Flavor Physics at Future Colliders

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Searching for Flavorful New Physics

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

2499 baryon number conserving dim. 6 operators in SMEFT

Grzadkowski et al. 1008.4884,

Alonso et al 1312.2014

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$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r) \widetilde{H}\, G^A_{\mu\nu}$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \tau^I \widetilde{H}\, W^I_{\mu\nu}$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r) \widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
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4 fermion interactions

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$1: X^3$		$2: H^6$		$3: H^4 D^2$		$5: \psi^2 H^3 + \text{h.c.}$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$			Q_{HD}	$(H^\dagger D_\mu H)^* (H^\dagger D_\mu H)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$						

$4: X^2 H^2$		$6: \psi^2 X H + \text{h.c.}$		$7: \psi^2 H^2 D$	
Q_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I H W^I_{\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde H\, G^A_{\mu\nu}$	Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde H\, W^I_{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$	Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I H\, W^I_{\mu\nu}$	Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
$Q_{H\widetilde WB}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$		$8: (\bar R R)(\bar R R)$		$8: (\bar L L)(\bar R R)$	
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}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
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		$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
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dipole transitions

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Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$
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Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$

$8: (\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$8: (\bar{L}R)(\bar{R}L) + \text{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8: (\bar{L}R)(\bar{L}R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$

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Grzadkowski et al. 1008.4884,

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$1: X^3$		$2: H^6$		$3: H^4D^2$		$5: \psi^2H^3 + \text{h.c.}$	
Q_G	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
$Q_{\tilde G}$	$f^{ABC}\tilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$			Q_{HD}	$(H^\dagger D_\mu H)^*(H^\dagger D_\mu H)$	Q_{uH}	$(H^\dagger H)(\bar q_p u_r \tilde H)$
Q_W	$\epsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$					Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$
$Q_{\tilde W}$	$\epsilon^{IJK}\tilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$						

$4: X^2H^2$		$6: \psi^2XH + \text{h.c.}$		$7: \psi^2H^2D$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$Q_{H\tilde G}$	$H^\dagger H\, \tilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar l_p\tau^I\gamma^\mu l_r)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\tilde H\, G_{\mu\nu}^A$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$Q_{H\tilde W}$	$H^\dagger H\, \tilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\tilde H\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar q_p\sigma^{\mu\nu}u_r)\tilde H\, B_{\mu\nu}$	$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar q_p\tau^I\gamma^\mu q_r)$
$Q_{H\tilde B}$	$H^\dagger H\, \tilde B_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
Q_{HWB}	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$	Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$Q_{H\tilde WB}$	$H^\dagger\tau^I H\, \tilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	Q_{Hud} + h.c.	$i(\tilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

$8: (\bar LL)(\bar LL)$		$8: (\bar RR)(\bar RR)$		$8: (\bar LL)(\bar RR)$	
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}	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$8: (\bar LR)(\bar RL) + \text{h.c.}$		$8: (\bar LR)(\bar LR) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
		$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
		$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
		$Q_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\epsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$

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Searching for Flavorful New Physics

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar l_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
Q_{dH}	$(H^\dagger H)(\bar q_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G_{\mu\nu}^A$
Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W_{\mu\nu}^I$
Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$
Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar l_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar q_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$8: (\bar L L)(\bar L L)$	
Q_{ll}	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$

$8: (\bar R R)(\bar R R)$	
Q_{ee}	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$
Q_{uu}	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$
Q_{dd}	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$
Q_{eu}	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$
Q_{ed}	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L L)(\bar R R)$	
Q_{le}	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
Q_{lu}	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
Q_{ld}	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
Q_{qe}	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$8: (\bar L R)(\bar R L) + \text{h.c.}$	
Q_{ledq}	$(\bar l_p^j e_r)(\bar d_s q_{tj})$

$8: (\bar L R)(\bar L R) + \text{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar q_p^j u_r)\epsilon_{jk}(\bar q_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\epsilon_{jk}(\bar q_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar l_p^j e_r)\epsilon_{jk}(\bar q_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$

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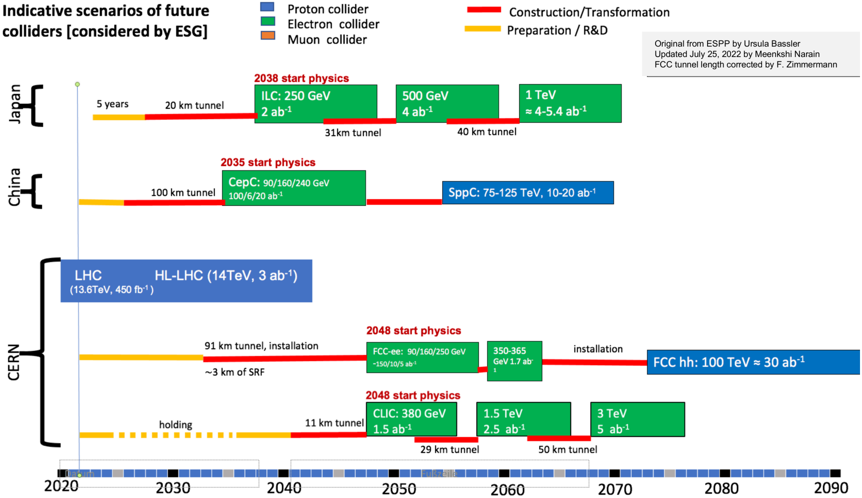
"Leave no stone unturned"
= probe as many operators as possible

Future Colliders

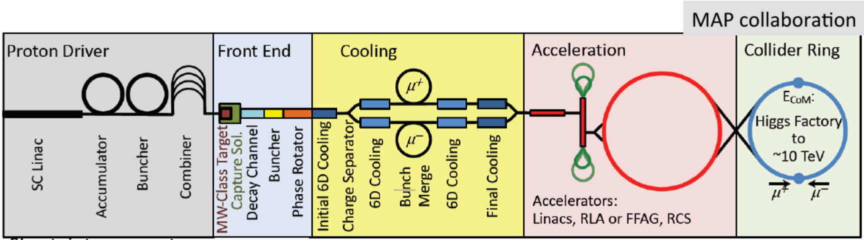


Karl Jacobs @ 2nd ECFA meeting on e^+e^- Higgs, electroweak, and top factories

Oct 11-13, 2023, Paestum, Italy

A Muon Collider?

Muon collider design is driven by finite muon lifetime



Short, intense proton bunches to produce hadronic showers

Muon are captured, bunched and then cooled by ionisation cooling in matter

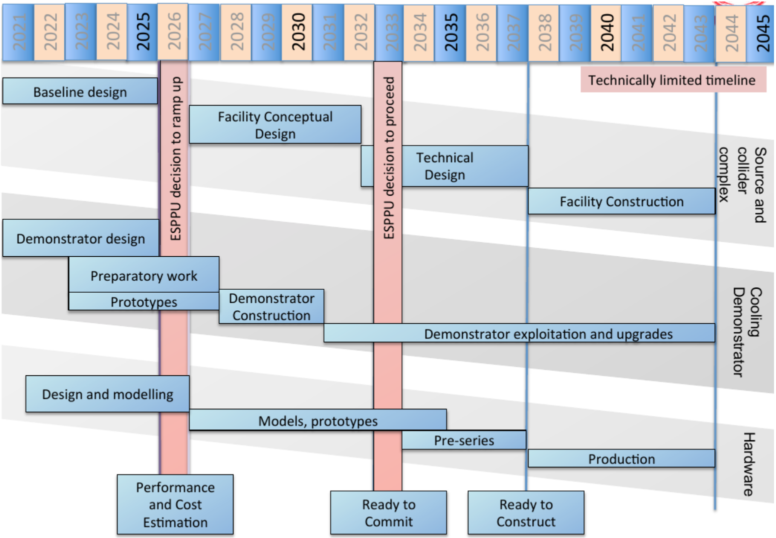
Collision

Acceleration to collision energy

Protons produce pions
Pions decay to muons

talk by D. Schulte @ Muon Collider Agora, Feb 16 2022

A Muon Collider!

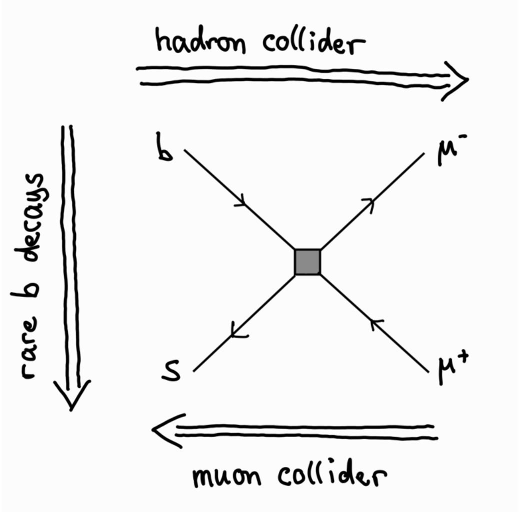


talk by D. Schulte @ Muon Collider Agora, Feb 16 2022

Part 1:

Collider Probes of $b \to s\mu\mu$

based on 2306.15017 with A. Gadam and S. Profumo


hadron collider
rare b decays
b
μ⁻
s
μ⁺
muon collider

Non-Standard $\mu^+\mu^- \to bs$ at a Muon Collider

$$\Delta C_9(\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell) \quad , \quad \Delta C_{10}(\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \gamma_5 \ell)$$

Non-Standard $\mu^+\mu^- \to bs$ at a Muon Collider

$$\Delta C_9 (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell) \quad , \quad \Delta C_{10} (\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \gamma_5 \ell)$$

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\Big(1 + \cos^2\theta + \frac{8}{3} A_{\rm FB} \cos\theta\Big)$$
$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\Big(1 + \cos^2\theta - \frac{8}{3} A_{\rm FB} \cos\theta\Big)$$

Total cross section increases with the center of mass energy
(unless the contact interaction is resolved)

$$\sigma(\mu^+\mu^- \to bs) = \frac{G_F^2 \alpha^2}{8\pi^3} |V_{tb} V_{ts}^*|^2 \, s \, \Big(|\Delta C_9|^2 + |\Delta C_{10}|^2\Big)$$

$$\Delta C_9(\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \ell) \quad , \quad \Delta C_{10}(\bar{s}\gamma_\alpha P_L b)(\bar{\ell}\gamma^\alpha \gamma_5 \ell)$$

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta + \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta - \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

Total cross section increases with the center of mass energy
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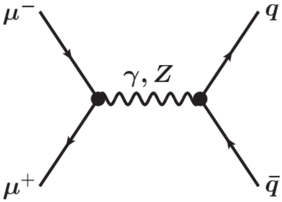
$$\sigma(\mu^+\mu^- \to bs) = \frac{G_F^2\alpha^2}{8\pi^3}|V_{tb}V_{ts}^*|^2 \, s \left(|\Delta C_9|^2 + |\Delta C_{10}|^2\right)$$

Forward backward asymmetry is sensitive to the chirality strcuture

$$A_{\rm FB} = \frac{-3\mathrm{Re}(\Delta C_9 \Delta C_{10}^*)}{2(|\Delta C_9|^2 + |\Delta C_{10}|^2)}$$

Need charge tagging to measure the forward backward asymmetry

Main Background



- Mistagged dijets

$$\sigma_{bg}^{jj} = \sum_{q=b,c,s,d,u} 2\epsilon_q(1-\epsilon_q)\sigma(\mu^+\mu^- \to q\bar{q})$$

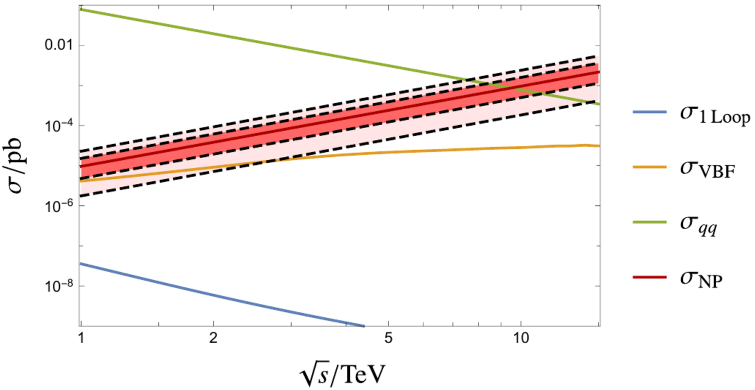
- Assume b tagging comparable to current LHC performance

$$\epsilon_b = 70\%\ , \quad \epsilon_c = 10\%\ , \quad \epsilon_u = \epsilon_d = \epsilon_s = 1\%$$

- Turns out to be the dominant background.

Signal vs. Background

WA, Gadam, Profumo 2203.07495, 2306.15017



- Main background falls with $\sqrt{s}$; new physics signal increases.
- Signal/Background ~ 1 for $\sqrt{s} \sim 10$ TeV.

Forward Backward Asymmetry and Charge Tagging

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\Big(1 + \cos^2\theta + \frac{8}{3}A_{\text{FB}}\cos\theta\Big)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\Big(1 + \cos^2\theta - \frac{8}{3}A_{\text{FB}}\cos\theta\Big)$$

Need charge tagging to measure the forward backward asymmetry

Forward Backward Asymmetry and Charge Tagging

$$\frac{d\sigma(\mu^+\mu^- \to b\bar{s})}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta + \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

$$\frac{d\sigma(\mu^+\mu^- \to \bar{b}s)}{d\cos\theta} = \frac{3}{16}\sigma(\mu^+\mu^- \to bs)\left(1 + \cos^2\theta - \frac{8}{3}A_{\rm FB}\cos\theta\right)$$

Need charge tagging to measure the forward backward asymmetry

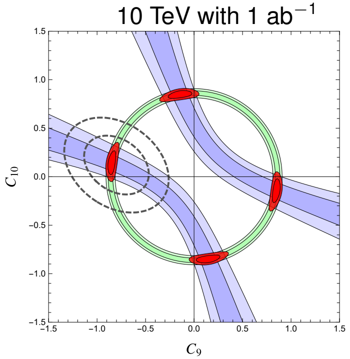
Imperfect charge tagging dilutes the forward backward asymmetry

$$A_{\rm FB}^{\rm obs} = (2\epsilon_\pm - 1)\left(\frac{N_{\rm sig}}{N_{\rm tot}}A_{\rm FB} + \frac{N_{\rm bg}}{N_{\rm tot}}A_{\rm FB}^{\rm bg}\right)$$

As a benchmark, we assume charge tagging efficiency as at LEP
$\epsilon_\pm \simeq 70\%$ (how realistic is this?)

Sensitivity Projections

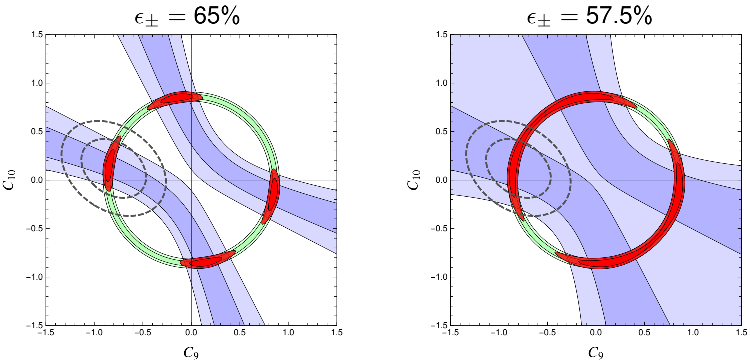
WA, Gadam, Profumo 2203.07495 and 2306.15017



- Branching ratio (green) and A_{FB} (blue) are complementary.
- In dashed: our global rare B decay fit.
- If there is new physics in $b \to s\ell\ell$, a 10 TeV muon collider would clearly see it, and one does not need to worry about hadronic uncertainties.

(see also Huang et al. 2103.01617; Asadi et al. 2104.05720; Azatov et al. 2205.13552)

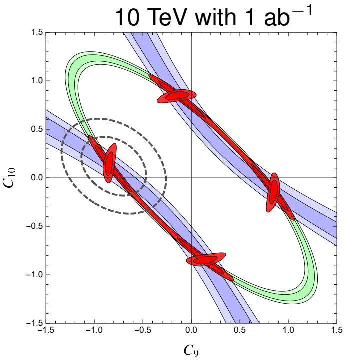
Impact of Charge Tagging



- The forward backward asymmetry gives useful information for charge tagging as low as $\sim 60\%$.
- For $\epsilon_\pm \lesssim 57.5\%$ two of the four red regions start to merge.

Impact of Beam Polarization

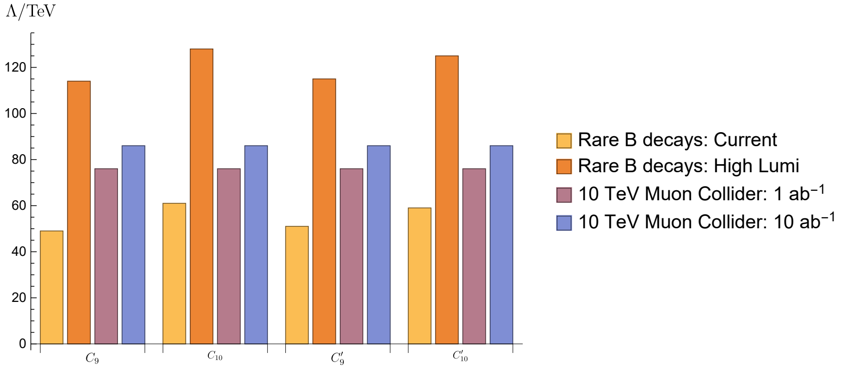
WA, Gadam, Profumo 2203.07495 and 2306.15017



- So far had assumed that muon beams are upolarized.
- Can expect a typical residual polarization of $\sim$ 20% from pion decay. Higher polarization could be obtained at the cost of luminosity.
- Plots show the case of 50% polarization.

In the Absence of New Physics

WA, Gadam, Profumo 2203.07495 and 2306.15017



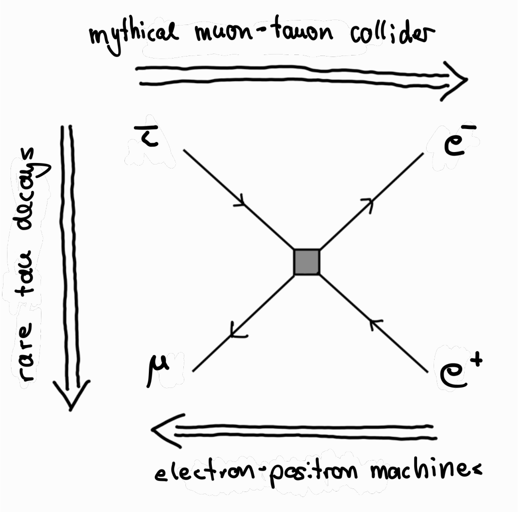
- In the absence of new physics, rare B decays and a 10 TeV muon collider have comparable sensitivity to muon specific new physics.
- Rare B decays have the advantage that a small new physics amplitude can interfere with the SM.
- At a muon collider one has to look for $|\text{new physics}|^2$.

Part 2:

Collider Probes of Lepton Flavor Violation

based on 2305.03869 with P. Munbodh and T. Oh

Collider Probes of Lepton Flavor Violation



Lepton Flavor Violation

- In the SM, charged lepton flavor violation is suppressed by the tiny neutrino mass splittings

$$\text{e.g.} \quad \mathrm{BR}(\mu \to 3e) \sim \mathrm{BR}(\mu \to e\nu_e\nu_\mu) \left| \frac{g^2}{16\pi^2} \frac{\Delta m_\nu^2}{m_W^2} \right|^2 \sim 10^{-50}$$

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3) At high energies in non-resonant production: $e^+e^- \to \tau\mu$, ...

New Physics Sensitivity of LFV at Low Energies

- Generic scaling of a new physics effect with the flavor changing coupling g_{NP} and the new physics scale Λ_{NP}

$$\frac{\mathrm{BR}(\mu \to 3e)}{\mathrm{BR}(\mu \to e\nu_\mu\bar{\nu}_e)} \sim g_{\mathrm{NP}}^2 \left(\frac{v}{\Lambda_{\mathrm{NP}}}\right)^4 \lesssim 10^{-12}$$

$$\frac{\mathrm{BR}(\tau \to 3\mu)}{\mathrm{BR}(\tau \to \mu\nu_\mu\bar{\nu}_\tau)} \sim g_{\mathrm{NP}}^2 \left(\frac{v}{\Lambda_{\mathrm{NP}}}\right)^4 \lesssim 10^{-8}$$

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- For O(1) couplings, this corresponds to new physics scales of

$$\Lambda_{\rm NP} \gtrsim 100~\text{TeV} \quad \text{for muons}$$

$$\Lambda_{\rm NP} \gtrsim 10~\text{TeV} \quad \text{for taus}$$

New Physics Sensitivity of Heavy Resonance Decays

- Consider LFV decays of the Z boson, the Higgs, the top in the presence of generic new physics

$$\frac{\text{BR}(Z \to \mu e)}{\text{BR}(Z \to \mu\mu)} \sim g_{\text{NP}}^2 \left(\frac{v}{\Lambda_{\text{NP}}}\right)^4 , \qquad \frac{\text{BR}(H \to \tau\mu)}{\text{BR}(H \to \tau\tau)} \sim g_{\text{NP}}^2 \left(\frac{v}{\Lambda_{\text{NP}}}\right)^4$$

$$\frac{\text{BR}(t \to c\mu e)}{\text{BR}(t \to Wb)} \sim \frac{g_{\text{NP}}^2}{16\pi^2} \left(\frac{v}{\Lambda_{\text{NP}}}\right)^4$$

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- Same dependence on new physics as the low energy probes, but typically much less Z, Higgs, top available in experiments.

- Note: these are extremely generic/naive expectations; situation can be very different in concrete models.

[for a review see WA, Caillol, Dam, Xella, Zhang 2205.10576]

Example: LFV Z Decays

- Results from the LHC: ATLAS (139 fb^{-1})

  Phys.Rev.Lett. 127 (2022) 271801; Nature Phys. 17 (2021) 7, 819-825; ATLAS-CONF-2021-042

$$\text{BR}(Z \to \mu e) < 3.04 \times 10^{-7}$$
$$\text{BR}(Z \to \tau e) < 5.0 \times 10^{-6}$$
$$\text{BR}(Z \to \tau \mu) < 6.5 \times 10^{-6}$$

- Slightly better than LEP bounds for all decay modes.

- In all searches there are backgrounds $\Rightarrow$ expect sensitivities to improve with $\sqrt{\mathcal{L}}$, i.e. $\sim$ factor of 5 at the HL-LHC.

Expected Sensitivities at Proposed Z Pole Machines

based on FCC-ee study Dam 1811.09408 (see also the FCC-ee whitepaper 2203.06520)

$Z \to \mu e$

- background from $Z \to \tau\tau \to \mu\nu\nu\ e\nu\nu$ is under control. Momentum resolution of 10^{-3} and Z mass constraint implies background rate of $\sim 10^{-11}$.
- main background: $Z \to \mu\mu$ where one muon suffers from "catastrophic" bremsstrahlung and is identified as electron.
- mis-id probability $\sim 10^{-7}$ limits the sensitivity to $\text{BR}(Z \to \mu e) \sim 10^{-8}$.
- With improved e/μ separation (dE/dx) might be able to go down to $\text{BR}(Z \to \mu e) \sim 10^{-10}$.

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$Z \to \tau e$ and $Z \to \tau\mu$

- minimize τ vs μ, e mis-id $\to$ focus on hadronic taus
- background from $Z \to \tau_{\text{had}}\tau \to \tau_{\text{had}}\ell\nu\nu$
- limits sensitivity to $\text{BR}(Z \to \tau\ell) \sim 10^{-9}$

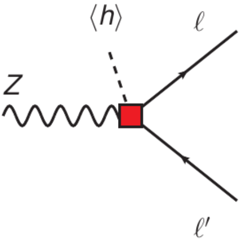
LFV Z Decays in the EFT Framework

- Parameterize New Physics in a systematic and controlled way: in terms of dim-6 operators of the SMEFT

dipoles

$$\mathcal{O}_{dW} = (\bar{\ell}\sigma^{\mu\nu}\tau^a P_R \ell')H \;\; W^a_{\mu\nu}$$

$$\mathcal{O}_{dB} = (\bar{\ell}\sigma^{\mu\nu} P_R \ell')H \;\; B_{\mu\nu}$$

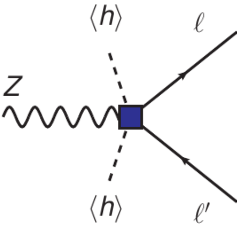


Higgs currents

$$\mathcal{O}^{(3)}_{hl} = (H^\dagger i \overleftrightarrow{D}^a_\mu H)(\bar{\ell}\gamma^\mu \tau^a P_L \ell')$$

$$\tilde{\mathcal{O}}^{(1)}_{hl} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu P_L \ell')$$

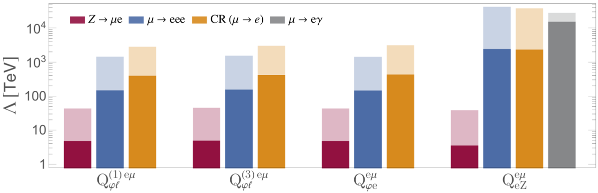
$$\mathcal{O}_{he} = (H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{\ell}\gamma^\mu P_R \ell')$$



Comparison with Low Energy Probes

- Many flavor violating low energy processes will be affected as well.
- Severe indirect constraints on $Z \to \mu e$ from $\mu \to e\gamma$, $\mu \to 3e$, $\mu \to e$ conversion (barring accidental cancellations).

Calibbi, Marcano, Roy 2107.10273



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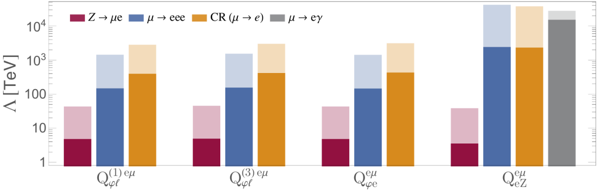
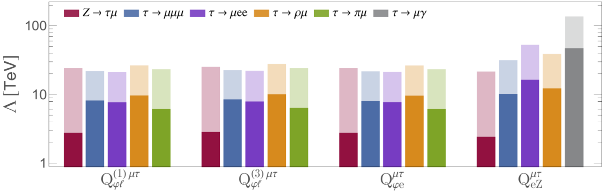


- Complementary sensitivity in the case of taus.



New Physics Sensitivity of Non-Resonant LFV

- The scaling of LFV cross sections with the center of mass energy depends on the type of operator:

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- In WA, Munbodh, Oh 2305.03869 we show that high-energy runs of FCC-ee/CEPC have sensitivity that is comparable and complementary to other probes.

(see also Murakami, Tait 1410.1485 for a study of $e^+e^- \to \tau e$ at linear colliders)

Systematic SMEFT Parameterization of New Physics

dipoles

$$\mathcal{O}_{dW} = (\bar\tau \sigma^{\alpha\beta} T^a P_R \mu) H \;\; W^a_{\alpha\beta}$$

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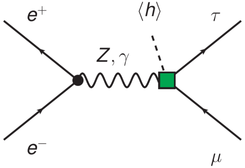

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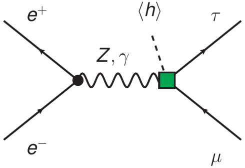

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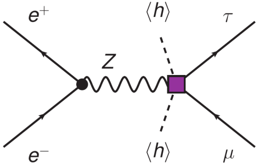

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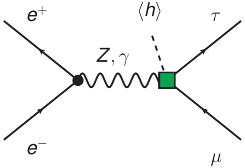

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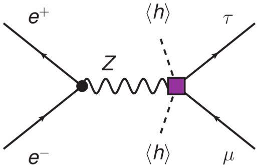


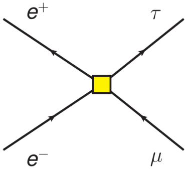
4-fermion contact interactions

$$\mathcal{O}_{\ell\ell} = (\bar{e}\gamma^\alpha P_L e)(\bar{\tau}\gamma_\alpha P_L \mu)$$

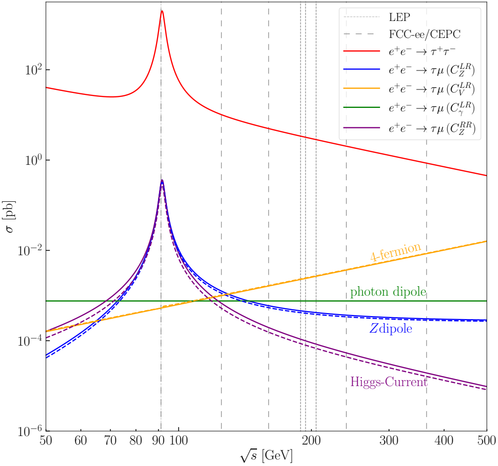
$$\mathcal{O}_{ee} = (\bar{e}\gamma^\alpha P_R e)(\bar{\tau}\gamma_\alpha P_R \mu)$$

$$\mathcal{O}_{\ell e} = (\bar{e}\gamma^\alpha P_L e)(\bar{\tau}\gamma_\alpha P_R \mu)$$

$$\mathcal{O}_{e\ell} = (\bar{e}\gamma^\alpha P_R e)(\bar{\tau}\gamma_\alpha P_L \mu)$$



Dependence on the Center of Mass Energy



WA, Munbodh, Oh 2305.03869

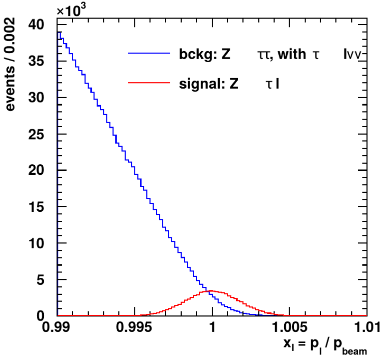
(in the plot $\Lambda_{\rm NP} = 3$ TeV, $C_i = 1$)

- $\tau^+\tau^-$ background falls like $1/s$
- $\tau\mu$ production increases linearly with s for 4-fermion operators
- $\tau\mu$ production is flat in s for dipole operators
- $\tau\mu$ production falls like $1/s$ for Higgs current operators
- resonance at $s = m_Z^2$ if Z-mediated

signal: $e^+e^- \to \tau\mu$

bkg: $e^+e^- \to \tau^+\tau^- \to \tau\mu\nu\nu$

- Signal is a sharp peak at $x = p_\mu / p_{\text{beam}} = 1$
- Background is a smooth distribution with $x \lesssim 1$
- Width of the signal peak and spread of background to $x > 1$ is determined by the beam energy spread and the muon momentum resolution.



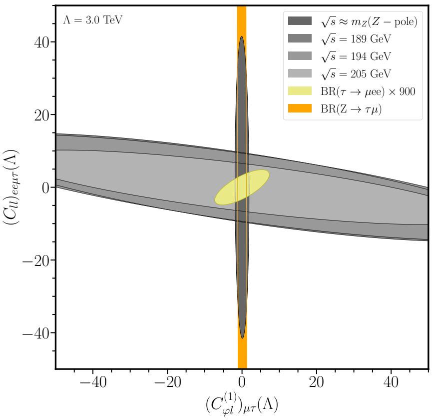
Dam 1811.09408

(study on the Z peak)

- Impact of initial state radiation? (work in progress with Munbodh)

Existing Constraints from LEP

WA, Munbodh, Oh 2305.03869



- LEP has searched for $e^+e^- \to \tau\mu$ at the Z pole (e.g. OPAL Z.Phys.C 67 (1995) 555-564) and at $\sqrt{s} \sim 200$ GeV (OPAL PLB 519, (2001) 23-32).
- Z pole search mainly sensitive to the Higgs current operators.
- High $\sqrt{s}$ search mainly sensitive to 4-fermion operators.
- LEP searches have sensitivity comparable to $Z \to \tau\mu$ at the LHC, but cannot compete with tau decays.

Projections for FCC-ee

machine and detector parameters from FCC-ee CDR vol. 2, 1909.12245, 2107.02686, 2203.06520

$\sqrt{s}$ [GeV]	$\mathcal{L}_{\rm int}$ [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon^{x_c}_{\rm bkg}$ [10^{-6}]	$N_{\rm bkg}$	σ [ab]
91.2 (Z-pole)	75	0.93	1.35	1.55	9700 ± 100	45
87.7 (off-peak)	37.5	0.93	1.33	1.46	520 ± 20	21
93.9 (off-peak)	37.5	0.93	1.37	1.59	930 ± 30	28
125 (H)	20	0.03	1.60	1.44	12 ± 3	8
160 (WW)	12	0.93	1.89	2.44	6 ± 2	10
240 (ZH)	5	1.17	2.60	4.39	2 ± 1	18
365 ($t\bar{t}$)	1.5	1.32	3.78	8.61	0.5 ± 0.7	50

- Estimate background efficiency by imposing a cut $x > 1$. (could be further optimized)
- Expect sizable background on the Z-peak, very few background events at higher energies.
- Can achieve sensitivity to $e^+e^- \to \tau\mu$ cross sections of $\mathcal{O}$(10 ab).

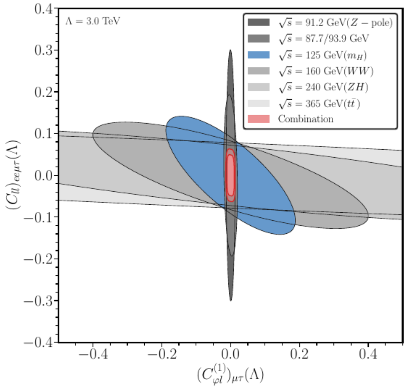
Projections for CEPC

machine and detector parameters from 1809.00285, 1811.10545, 2203.09451, 2205.08553

$\sqrt{s}$ [GeV]	$\mathcal{L}_{\rm int}$ [ab^{-1}]	$\frac{\delta\sqrt{s}}{\sqrt{s}}$ [10^{-3}]	$\frac{\delta p_T}{p_T}$ [10^{-3}]	$\epsilon_{\rm bkg}^{x_c}$ [10^{-6}]	$N_{\rm bkg}$	σ [ab]
91.2 (Z-pole)	50	0.92	1.35	1.53	6400 ± 80	55
87.7 (off-peak)	25	0.92	1.33	1.46	350 ± 20	27
93.9 (off-peak)	25	0.92	1.37	1.59	620 ± 25	35
160 (WW)	6	0.99	1.89	2.49	3 ± 2	17
240 (ZH)	20	1.20	2.60	4.42	7 ± 3	6.6
360 ($t\bar{t}$)	1	1.41	3.74	8.61	0.3 ± 0.5	72

- Estimate background efficiency by imposing a cut $x > 1$. (could be further optimized)
- Expect sizable background on the Z-peak, very few background events at higher energies.
- Can achieve sensitivity to $e^+e^- \to \tau\mu$ cross sections of $\mathcal{O}$(10 ab).

WA, Munbodh, Oh 2305.03869



- As in the case of LEP, the Z-pole searches and the high-$\sqrt{s}$ searches are complementary.

Complementarity of Different Observables (FCC-ee)

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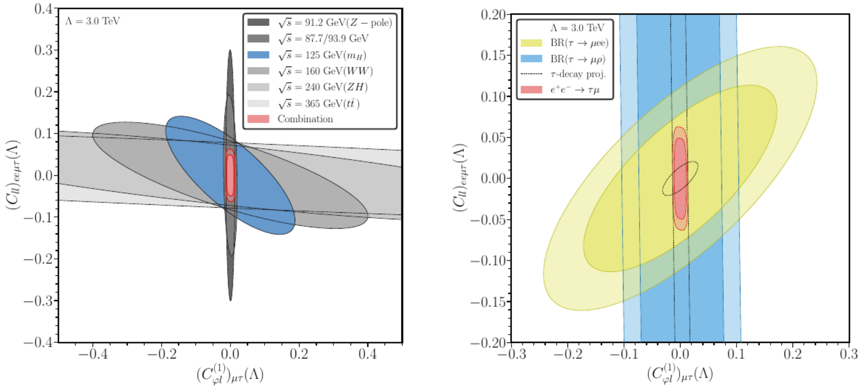

- As in the case of LEP, the Z-pole searches and the high-$\sqrt{s}$ searches are complementary.
- Expected FCC-ee sensitivity rivals the one from current (BaBar/Belle) and future (Belle II) searches for LFV τ decays.

  (Note: FCC-ee/CEPC can probably test rare τ decays even better than Belle II.)

Complementarity of Different Observables (CEPC)

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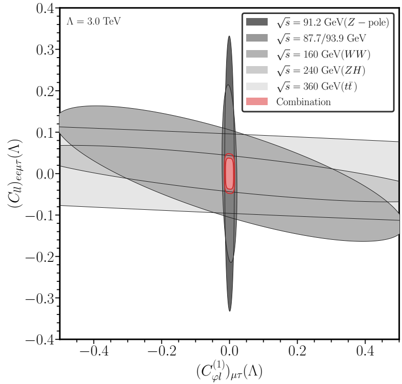

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Complementarity of Different Observables (CEPC)

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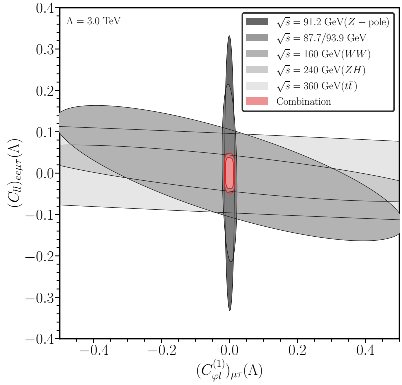

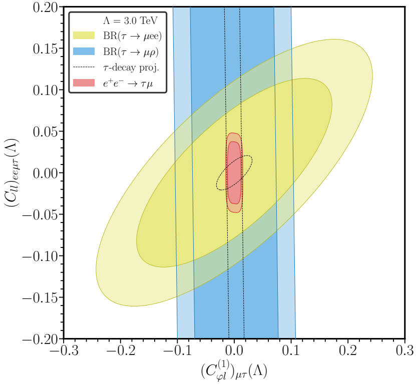

- As in the case of LEP, the Z-pole searches and the high-$\sqrt{s}$ searches are complementary.
- Expected CEPC sensitivity rivals the one from current (BaBar/Belle) and future (Belle II) searches for LFV τ decays.

(Note: FCC-ee/CEPC can probably test rare τ decays even better than Belle II.)

Summary of Generic Sensitivities

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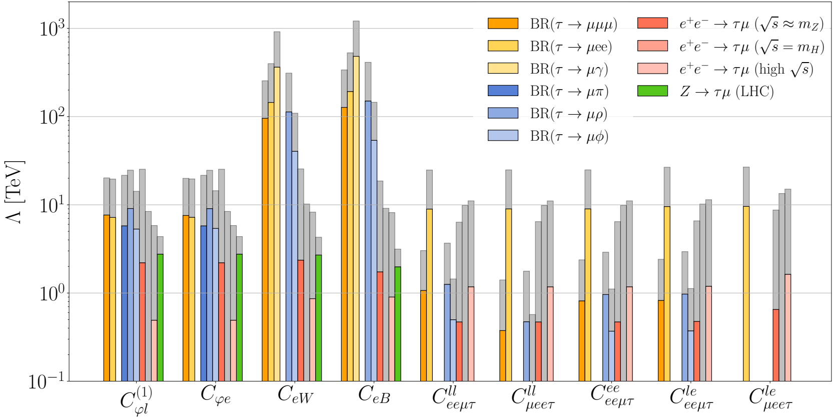

If a Signal is Seen ...

- If a signal is seen at one $\sqrt{s}$:
  $\Rightarrow$ look at different $\sqrt{s}$ to identify the operator class
  (dipole, Higgs current, 4-fermion)

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- The signal can be further characterized by angular distributions
  ($\theta =$ angle between the beam axis and the outgoing muon)
  and CP asymmetries ($\tau^+\mu^-$ vs. $\tau^-\mu^+$)

$$\frac{1}{\sigma_{\rm tot}}\frac{d(\sigma+\bar\sigma)}{d\cos\theta} = \frac{3}{8}(1-F_D)(1+\cos^2\theta) + A_{\rm FB}\cos\theta + \frac{3}{4}F_D\sin^2\theta \ ,$$
$$\frac{1}{\sigma_{\rm tot}}\frac{d(\sigma-\bar\sigma)}{d\cos\theta} = \frac{3}{8}(A^{\rm CP}-F_D^{\rm CP})(1+\cos^2\theta) + A_{\rm FB}^{\rm CP}\cos\theta + \frac{3}{4}F_D^{\rm CP}\sin^2\theta \ ,$$

- For a sufficiently large signal, it might be possible to significantly narrow down the chirality structure of the operator that is responsible for $e^+e^- \to \tau\mu$

Summary

- $\mu^+\mu^- \to bs$ at a 10 TeV muon collider is a interesting probe of new physics.
- Could test the “B anomalies” without having to worry about hadronic effects.
- In the absence of new physics, could probe $(\mu\mu)(bs)$ contact interactions at scales of $\sim$ 80 TeV.

Summary

- $\mu^+\mu^- \to bs$ at a 10 TeV muon collider is a interesting probe of new physics.
  - Could test the "B anomalies" without having to worry about hadronic effects.
  - In the absence of new physics, could probe $(\mu\mu)(bs)$ contact interactions at scales of $\sim$ 80 TeV.
- Non-resonant $e^+e^- \to \tau\mu$ offers interesting opportunities to probe lepton flavor violation at FCC-ee/CEPC.
  - Different LFV operators show characteristic dependence on the center of mass energy.
  - Estimated sensitivity rivals the one from rare tau decays.

Back Up

Another $\tau\mu$ Background at High Energies?

$$e^+e^- \to W^+W^- \to \tau\mu\nu\nu$$

- Muon momentum does not extend all the way to $x = 1$
- Decay kinematics is such that

$$x < \frac{1}{2}\left(1 + \sqrt{1 - \frac{4m_W^2}{s}}\right) < 1$$

- e.g. for $\sqrt{s} = 240$ GeV one has $x \lesssim 0.87$

$\Rightarrow$ this background is not an issue.