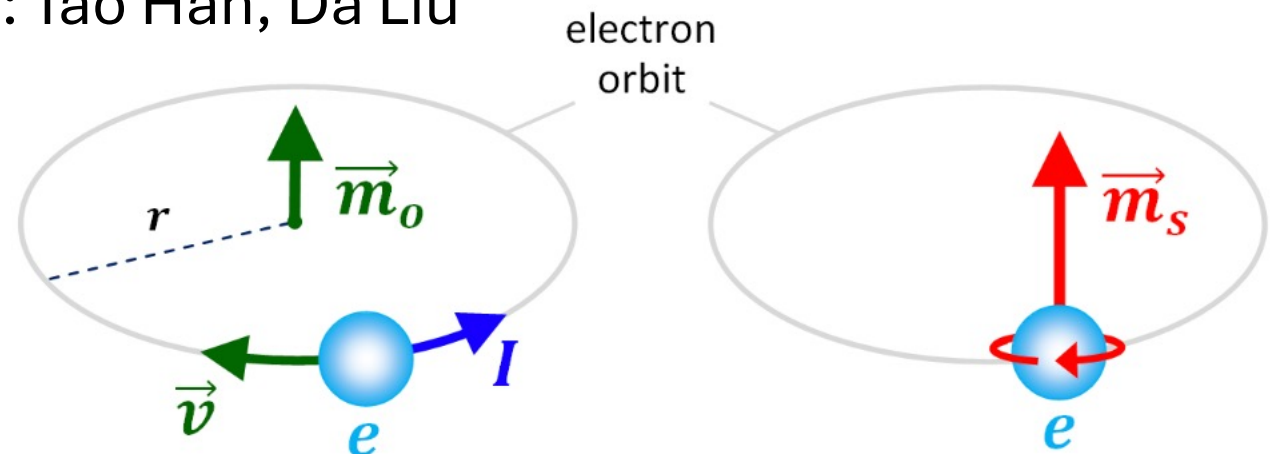
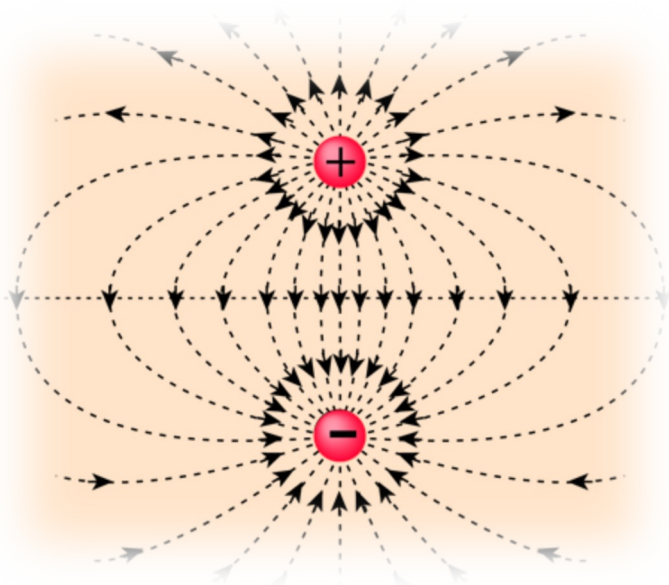


Dipole operator in SMEFT

Si Wang
siw34@pitt.edu
University of Pittsburgh

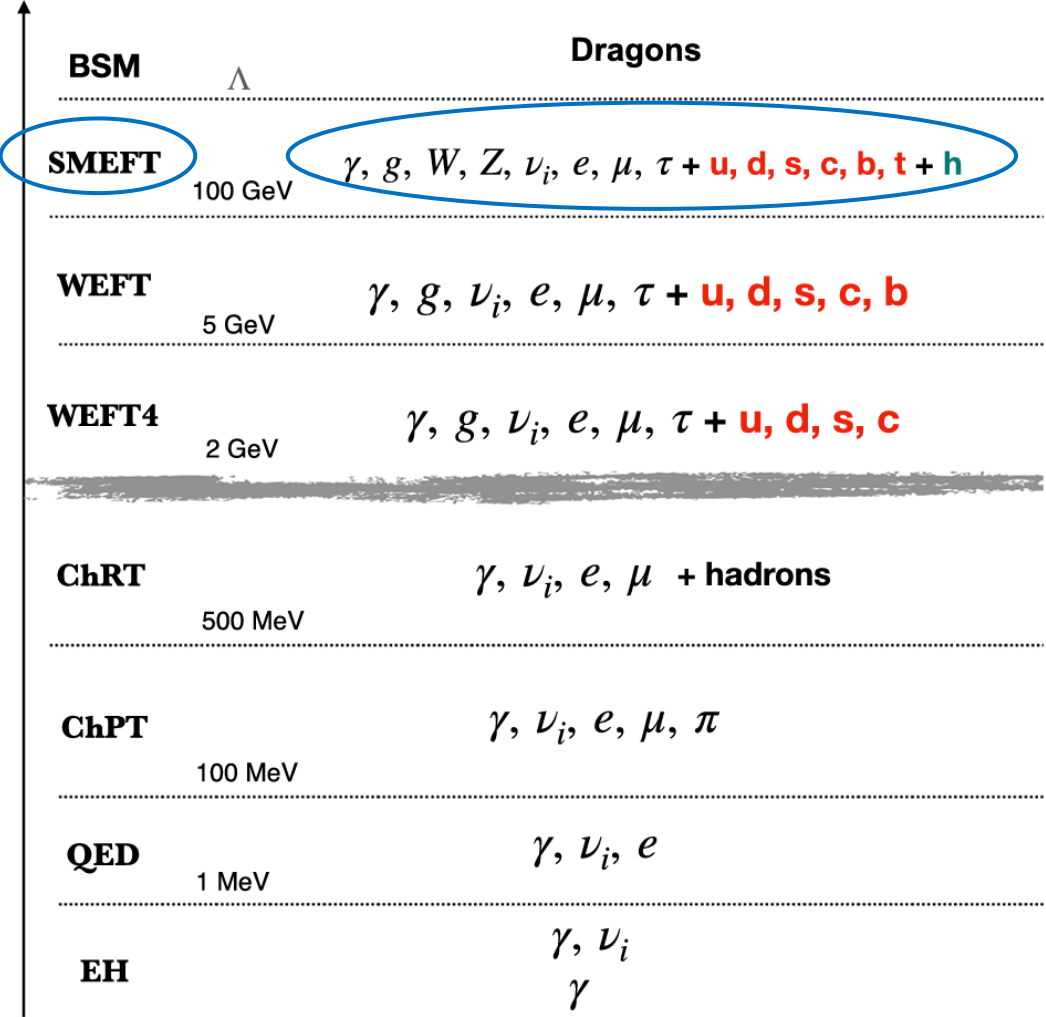
DPF-Pheno 2024
May 13, 2024

Collaborators: Tao Han, Da Liu



By S.Zurek

Standard Model Effective Field Theory (SMEFT)



$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

[Lectures on SMEFT, Adam Falkowski(2023)]

Wilson Coefficients

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i + \dots$$

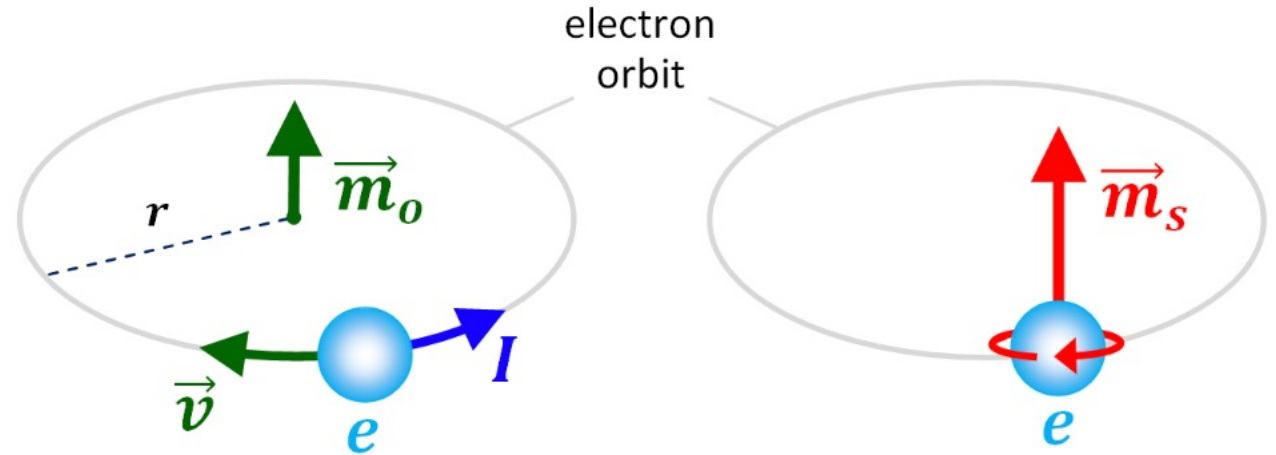
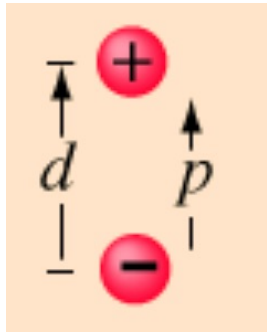
$$\mathcal{O}_{uB} = y_u g' \bar{Q}_L \sigma^{\mu\nu} u_R \tilde{H} B_{\mu\nu}$$

$$\mathcal{O}_{uW} = y_u g \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \tilde{H} W_{\mu\nu}^a$$

$$C_{u\gamma} = c_w C_{uB} - s_w C_{uW}$$

$$C_{uZ} = s_w C_{uB} + c_w C_{uW}$$

Dipole Moment



Electric Dipole Moment:

$$\vec{p} = q\vec{d}$$

$$d_t$$

Magnetic dipole moment:

$$\vec{m}_o = IA\vec{a}$$

$$\vec{m}_s = \frac{q}{mc}\vec{S}$$

$$a_t$$

By S.Zurek

Dipole Moment in QFT

$$\mathcal{L} = \frac{C_{tB}}{\Lambda^2} \bar{t}_L \sigma^{\mu\nu} t_R H B_{\mu\nu} + \frac{C_{tW}}{\Lambda^2} t_L \sigma^{\mu\nu} \sigma^a t_R H W_{\mu\nu}^a$$

$$C_{u\gamma} = c_w C_{uB} - s_w C_{uW}$$

$$C_{uZ} = s_w C_{uB} + c_w C_{uW}$$

$$\mathcal{L} = \frac{1}{2} \bar{t}_L \sigma^{\mu\nu} \left(a_t \frac{Q_t}{2m_t} - i d_t \gamma_5 \right) t_R F_{\mu\nu}$$

Dipole moments: a_t d_t

$$\mathcal{L}_{t\bar{t}\gamma} = e \bar{t} \left(Q_t \gamma_\mu A^\mu + \frac{1}{4m_t} \sigma_{\mu\nu} F^{\mu\nu} (a_V + i a_A \gamma_5) \right) t$$

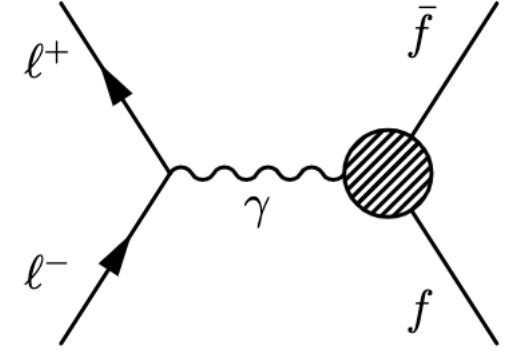
$$a_V = -\frac{2\sqrt{2}}{e} \frac{vm_t}{\Lambda^2} \text{Re}[C_{t\gamma}]$$

$$a_A = -\frac{2\sqrt{2}}{e} \frac{vm_t}{\Lambda^2} \text{Im}[C_{t\gamma}]$$

Dipole Moments of Tau

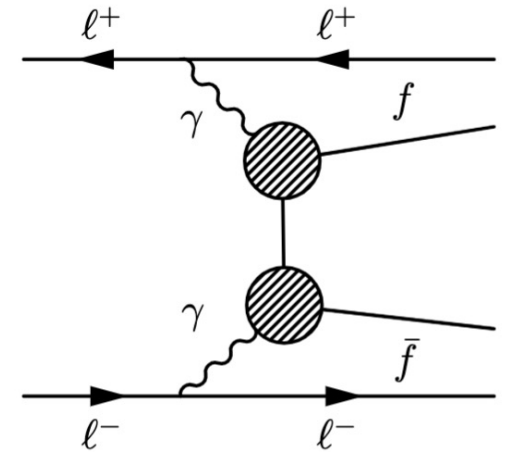
particle	Original Results		Process	Reference
	a_τ	$ d_\tau $ (e cm)		
τ	$[-0.052, 0.058]$ $[-1.8e-3, 1.8e-3]$	$3.1e-16$ (2σ) $1e-17$ (2σ)	$e^+e^- \rightarrow \tau^+\tau^-\gamma$ (LEP Z pole) $pp \rightarrow \tau^+\tau^-$ (LHC Run2)	9803 2307.14133

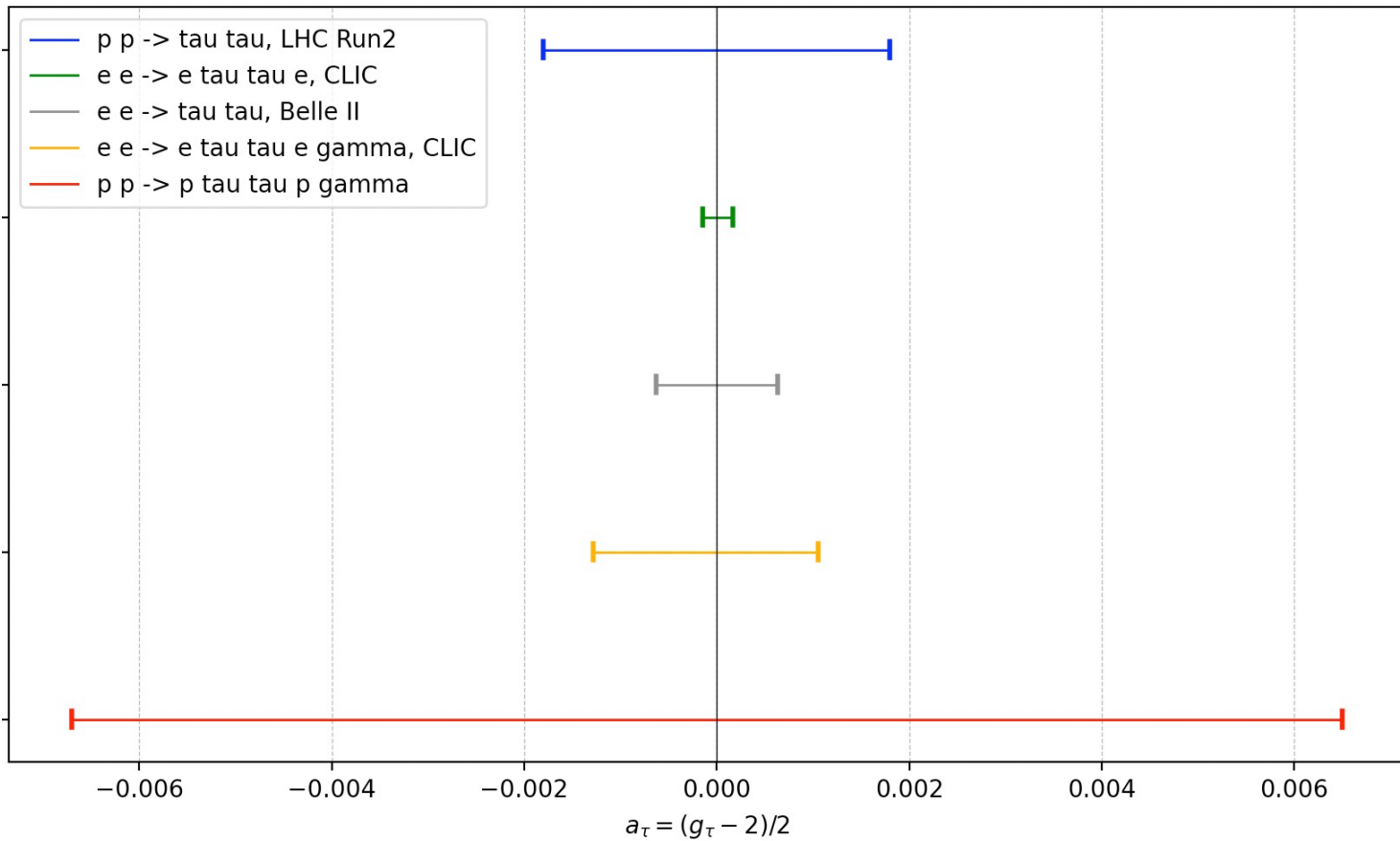
TABLE XIV. Current experiments τ Dipole moments Constraints.



particle	Original Results		Process	Reference
	a_τ	$ d_\tau $ (e cm)		
τ	$[-1.5e-4, 1.7e-4]$	$9.04e-19$ (2σ)	$e^+e^- \rightarrow e^+\tau^+\tau^-e^-$ (CLIC)	1804.02373
	$[-6.3e-4, 6.3e-4]$	$1.7e-17$ (2σ)	$e^+e^- \rightarrow \tau^+\tau^-$ (Belle II)	2401.04449
	$[-1.28e-3, 1.05e-3]$	$6.439e-18$ (2σ)	$e^+e^- \rightarrow e^+\tau^+\tau^- \gamma e^-$ (CLIC)	1903.04135
	$[-2.65e-3, 2.46e-3]$	$1.437e-17$ (2σ)	$e^-p \rightarrow e^-\tau^+\tau^-\gamma p$ ($\gamma\gamma$ fusion)	1903.04135
	$[-6.7e-3, 6.5e-3]$	$3.692e-17$ (2σ)	$pp \rightarrow p \tau^+\tau^-\gamma p$ ($\gamma\gamma$ fusion)	1903.04135
	$[-2.42e-3, 7.1e-4]$	$7.31e-18$ (2σ)	$\mu^+\mu^- \rightarrow \mu^+ \tau^+\tau^- \mu^-$ ($\gamma^*\gamma^*$ fusion)	1811.01188
	$[-4.6e-3, 8.3e-3]$	$1.2e-16$ (1σ)	$pb pb \rightarrow pb \tau^+\tau^- pb$ ($\gamma\gamma$ fusion)	1908.05180

TABLE XV. Future experiments τ Dipole moments Constraints.





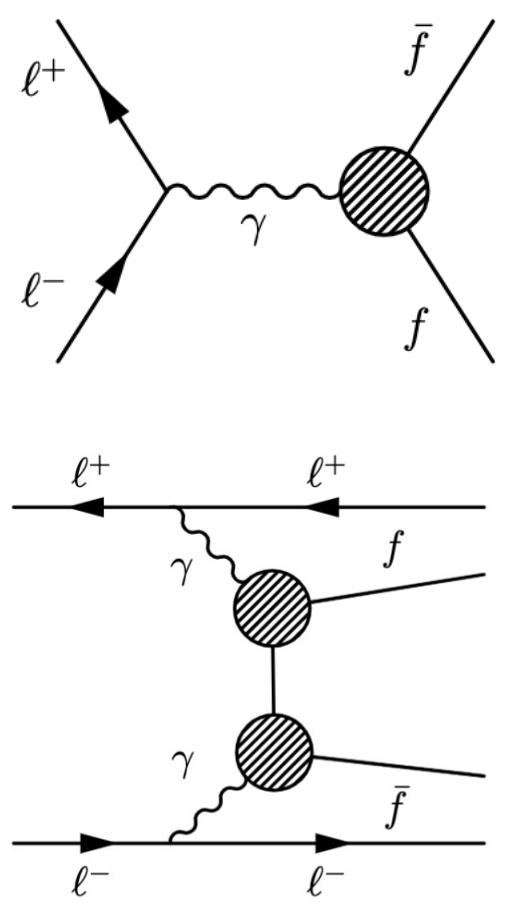
$$\sigma = |\mathcal{M}_{SM}|^2 + \boxed{2|\mathcal{M}_{SM}\mathcal{M}_{NP}|} + |\mathcal{M}_{NP}|^2$$

Cross section Inteferece term \longrightarrow 0

$$\mathcal{O}_{uB} = y_u g' \bar{Q}_L \sigma^{\mu\nu} u_R \tilde{H} B_{\mu\nu}$$

$$\mathcal{O}_{uW} = y_u g \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \tilde{H} W_{\mu\nu}^a$$

New Physics:
helicity the same



SM:
helicity flip

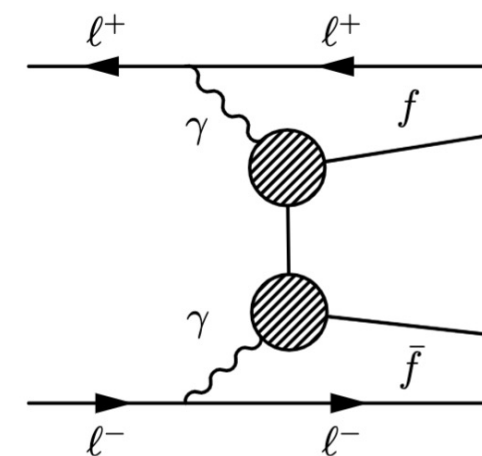
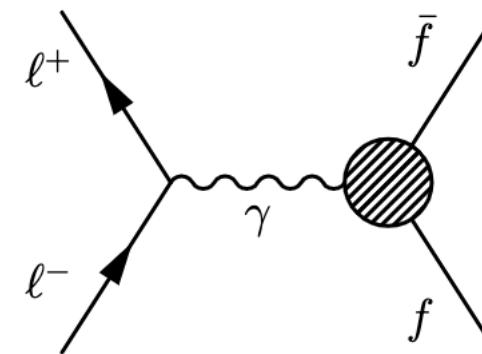
Dipole Moments of Top

particle	Original Results		Process	Reference
	a_V	$ a_A $		
top	$\frac{C_{tB}}{\Lambda^2} = [-4.5, 1.2]$	$\frac{C_{tW}}{\Lambda^2} = [-0.12, 0.51] (2\sigma)$	LEP, LHC Run2 global fitting	2012.02779
	$[-0.098, 0.023]$	$\frac{C_{tB}}{\Lambda^2} = 0(2\sigma)$	Transferred from Wilson Coefficient	2012.02779
	$[-0.035, 0.038]$	$[-0.17, 0.16](1\sigma)$	LHC 300 fb^{-1} , $gg \rightarrow t\bar{t}$ production	hep-ph/0601112
	$[-0.5, 1.5]$	$[-2, 0.3](1\sigma)$	Tevatron $t\bar{t}\gamma$ production	1212.6575

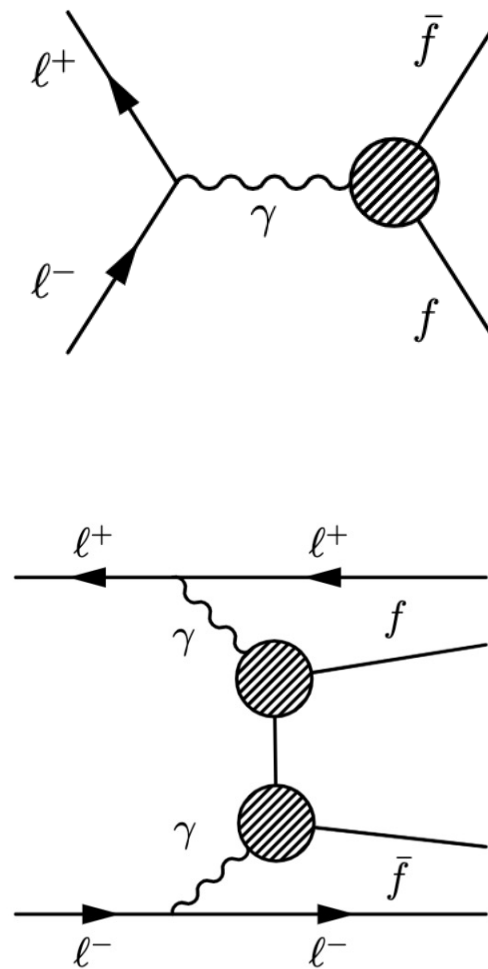
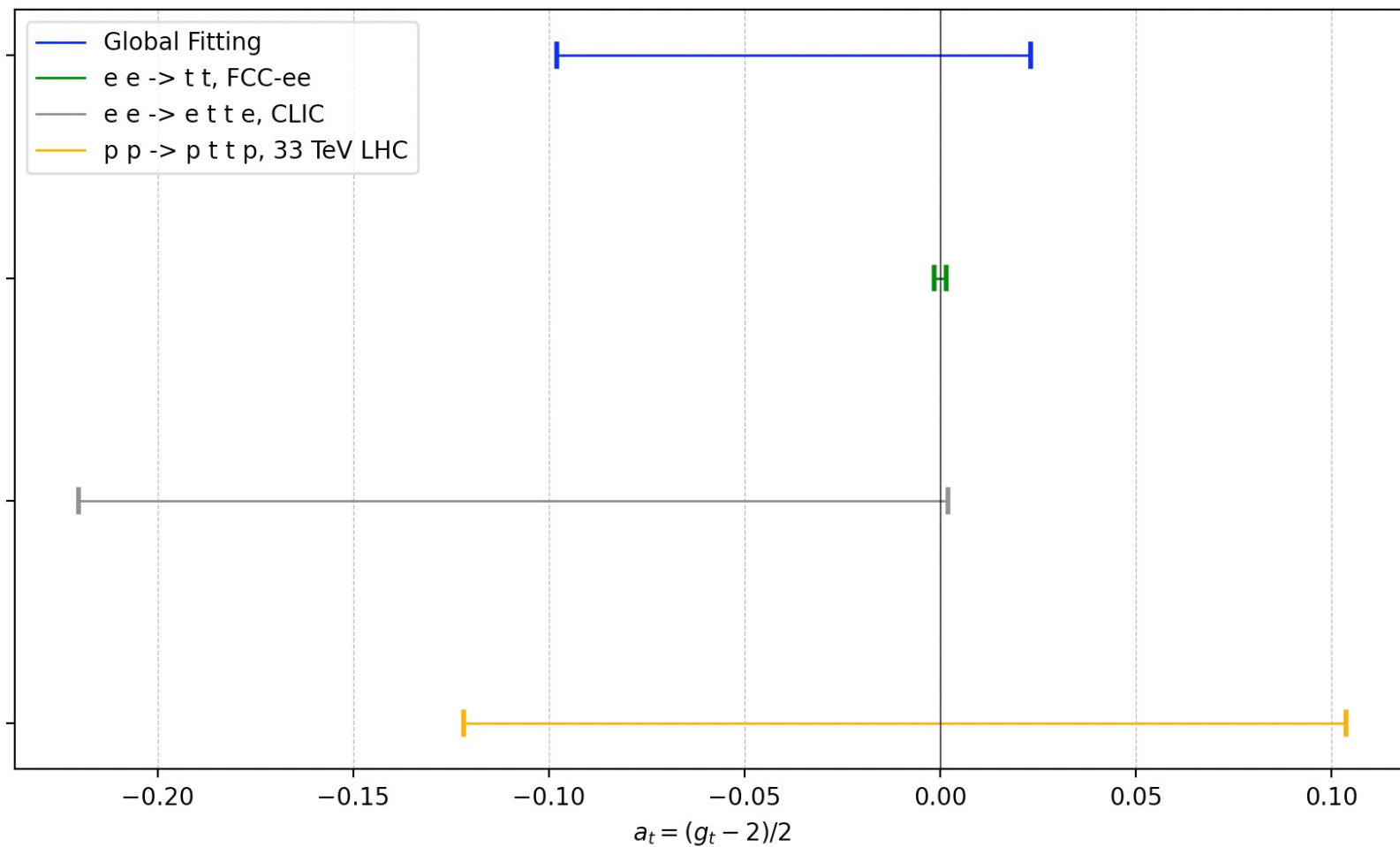
TABLE XVI. Current top Dipole moments Constraints.

particle	Original Results		Process	Reference
	a_V	$ a_A $		
top	$[-8.1e-4, 8.1e-4]$	$0.14 (1\sigma)$	$e^+e^- \rightarrow t\bar{t}$ production at the FCC-ee	1503.01325
	$[-0.001, 0.001]$	$- (1\sigma)$	$e^+e^- \rightarrow t\bar{t}$ production at the ILC	1307.8102
	$[-0.0234, 0.0325]$	$0.0277 (2\sigma)$	$\gamma e^- \rightarrow t\bar{b}\nu_e$ (single top at CLIC)	1602.05991
	$[-0.2203, 0.0020]$	$0.0206 (2\sigma)$	$e^+e^- \rightarrow e^+t\bar{t}e^-$ (CLIC, $\gamma\gamma$ fusion best)	1702.03708
	$[-0.1218, 0.1036]$	$0.0815 (1\sigma)$	$pp \rightarrow pt\bar{t}p$ ($\gamma\gamma$ fusion) (33 TeV LHC)	1504.06695

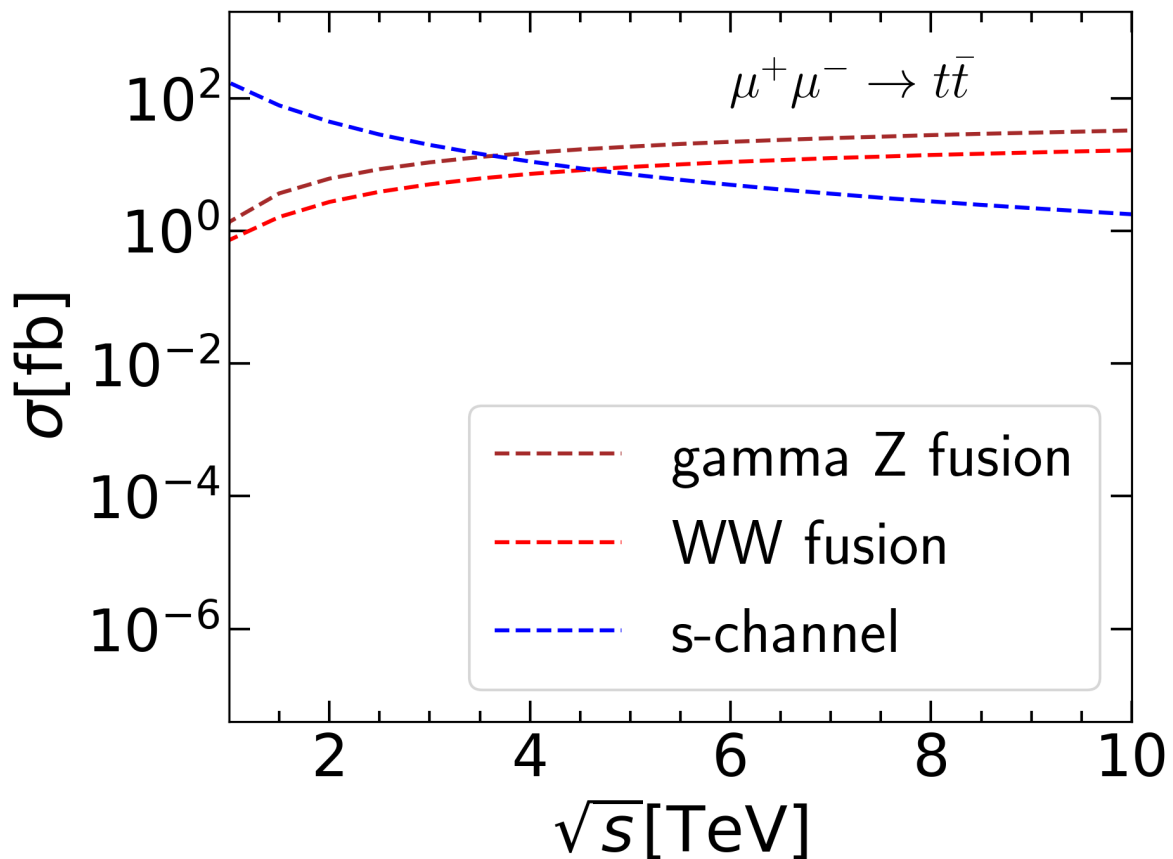
TABLE XVII. Future top Dipole moments Constraints.



Dipole Moment of Top



Cross Section

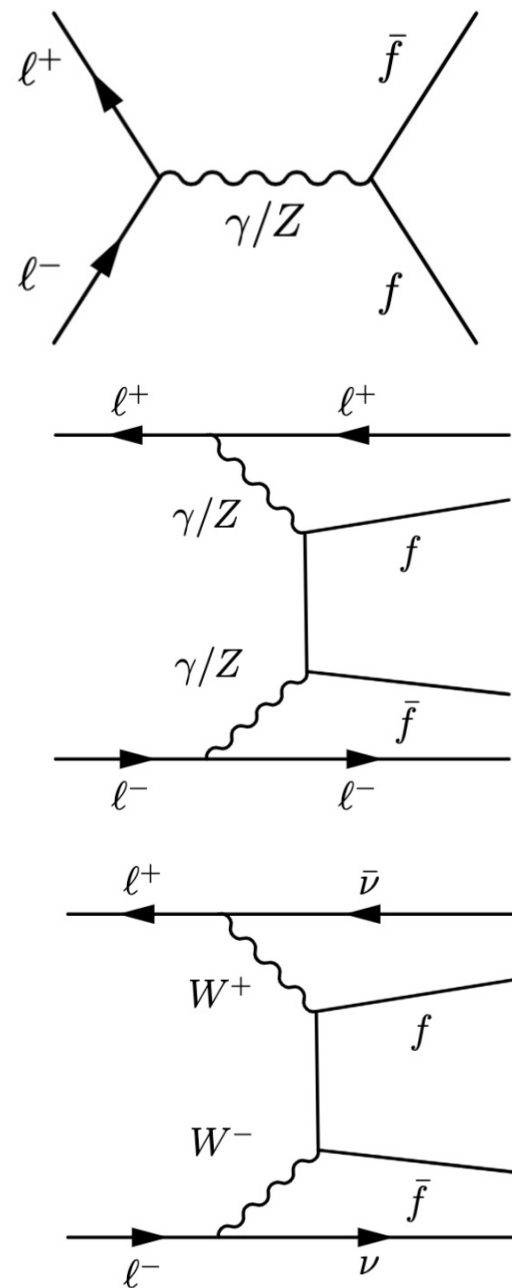


$$\mu^+ \mu^- \rightarrow \mu^+ \mu^- t\bar{t}$$

$$M_{\ell\ell} > 150\text{GeV}$$

$$\mu^+ \mu^- \rightarrow \nu\bar{\nu} t\bar{t}$$

No other Lepton cuts



Sensitivity

$$C_{tB} = 1 \quad \Lambda = 10 \text{ TeV}$$

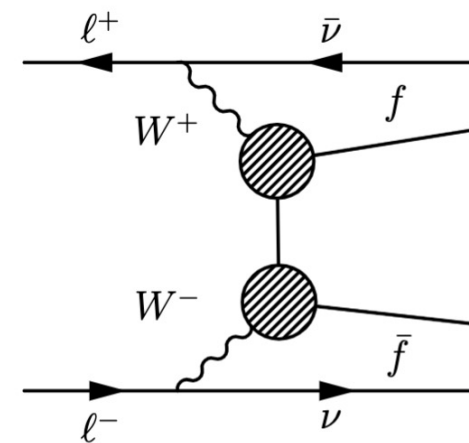
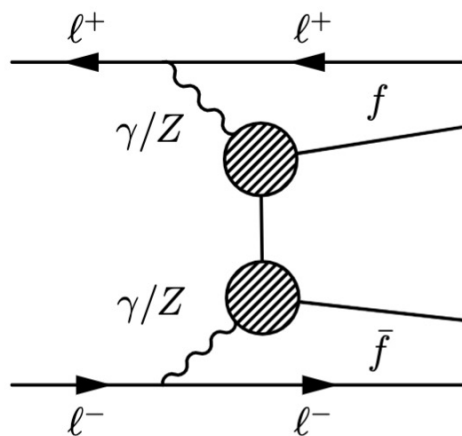
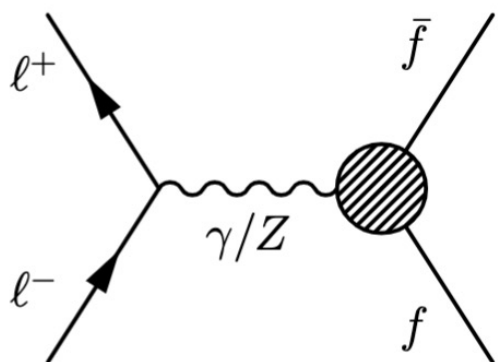
[pb]	$\mu^+\mu^- \rightarrow tt$			$\mu^+\mu^- \rightarrow \mu^+\mu^-tt \ \& \ \mu^+\mu^- \rightarrow \nu\bar{\nu}tt$		
\sqrt{s}	1 TeV	3 TeV	10 TeV	1 TeV	3 TeV	10 TeV
SM	0.172	1.95e-2	1.74e-3	2.08e-3	1.56e-2	3.70e-2
NP=1	0.174	1.97e-2	1.78e-3	2.10e-3	1.57e-2	3.73e-2
S/\sqrt{B}	4.82	1.43	3.03	0.439	0.801	4.93

Luminosity:

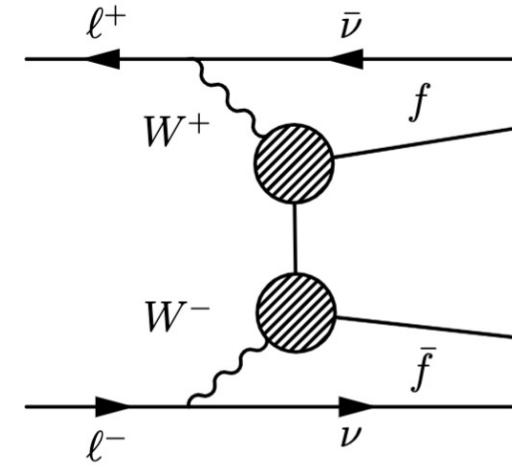
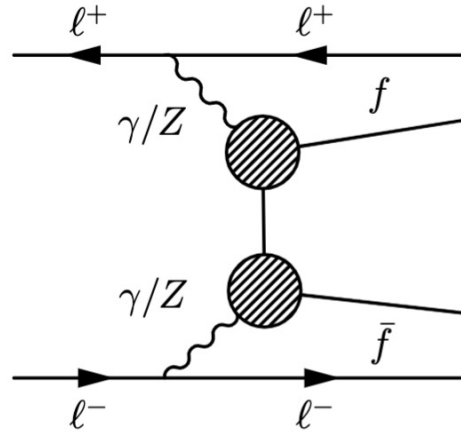
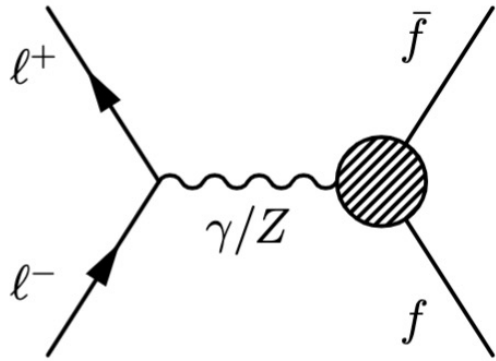
$$1, 3\text{TeV} : 10^3 \text{ fb}^{-1}$$

$$10\text{TeV} : 10^4 \text{ fb}^{-1}$$

$$|\eta_t| < 2.44 \quad M_{\ell\ell} > 150\text{GeV}$$



Summary



At low energy, s-channel has better sensitivity.

At high energy, fusion process has better sensitivity.

Back Up

particle	Original Results		Process	Reference
	a_c	$ d_c $ (e cm)		
charm	$[-6.8e-3, 6.8e-3]$	$8.9e-17$ (1σ)	LEP-I,Z decay	hep-ph/9403304
bottom	a_b	$ d_b $ (e cm)	Process	Reference
	$[-4.5e-2, 4.5e-2]$	$8.9e-17$ (1σ)	LEP-I,Z decay	hep-ph/9403304

LEP I data, 209 GeV

TABLE XIII. Current charm and bottom Dipole moments Constraints.

particle	Original Results		Process	Reference
	a_τ	$ d_\tau $ (e cm)		
τ	$[-0.052, 0.058]$ $[-1.8e-3, 1.8e-3]$	$3.1e-16$ (2σ) $1e-17$ (2σ)	$e^+e^- \rightarrow \tau^+\tau^-\gamma$ (LEP Z pole) $pp \rightarrow \tau^+\tau^-$ (LHC Run2)	9803 2307.14133

3 ab⁻¹, s- channel, only photon NP

TABLE XIV. Current experiments τ Dipole moments Constraints.

particle	Original Results		Process	Reference
	a_τ	$ d_\tau $ (e cm)		
τ	$[-1.5e-4, 1.7e-4]$	$9.04e-19$ (2σ)	$e^+e^- \rightarrow e^+\tau^+\tau^-e^-$ (CLIC)	1804.02373
	$[-6.3e-4, 6.3e-4]$	$1.7e-17$ (2σ)	$e^+e^- \rightarrow \tau^+\tau^-$ (Belle II)	2401.04449
	$[-1.28e-3, 1.05e-3]$	$6.439e-18$ (2σ)	$e^+e^- \rightarrow e^+\tau^+\tau^- \gamma e^-$ (CLIC)	1903.04135
	$[-2.65e-3, 2.46e-3]$	$1.437e-17$ (2σ)	$e^-p \rightarrow e^-\tau^+\tau^-\gamma p$ ($\gamma\gamma$ fusion)	1903.04135
	$[-6.7e-3, 6.5e-3]$	$3.692e-17$ (2σ)	$pp \rightarrow p \tau^+\tau^-\gamma p$ ($\gamma\gamma$ fusion)	1903.04135
	$[-2.42e-3, 7.1e-4]$	$7.31e-18$ (2σ)	$\mu^+\mu^- \rightarrow \mu^+ \tau^+\tau^-\mu^-$ ($\gamma\gamma$ fusion)	1811.01188
	$[-4.6e-3, 8.3e-3]$	$1.2e-16$ (1σ)	$pb pb \rightarrow pb \tau^+\tau^- pb$ ($\gamma\gamma$ fusion)	1908.05180

CLIC 3 TeV, 3000 fb⁻¹
 Belle II, 10 GeV, 1 ab⁻¹
 CLIC 3 TeV, 3000 fb⁻¹
 FCC-he, 10 TeV, 1000 fb⁻¹
 LHC, 14 TeV, 300fb⁻¹
 6 TeV, 710 fb⁻¹
 2 nb⁻¹, ultraperipheral collision(UPC)

particle	Original Results		Process	Reference
	a_V	$ a_A $		
top	$\frac{C_{tB}}{\Lambda^2} = [-4.5, 1.2]$	$\frac{C_{tW}}{\Lambda^2} = [-0.12, 0.51] (2\sigma)$	LEP, LHC Run2 global fitting	2012.02779
	$[-0.098, 0.023]$	$\frac{C_{tB}}{\Lambda^2} = 0(2\sigma)$	Transferred from Wilson Coefficient	2012.02779
	$[-0.035, 0.038]$	$[-0.17, 0.16](1\sigma)$	LHC 300 fb^{-1} , $gg \rightarrow t\bar{t}$ production	hep-ph/0601112

particle	Original Results		Process	Reference
	a_V	$ a_A $		
top	$[-8.1e-4, 8.1e-4]$	0.14 (1σ)	$e^+e^- \rightarrow t\bar{t}$ production at the FCC-ee	1503.01325
	$[-0.001, 0.001]$	- (1σ)	$e^+e^- \rightarrow t\bar{t}$ production at the ILC	1307.8102
	$[-0.0234, 0.0325]$	0.0277 (2σ)	$\gamma e^- \rightarrow \bar{t}b\nu_e$ (single top at CLIC)	1602.05991
	$[-0.2203, 0.0020]$	0.0206 (2σ)	$e^+e^- \rightarrow e^+t\bar{t}e^-$ (CLIC, $\gamma\gamma$ fusion best)	1702.03708
	$[-0.1218, 0.1036]$	0.0815 (1σ)	$pp \rightarrow pt\bar{t}p$ ($\gamma\gamma$ fusion) (33 TeV LHC)	1504.06695

365 GeV, 2.4 ab-1
500 GeV, 500 fb-1
3 TeV, 2000 fb-1
3 TeV, 2000 fb-1
33 TeV, 3000 fb-1

TABLE XVII. Future top Dipole moments Constraints.