CP Violating Top Yukawa Coupling at the Future Muon Collider

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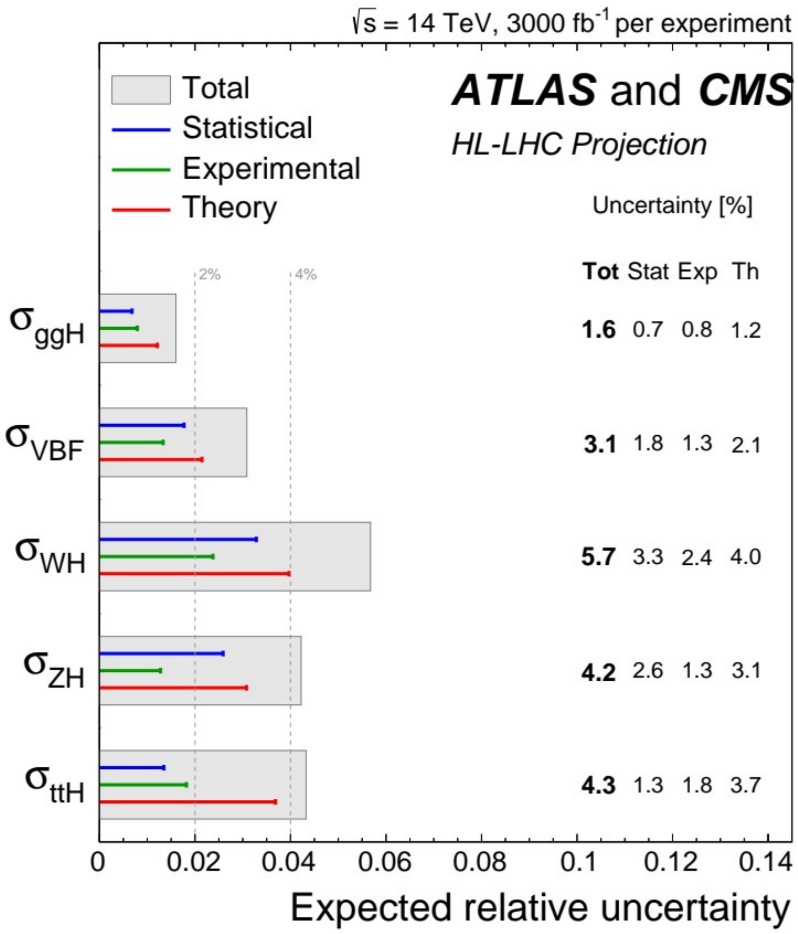
arXiv:2203.08127 [hep-ph]
arXiv:2xxx.xxxxx [hep-ph]

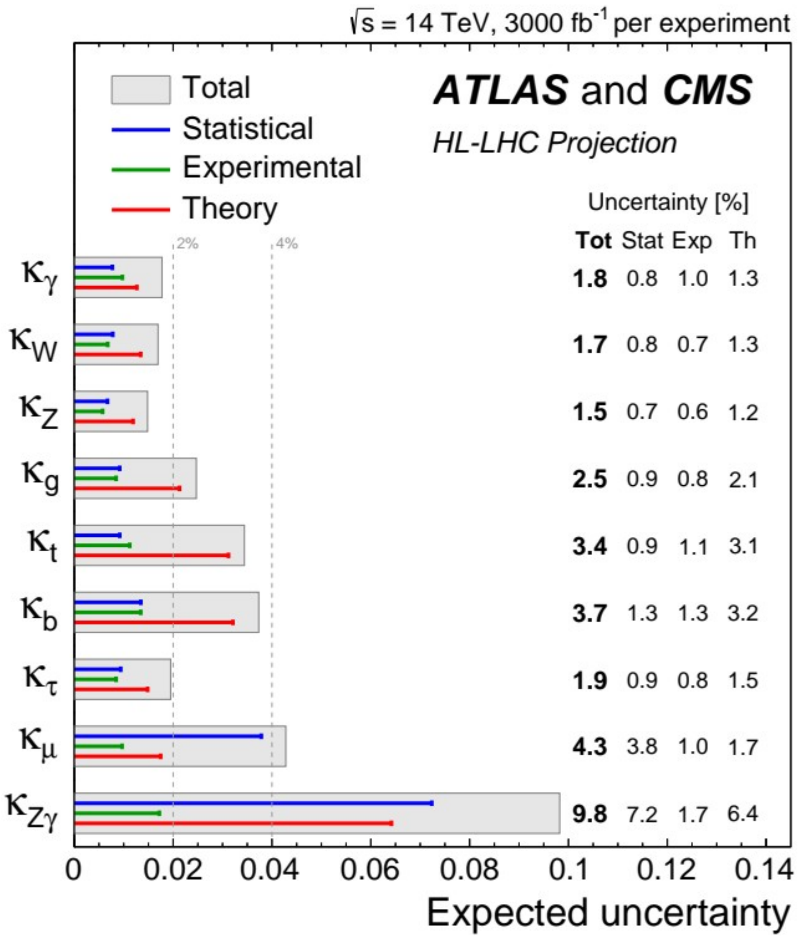
Motivation

- Higgs top coupling violation:
  - Higgs coupling measurements are a major portion of the LHC physics goals, and motivation for future colliders.
  - Higgs couplings to gauge bosons directly test mechanism of EW symmetry breaking.
  - Top quark most massive particle: top Yukawa one of the largest couplings in the Standard Model.
  - Measuring strengths and properties of top Yukawa of particular interest.
- Many studies at many different colliders: HL-LHC, 100 TeV pp colliders, linear electron positron colliders, etc.
  - In particular, interested in direct probes of top quark Yukawa.
  - Use coupling modifier on next few pages:

$$\kappa_t = \frac{y_t}{y_{t,SM}}$$

ttH and top Yukawa at the HL-LHC

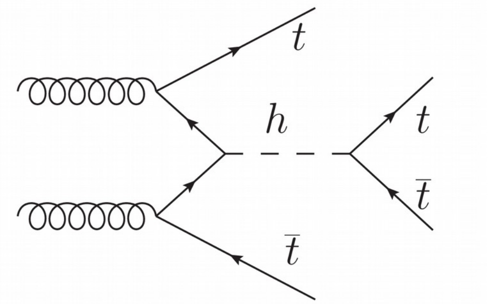




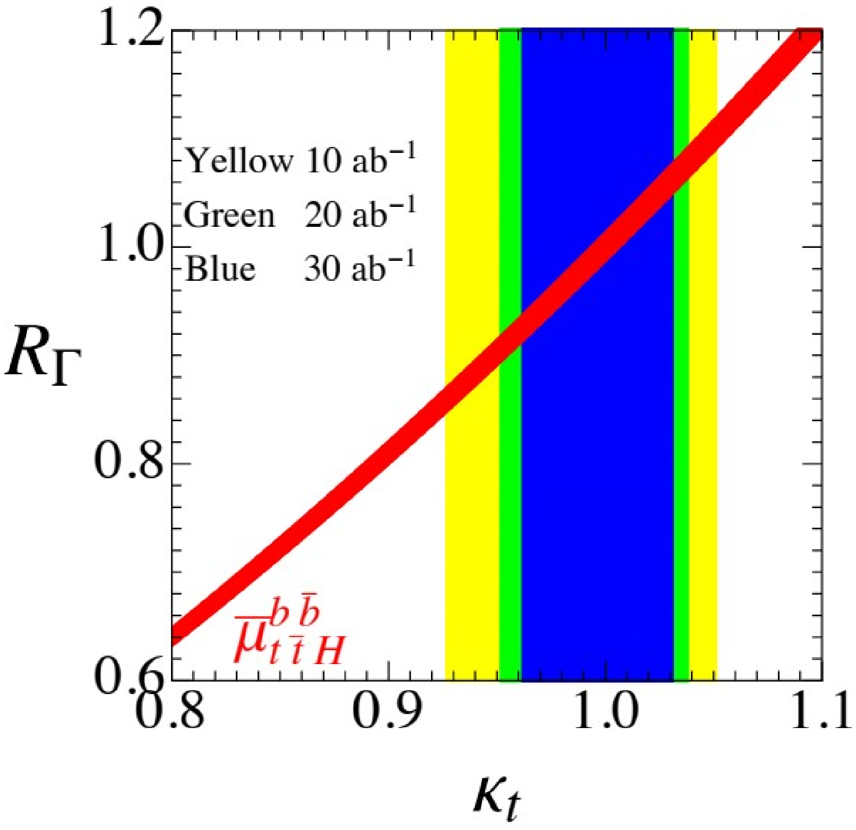
arXiv:1902.00134

Top Yukawa at 100 TeV

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

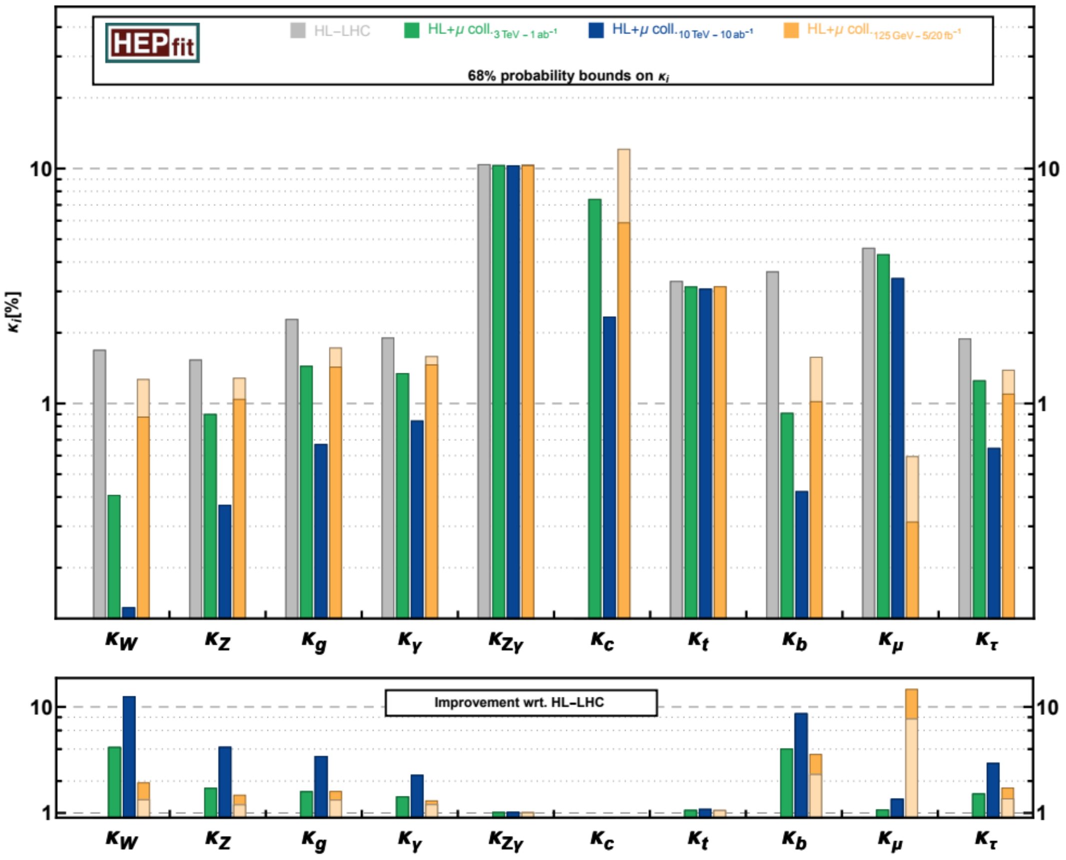


  - Yellow: 10 ab^{-1}
  - Green: 20 ab^{-1}
  - Blue: 30 ab^{-1}
- $R_\Gamma = \Gamma_H / \Gamma_{H,SM}$



arXiv:1606.09408

Top Quark Yukawa at Muon Colliders



arXiv:2203.07261

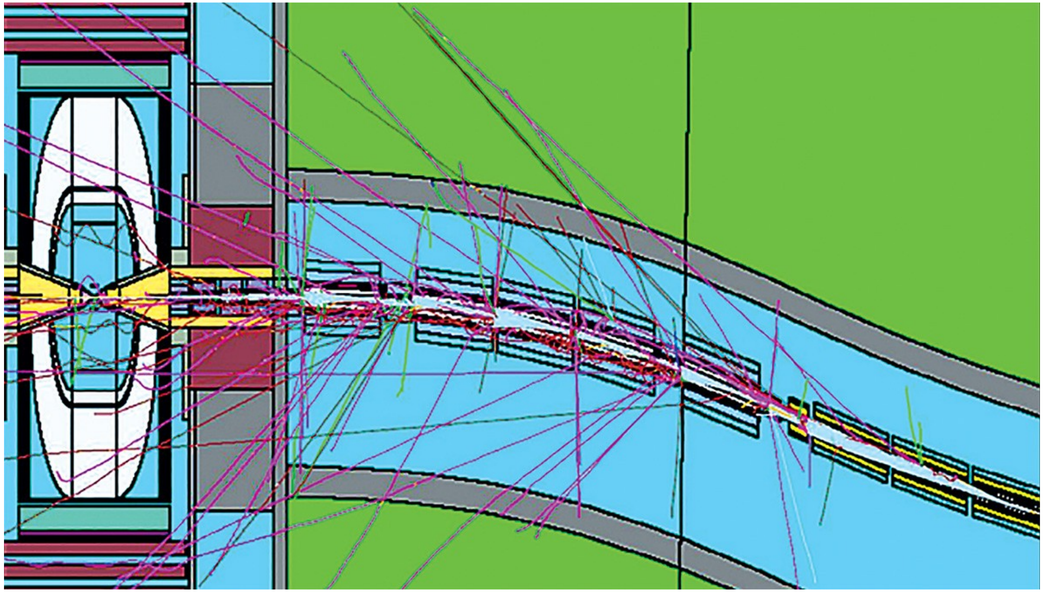
Properties of top quark Yukawa

- 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.
- Will focus on CP properties of the top Yukawa.
  - Will parameterize the top Yukawa as:

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

  - Current constraints from ATLAS: $|\alpha| < 0.75 (43°)$ PRL 125 (2020) 061802

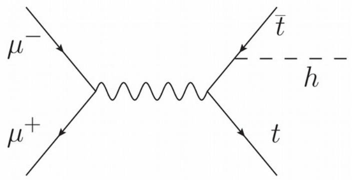
Muon Colliders



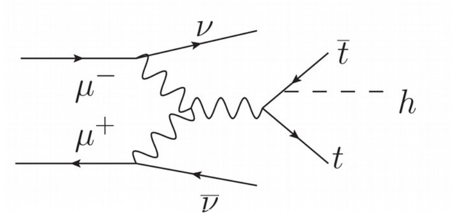
- Hadron colliders can be messy environments.
- Circular electron positron colliders are limited by energy loss in bremsstrahlung.
- Muons are fundamental particles.
  - Cleaner environment than hadron colliders.
- Muons are 200 times more massive than electrons suppressing bremsstrahlung.
  - High energy circular colliders.

Direct tests

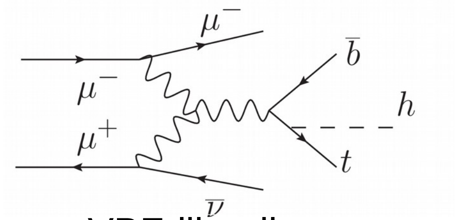
- Directly probe top Yukawa, need processes with a Higgs and top in final state.
- Representative diagrams:
  - tth:

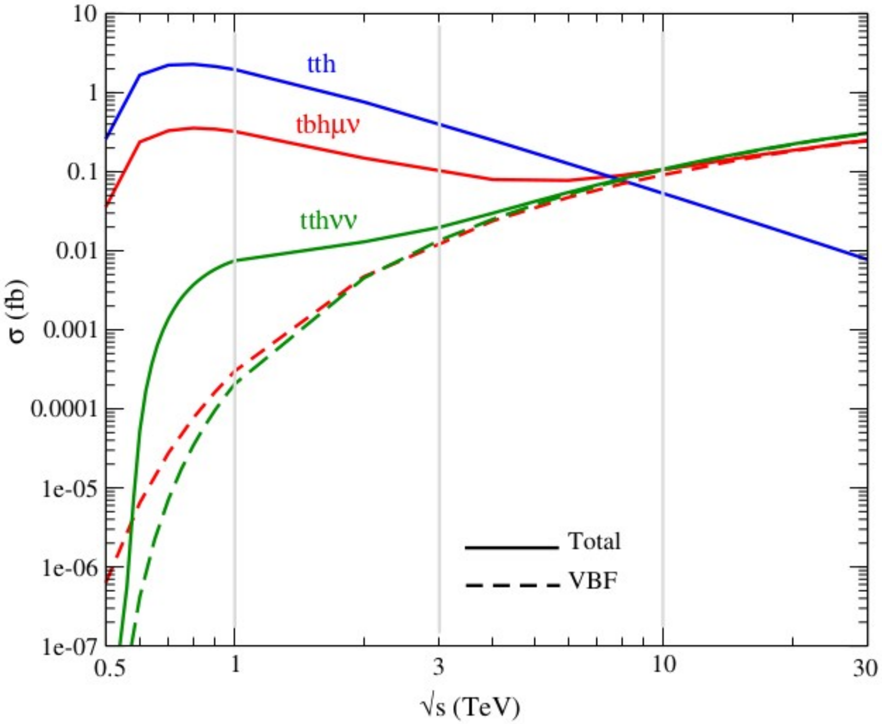


  - tthνν



  - tbhνμ





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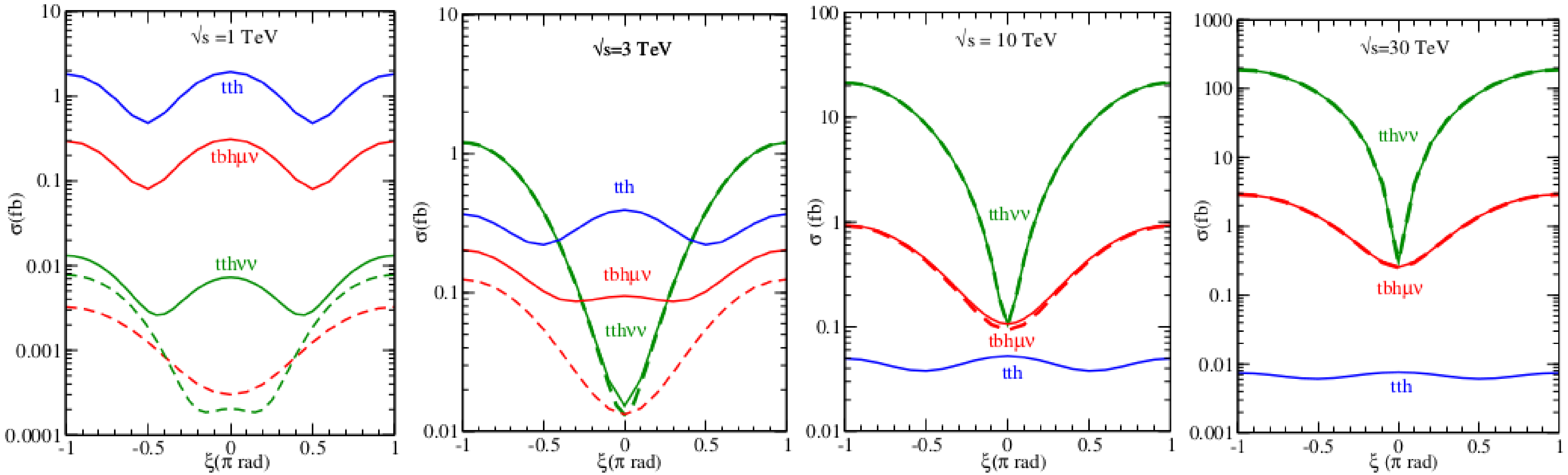
- Dotted lines are VBF-like diagrams.
  - Dominate at high energy due to collinear enhancement: $\log\left(E^2/M_W^2\right)$

Han, Liu, Low, Wang, PRD 103 (2021) 013002; Costantini, et al. JHEP 09 (2020) 080; etc. etc.

Cross Section Dependence on Phase



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- Very different behaviour at different energies and for different diagram types.
- Dashed: VBF-like diagrams.

Cross Section Dependence

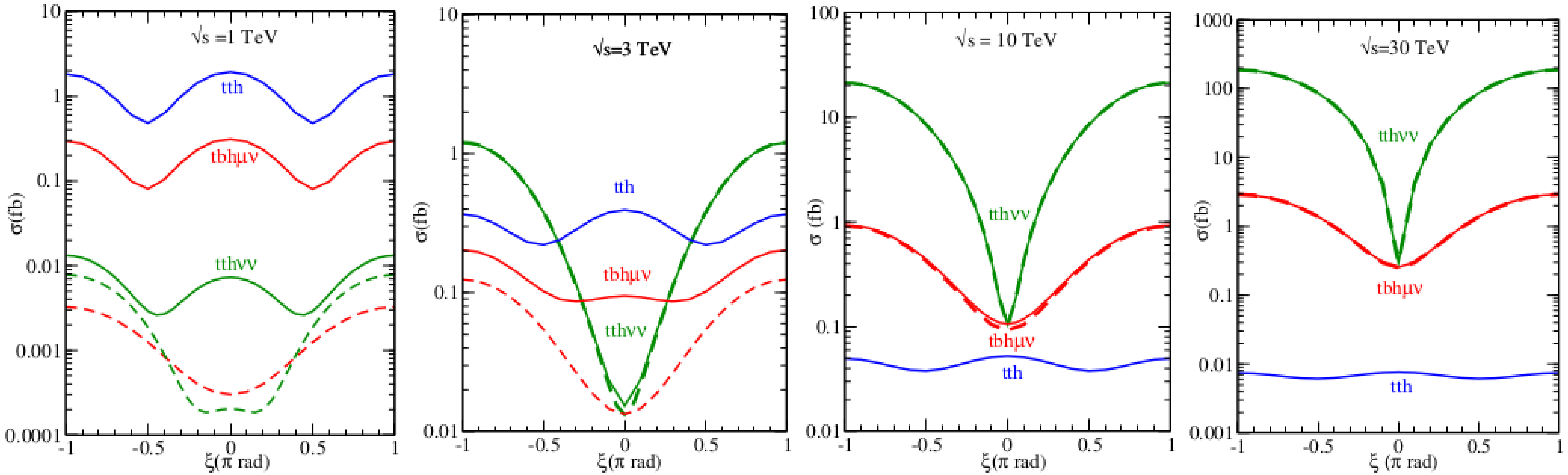
$$\sigma(X) = C_X^4 \cos^4\alpha + C_X^3 \cos^3\alpha + C_X^2 \cos^2\alpha + C_X^1 \cos\alpha + C_x^0$$

	$t\bar{t}h$				$tbh\mu\nu$				$t\bar{t}h\nu\bar{\nu}$			
$\sqrt{s}$ (TeV)	1	3	10	30	1	3	10	30	1	3	10	30
C^4	-	-	-	-	-	-	-	-	$-1.35 \cdot 10^{-4}$	$-4.41 \cdot 10^{-3}$	0.019	-0.43
C^3	-	-	-	-	-	-	-	-	$7.04 \cdot 10^{-5}$	-0.013	-0.17	-0.13
C^2	1.40	0.16	0.01	$1.42 \cdot 10^{-3}$	0.22	0.05	0.08	0.20	$7.44 \cdot 10^{-3}$	0.24	2.16	8.09
C^1	0.05	0.01	$1.41 \cdot 10^{-3}$	$9.68 \cdot 10^{-5}$	$8.35 \cdot 10^{-3}$	-0.05	-0.41	-1.33	$-3.00 \cdot 10^{-3}$	-0.58	-10.43	-93.23
C^0	0.48	0.22	0.04	$6.10 \cdot 10^{-3}$	0.08	0.10	0.44	1.38	$2.89 \cdot 10^{-3}$	0.38	8.53	86.00

TABLE II: Coefficients for $t\bar{t}h, tbh\mu\nu$ and $t\bar{t}h\nu\bar{\nu}$ cross section parametrization.

- At the SM values, strong destructive interference in tth$\nu\nu$ and tbh$\mu\nu$ at high energies.
- Total cross section very sensitive to CP angle.

Cross Section Dependence on Phase



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- At 10 and 30 TeV, cross section measurement by itself very sensitive to CP-violating phase.
- See similar effects in single t+h production at hadron colliders.

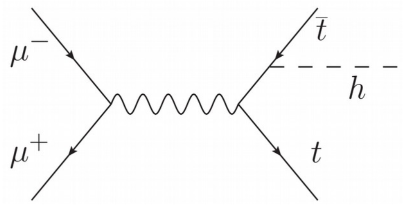
Collider Study

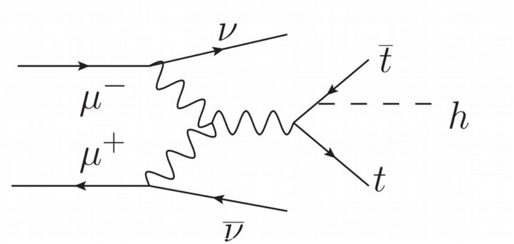
Collider Study

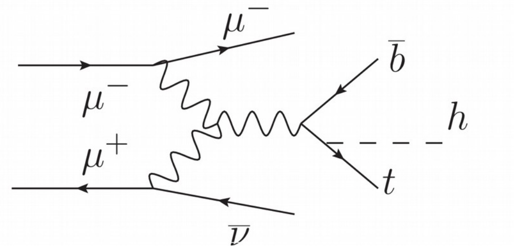
- Signals under consideration:
  - tth
  - tthνν
  - tbhμν
  - Semi-leptonic top decays
  - $h \rightarrow b\bar{b}$

$$\mu^+\mu^- \rightarrow 4b + 2j + l + MET$$

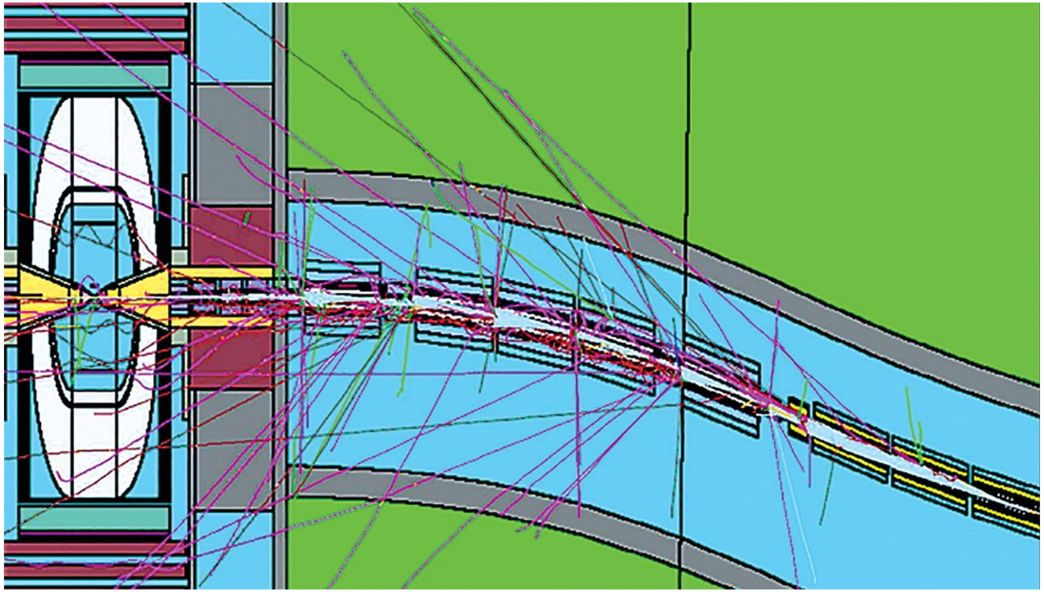
- Backgrounds considered:
  - Gluon splitting: $gb\bar{b}/gt\bar{t} \rightarrow b\bar{b}t\bar{t}$
  - EW vector boson radiation: $t\bar{t}Z/\gamma^* \rightarrow t\bar{t}b\bar{b}$
  - Off-shell WW: $W^*W^* \rightarrow t\bar{b}\bar{t}b$
  - VBF-type without Higgs: $t\bar{t}b\bar{b}\nu\bar{\nu}$







Basic Acceptance Cuts

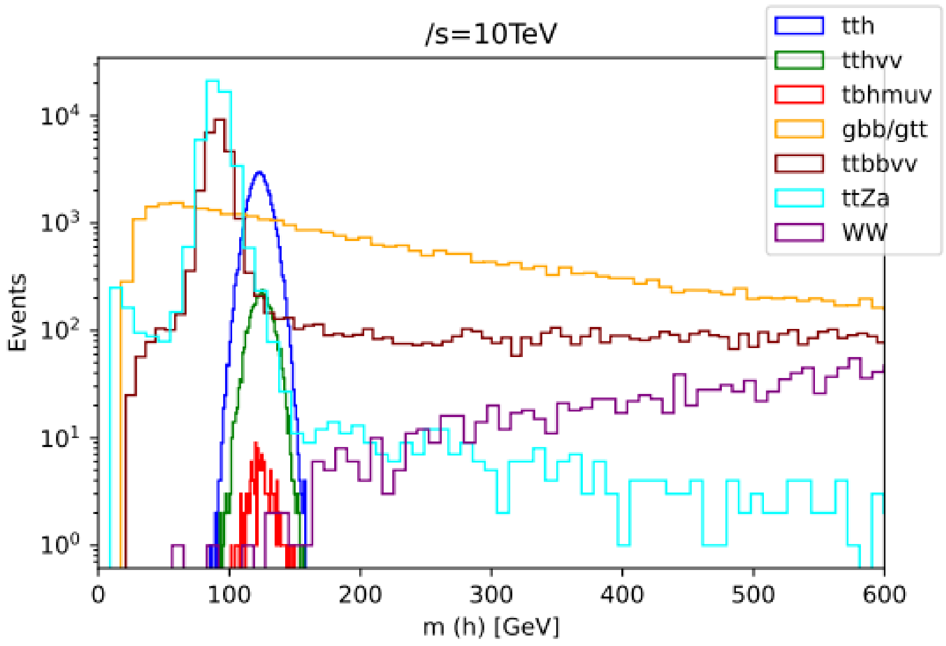


- Beam induced background mitigate by shielding nozzles to block in-beam decays.
- Isolation and acceptance cuts: $|\eta|<2.5, \Delta R>0.4, p_T>30\,GeV$
  - Signal: 4 b-jets, 2 jets, one lepton, MET

$$\mu^+\mu^- \to 4b+2j+l+MET$$

- Use Gaussian smearing of jets for detector effects: $\frac{\Delta E}{E}=0.1$

Higgs Mass Cut



- Best discriminator between signal and background is cut on reconstructed Higgs mass:

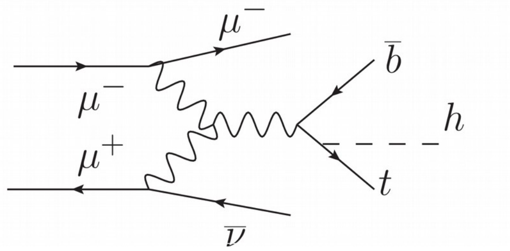
$$100\,GeV < m_h < 150\,GeV$$

Cut Flow

$S/\sqrt{S+B}$

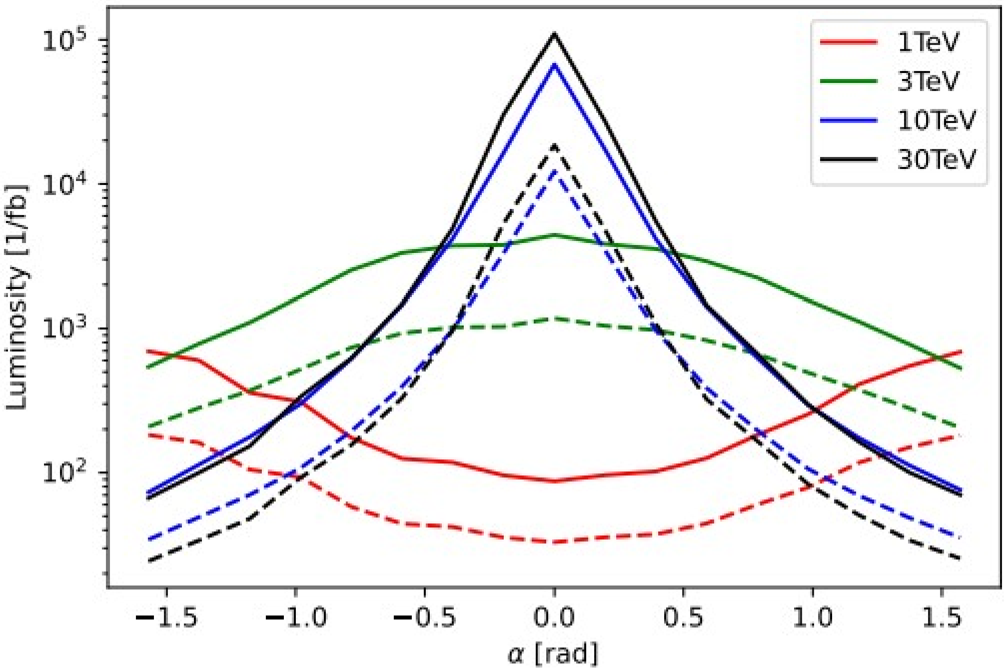
/s [TeV]	Cuts	tth [fb]	tthvv [fb]	tbhmuv [fb]	bkg [fb]	sig	bkg	Significance
1	Generation cuts	0.28	0.0011	0.096	0.24	37.71	23.95	4.8
L = 100 [1/fb]	η+pT+ΔR	0.0499	0.000146	0.0253	0.039	7.54	3.9	2.23
	η+pT+ΔR+M	0.0497	0.000146	0.0253	0.0053	7.52	0.53	2.65
10	Generation cuts	0.0076	0.015	0.028	0.72	511	7162	5.8
L = 10000 [1/fb]	η+pT+ΔR	6e-7	0.00092	–	0.023	9.24	229	0.6
	η+pT+ΔR+M	6e-7	0.00092	–	0.002	9.24	20.2	1.7
30	Generation cuts	0.001	0.044	0.032	4.02	778	40224	3.8
L = 10000 [1/fb]	η+pT+ΔR	–	0.00145	6.9e-6	0.084	14.6	837	0.5
	η+pT+ΔR+M	–	0.0014	6.9e-6	0.0084	14.1	83.7	1.43

- At 1 TeV, tth dominates
- At 10 and 30 TeV, tth$\nu\nu$ dominates.
  - tbh$\mu\nu$ is suppressed after acceptance cuts.



Luminosity needed for Discovery

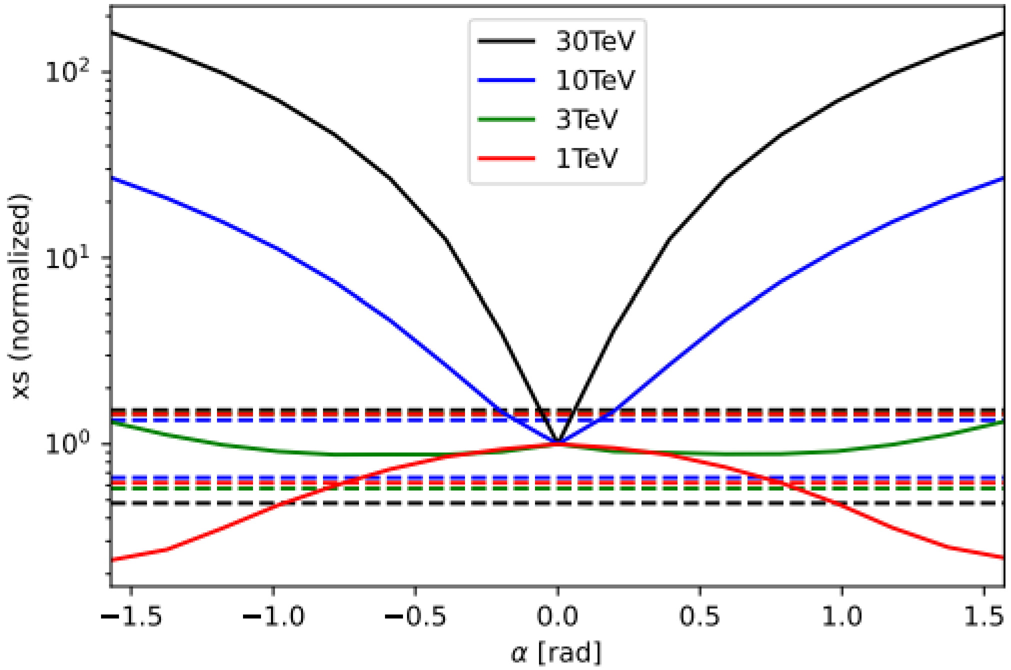
- Solid: Luminosity needed for 5σ discovery.
- Dashed: Luminosity needed for 2σ signal.
- Differences between energies due to differences in cross dependence on α
- Luminosity benchmarks:
  - 1 TeV: 100 fb^{-1}
  - 3 TeV: 1 ab^{-1}
  - 10 TeV: 10 ab^{-1}
  - 30 TeV: 10 ab^{-1}



2σ α bounds

- Benchmark luminosities:
  - 1 TeV: 100 fb^{-1}
  - 3 TeV: 1 ab^{-1}
  - 10 TeV: 10 ab^{-1}
  - 30 TeV: 10 ab^{-1}
- Statistics dominated.
  - Adding 5% or 10% systematics makes little difference.
- Sharp dependence on α at 10 TeV and 30 TeV provides strong constraints.
- At 3 TeV, cross section relatively independent on α.
- Precision on top Yukawa in ttH comparable to previous results.
  - Previous results on κ_t considered all Higgs decays in the kappa framework.
  - κ_t appears in $h\to\gamma\gamma, h\to gg, h\to Z\gamma$

Forslund, Meade, arXiv:2203.09425



Comparison to Other 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}
$\|\alpha\| \lesssim 9^\circ$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	10 TeV $\mu^+\mu^-$	10 ab^{-1}
$\|\alpha\| \lesssim 3^\circ$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	30 TeV $\mu^+\mu^-$	10 ab^{-1}

Barman, et al., arXiv:2203.0817

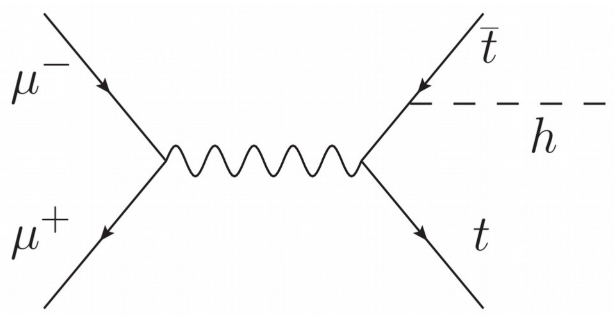
- [1] Goncalves, Kim, Kong, Wu, JHEP 01 (2022) 158
- [2] Barman, Goncalves, Kling, PRD105 (2022) 035023
- [3] Cassidy, Dong Kong, IML, Zheng, Zhang, arXiv:2xxx.xxxxx

CP Observables

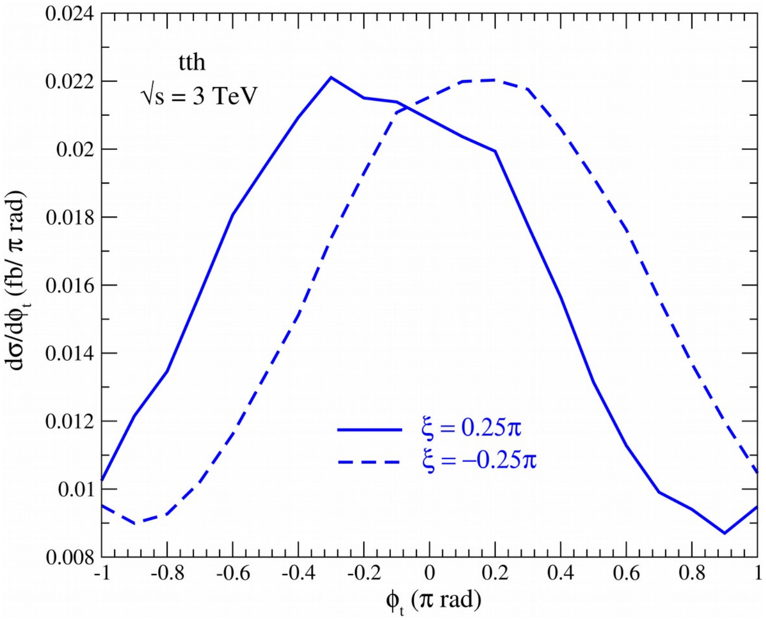
Parton Level Observables

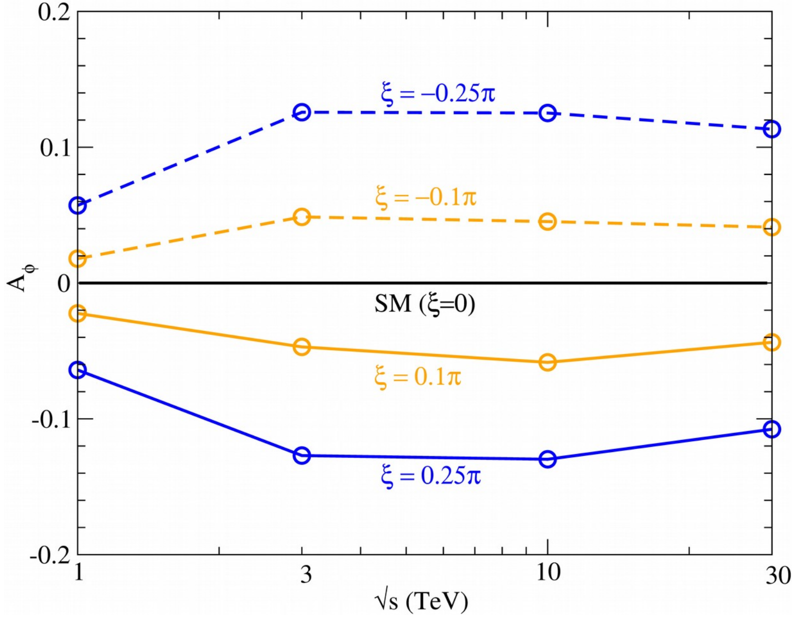
- Once there is an observation, need to tie down CP properties.
  - Previous study only considered total rates.
  - Very powerful at high energy muon colliders.
- Need observable sensitive to CP violating couplings:
- $\mu^+\mu^- \rightarrow t\bar{t}h$
  - Consider angle ϕ between plane created by $t\bar{t}$ system and production plane of Higgs and $t\bar{t}$ system
  - Also define the asymmetry:

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



Parton Level Observables





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

- Also looking into triple products:

$$O_{\mu h t} = \frac{(\vec{p}_\mu \times \vec{p}_h)\cdot \vec{p}_t}{|\vec{p}_\mu \times \vec{p}_h||\vec{p}_t|}, \overline{O}_{\mu h t} = \frac{(\vec{p}_{\bar{\mu}} \times \vec{p}_h)\cdot \vec{p}_{\bar{t}}}{|\vec{p}_{\bar{\mu}} \times \vec{p}_h||\vec{p}_{\bar{t}}|}$$

Conclusions

- 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.

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}
$\|\alpha\| \lesssim 9^\circ$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	10 TeV $\mu^+\mu^-$	10 ab^{-1}
$\|\alpha\| \lesssim 3^\circ$ [3]	semileptonic $t\bar{t}(h \to b\bar{b})$	30 TeV $\mu^+\mu^-$	10 ab^{-1}

- Once a discovery is made, will need to verify that this is from CP violation.
  - Investigating different observables that could give this confirmation.
- At higher energies, $\log\left(E^2/M_W^2\right)$ enhancement from VBF becomes 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.

Thank You

Reconstructing Higgs

$$\chi^2 = \min_{p_\nu} \left[\frac{(m_{b_{1l}\nu} - m_t)^2}{\sigma_t^2} + \frac{(m_{l\nu} - m_W)^2}{\sigma_W^2} + \frac{(m_{b_{2jj}} - m_t)^2}{\sigma_t^2} + \frac{(|p_{T,t}| - |p_{T,\bar{t}}|)^2}{\sigma_{p_T}^2} \frac{(m_{b_3 b_4} - m_H)^2}{\sigma_H^2} \right]$$

- Twelve combinations of b-quarks.
  - Construct χ^2 to reconstruct top quarks and Higgs.
  - Choose combination with smallest χ^2.