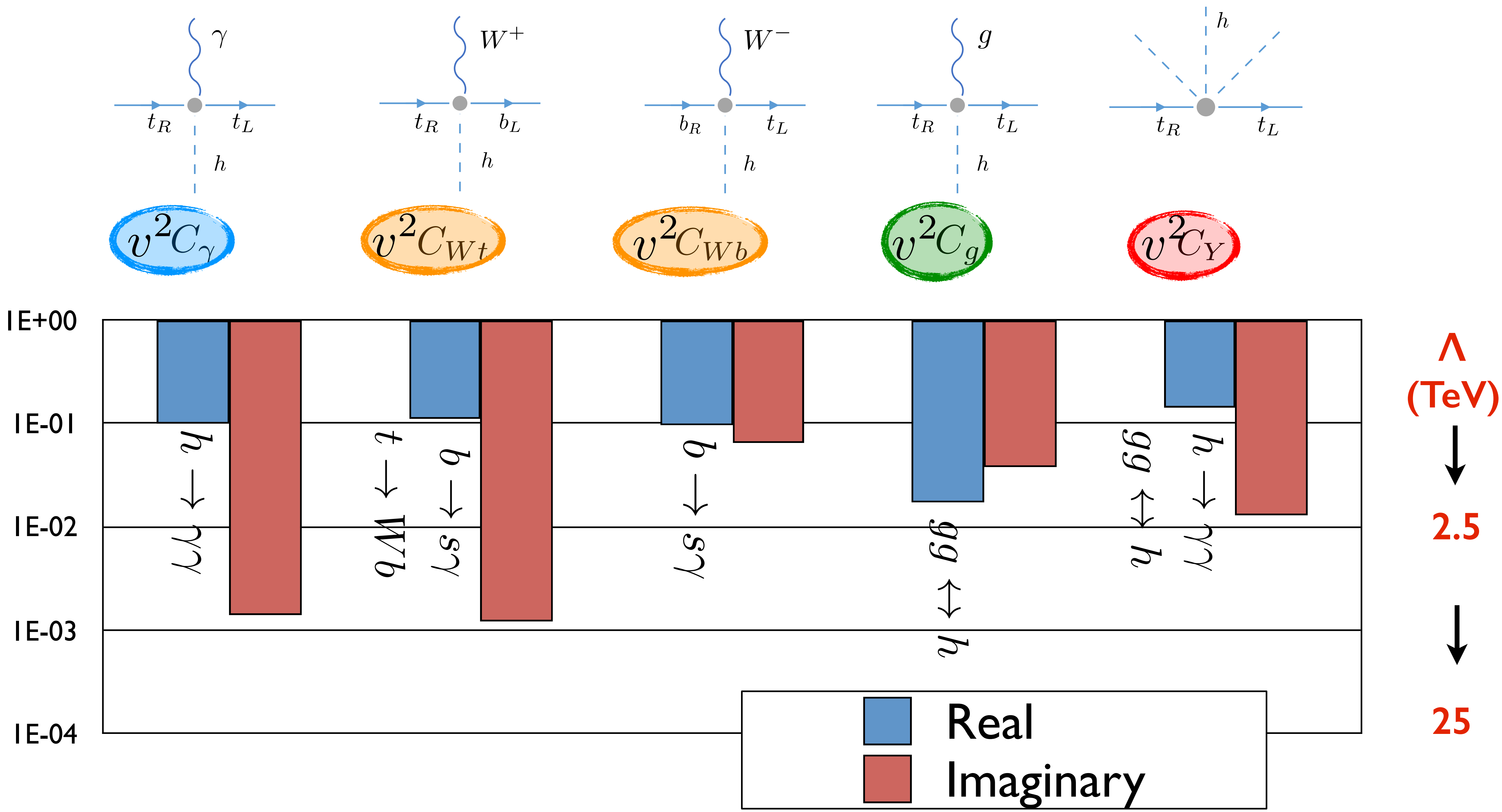
  - Hadronic/nuclear EDM uncertainties
  - Long-distance uncertainties in $A_{CP}(b \to s\gamma)$

CKMFitter Group, Charles et al, '05

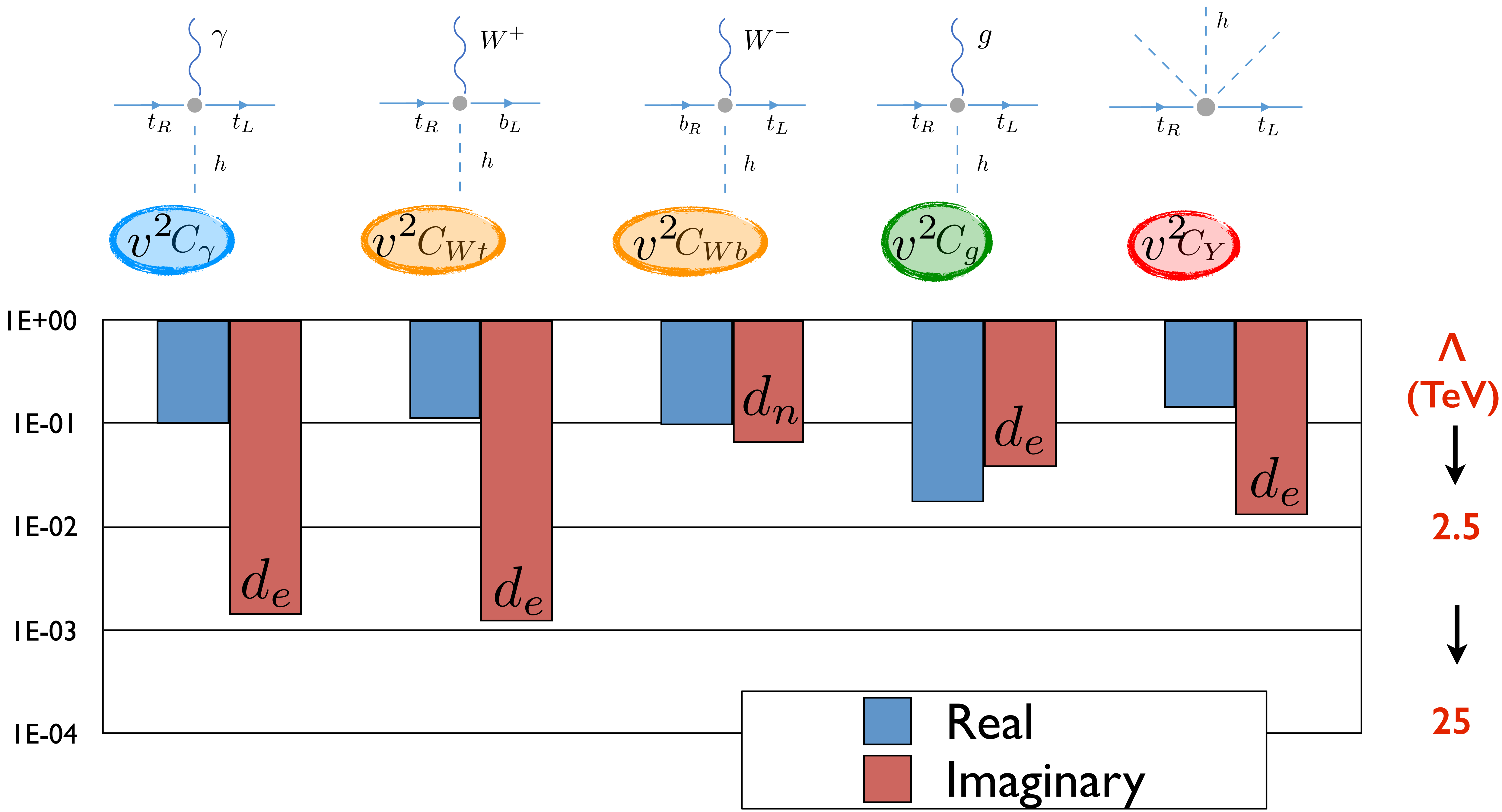
Constraints



Constraints

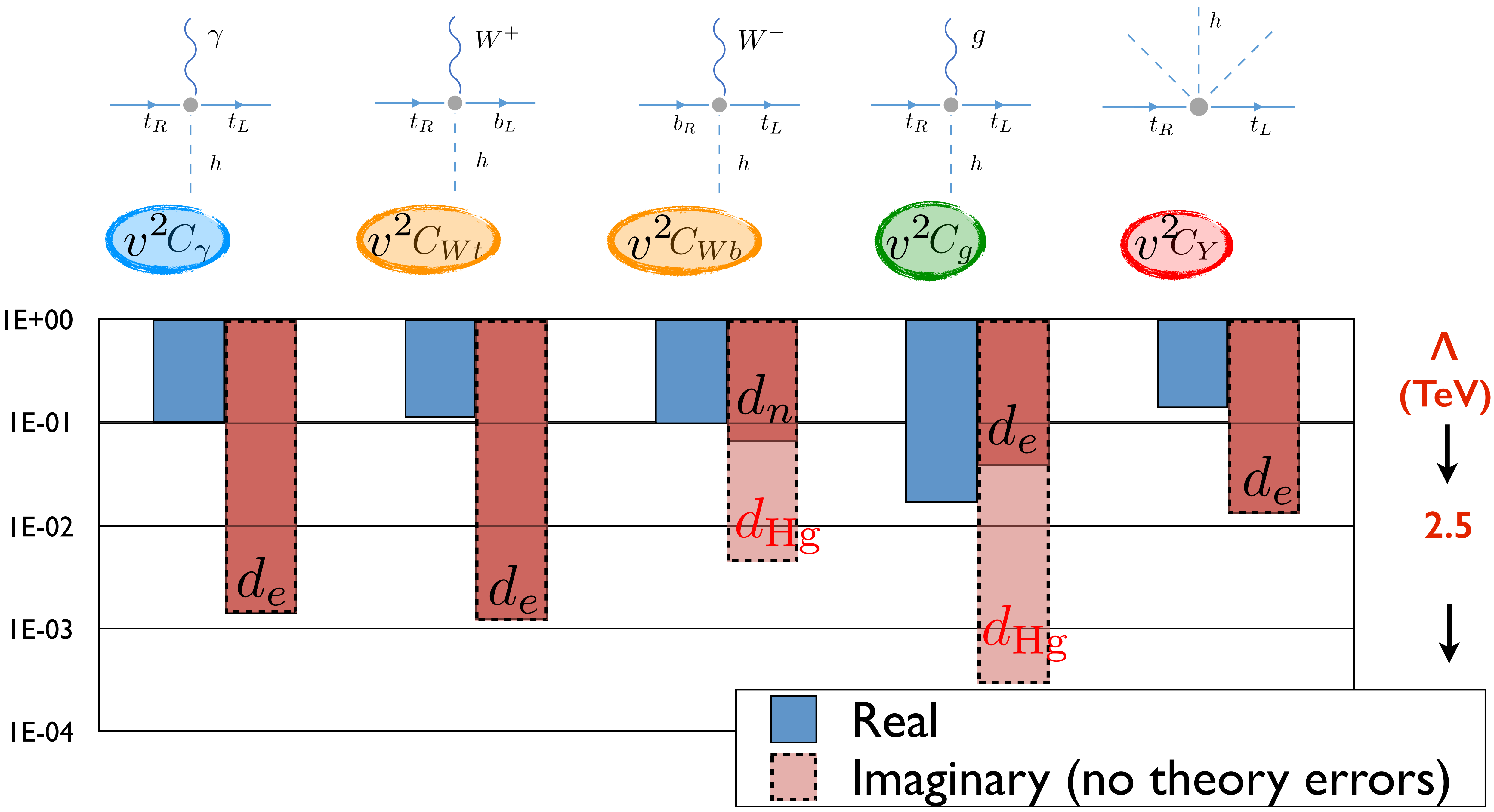


Constraints



Constraints

Impact of theoretical uncertainties



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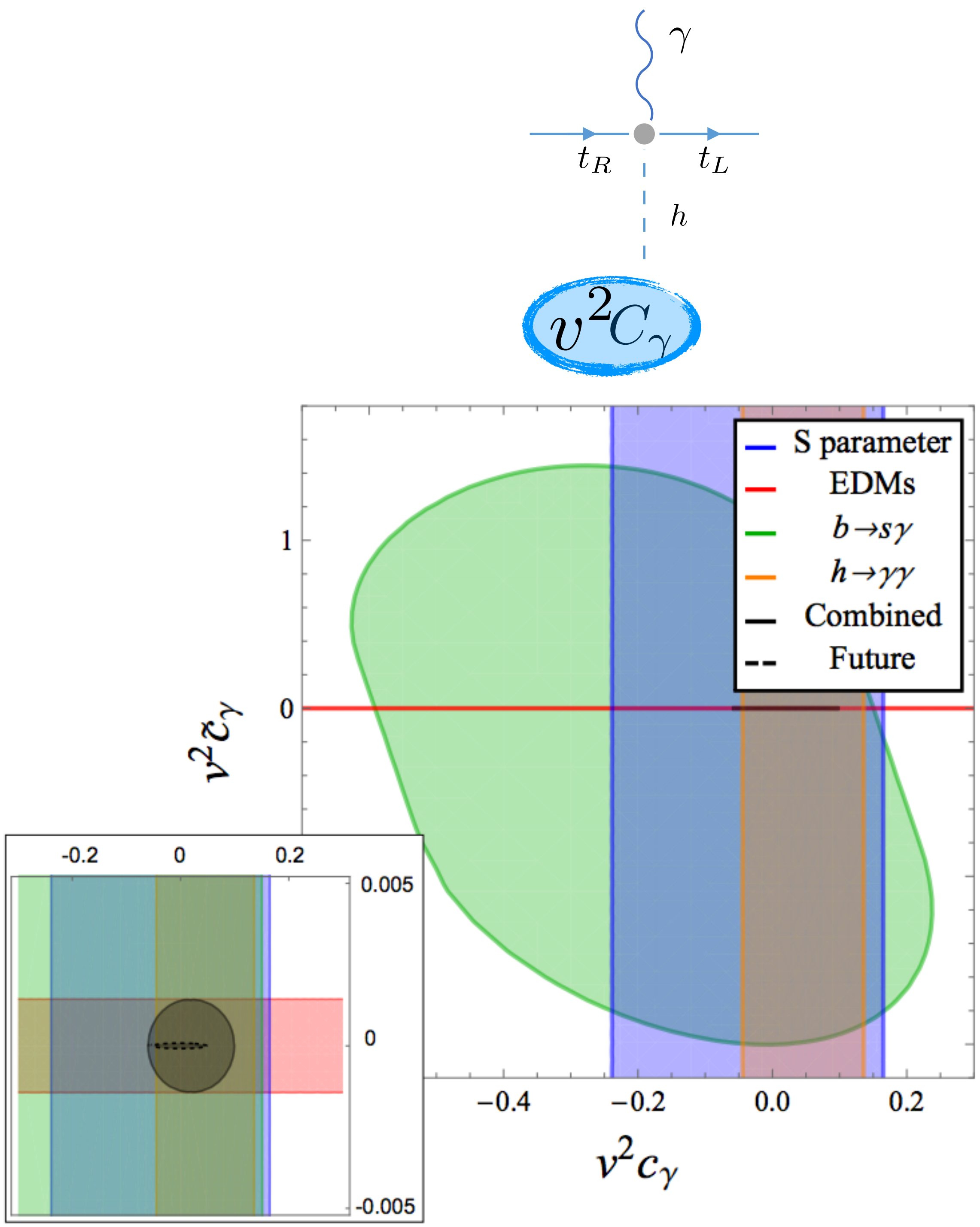
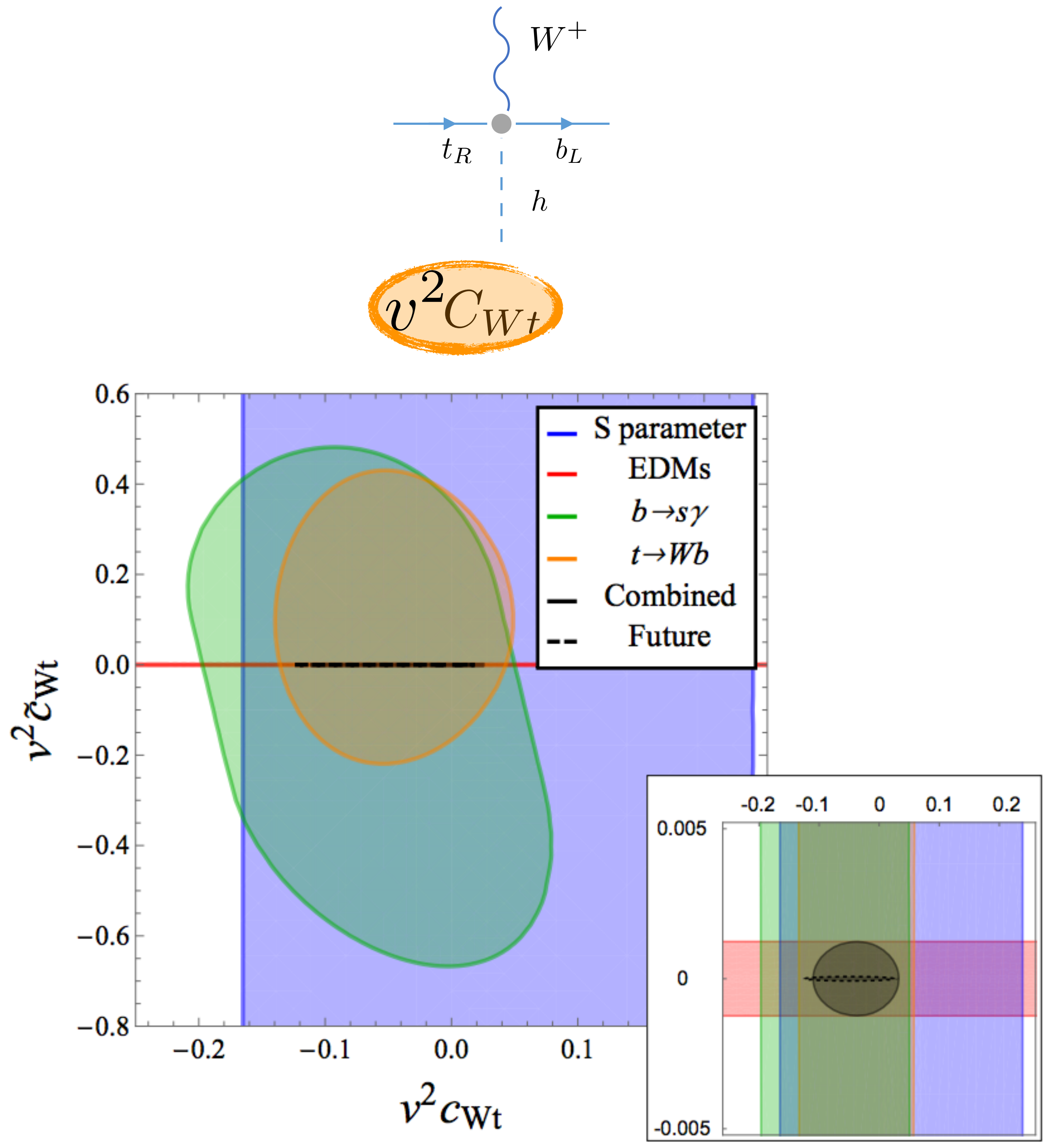
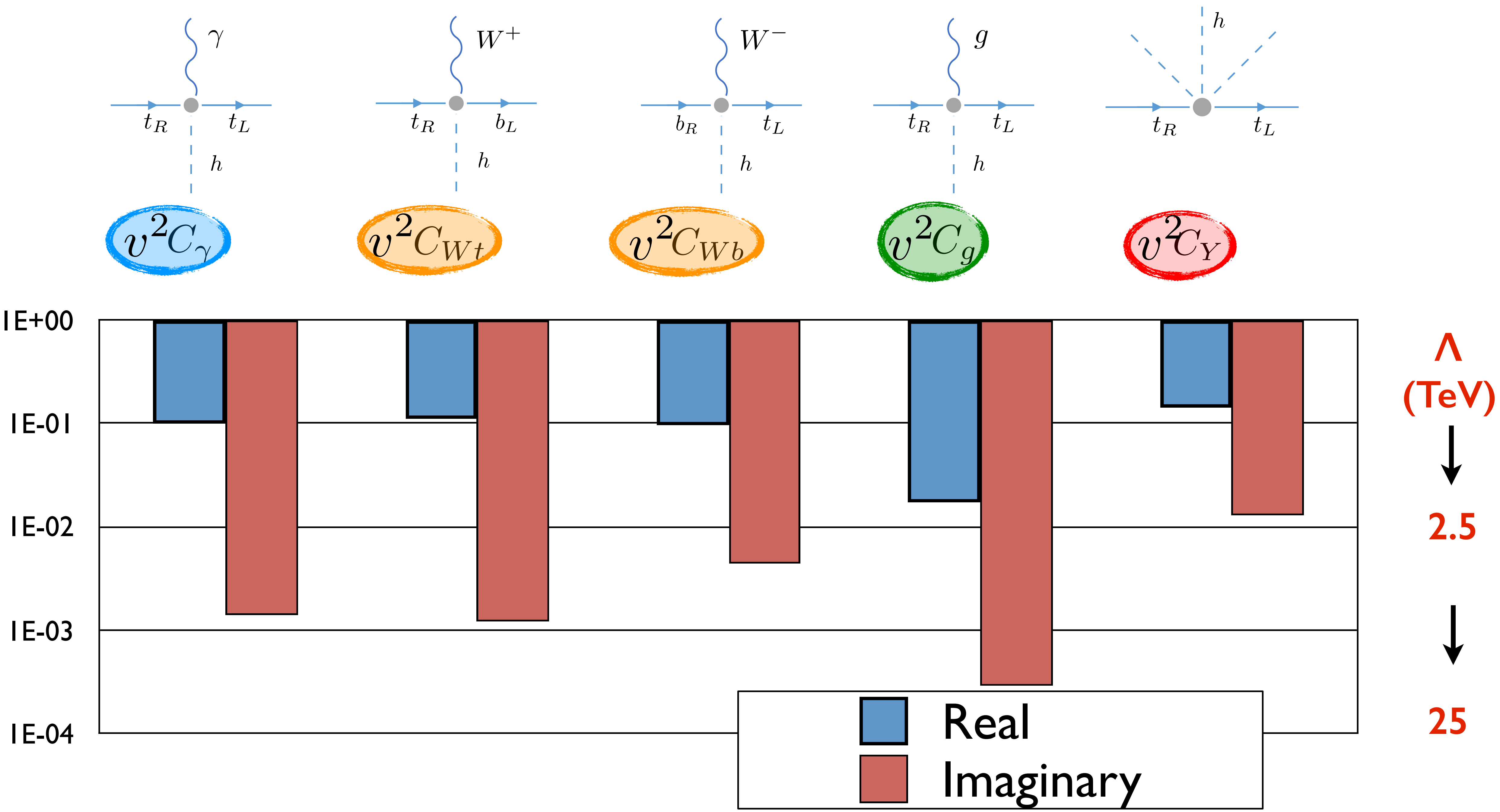




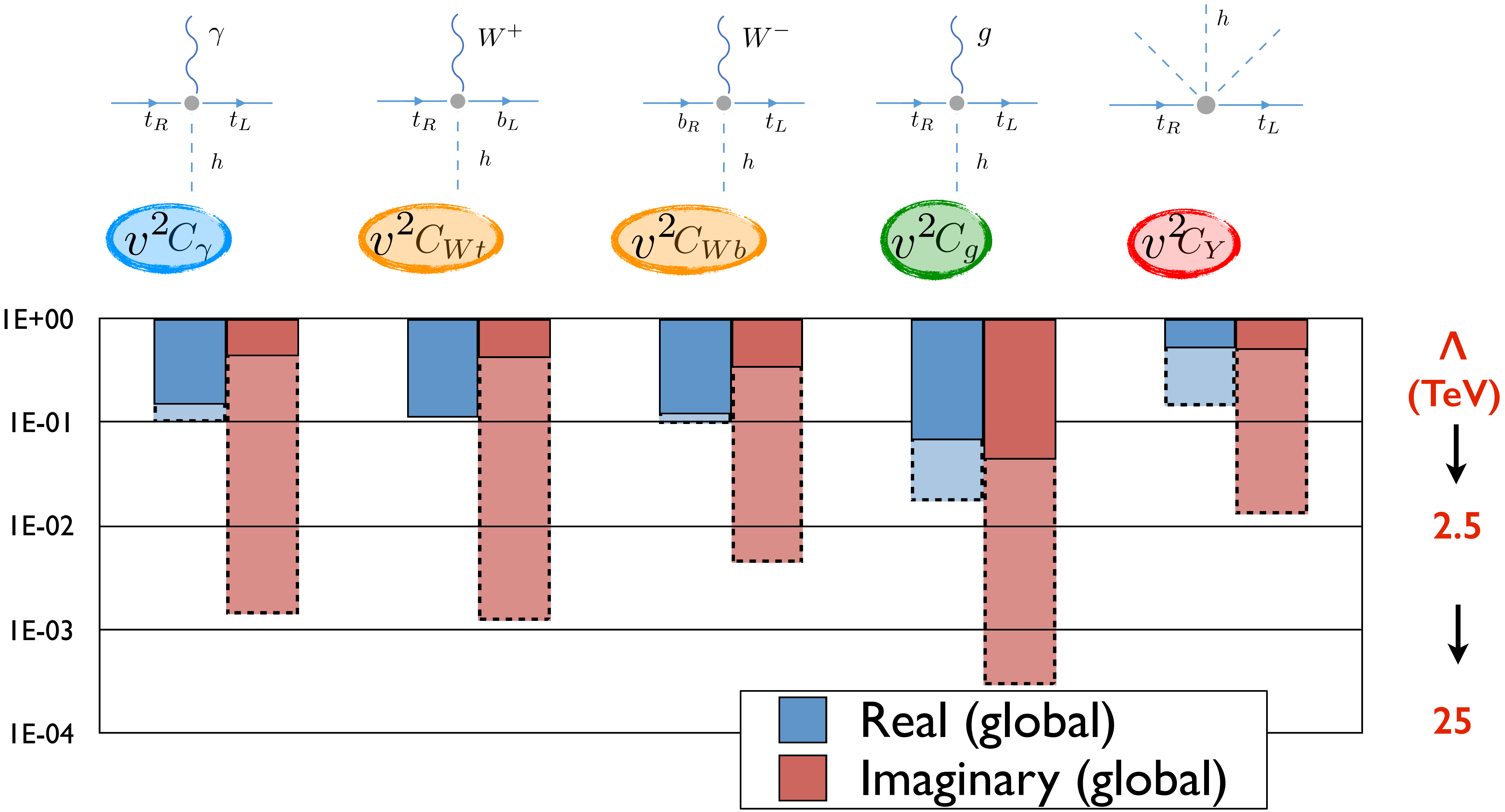
Constraints

Global analysis



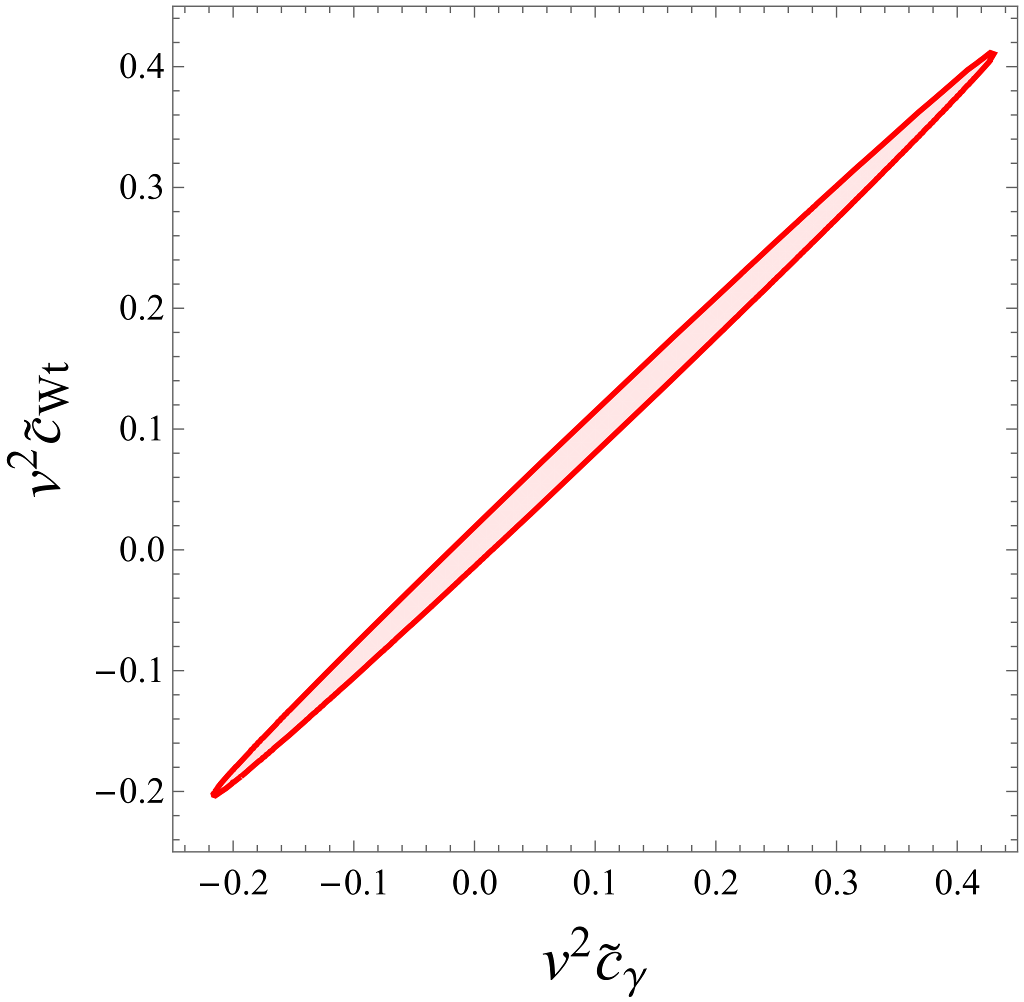
Constraints

Global analysis



Global constraints

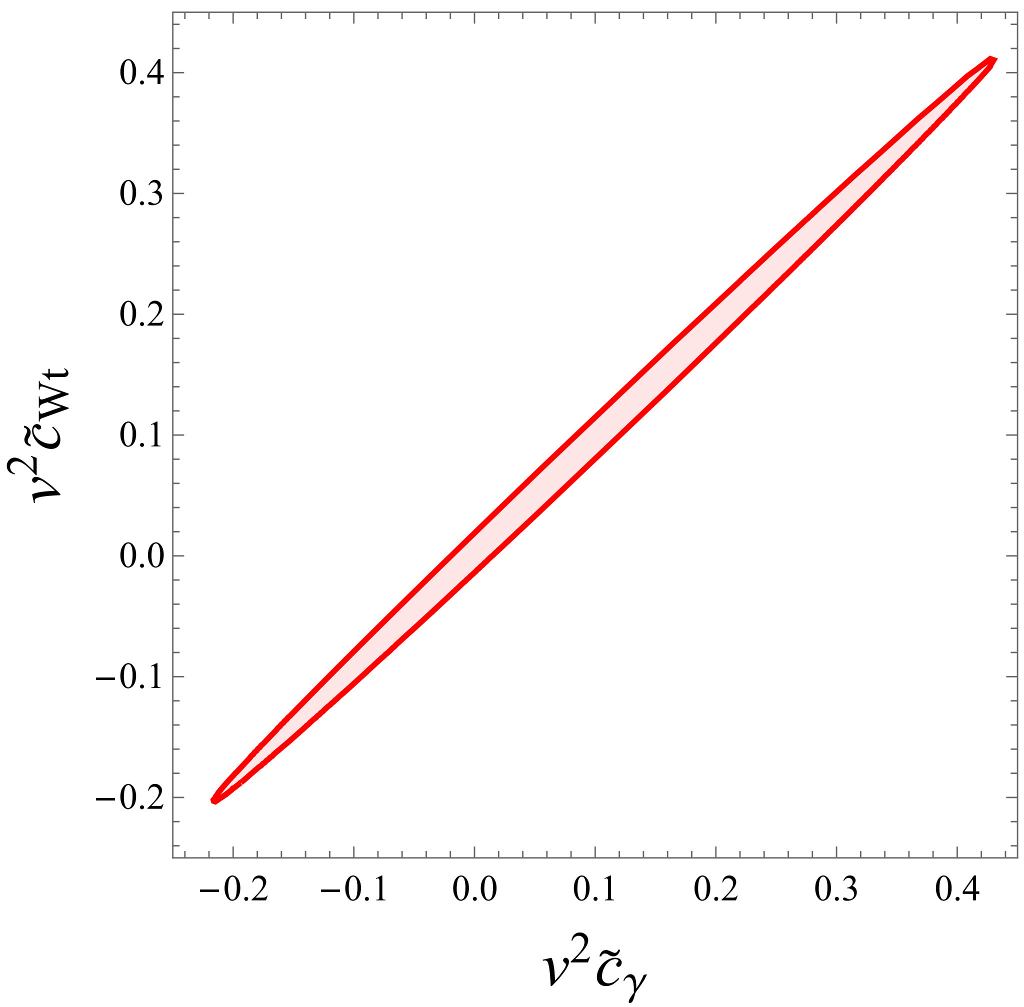
Global (central) analysis

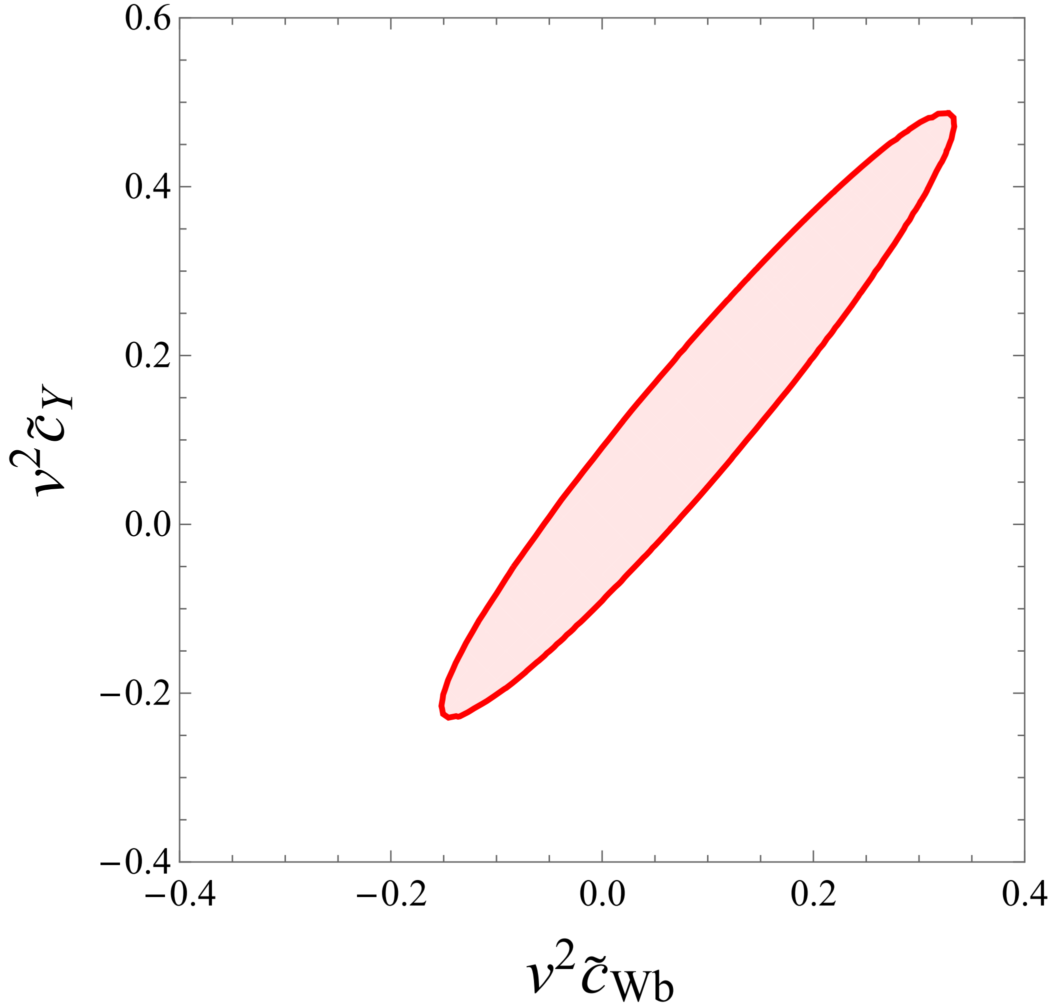


- The electron EDM allows for a free direction, only killed by the helicity fractions $\delta^-(t \to W^+ b)$

Global constraints

Global (central) analysis



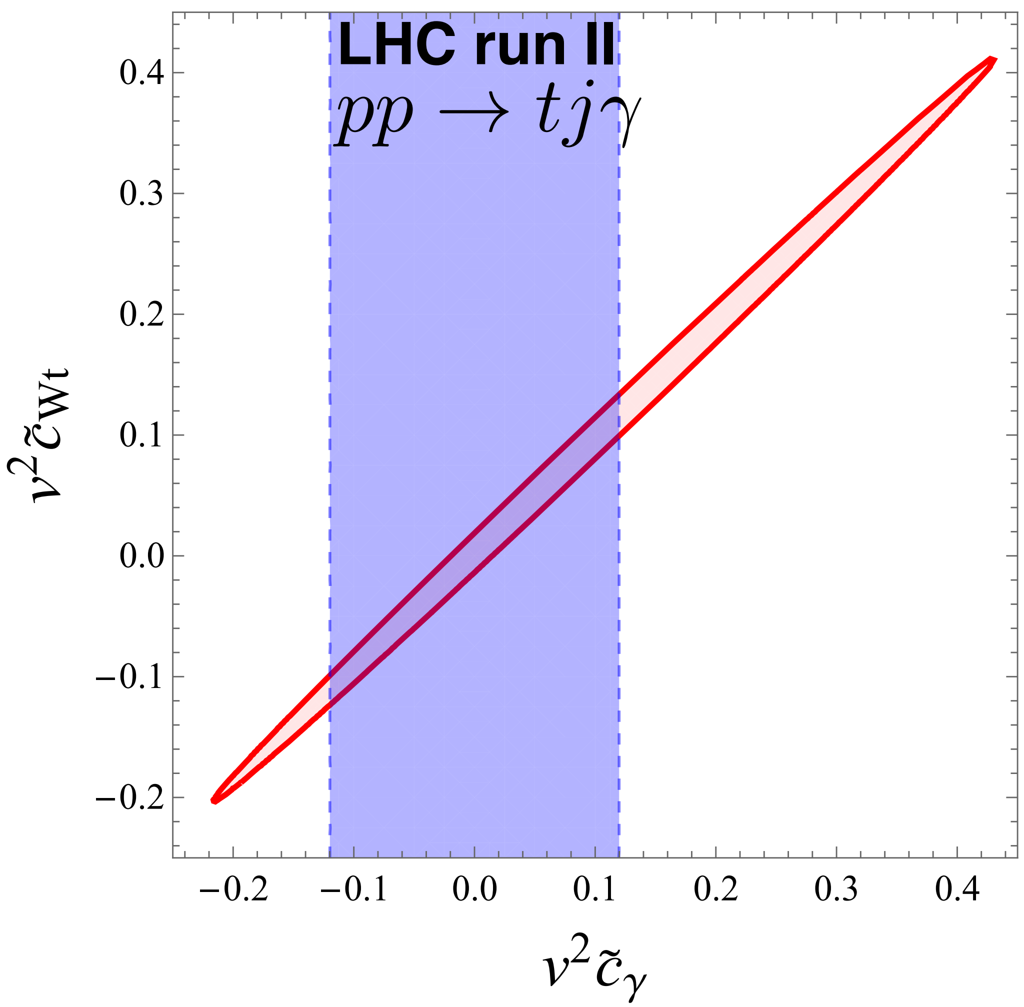


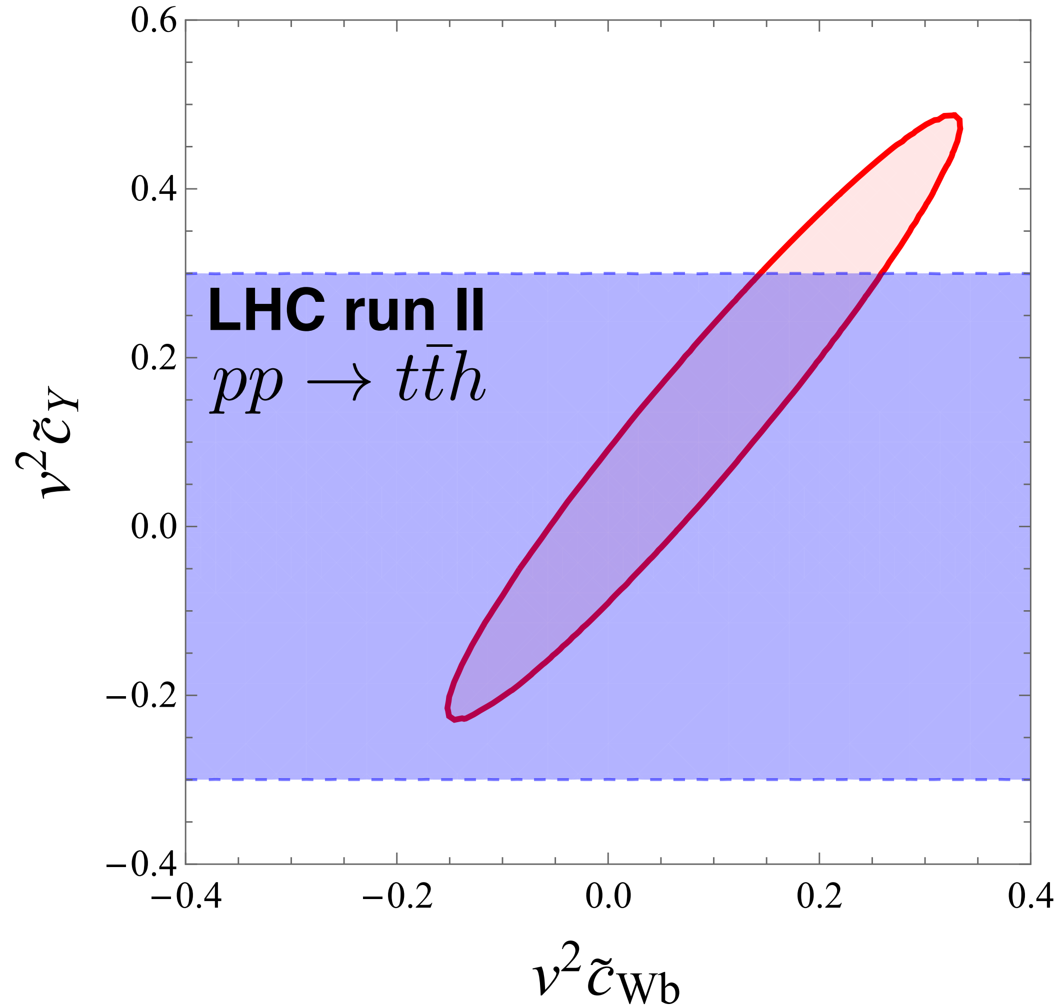
- The electron EDM allows for a free direction, only killed by the helicity fractions $\delta^-(t \to W^+ b)$

- Here the neutron EDM allows for a free direction, only killed by $b \to s\gamma$

Global constraints

Global (central) analysis



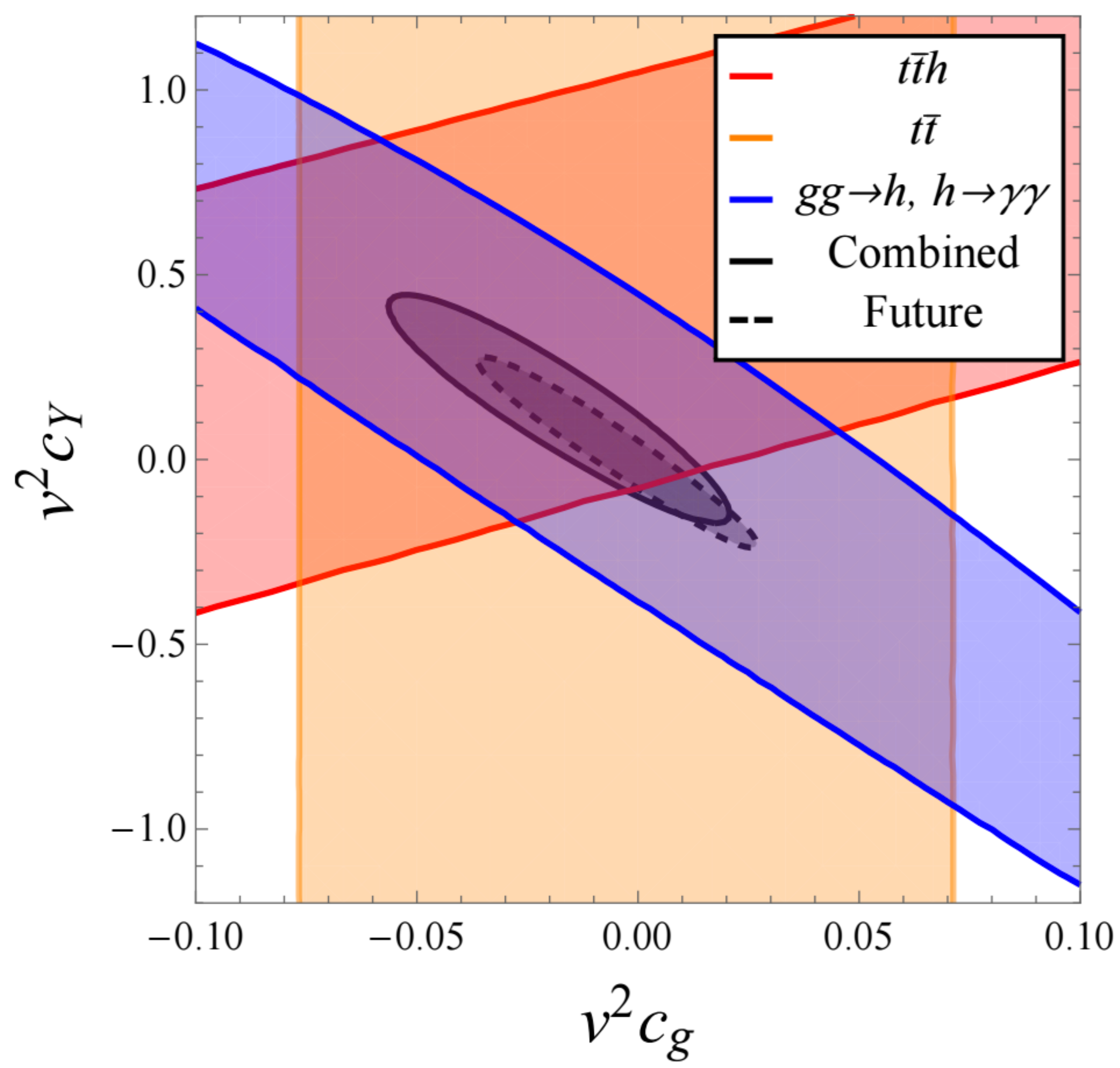


Etesami, Khatibi, Najafabadi, '16;

Mileo, Kiers, Szynkman, Crane, Gegner, '16

Global constraints

real parts



Summary/Conclusions

- EDMs stringently constrain Higgs-top couplings
- Lead to best constraints in the single coupling analysis
  - Up to 3 orders of magnitude improvement due to the 'two-step mechanism'
- These constraints are weakened by:
  - Theory uncertainties related to the neutron/mercury EDMs
  - Possible cancellations between the top-Higgs couplings
    - Complementarity with Flavor & Collider becomes important
- CP-odd observables at LHC run-II:
  - Not competitive with EDMs in the single-coupling case
  - But very helpful in excluding free directions in the global analysis

Thank you for your attention!

Backup slides

Running results

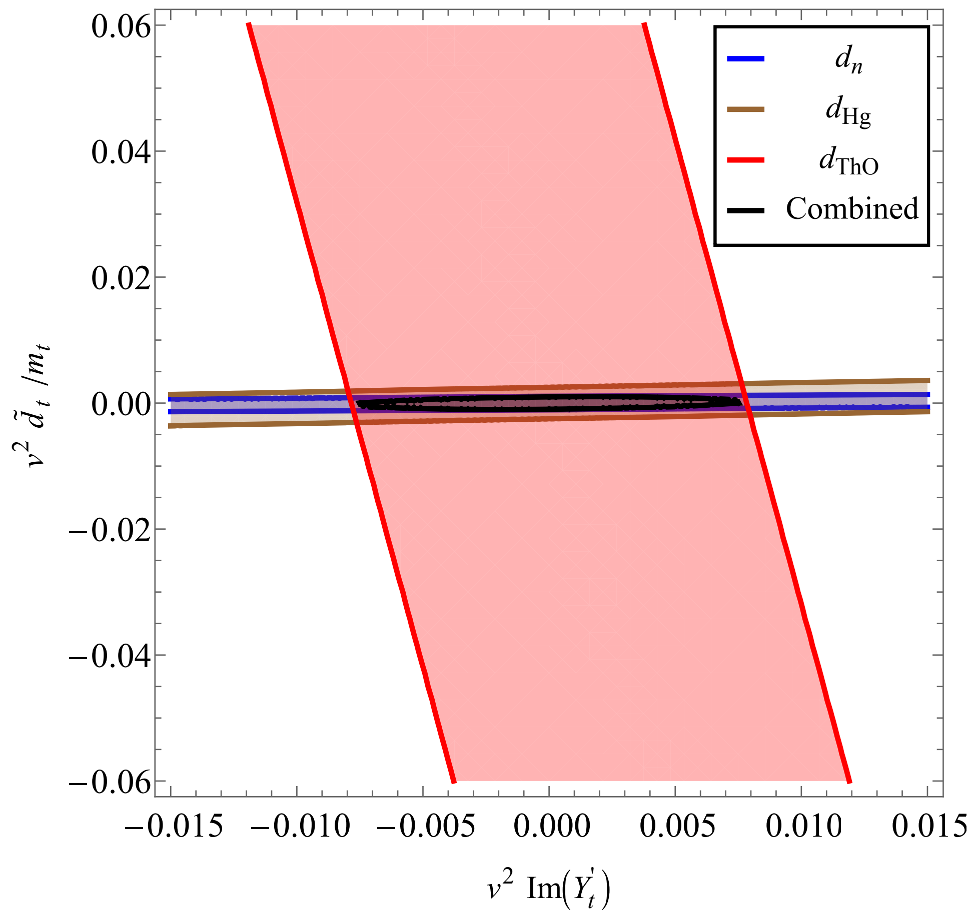
$\Lambda = 1\,\mathrm{TeV}$	$c_\gamma(\Lambda)$	$c_g(\Lambda)$	$c_{Wt}(\Lambda)$	$c_{Wb}(\Lambda)$	$c_Y(\Lambda)$
$c_\gamma(m_t^+)$	0.86	0.13	$-9.2 \cdot 10^{-3}$	$-7.7 \cdot 10^{-6}$	$-$
$c_g(m_t^+)$	$2.8 \cdot 10^{-3}$	0.87	-0.021	$-1.2 \cdot 10^{-8}$	$-$
$c_{Wt}(m_t^+)$	$-5.4 \cdot 10^{-5}$	-0.033	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

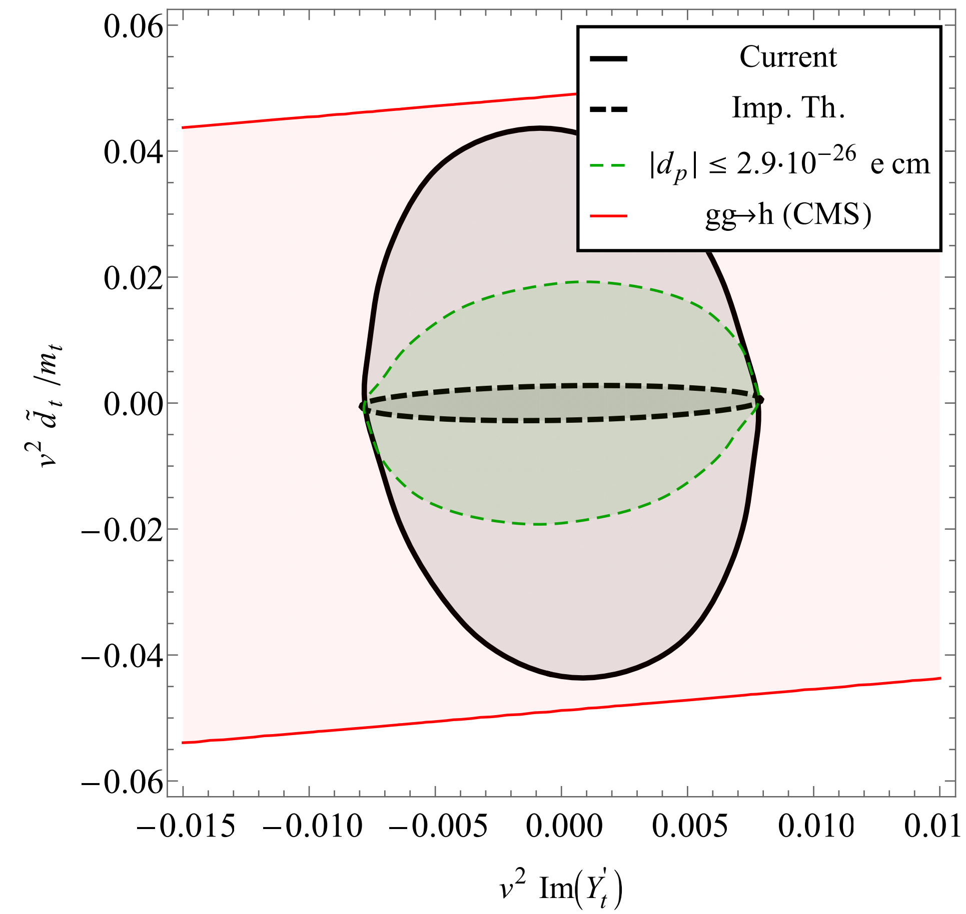
$\Lambda = 1\,\text{TeV}$	$\tilde{c}_\gamma(\Lambda)$	$\tilde{c}_g(\Lambda)$	$\tilde{c}_{Wt}(\Lambda)$	$\tilde{c}_{Wb}(\Lambda)$	$\tilde{c}_Y(\Lambda)$
$\tilde{c}_\gamma^{(e)}(\Lambda_\chi)$	$3.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-5}$	$-4.4 \cdot 10^{-4}$	$2.3 \cdot 10^{-8}$	$4.0 \cdot 10^{-5}$
$\tilde{c}_\gamma^{(u)}(\Lambda_\chi)$	$1.4 \cdot 10^{-4}$	$6.3 \cdot 10^{-4}$	$-1.2 \cdot 10^{-4}$	$-2.9 \cdot 10^{-6}$	$-6.1 \cdot 10^{-5}$
$\tilde{c}_g^{(u)}(\Lambda_\chi)$	$3.9 \cdot 10^{-6}$	$1.1 \cdot 10^{-3}$	$-1.9 \cdot 10^{-5}$	$-1.7 \cdot 10^{-5}$	$-1.0 \cdot 10^{-4}$
$\tilde{c}_\gamma^{(d)}(\Lambda_\chi)$	$2.0 \cdot 10^{-4}$	$8.6 \cdot 10^{-4}$	$-9.1 \cdot 10^{-4}$	$-2.9 \cdot 10^{-6}$	$-6.1 \cdot 10^{-5}$
$\tilde{c}_g^{(d)}(\Lambda_\chi)$	$2.9 \cdot 10^{-6}$	$1.3 \cdot 10^{-3}$	$-2.4 \cdot 10^{-5}$	$-1.7 \cdot 10^{-5}$	$-1.0 \cdot 10^{-4}$
$\tilde{c}_\gamma^{(s)}(\Lambda_\chi)$	$1.9 \cdot 10^{-4}$	$8.6 \cdot 10^{-4}$	$-9.5 \cdot 10^{-4}$	$-2.9 \cdot 10^{-6}$	$-6.1 \cdot 10^{-5}$
$\tilde{c}_g^{(s)}(\Lambda_\chi)$	$2.9 \cdot 10^{-6}$	$1.3 \cdot 10^{-3}$	$-2.4 \cdot 10^{-5}$	$-1.7 \cdot 10^{-5}$	$-1.0 \cdot 10^{-4}$
$C_{\tilde{G}}(\Lambda_\chi)$	$-2.8 \cdot 10^{-6}$	$-8.8 \cdot 10^{-4}$	$2.2 \cdot 10^{-5}$	$7.8 \cdot 10^{-5}$	$-8.1 \cdot 10^{-7}$

Complementary examples

Top Yukawa vs top color-EDM



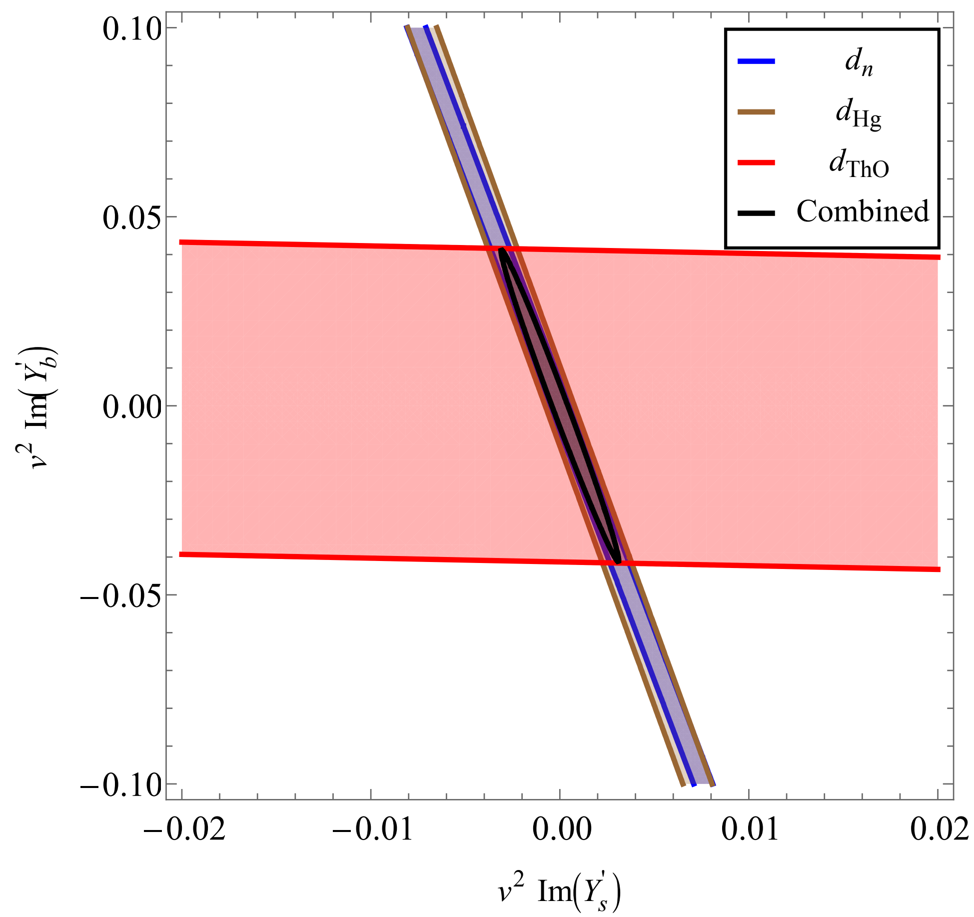
Central



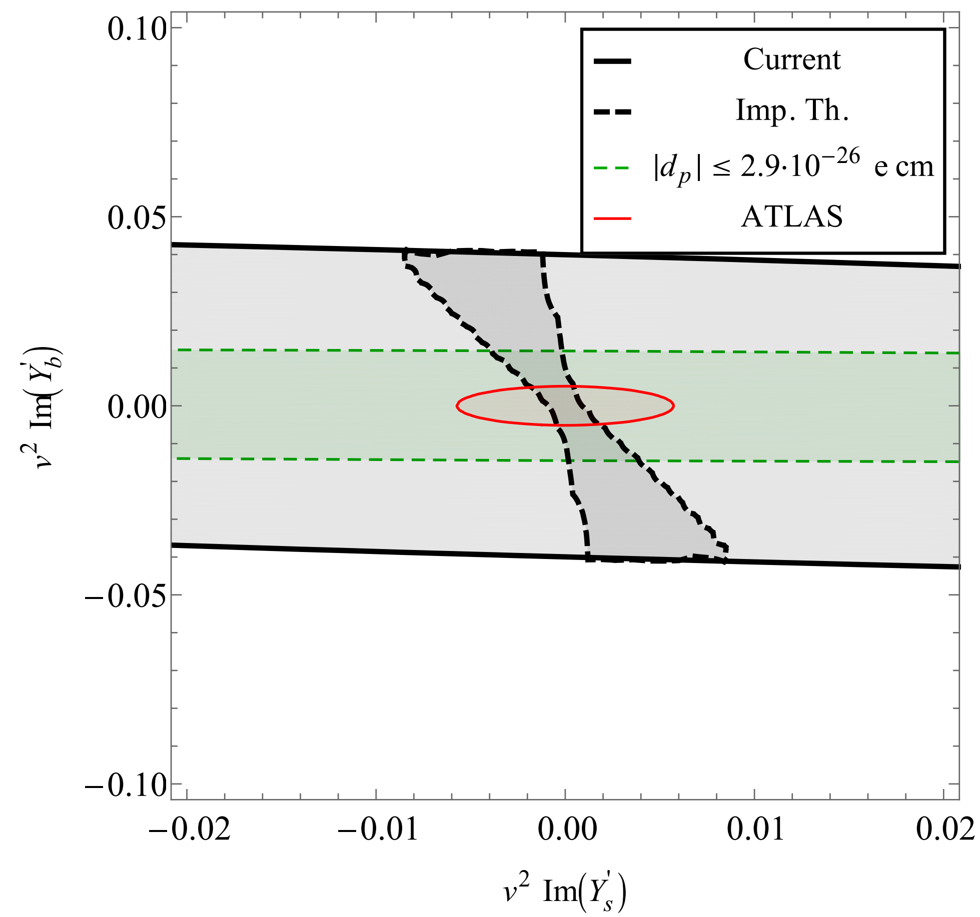
Minimized

Complementary examples

Strange Yukawa vs bottom Yukawa



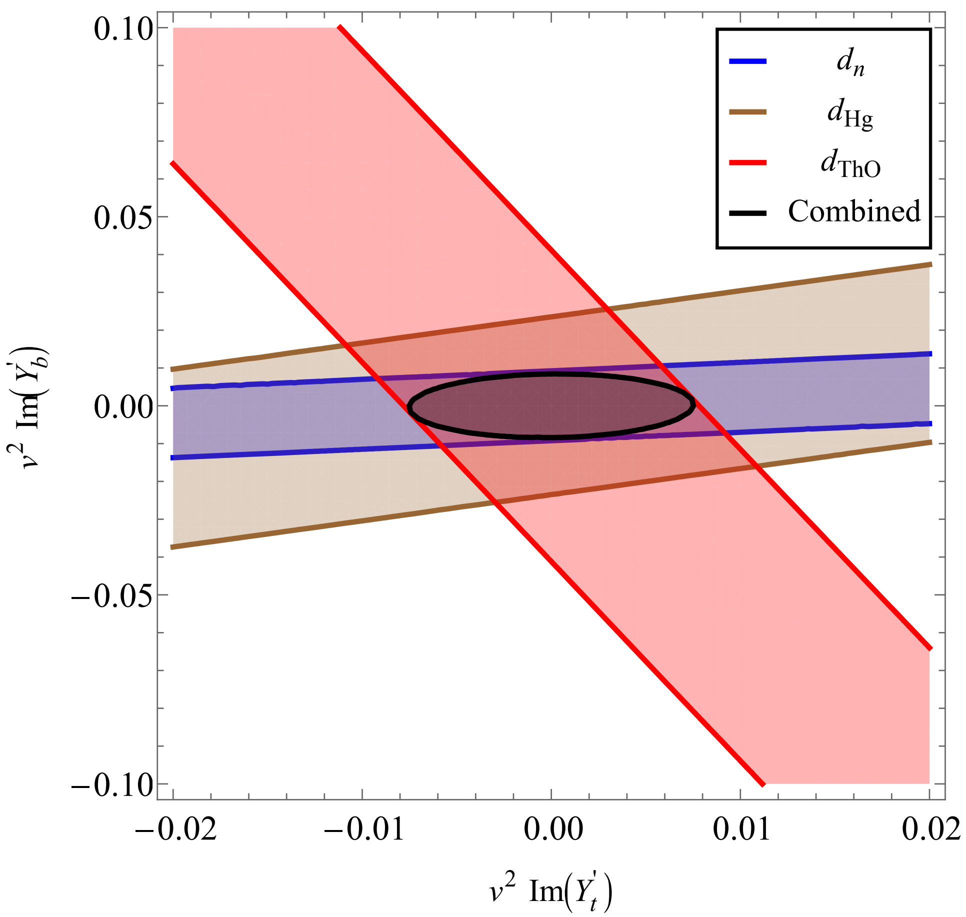
Central



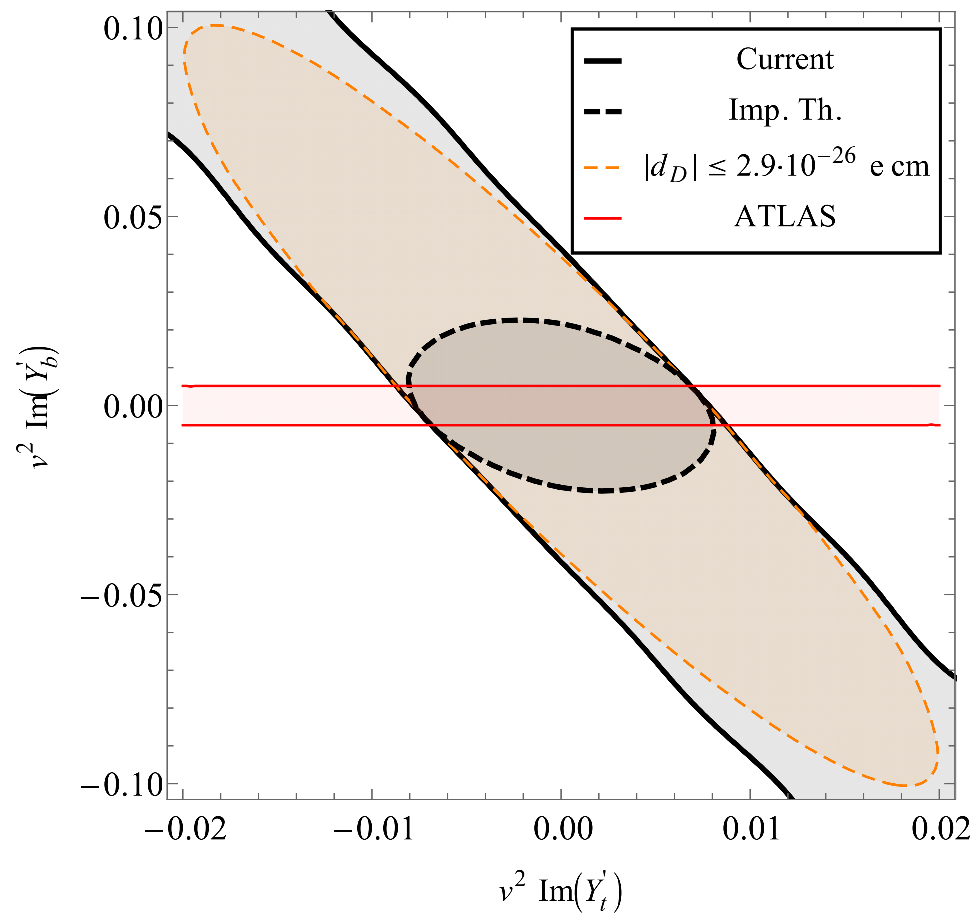
Minimized

Complementary examples

Top Yukawa vs bottom Yukawa

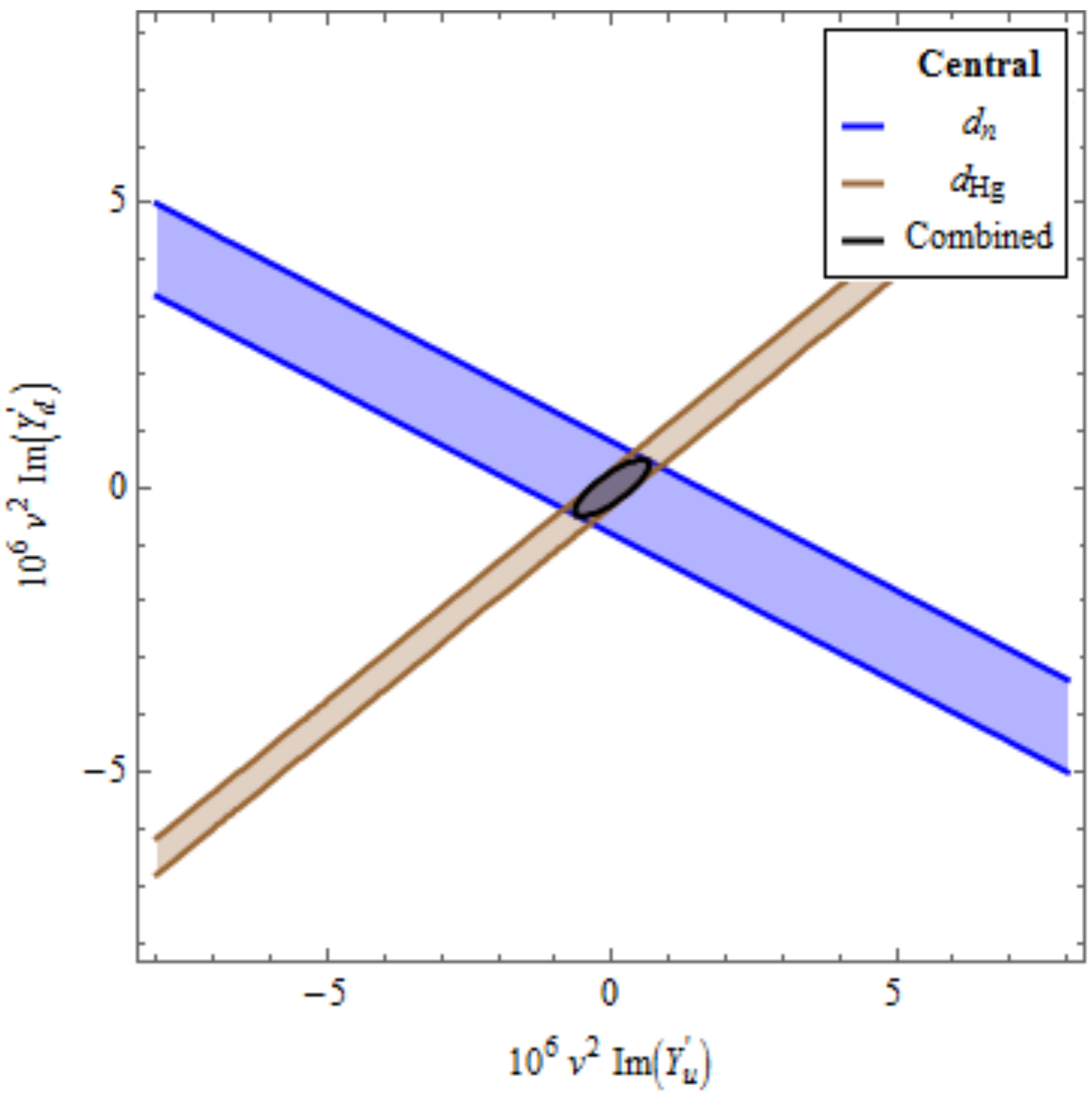


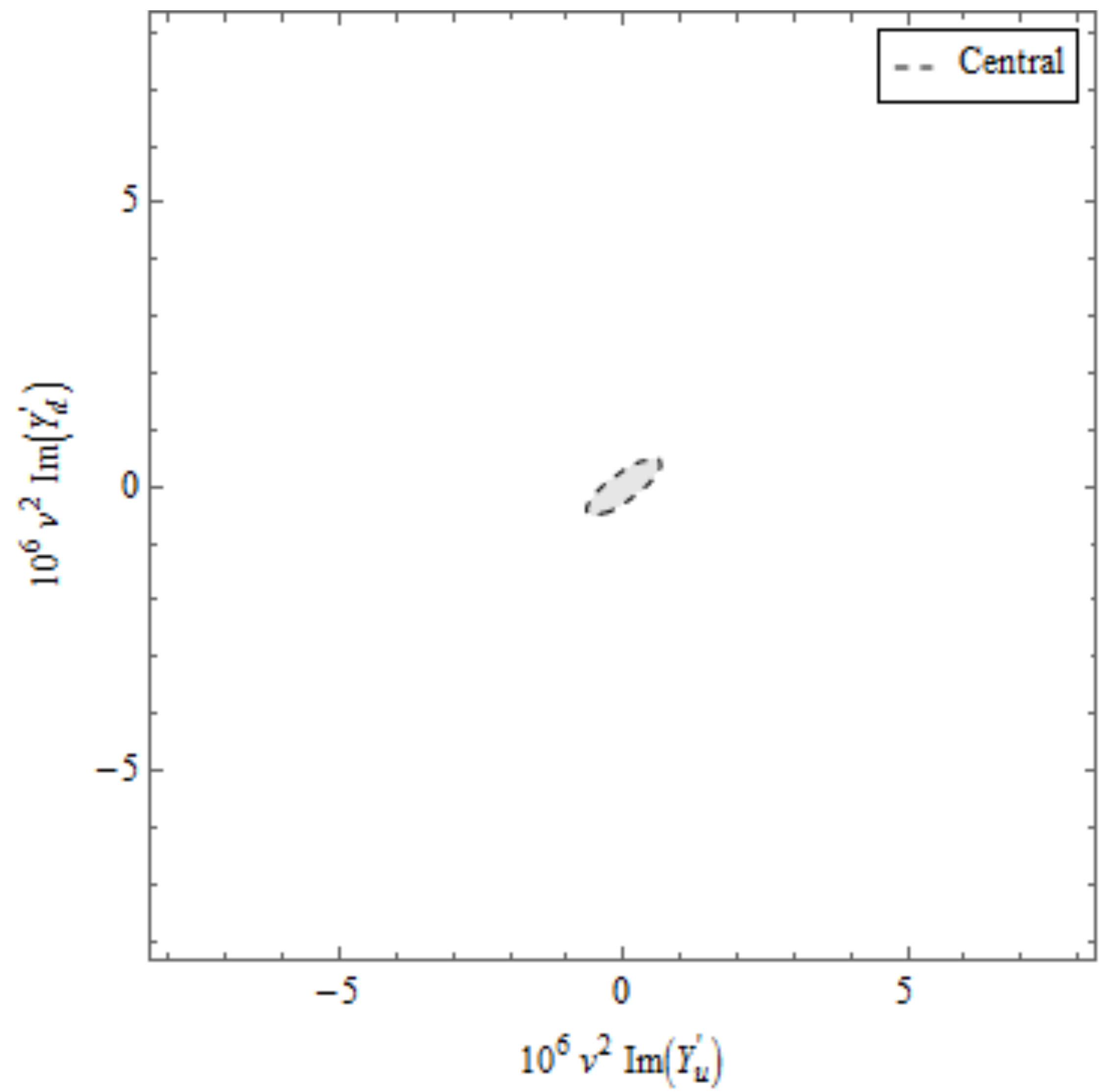
Central



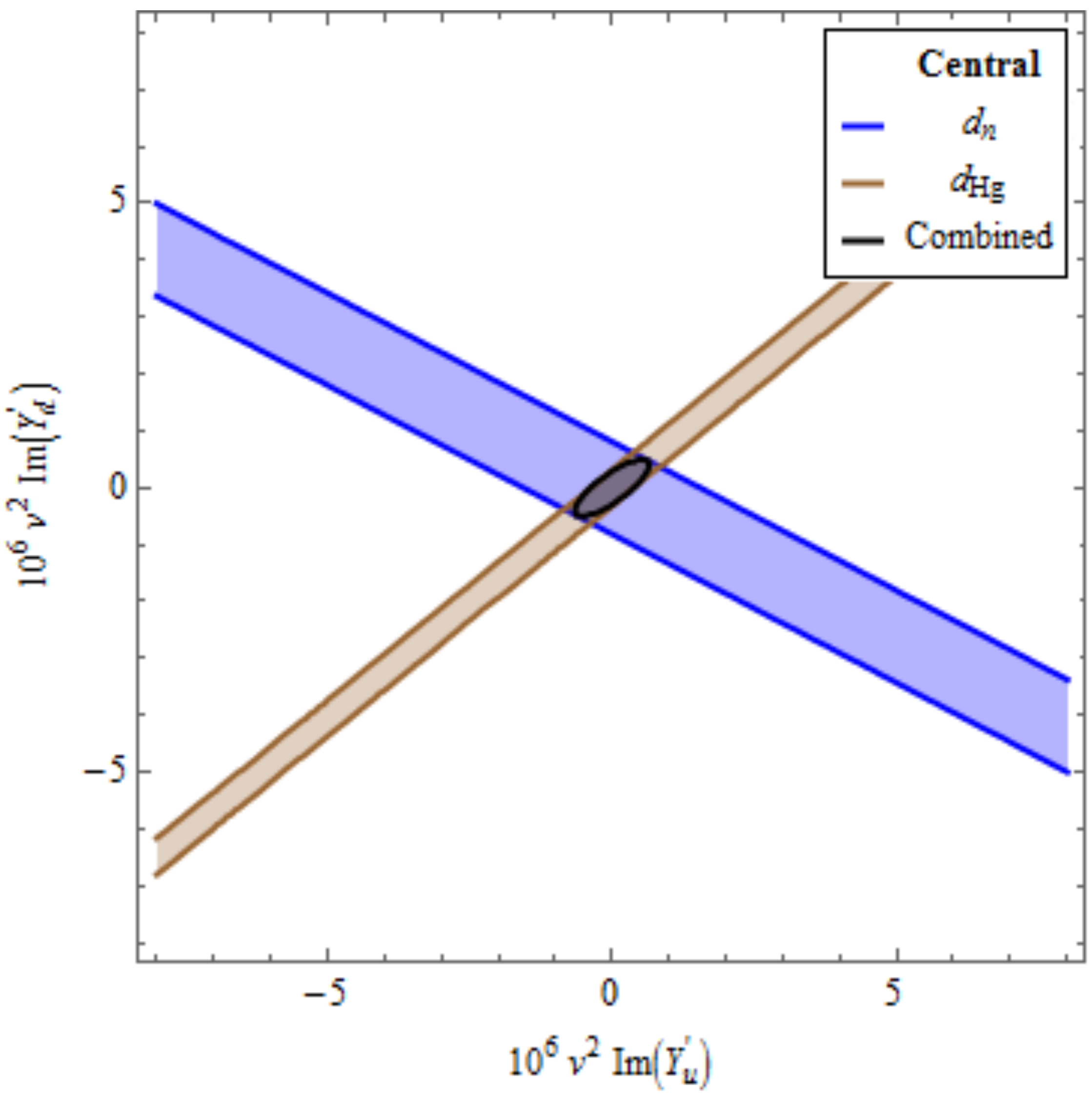
Minimized

Two-coupling analysis

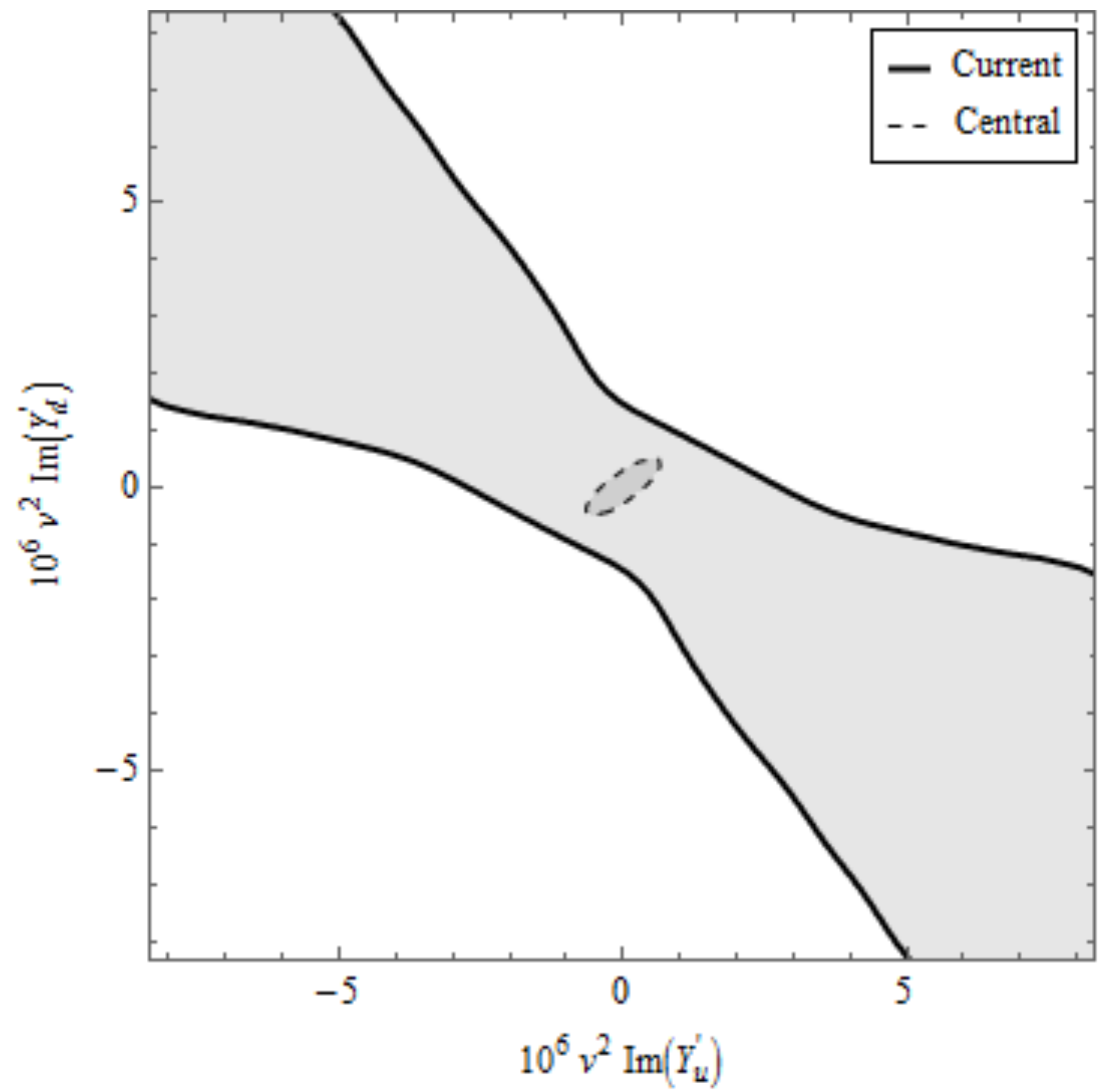




Two-coupling analysis



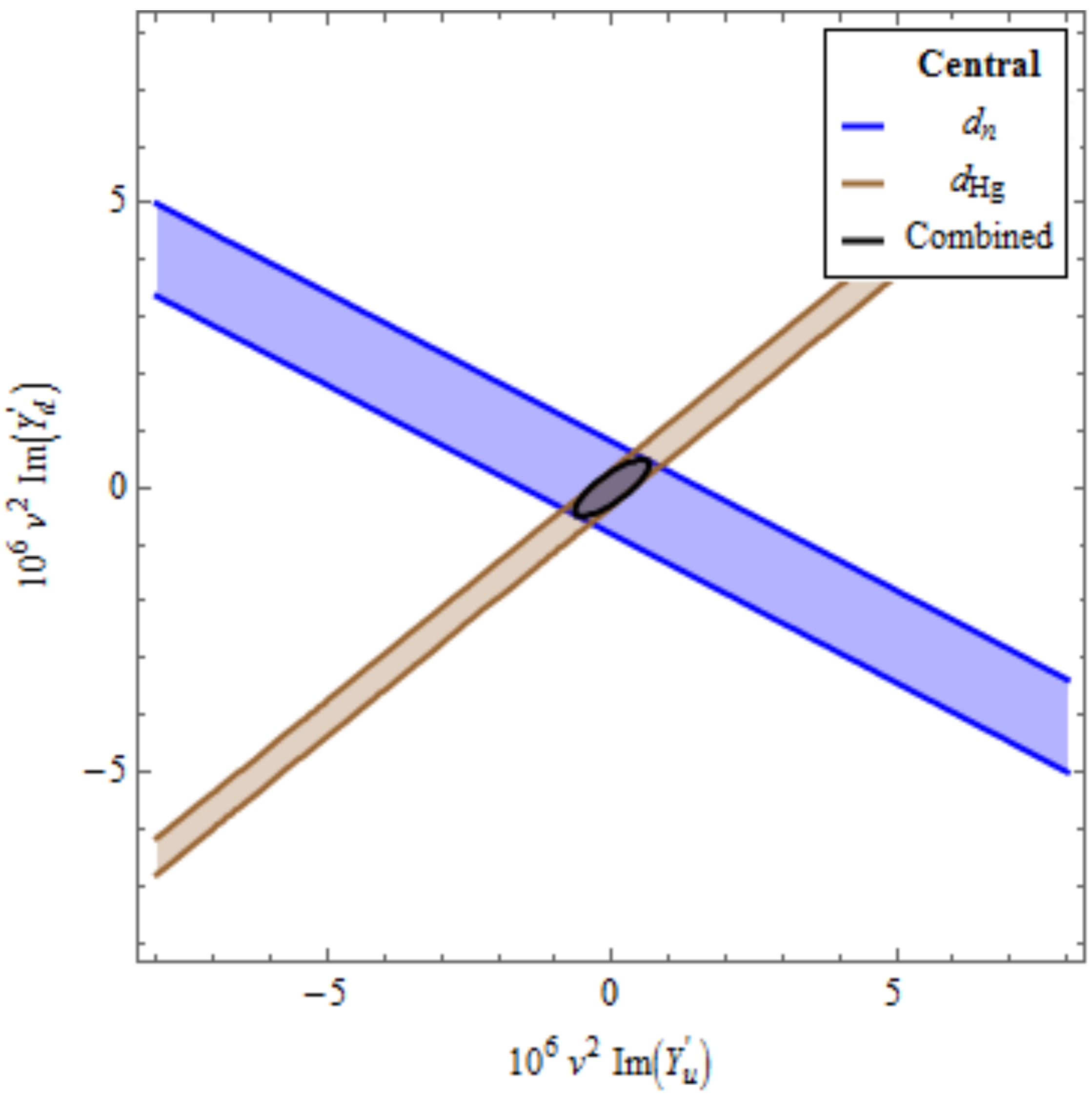
Central Case



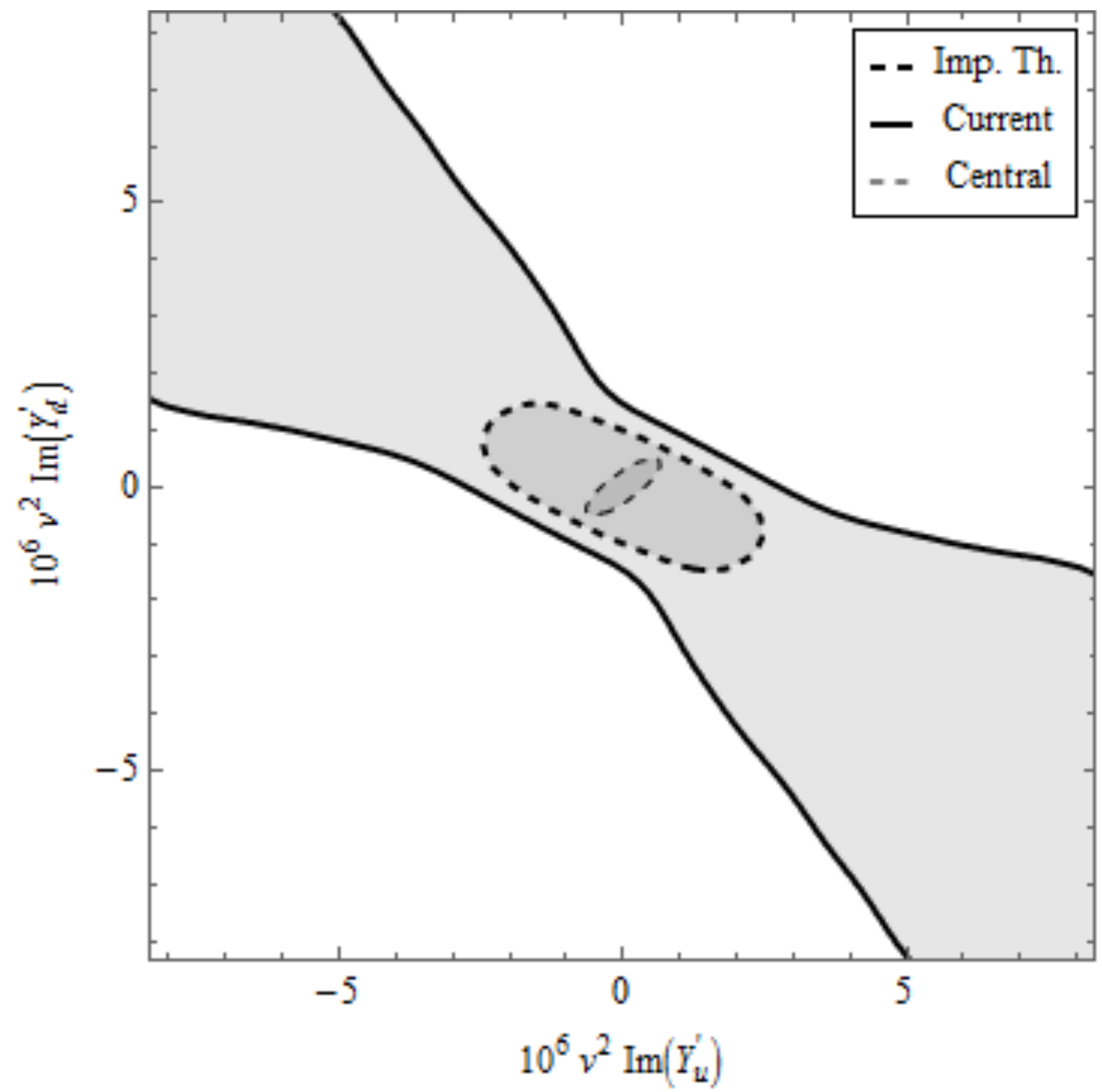
Minimized

- The Minimized procedure weakens the bounds

Two-coupling analysis



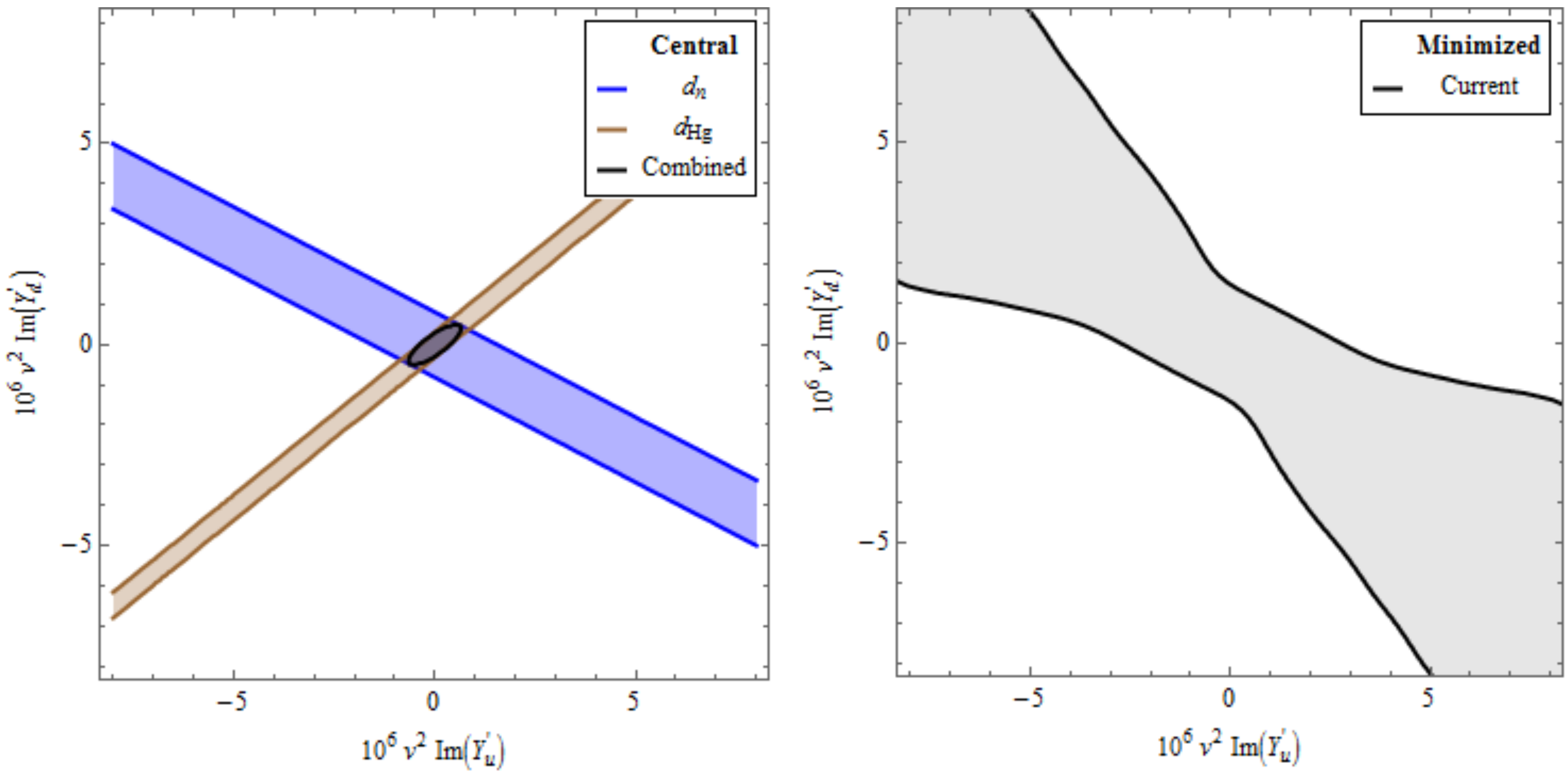
Central Case



Improved Theory

- Improved theory again gets close to the Central Case

Two-coupling analysis

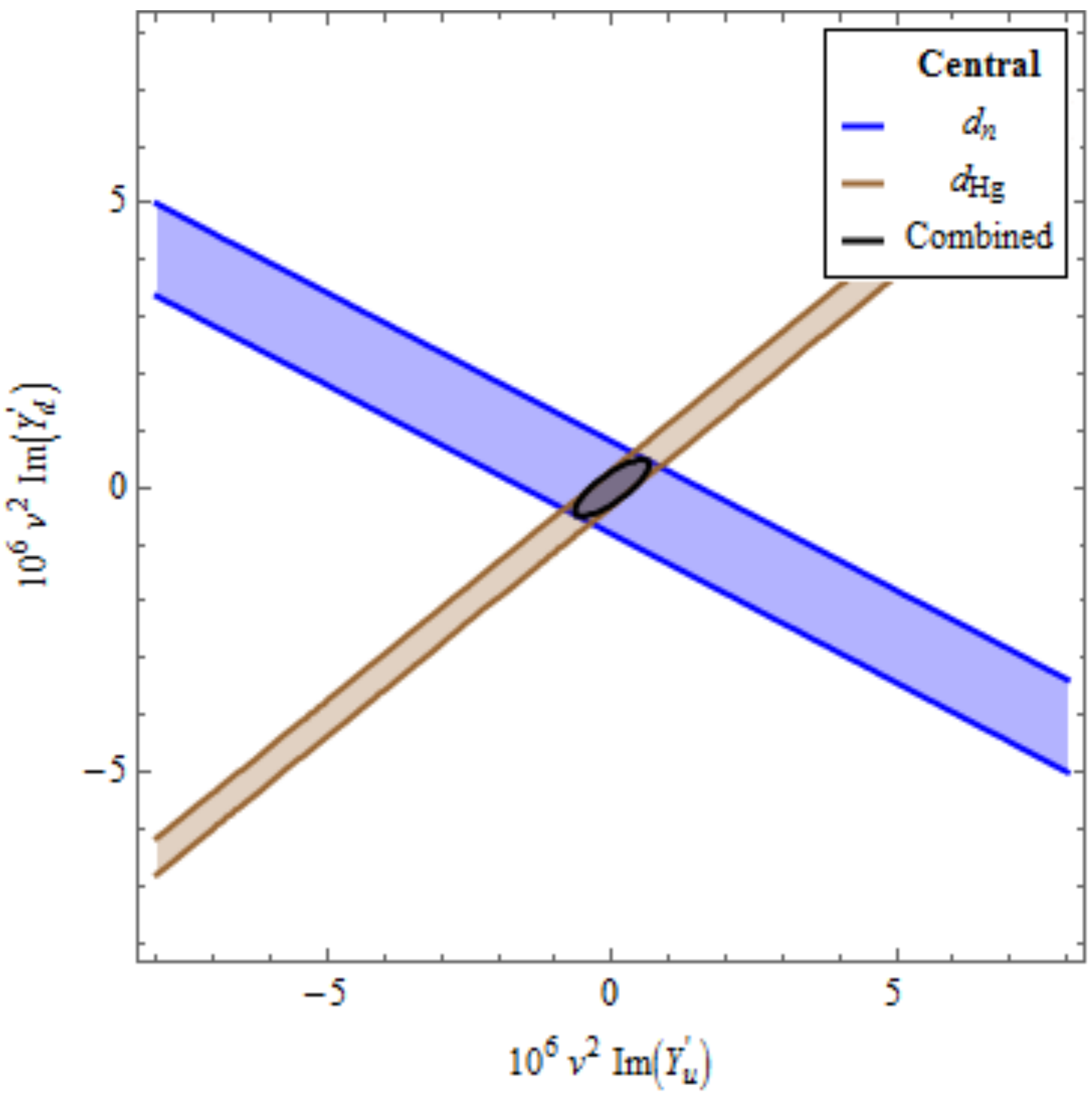


Central Case

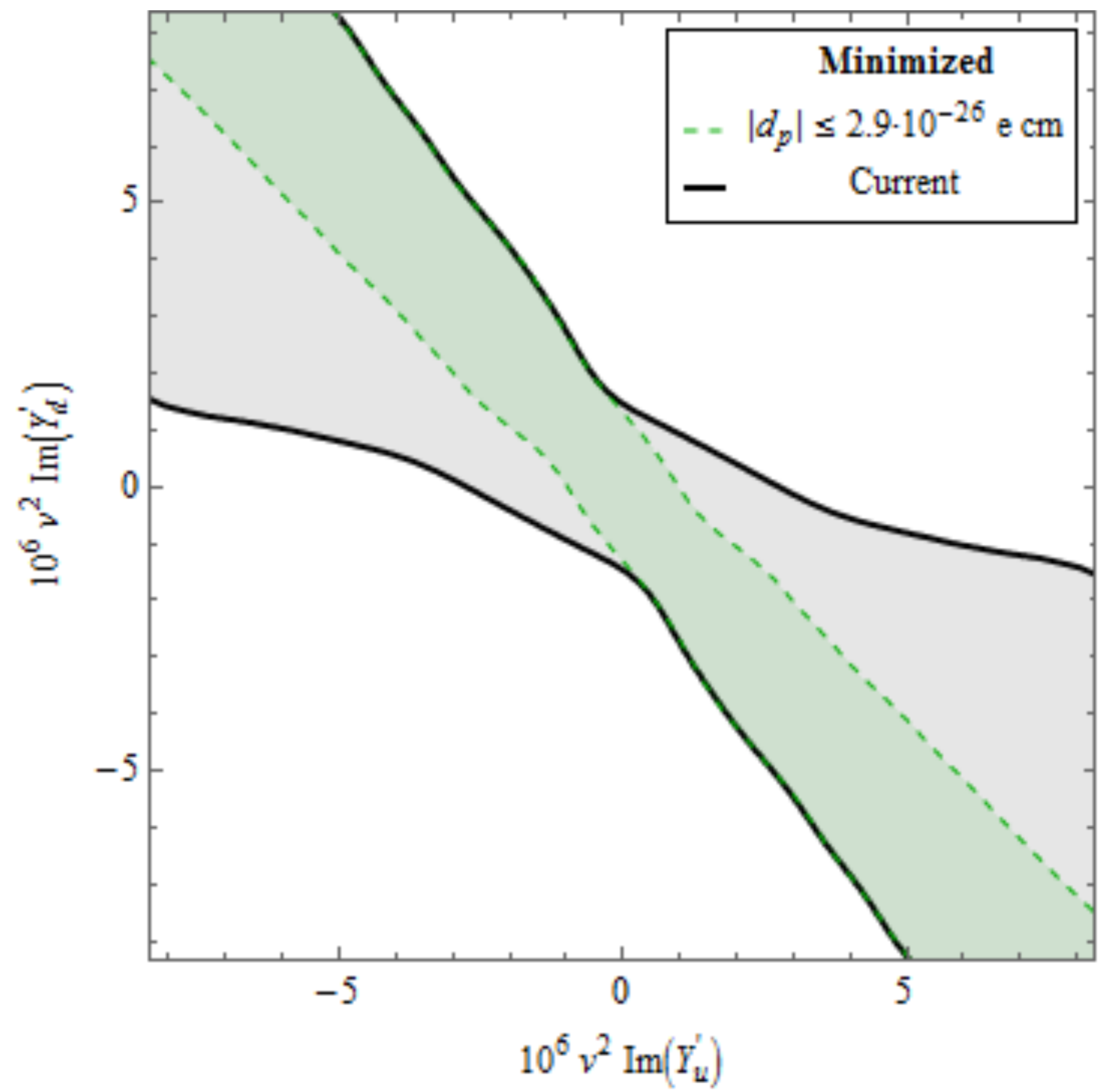
New measurements

- Other possible improvements; new EDM measurements d_p, d_{Ra}, and d_D at the current d_n sensitivity

Two-coupling analysis



Central Case



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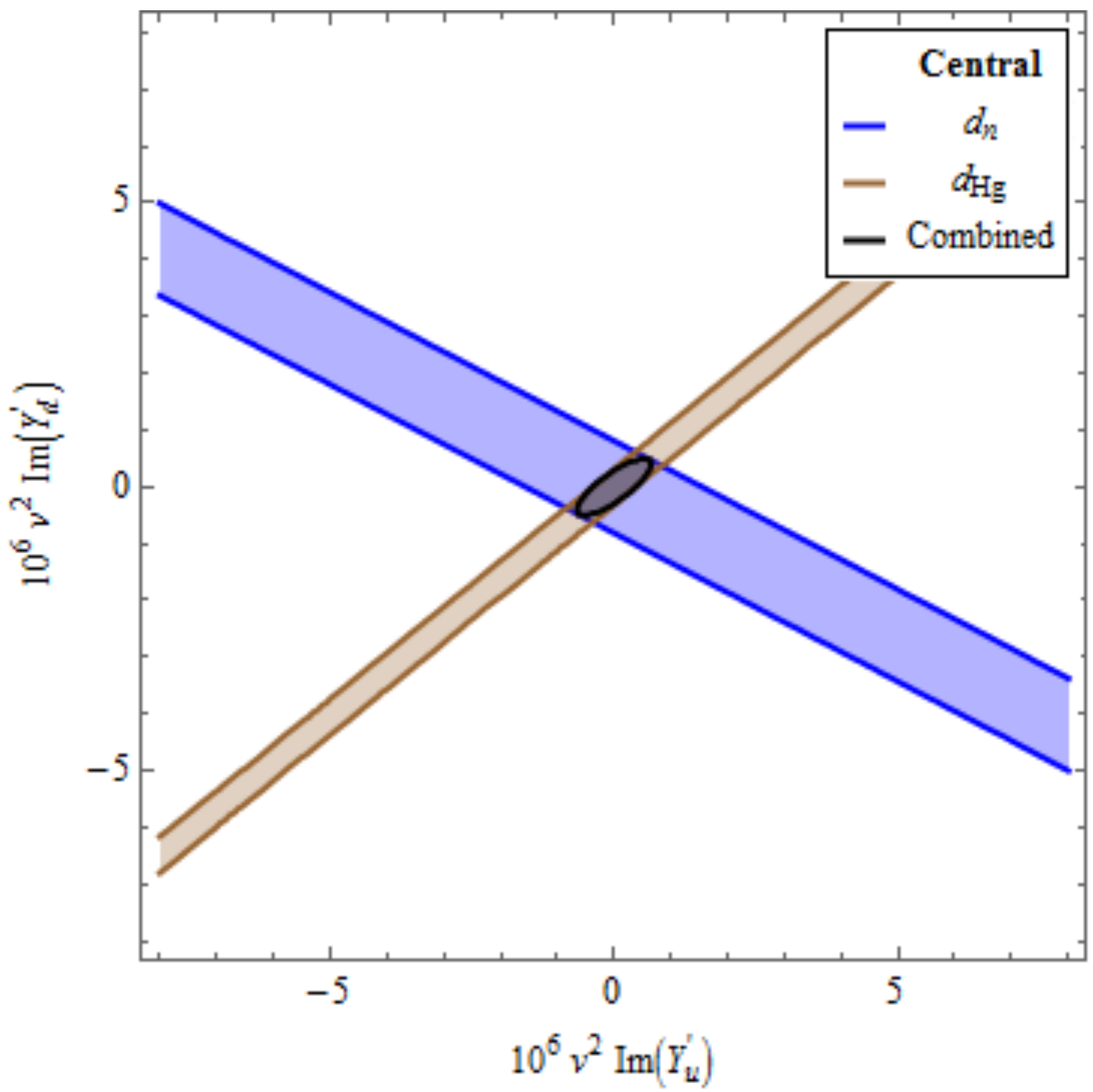
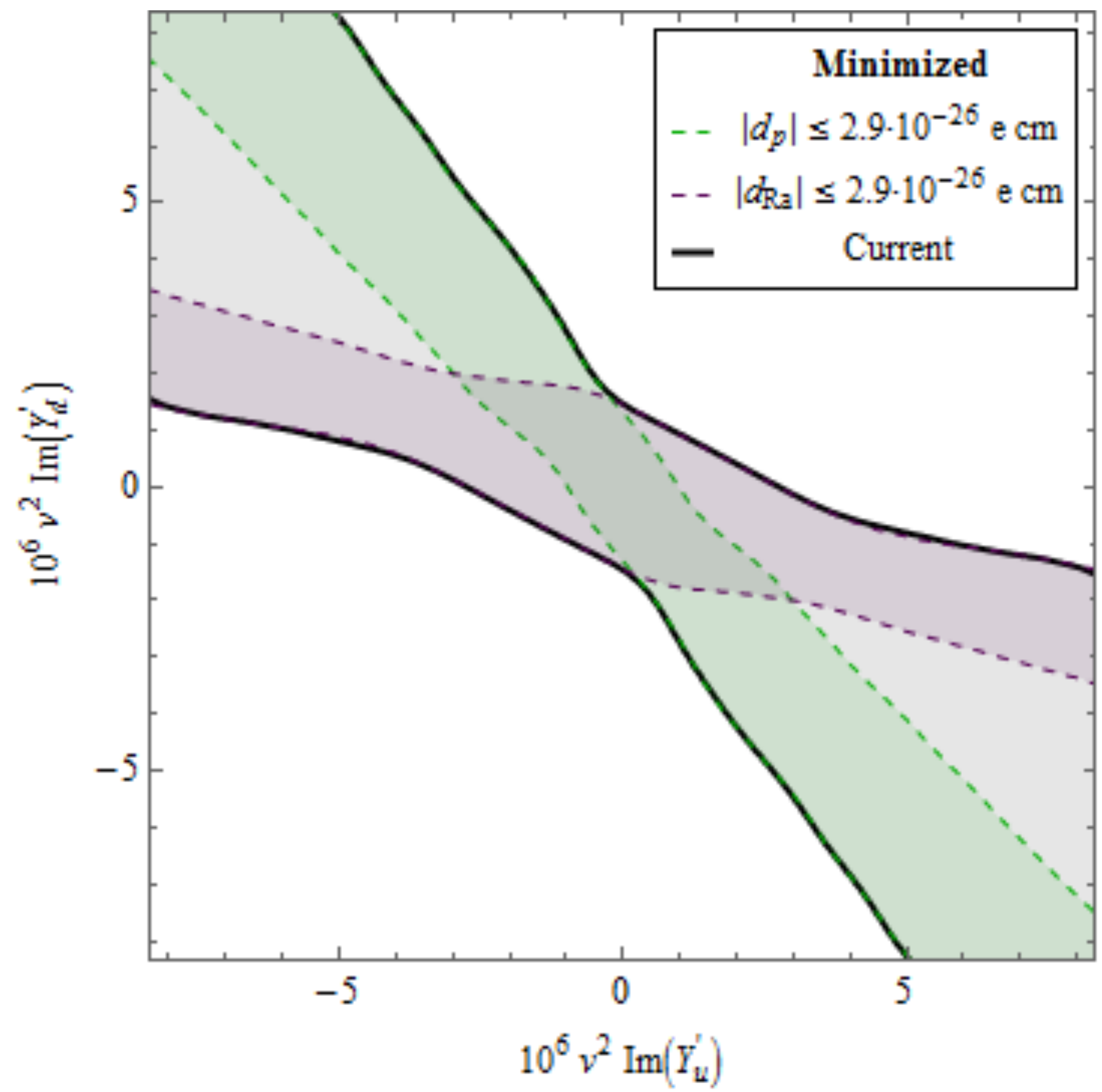
d_p, d_{Ra}, and d_D at the current d_n sensitivity

Two-coupling analysis



Central Case



New measurements

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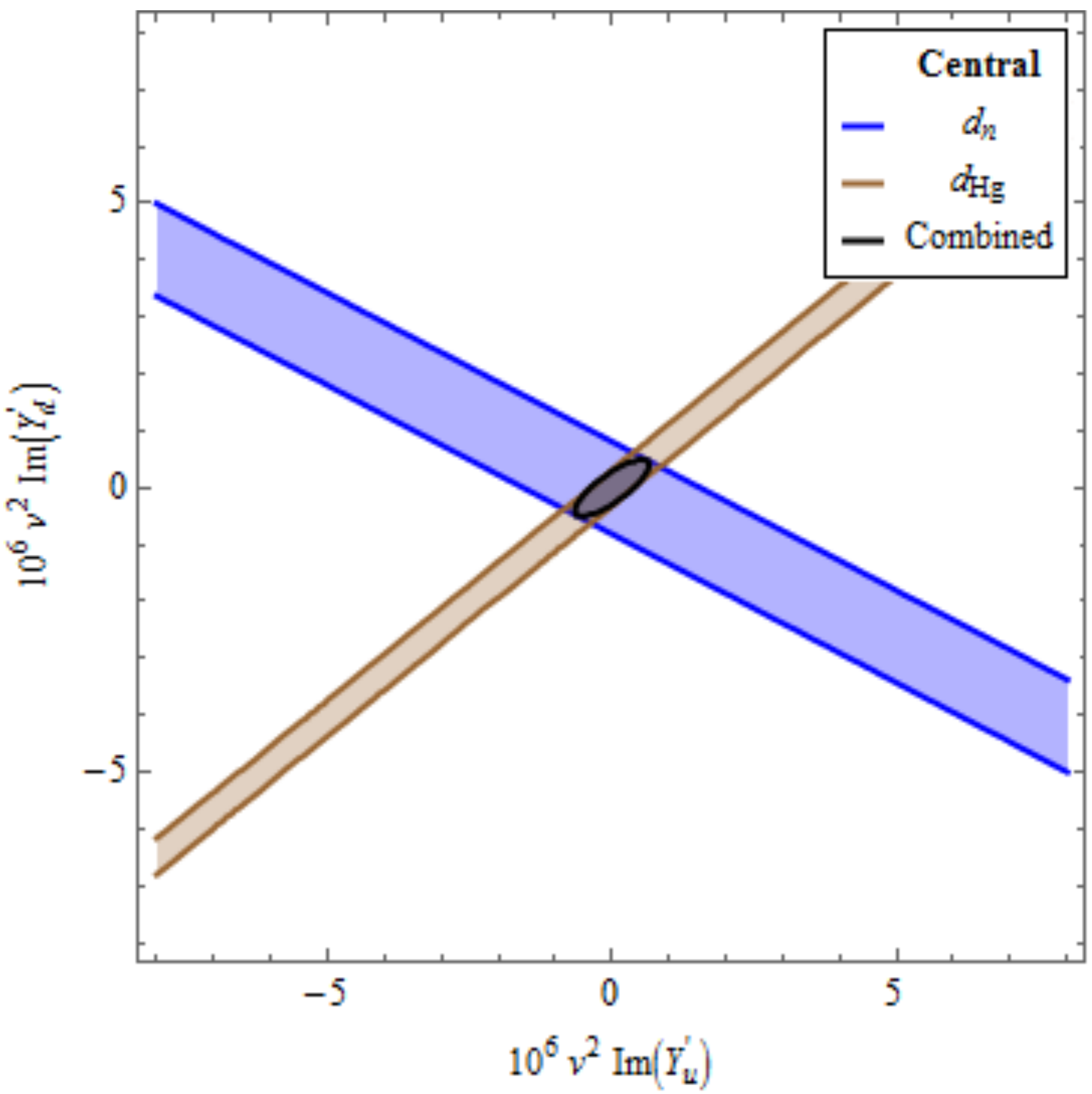

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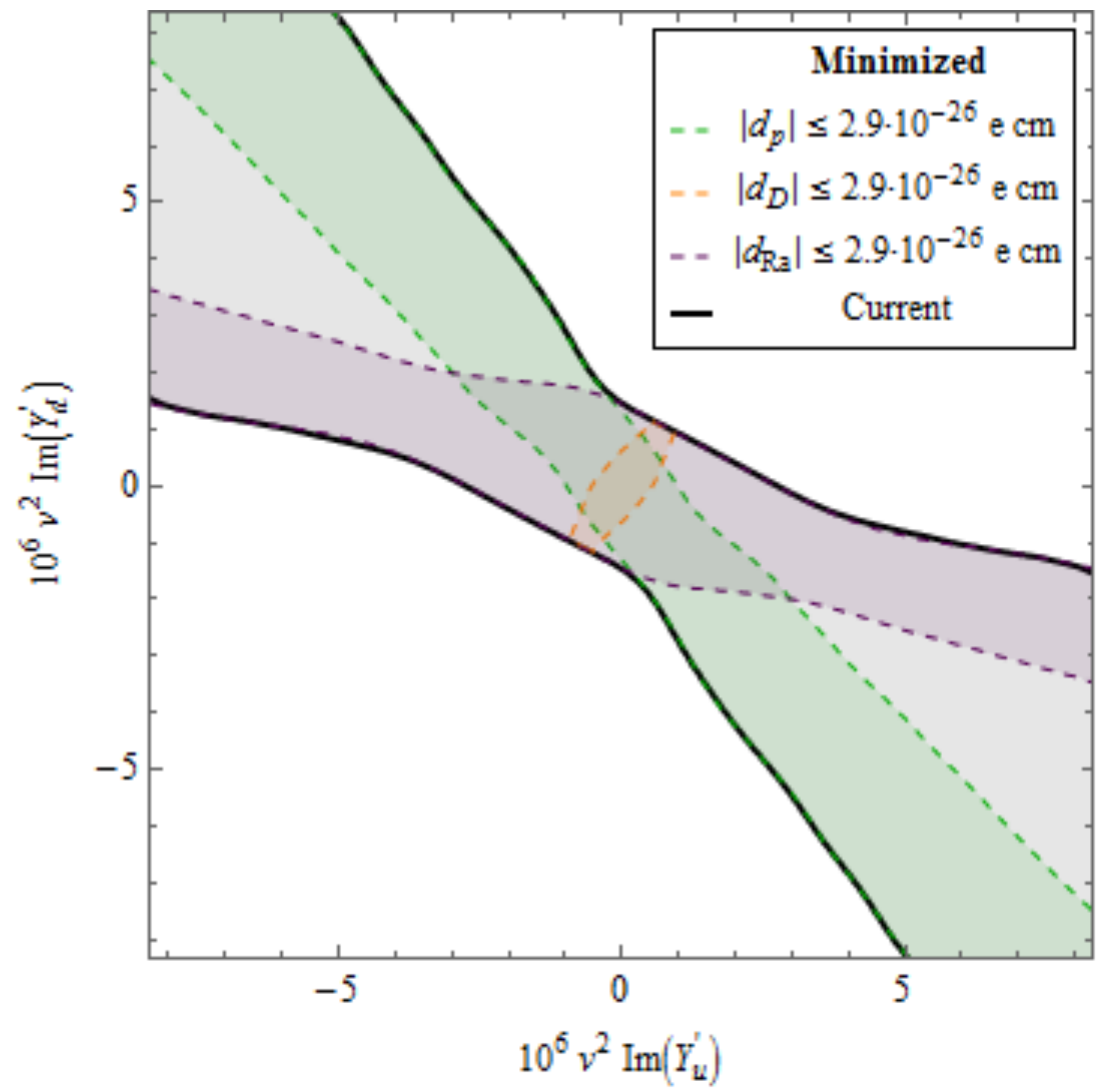
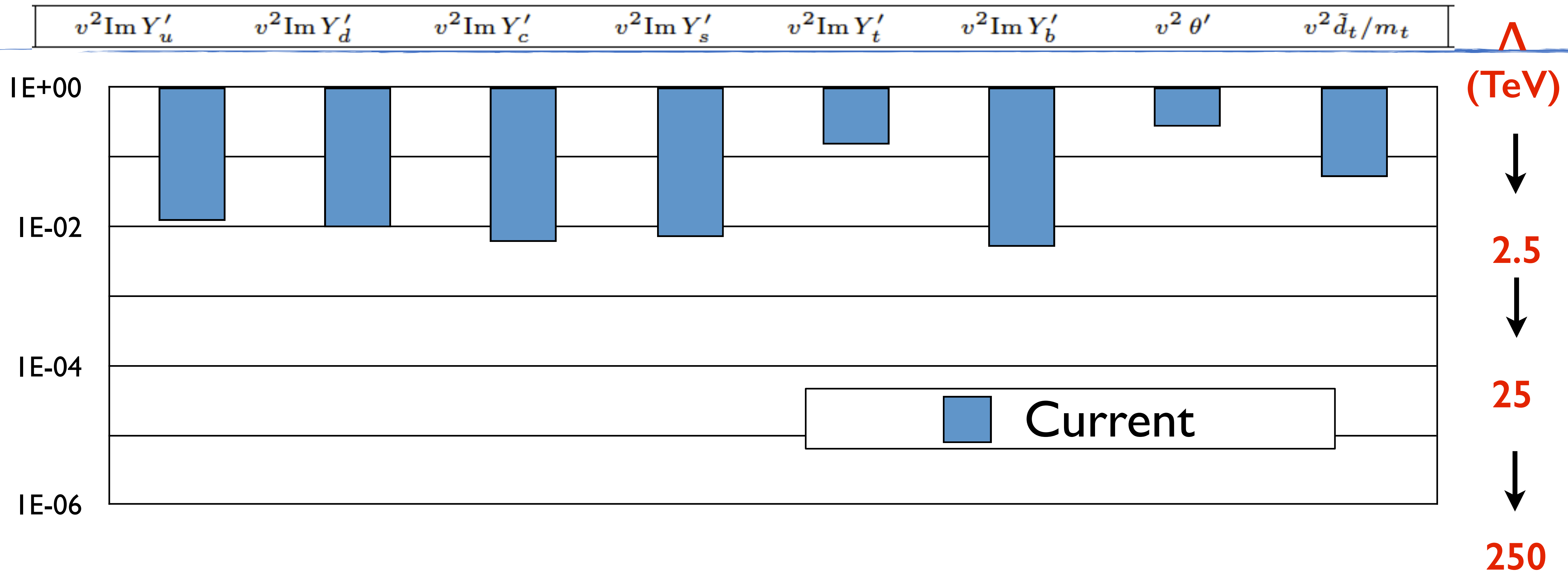


New measurements

- Other possible improvements; new EDM measurements

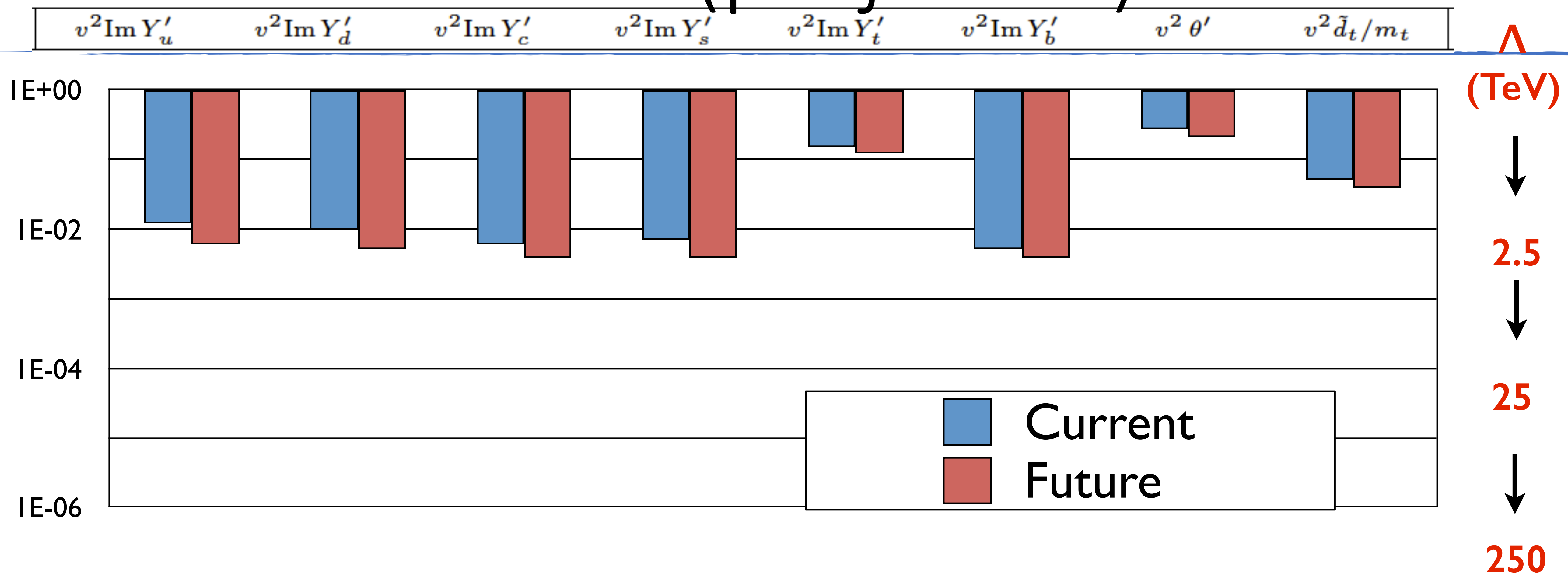
d_p, d_{Ra}, and d_D at the current d_n sensitivity

LHC constraints



- O(10%, 1%) constraints

LHC constraints (projected)



- The constraints improve by up to a factor of 2 at LHC run 2
  Assuming 10% uncertainty on the signal strength of the gluon-fusion channels:
  $gg \to h \to \gamma\gamma,\, WW^*,\, ZZ^*$

- The BSM contributions to gluon fusion grow at the same rate as the SM contribution

Nucleon EDMs

Quark EDM contribution

$$d_n = d_n(d_q, \tilde{d}_q, d_W)$$

$$d_p = d_p(d_q, \tilde{d}_q, d_W)$$

- Lattice results
- O(10%) uncertainty
- Strange contribution consistent with zero

	$d_u(1\,\mathrm{GeV})$	$d_d(1\,\mathrm{GeV})$	$d_s(1\,\mathrm{GeV})$
d_n	-0.22 ± 0.03	0.74 ± 0.07	0.0077 ± 0.01
d_p	0.74 ± 0.07	-0.22 ± 0.03	0.0077 ± 0.01

T. Bhattacharya *et al*, ‘15

Nucleon EDMs

Quark color-EDM contribution

$$d_n = d_n(d_q, \tilde{d}_q, d_W)$$

$$d_p = d_p(d_q, \tilde{d}_q, d_W)$$

- QCD sum-rule calculations
- O(50%) uncertainty
- Strange situation not yet settled

	$e\,\tilde{d}_u(1\,\mathrm{GeV})$	$e\,\tilde{d}_d(1\,\mathrm{GeV})$	$e\,\tilde{d}_s(1\,\mathrm{GeV})$
d_n	-0.55 ± 0.28	-1.1 ± 0.55	xxx
d_p	1.30 ± 0.65	0.60 ± 0.30	xxx

M. Pospelov & A. Ritz, ’05, (Hisano et al. ’12)

Nucleon EDMs

Weinberg contribution

$$d_n = d_n(d_q,\, \tilde{d}_q,\, d_W)$$

$$d_p = d_p(d_q,\, \tilde{d}_q,\, d_W)$$

- QCD sum-rule calculations
- O(100%) uncertainty (QCD sum-rules + naive dimensional analysis estimate)
- Unknown sign

	$e\, d_W(1\,\text{GeV})$
d_n	$\pm(50 \pm 40)$ MeV
d_p	$\mp(50 \pm 40)$ MeV

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

Pion-nucleon couplings

Hadronic uncertainties

Quark color-EDM contributions

- QCD sum-rule calculations
- Uncertainties *O*(>100%)

$$\bar{g}_0 = (5 \pm 10)(\tilde{d}_u + \tilde{d}_d)\,\mathrm{fm}^{-1} \quad , \qquad \bar{g}_1 = (20^{+40}_{-10})(\tilde{d}_u - \tilde{d}_d)\,\mathrm{fm}^{-1}$$

M. Pospelov, Annals Phys, ’02

Mercury EDM

Nuclear uncertainties

$$d_A = \mathcal{A}_A (\alpha_n \, \mathrm{fm}^2, \, \alpha_p \, \mathrm{fm}^2, \, a_0 \, e \, \mathrm{fm}^3, \, a_1 \, e \, \mathrm{fm}^3) \cdot \begin{pmatrix} d_n \\ d_p \\ \bar{g}_0 \\ \bar{g}_1 \end{pmatrix}$$

Atomic screening

- Fairly well-known

Engel, van Kolck, Ramsey-Musolf '13

	Atomic screening $\mathcal{A}(\mathrm{fm}^{-2})$	Best values of $a_{0,1}$: a_0	Best values of $a_{0,1}$: a_1	Estimated ranges of $a_{0,1}$: a_0	Estimated ranges of $a_{0,1}$: a_1
^{129}Xe	$(0.33 \pm 0.05) \cdot 10^{-4}$	-0.10	-0.076	$\{-0.063, -0.63\}$	$\{-0.038, -0.63\}$
^{199}Hg	$-(2.8 \pm 0.6) \cdot 10^{-4}$	0.13	± 0.25	$\{0.063, 0.63\}$	$\{-0.38, 1.14\}$
^{225}Ra	$-(7.7 \pm 0.8) \cdot 10^{-4}$	-19	76	$\{-12.6, -76\}$	$\{51, 303\}$

Dzuba, Flambaum, '09, '12; Singh, Sahoo, '15;

Mercury EDM

Nuclear uncertainties

$$d_A = \mathcal{A}_A \left(\alpha_n\,\mathrm{fm}^2,\ \alpha_p\,\mathrm{fm}^2,\ a_0\,e\,\mathrm{fm}^3,\ a_1\,e\,\mathrm{fm}^3\right) \cdot \begin{pmatrix} d_n \\ d_p \\ \bar{g}_0 \\ \bar{g}_1 \end{pmatrix}$$

Atomic screening
- Fairly well-known

Nucleon-EDM contributions
- Fairly well-known (for Mercury)

$$\alpha_n = 1.9 \pm 0.1$$
$$\alpha_p = 0.20 \pm 0.06$$

Engel, van Kolck, Ramsey-Musolf '13

	Atomic screening $\mathcal{A}(\mathrm{fm}^{-2})$	Best values of $a_{0,1}$		Estimated ranges of $a_{0,1}$	
		a_0	a_1	a_0	a_1
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Dmitriev & Sen'kov, '03

Mercury EDM

Nuclear uncertainties

$$d_A = \mathcal{A}_A \left(\alpha_n\,\mathrm{fm}^2,\ \alpha_p\,\mathrm{fm}^2,\ a_0\,e\,\mathrm{fm}^3,\ a_1\,e\,\mathrm{fm}^3 \right) \cdot \begin{pmatrix} d_n \\ d_p \\ \bar{g}_0 \\ \bar{g}_1 \end{pmatrix}$$

Atomic screening

- Fairly well-known

Nucleon-EDM contributions

- Fairly well-known (for Mercury)

$$\alpha_n = 1.9 \pm 0.1$$
$$\alpha_p = 0.20 \pm 0.06$$

Pion-nucleon contributions

- Large allowed ranges, including zero for $\bar{g}_1$

Engel, van Kolck, Ramsey-Musolf '13

	Atomic screening	Best values of $a_{0,1}$		Estimated ranges of $a_{0,1}$	
	$\mathcal{A}(\mathrm{fm}^{-2})$	a_0	a_1	a_0	a_1
^{129}Xe	$(0.33 \pm 0.05) \cdot 10^{-4}$	-0.10	-0.076	$\{-0.063, -0.63\}$	$\{-0.038, -0.63\}$
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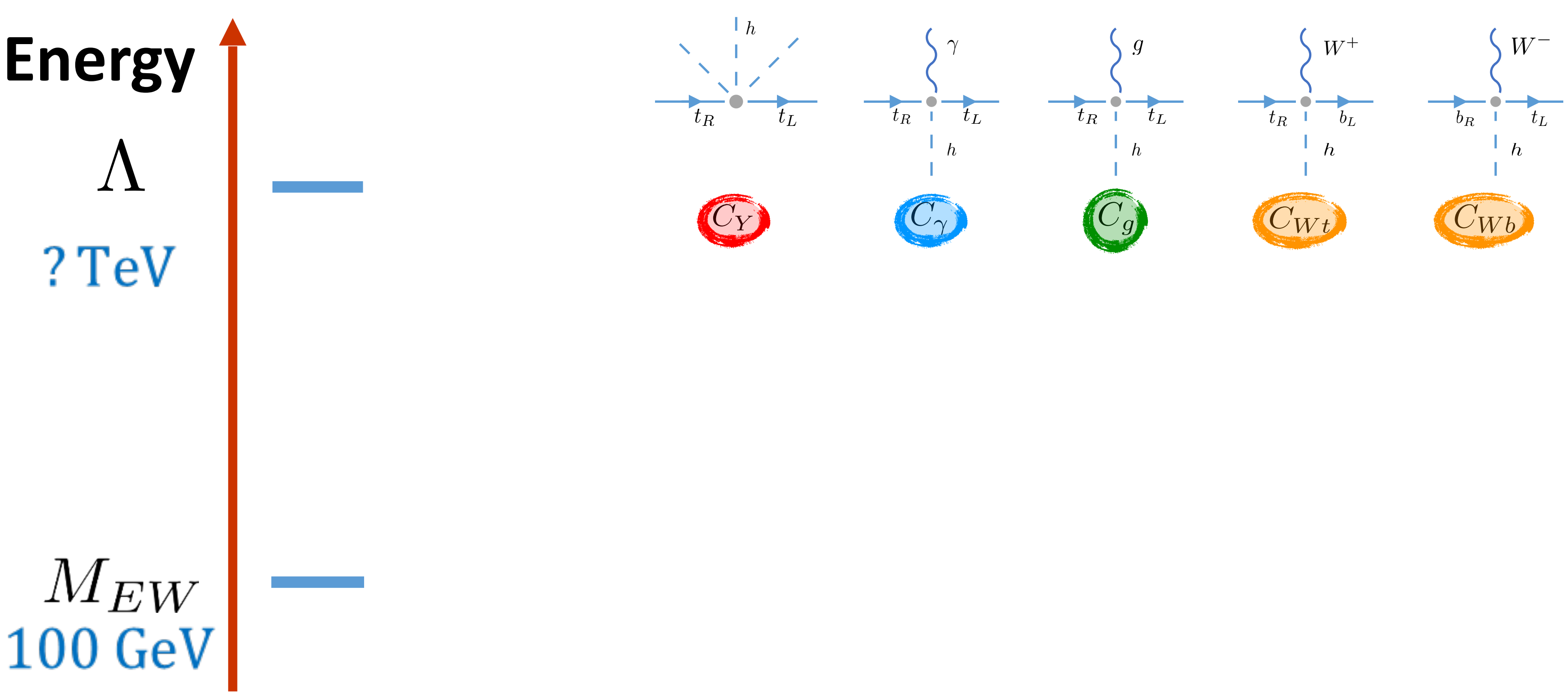
de Jesus, Engel, '05; Ban, Dobaczewski, Engel, Shukla, '10;

Mixing among top-Higgs couplings

$$\frac{d}{d\ln\mu}\begin{pmatrix} C_\gamma \\ C_g \\ C_{Wt} \\ C_{Wb} \\ C_Y \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & \gamma_{Wt\to\gamma} & \gamma_{Wb\to\gamma} & 0 \\ \gamma_{\gamma\to g} & 16C_F-4N_c & \gamma_{Wt\to g} & 0 & 0 \\ 0 & 2C_F & 8C_F & 0 & 0 \\ 0 & 0 & 0 & 8C_F & 0 \\ 0 & 30C_F y_t^2 & 0 & 0 & 0 \end{pmatrix}\cdot\begin{pmatrix} C_\gamma \\ C_g \\ C_{Wt} \\ C_{Wb} \\ C_Y \end{pmatrix}$$



Degrassi, Franco, Marchetti, Silvestrini, ’05; Jenkins, Manohar, Trott et al, ’13, ’14

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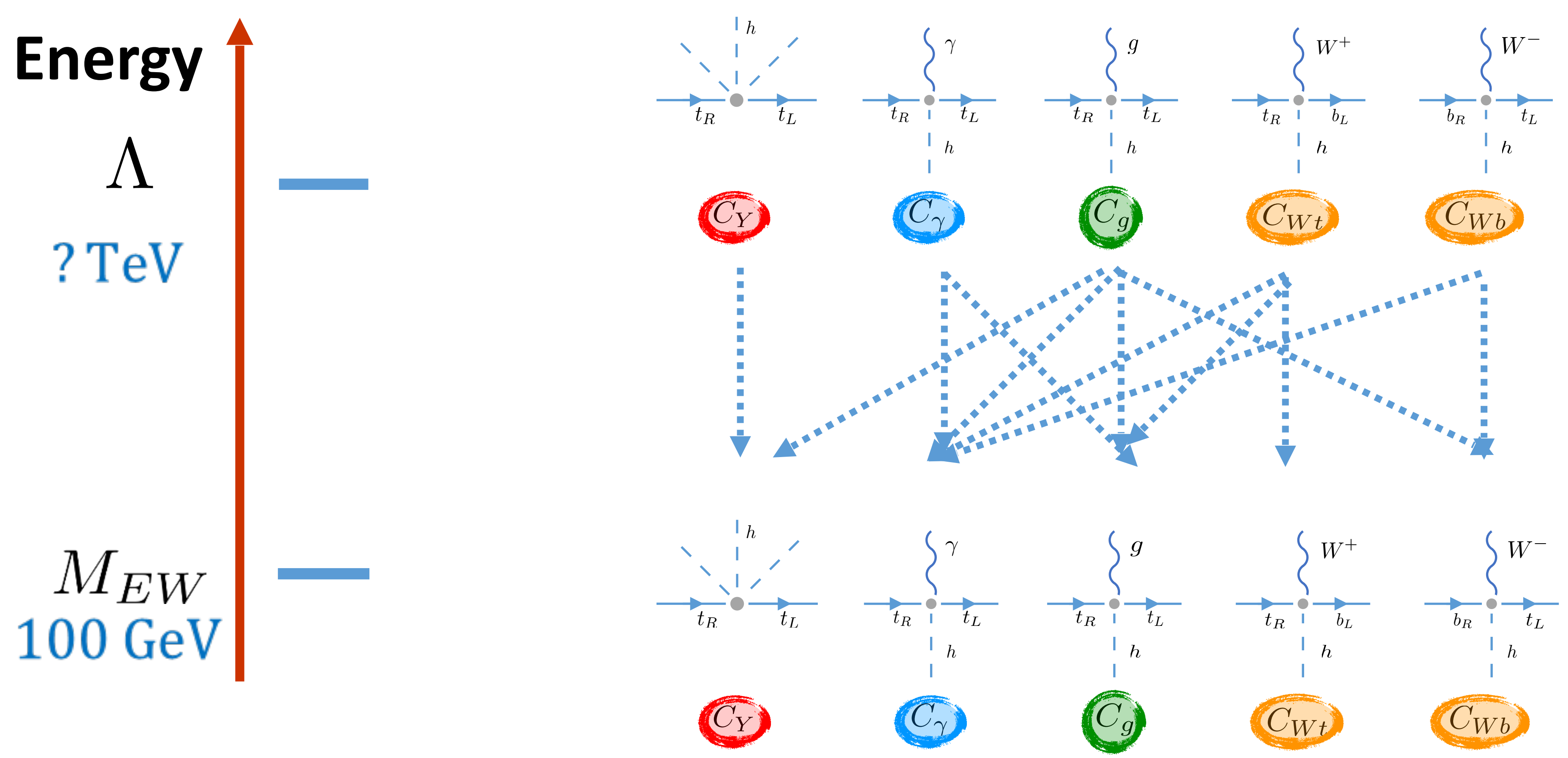

Degrassi, Franco, Marchetti, Silvestrini, ’05; Jenkins, Manohar, Trott et al, ’13, ’14

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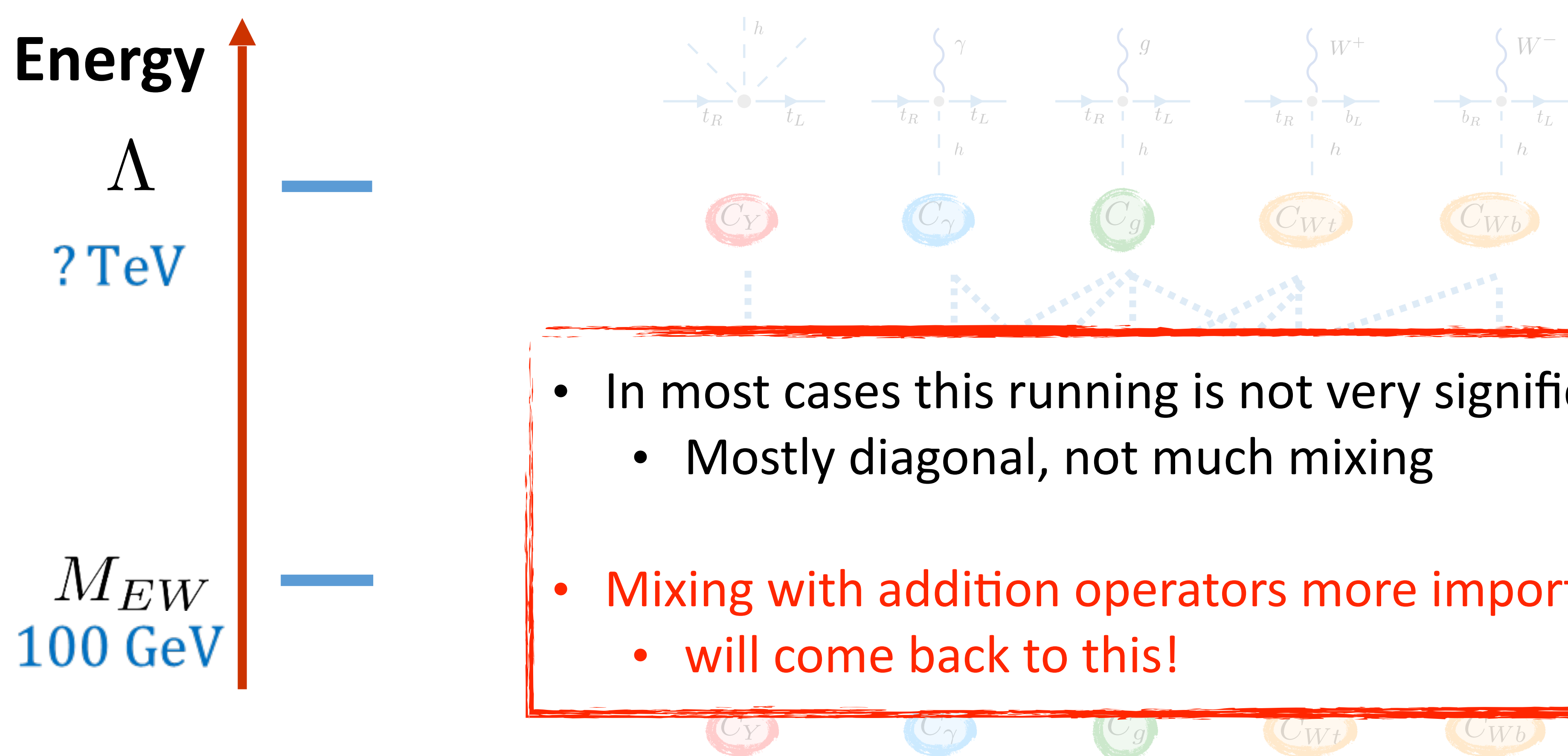
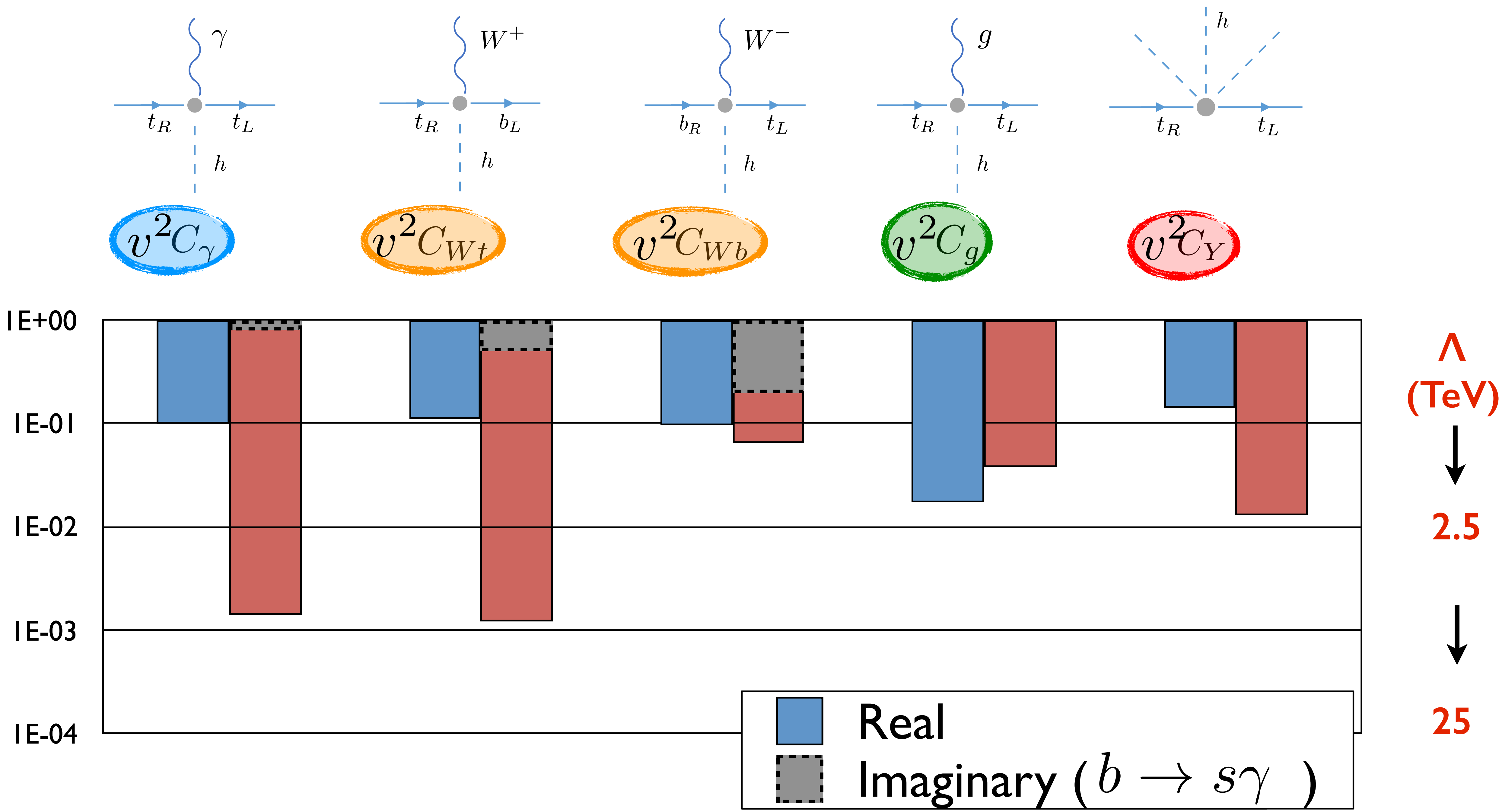


- In most cases this running is not very significant
  - Mostly diagonal, not much mixing
- Mixing with addition operators more important
  - will come back to this!

Degrassi, Franco, Marchetti, Silvestrini, ’05; Jenkins, Manohar, Trott et al, ’13, ’14

Constraints

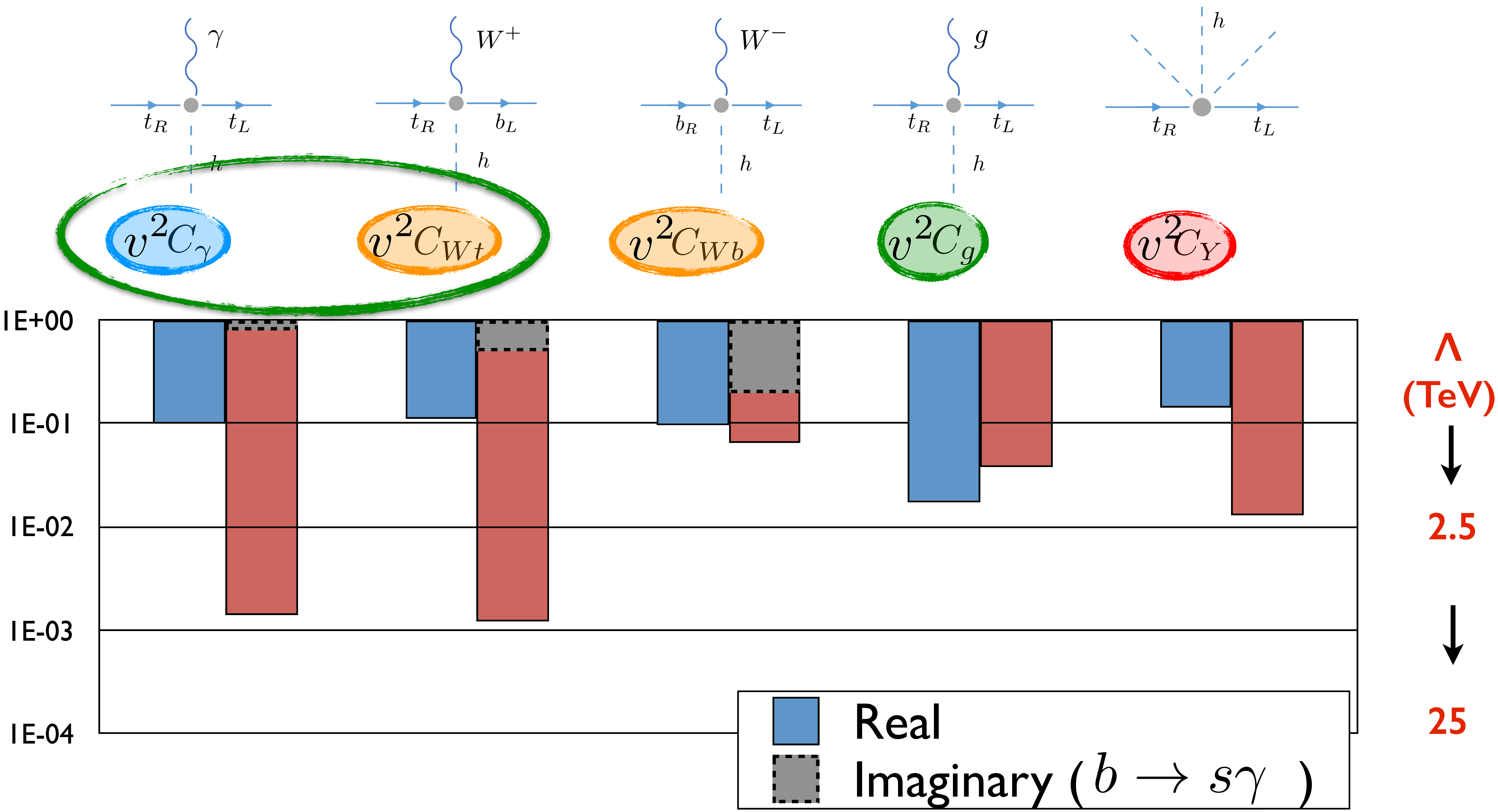
Real parts



Kamenik, Papucci, Weiler, '13; Grzadkowski, Misiak, '08

Constraints

Real parts

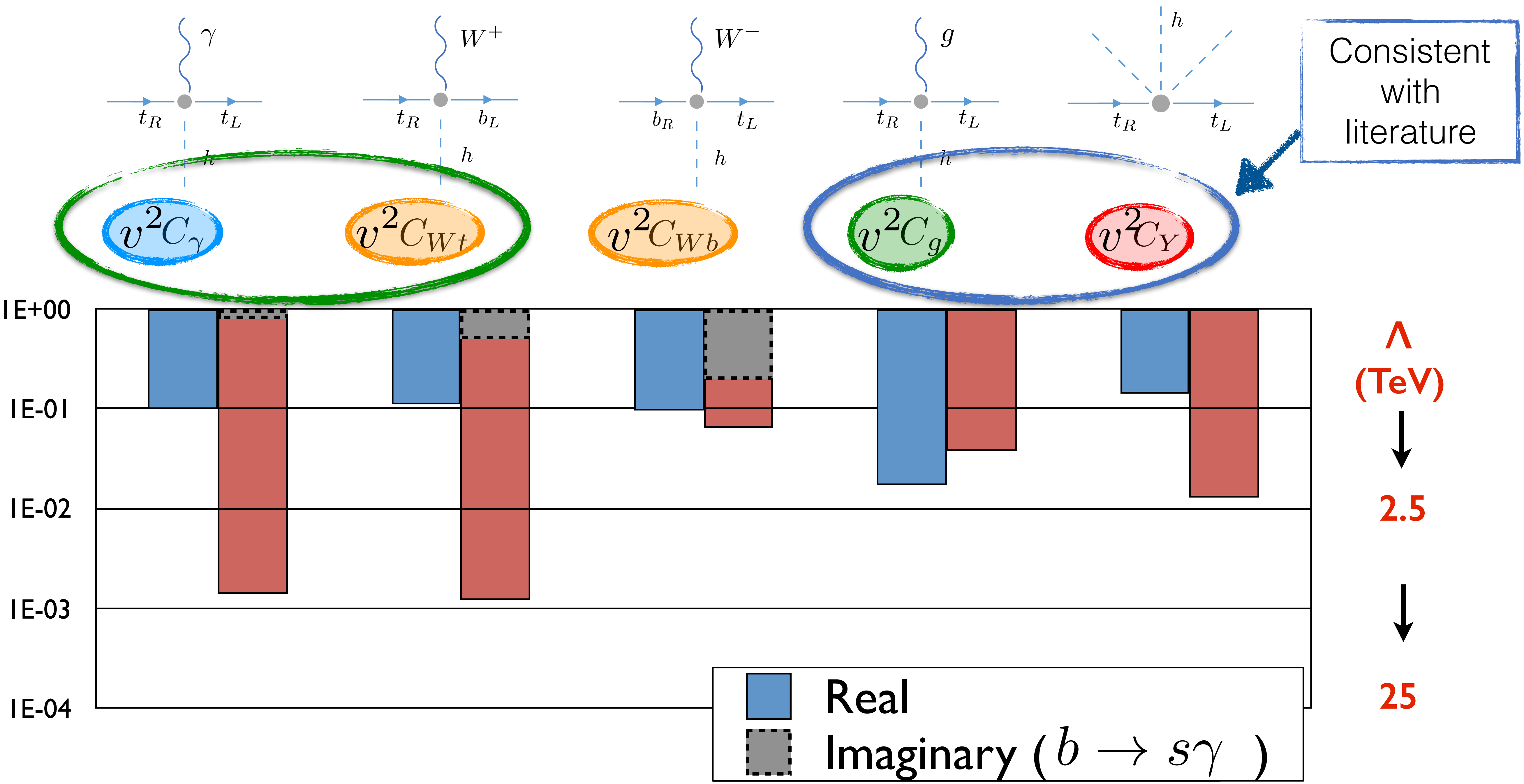


- The 'two-step' mechanism improves previous bounds by **three orders of magnitude**

Kamenik, Papucci, Weiler, '13; Grzadkowski, Misiak, '08

Constraints

Real parts



- The ‘two-step’ mechanism improves previous bounds by **three orders of magnitude**
- Remaining constraints are consistent with the literature

Kamenik, Papucci, Weiler, ’13; Grzadkowski, Misiak, ‘08

Direct collider observables

Single top

$$
\begin{aligned}
\frac{\sigma_t(7\text{ TeV})}{\text{pb}} &= (41.9 \pm 1.8) - (9.4 \pm 0.3)\ v^2 c_{Wt} + (15.6 \pm 0.2)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right) ,\\
\frac{\sigma_{\bar{t}}(7\text{ TeV})}{\text{pb}} &= (22.7 \pm 1.0) - (0.3 \pm 0.1)\ v^2 c_{Wt} + (5.5 \pm 0.2)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right) ,\\
\frac{\sigma_t(8\text{ TeV})}{\text{pb}} &= (56.4 \pm 2.4) - (11.7 \pm 0.3)\ v^2 c_{Wt} + (21.0 \pm 0.5)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right) ,\\
\frac{\sigma_{\bar{t}}(8\text{ TeV})}{\text{pb}} &= (30.7 \pm 1.3) - (0.5 \pm 0.2)\ v^2 c_{Wt} + (7.7 \pm 0.2)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right) ,\\
\frac{\sigma_t(13\text{ TeV})}{\text{pb}} &= (136\ \pm 5.4) - (26.2 \pm 0.4)\ v^2 c_{Wt} + (57.0 \pm 1.0)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right) ,\\
\frac{\sigma_{\bar{t}}(13\text{ TeV})}{\text{pb}} &= (81.0 \pm 4.1) - (2.6 \pm 0.4)\ v^2 c_{Wt} + (24.7 \pm 1.0)\left((v^2 c_{Wt})^2 + (v^2 \tilde{c}_{Wt})^2\right) .
\end{aligned}
$$

Direct collider observables

Helicity fractions

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

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

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

Direct collider observables

tt, tth

$$\frac{\sigma_{t\bar{t}}(1.96\,\text{TeV})}{\text{pb}} = (7.45 \pm 0.44) - (10.8 \pm 0.6)(v^2 c_g) + (7.1 \pm 0.7)(v^2 c_g)^2 + (2.5 \pm 0.5)(v^2 \tilde{c}_g)^2$$

$$\frac{\sigma_{t\bar{t}}(8\,\text{TeV})}{\text{pb}} = (252.9 \pm 20) - (333 \pm 28)\left(v^2 c_g\right) + (476 \pm 44)\left(v^2 c_g\right)^2 + (336 \pm 33)\left(v^2 \tilde{c}_g\right)^2 .$$

$$\begin{aligned}
\mu_{t\bar{t}h}(8\,\text{TeV}) &= \left(1 + v^2 c_Y\right)^2 + (0.33 \pm 0.02)(v^2 \tilde{c}_Y)^2 - (7.11 \pm 0.02)(v^2 c_g) \\
&\quad + (52 \pm 5)(v^2 c_g)^2 + (44 \pm 4)(v^2 \tilde{c}_g)^2 \\
&\quad - (11.0 \pm 0.1)\left(v^2 c_g\right)\left(v^2 c_Y\right) - (0.12 \pm 0.16)\left(v^2 \tilde{c}_g\right)\left(v^2 \tilde{c}_Y\right) \\
\mu_{t\bar{t}h}(14\,\text{TeV}) &= \left(1 + v^2 c_Y\right)^2 + (0.42 \pm 0.01)(v^2 \tilde{c}_Y)^2 - (7.57 \pm 0.03)\left(v^2 c_g\right) \\
&\quad + (80 \pm 5)\left(v^2 c_g\right)^2 + (72 \pm 5)\left(v^2 \tilde{c}_g\right)^2 \\
&\quad - (11.5 \pm 0.1)\left(v^2 c_g\right)\left(v^2 c_Y\right) - (0.79 \pm 0.06)\left(v^2 \tilde{c}_g\right)\left(v^2 \tilde{c}_Y\right).
\end{aligned}$$