CP Violating Top Yukawa Coupling at the Future Muon Collider

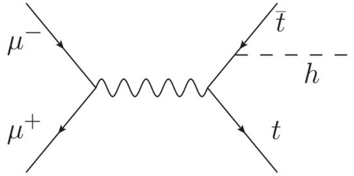
Ian Lewis
(University of Kansas)

Morgan Cassidy, Cosmos Dong, KC Kong,
Jenny Zhang, Yajuan Zheng

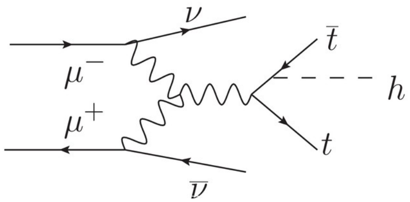
arXiv:2311.07645 [hep-ph]
JHEP 05 (2024) 176

Direct Probes of Top Yukawa

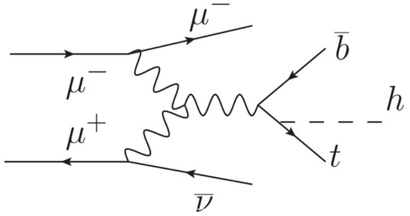
- Directly probe top Yukawa, need processes with a Higgs and top in final state.
- Representative diagrams:
  - tth:



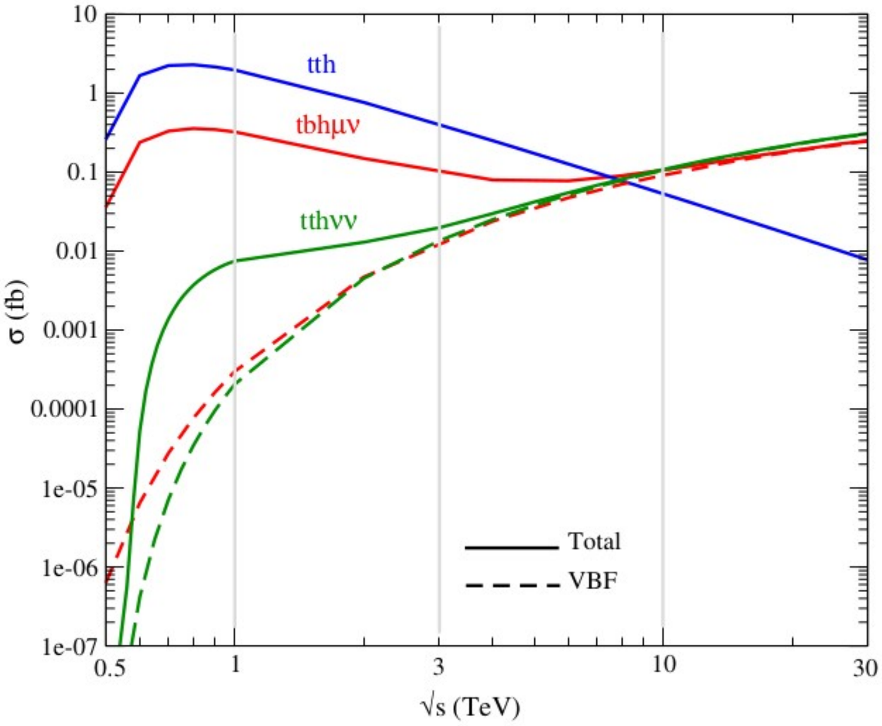
  - tthνν



  - tbhνμ



- Dotted lines are VBF-like diagrams.



Cassidy, Dong, Kong, **IML**, Zhang, Zheng, JHEP 05 (2024) 176

CP violating top quark Yukawa

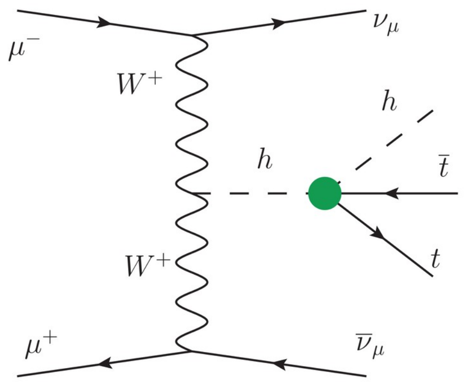
- The typical angular parameterization is not gauge invariant, can cause spurious growth with energy.

$$\kappa_{htt}\frac{m_t}{v}h\bar{t}\left(\cos\xi+i\,\gamma_5\sin\xi\right)t$$

- Use SMEFT to parameterize shift in a gauge invariant way:

$$\begin{aligned}\mathcal{L}_{htt,\mathrm{SMEFT}} &= -y_t\bar{Q}_L\widetilde{\Phi}t_R - c_t\Phi^\dagger\Phi\bar{Q}_L\widetilde{\Phi}t_R + \mathrm{h.c.}\\ &= -m_t\bar{t}t - g_{htt}h\bar{t}\left(\cos\xi + i\,\gamma_5\,\sin\xi\right)t\\ &\quad -\frac{3}{2}g_{htt}\frac{h^2}{v}\left(1+\frac{h}{3\,v}\right)\bar{t}\left(\cos\xi - \frac{1}{\kappa_{htt}} + i\,\gamma_5\,\sin\xi\right)t,\end{aligned}$$

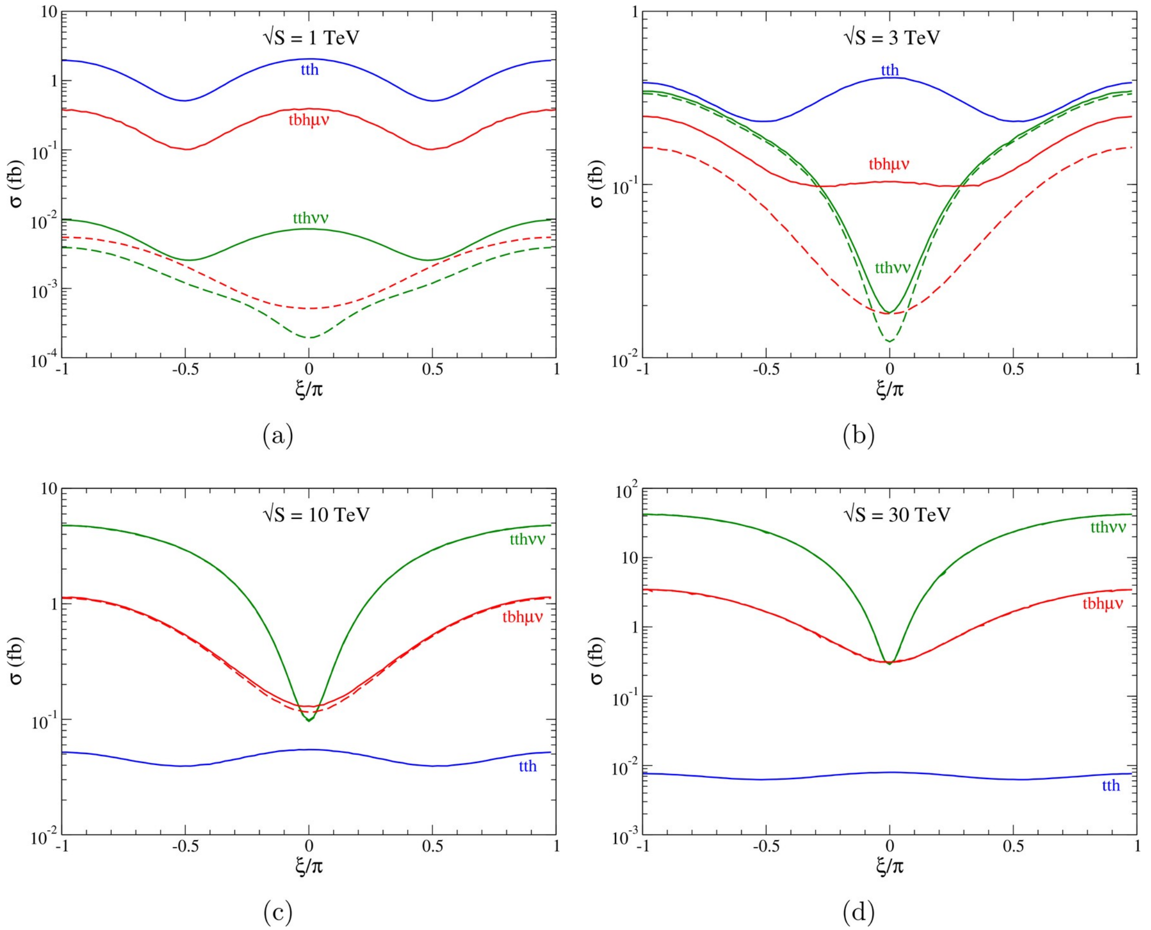
$$g_{htt} \equiv (m_t/v)\kappa_{htt}$$



- Introduces a new 4-point interaction: t-t-h-h.

Cross Section Dependence on Phase

- Dashed: VBF-like diagrams.
- Very different behaviour at different energies and for different diagram types.
  - S-channel type diagrams peak at the SM value
  - VBF style diagrams are at a minimum at the SM value.
- VBF style diagrams strongly dependent on CP violating phase at high energies.
- Can parameterize cross sections in terms of the CP-violating phase.
  - Cross sections are CP-even.
  - Can only depend on powers of $\cos\theta$



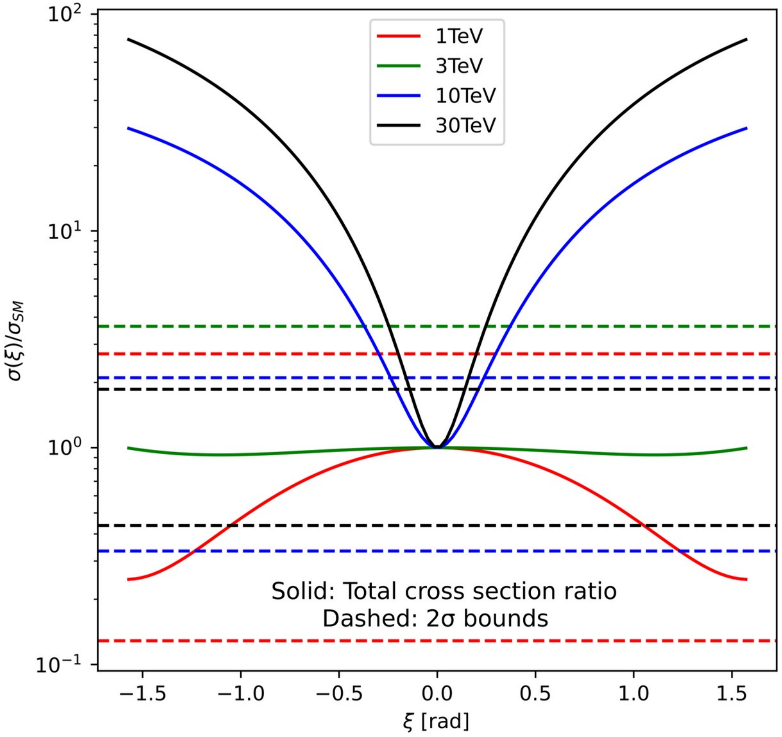
(a) (b) (c) (d)

Cassidy, Dong, Kong, **IML**, Zhang, Zheng, JHEP 05 (2024) 176

ξ bounds

- Benchmark luminosities:
  - 1 TeV: 100 fb^{-1}
  - 3 TeV: 1 ab^{-1}
  - 10 TeV: 10 ab^{-1}
  - 30 TeV: 10 ab^{-1}
- Signals added together and 90% b-tagging rate applied.
  - Sharp dependence on ξ at 10 TeV and 30 TeV provides strong constraints.
- Precision on top Yukawa in ttH comparable to previous results.

Forslund, Meade, arXiv:2203.09425



Projected 1σ (2σ) bounds on $\lvert\xi\rvert$			
ε_b	$\sqrt{s}=1$ TeV	$\sqrt{s}=10$ TeV	$\sqrt{s}=30$ TeV
0.6	*	$\lvert\xi\rvert < 15^\circ$ (23°)	$\lvert\xi\rvert < 8.6^\circ$ (14°)
0.7	*	$\lvert\xi\rvert < 12^\circ (19^\circ)$	$\lvert\xi\rvert < 7.2^\circ$ (11°)
0.8	$\lvert\xi\rvert < 67^\circ$ (*) or $\lvert\xi\rvert > 114^\circ$ (*)	$\lvert\xi\rvert < 10^\circ$ (16°)	$\lvert\xi\rvert < 6.2^\circ$ (9.3°)
0.9	$\lvert\xi\rvert < 57^\circ$ (*) or $\lvert\xi\rvert > 125^\circ$ (*)	$\lvert\xi\rvert < 9.0^\circ$ (14°)	$\lvert\xi\rvert < 5.4^\circ$ (8.0°)

Cassidy, Dong, Kong, **IML**, Zhang, Zheng, JHEP 05 (2024) 176

Thank You

ξ bounds

Projected 1σ (2σ) bounds on $|\xi|$			
ε_b	$\sqrt{s} = 1$ TeV	$\sqrt{s} = 10$ TeV	$\sqrt{s} = 30$ TeV
0.6	*	$|\xi| < 15^\circ$ (23°)	$|\xi| < 8.6^\circ$ (14°)
0.7	*	$|\xi| < 12^\circ (19^\circ)$	$|\xi| < 7.2^\circ$ (11°)
0.8	$|\xi| < 67^\circ$ (*) or $|\xi| > 114^\circ$ (*)	$|\xi| < 10^\circ$ (16°)	$|\xi| < 6.2^\circ$ (9.3°)
0.9	$|\xi| < 57^\circ$ (*) or $|\xi| > 125^\circ$ (*)	$|\xi| < 9.0^\circ$ (14°)	$|\xi| < 5.4^\circ$ (8.0°)

Cassidy, Dong, Kong, **IML**, Zhang, Zheng, 2311.07645

- Comparing different b-tagging efficiency scenarios.
- Favorably compares to other direct probes at proposed future colliders:

Bounds on α at 95% CL ($\kappa_t = 1$)	Channel	Collider	Luminosity
$|\alpha| \lesssim 36^\circ$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	HL-LHC	3 ab^{-1}
$|\alpha| \lesssim 25^\circ$ [2]	$t\bar{t}(h \to \gamma\gamma)$ combination	HL-LHC	3 ab^{-1}
$|\alpha| \lesssim 3^\circ$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	100 TeV FCC	30 ab^{-1}

Barman, et al., arXiv:2203.0817

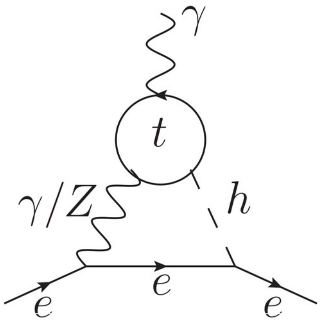
Properties of top quark Yukawa

- Beyond strength of coupling, interested in properties of the Higgs boson.
  - Is it a CP eigenstate?
  - Many measurements and studies on this.
  - Measure in couplings to tau's, gauge bosons, and top quark.
  - Different couplings can have different CP properties.
- Will focus on CP properties of the top Yukawa.
  - Will parameterize the top Yukawa as:

$$\kappa_t \frac{m_t}{v} h \bar{t} \left(\cos \xi + i \gamma_5 \sin \xi \right) t$$

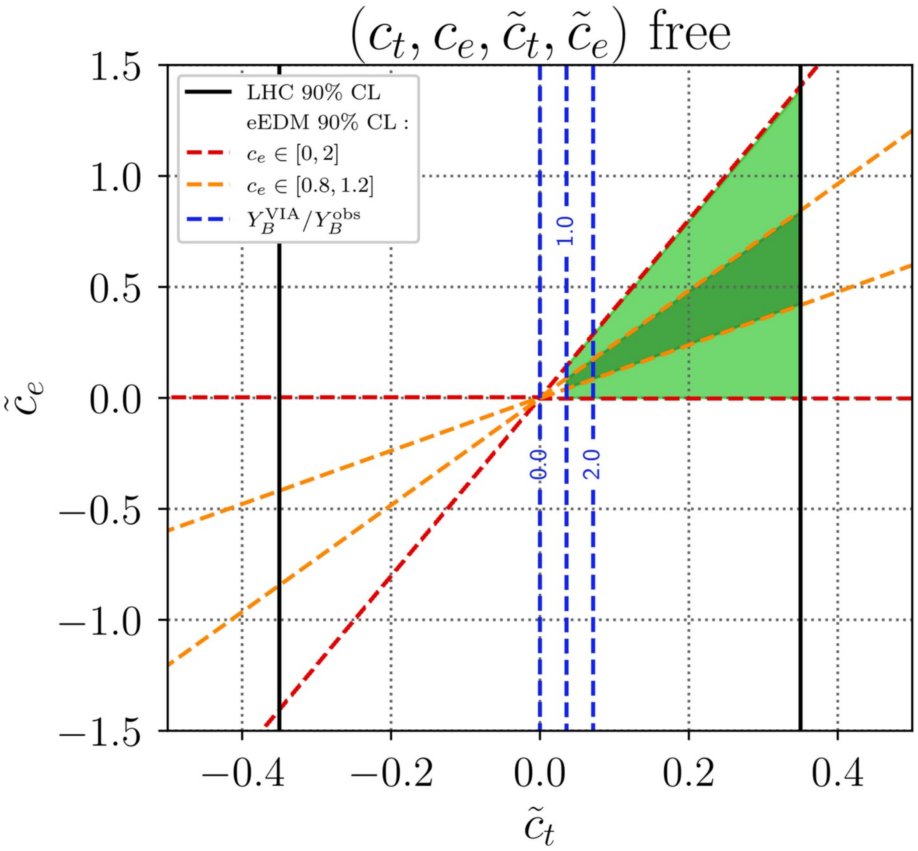
  - Older constraints from ATLAS: $|\xi| < 0.75 \left(43° \right)$ PRL 125 (2020) 061802
  - Current constraints from ATLAS: $\xi = 11°^{+52°}_{-73°}, \kappa_t = 0.84^{+0.30}_{-0.46}$ arXiv: 2303.05974[hep-ph]
- Can be bounded very strongly by EDMs. Need direct measurements, though.

EDM Constraints



- Very strong constraints on electron EDMs.
  - $|\xi|<0.0014\,(0.08\,°)$ Brod et al JHEP08 (2022) 294
- The strong constraints depend on electron-Higgs coupling.
  - Not observed yet.
  - If we allow it to change can greatly relax constraints.
  - Hence, direct measurement of CP-violating are important
- Similar results for neutron EDMs

Brod, Haisch, Zupan JHEP 11 (2013)



Bahl et al EPJC82 (2022) 604

$$\mathcal{L}_{\rm yuk} = -\sum_{f=u,d,c,s,t,b,e,\mu,\tau} \frac{y_f^{\rm SM}}{\sqrt{2}} \bar{f}\,(c_f + i\gamma_5 \tilde{c}_f)\, f H,$$

Direct Searches at Future colliders

- Need processes with Higgs+top in the final state to directly probe top quark Yukawa

Bounds on α at 95% CL ($\kappa_t = 1$)	Channel	Collider	Luminosity
$\lvert\alpha\rvert \lesssim 36^\circ$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 25^\circ$ [2]	$t\bar{t}(h \to \gamma\gamma)$ combination	HL-LHC	3 ab^{-1}
$\lvert\alpha\rvert \lesssim 3^\circ$ [1]	dileptonic $t\bar{t}(h \to b\bar{b})$	100 TeV FCC	30 ab^{-1}

Barman, et al., arXiv:2203.0817

$$f_{CP}^{Hf\bar{f}} = \sin^2\left(\alpha^{Hf\bar{f}}\right)$$

Collider	pp	pp	pp	e^+e^-	e^+e^-	e^+e^-	e^+e^-	e^-p	$\gamma\gamma$	$\mu^+\mu^-$	$\mu^+\mu^-$	target
E (GeV)	14,000	14,000	100,000	250	350	500	1,000	1,300	125	125	3,000	(theory)
$\mathcal{L}$ (fb^{-1})	300	3,000	30,000	250	350	500	1,000	1,000	250	20	1,000	
HZZ/HWW	$4.0{\cdot}10^{-5}$	$2.5{\cdot}10^{-6}$	✓	$3.9{\cdot}10^{-5}$	$2.9{\cdot}10^{-5}$	$1.3{\cdot}10^{-5}$	$3.0{\cdot}10^{-6}$	✓	✓	✓	✓	$< 10^{-5}$
$H\gamma\gamma$	–	0.50	✓	–	–	–	–	–	0.06	–	–	$< 10^{-2}$
$HZ\gamma$	–	$\sim$1	✓	–	–	–	$\sim$1	–	–	–	–	$< 10^{-2}$
Hgg	0.12	0.011	✓	–	–	–	–	–	–	–	–	$< 10^{-2}$
$Ht\bar{t}$	0.24	0.05	✓	–	–	0.29	0.08	✓	–	–	✓	$< 10^{-2}$
$H\tau\tau$	0.07	0.008	✓	0.01	0.01	0.02	0.06	–	✓	✓	✓	$< 10^{-2}$
$H\mu\mu$	–	–	–	–	–	–	–	–	–	✓	–	$< 10^{-2}$

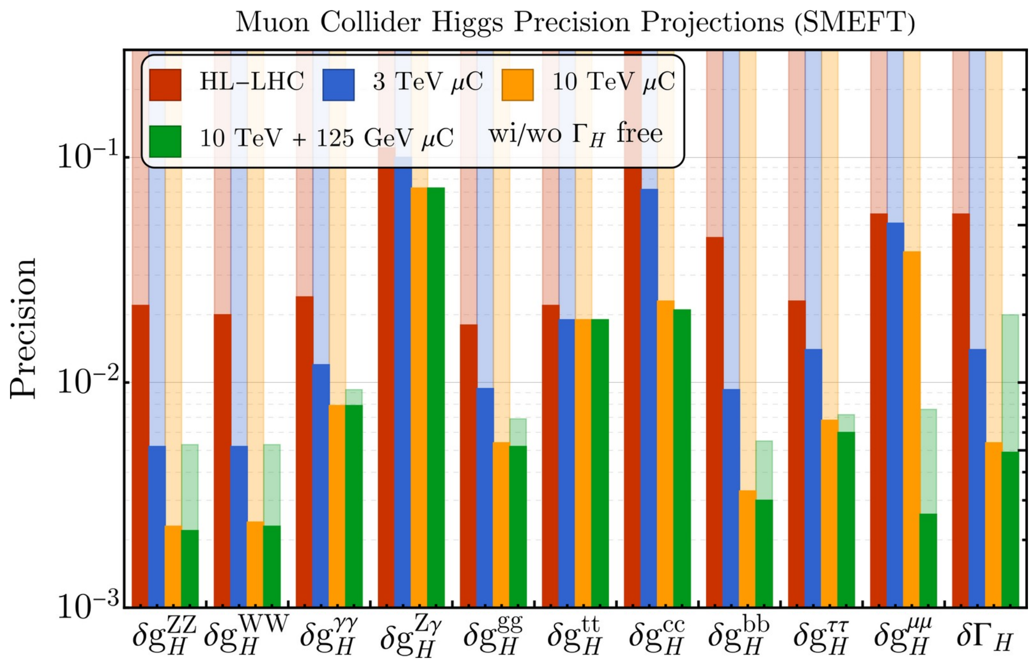
Gritsan et al arXiv:2205.07715

Measuring Top Yukawa at Muon Colliders

- Direct probe: top+Higgs production.
  - 3 TeV: $\Delta\sigma/\sigma = 61\%$
  - 10 TeV: $\Delta\sigma/\sigma = 53\%$

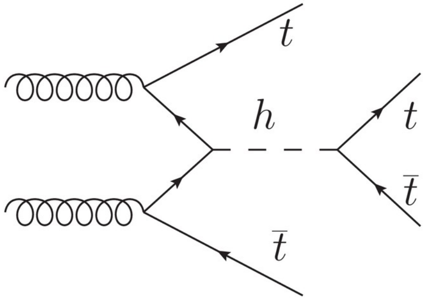
  Forslund, Meade, JHEP08 (2022) 185
- Compare to combinations with HL-LHC.

  Muon Collider Forum Report, arXiv:2209.01318

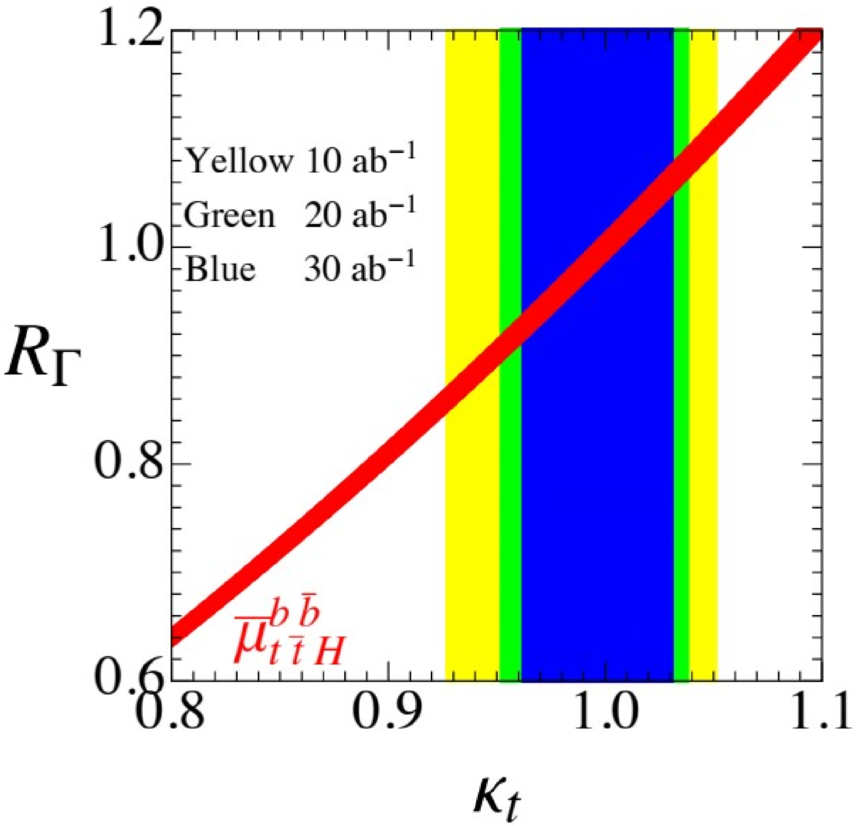


Top Yukawa at 100 TeV

- Bands for κ_t measurement from $t\bar{t}t\bar{t}$



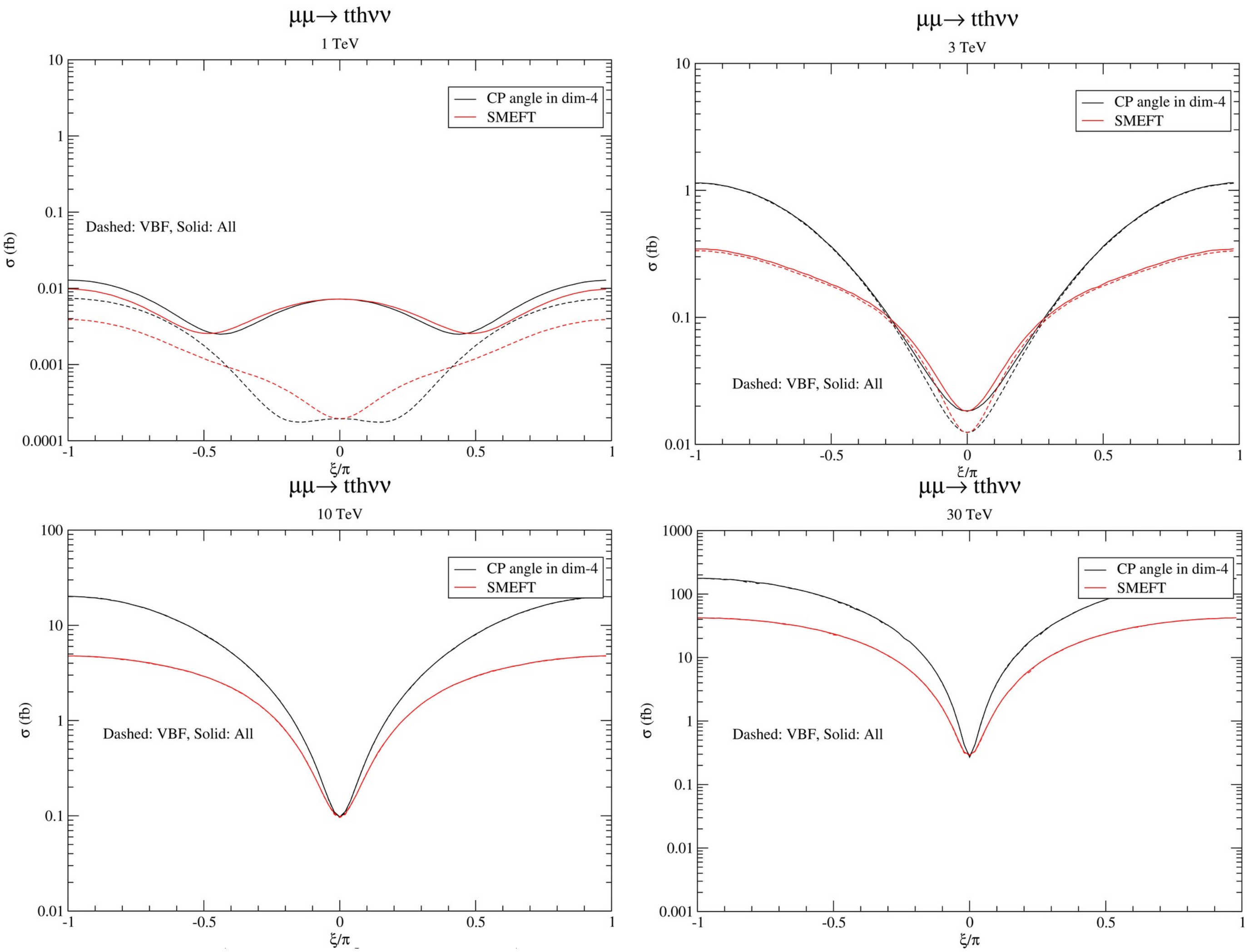
  - Yellow: 10 ab^{-1}
  - Green: 20 ab^{-1}
  - Blue: 30 ab^{-1}
- $R_\Gamma = \Gamma_H / \Gamma_{H,SM}$



arXiv:1606.09408

Importance of EFT

- Comparing SMEFT and dimension-4 angular parameterizations.



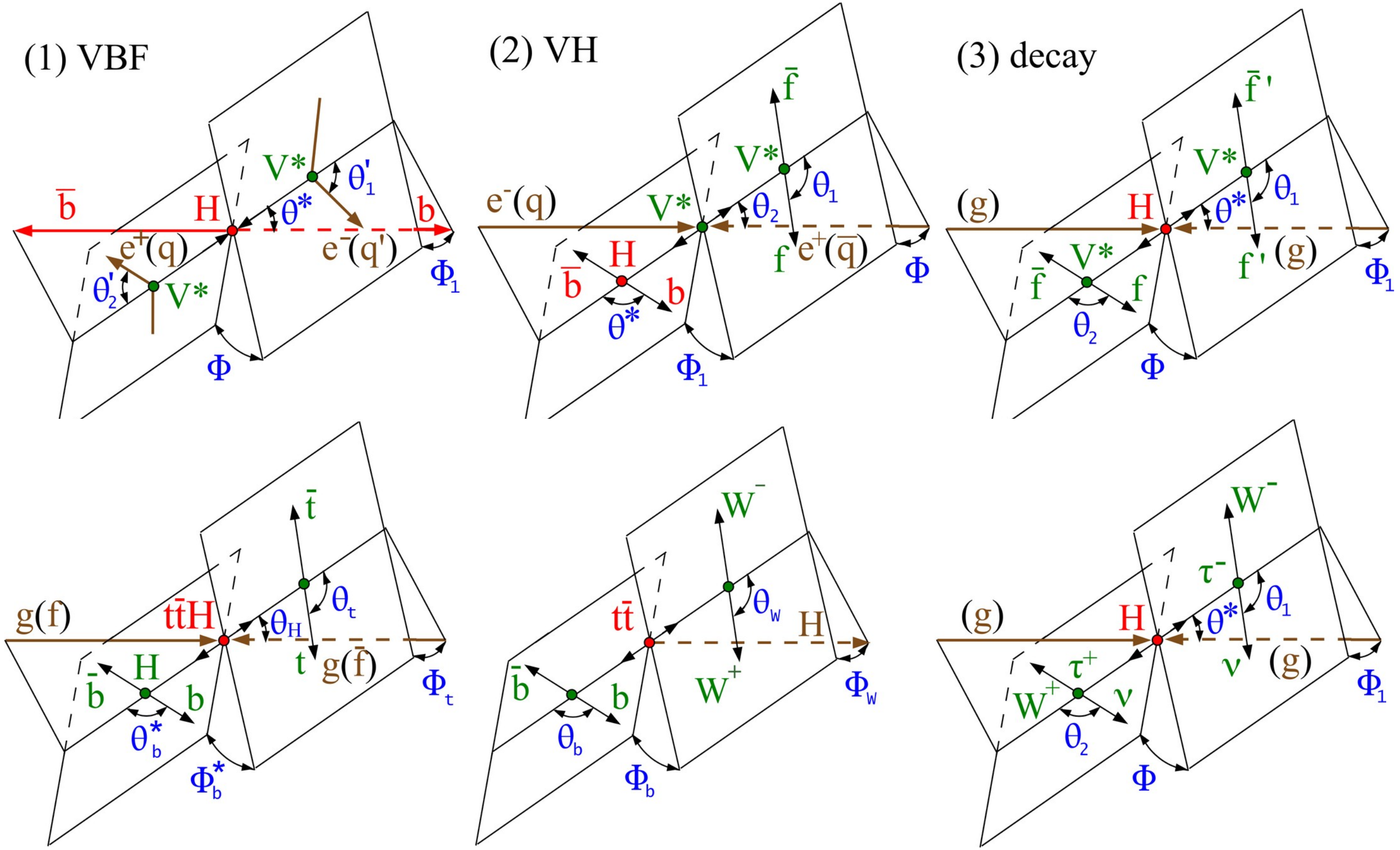
CP Violating Variables

Observables Sensitive to CP violation

- Cross section very sensitive to CP violating angle.
- However, to cross section is CP-even.
  - Observe a deviation, no guarantee that the there is true CP violation.
- Observables sensitive to CP violation are angles between different production and decay planes and/or triple products.
- Will investigate several process by process.
- Purely theoretical investigation with no decays.
  - It is likely that first indication of a CP violating phase at a muon collider with energies of 10 TeV or larger would be a change in the total cross section.
  - Measuring CP violating observables would be needed to verify source of change in cross section.

Typical CPV variables

- Create angles between production/decay planes or triple products.



Gritsan et al arXiv:2205.07715

tth

- First, consider tth production.

$$\mu^+\mu^- \to t\bar{t}h,$$

- Create an angle between the tt system and initial anti-muon-Higgs system. Bar-Shalom, Atwood, Eilam, Soni PRD53 (1996) 1162; Hagiwara, Yokoya, Zheng JHEP02 (2018) 180; etc.
  - Define the momentum of the planes:

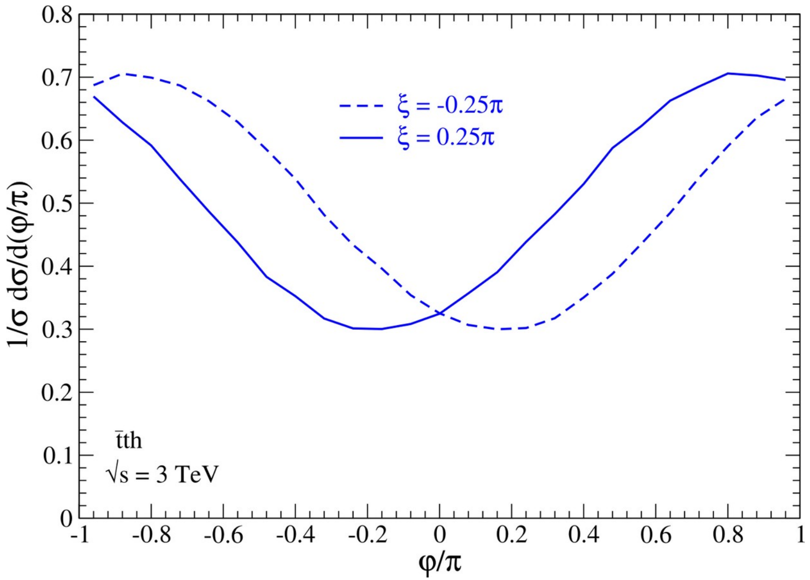
$$\vec{p}_{t\bar{t}} = \vec{p}_t + \vec{p}_{\bar{t}}.$$

$$\vec{p}_{h\mu^-} = \vec{p}_h + \vec{p}_{\mu^-}$$

- Create the observable, which is the angle between the planes:

$$\phi = \text{sign}\left[\vec{p}_{t\bar{t}} \cdot (\vec{p}_{\mu^-} \times \vec{p}_t)\right] \arccos\left[\frac{\vec{p}_{h\mu^-} \times \vec{p}_{\mu^-}}{|\vec{p}_{h\mu^-} \times \vec{p}_{\mu^-}|} \cdot \frac{\vec{p}_{t\bar{t}} \times \vec{p}_t}{|\vec{p}_{t\bar{t}} \times \vec{p}_t|}\right]$$

CP violating observable for tth

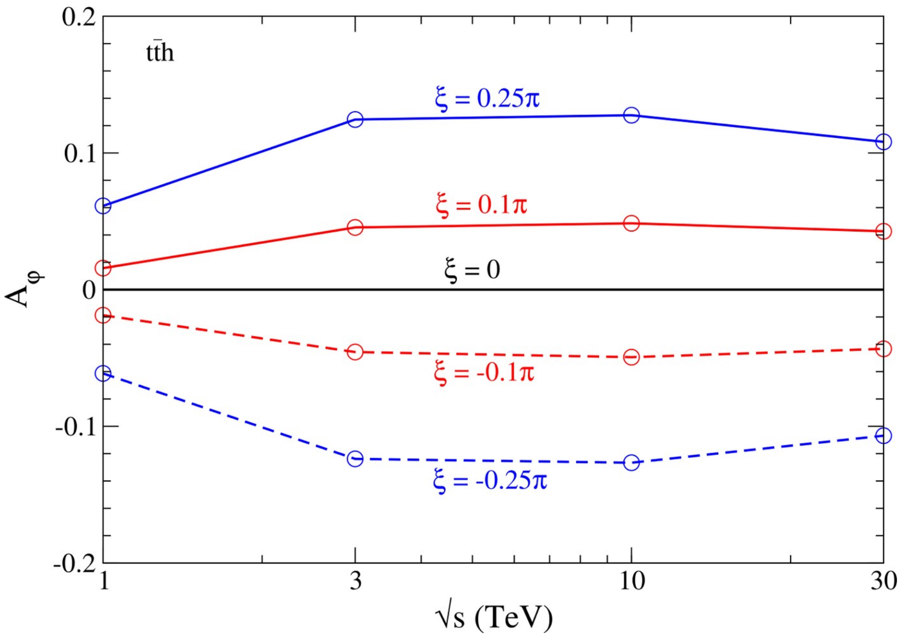


Cassidy, Dong, Kong, **IML**, Zhang, Zheng, 2311.07645

$$\phi = \mathrm{sign}\left[\vec{p}_{t\bar{t}} \cdot (\vec{p}_{\mu^-} \times \vec{p}_t)\right] \arccos\left[\frac{\vec{p}_{h\mu^-} \times \vec{p}_{\mu^-}}{|\vec{p}_{h\mu^-} \times \vec{p}_{\mu^-}|} \cdot \frac{\vec{p}_{t\bar{t}} \times \vec{p}_t}{|\vec{p}_{t\bar{t}} \times \vec{p}_t|}\right]$$

- Clearly dependent on the sign of the angle.
  - Sensitive to CPV
- Note: Show results for 3 TeV. As we will show, at this energy the CPV observables may need be necessary.
  - Cross section measurements turn out to be relatively insensitive to CPV at this energy.

Asymmetry Parameter



Cassidy, Dong, Kong, **IML**, Zhang, Zheng, 2311.07645

- Define asymmetry to maximally utilize data:

$$A_\phi = \frac{\sigma(\phi > 0) - \sigma(\phi < 0)}{\sigma(\phi > 0) + \sigma(\phi < 0)}$$

tbhνμ and tthνν

- Consider both processes:

$$\mu^+\mu^- \to t\bar{t}h\nu\bar{\nu} \equiv t\bar{t}h\nu_\ell\bar{\nu}_\ell \quad (\ell = e,\ \mu \text{ and } \tau),$$
$$\mu^+\mu^- \to tbh\mu\nu \equiv t\bar{b}h\mu^-\nu_\mu + \bar{t}bh\mu^+\bar{\nu}_\mu;$$

- Many more possible momentum to create observables.

Bar-Shalom, Atwood, Eilam, Soni PRD53 (1996) 1162; The Higgs Hunters Guide, Gunion, He, PRL76 (1996) 4468

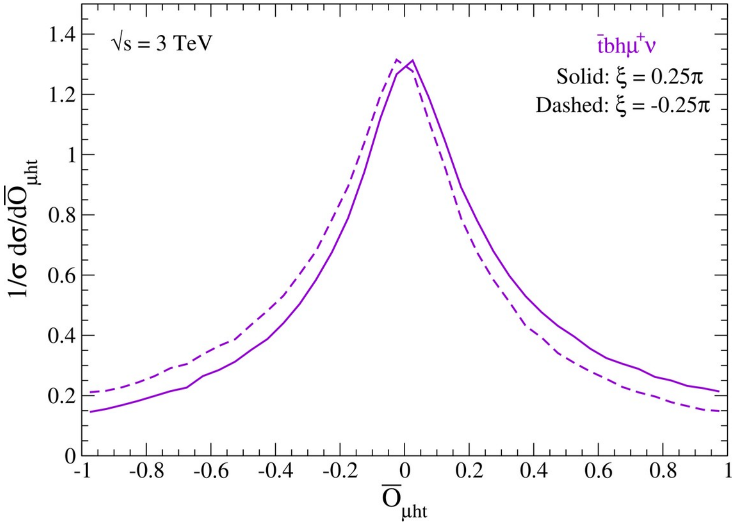
  - For both cases, create a triple product between the final state top quark, Higgs, and initial state muon:

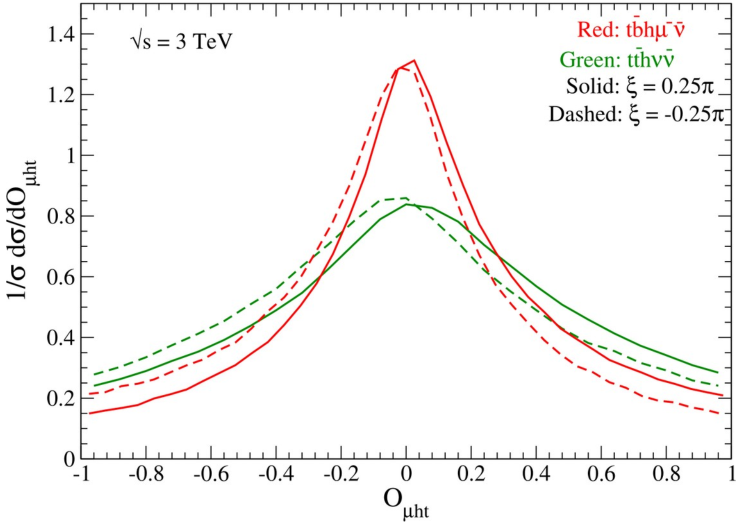
$$\mathcal{O}_{\mu h t} \equiv \frac{(\vec{p}_{\mu^-} \times \vec{p}_h) \cdot \vec{p}_t}{|\vec{p}_{\mu^-} \times \vec{p}_h||\vec{p}_t|};$$

- For tbhνμ with consider process with top quark and anti-top quark separately.
  - For anti-top quark can define conjugate triple product.

$$\overline{\mathcal{O}}_{\mu h t} \equiv \frac{(\vec{p}_{\mu^+} \times \vec{p}_h) \cdot \vec{p}_{\bar{t}}}{|\vec{p}_{\mu^+} \times \vec{p}_h||\vec{p}_{\bar{t}}|}.$$

tbhνμ and tthνν





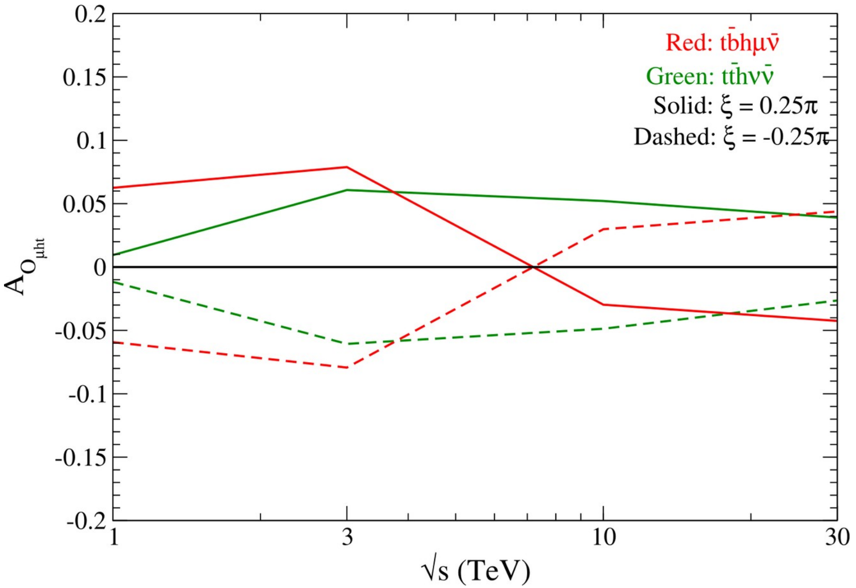
Cassidy, Dong, Kong, **IML**, Zhang, Zheng, 2311.07645

- CPV observables:

$$\mathcal{O}_{\mu ht} \equiv \frac{(\vec{p}_{\mu^-} \times \vec{p}_h) \cdot \vec{p}_t}{|\vec{p}_{\mu^-} \times \vec{p}_h||\vec{p}_t|}, \qquad \overline{\mathcal{O}}_{\mu ht} \equiv \frac{(\vec{p}_{\mu^+} \times \vec{p}_h) \cdot \vec{p}_{\bar{t}}}{|\vec{p}_{\mu^+} \times \vec{p}_h||\vec{p}_{\bar{t}}|}.$$

  - Separation for signs of CP violating angle.
  - tbhνμ αnd conjugate process have similar behavior.
  - tbhνμ is more peaked near zero than tthνν
  - Separation is relatively small, look at asymmetry parameters.

Asymmetry Parameters



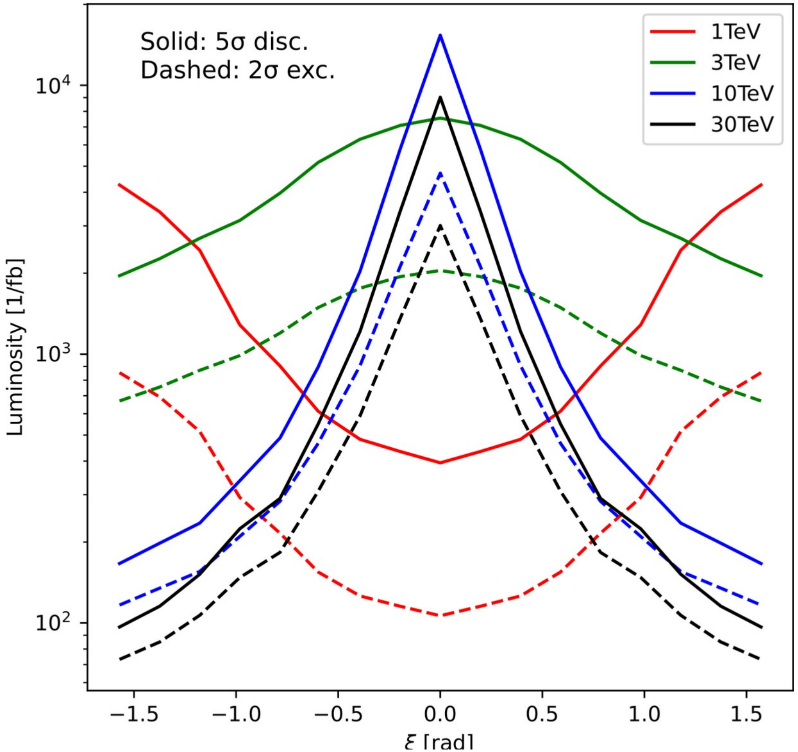
Cassidy, Dong, Kong, **IML**, Zhang, Zheng, 2311.07645

- Define asymmetry parameter:

$$A_{\mathcal{O}_{\mu ht}} = \frac{\sigma(\mathcal{O}_{\mu ht} > 0) - \sigma(\mathcal{O}_{\mu ht} < 0)}{\sigma(\mathcal{O}_{\mu ht} > 0) + \sigma(\mathcal{O}_{\mu ht} < 0)}$$

Luminosity needed for Discovery

- Solid: Luminosity needed for 5σ discovery.
- Dashed: Luminosity needed for 2σ exclusion.
- All signals added together
  - Differences between energies due to differences in cross dependence on ξ
- 90% b-tagging efficiency applied.
- Luminosity benchmarks:
  - 1 TeV: 100 fb^{-1}
  - 3 TeV: 1 ab^{-1}
  - 10 TeV: 10 ab^{-1}
  - 30 TeV: 10 ab^{-1}



Cassidy, Dong, Kong, **IML**, Zhang, Zheng, 2311.07645

Cross Section Dependence

- At the SM values, strong destructive interference in $tth\nu\nu$ and $tbh\mu\nu$ at high energies.
  - Interference between Higgs radiated from gauge boson or top quarks.

$$\sigma_{tbh\mu\nu}(\xi = 0) = 0.31 \text{ fb} \quad \sigma_{tth\nu\nu}(\xi = 0) = 0.31 \text{ fb}.$$
$$\sigma_{tbh\mu\nu}(\xi = \pm\pi) = 3.5 \text{ fb} \quad \sigma_{tth\nu\nu}(\xi = \pm\pi) = 43 \text{ fb}.$$

  - Similar effect in single top+Higgs production at the LHC.
    - Small SM cross section, but very large enhancement for wrong sign Yukawas.
- Total cross section very sensitive to CP angle.

$$\sigma(X) = C_X^4 \cos^4\xi + C_X^3 \cos^3\xi + C_X^2 \cos^2\xi + C_X^1 \cos\xi + C_x^0$$

Process	$\sqrt{s}$ (TeV)	C^0 (fb)	C^1 (fb)	C^2 (fb)	C^3 (fb)	C^4 (fb)
$t\bar{t}h$	1	0.511	0.0465	1.523	-	-
	3	0.233	0.0134	0.173	-	-
	10	0.0397	$1.48 \cdot 10^{-3}$	0.0142	-	-
	30	$6.33 \cdot 10^{-3}$	$1.69 \cdot 10^{-4}$	$1.53 \cdot 10^{-3}$	-	-
$tbh\mu\nu$	1	0.108	$8.29 \cdot 10^{-3}$	0.312	-	-
	3	0.122	-0.0717	0.0537	-	-
	10	0.537	-0.503	0.0967	-	-
	30	1.66	-1.57	0.224	-	-
$t\bar{t}h\nu\bar{\nu}$	1	$2.57 \cdot 10^{-3}$	$-5.83 \cdot 10^{-4}$	$6.12 \cdot 10^{-3}$	$-6.88 \cdot 10^{-4}$	$-1.70 \cdot 10^{-4}$
	3	0.184	-0.119	$4.25 \cdot 10^{-3}$	-0.0468	$-4.50 \cdot 10^{-3}$
	10	2.92	-2.06	-0.468	-0.280	-0.0149
	30	23.9	-20.4	-2.52	-0.712	0.0446

Cassidy, Dong, Kong, **IML**, Zhang, Zheng, 2311.07645

Conclusions

- The possibility of a muon collider has gained renewed interest.
- Studied CP-violating top Yukawa at muon colliders.
  - At high energies, VBF diagrams dominate.
  - Due to strong destructive interference in SM, total rates very sensitive CP violating angle.
  - Studied several CP violating observables.
- Performed a collider study showing a pure rate measurement can be sensitive to a CP-violating top Yukawa.
  - Results at 10 and 30 TeV compare favorably to other direct tests at future colliders.
- Once a discovery is made, will need to verify that this is from CP violation.
  - Investigating different observables that could give confirmation of a change of rate comes from CP-violation
- At a 3 TeV muon collider, rate measurements insensitive to a CP violating angle.
  - True CP violating observables may be needed to find a CP-violating top Yukawa at this energy.
- At energies above 30 TeV, $\log\left(E^2/M_W^2\right)$ enhancement from VBF becomes very large
  - Need to use EW pdfs

Chen, Han, Tweedie, JHEP 11 (2017) 093; Ruiz, Costantini, Maltoni, Mattelaer, 2111.02442; Han, Ma, Xie, 2203.11129; etc. etc.