EF workshop, Joint EF01-02 session

Update on Higgs Studies at a Muon Collider

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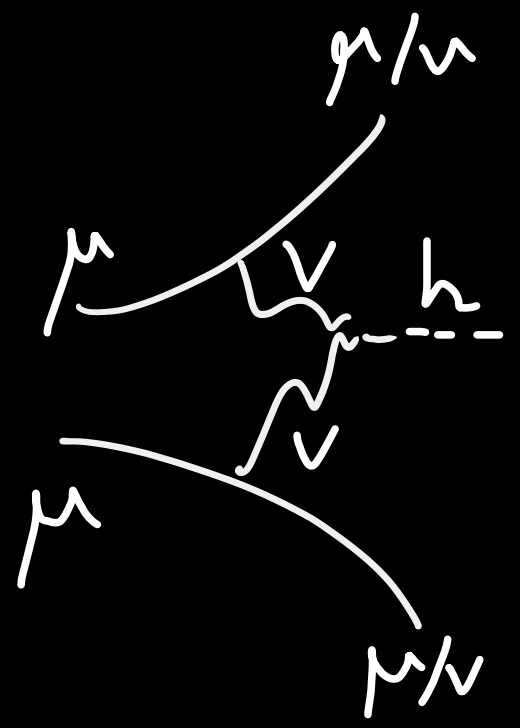
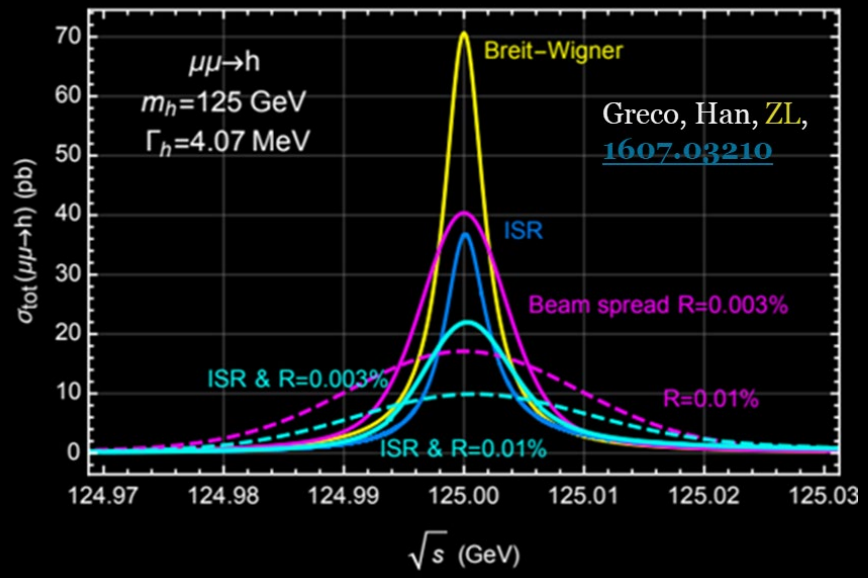
09/01/2021

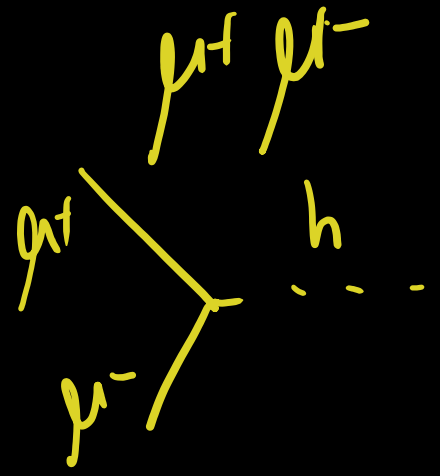
Higgs at MuC



+ many more modes

In this talk, I will focus on the SM-like Higgs at high energy muon colliders.





125 GeV resonant Higgs muon collider: Very unique and complementary Higgs precision measurements on width, couplings, and especially muon Yukawas. See recent development here (Snowmass Muon Collider Forum talk): https://indico.fnal.gov/event/50346/#2-physics-at-the-125-gev-muon

Higgs at High-Energy MuC

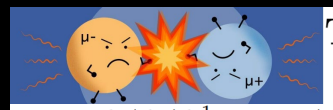
High Energy Muon Collider provides a vibrant and growing Higgs physics program:

- Baseline Precision couplings
- Higgs Self-coupling
- Top Yukawa through interference
- Muon Yukawa at different energies
- Probing EDM, MDM operators
- + many more

Baseline Higgs Measurements

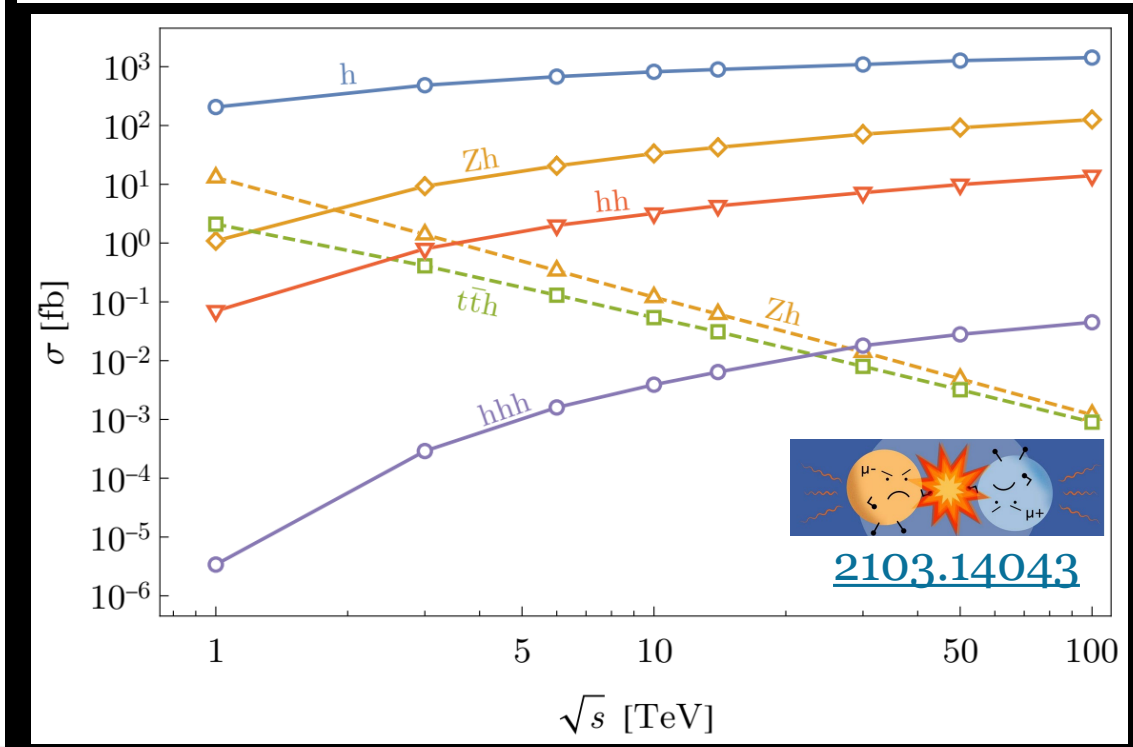
10 TeV @ 10 ab^{-1}

Production	Decay	Rate [fb]	$A \cdot \epsilon$ [%]	$\Delta\sigma/\sigma$ [%]
W-fusion	bb	490	7.4	0.17
	cc	24	1.4	1.7
	jj	72	37	0.19
	$\tau^+\tau^-$	53	6.5	0.54
	$WW^*(jj\ell\nu)$	53	21	0.30
	$WW^*(4j)$	86	4.9	0.49
	$ZZ^*(4\ell)$	0.1	6.6	12
	$ZZ^*(jj\ell^+\ell^-)$	2.1	8.9	2.3
	$ZZ^*(4j)$	11	4.6	1.4
	$\gamma\gamma$	1.9	33	1.3
	$Z(jj)\gamma$	0.9	27	2.0
	$\mu^+\mu^-$	0.2	37	0.37
Z-fusion	bb	51	8.1	0.49
	$WW^*(4j)$	8.9	6.2	1.3
W-fusion tth	bb	0.06	12	12



The Muon Smasher's Guide

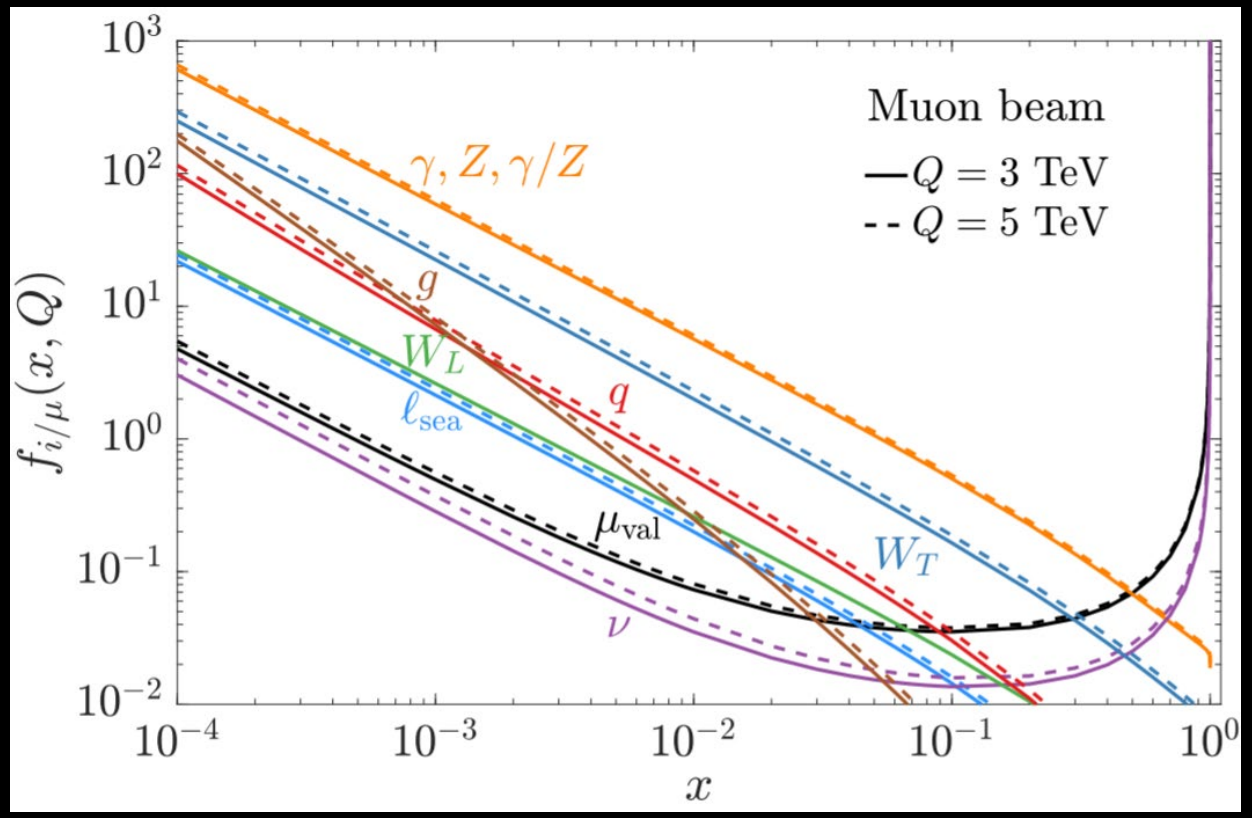
Hind Al Ali[1], Nima Arkani-Hamed[2], Ian Banta[1], Sean Benevedes[1], Dario Buttazzo[3], Tianji Cai[1], Junyi Cheng[1], Timothy Cohen[4], Nathaniel Craig[1], Majid Ekhterachian[5], JiJi Fan[6], Matthew Forslund[7], Isabel Garcia Garcia[8], Samuel Homiller[9], Seth Koren[10], Giacomo Koszegi[1], Zhen Liu[5,11], Qianshu Lu[9], Kun-Feng Lyu[12], Alberto Mariotti[13], Amara McCune[1], Patrick Meade[7], Isobel Ojalvo[14], Umut Oktem[1], Diego Redigolo[15,16], Matthew Reece[9], Filippo Sala[17], Raman Sundrum[5], Dave Sutherland[18], Andrea Tesi[16,19] Timothy Trott[1], Chris Tully[14], Lian-Tao Wang[10], and Menghang Wang[1]

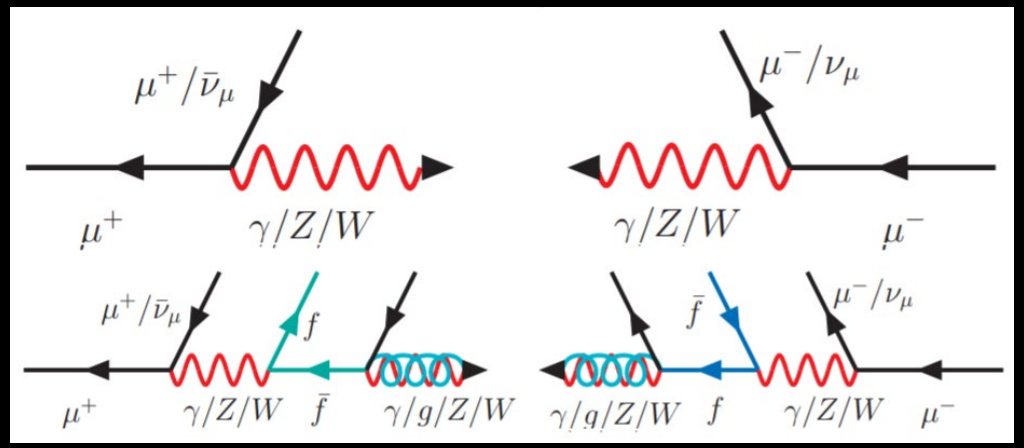


See also discussion in T. Han, Y. Ma, K.-P. Xie, 2007.14300; Costanini, De Lillo, Maltoni, Mantani, Mattelaer, 2005.10289

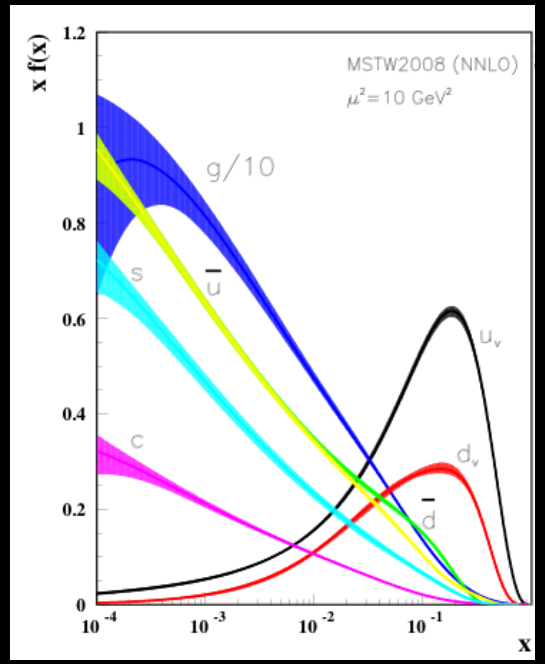
Muon "structure"

When colliding high energy leptons, we are colliding a bunch of electroweak states.





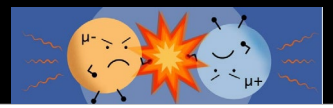
Quite different from proton



See in-depth discussion by T. Han, Y. Ma, K.-P. Xie, 2007.14300, 2103.09844; Ali et al, Muon Smasher's guide 2103.14043

Higgs Precision

Fit Result [%]

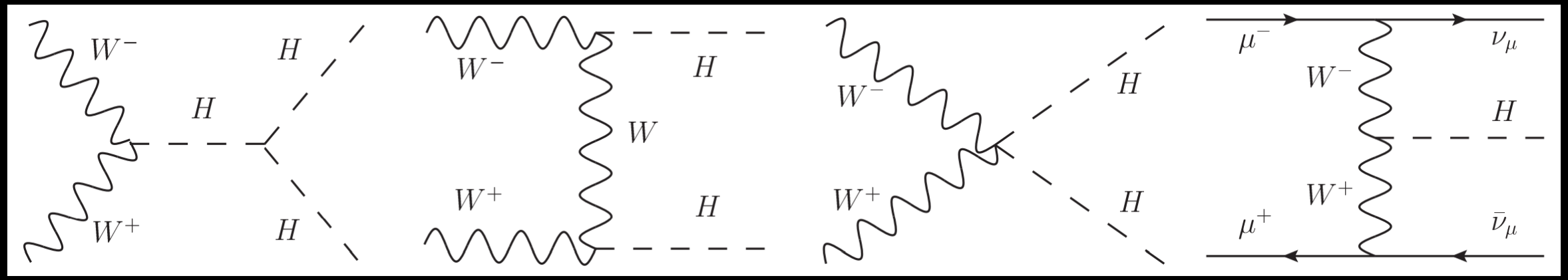


	10 TeV Muon Collider	with HL-LHC	with HL-LHC + 250 GeV e^+e^-
κ_W	0.06	0.06	0.06
κ_Z	0.23	0.22	0.10
κ_g	0.15	0.15	0.15
κ_γ	0.64	0.57	0.57
$\kappa_{Z\gamma}$	1.0	1.0	0.97
κ_c	0.89	0.89	0.79
κ_t	6.0	2.8	2.8
κ_b	0.16	0.16	0.15
κ_μ	2.0	1.8	1.8
κ_τ	0.31	0.30	0.27

Multi-Higgs & Higgs Self-couplings

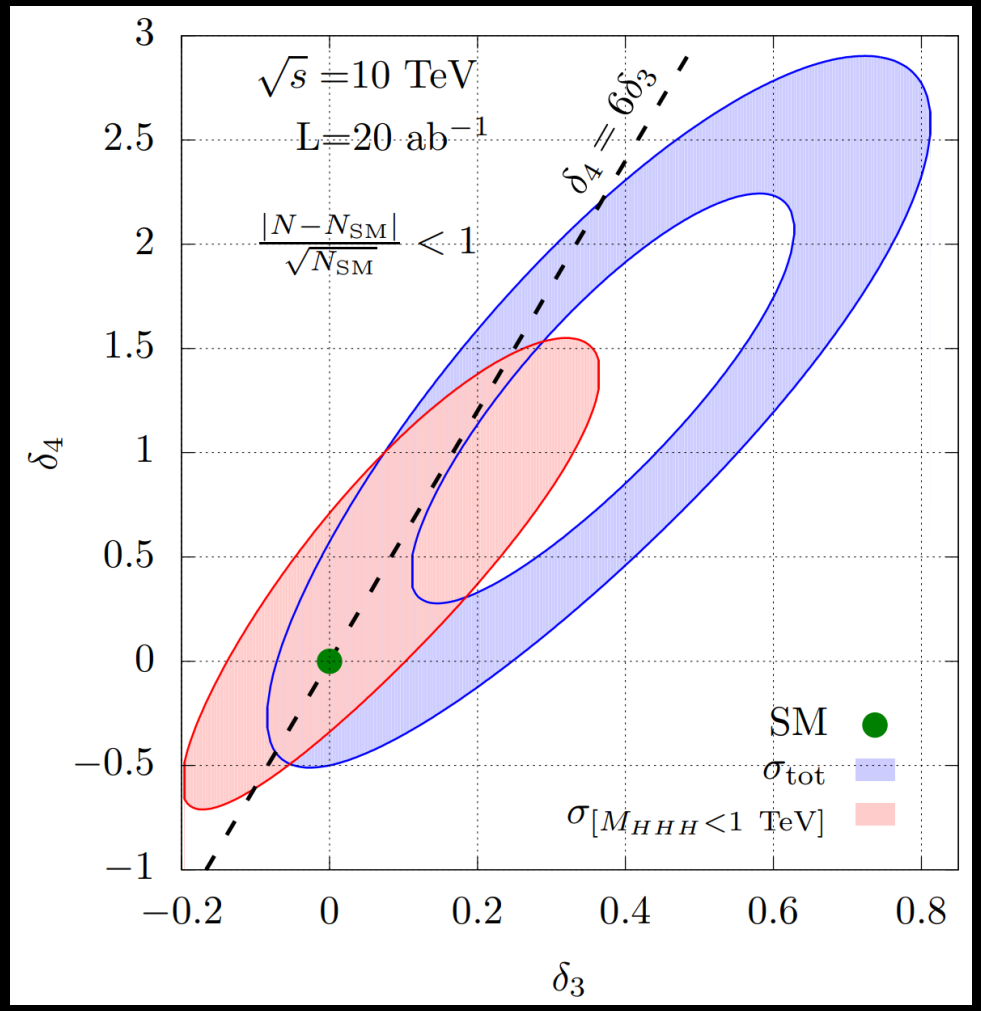
$\sqrt{s}$ (lumi.)	3 TeV (1 ab^{-1})	6 (4)	10 (10)	14 (20)	30 (90)	Comparison
WWH ($\Delta\kappa_W$)	0.26%	0.12%	0.073%	0.050%	0.023%	0.1% [41]
$\Lambda/\sqrt{c_i}$ (TeV)	4.7	7.0	9.0	11	16	(68% C.L.)
ZZH ($\Delta\kappa_Z$)	1.4%	0.89%	0.61%	0.46%	0.21%	0.13% [17]
$\Lambda/\sqrt{c_i}$ (TeV)	2.1	2.6	3.2	3.6	5.3	(95% C.L.)
$WWHH$ ($\Delta\kappa_{W_2}$)	5.3%	1.3%	0.62%	0.41%	0.20%	5% [36]
$\Lambda/\sqrt{c_i}$ (TeV)	1.1	2.1	3.1	3.8	5.5	(68% C.L.)
HHH ($\Delta\kappa_3$)	25%	10%	5.6%	3.9%	2.0%	5% [22, 23]
$\Lambda/\sqrt{c_i}$ (TeV)	0.49	0.77	1.0	1.2	1.7	(68% C.L.)

Allow %-level trilinear Higgs measurements, and a consistent measurement between gauge boson-Higgs coupling measurements.



T. Han, D. Liu, I. Low, X. Wang, 2008.12204

Multi-Higgs & Higgs Self-couplings

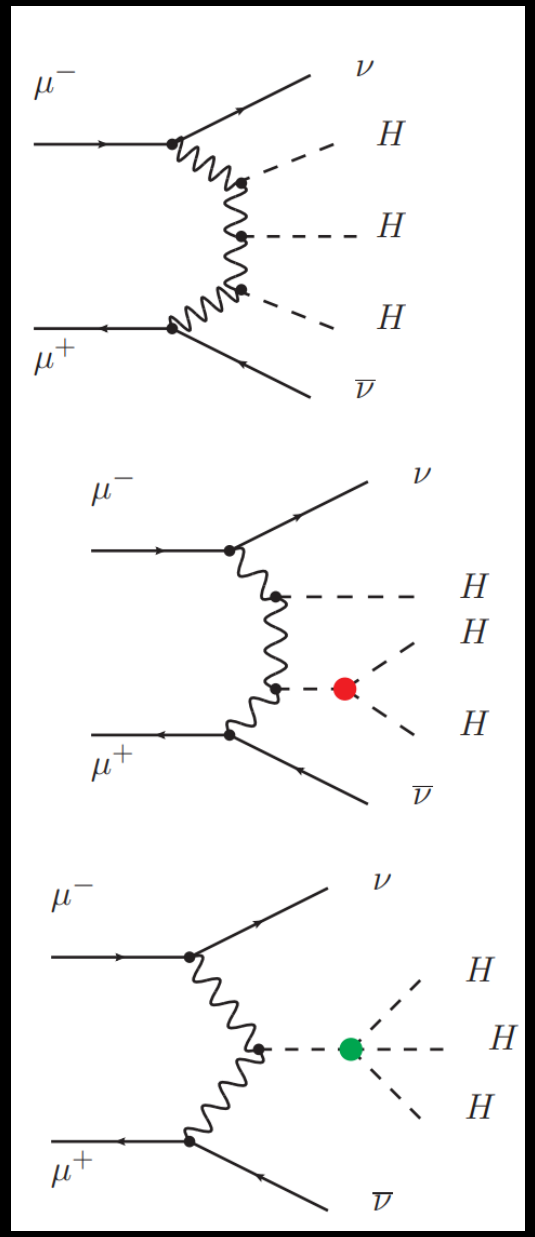


O(1) quartic determination possible.

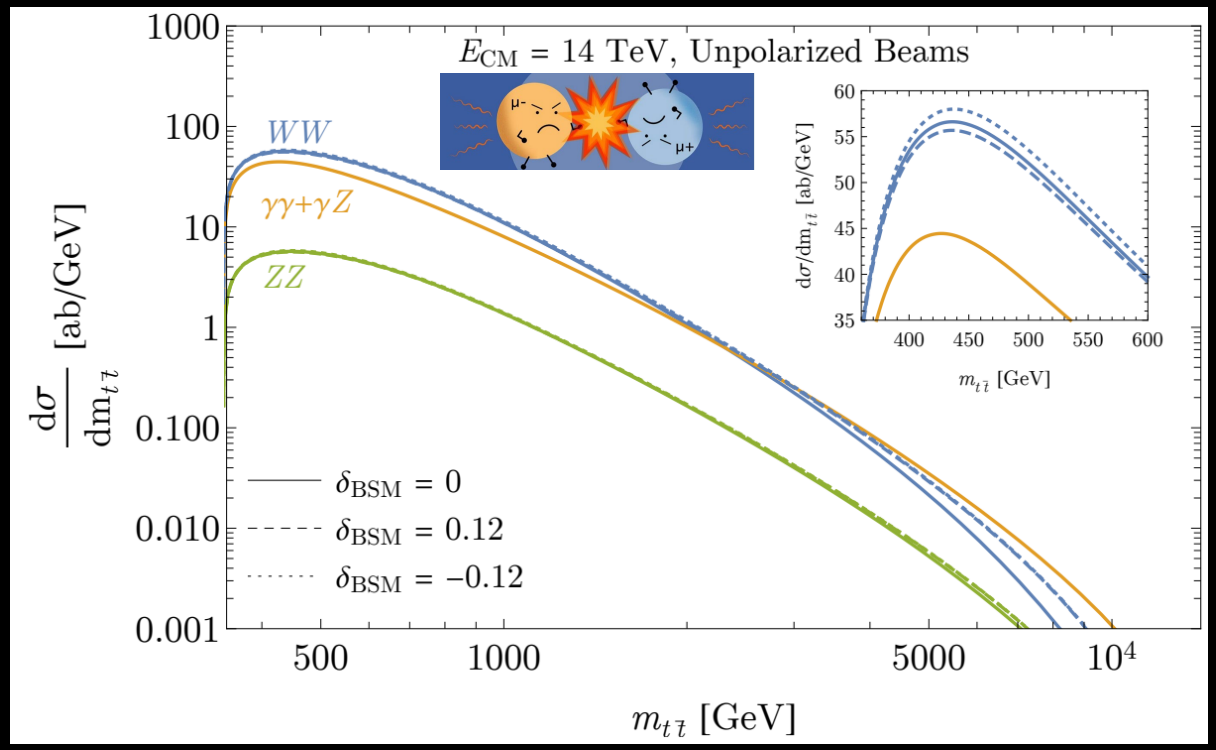
Chiesa, Maltoni, Mantani, Mele, Piccinini, 2003.13628

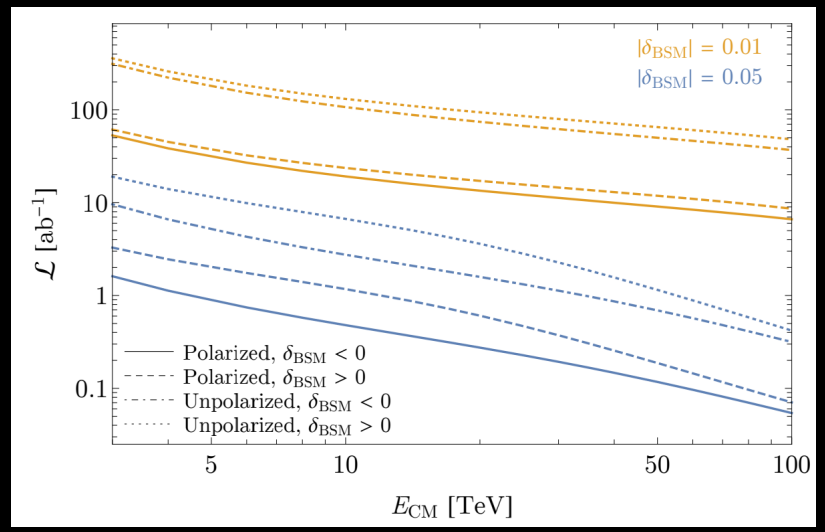
Correlated measurements of trilinear and quartic couplings reveals deep information about EFT and EWPT.

e.g, Huang, Joglekar, Wagner, 1512.00068 , Falkowski, Gonzalez-Alonso, Grejio, Marzocca, M. Son, 1609.06312, Chang, Luty, 1902.05556,+Abu-Ajamieh, M. Chen, 2009.11293; DiHiggs review 1910.00012



Top Yukawa from interference





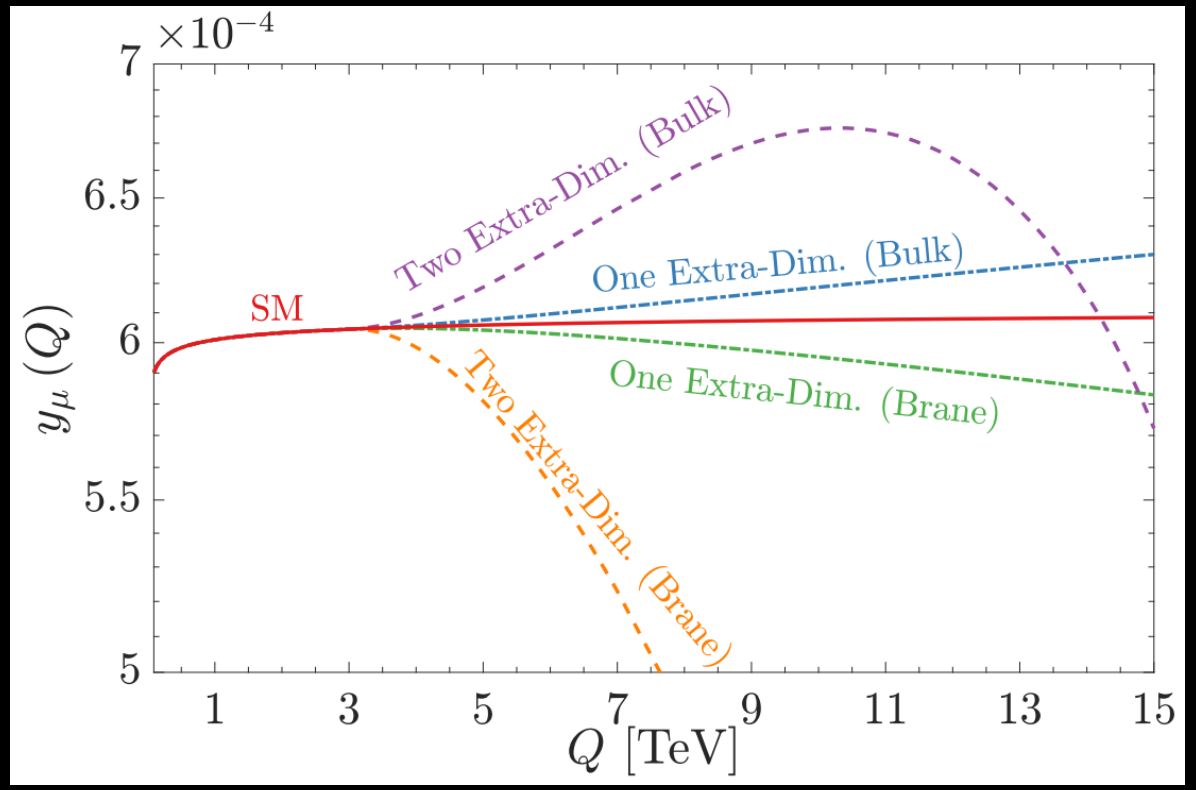
$t\bar{t}$ dominated by WW-fusion. The $W_L W_L$ contribution is large and sensitive to Higgs Yukawa deviations.
Higgs unitarize the $W_L W_L \to t\bar{t}$ to be $\log \hat{s}$.

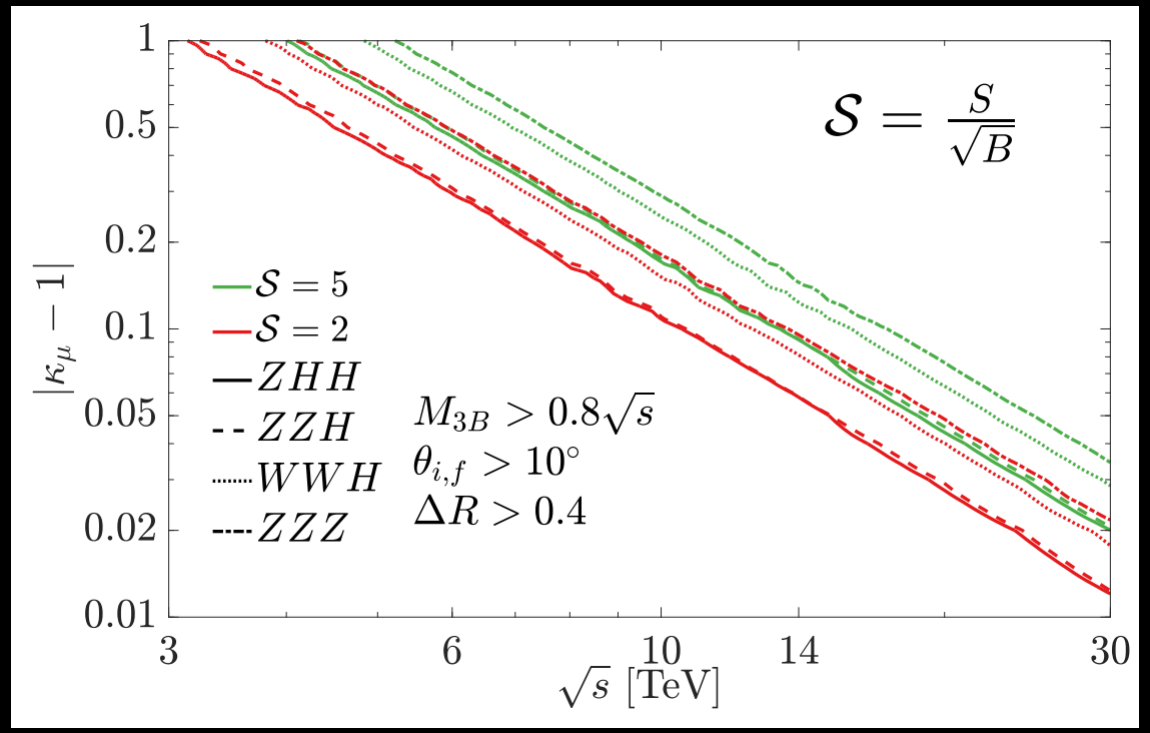
$$\mathcal{M}(W_L^+ W_L^- \to t\bar{t}) \simeq -\frac{m_t}{v^2}\delta_{BSM}\sqrt{\hat{s}}$$

Higgs Muon Couplings

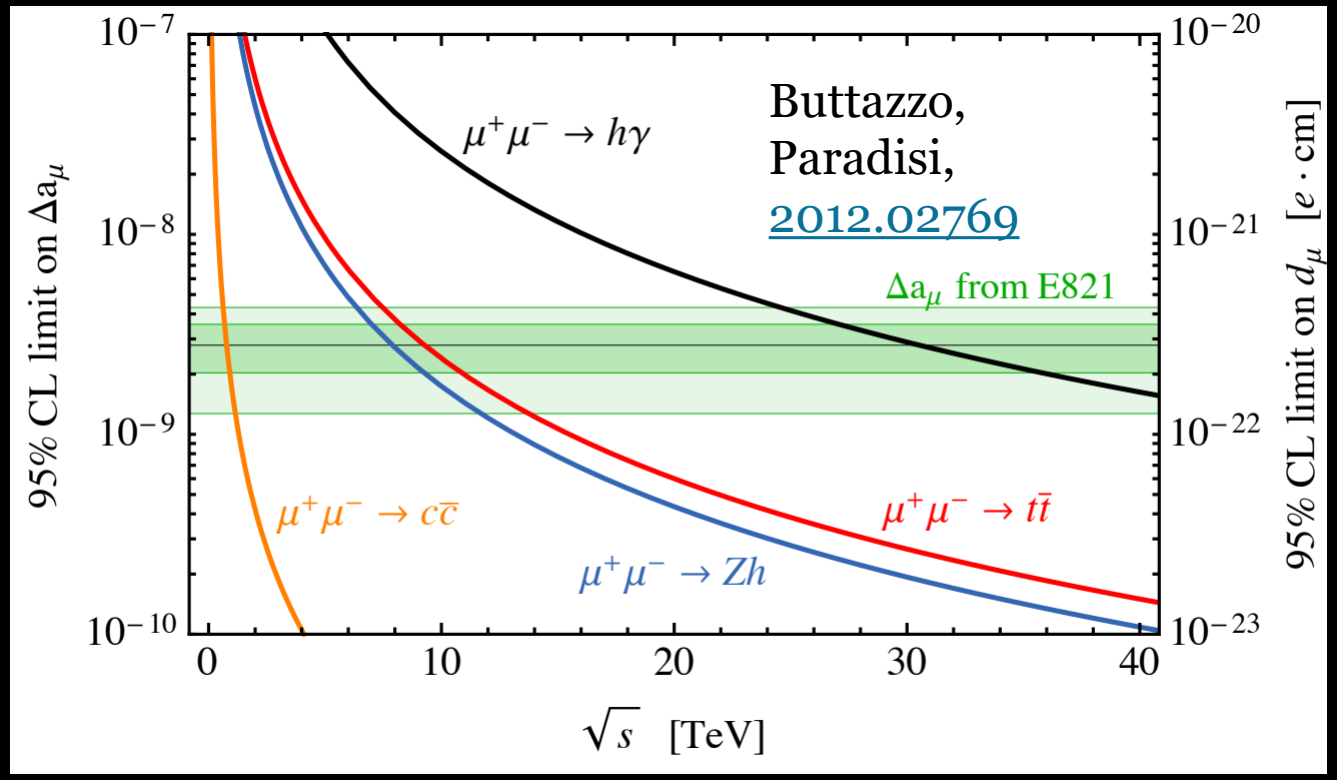
Running Yukawa

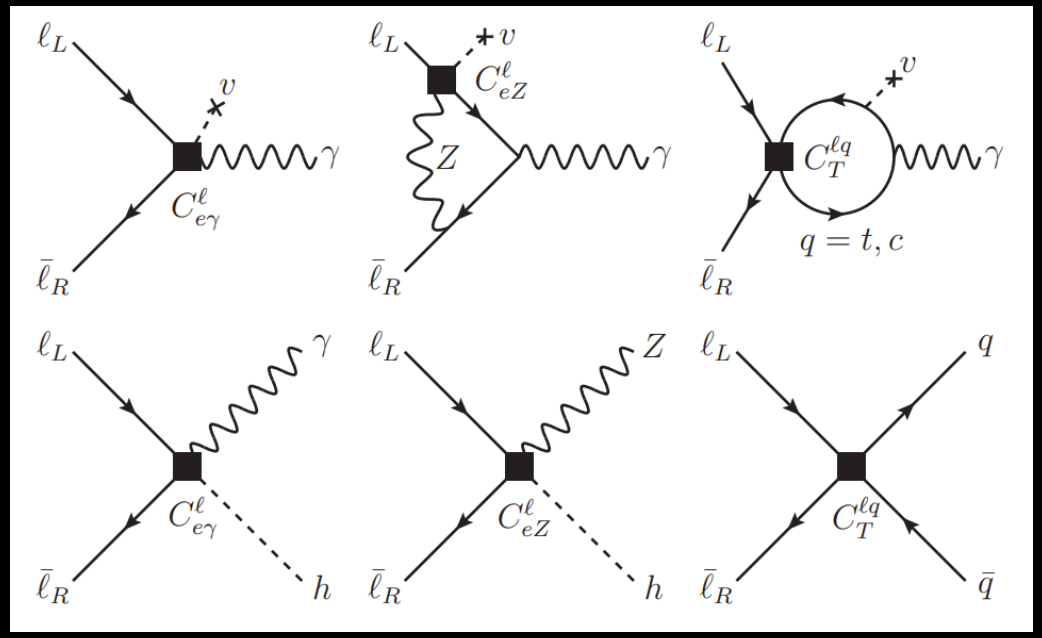
T. Han, W. Kilian, N. Kreher, Y. Ma, J. Reuter, 2108.05362





Complementarity: Muon g-2

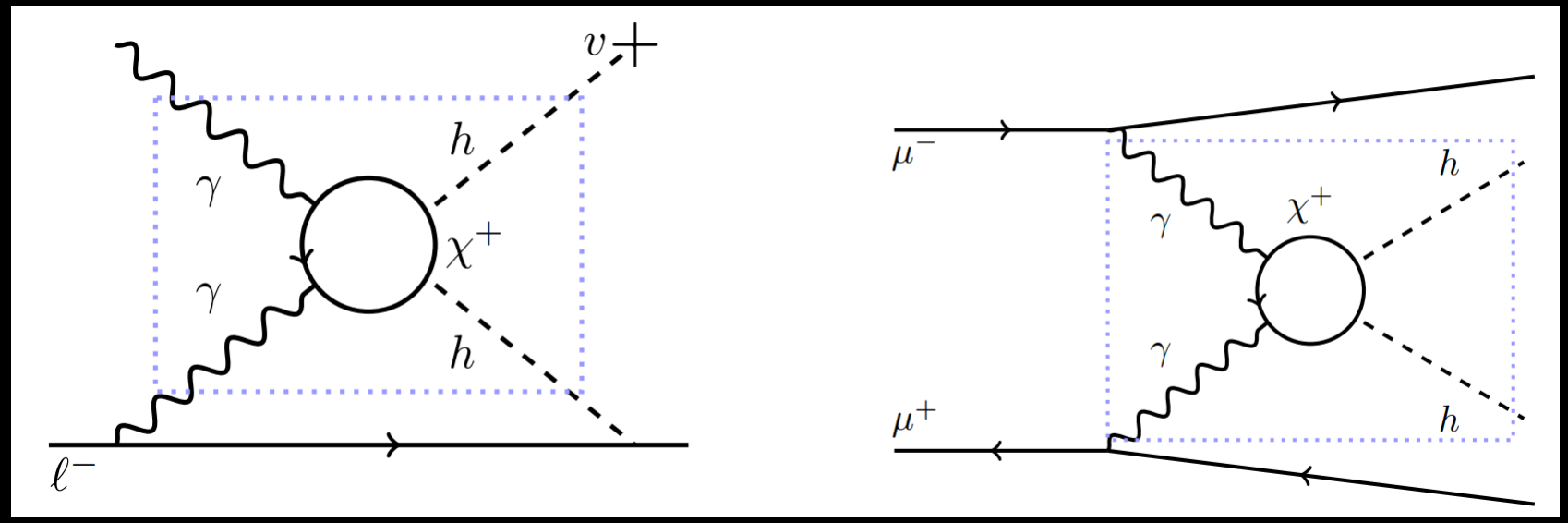




$$\mathcal{L} = \frac{C^\ell_{eB}}{\Lambda^2}(\bar{\ell}_L\sigma^{\mu\nu}e_R)HB_{\mu\nu} + \frac{C^\ell_{eW}}{\Lambda^2}(\bar{\ell}_L\sigma^{\mu\nu}e_R)\tau^I HW^I_{\mu\nu} + \frac{C^\ell_T}{\Lambda^2}(\bar{\ell}^a_L\sigma_{\mu\nu}e_R)\varepsilon_{ab}(\overline{Q}^b_L\sigma^{\mu\nu}u_R) + h.c. \quad (2$$

Also see various model-specific (complementary / comprehensive) discussions in Capdevilla, Curtin, Kahn, Krnjaic, 2006.16277, 2101.10334; W. Yin, Yamaguchi, 2012.03928; N. Chen, B. Wang, C.-Y., Yao, 2102.05619; Dermisek, Hermanek, McGinnis, 2108.10950

Complementarity: EDM



$$d_e \sim \sin(\delta_{\rm CP}) \frac{e\, m_e}{M^2} \left(\frac{\alpha}{4\pi}\right)^k \simeq 10^{-32}\, e\,\text{cm} \sin(\delta_{\rm CP}) \times \begin{cases} (1\ \text{PeV}/M)^2 & \text{for } k=1 \\ (20\ \text{TeV}/M)^2 & \text{for } k=2 \end{cases}$$

Summary

High Energy Muon Collider provides a vibrant and growing Higgs physics program:

- Baseline Precision couplings
- Higgs Self-coupling
- Top Yukawa through interference
- Muon Yukawa at different energies
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- + many more

$$\beta_{y_t} = \frac{\mathrm{d}y_t}{\mathrm{d}t} = \frac{y_t}{16\pi^2}\left(\frac{9}{2}y_t^2 - 8g_3^2 - \frac{9}{4}g_2^2 - \frac{17}{20}g_1^2\right), \tag{2.1}$$

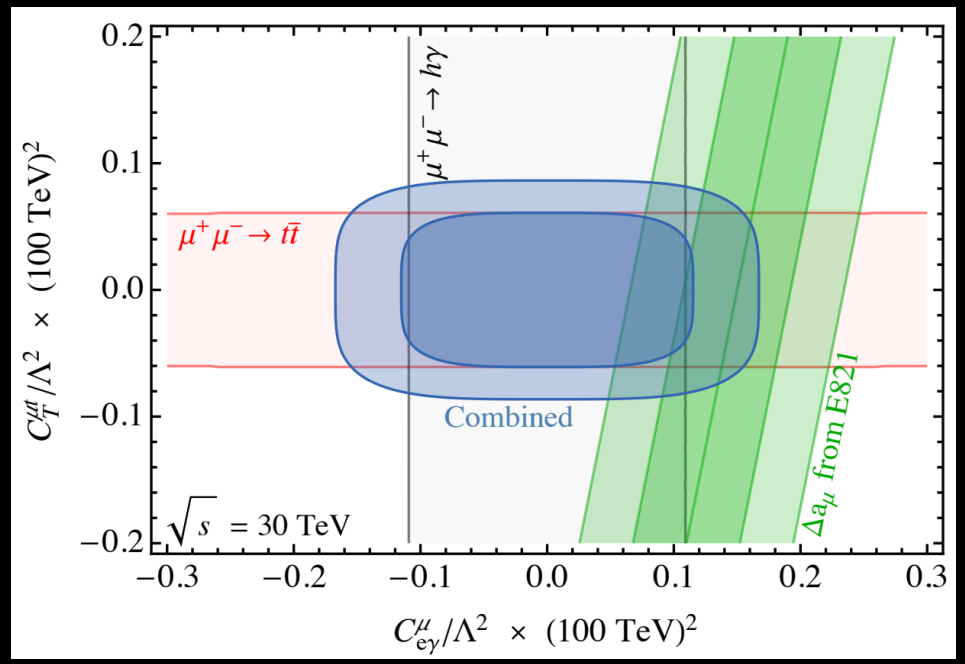
$$\beta_{y_\mu} = \frac{\mathrm{d}y_\mu}{\mathrm{d}t} = \frac{y_\mu}{16\pi^2}\left(3y_t^2 - \frac{9}{4}(g_2^2 + g_1^2)\right), \tag{2.2}$$

$$\beta_v = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{v}{16\pi^2}\left(\frac{9}{4}g_2^2 + \frac{9}{20}g_1^2 - 3y_t^2\right), \tag{2.3}$$

$$\beta_{g_i} = \frac{\mathrm{d}g_i}{\mathrm{d}t} = \frac{b_i g_i^3}{16\pi^2}, \tag{2.4}$$

with $t = \ln(Q/M_Z)$ and the coefficients b_i for the gauge couplings (g_1, g_2, g_3) given as

$$b_i^{\mathrm{SM}} = (41/10, -19/6, -7). \tag{2.5}$$



$\sqrt{s}$ (TeV)	Lumi (ab^{-1})	Constraints on δ_4 (with $\delta_3 = 0$) x-sec only, acceptance cuts		
		1 σ	2 σ	3 σ
6	12	$[-0.50, 0.70]$	$[-0.74, 0.95]$	$[-0.93, 1.15]$
10	20	$[-0.37, 0.54]$	$[-0.55, 0.72]$	$[-0.69, 0.85]$
14	33	$[-0.28, 0.43]$	$[-0.42, 0.58]$	$[-0.52, 0.68]$
30	100	$[-0.15, 0.30]$	$[-0.24, 0.38]$	$[-0.30, 0.45]$
3	100	$[-0.34, 0.64]$	$[-0.53, 0.82]$	$[-0.67, 0.97]$