Constraining new CP violation using EDMs and the LHC

Based on:

Y.T. Chien, V. Cirigliano, E. Mereghetti, J. de Vries, WD
JHEP **1602**, 011 (2016), arXiv:1510.00725

Wouter Dekens

New Mexico CONSORTIUM

Los Alamos NATIONAL LABORATORY EST. 1943

Beyond the standard model?

- Baryon asymmetry of the Universe

- The Sakharov conditions:
  - Baryon number violation
  - Out of thermal equilibrium
  - C and CP violation

- Hard to explain in the SM
  - CP-violating New Physics?

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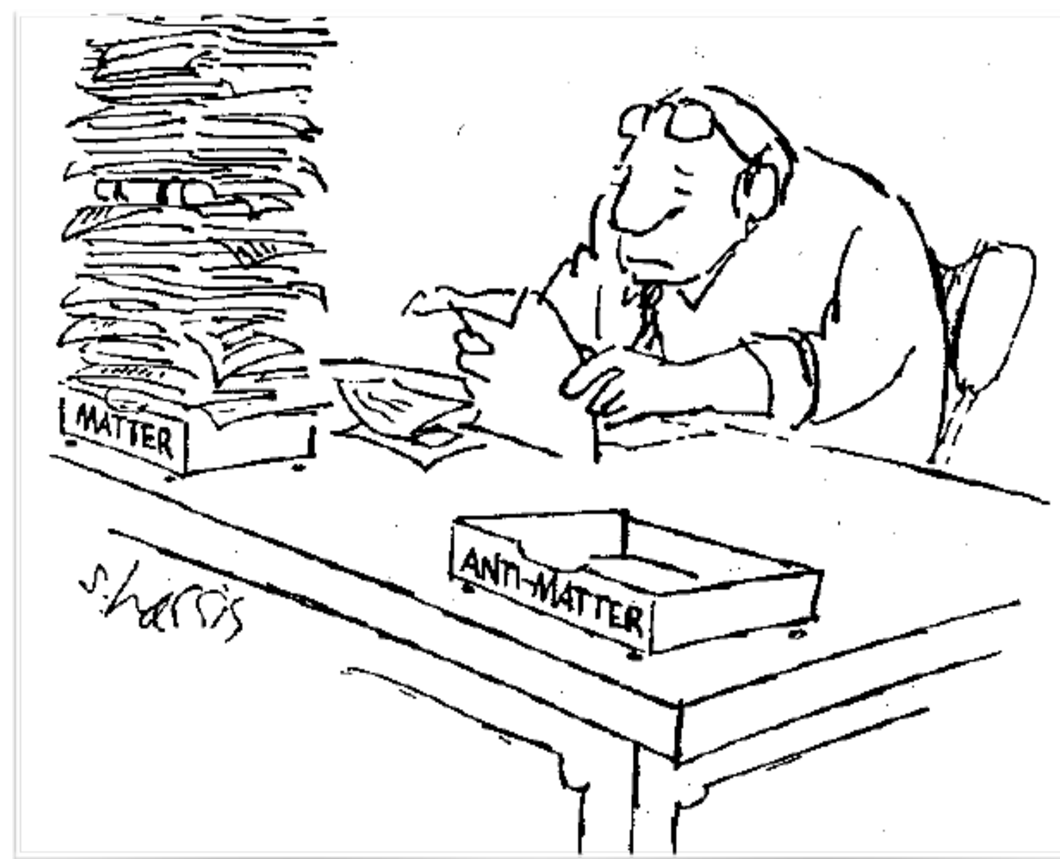
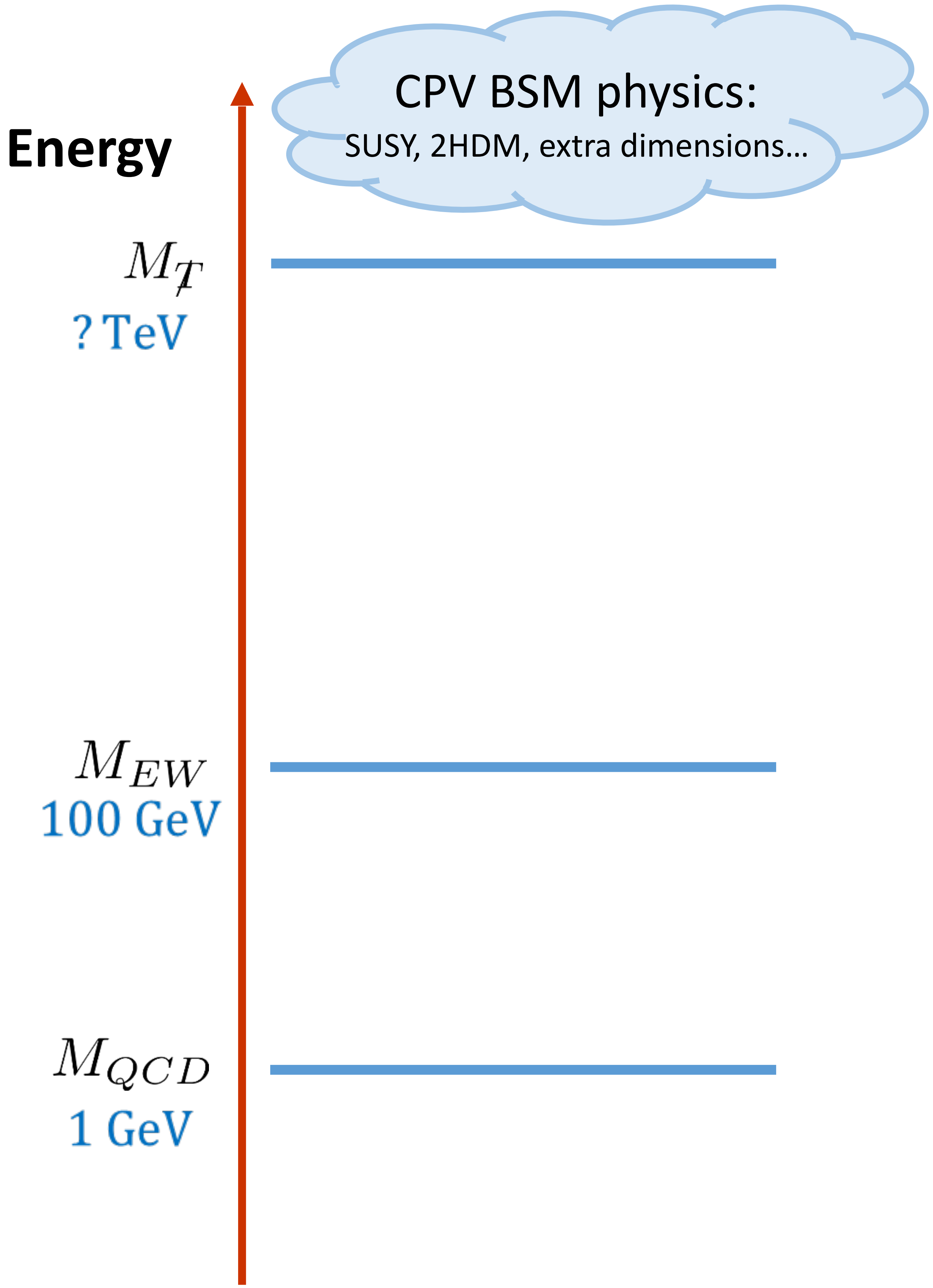
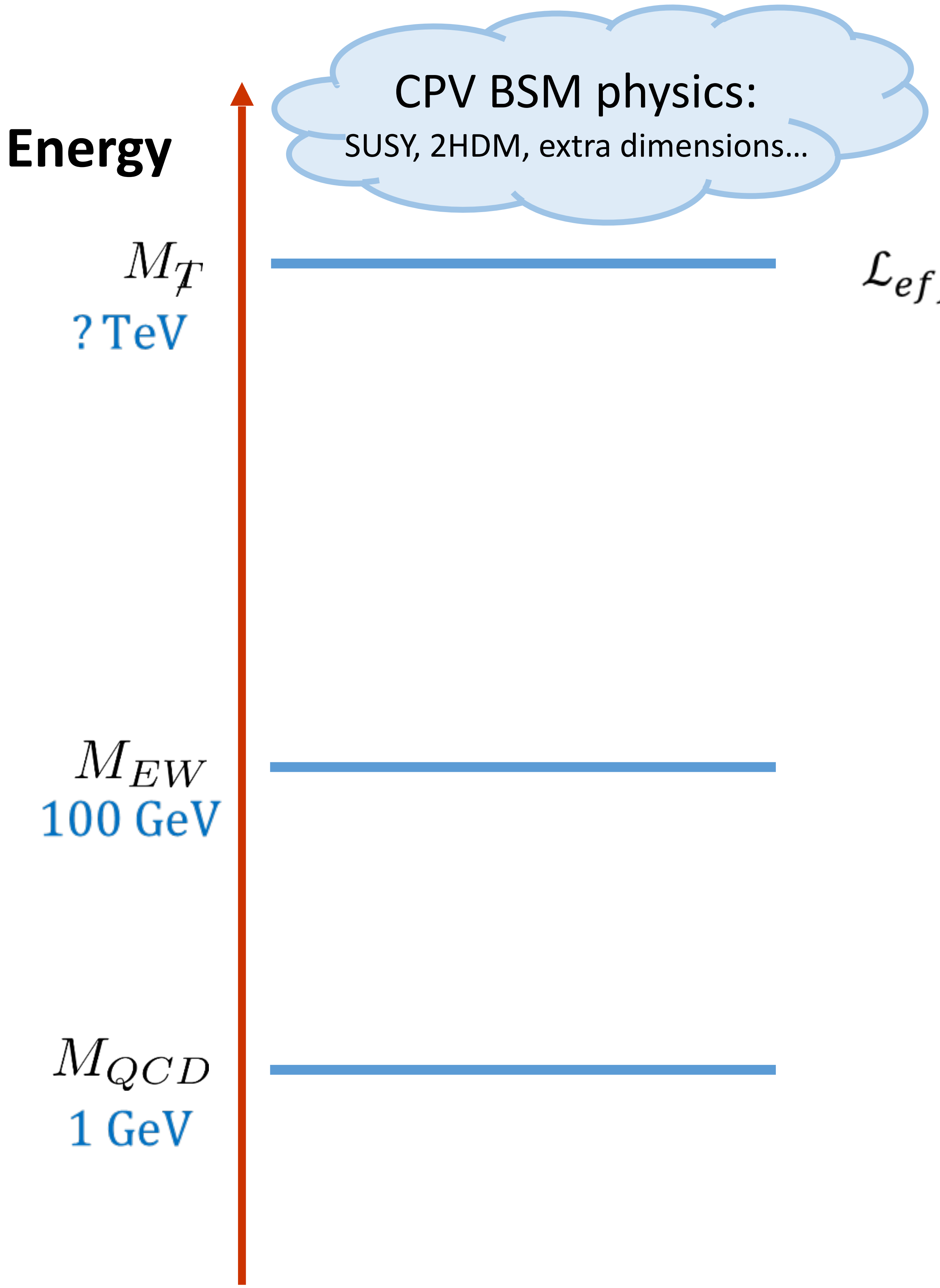



CPV BSM physics:
SUSY, 2HDM, extra dimensions…
Energy
$M_{\not{T}}$
? TeV
M_{EW}
100 GeV
M_{QCD}
1 GeV



If the NP is heavy enough:
Effective Field Theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_i^{(5)}}{M_T} O_i^{(5)} + \frac{c_i^{(6)}}{M_T^2} O_i^{(6)} + \cdots$$

Effective Field Theory

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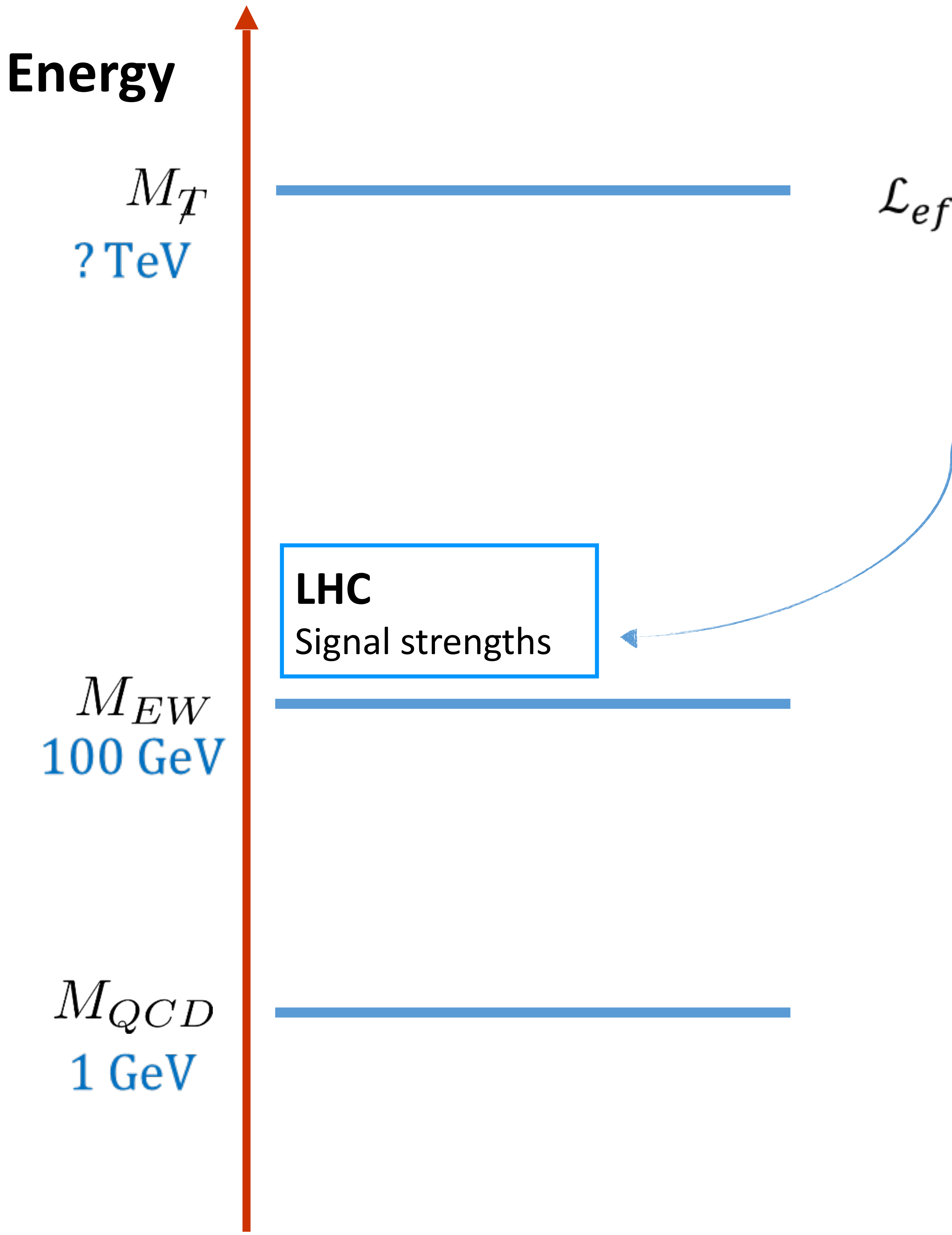
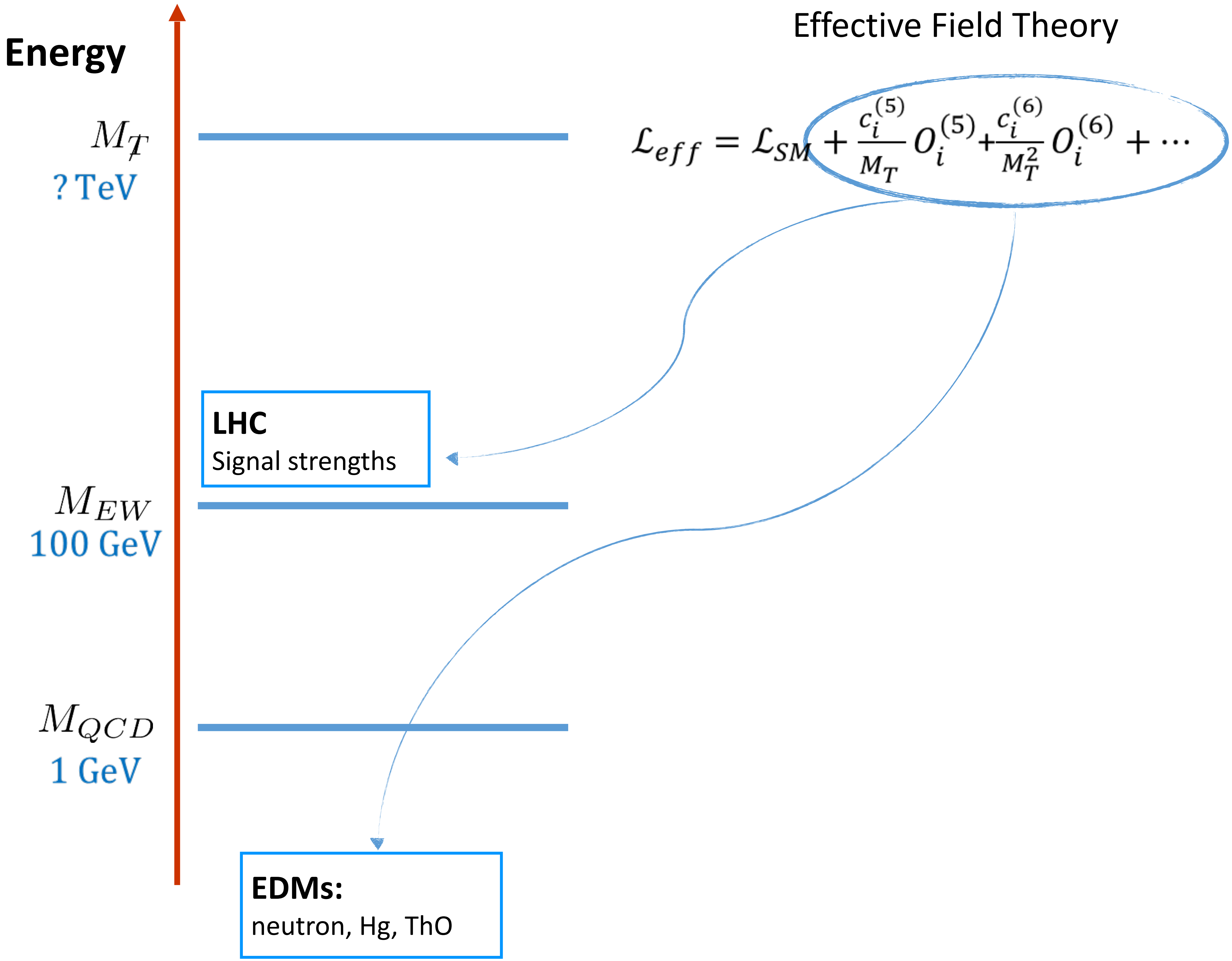


Effective Field Theory



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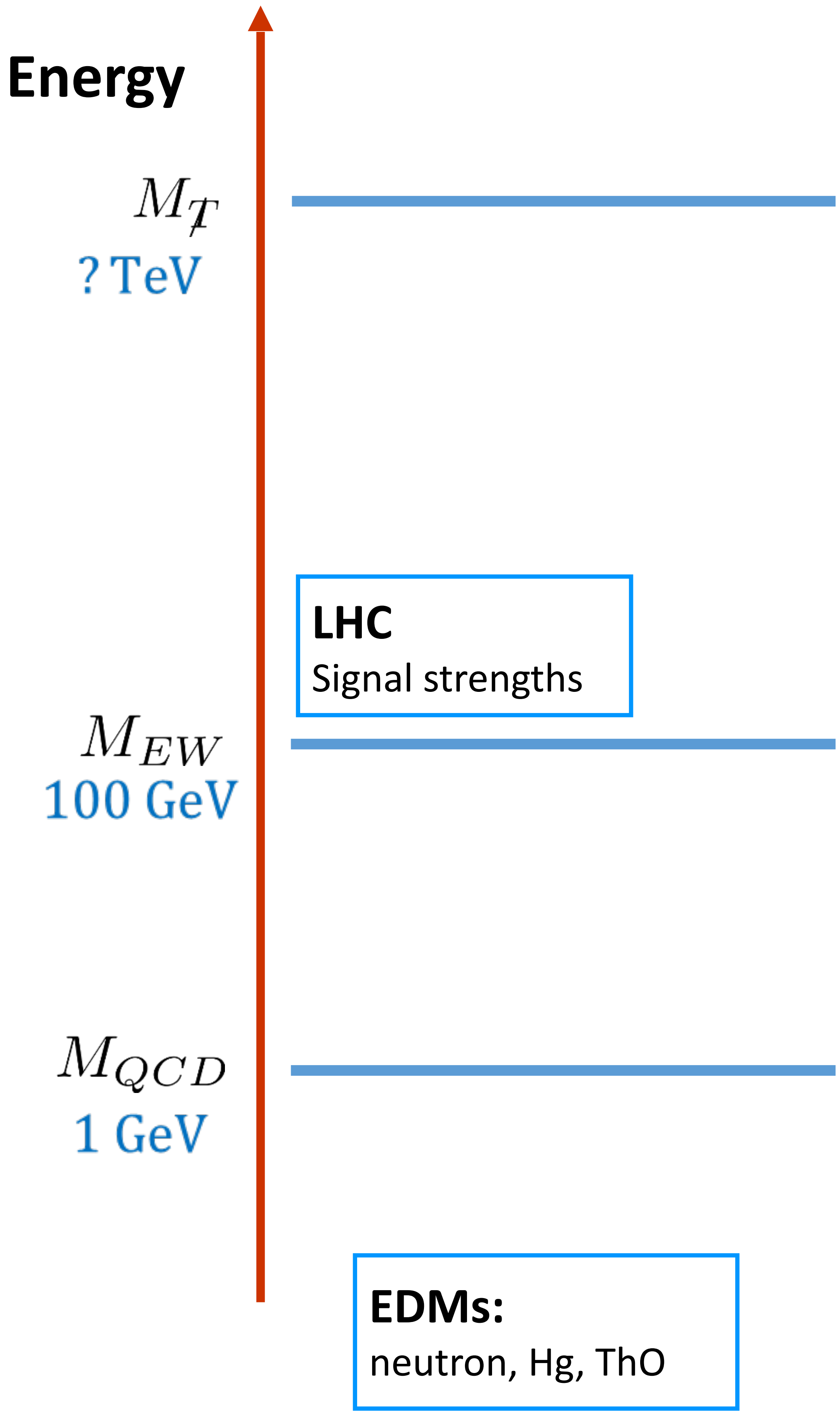
RG evolution



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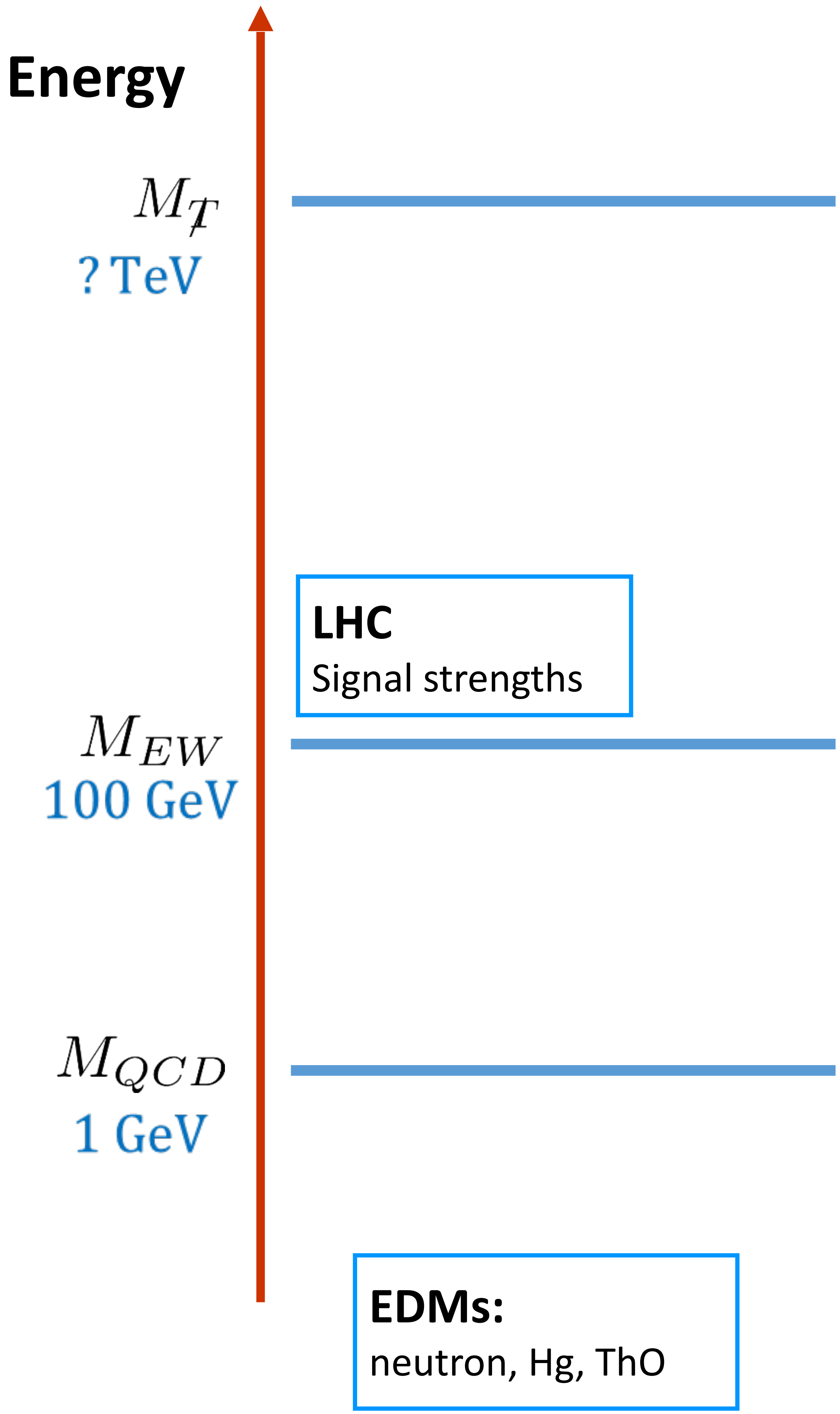
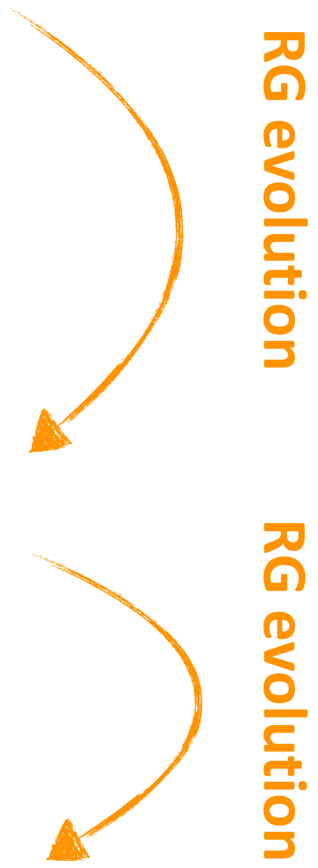
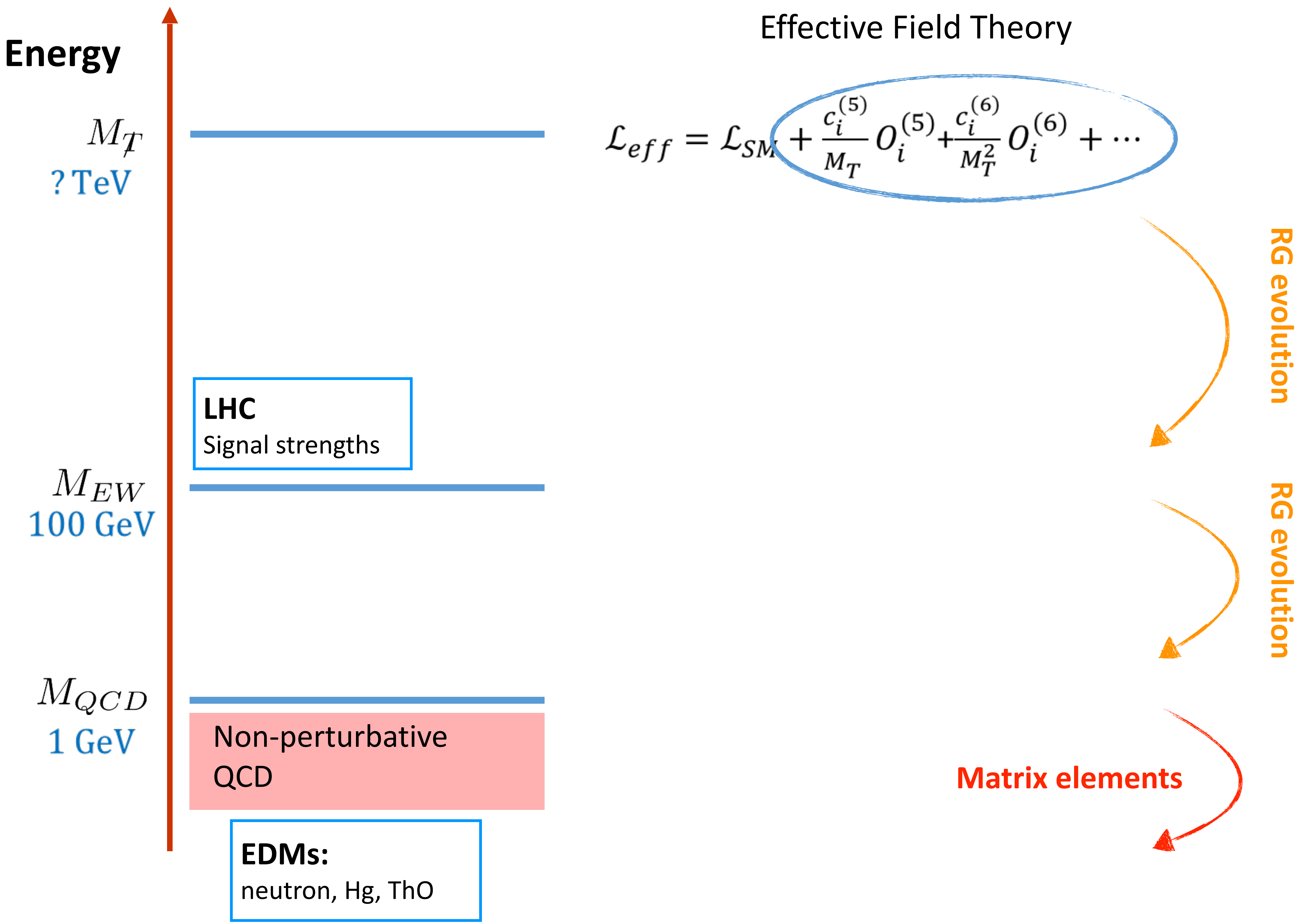
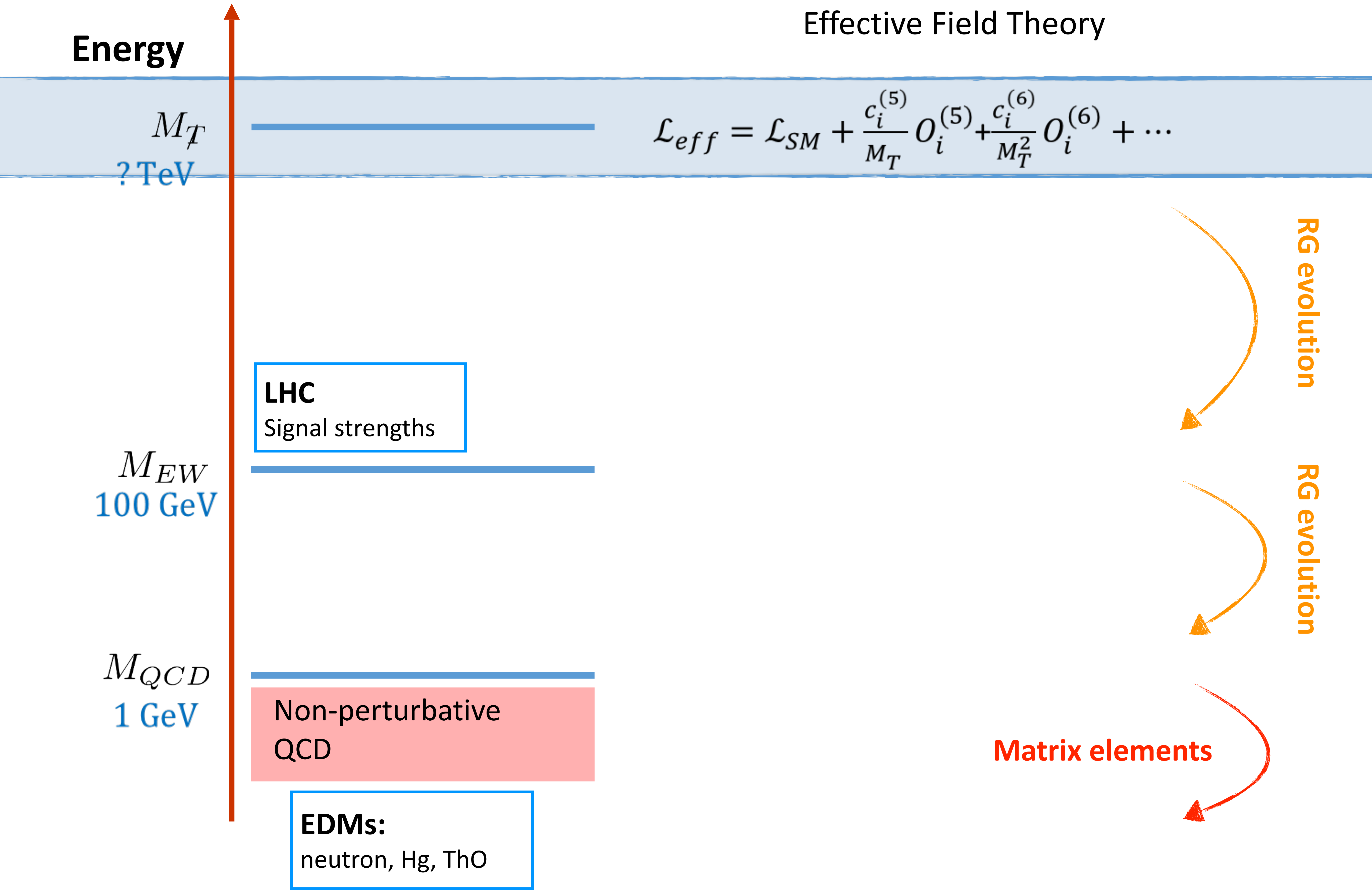





Effective Field Theory
$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_i^{(5)}}{M_T} O_i^{(5)} + \frac{c_i^{(6)}}{M_T^2} O_i^{(6)} + \cdots$
Energy
M_T
? TeV
LHC
Signal strengths
M_{EW}
100 GeV
M_{QCD}
1 GeV
Non-perturbative
QCD
EDMs:
neutron, Hg, ThO
RG evolution
RG evolution
Matrix elements

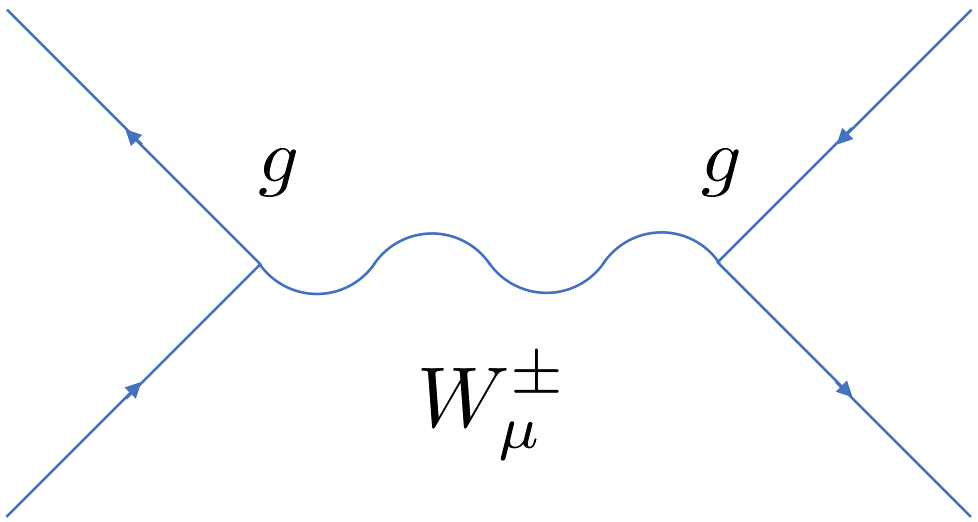
Effective Field Theory



Effective Field Theory

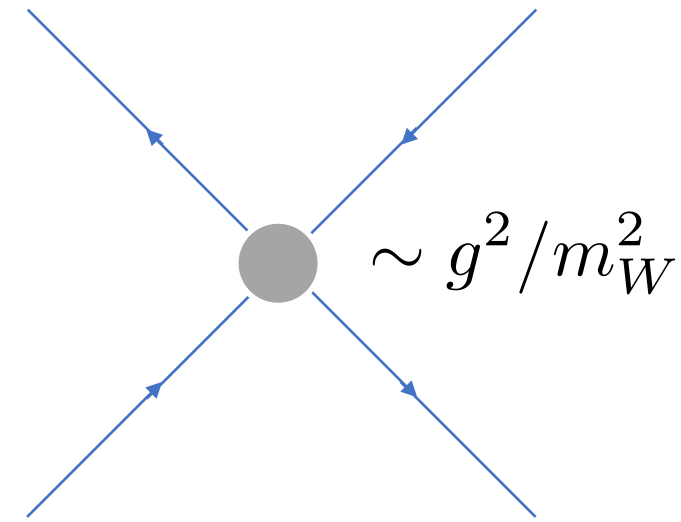
Fermi theory

'Fundamental' theory



$q^2 \ll m_W^2$

Effective theory



$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\bar{u}_L\gamma^\mu d_L W_\mu^+ + \text{h.c.}$$

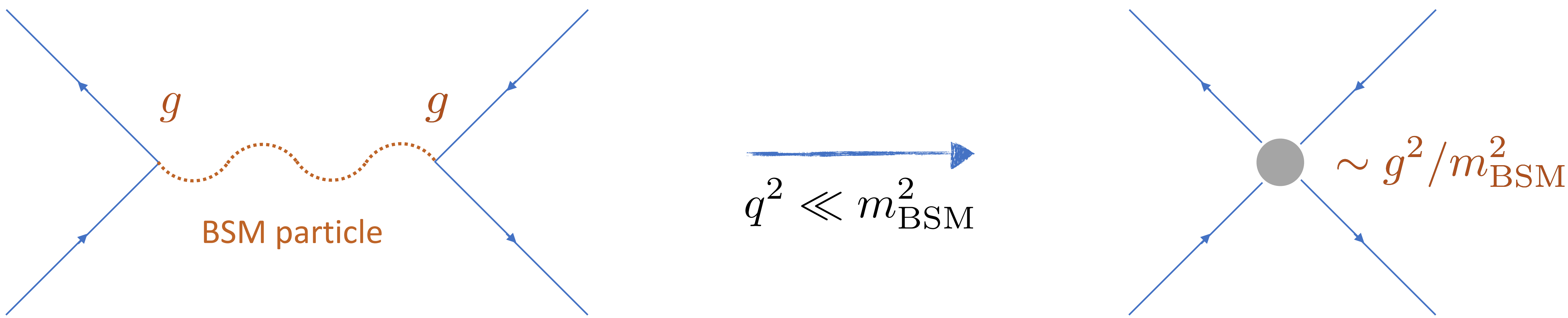
$$\mathcal{L}_{eff} \sim \frac{g^2}{m_W^2}(\bar{\psi}_L\gamma^\mu\psi_L)(\bar{\psi}_L\gamma_\mu\psi_L)$$

Effective Field Theory

Describing BSM physics

'Fundamental' theory

Effective theory



$$\mathcal{L} = ??$$

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{c_i^{(5)}}{M_T} O_i^{(5)} + \frac{c_i^{(6)}}{M_T^2} O_i^{(6)} + \cdots$$

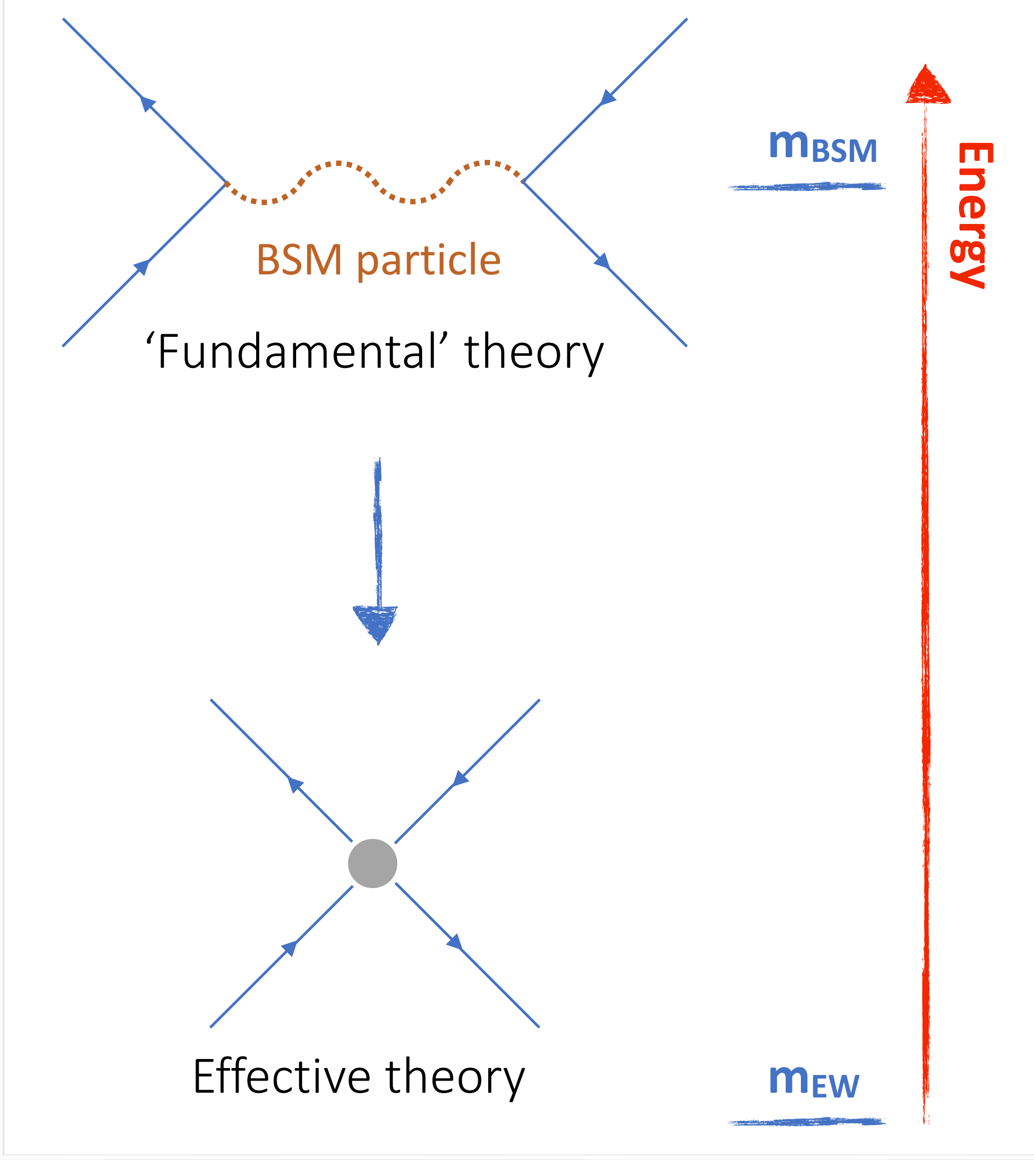
- At low energies, E<<$m_{\rm BSM}$, BSM physics can be described by higher-dimensional operators
- These can be ordered by their dimension, with expansion parameter $\dfrac{E,\, M_{\rm EW}}{M_T}$

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

Describing BSM physics

Dimension five operators

- One term, generates Majorana neutrino masses

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

Dimension six operators

- 59 operators (2499 including all flavor structures)
- 27 CP-violating terms (1149 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}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\,G^A_{\mu\nu}$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
					$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
					$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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

Choice of operators

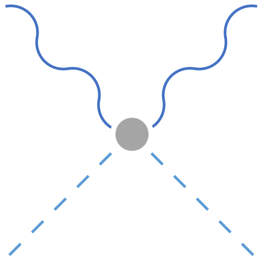
CP-violating BEH couplings to quarks and gluons

$$\mathcal{L}_6 = -\theta' \frac{\alpha_s}{32\pi}\,\varepsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} (\varphi^\dagger\varphi) + \sqrt{2}\varphi^\dagger\varphi\,(\bar{q}_L Y_u' u_R \tilde{\varphi} + \bar{q}_L Y_d' d_R \varphi) - \frac{1}{\sqrt{2}} \bar{q}_L \sigma\cdot G \tilde{\Gamma}_u u_R \frac{\tilde{\varphi}}{v} - \frac{1}{\sqrt{2}} \bar{q}_L \sigma\cdot G \tilde{\Gamma}_d d_R \frac{\varphi}{v} + \text{h.c.}$$

- Scalar-gluon interaction

θ'

gluon-scalar



- Top quark chromo-EDM

$\tilde{d}_t$

gluon-quark-scalar

- Yukawa interactions

Y_q'

quark-scalar

Choice of operators

CP-violating BEH couplings to quarks and gluons

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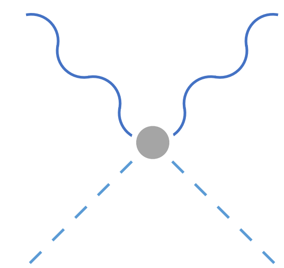
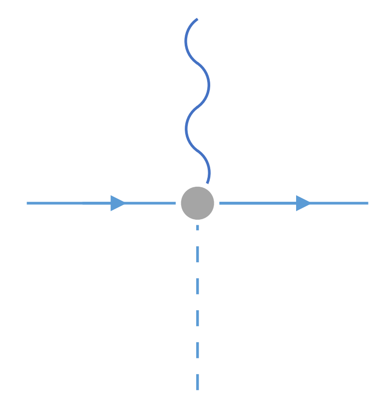
- Scalar-gluon interaction

θ'
gluon-scalar



- Top quark chromo-EDM

$\tilde{d}_t$
gluon-quark-scalar



- Yukawa interactions

Y'_q
quark-scalar

Choice of operators

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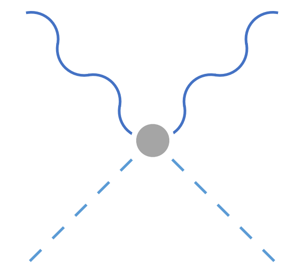
$$\mathcal{L}_6 = -\theta' \frac{\alpha_s}{32\pi} \varepsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta} (\varphi^\dagger \varphi) + \sqrt{2} \varphi^\dagger \varphi \left(\bar{q}_L Y'_u u_R \tilde{\varphi} + \bar{q}_L Y'_d d_R \varphi \right)$$
$$- \frac{1}{\sqrt{2}} \bar{q}_L \, \sigma \cdot G \, \tilde{\Gamma}_u u_R \frac{\tilde{\varphi}}{v} - \frac{1}{\sqrt{2}} \bar{q}_L \, \sigma \cdot G \, \tilde{\Gamma}_d d_R \frac{\varphi}{v} + \text{h.c.}$$

- Scalar-gluon interaction

θ'

gluon-scalar



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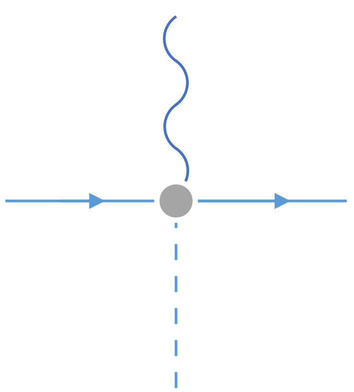
$\tilde{d}_t$

gluon-quark-scalar



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Y'_q

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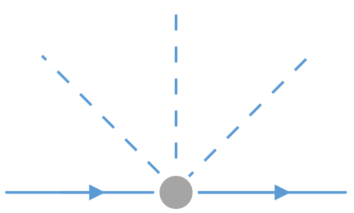
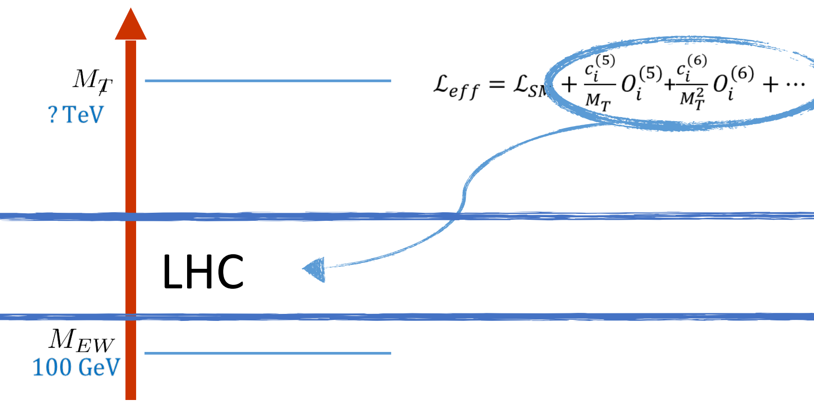
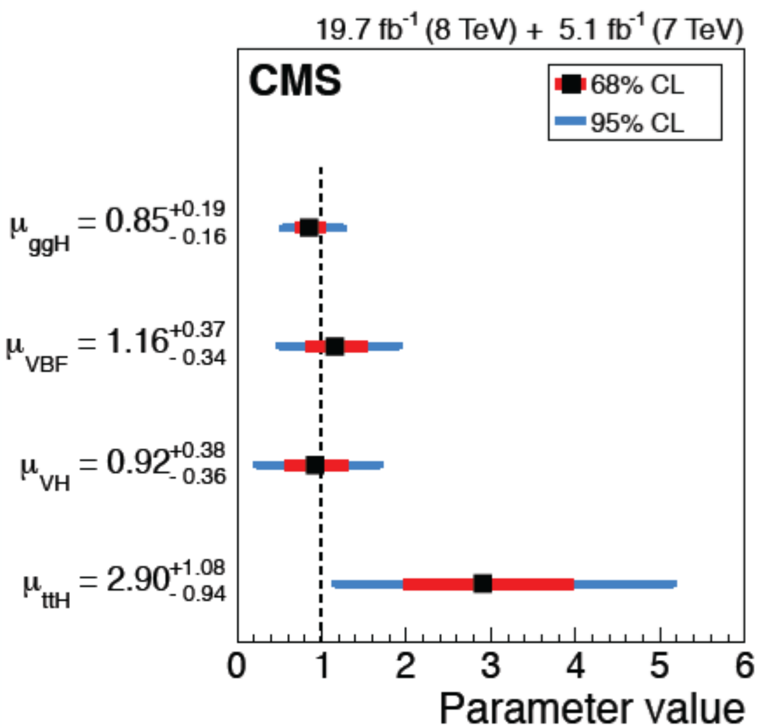
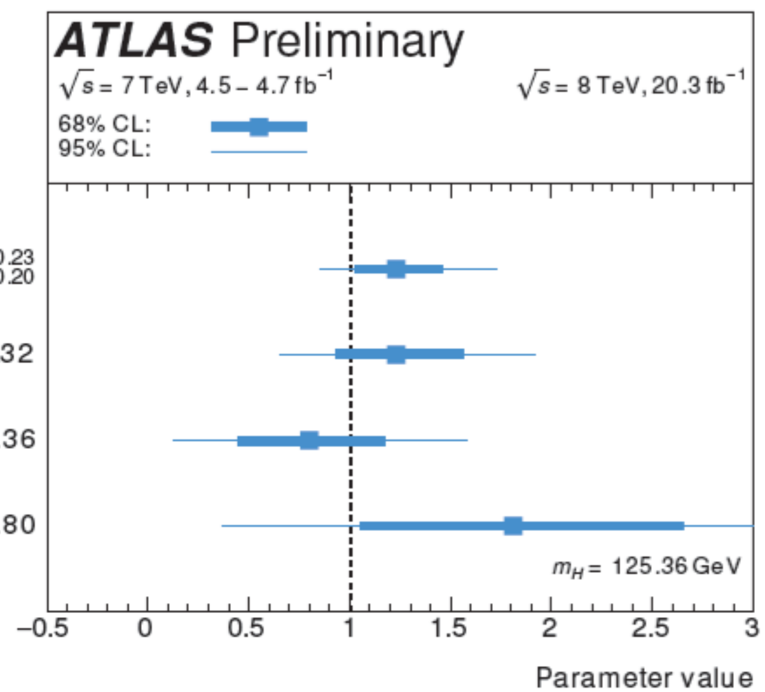


Observables

Colliders



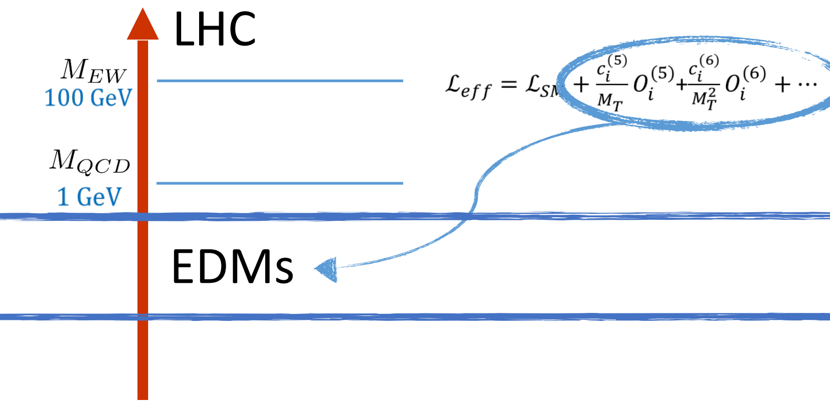




- The dim6 operators contribute to BEH boson production and decay
- Signal strengths $\mu(i \to h \to f) \equiv \frac{\sigma_{\rm BSM}(i \to h)}{\sigma_{\rm SM}(i \to h)} \frac{\rm BR_{BSM}(h \to f)}{\rm BR_{SM}(h \to f)}$

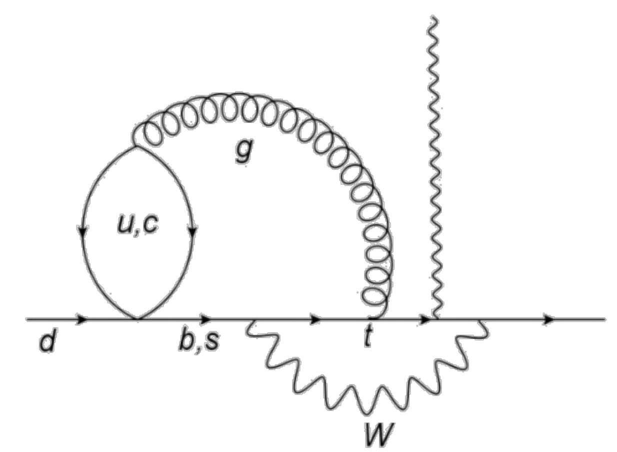
Observables

Electric Dipole Moments



EDMs in the SM

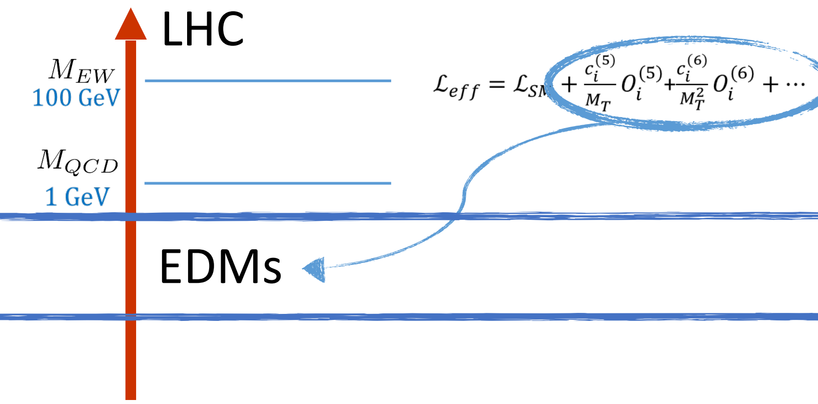
- The electroweak contribution is negligible



- 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 $\bar{\theta} = 0$

Observables

Electric Dipole Moments



Current experimental status

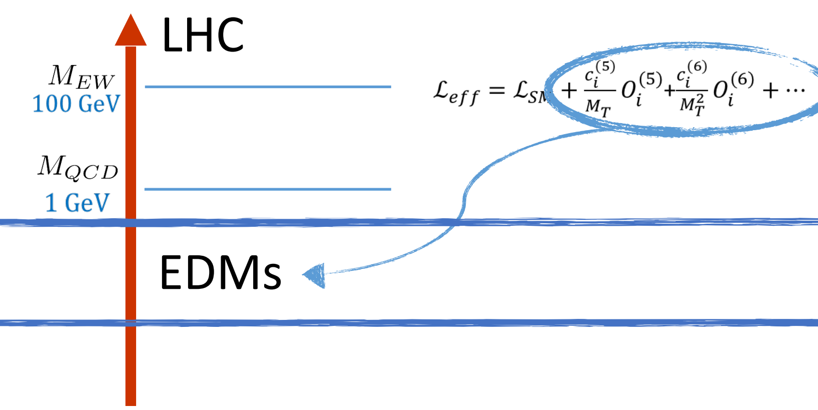
Limits	neutron	mercury	ThO
Current (e cm)	$2.9\text{x}10^{-26}$	$7.4\text{x}10^{-30}$	$8.7\text{x}10^{-29}$
	Baker *et al*, '06	Graner *et al*, '16	ACME collaboration, '14

Expected Limits

Limits	neutron	ThO
Expected (e cm)	$1.0\text{x}10^{-28}$	$5.0\text{x}10^{-30}$

Observables

Electric Dipole Moments



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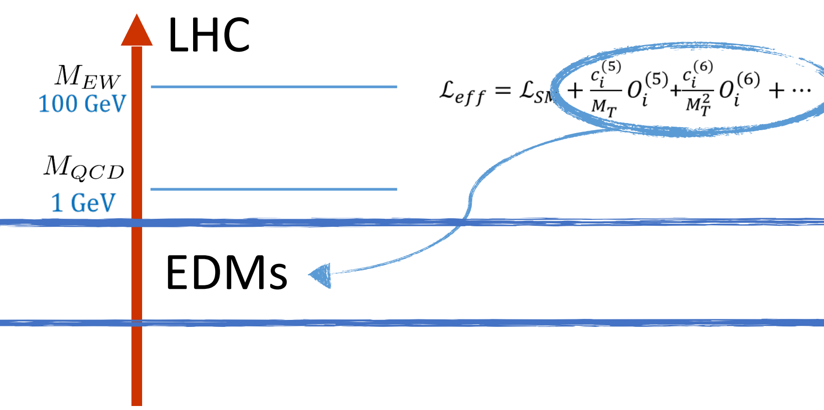

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Recent factor 4 improvement

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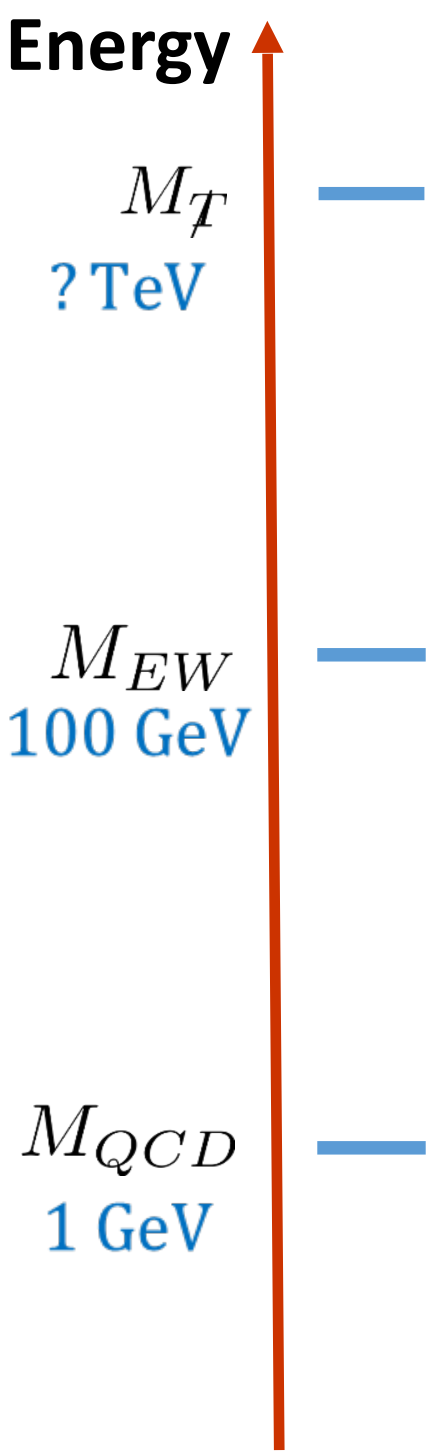
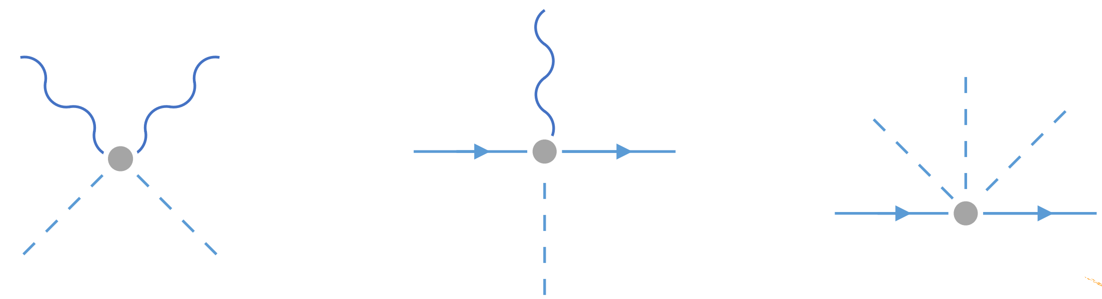
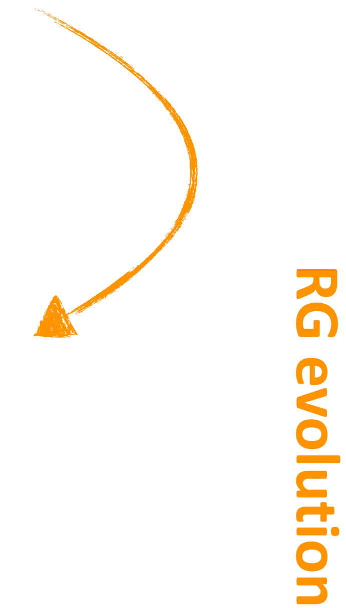
Connection to LHC



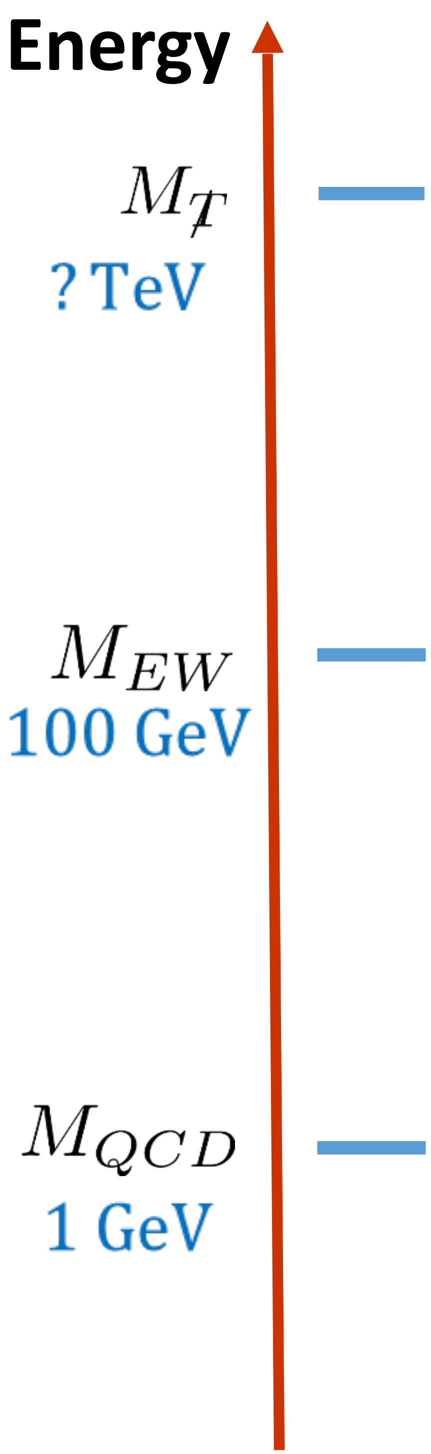
θ'	$\tilde{d}_t$	Y'_q
gluon-scalar	gluon-quark-scalar	quark-scalar

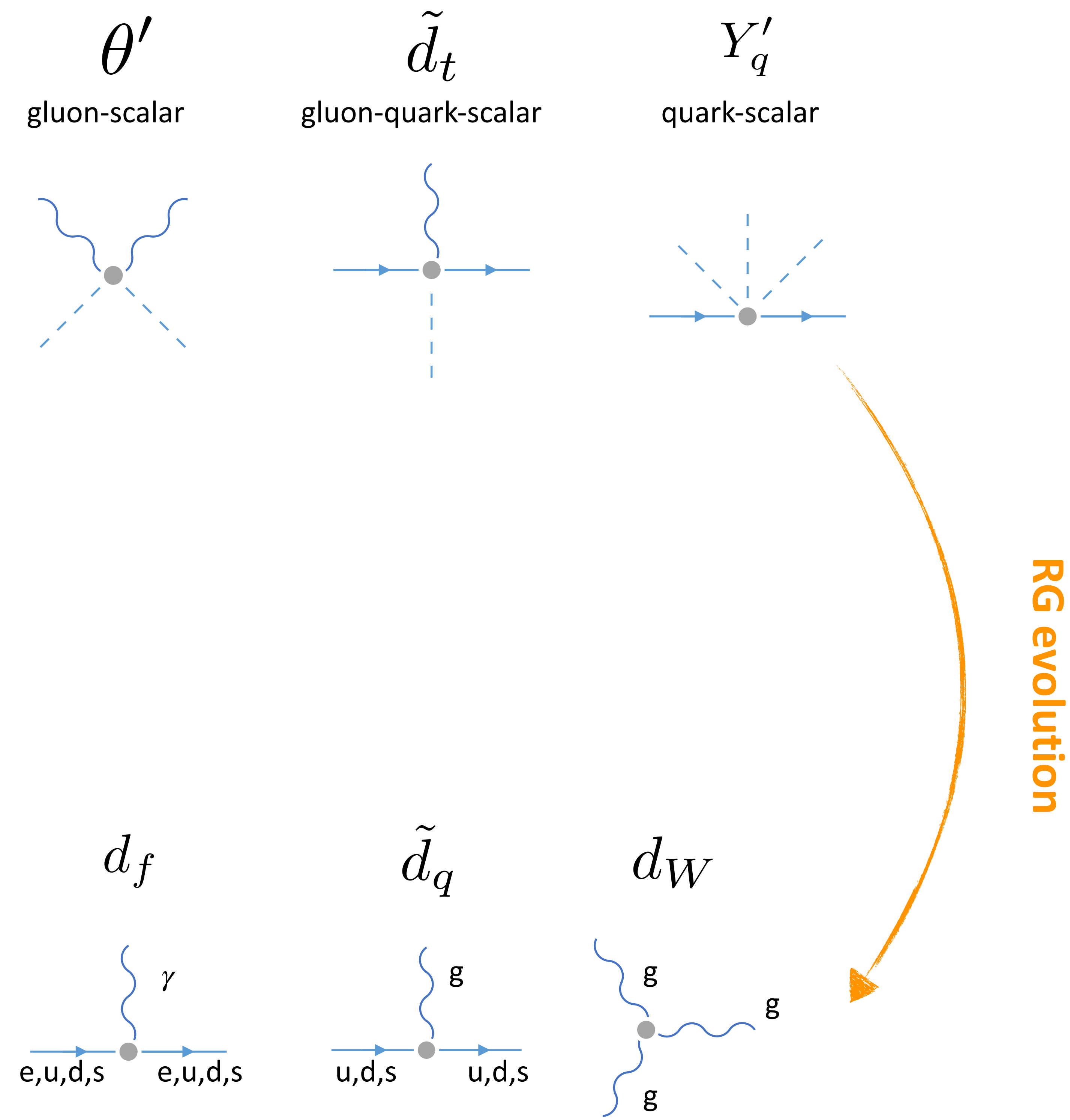




LHC processes:
pp->h->f
pp->tt

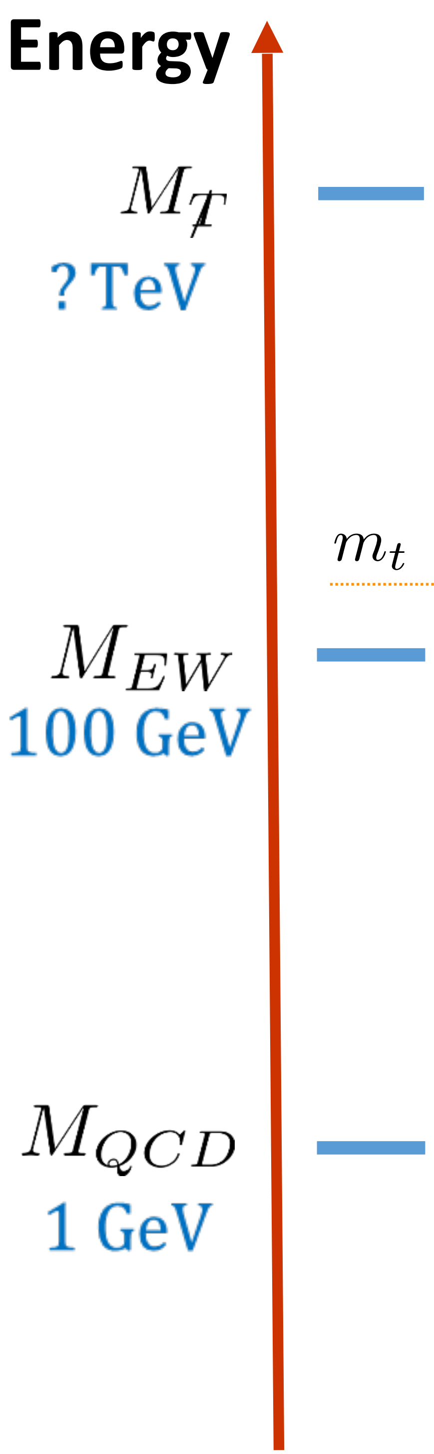
Connection to EDMs

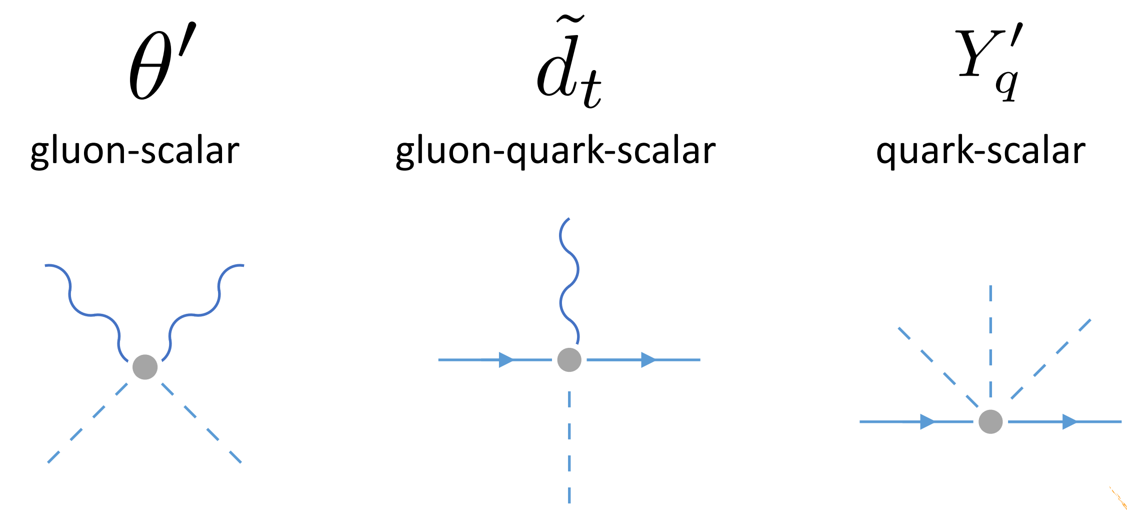




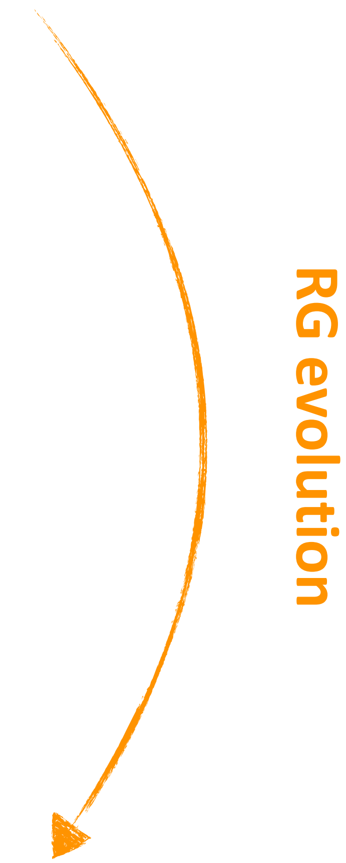
$$\mathcal{L}_6 = -\frac{i}{2}\sum_{f=e,u,d,s}\bar{f}\sigma\cdot F\gamma_5 f - \frac{i}{2}\sum_{q=u,d,s}\bar{q}\sigma\cdot G\gamma_5 q + \frac{d_W}{3}f_{abc}G^a G^b \tilde{G}^c$$

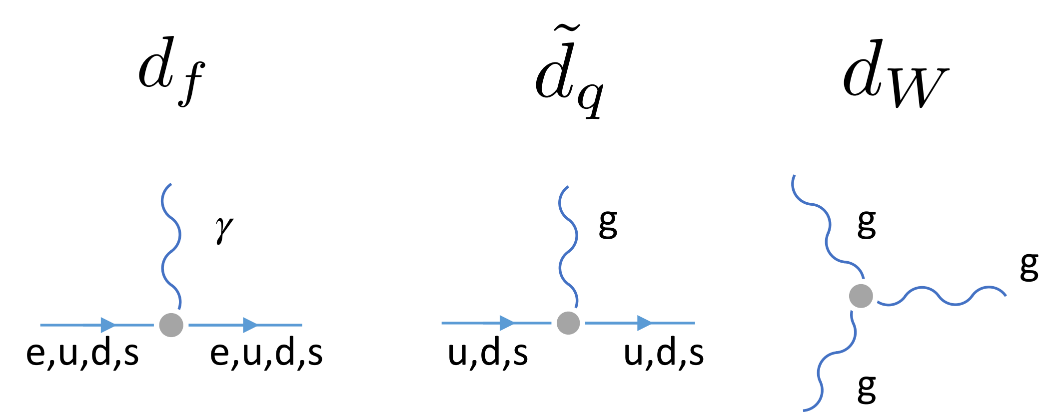
Connection to EDMs





Integrate out heavy SM fields
W, Z, H, t

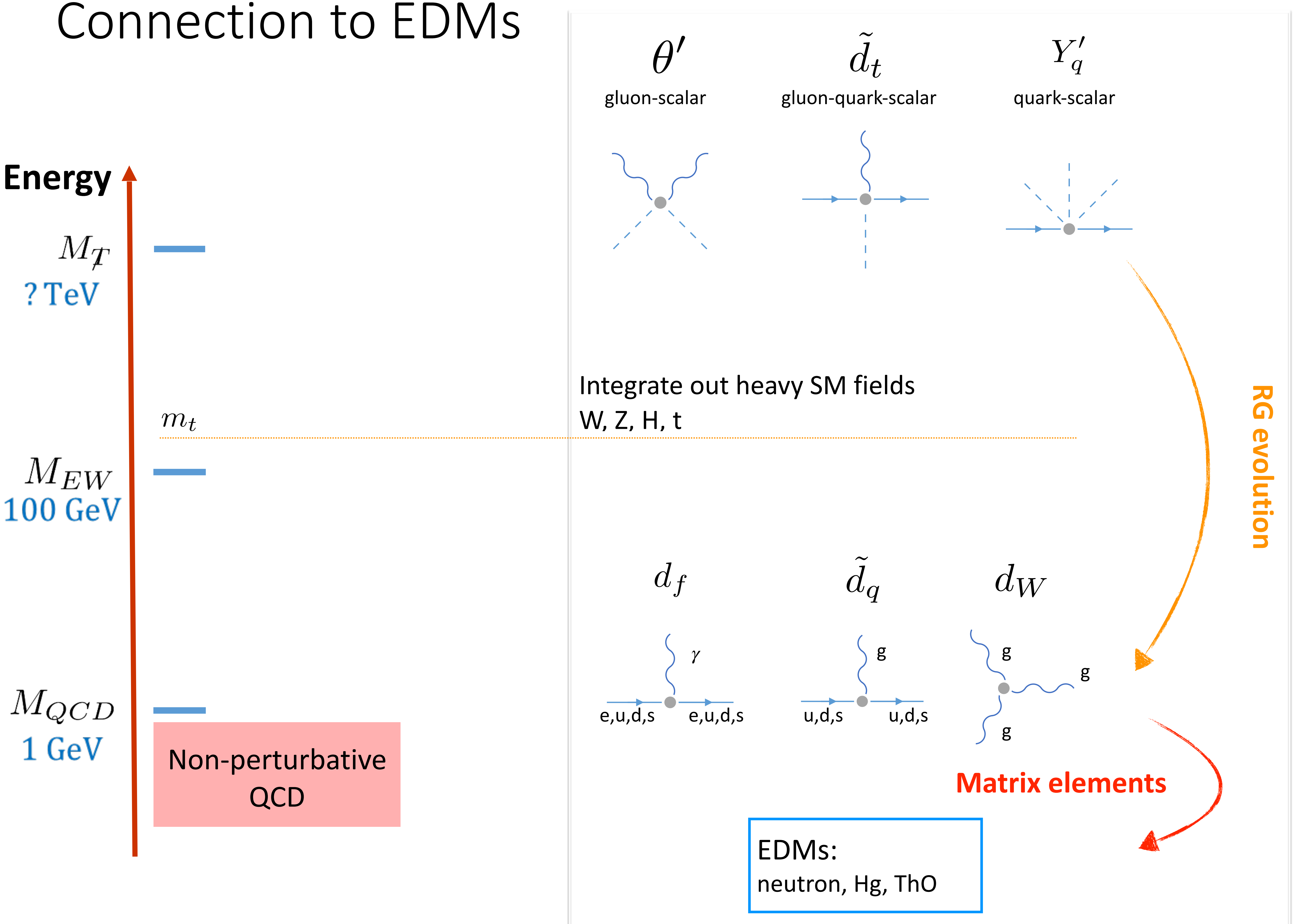




$$\mathcal{L}_6 = -\frac{i}{2} \sum_{f=e,u,d,s} \bar{f}\sigma \cdot F\gamma_5 f - \frac{i}{2} \sum_{q=u,d,s} \bar{q}\sigma \cdot G\gamma_5 q$$

$$+\frac{d_W}{3} f_{abc} G^a G^b \tilde{G}^c$$

Connection to EDMs

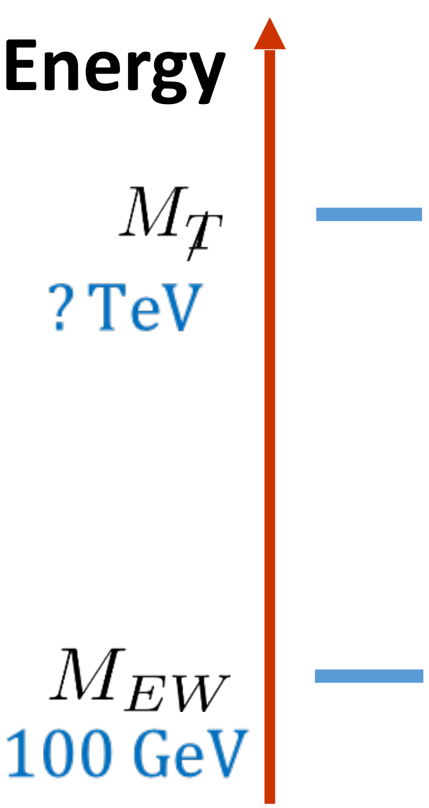


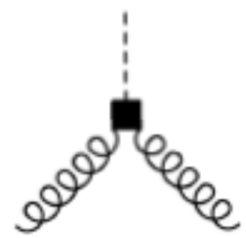
RGEs

Evolution to the electroweak scale

$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F - 4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C + 2n_f + \beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix}$$

θ'

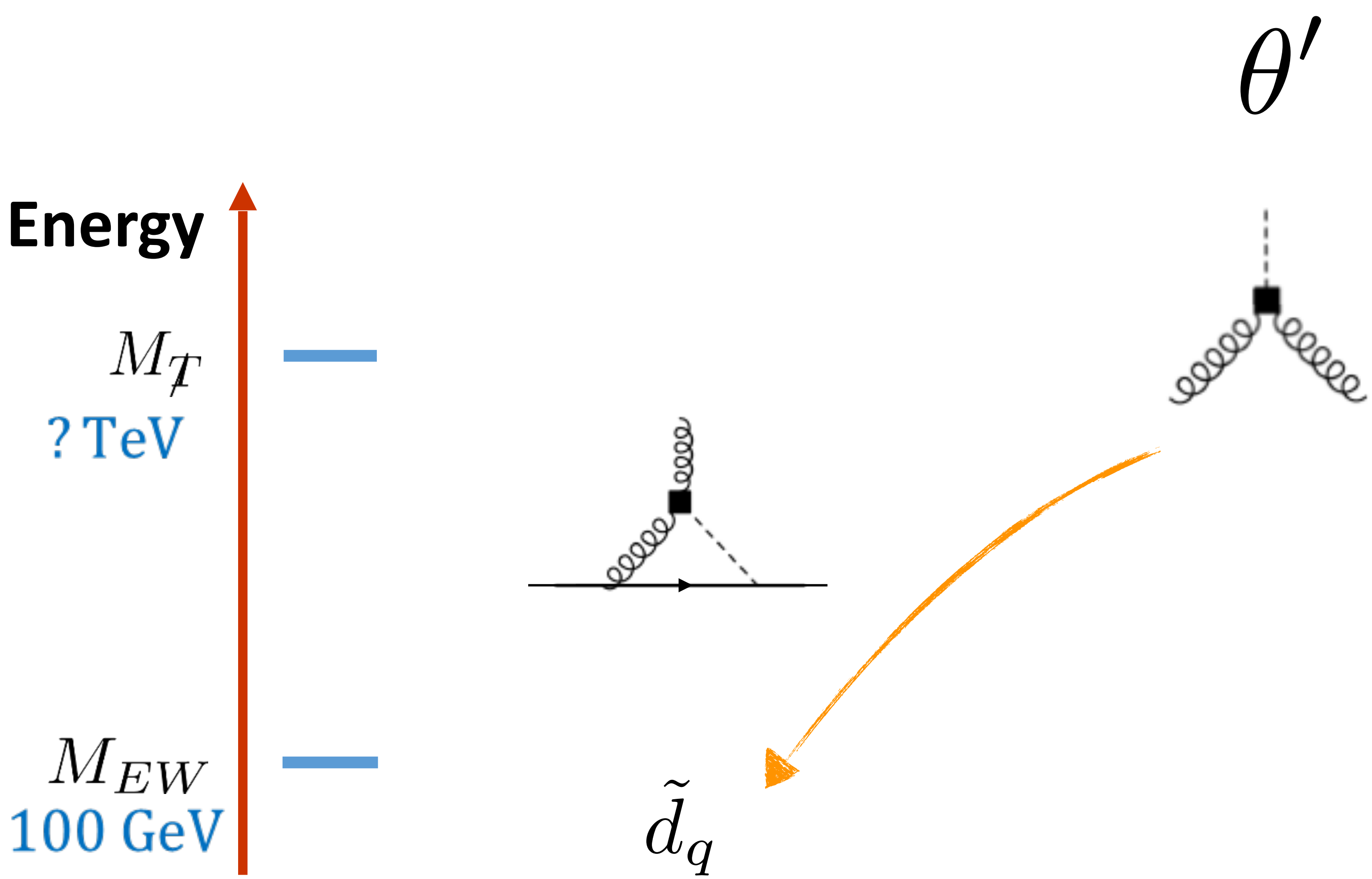




RGEs

Evolution to the electroweak scale

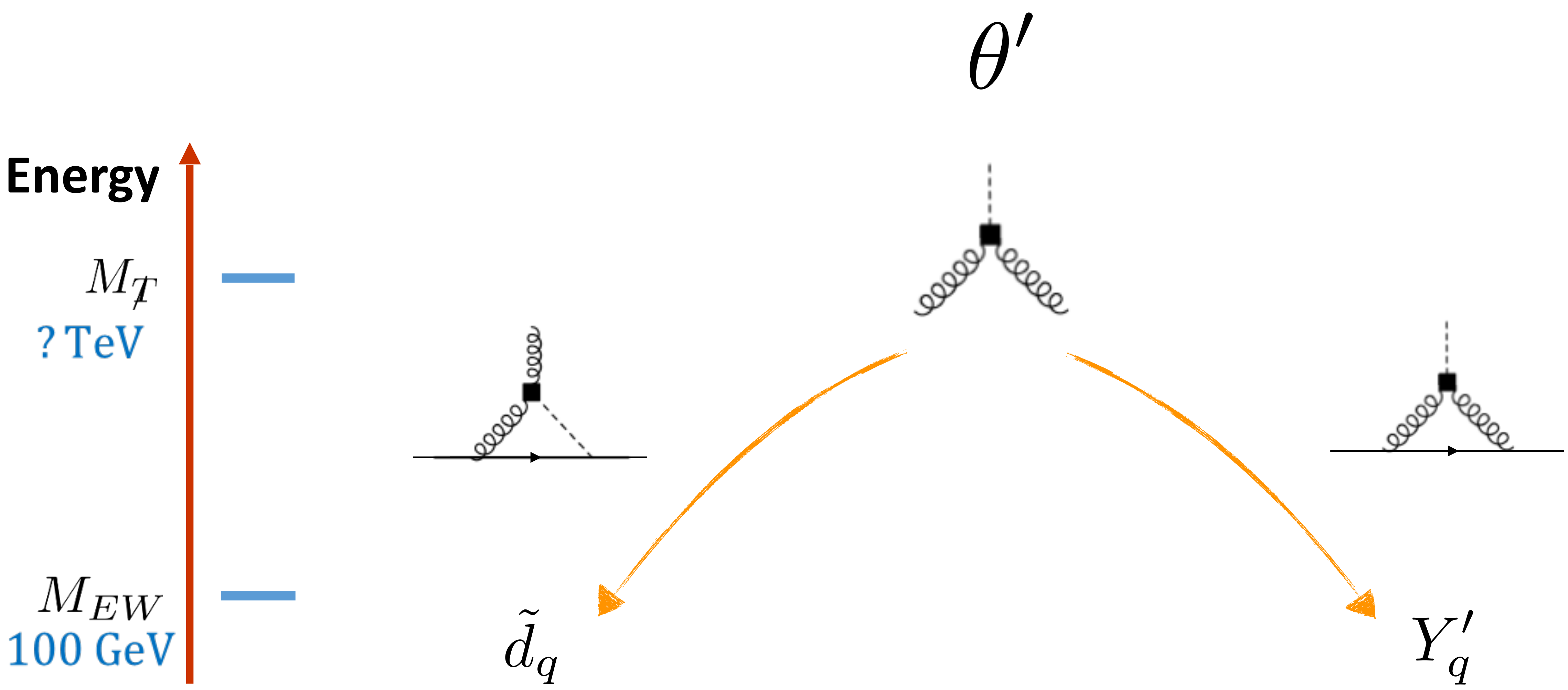
$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y'_q \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F - 4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C + 2n_f + \beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y'_q \\ \theta' \end{pmatrix}$$



RGEs

Evolution to the electroweak scale

$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_qm_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y'_q \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F-4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C+2n_f+\beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_qm_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y'_q \\ \theta' \end{pmatrix}$$

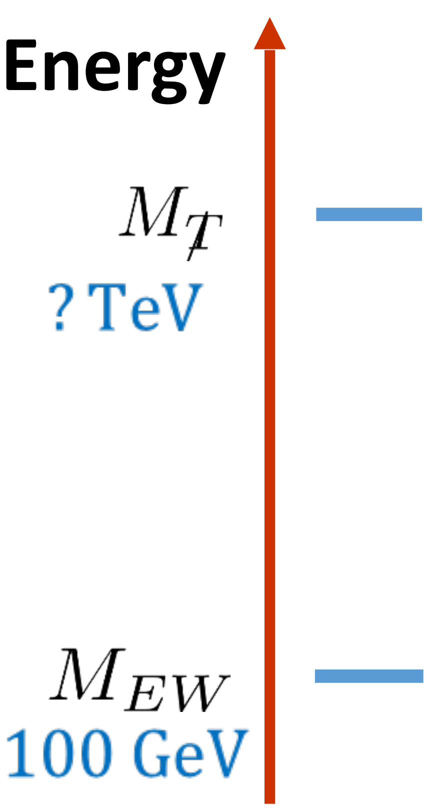


RGEs

Evolution to the electroweak scale

$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F - 4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C + 2n_f + \beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix}$$

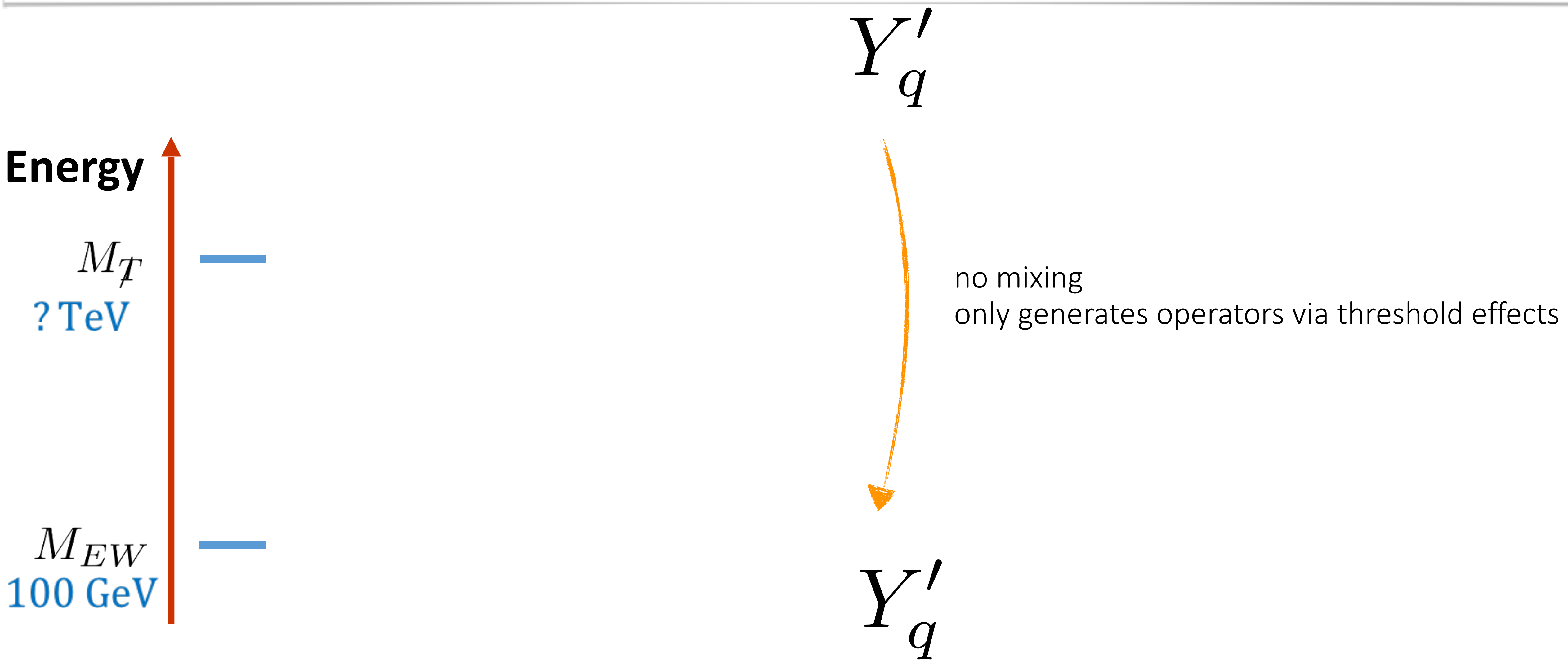
$$Y_q'$$



RGEs

Evolution to the electroweak scale

$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y'_q \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F - 4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C + 2n_f + \beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y'_q \\ \theta' \end{pmatrix}$$

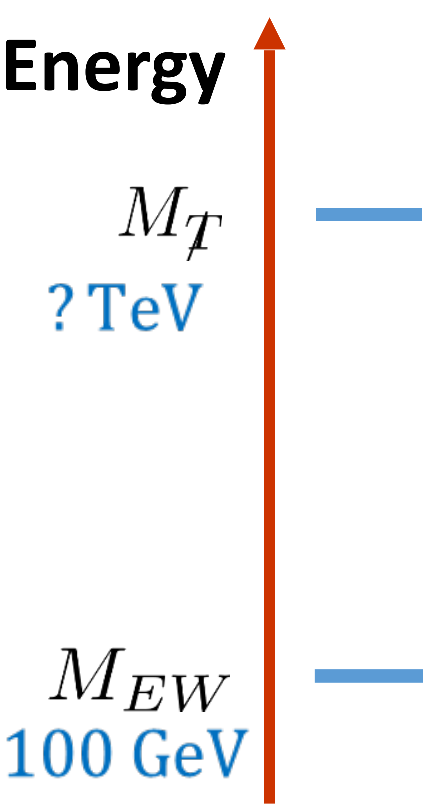


RGEs

Evolution to the electroweak scale

$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F - 4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C + 2n_f + \beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix}$$

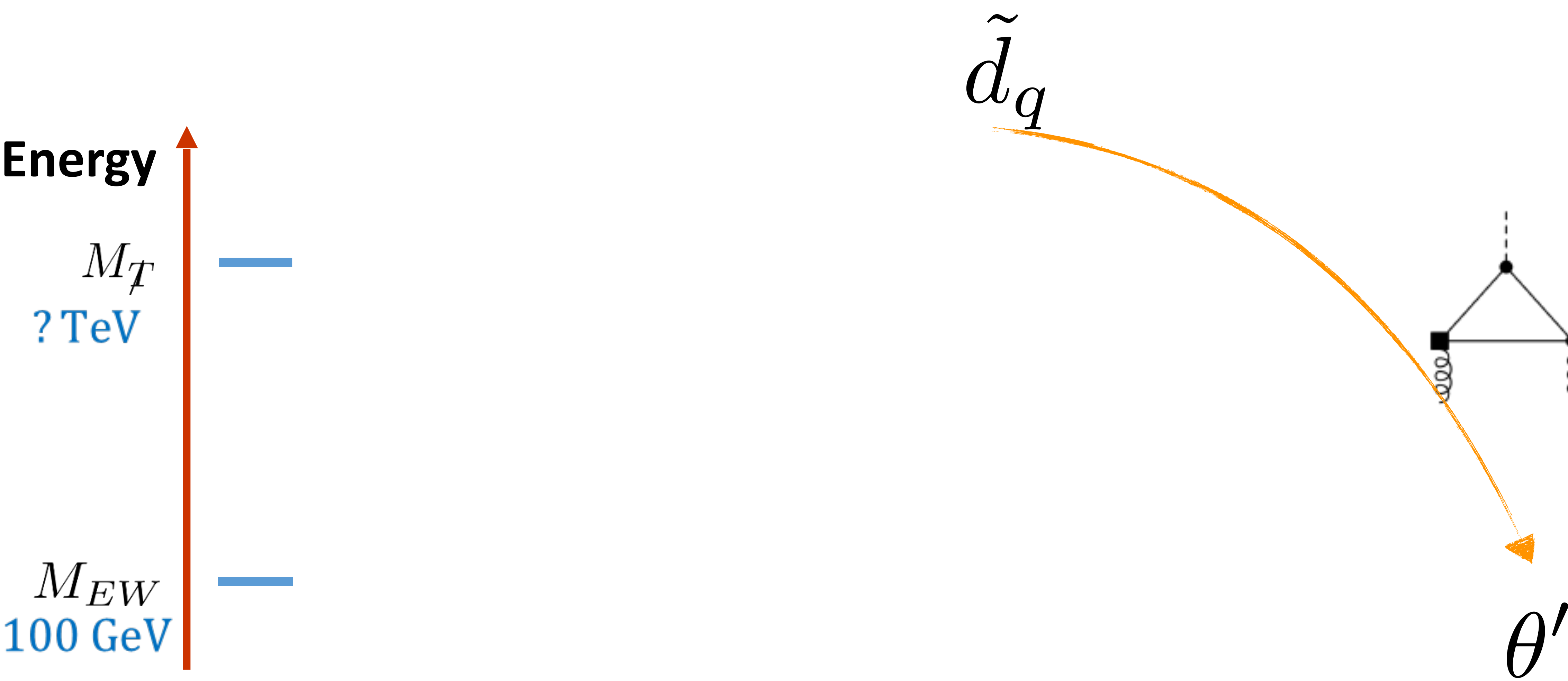
$$\tilde{d}_q$$



RGEs

Evolution to the electroweak scale

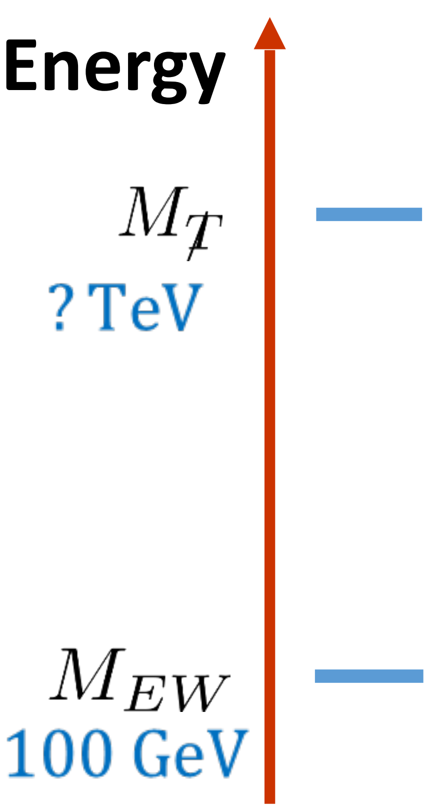
$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y'_q \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F - 4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C + 2n_f + \beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y'_q \\ \theta' \end{pmatrix}$$

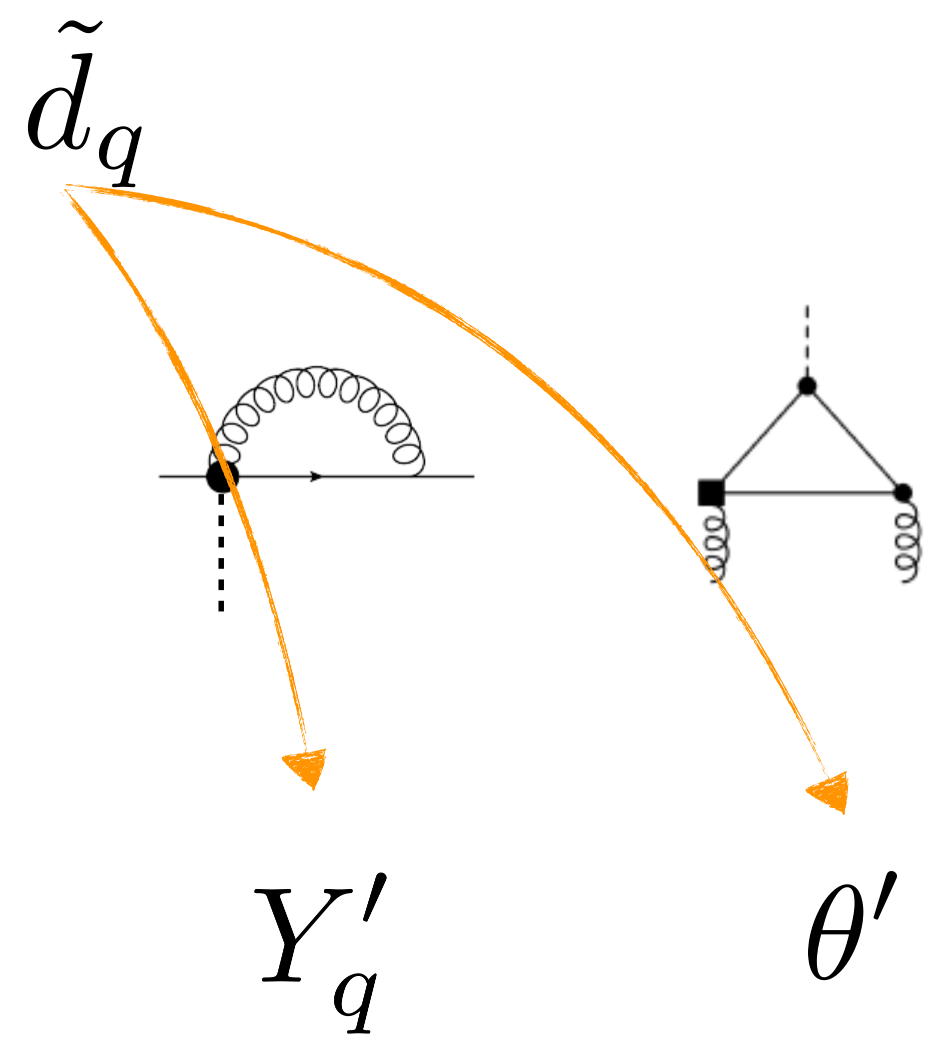


RGEs

Evolution to the electroweak scale

$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F - 4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C + 2n_f + \beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix}$$

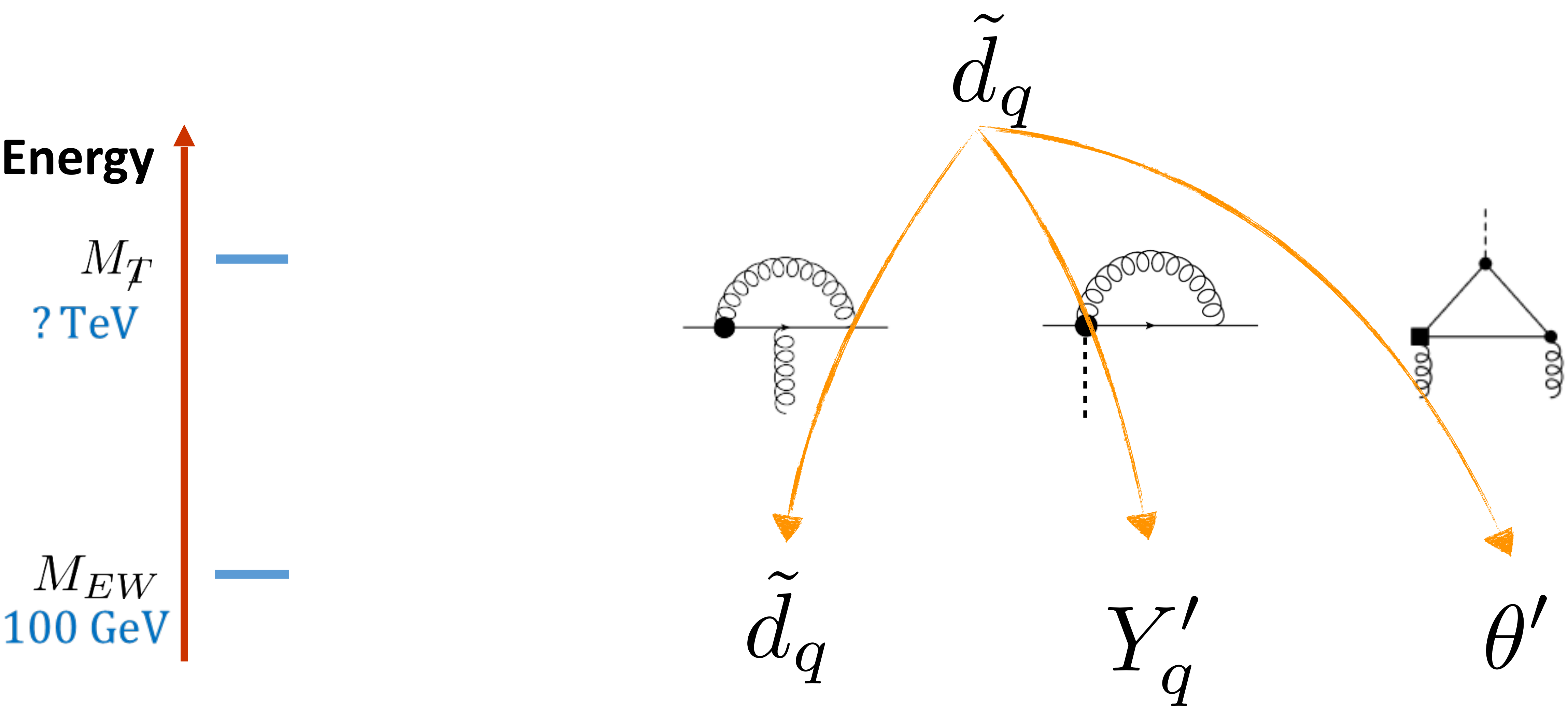




RGEs

Evolution to the electroweak scale

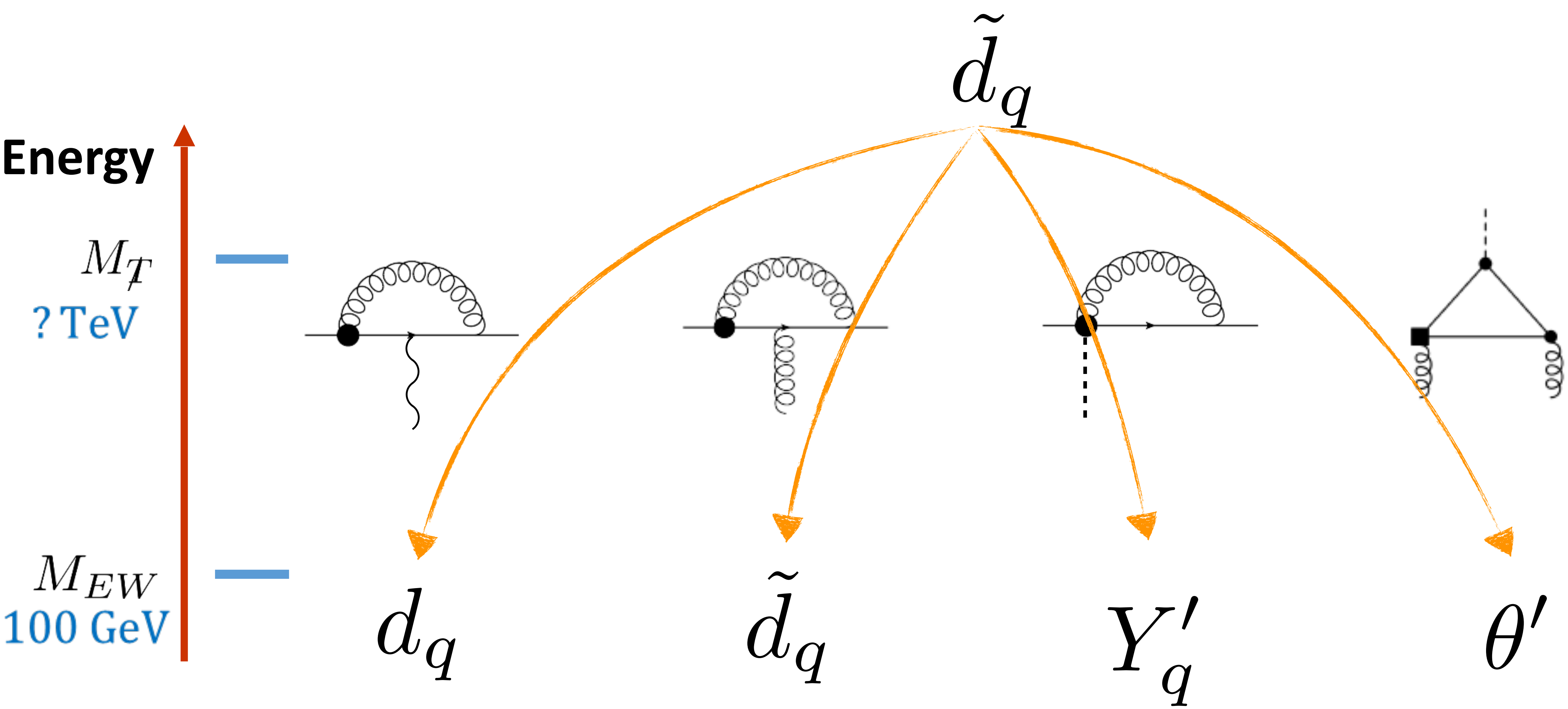
$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y'_q \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F - 4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C + 2n_f + \beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y'_q \\ \theta' \end{pmatrix}$$



RGEs

Evolution to the electroweak scale

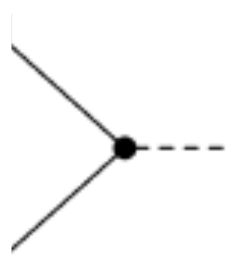
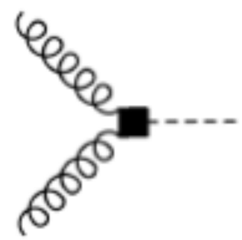
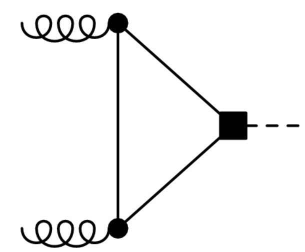
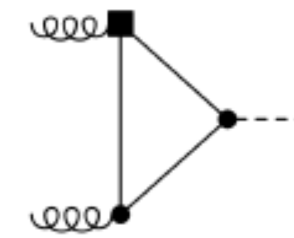
$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F - 4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C + 2n_f + \beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix}$$



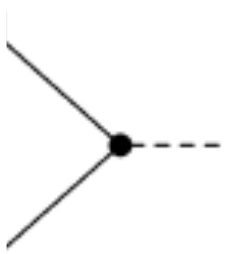
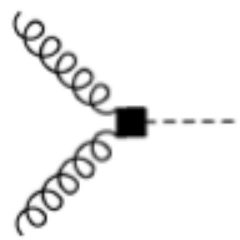
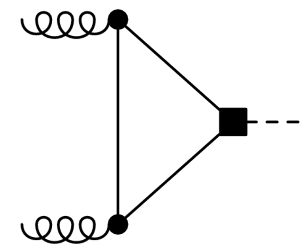
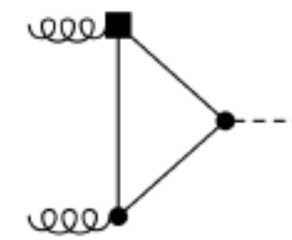
LHC constraints

Process	$Y'_{q\neq t}$	θ'	Y'_t	$\tilde{d}_t$

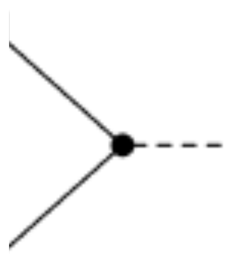
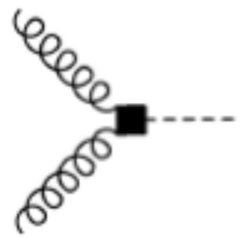
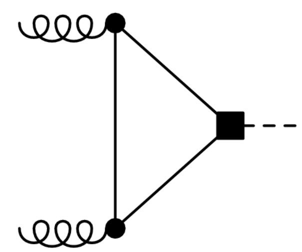
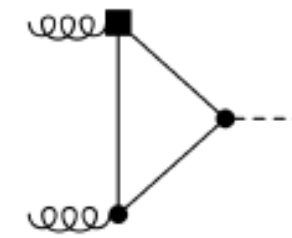
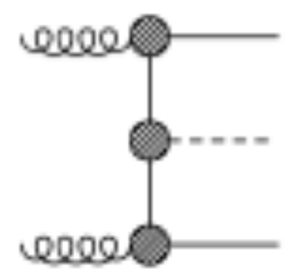
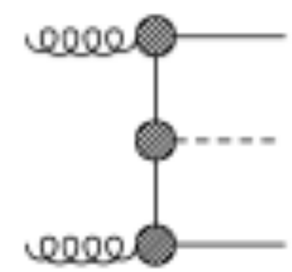
LHC constraints

Process	$Y'_{q\neq t}$	θ'	Y'_t	$\tilde{d}_t$
$pp \to h$				

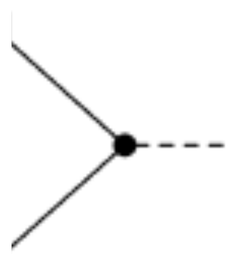
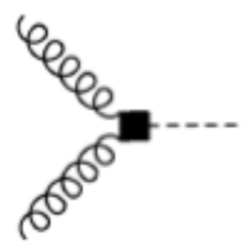
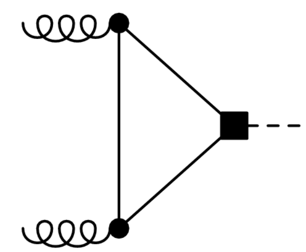
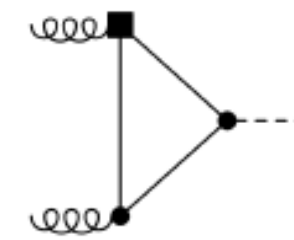
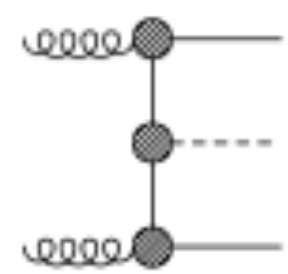
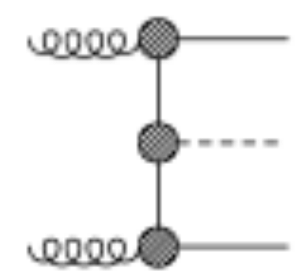
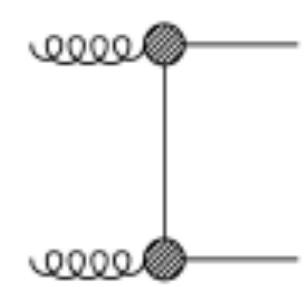
LHC constraints

Process	$Y'_{q\neq t}$	θ'	Y'_t	$\tilde{d}_t$
$pp \to h$				
	$h \to q\bar{q},\ b\bar{b}$			

LHC constraints

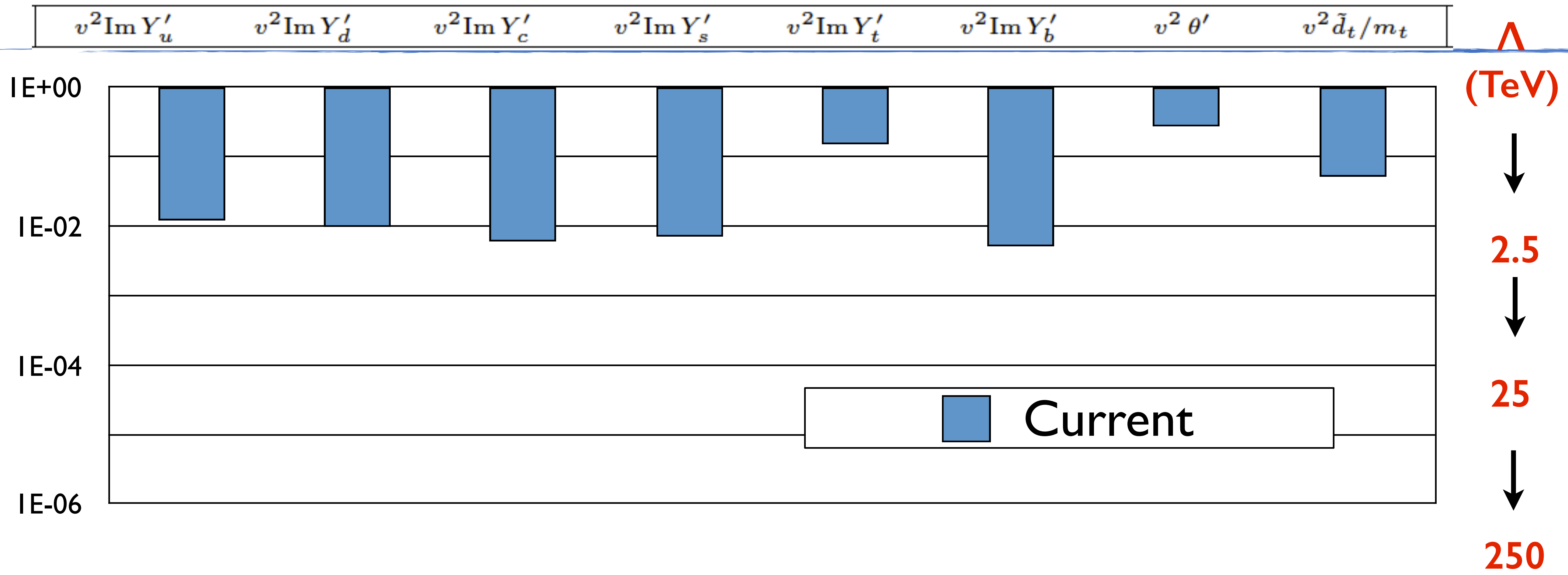
Process	$Y'_{q\neq t}$	θ'	Y'_t	$\tilde{d}_t$
$pp \to h$				
	$h \to q\bar{q},\ b\bar{b}$			
$pp \to t\bar{t}h$				

LHC constraints

Process	$Y'_{q\neq t}$	θ'	Y'_t	$\tilde{d}_t$
$pp \to h$	 $h \to q\bar{q},\ b\bar{b}$			
$pp \to t\bar{t}h$				
$pp \to t\bar{t}$				

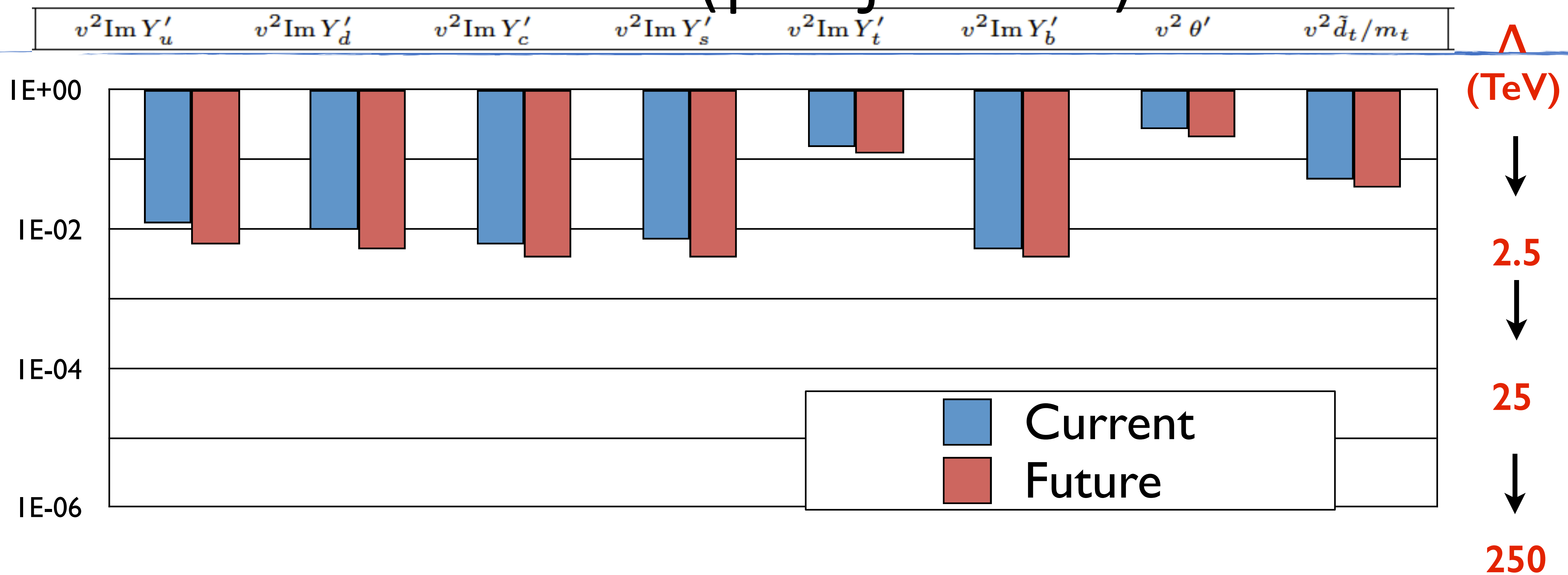
- Most stringent constraints from BEH boson production (& decay)

LHC constraints



- O(10%, 1%) constraints

LHC constraints (projected)



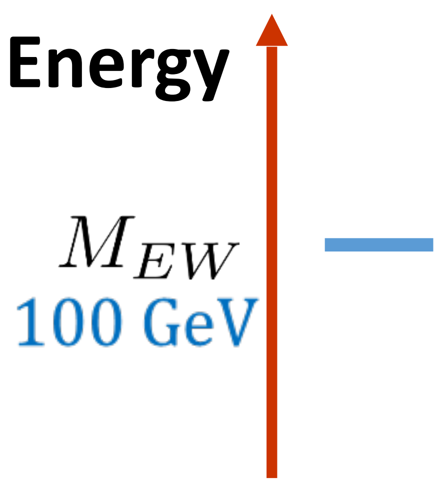
- The constraints improve by up to a factor of 2 at LHC run 2
  Assuming 10% uncertainty on the signal strength of the gluon-fusion channels:
  $gg \to h \to \gamma\gamma,\, WW^*,\, ZZ^*$

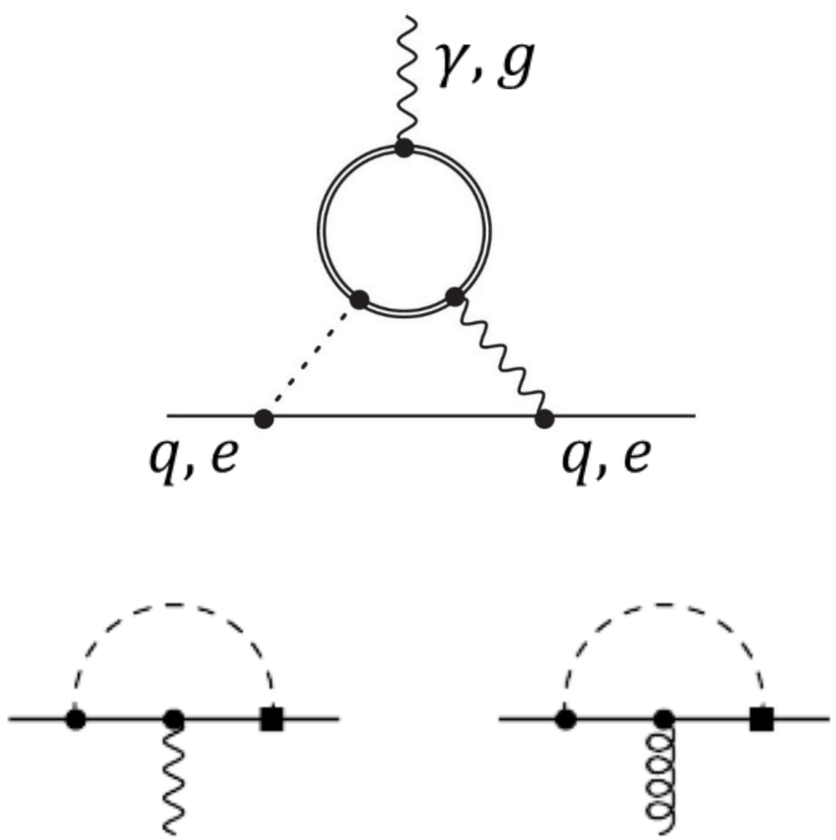
- The BSM contributions to gluon fusion grow at the same rate as the SM contribution

Threshold corrections

At the electroweak scale

$$Y'_q$$





$$d_e \quad d_q \quad \tilde{d}_q$$

Threshold corrections

At the electroweak scale

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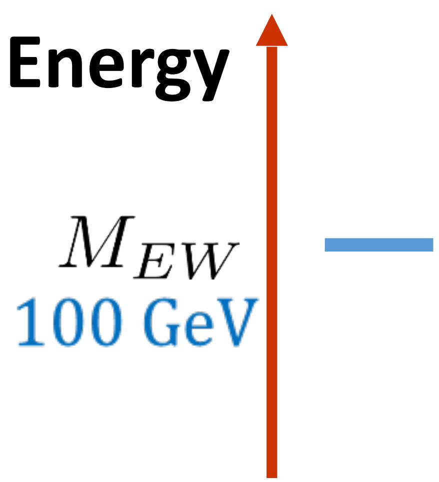
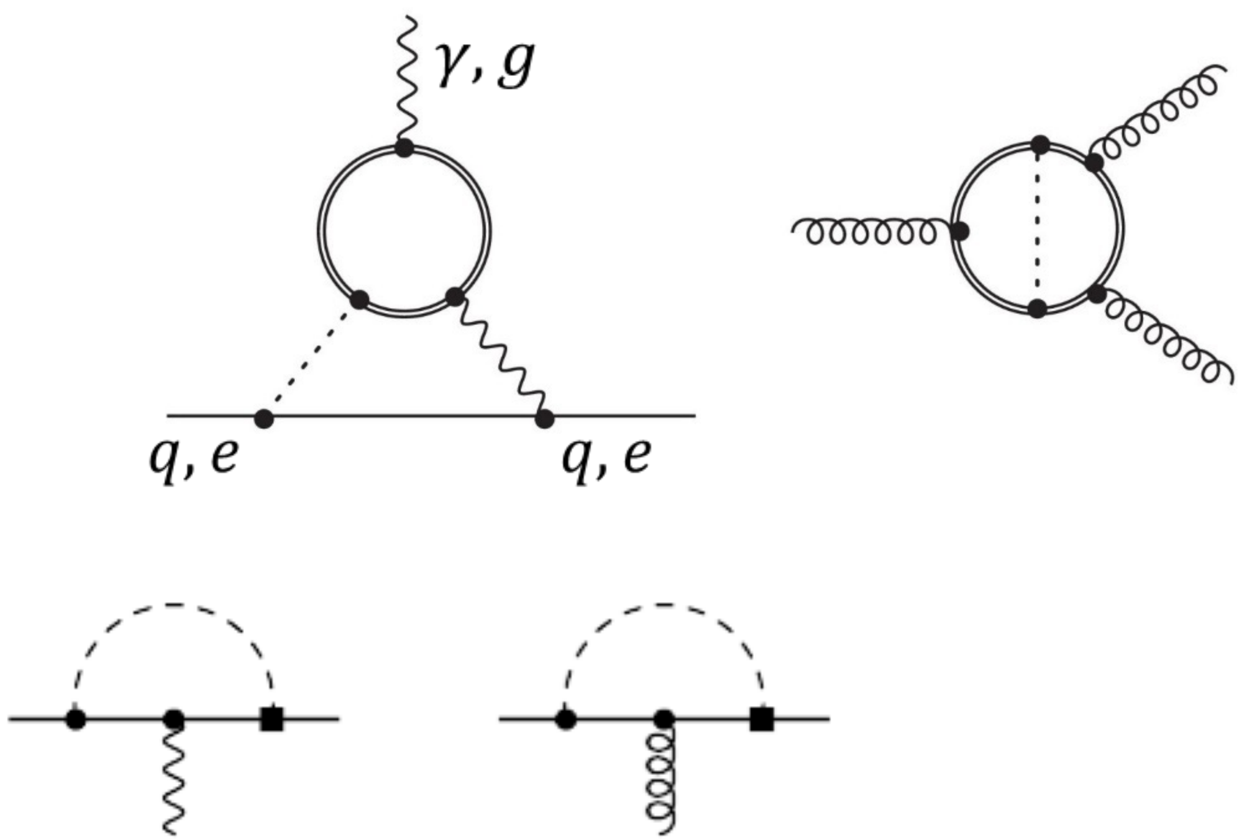


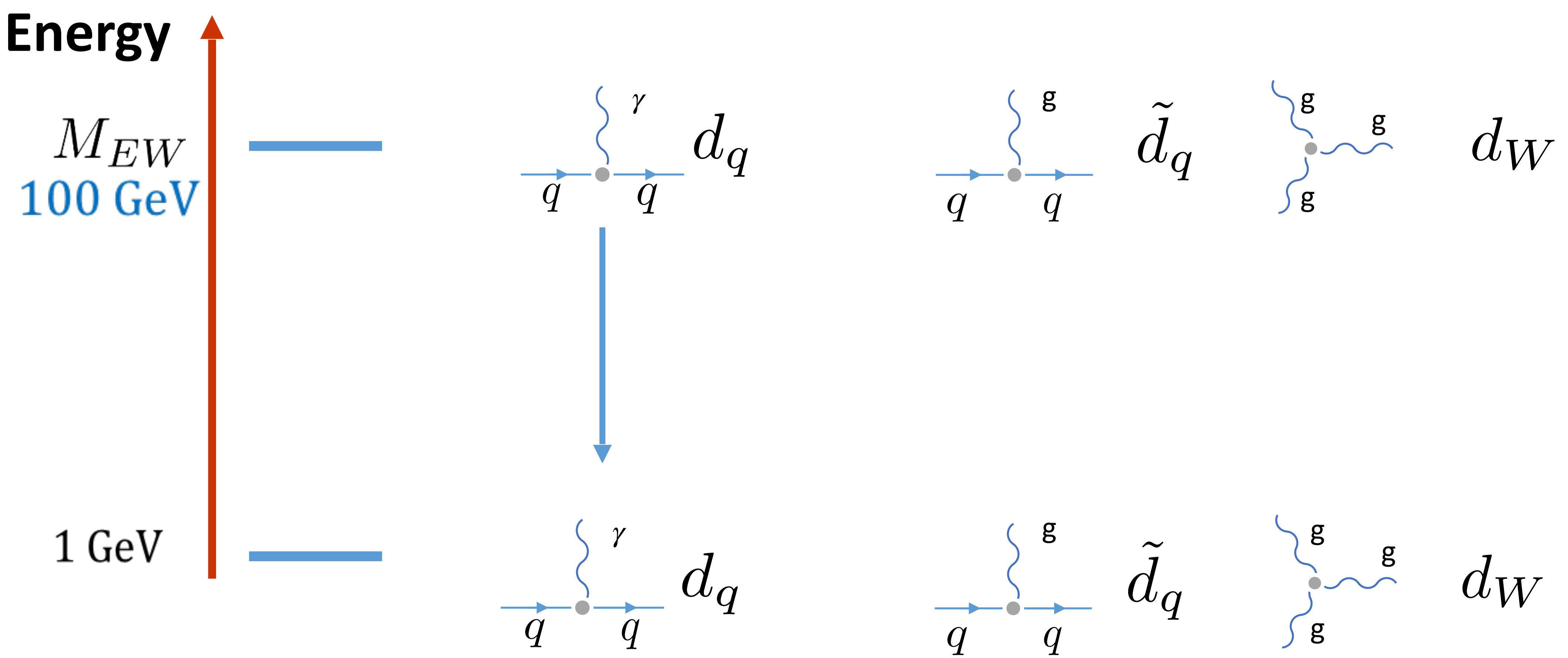


d_e d_q $\tilde{d}_q$ d_W

RGEs

Evolution to the QCD scale

$$\frac{d}{d\ln\mu}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix} = \frac{\alpha_s}{4\pi}\begin{pmatrix} 8C_F & -8C_F & 0 & 0 & 0 \\ 0 & 16C_F-4N_C & 2N_C & 0 & -1/4\pi^2 \\ 0 & 0 & N_C+2n_f+\beta_0 & 0 & 0 \\ 0 & -18C_F\left(\frac{m_q}{v}\right)^3 & 0 & -6C_F & 12C_F\frac{\alpha_s}{4\pi}\frac{m_q}{v} \\ 0 & -8\frac{4\pi}{\alpha_s}\left(\frac{m_q}{v}\right)^2 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} d_q/eQ_q m_q \\ \tilde{d}_q/m_q \\ d_W/g_s \\ Y_q' \\ \theta' \end{pmatrix}$$



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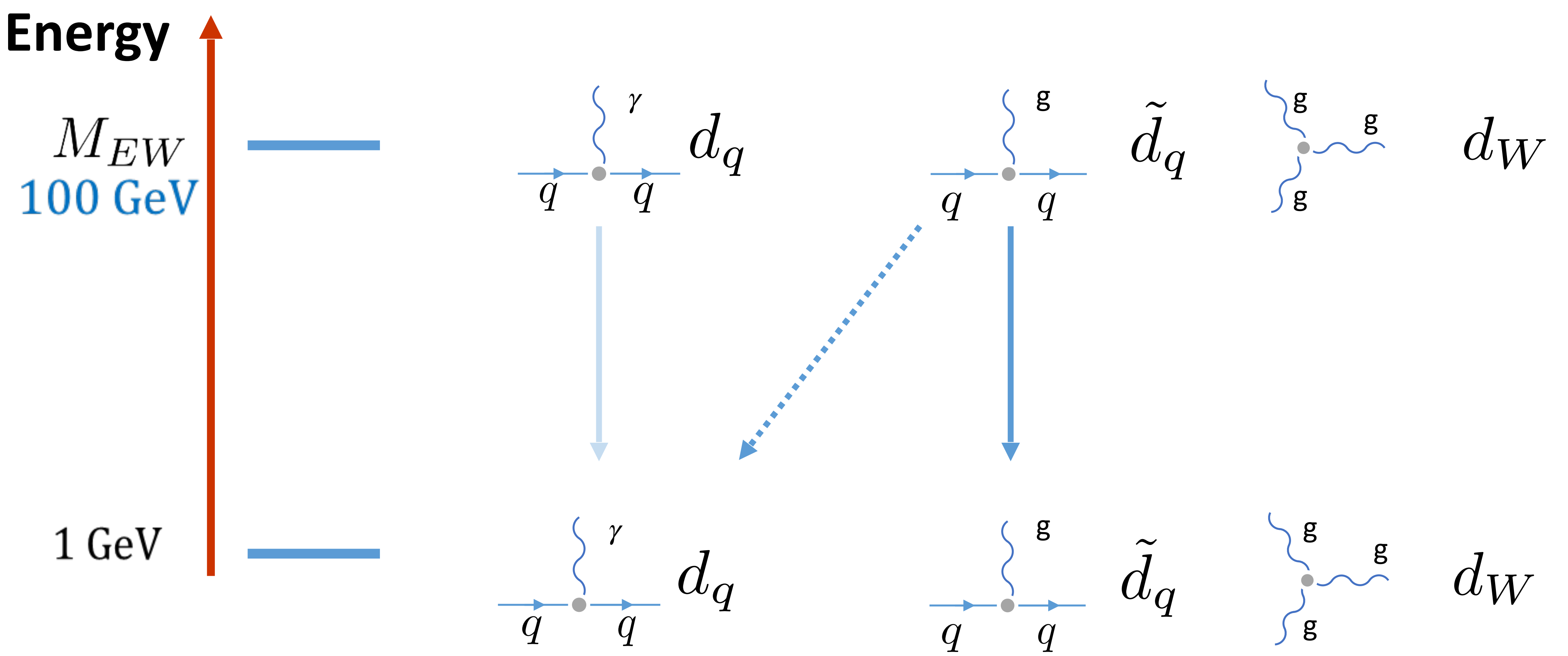

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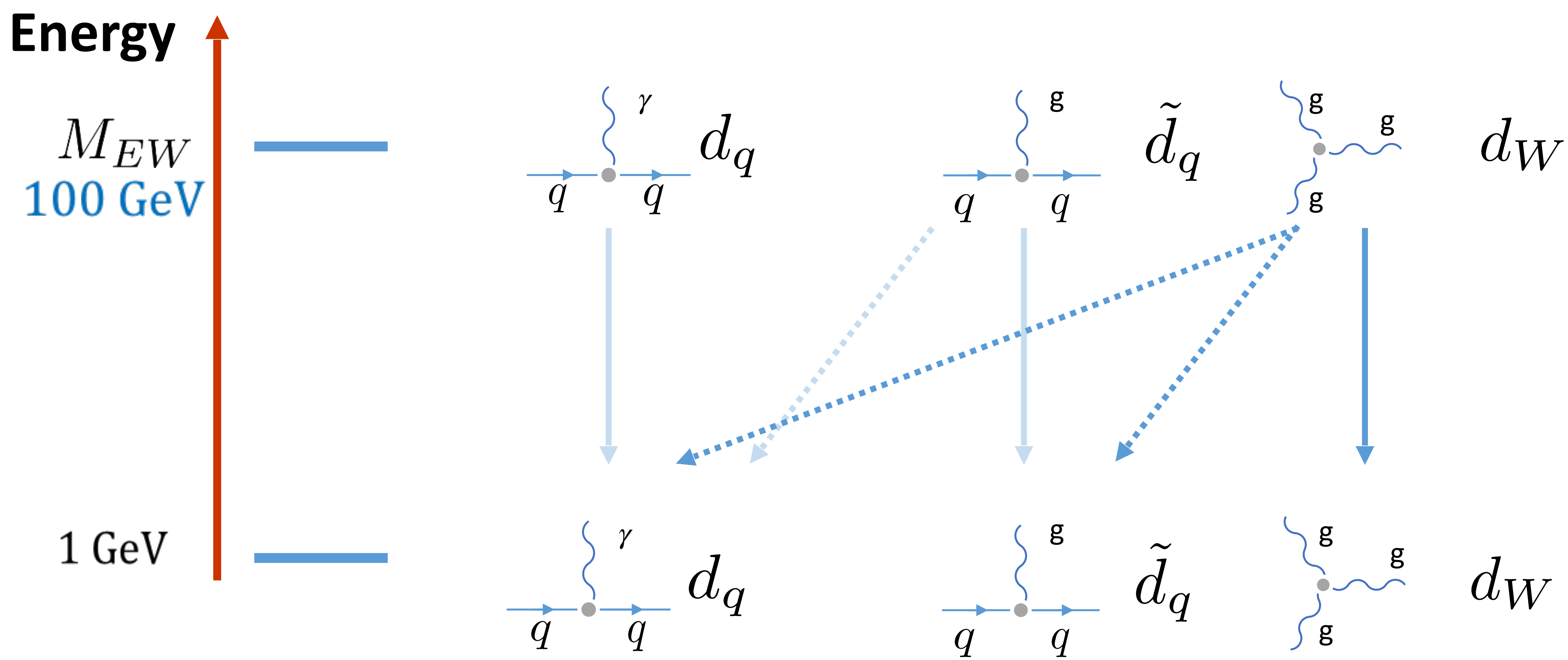
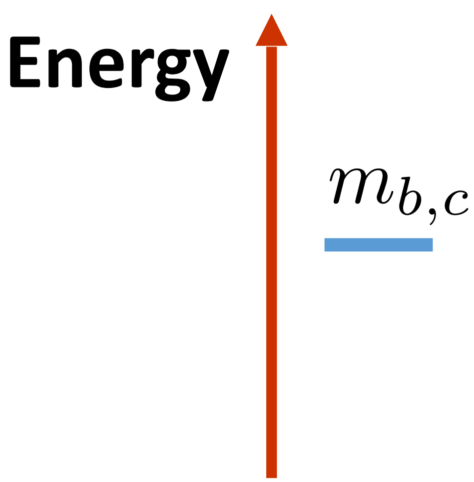
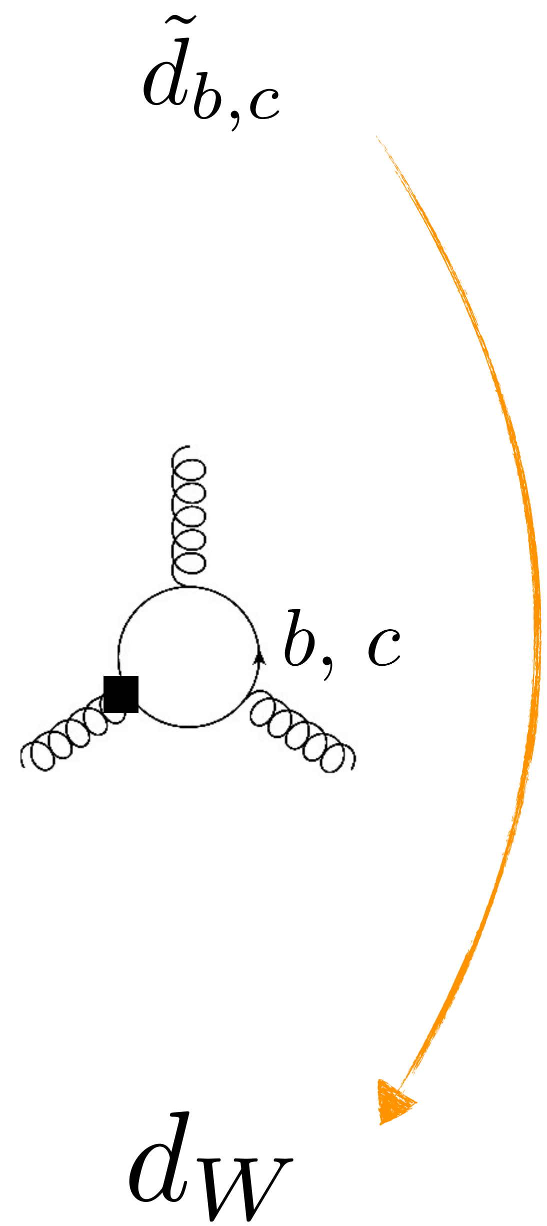


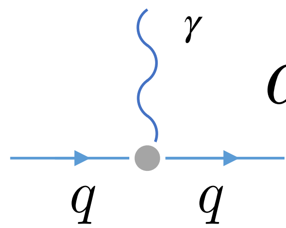
Threshold corrections

At the bottom & charm mass scales

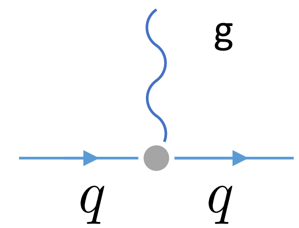




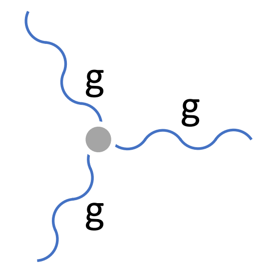
Below 1 GeV



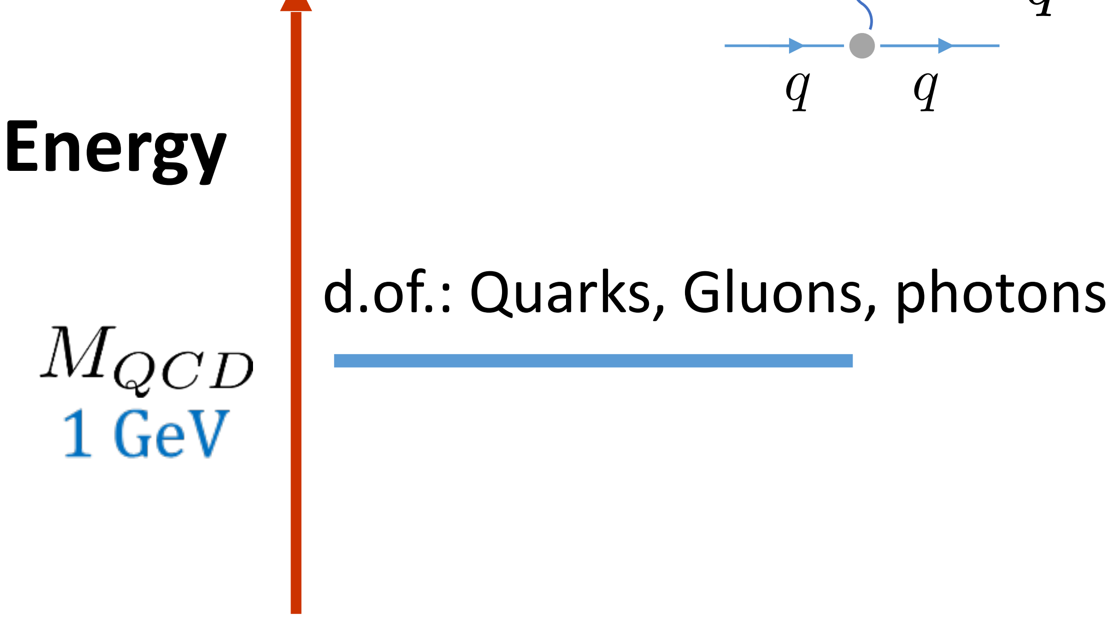
d_q



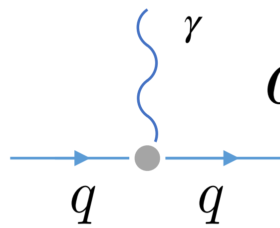
$\tilde{d}_q$



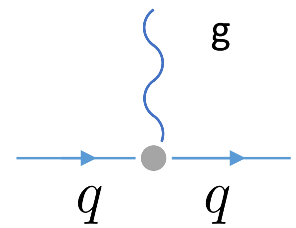
d_W



Below 1 GeV



d_q



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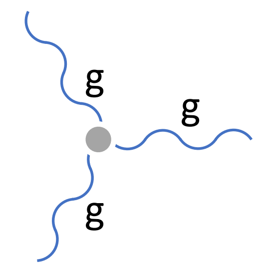


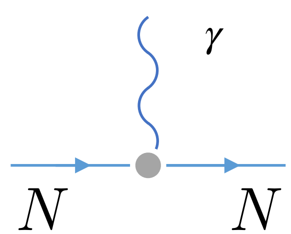
d_W

Energy

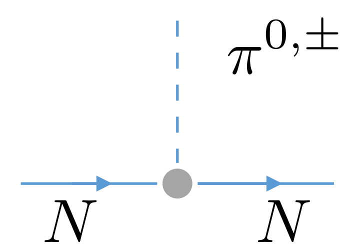
d.of.: Quarks, Gluons, photons

M_{QCD}
1 GeV

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



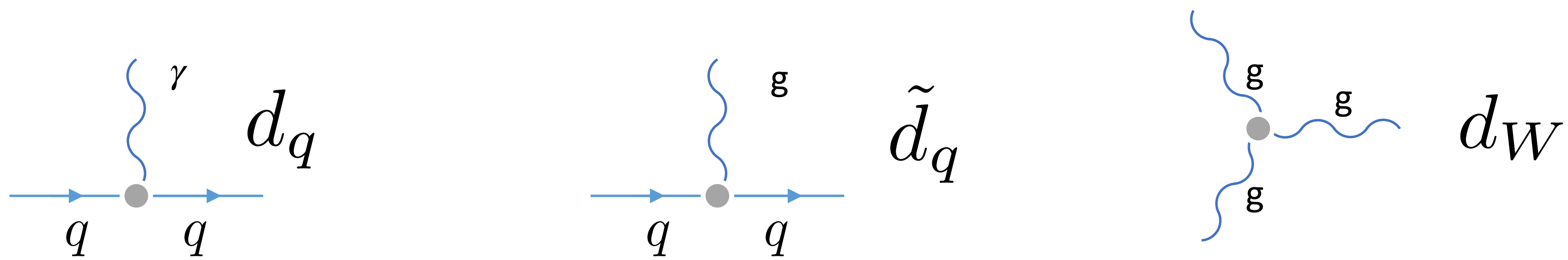
$d_{n,p}$



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

$$\mathcal{L}_{\chi PT} = -2\overline{N}(\bar{d}_0 + \bar{d}_1\tau_3)S^\mu N v^\nu F_{\mu\nu} + \bar{g}_0\overline{N}\,\pi\cdot\tau\,N + \bar{g}_1\overline{N}\,\pi_3\,N$$

Below 1 GeV



Energy

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Matrix Elements

$d_{n,p}$ $\bar{g}_{0,1}$

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Nucleon EDMs

Hadronic uncertainties

$$d_N = (\mu_{N,d_q},\, \mu_{N,\tilde{d}_q},\, \mu_{N,d_W}) \cdot \begin{pmatrix} d_q \\ \tilde{d}_q \\ d_W \end{pmatrix}$$

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Quark EDM contribution

- 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

Lattice QCD, T. Bhattacharya *et al*, '15

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Quark color-EDM contribution

- QCD sum-rule calculations
- O(50%) uncertainty
- Strange situation unsettled

	$e\,\tilde{d}_u(1\,\mathrm{GeV})$	$e\,\tilde{d}_d(1\,\mathrm{GeV})$	$e\,\tilde{d}_s(1\,\mathrm{GeV})$
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

Nucleon EDMs

Hadronic uncertainties

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Weinberg contribution

- QCD sum-rule calculations
- O(100%) uncertainty (based on naive dimensional analysis estimates)
- Unknown sign

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

Demir, Pospelov, Ritz, '03

Pion-nucleon couplings

Hadronic uncertainties

$$\bar{g}_{0,1} = (\mu_{\bar{g}_{0,1},d_q}, \mu_{\bar{g}_{0,1},\tilde{d}_q}, \mu_{\bar{g}_{0,1},d_W}) \cdot \begin{pmatrix} d_q \\ \tilde{d}_q \\ d_W \end{pmatrix}$$

~ 0 ~ 0

Pion-nucleon couplings

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Quark color-EDM contributions

- QCD sum-rule calculations
- O(>100%) uncertainty

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

M. Pospelov, Annals Phys, '02

Atomic EDMs

Nuclear uncertainties

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

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Atomic screening

- Fairly well-known

	Atomic screening $\mathcal{A}(\mathrm{fm}^{-2})$
^{129}Xe	$(0.33 \pm 0.05)\cdot 10^{-4}$
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Engel *et al*, ‘13

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Nucleon-EDM contributions

- Fairly well-known (for Mercury)

$$\alpha_n = 1.9 \pm 0.1$$

$$\alpha_p = 0.20 \pm 0.6$$

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Engel *et al*, ‘13 , Dmitriev & Sen’kov, ’03

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Pion-nucleon contributions

- Large allowed ranges, sometimes including zero

	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
^{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	$\{-12.6, -76\}$	$\{51, 303\}$

Engel *et al*, '13 , Dmitriev & Sen'kov, '03

EDM summary

ThO measurement

- Effectively a constraint on the electron EDM in our case
- No hadronic uncertainties

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Derive constraints in several ways:

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Known to 25%

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

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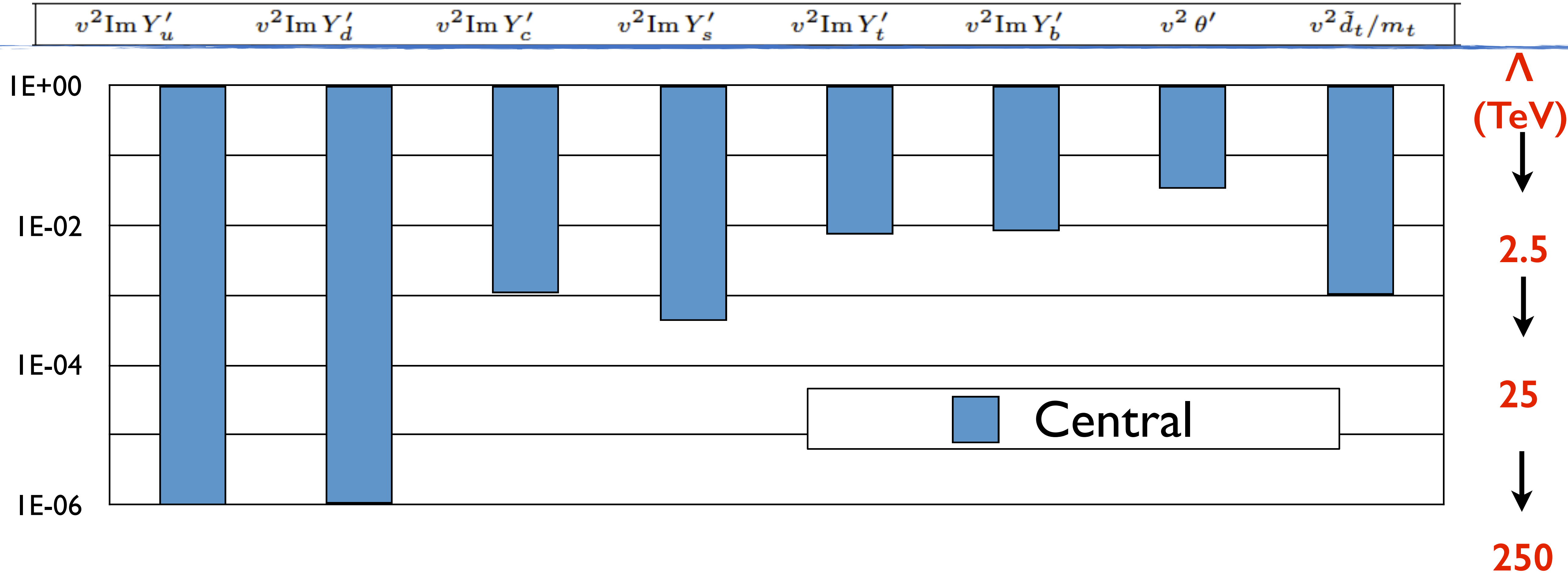
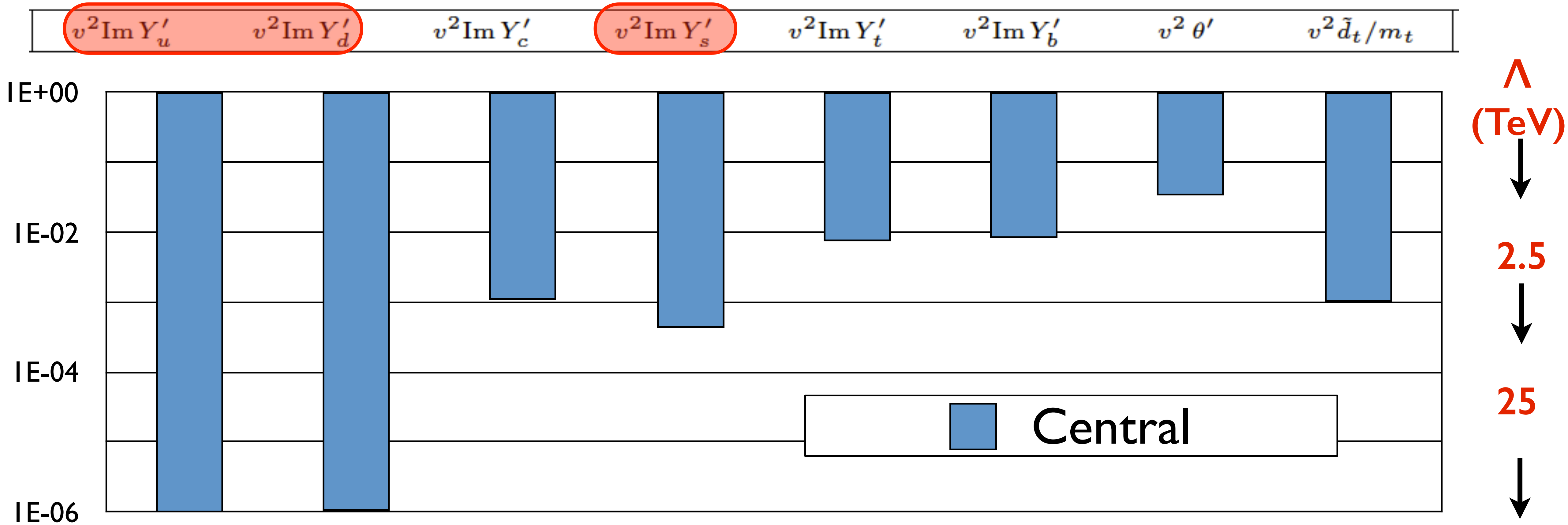
Known to 25%: $\mu_{N,\tilde{d}_q}$

Known to 50%: μ_{N,d_W}, $a_0\,e\,\mathrm{fm}^3$, $a_1\,e\,\mathrm{fm}^3$, $\bar{g}_0$, $\bar{g}_1$

EDM constraints



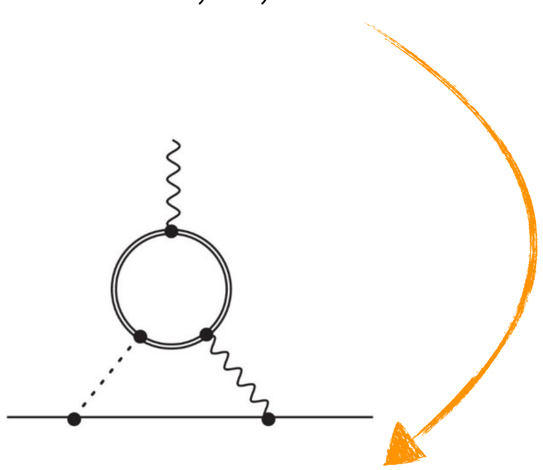
EDM constraints



Light Yukawa

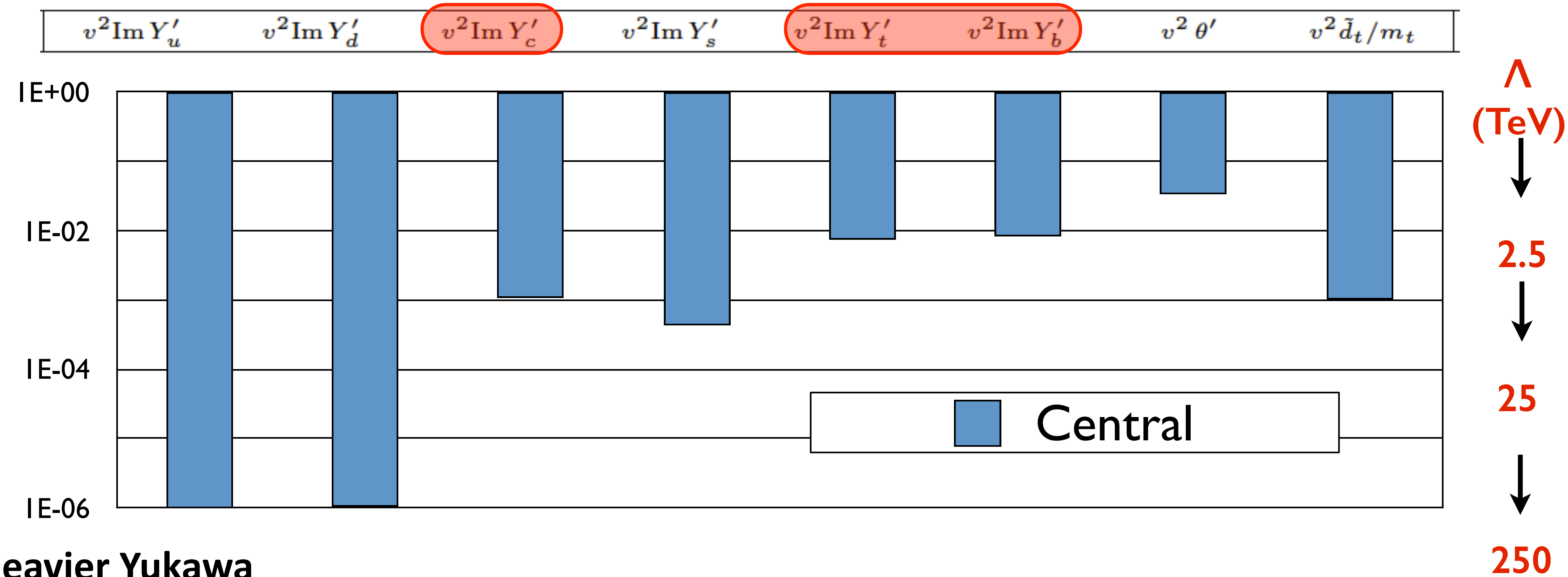
$Y'_{u,d,s}$

- Contribute mainly to the light (color) EDMs
- Results in neutron and mercury EDMs



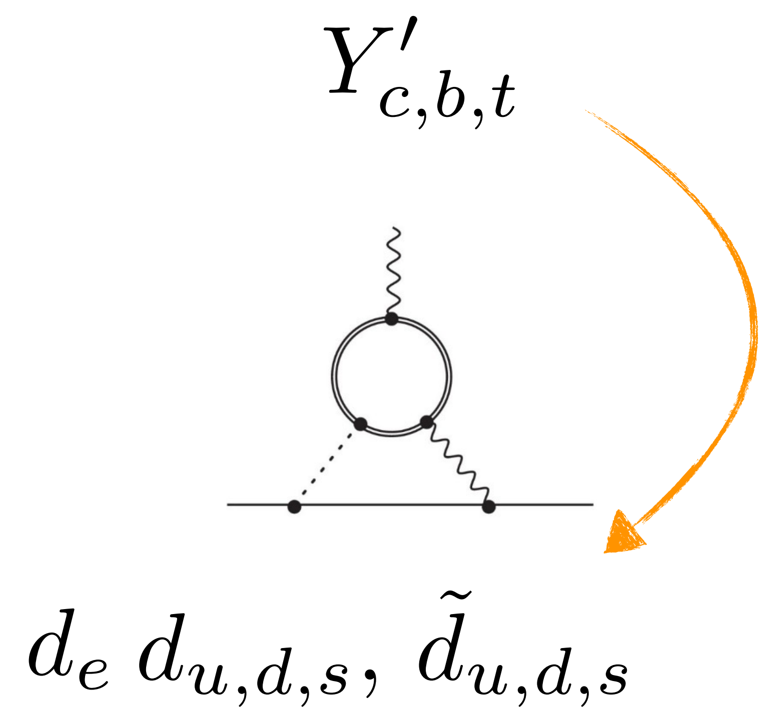
$d_{u,d,s},\ \tilde{d}_{u,d,s}$

EDM constraints

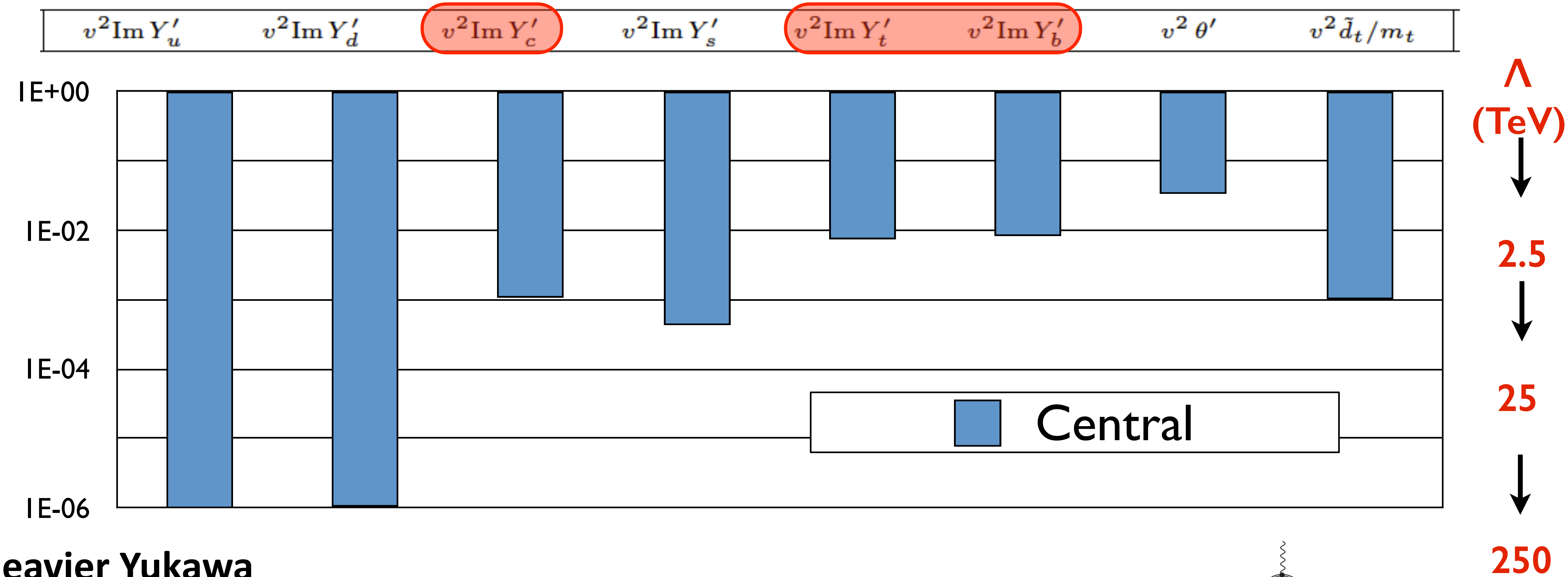


Heavier Yukawa

- Contributions to light (color) EDMs
- Contributions to the Weinberg
- Electron EDM is generated

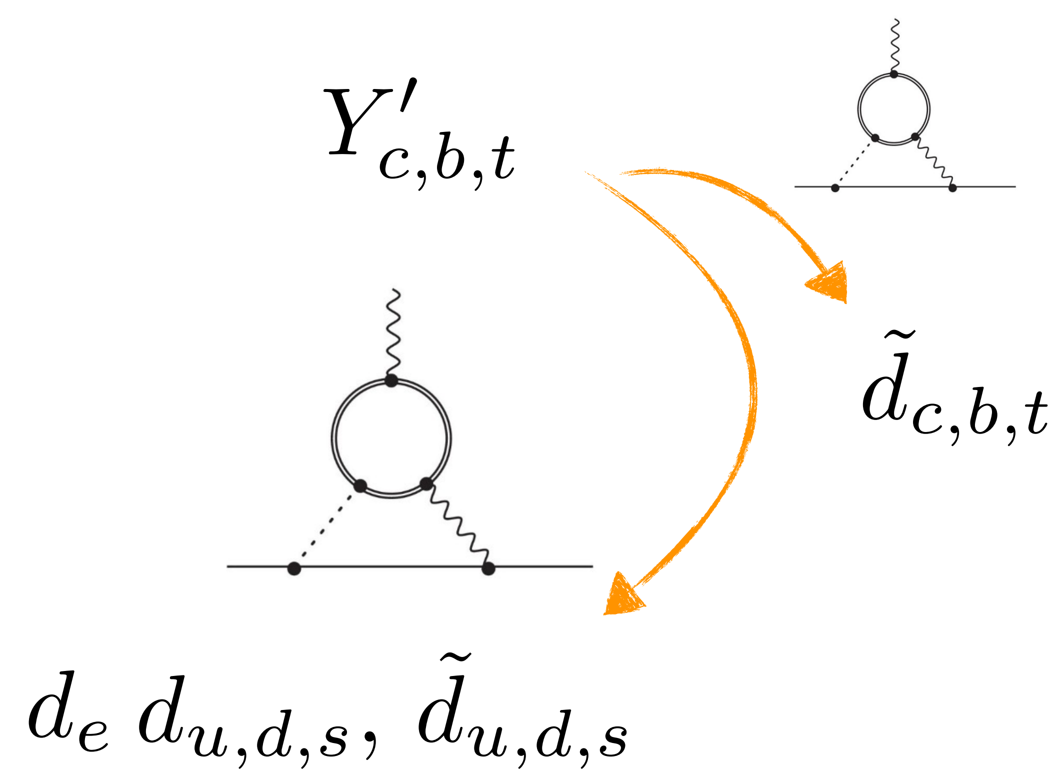


EDM constraints

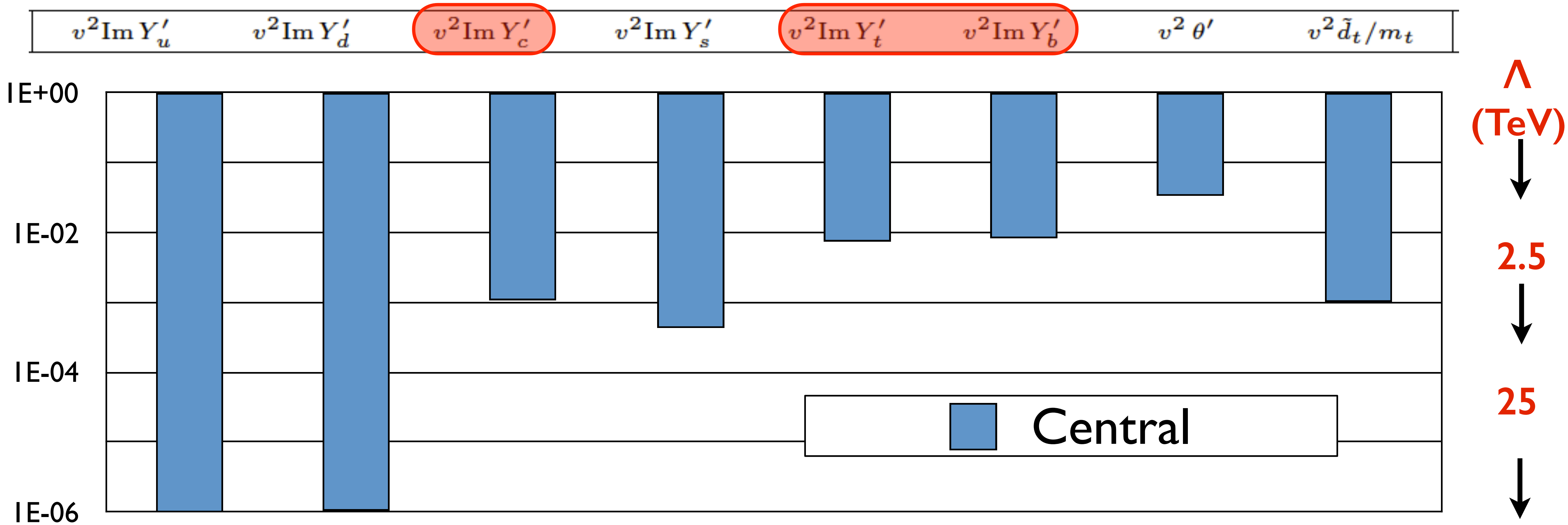


Heavier Yukawa

- Contributions to light (color) EDMs
- Contributions to the Weinberg
- Electron EDM is generated



EDM constraints



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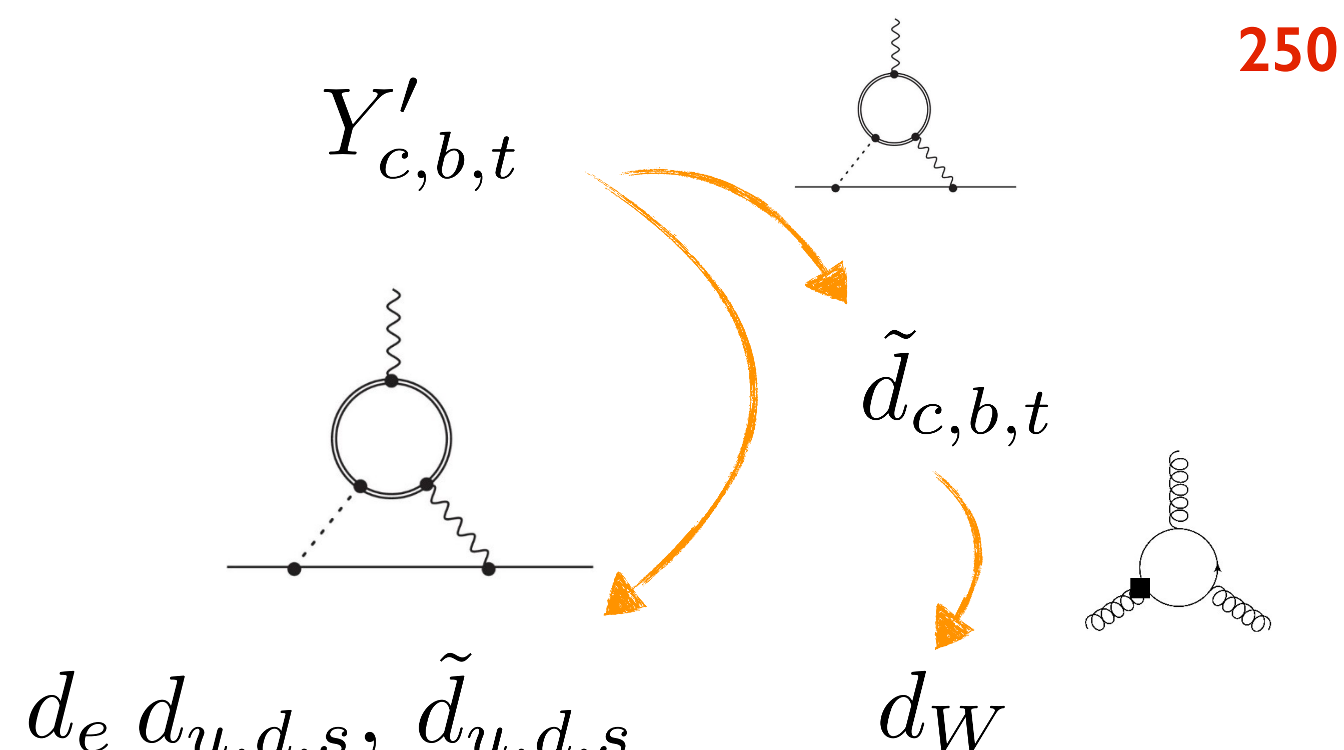

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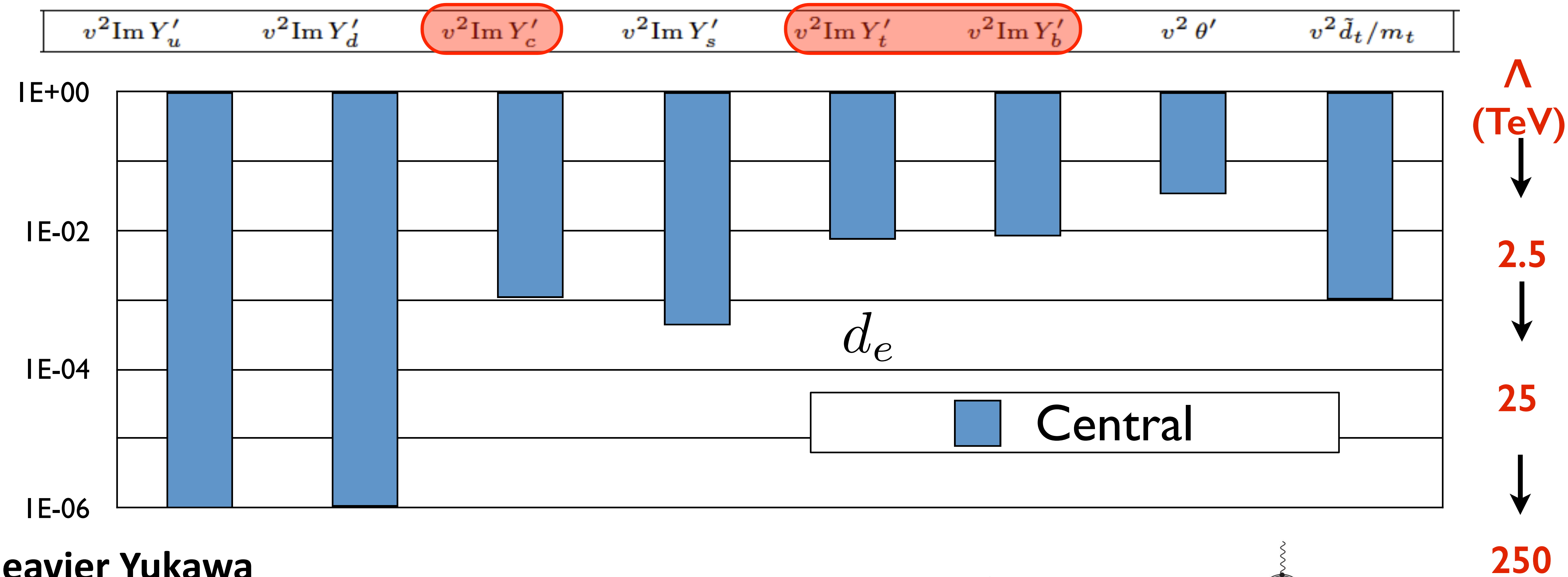

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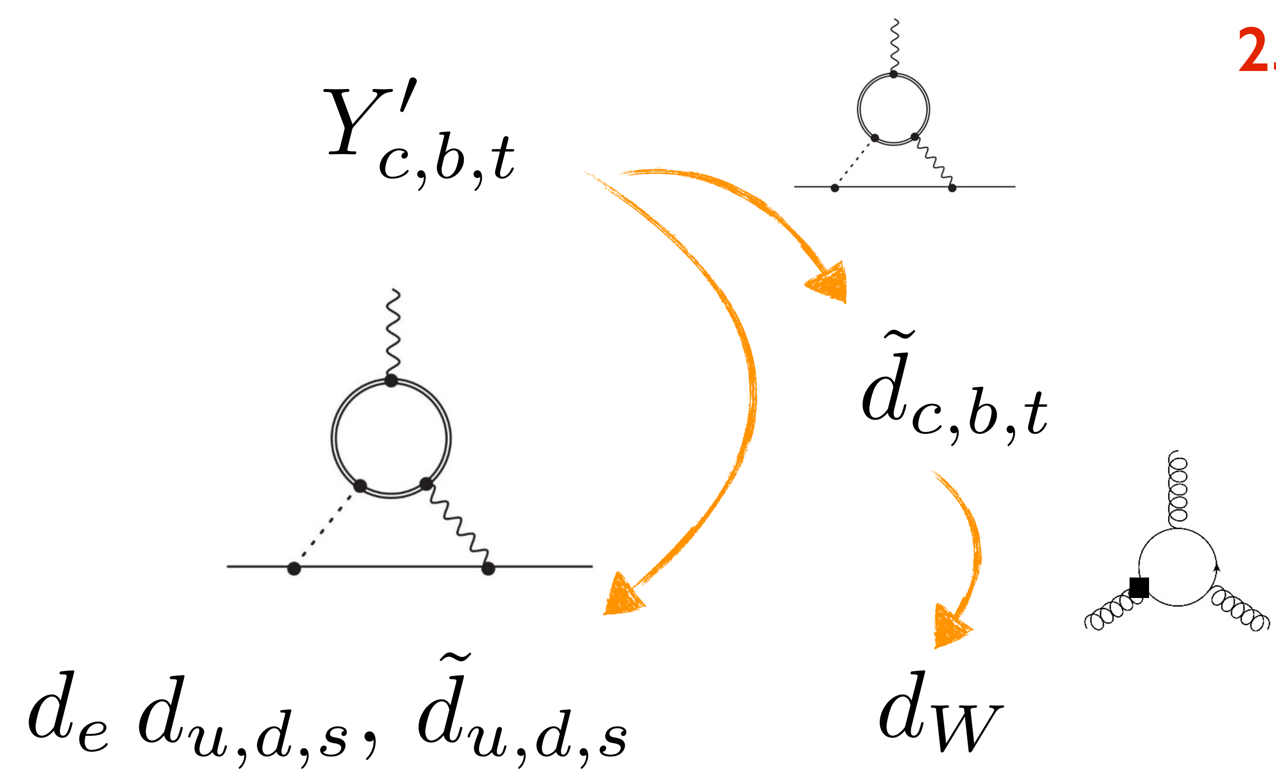

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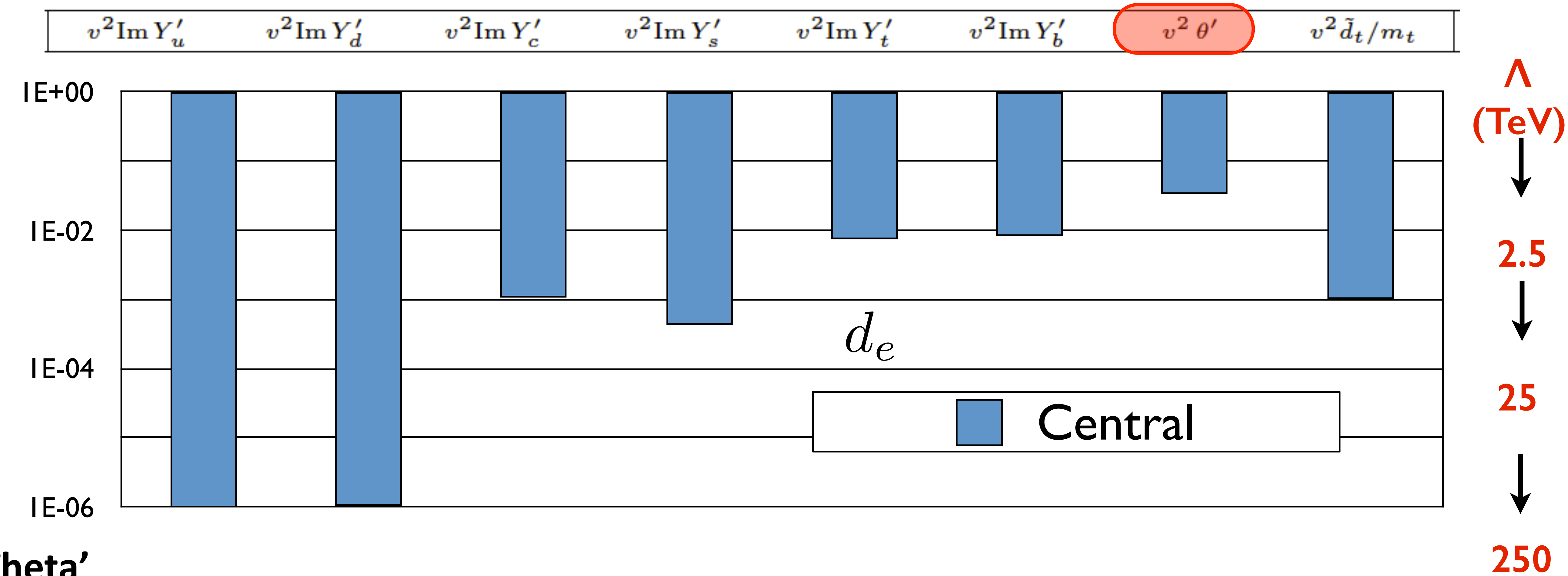
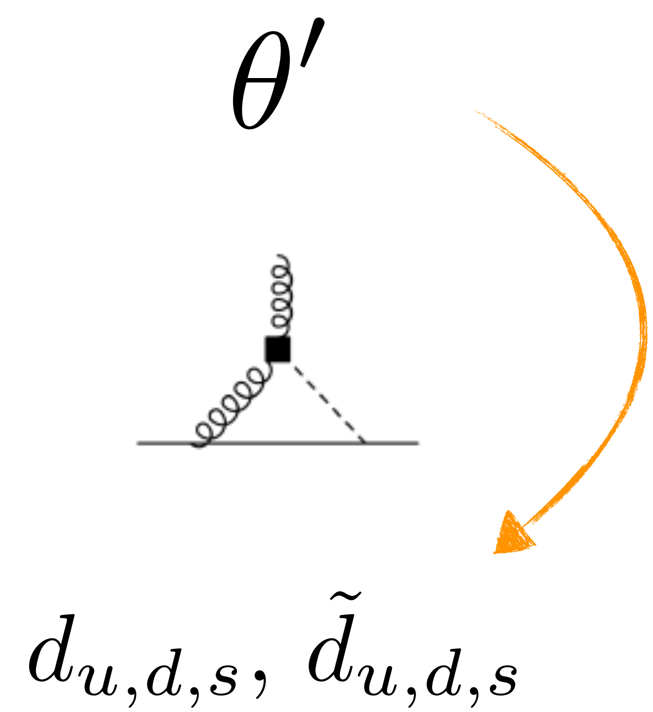
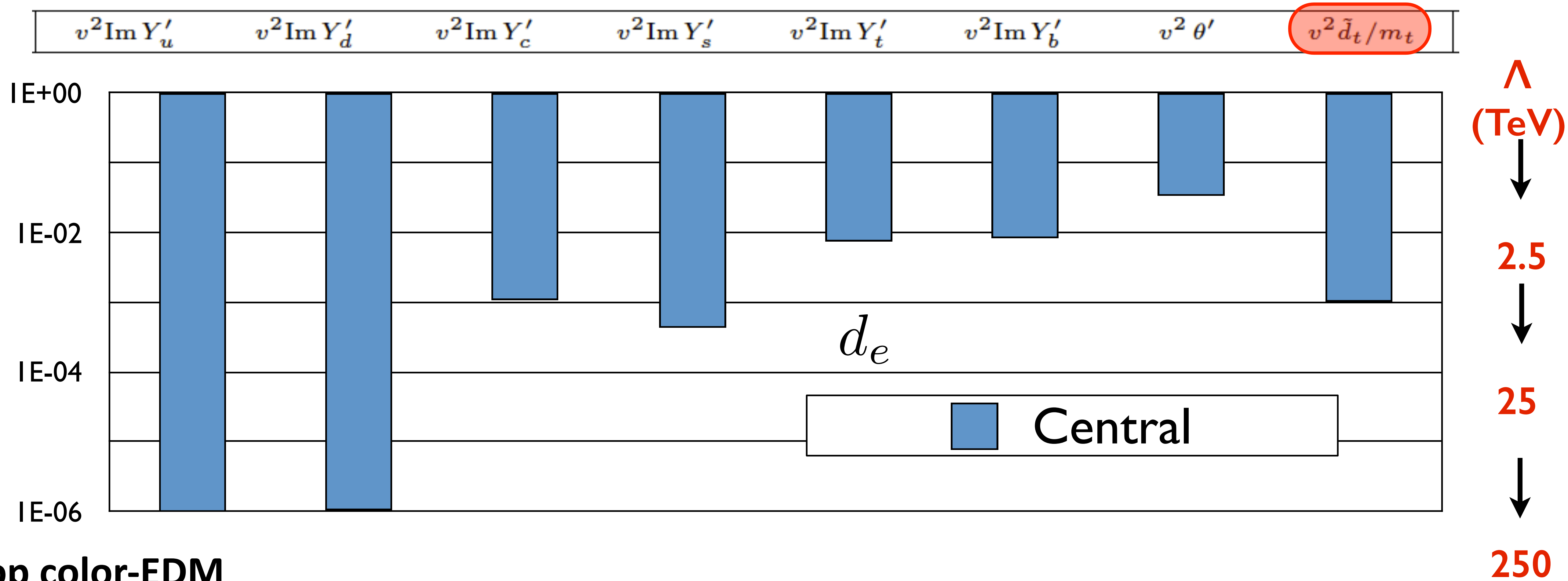


Theta'

- Contribute mainly to the light (color) EDMs
- Results in neutron and mercury EDMs

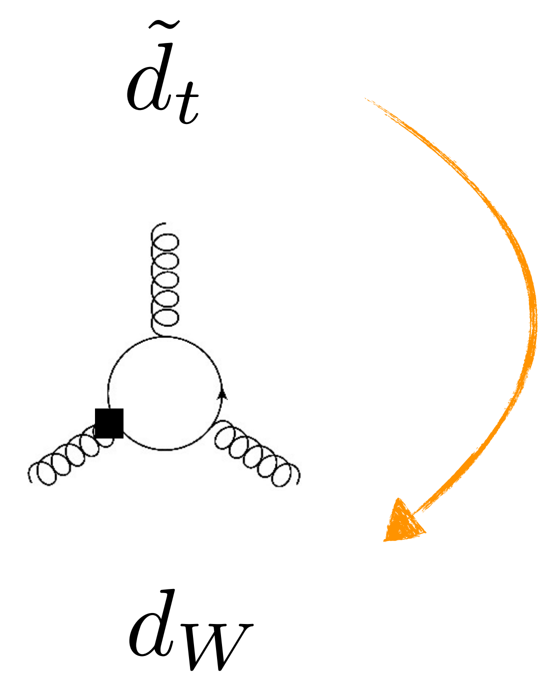


EDM constraints

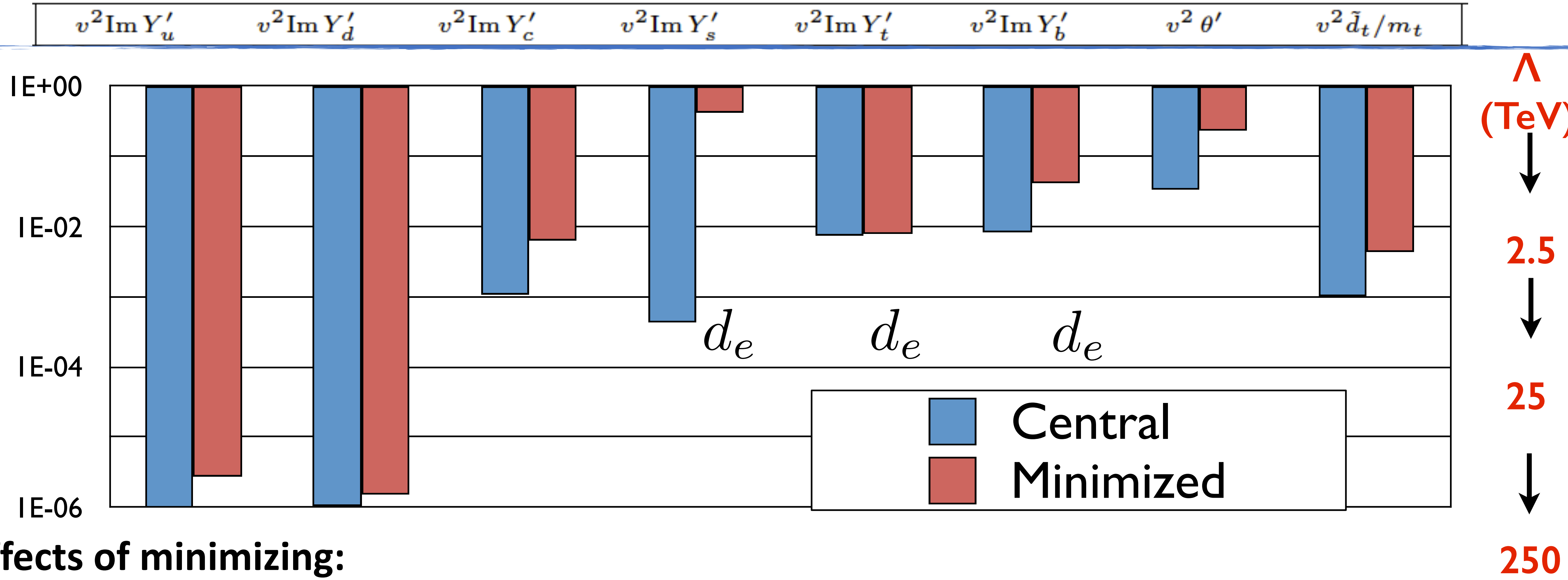


Top color-EDM

- Mainly contributes to the Weinberg
- Results in neutron and mercury EDMs



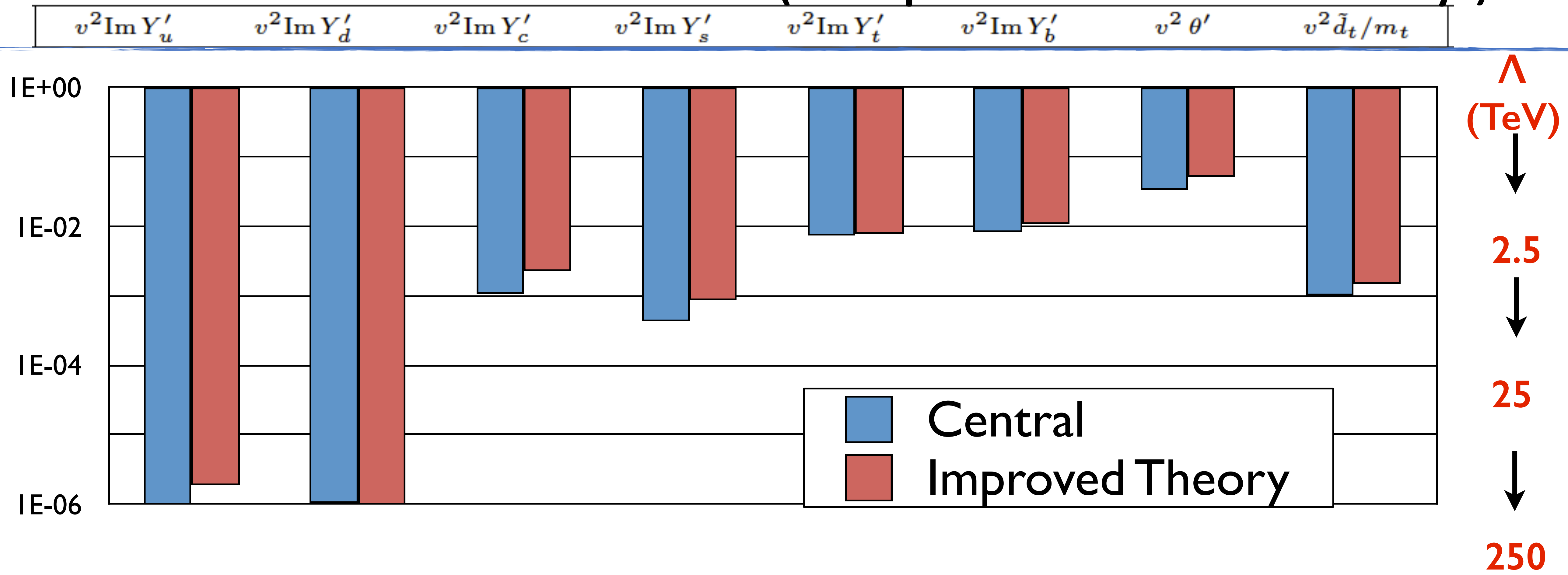
Minimized EDM constraints



Effects of minimizing:

- No Hg constraints for any coupling,
- Neutron EDM bounds much weaker, eEDM takes over in several cases
- Largest effects due to
  - Poorly known matrix elements (sEDM, Weinberg)
  - Cases where different contributions can cancel (θ', $Y'_{c,b}$)

EDM constraints (improved theory)



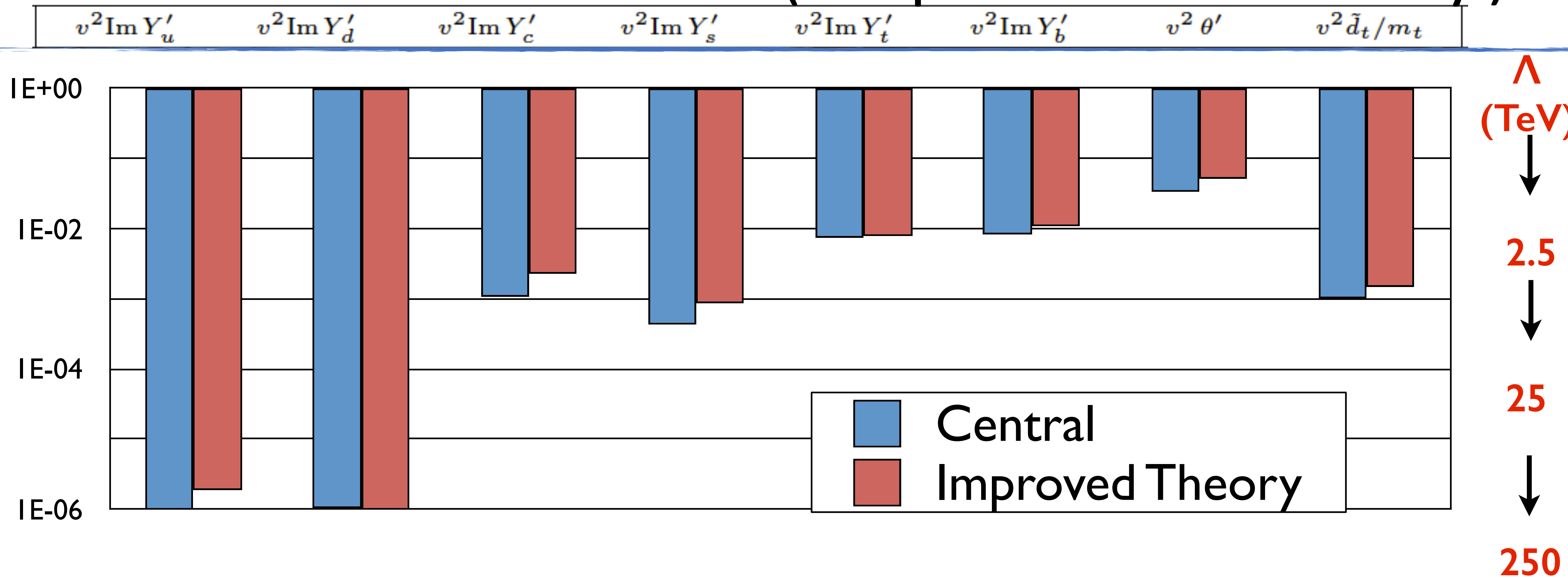
Assuming:

$$d_N = (\mu_{N,d_q}, \mu_{N,\tilde{d}_q}, \mu_{N,d_W}) \cdot \begin{pmatrix} d_q \\ \tilde{d}_q \\ d_W \end{pmatrix}$$

Known to 25%

Known to 50%

EDM constraints (improved theory)



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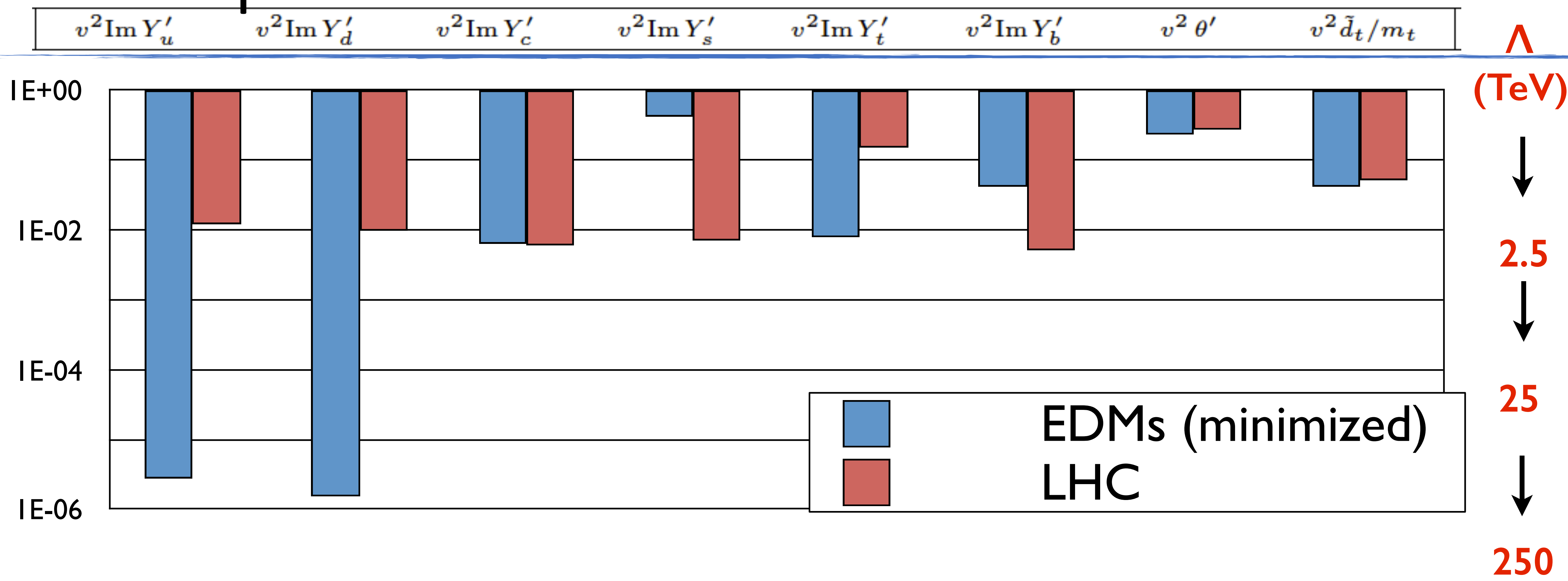
Known to 25%

Known to 50%

Close to central constraints

Comparison with the LHC



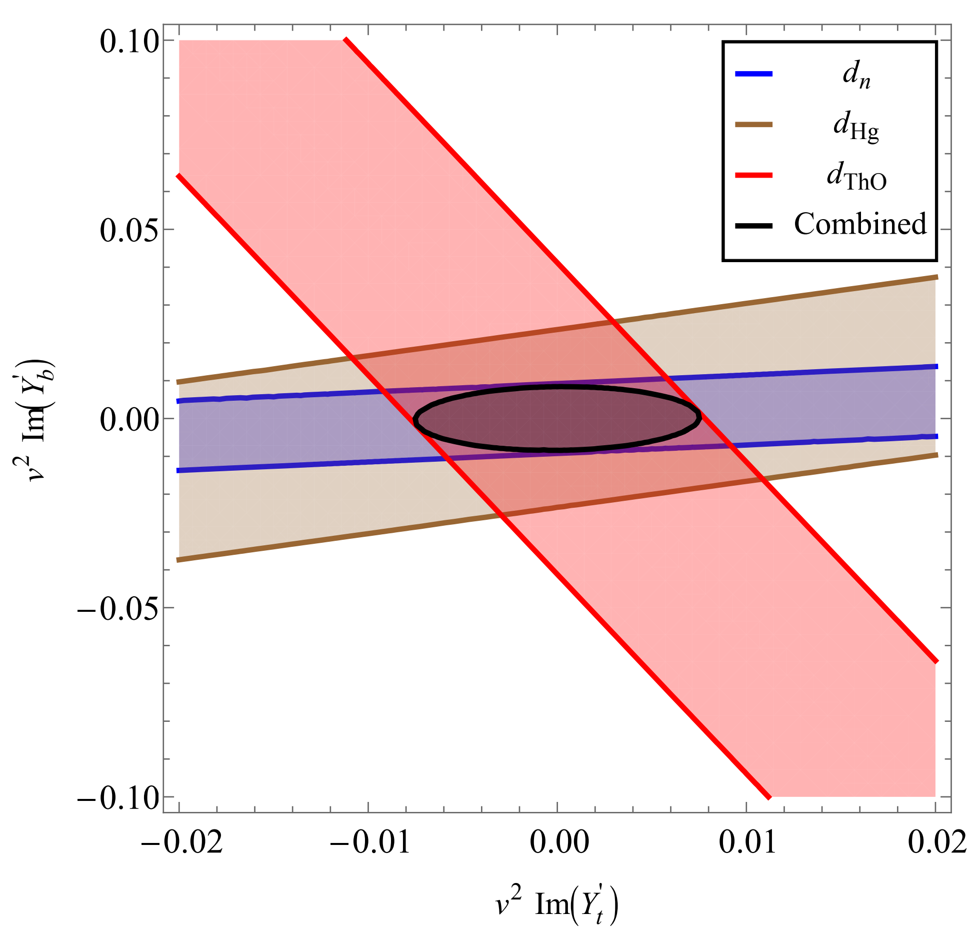
- EDMs win for the up, down and top Yukawa's

- Using the minimization procedure for EDMs the LHC is competitive or better for the rest

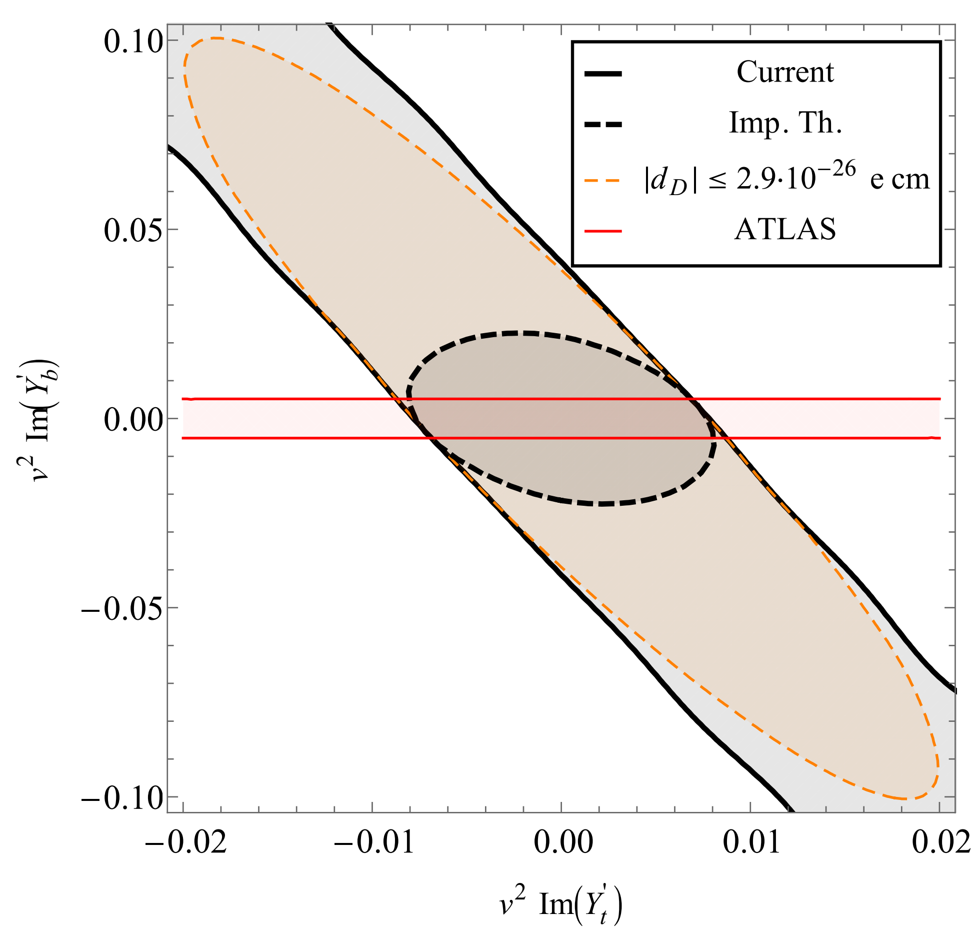
- Suggests complementarity

Complementary examples

Top Yukawa vs bottom Yukawa



Central



Minimized

Summar/Conclusions

Studied the effects of CP-violating scalar-quark & scalar-gluon couplings

- In BEH boson production at the LHC
- In EDM measurements

Both observables can probe these couplings > a few TeV

Best constraints come from combination of EDMs and the LHC
The LHC and EDMs are complementary in several cases

Uncertain matrix elements significantly affect EDM bounds ('minimized' case)

- Goal to get close to the naive 'central' case:

$$d_N = (\mu_{N,d_q}, \mu_{N,\tilde{d}_q}, \mu_{N,d_W}) \cdot \begin{pmatrix} d_q \\ \tilde{d}_q \\ d_W \end{pmatrix} \qquad d_A = \mathcal{A}_A(\alpha_n\,\mathrm{fm}^2,\ \alpha_p\,\mathrm{fm}^2,\ a_0\,e\,\mathrm{fm}^3,\ a_1\,e\,\mathrm{fm}^3) \cdot \begin{pmatrix} d_n \\ d_p \\ \bar{g}_0 \\ \bar{g}_1 \end{pmatrix}$$

Known to 25%

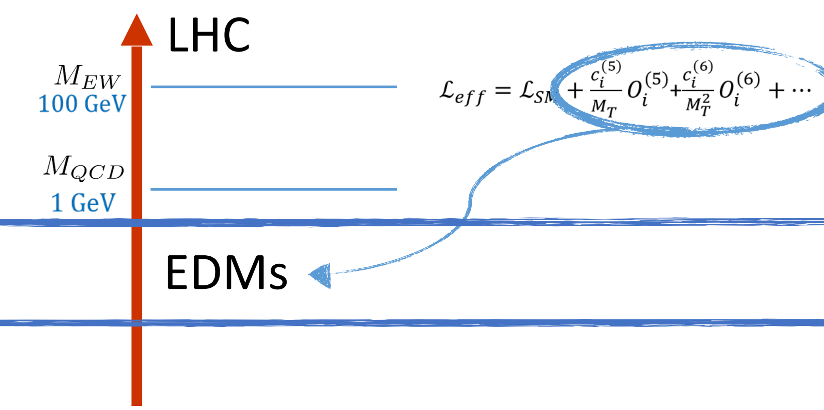
Known to 50%

Thank you for your attention!

Backup slides

Observables

Electric Dipole Moments



Current experimental status

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

Recent factor 4 improvement

Expected Limits

Limits	neutron	ThO	proton/ deuteron	Xenon	Radium
Expected (e cm)	1.0×10^{-28}	5.0×10^{-30}	1.0×10^{-29}	5.0×10^{-29}	1.0×10^{-27}

At 1 GeV

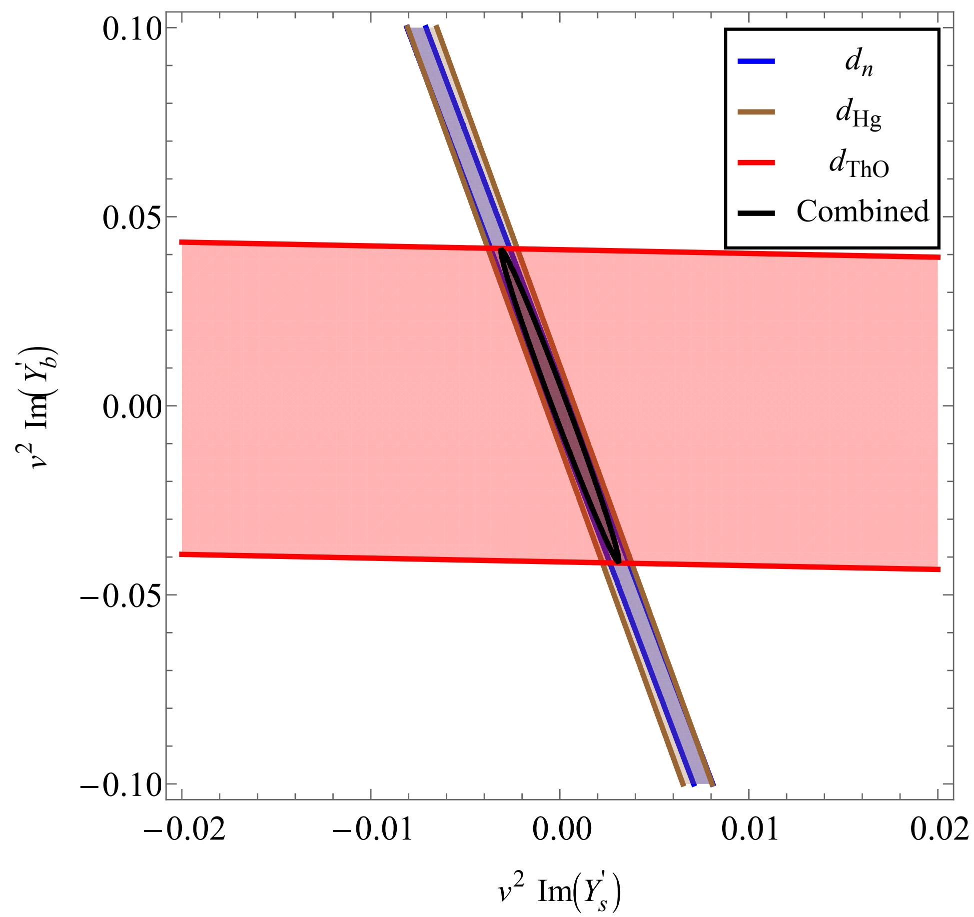
$M_T = 1\,\text{TeV}$	$\text{Im}\,Y'_u$	$\text{Im}\,Y'_d$	$\text{Im}\,Y'_c$	$\text{Im}\,Y'_s$	$\text{Im}\,Y'_t$	$\text{Im}\,Y'_b$	θ'	$\tilde{d}_t/m_t$
d_u/m_u	$15.e$	–	$2.8\cdot10^{-5}\,e$	–	$7.3\cdot10^{-5}\,e$	$7.1\cdot10^{-5}\,e$	$9.3\cdot10^{-5}\,e$	$4.2\cdot10^{-4}\,e$
$\tilde{d}_u/m_u$	$26.$	–	$9.8\cdot10^{-5}$	–	$1.9\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.1\cdot10^{-3}$
d_d/m_d	–	$-3.5\,e$	$-1.4\cdot10^{-5}\,e$	–	$-3.7\cdot10^{-5}\,e$	$-3.5\cdot10^{-5}\,e$	$-4.7\cdot10^{-5}\,e$	$-2.1\cdot10^{-4}\,e$
$\tilde{d}_d/m_d$	–	$12.$	$9.8\cdot10^{-5}$	–	$1.9\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.1\cdot10^{-3}$
d_s/m_s	–	–	$-1.4\cdot10^{-5}\,e$	$-0.18\,e$	$-3.7\cdot10^{-5}\,e$	$-3.5\cdot10^{-5}\,e$	$-4.7\cdot10^{-5}\,e$	$-2.1\cdot10^{-4}\,e$
$\tilde{d}_s/m_s$	–	–	$9.8\cdot10^{-4}$	0.62	$1.9\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.7\cdot10^{-4}$	$1.1\cdot10^{-3}$
d_e/m_e	–	–	$2.5\cdot10^{-5}\,e$	$1.3\cdot10^{-6}\,e$	$7.0\cdot10^{-5}\,e$	$1.3\cdot10^{-5}\,e$	$-7.2\cdot10^{-8}\,e$	$-8.0\cdot10^{-6}\,e$
d_W	–	–	$-1.5\cdot10^{-3}$	–	$2.7\cdot10^{-6}$	$-2.3\cdot10^{-4}$	$-7.3\cdot10^{-6}$	$-1.9\cdot10^{-3}$

Single-coupling constraints

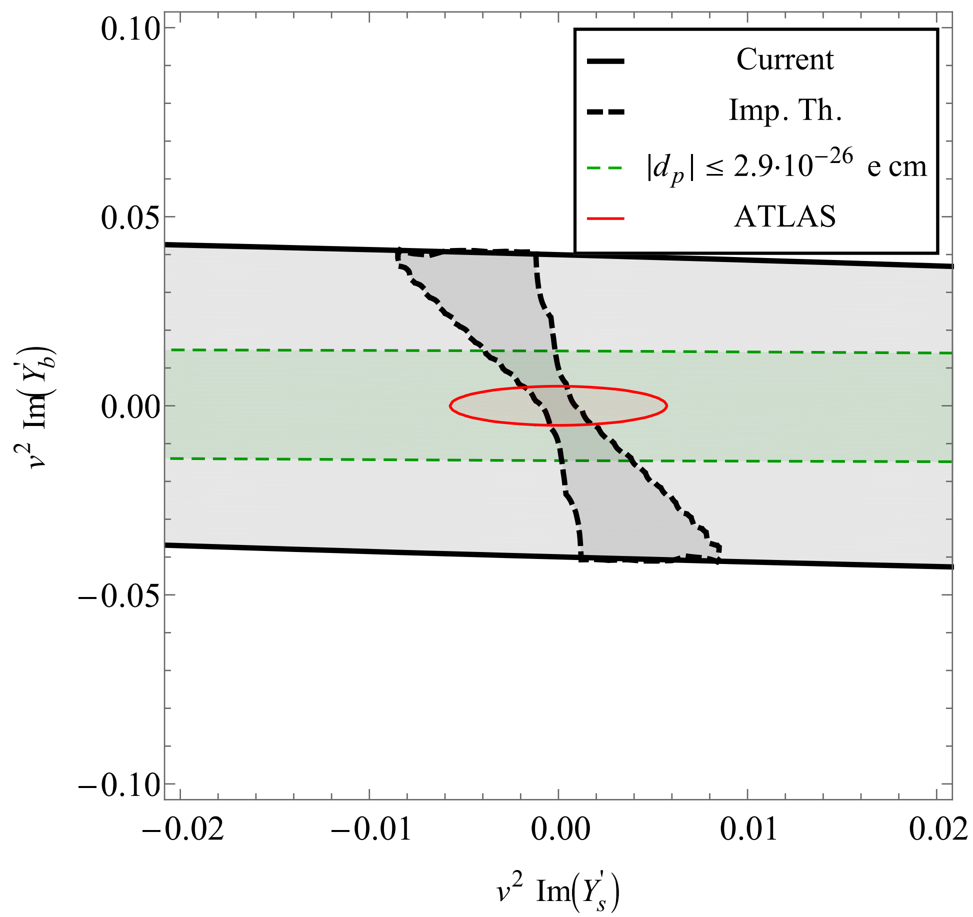
	$v^2 \mathrm{Im}\, Y'_u$	$v^2 \mathrm{Im}\, Y'_d$	$v^2 \mathrm{Im}\, Y'_c$	$v^2 \mathrm{Im}\, Y'_s$	$v^2 \mathrm{Im}\, Y'_t$	$v^2 \mathrm{Im}\, Y'_b$
Comb. Cen.	$3.9 \cdot 10^{-7}$	$3.0 \cdot 10^{-7}$	$1.1 \cdot 10^{-3}$	$4.3 \cdot 10^{-4}$	$7.6 \cdot 10^{-3}$	$8.4 \cdot 10^{-3}$
Comb. Min.	$2.8 \cdot 10^{-6}$	$1.5 \cdot 10^{-6}$	$6.3 \cdot 10^{-3}$	0.42	$7.8 \cdot 10^{-3}$	0.041
LHC	$0.6 \cdot 10^{-2}$	$0.7 \cdot 10^{-2}$	$2.0 \cdot 10^{-2}$	$1.5 \cdot 10^{-2}$	$15 \cdot 10^{-2}$	$3.8 \cdot 10^{-2}$

Complementary examples

Strange Yukawa vs bottom Yukawa



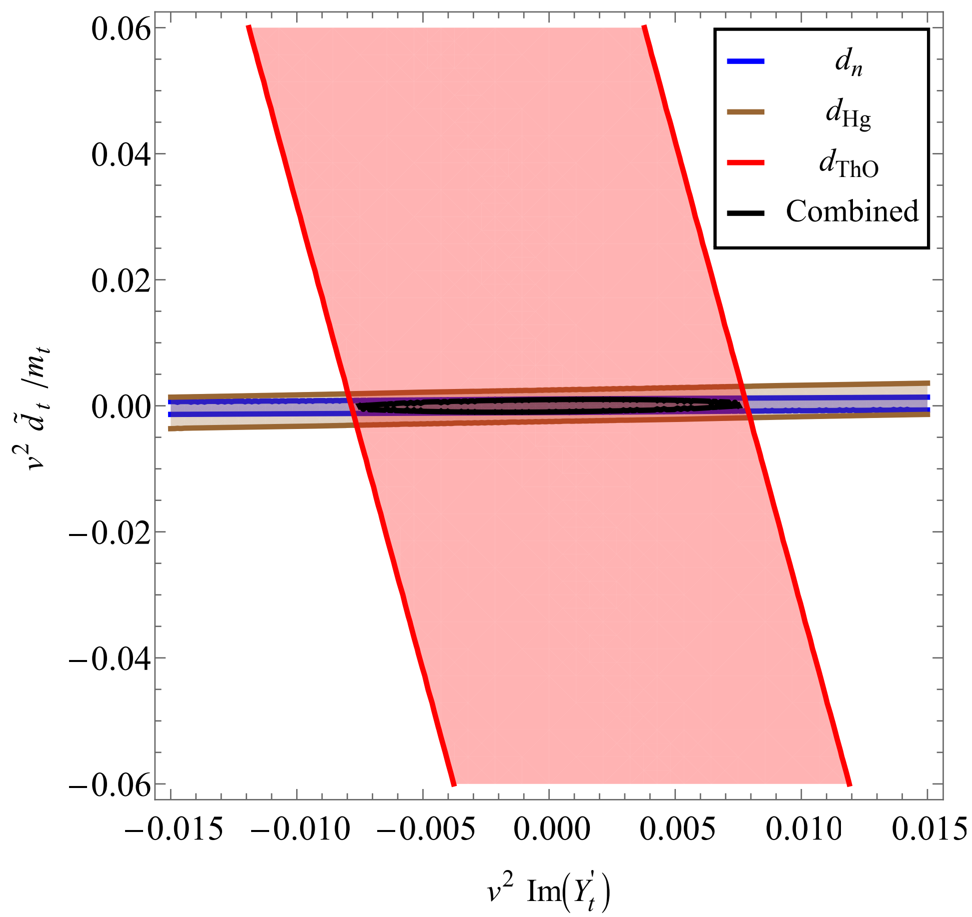
Central



Minimized

Complementary examples

Top Yukawa vs top color-EDM



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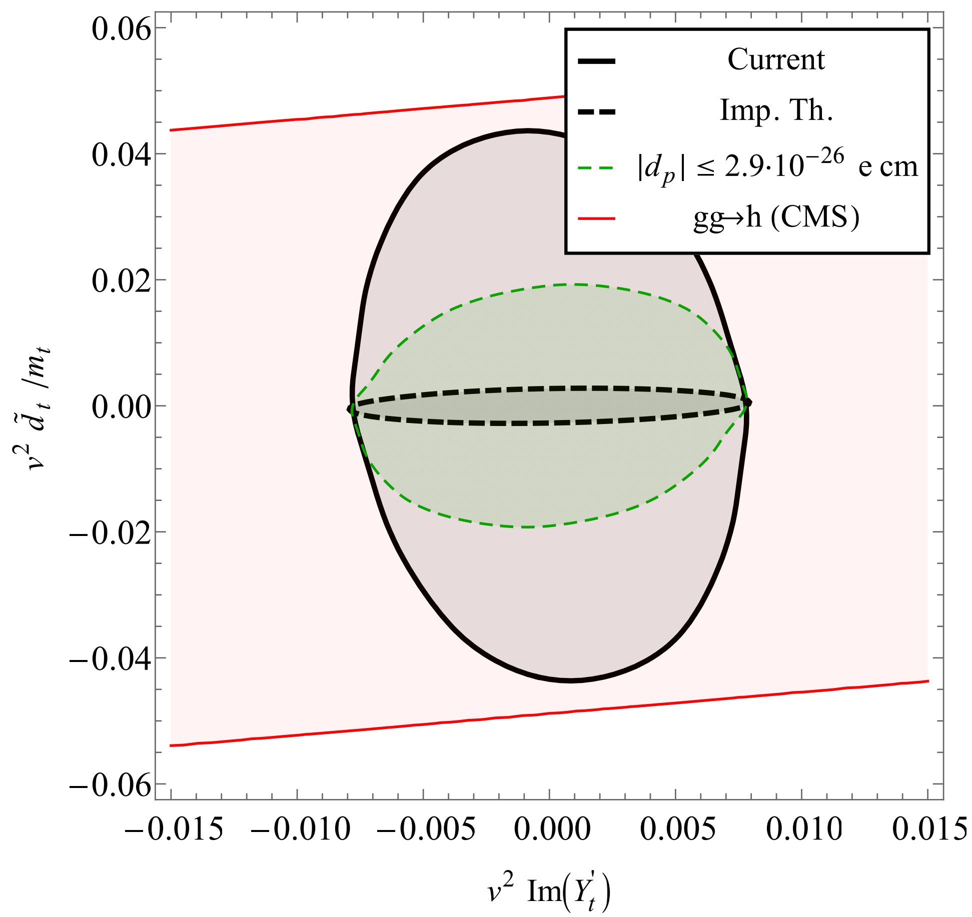
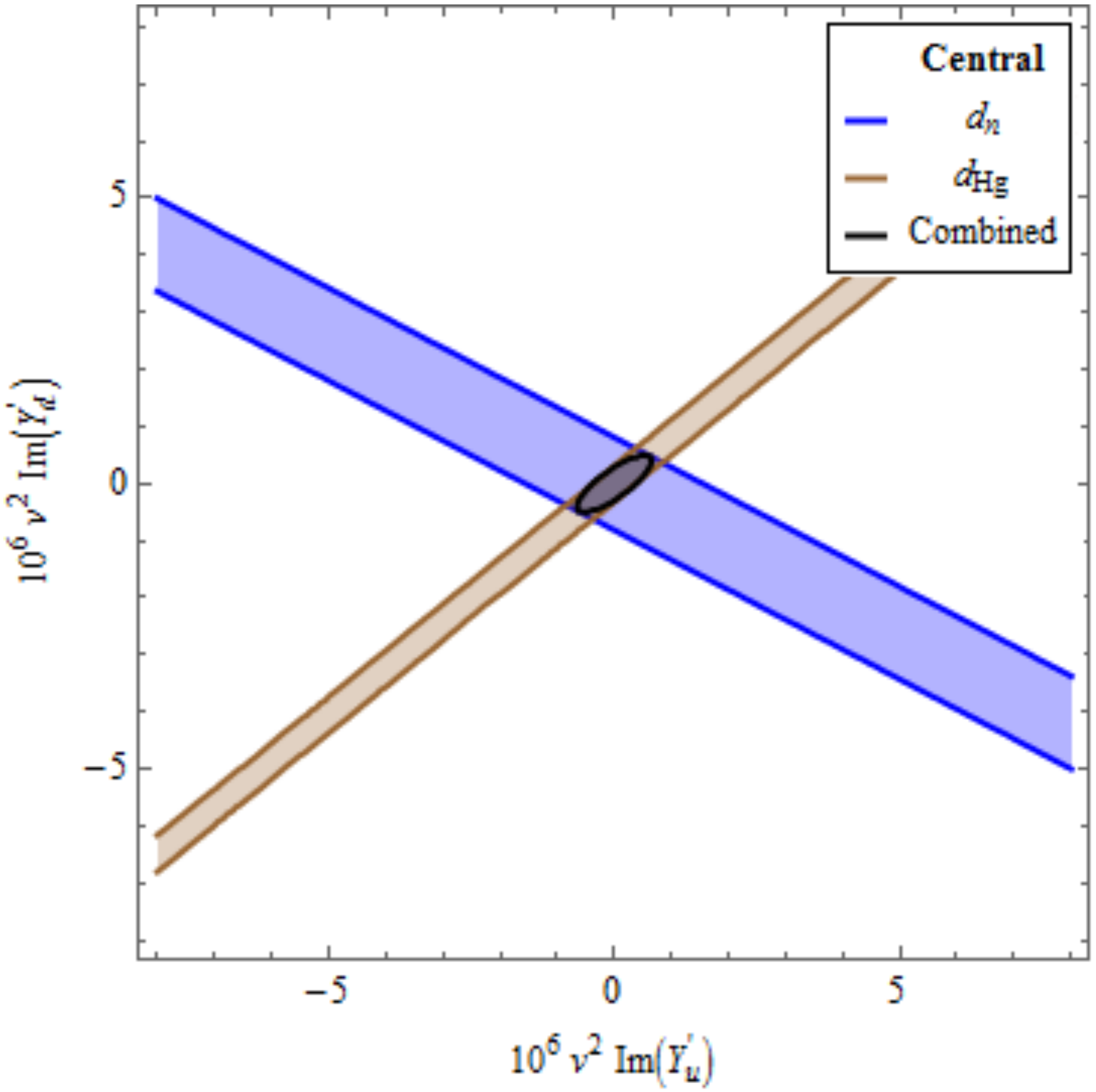
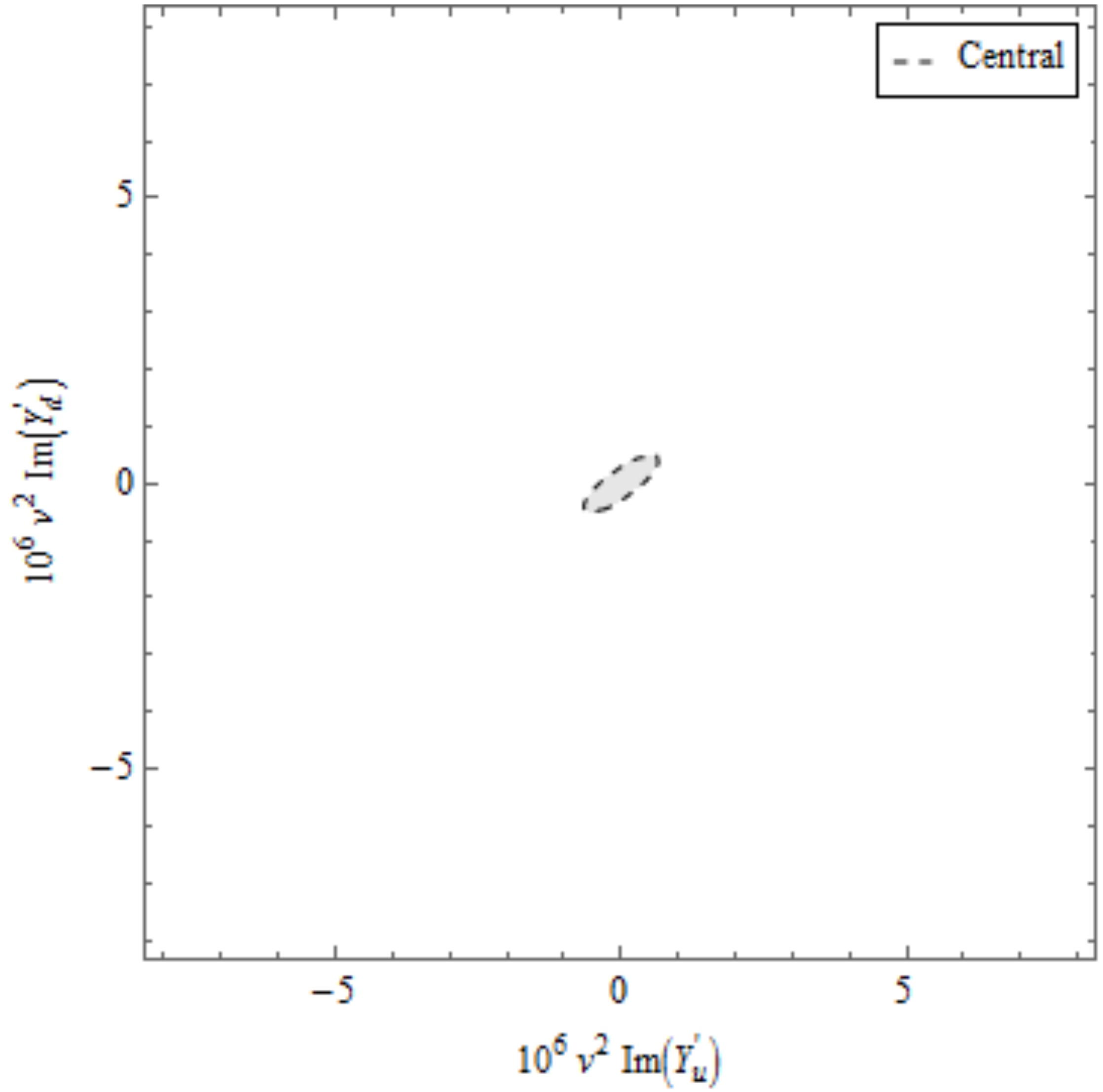


Minimized

Two-coupling analysis





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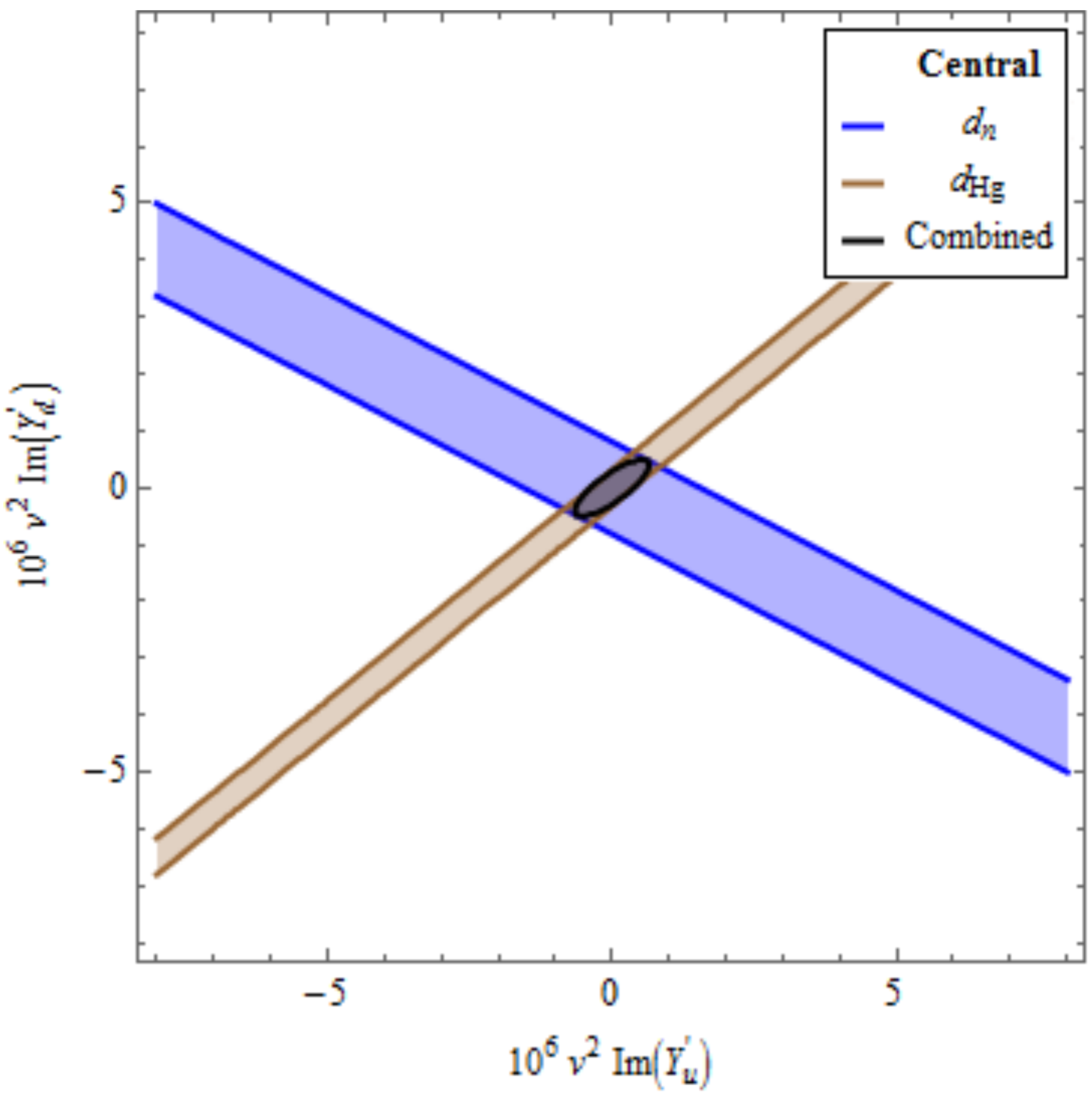
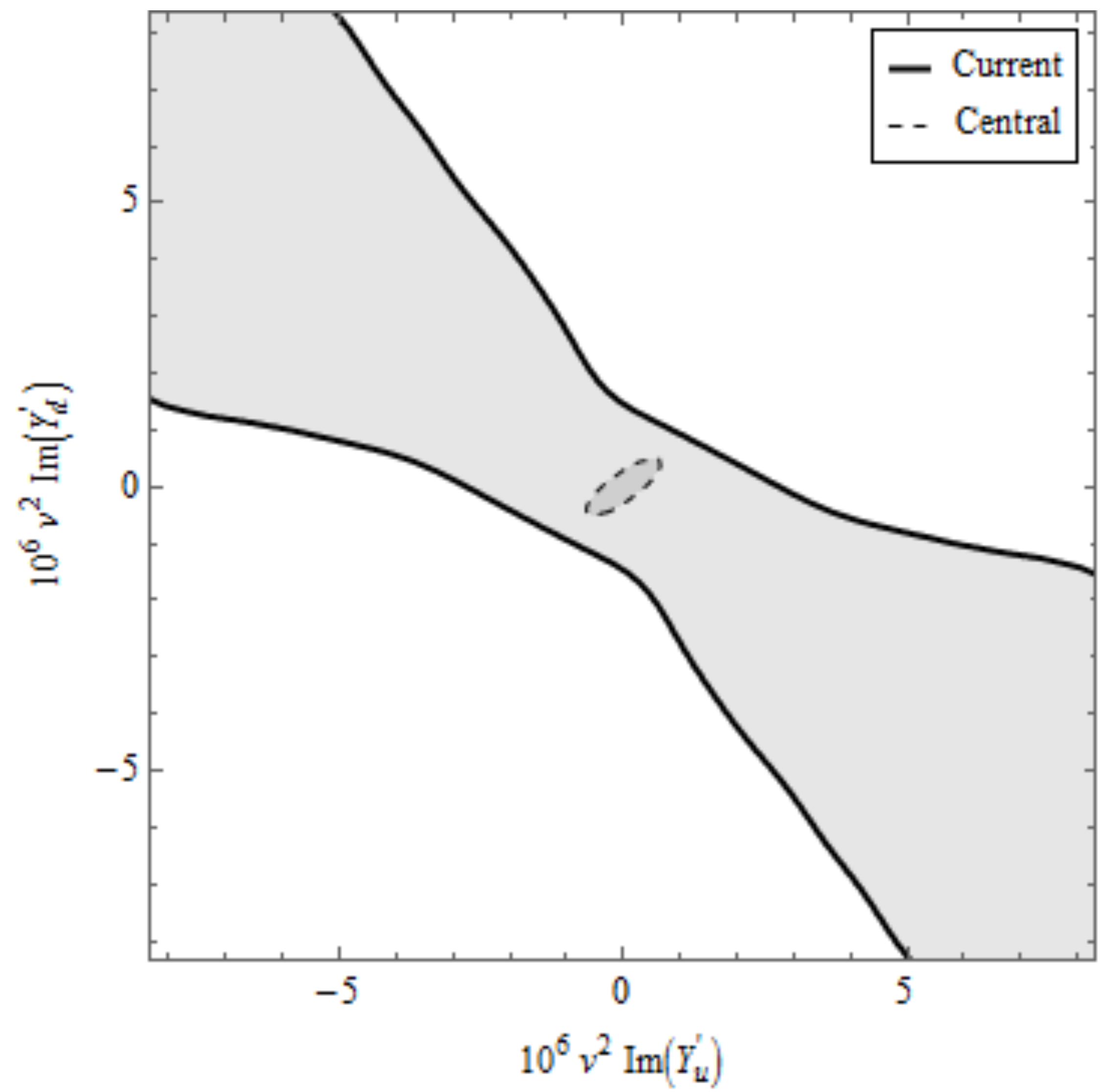


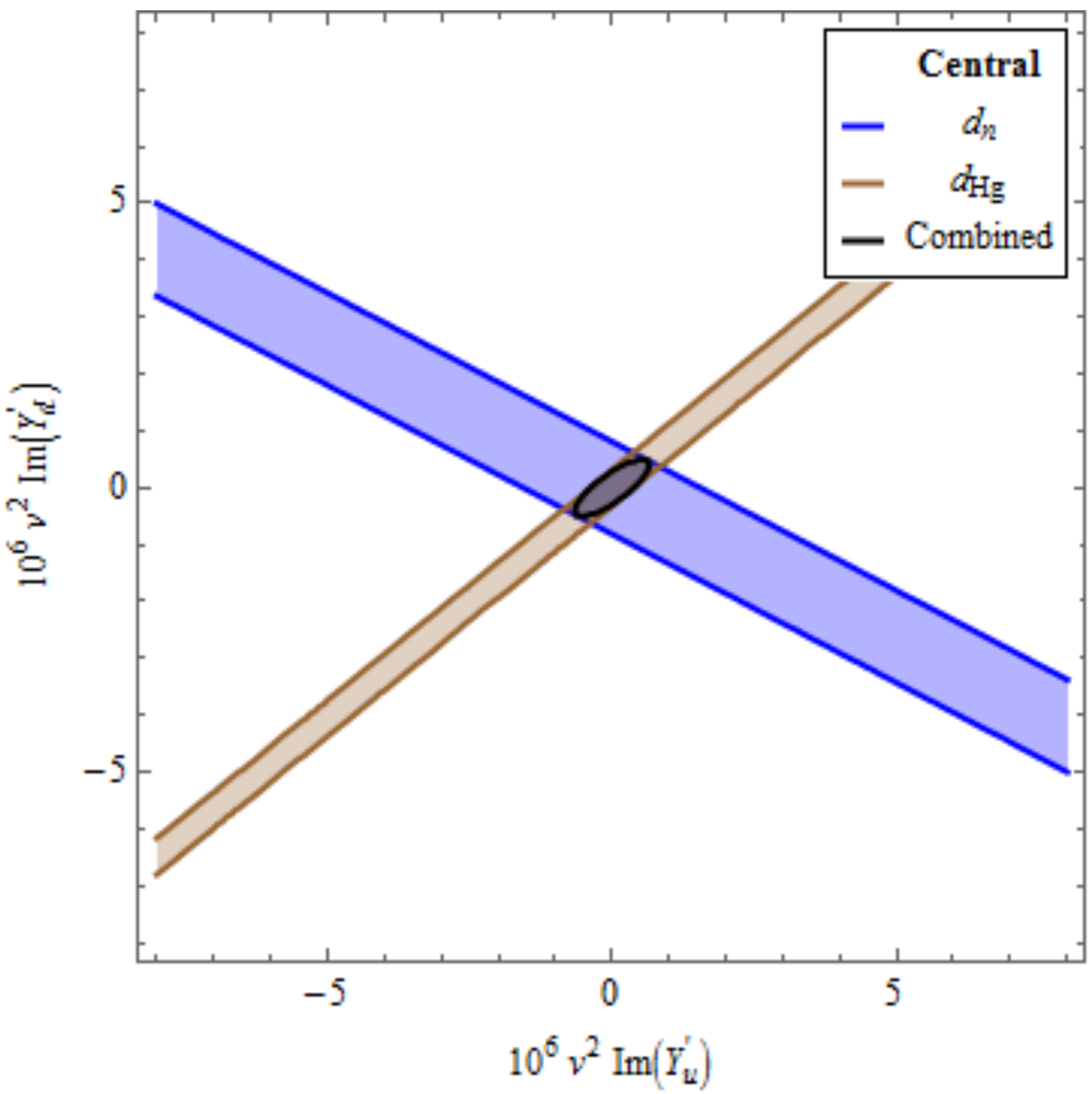
Central Case



Minimized

- The Minimized procedure weakens the bounds

Two-coupling analysis



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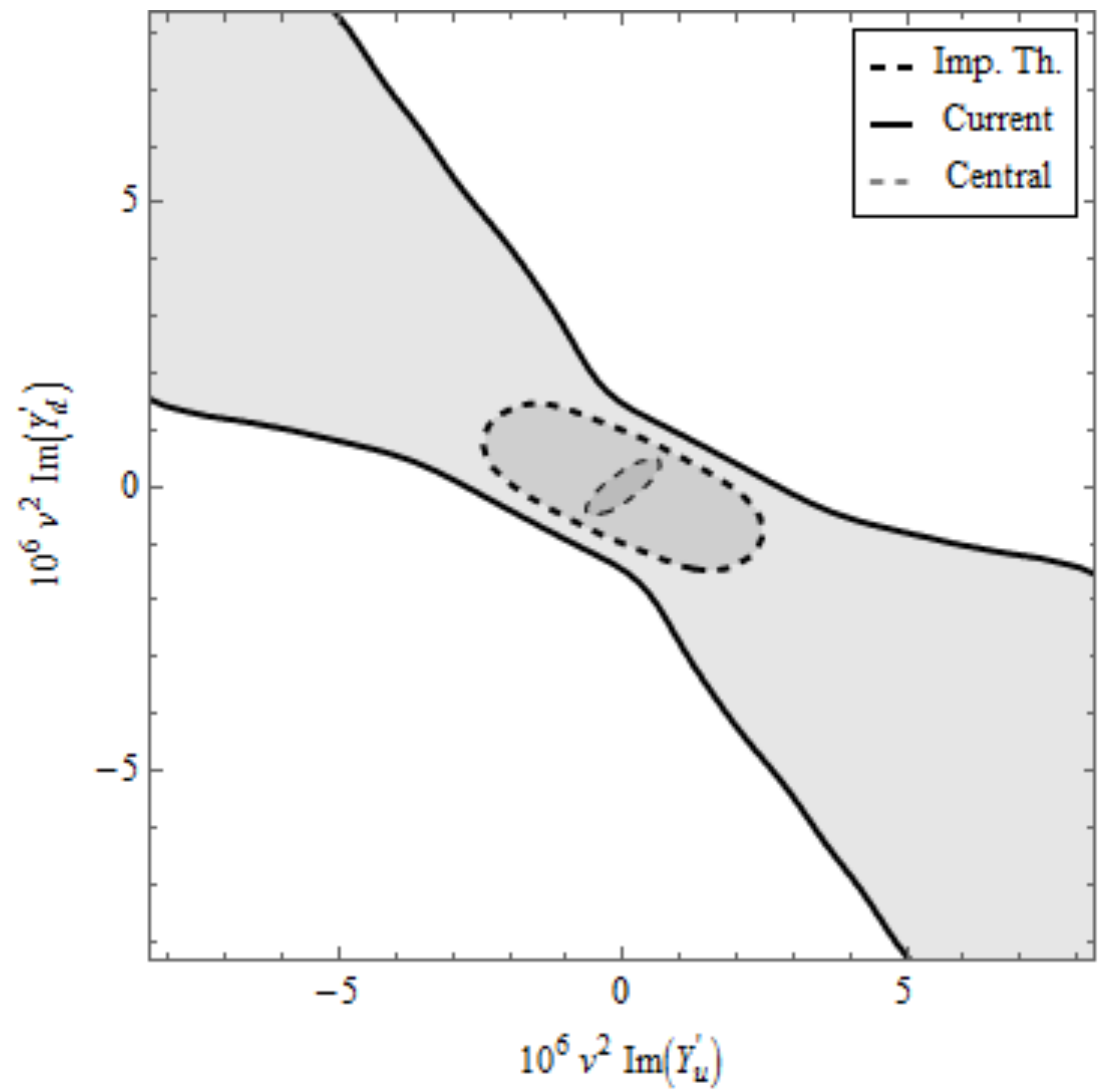
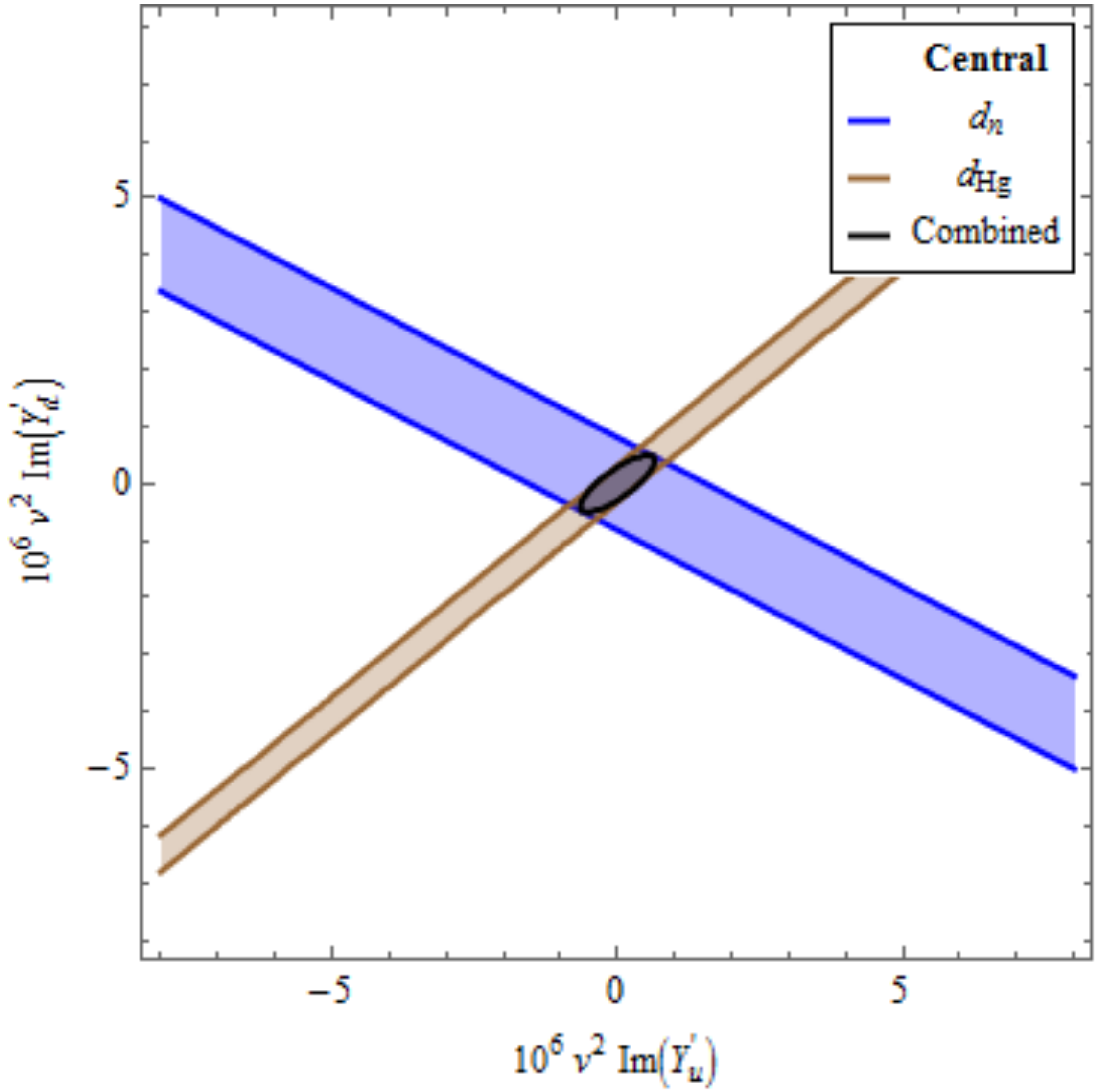


Improved Theory

- Improved theory again gets close to the Central Case

Two-coupling analysis



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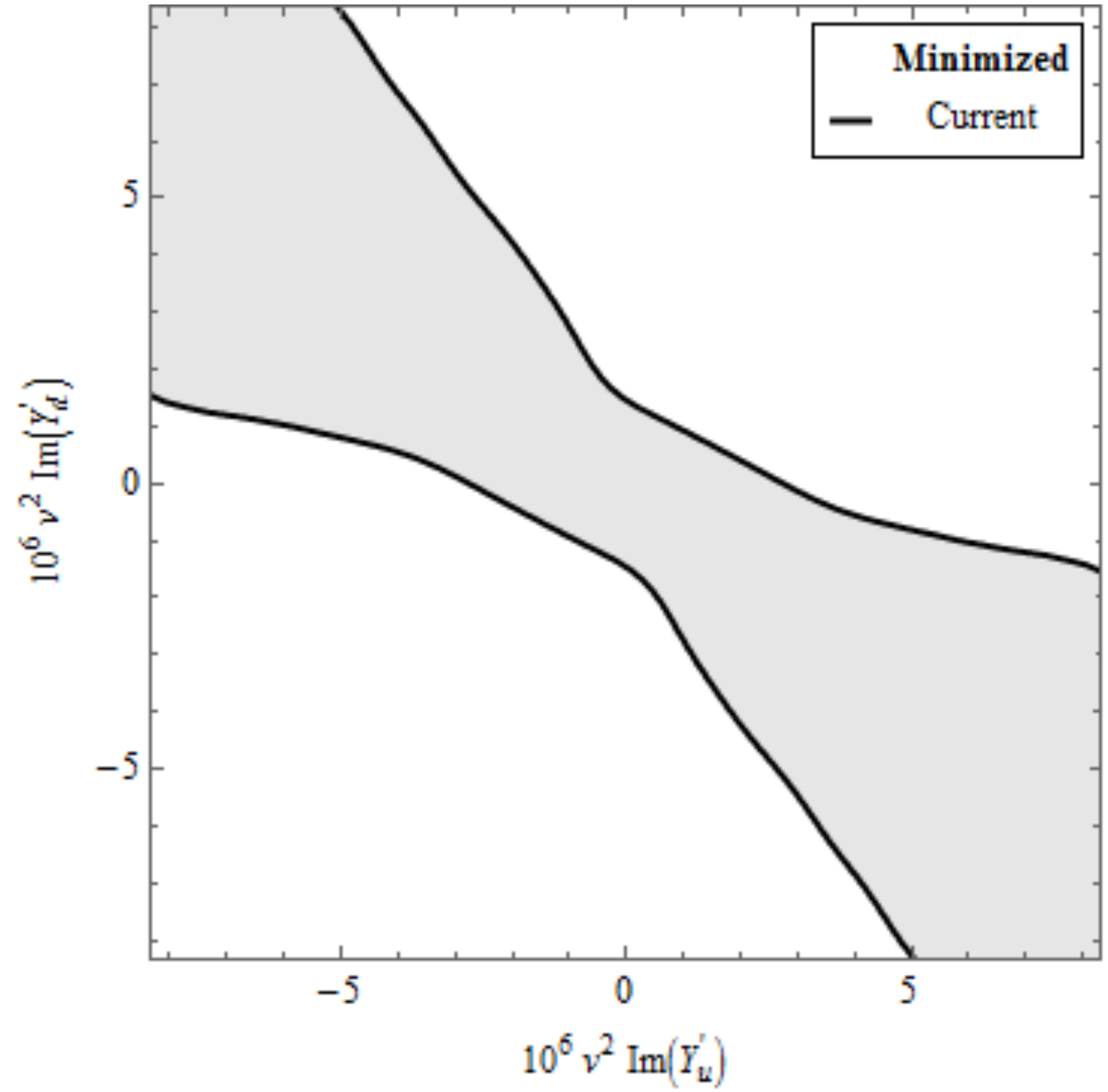
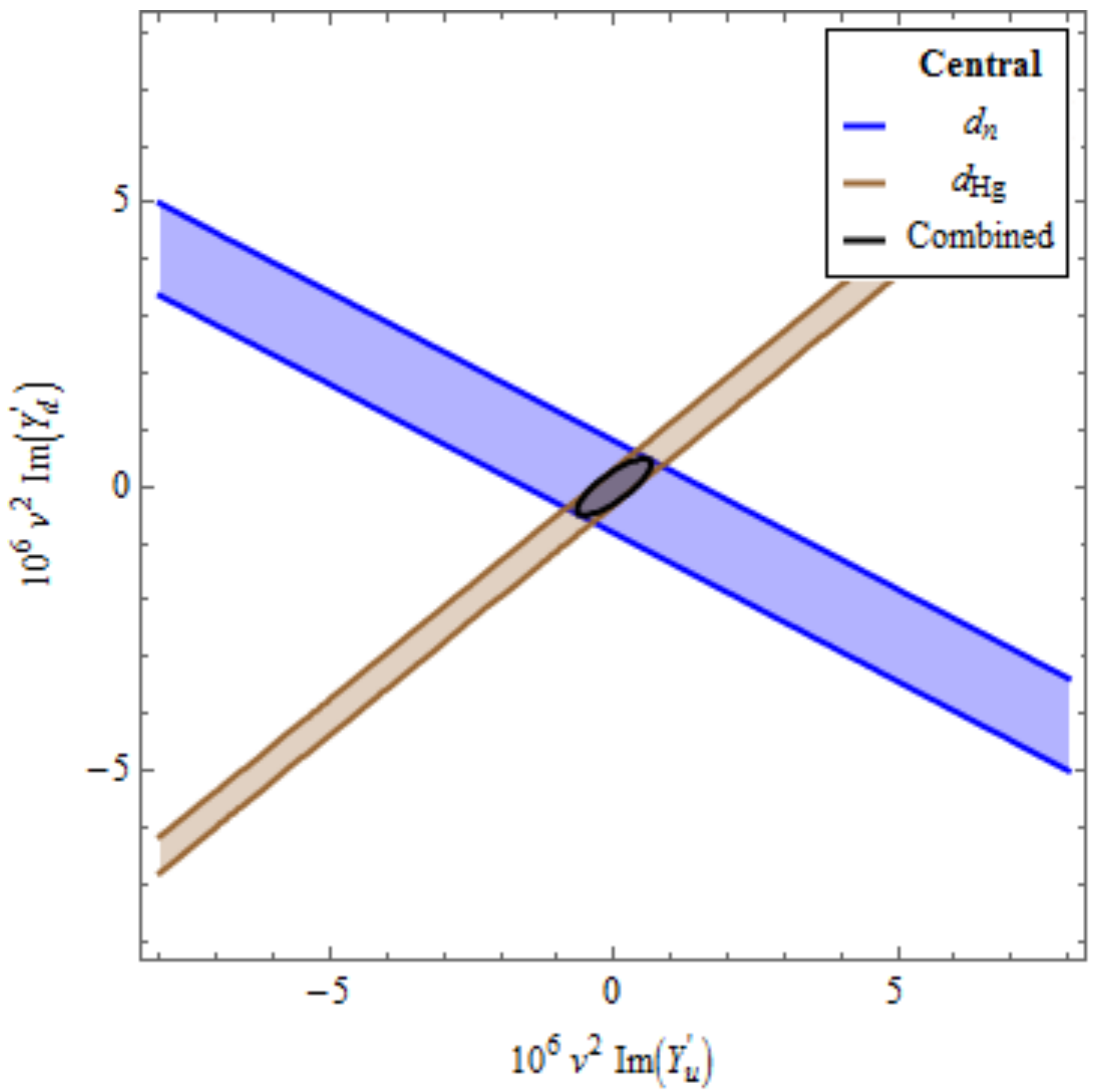


New measurements

- Other possible improvements; new EDM measurements

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

Two-coupling analysis



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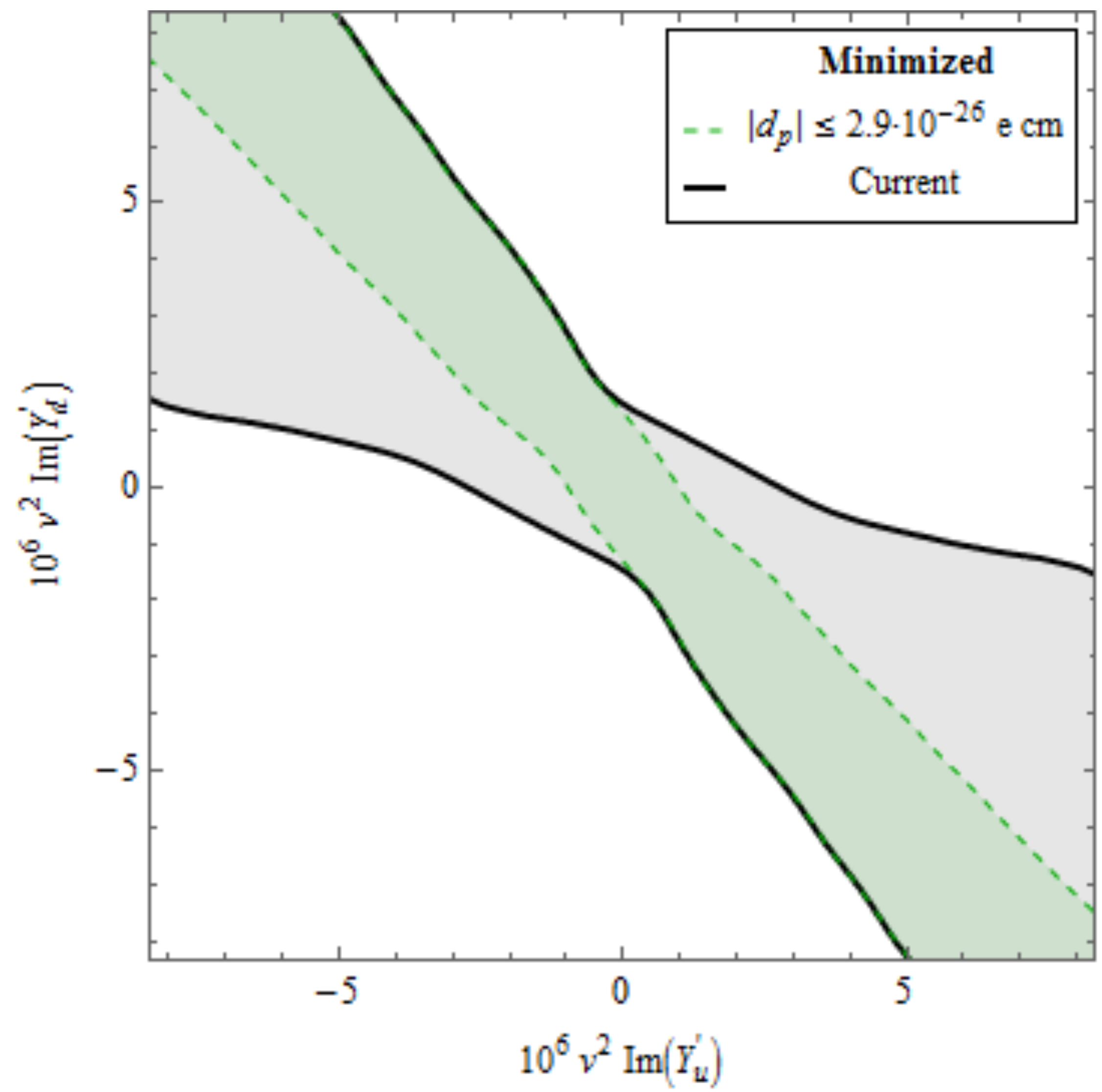

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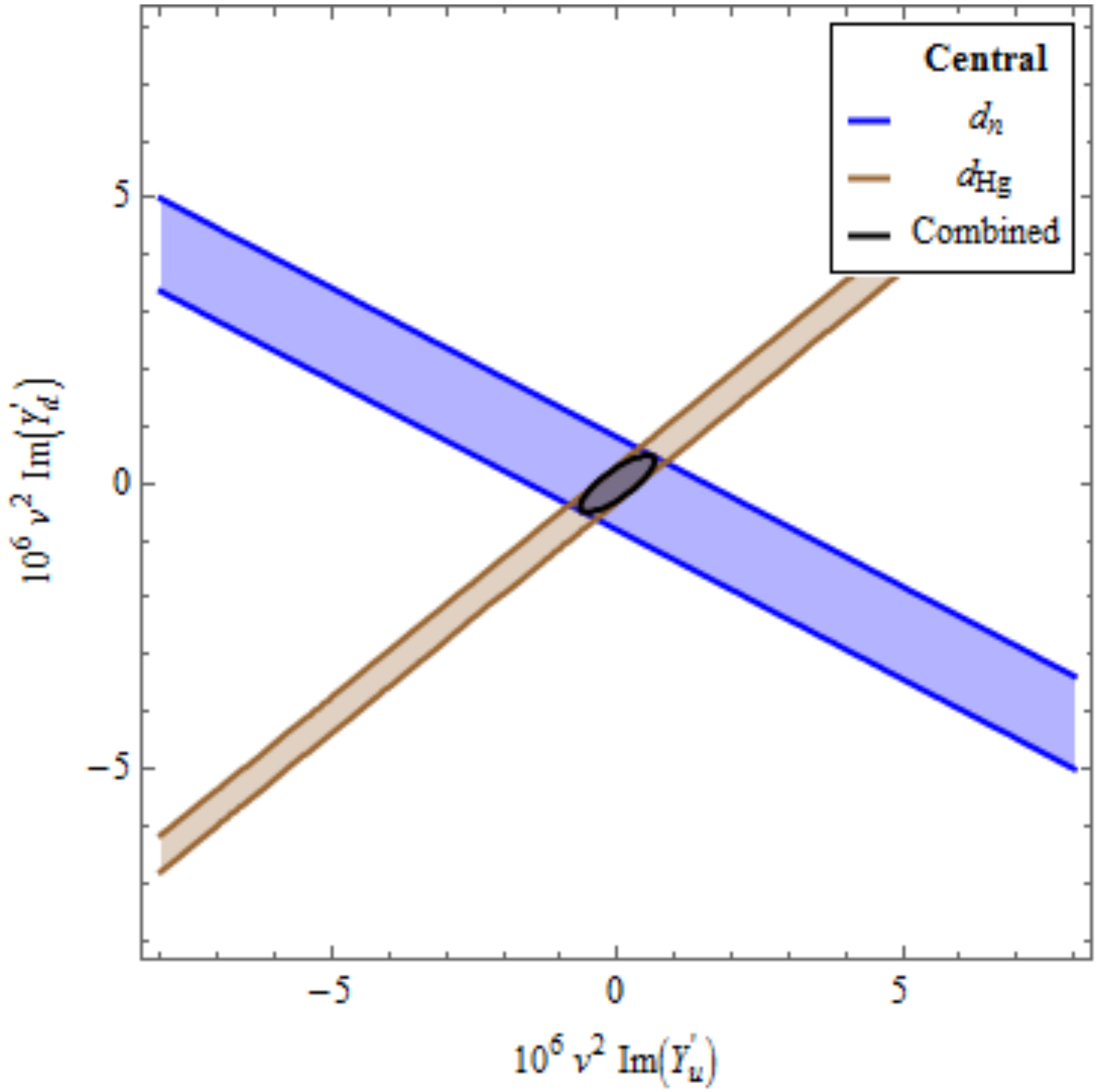

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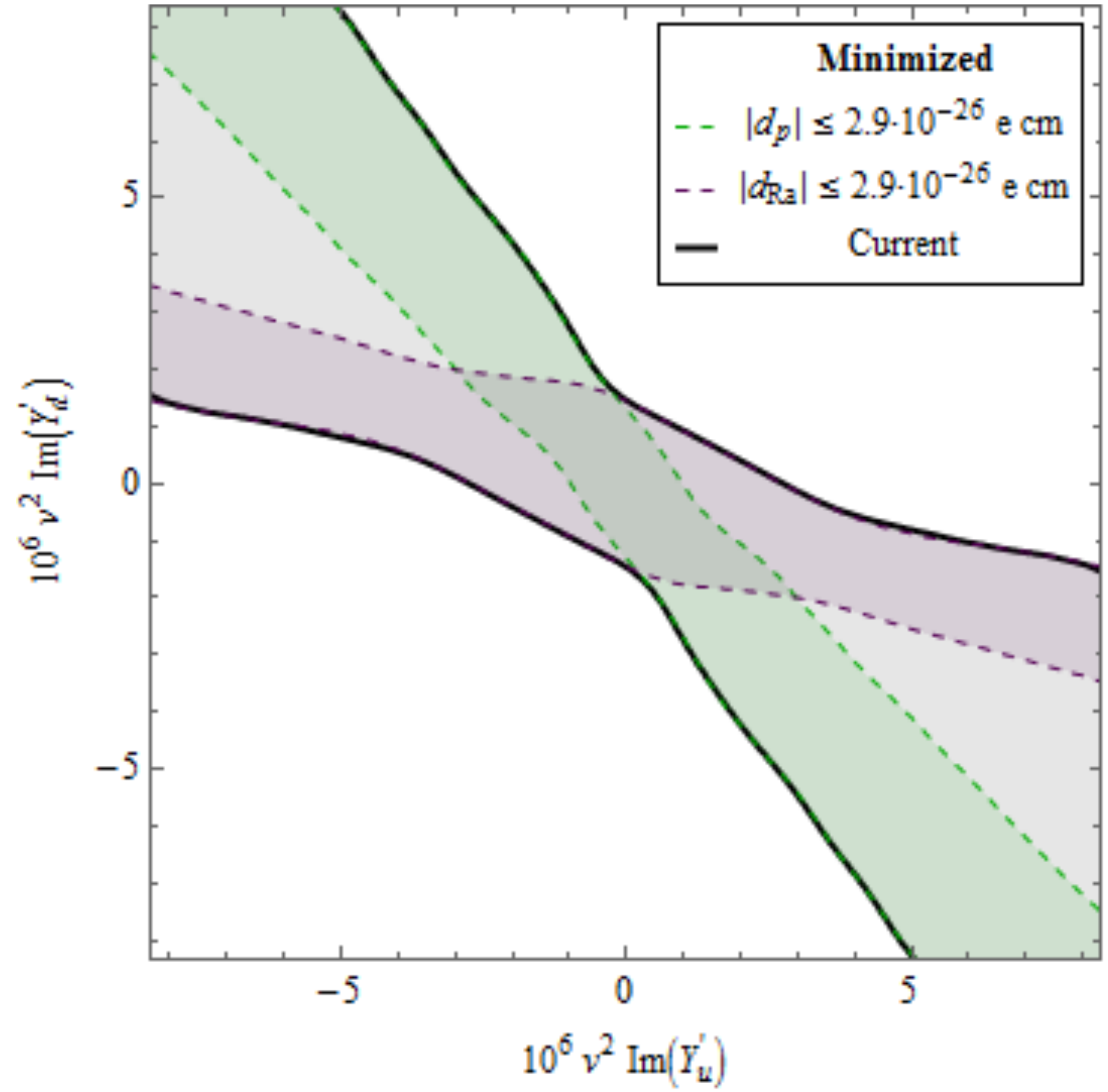

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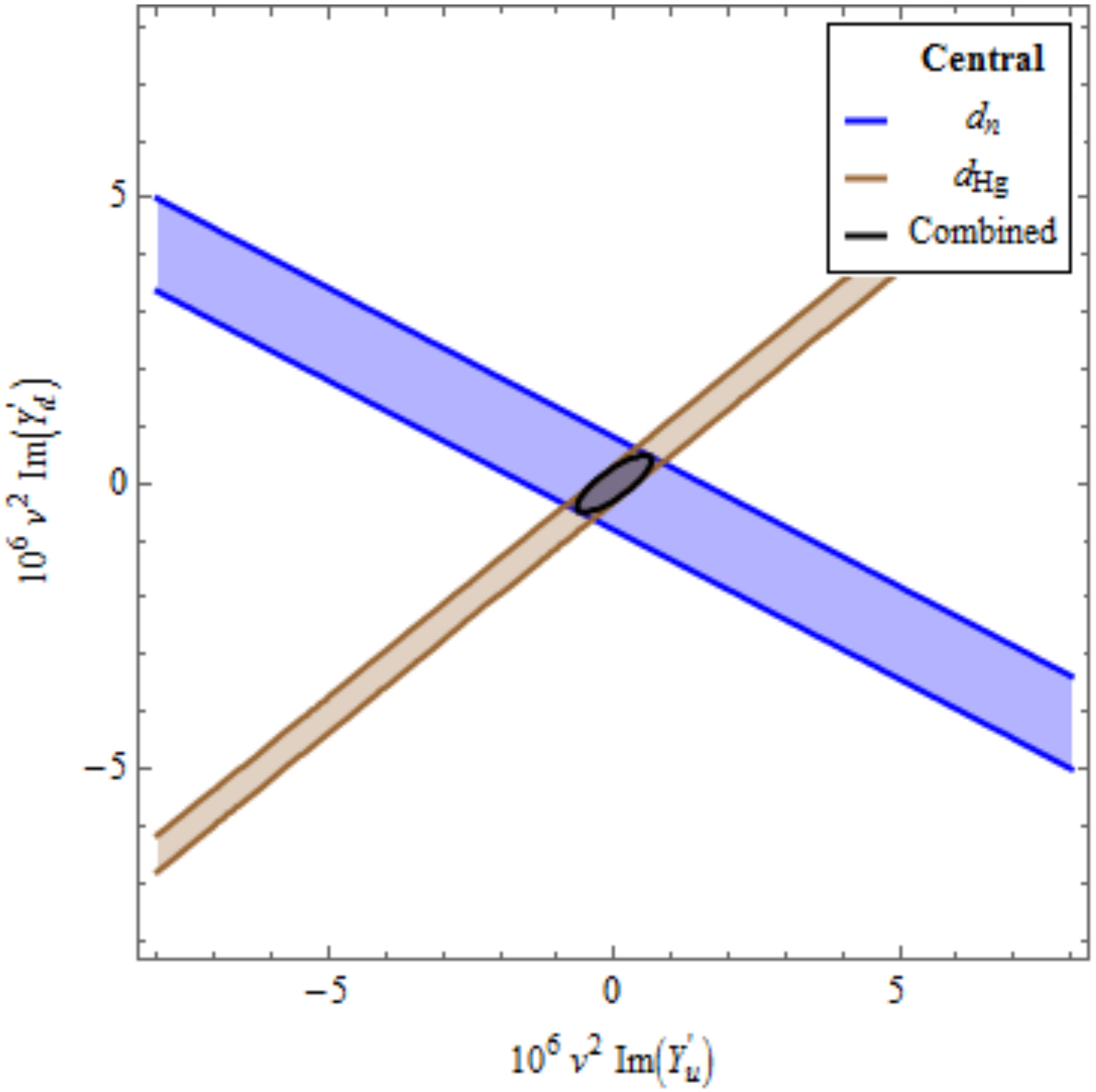

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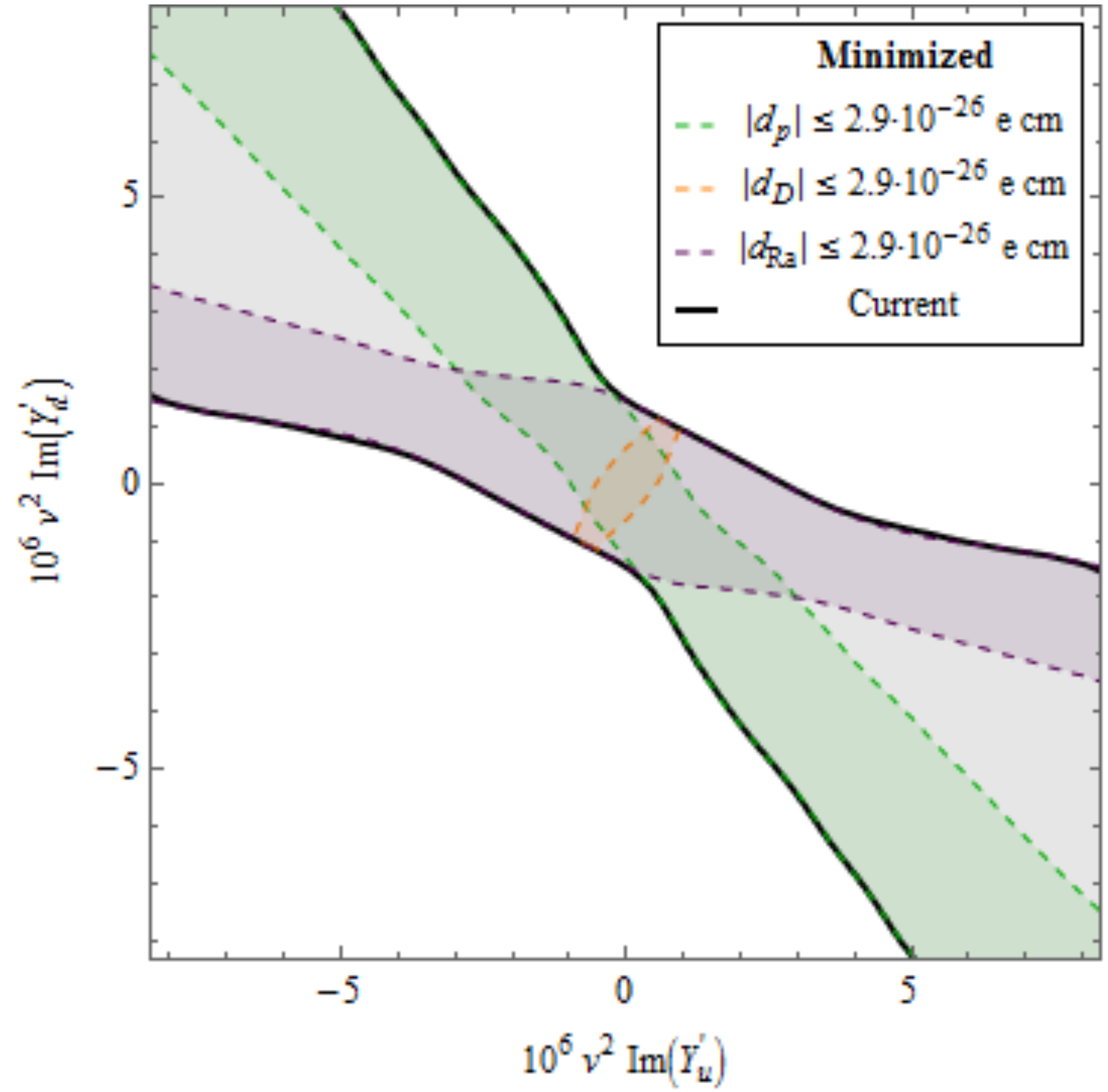

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