CP Violating Top Higgs Coupling at the Future Muon Collider

Morgan Cassidy (University of Kansas)
Zhongtian Dong, KC Kong, Ian Lewis, Yanzhe Zhang, Ya-Juan Zheng

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

Phenomenology Symposium, May 2023

Top Yukawa

- Top yukawa has one of the largest couplings in the SM
- EDMs provide an indirect probe, highly constraining
- Interest in direct measure of top Yukawa
- Parameterize the Top Yukawa by:

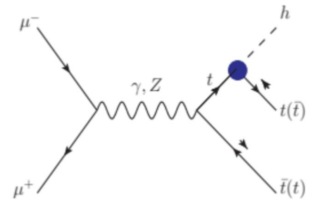
$$-\frac{m_t}{v}\kappa_t h\bar{t}(\cos\xi + i\gamma_5 \sin\xi)t$$

- $\xi = 0 \quad (\xi = \frac{\pi}{2})$ entirely CP even (odd) phase
- Current constraints by ATLAS: $|\xi| \leq 43^\circ$

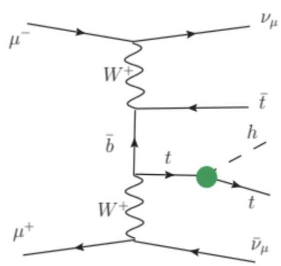
ATLAS collaboration (2020), CMS Collaboration (2016), (2019)

Production rate dependence on √s (SM)

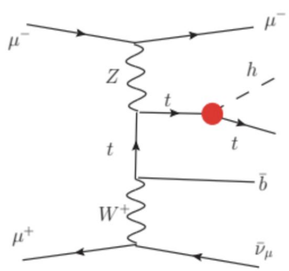
tth

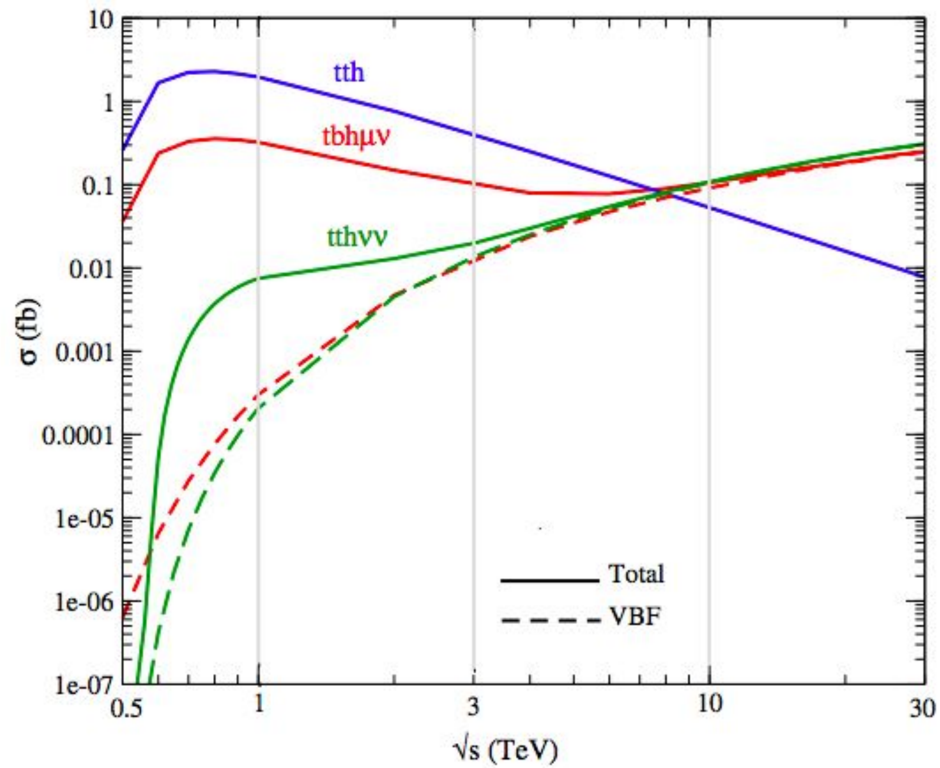


$tth\nu\nu$



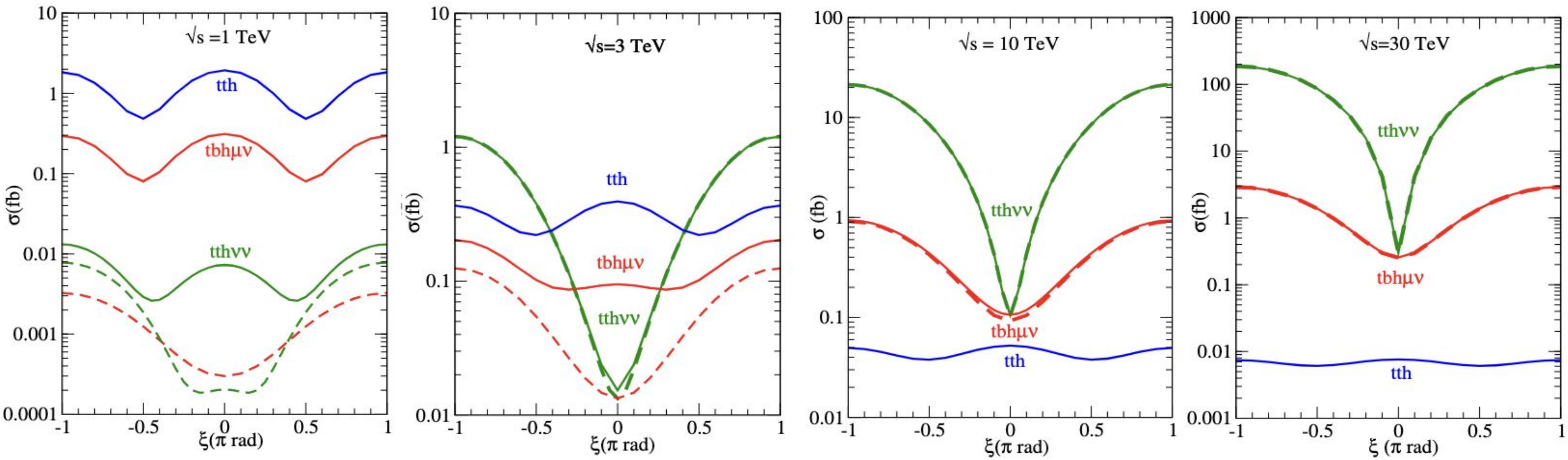
$tbh\mu\nu$





- Considering three direct processes
- Differing cross section dependence with energy:
  - VBF shown separately for $tth\nu\nu$ and $tbh\mu\nu$

Cross section dependence on CP phase



(c) (d)

- Cross section with varying CP phase from -π to π
- very different dependence for different processes at benchmark energies
- VBF also shown separately for tth$\nu\nu$ and tbh$\mu\nu$ by: - - - -

Cross section parameterization

$\sqrt{s}$ (TeV)	$t\bar{t}h$ 1	3	10	30	$tbh\mu\nu$ 1	3	10	30	$t\bar{t}h\nu\bar{\nu}$ 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

- Cross section strong dependence on magnitude of phase
- Look at coefficients: tth and tbhμν

$$\sigma = C_2 \cos^2 \xi + C_1 \cos \xi + C_0$$

Cross section parameterization

$\sqrt{s}$ (TeV)	$t\bar{t}h$ 1	$t\bar{t}h$ 3	$t\bar{t}h$ 10	$t\bar{t}h$ 30	$tbh\mu\nu$ 1	$tbh\mu\nu$ 3	$tbh\mu\nu$ 10	$tbh\mu\nu$ 30	$t\bar{t}h\nu\bar{\nu}$ 1	$t\bar{t}h\nu\bar{\nu}$ 3	$t\bar{t}h\nu\bar{\nu}$ 10	$t\bar{t}h\nu\bar{\nu}$ 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

- Cross section strong dependence on magnitude of phase
- Look at coefficients: $tth\nu\nu$

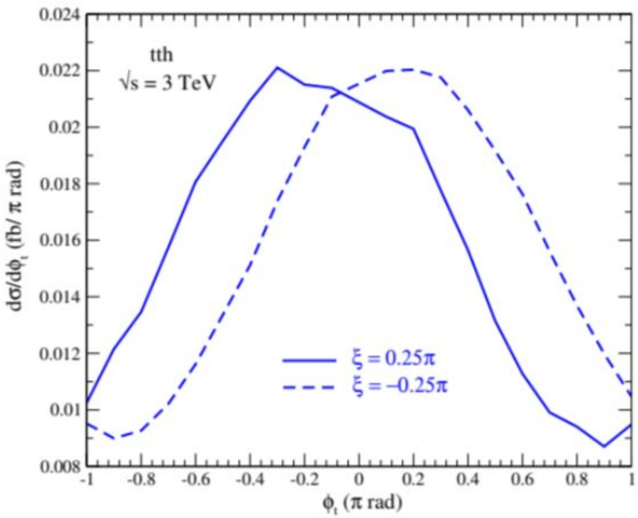
$$\sigma = C_4 \cos^4 \xi + C_3 \cos^3 \xi + C_2 \cos^2 \xi + C_1 \cos \xi + C_0$$

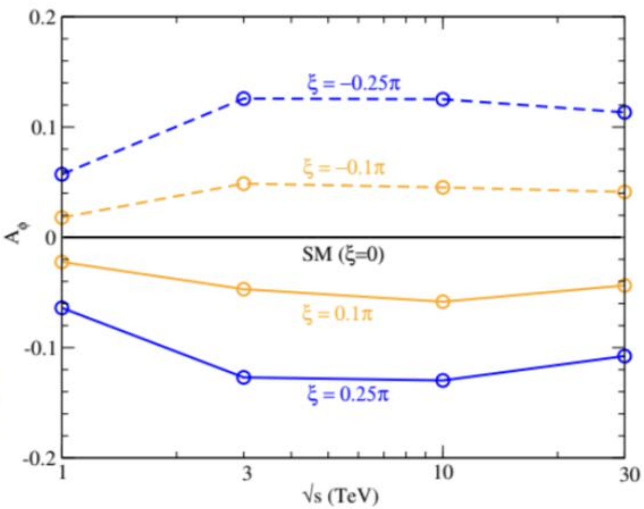
THE UNIVERSITY OF KANSAS KU

CPV observables

- With this, look at CPV observables
- For tth, define Asymmetry:

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





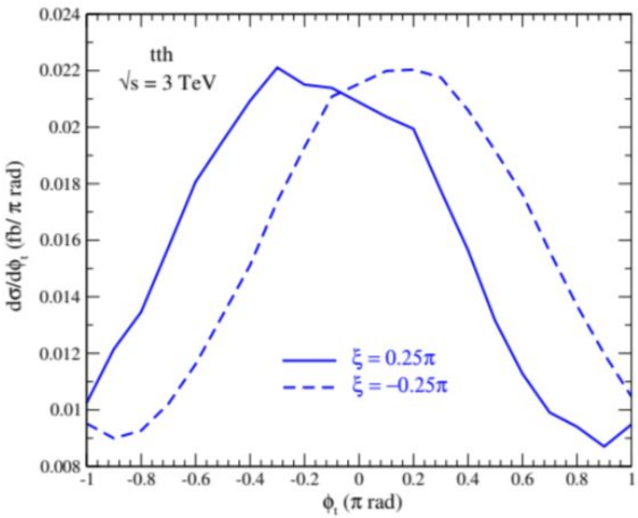
THE UNIVERSITY OF KANSAS

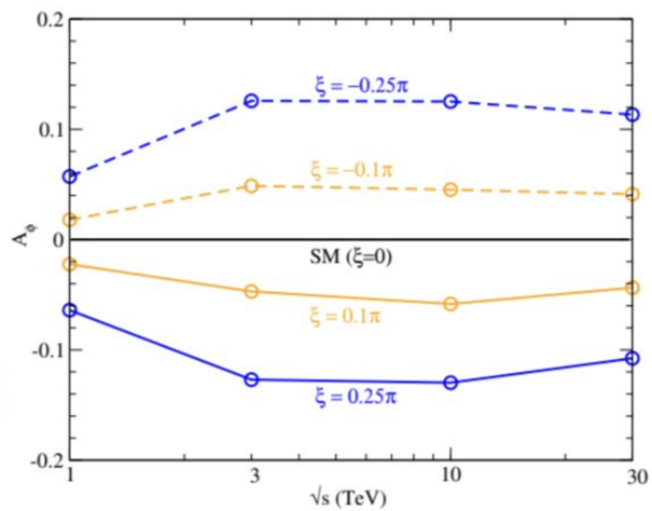
CPV observables

- With this, look at CPV observables
- For tth, define Asymmetry:

Angle between ttH production plane and tt system

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

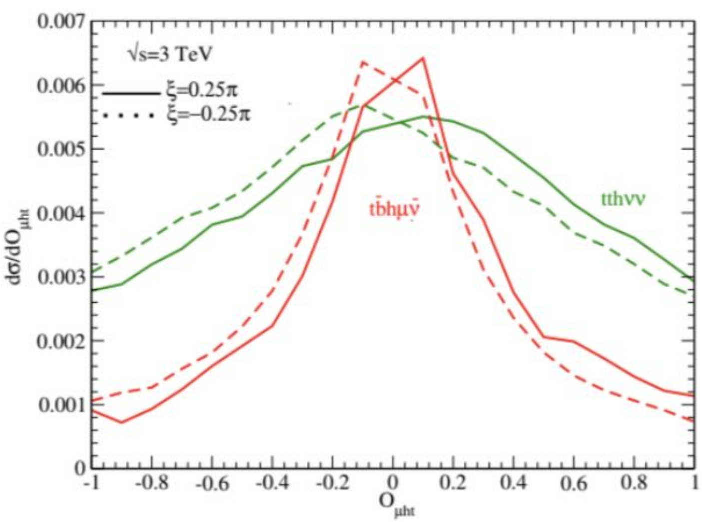


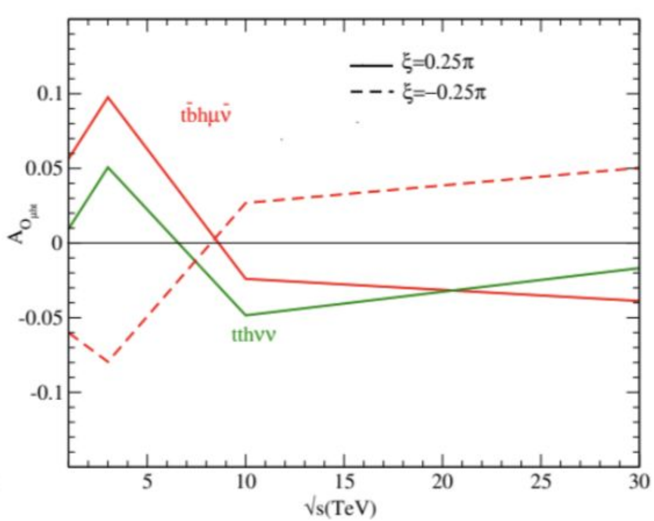


CPV observables

- With this, look at CPV observables
- And for tthνν and tbhμν, triple products:

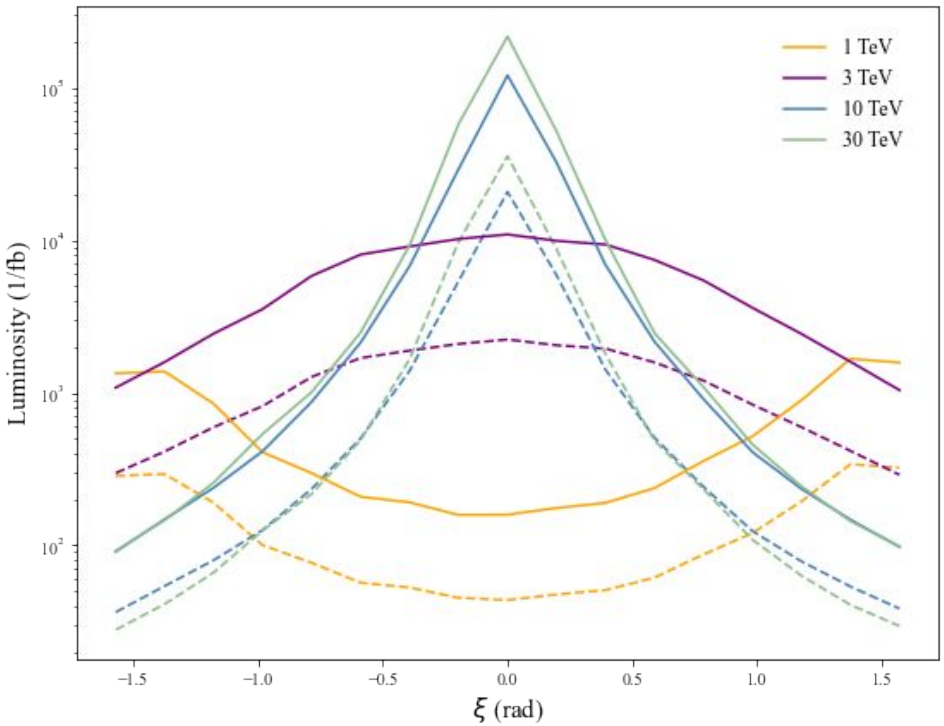
$$O_{\mu h t} = \frac{(\vec{p}_{\mu^-} \times \vec{p}_h)}{|\vec{p}_{\mu^-} \times \vec{p}_h|} \frac{\cdot \vec{p}_t}{|\vec{p}_t|} \qquad \bar{O}_{\mu h t} = \frac{(\vec{p}_{\mu^+} \times \vec{p}_h)}{|\vec{p}_{\mu^+} \times \vec{p}_h|} \frac{\cdot \vec{p}_{\bar{t}}}{|\vec{p}_{\bar{t}}|}$$





Luminosity for Discovery and Exclusion

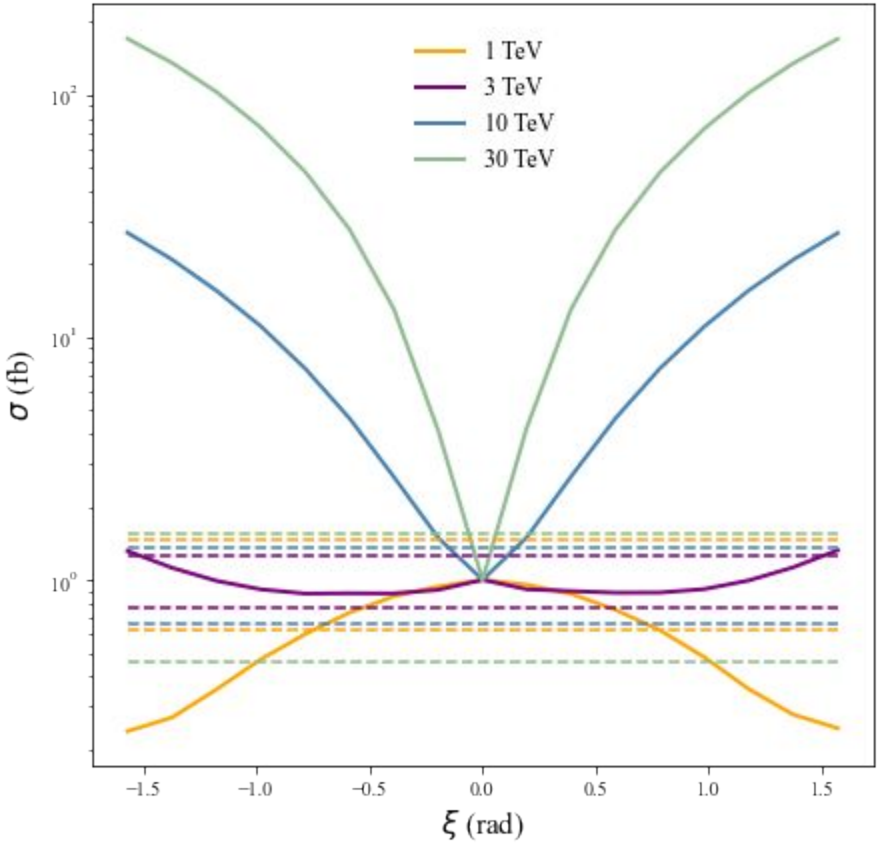
- Solid: Luminosity needed to achieve 5σ discovery
- Dashed: Luminosity needed for 2σ exclusion
- Different dependences due to cross sections
- Benchmark Luminosities:
  - 1 TeV → $100\ \mathrm{fb}^{-1}$
  - 3 TeV → $1{,}000\ \mathrm{fb}^{-1}$
  - 10 TeV → $10{,}000\ \mathrm{fb}^{-1}$
  - 30 TeV → $10{,}000\ \mathrm{fb}^{-1}$



Muon Colliders, Jean Pierre Delahaye et. al,https://arxiv.org/pdf/1901.06150.pdf
Snowmass, muon forum,https://snowmass21.org/energy/muon_forum

Phase Bounds

- Bounds on CP phase at 2σ
- Very constraining at high energies
- Little contribution from adding 5% or 10% systematics
- Benchmark Luminosities:
  - 1 TeV → 100 fb^{-1}
  - 3 TeV → 1,000 fb^{-1}
  - 10 TeV → 10,000 fb^{-1}
  - 30 TeV → 10,000 fb^{-1}



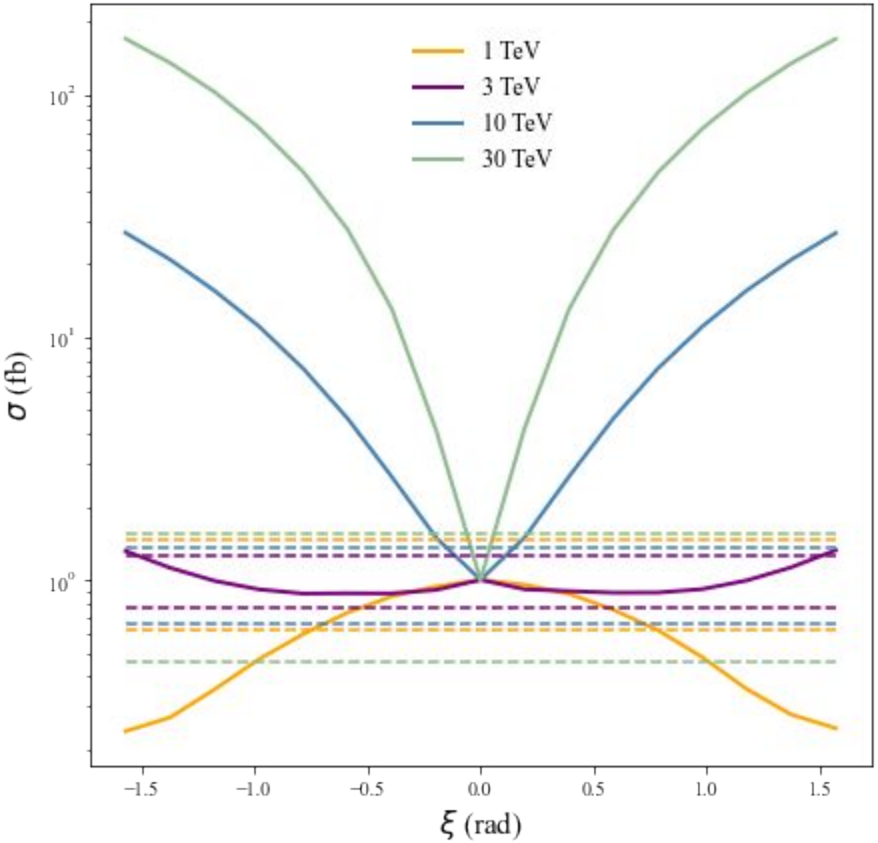
THE UNIVERSITY OF KANSAS

Phase Bounds

- Bounds on CP phase at 2σ
- Very constraining at high energies

Approximate values:

$|\xi| \lesssim 55°$ at 1 TeV
$|\xi| \lesssim 9°$ at 10 TeV
$|\xi| \lesssim 3°$ at 30 TeV
At 3 TeV relatively independent



Comparing Phase Bounds

ξ bounds at 95% CL	Channel	Collider
$\lvert\xi\rvert \lesssim 36°$	$dileptonic\ \ t\bar{t}(h \to b\bar{b})$	HL -LHC
$\lvert\xi\rvert \lesssim 25°$	$t\bar{t}(h \to \gamma\gamma)\ \ combination$	HL-LHC
$\lvert\xi\rvert \lesssim 3°$	$dileptonic\ \ t\bar{t}(h \to b\bar{b})$	100 TeV FCC
$\lvert\xi\rvert \lesssim 9°$	$semileptonic\ \ t\bar{t}(h \to b\bar{b})$	10 TeV muon collider
$\lvert\xi\rvert \lesssim 3°$	$semileptonic\ \ t\bar{t}(h \to b\bar{b})$	30 TeV muon collider

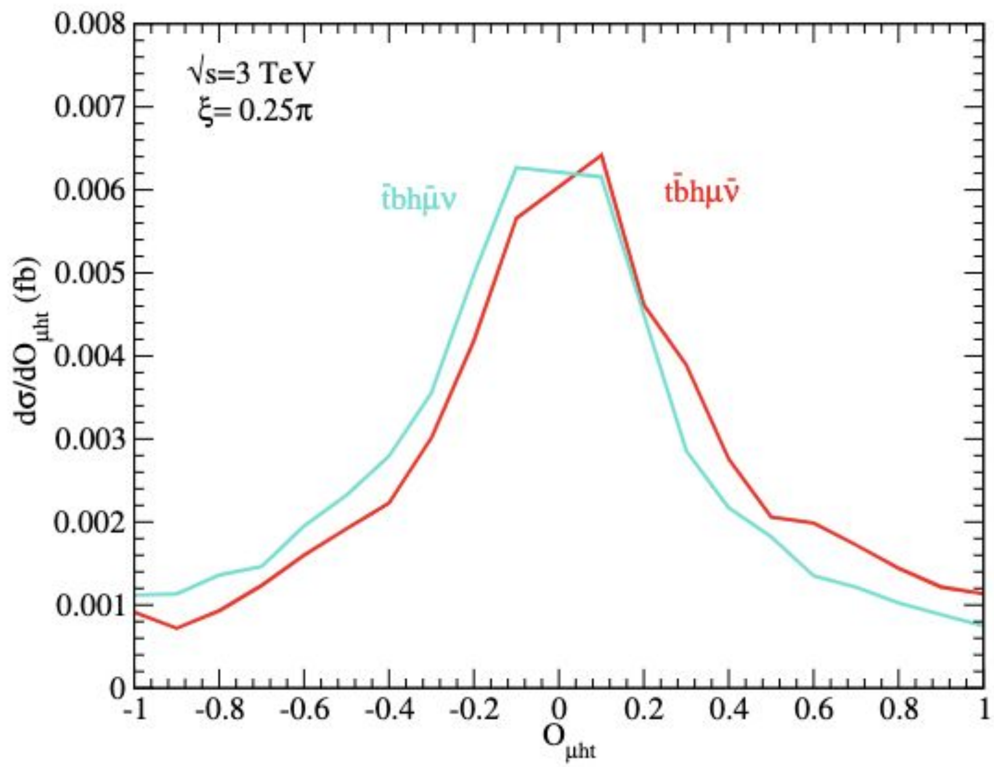
R. K. Barman, et.al (2022)

Conclusion

- Main contributions to cross section from VBF diagrams
- Cross Section strong dependence on CP phase due to constructive/destructive interference
- Triple products to study CP sensitivity
- Highly constrained phase at high energies

Extras

triple product for conjugate



- triple product difference in $tbh\mu\nu$ conjugate process

Muon Colliders

- Why consider a muon collider?
  - Fundamental particles
    - cleaner collision environments than pp
  - high energy achievability
  - smaller energy loss due to synchrotron radiation

- Disadvantages
  - muon decay
  - difficulty to collimate beams

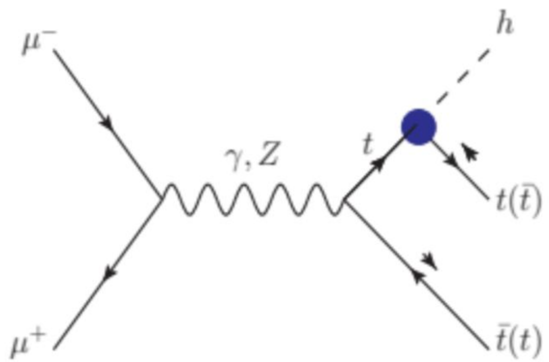
6D Ionization Cooling

Detector and Physics Performance at a Muon Collider, Nazar Bartosik et. al,
https://arxiv.org/abs/2001.04431

Signal

- Signal: $\mu^-\mu^+ \rightarrow 4bjj\ell + \not{E}_T$
  - Semi-leptonic top pair decays: $t \rightarrow bW^+, W^+ \rightarrow jj$; $\bar{t} \rightarrow \bar{b}W^-, W^- \rightarrow \ell^-\bar{\nu}_\ell$
  - Higgs decay channel: $h \rightarrow b\bar{b}$

- Backgrounds:
  - $gb\bar{b}/gt\bar{t}$
  - $t\bar{t}Z/\gamma$
  - WW
  - $t\bar{t}b\bar{b}\nu\bar{\nu}$



Cuts

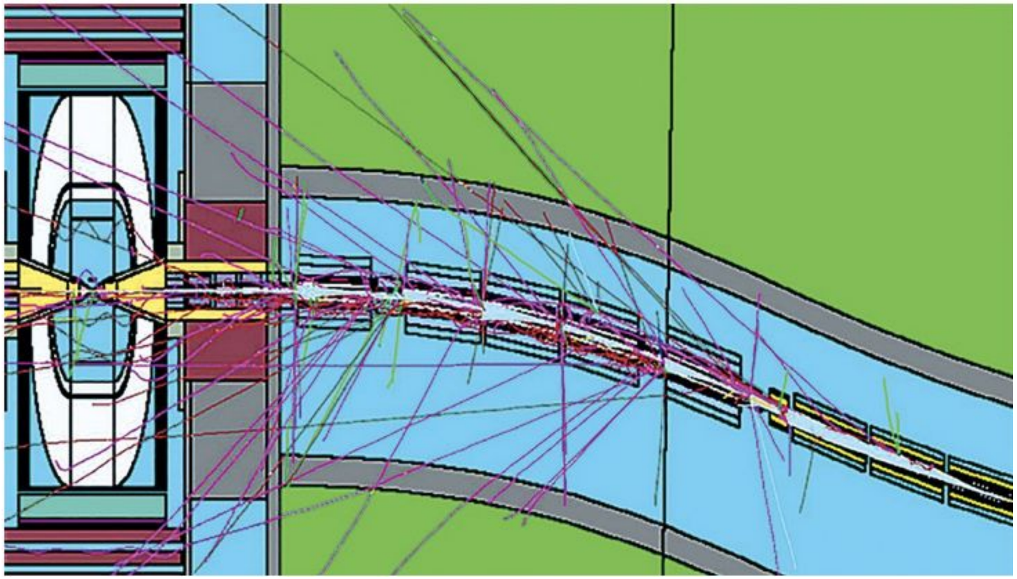
- With acceptance cuts

$\Delta R > 0.4$

$p_T > 30\ GeV$

$|\eta| < 2.5$

Due to detector shielding nozzles



Cuts

- With acceptance cuts

$\Delta R > 0.4$

$p_T > 30\ GeV$

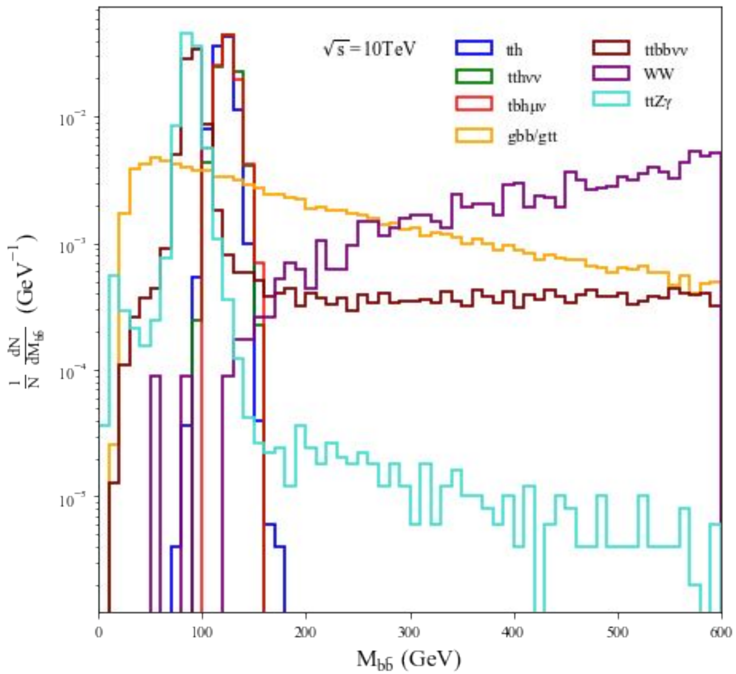
$|\eta| < 2.5$

$$\frac{\Delta E_{b,j}}{E_{b,j}} = 10\%$$

Use Gaussian smearing on jets to simulate detector effects

- Higgs mass cut

$$100\ \text{GeV} < m_{b\bar{b}} < 150\ \text{GeV}$$



Reconstruction

- 12 b quark combinations
- Find minimizing combination
- Use to reconstruct Higgs and top

$$\chi^2 \equiv \min_{p_\nu} \left[\frac{(m_{b_1 l+\nu} - m_t)^2}{\sigma_t^2} + \frac{(m_{l+\nu} - m_W)^2}{\sigma_W^2} + \frac{(m_{b_2 jj} - m_t)^2}{\sigma_t^2} + \frac{(|pT_t| - |pT_{\bar{t}}|)^2}{\sigma_{pT}^2} + \frac{(m_{b_3 b_4} - m_H)^2}{\sigma_H^2} \right]$$

5 GeV
5 GeV
5 GeV
100 GeV
5 GeV

Cutflow

	Cut	$tth(fb)$	$tth\nu\nu(fb)$	$tbh\mu\nu(fb)$	$gbb/gtt(fb)$	$ttbb\nu\nu(fb)$	$ttZ/\gamma(fb)$	$WW(fb)$	S	B	$\sqrt{S+B}$
1 TeV		0.2700	0.0011	0.0960	0.0415	0.0004	0.1740	0.0233	37.7000	23.9000	4.8030
	$4bjj\ell + E_T$	0.0480	0.0001	0.0248	0.0093	0.0001	0.0238	0.0048	7.3600	3.8000	2.2000
	$+m_{b\bar{b}}$	0.0480	0.0001	0.0248	0.0025	0.0000	0.0094	0.0022	7.3400	1.4000	2.4800
3 TeV		0.0569	0.0027	0.0270	0.0203	0.0135	0.0619	0.1800	86.7000	276.0000	4.5500
	$4bjj\ell + E_T$	0.0016	0.0003	0.0011	0.0010	0.0028	0.0017	0.0195	2.9000	24.9000	0.5500
	$+m_{b\bar{b}}$	0.0015	0.0003	0.0008	0.0002	0.0008	0.0002	0.0012	2.6600	2.4600	1.1700
10 TeV		0.0076	0.0153	0.0282	0.0036	0.2430	0.0116	0.4580	511.0000	7,160.0000	5.8300
	$4bjj\ell + E_T$	0.0000	0.0009	0.0000	0.0000	0.0215	0.0000	0.0000	9.0300	216.0000	0.6000
	$+m_{b\bar{b}}$	0.0000	0.0009	0.0000	0.0000	0.0037	0.0000	0.0000	9.0600	37.4000	1.3290
30 TeV		0.0011	0.0443	0.0324	0.0006	3.2400	0.0021	0.7800	778.0000	40,200.0000	3.8400
	$4bjj\ell + E_T$	0.0000	0.0014	0.0000	0.0000	0.0670	0.0000	0.0000	14.6000	670.0000	0.5500
	$+m_{b\bar{b}}$	0.0000	0.0014	0.0000	0.0000	0.0167	0.0000	0.0000	14.1000	167.0000	1.0400

- tth dominates at 1 TeV
- tth$\nu\nu$ dominates high energies, cuts kill tbh$\mu\nu$