CP Structure of the Top Yukawa at a Multi TeV Muon Collider

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Introduction

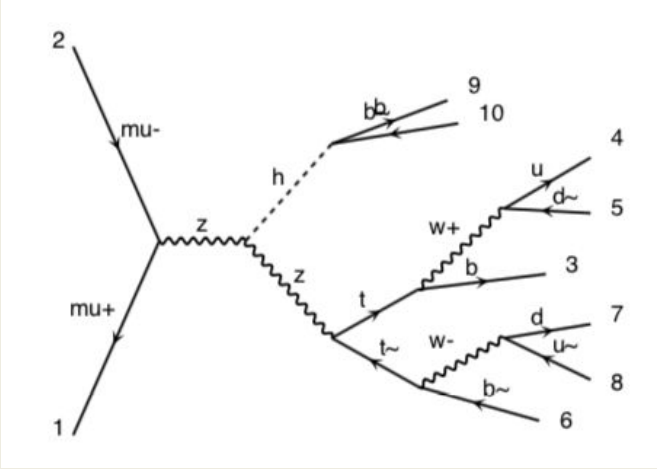
- Pt. II focus on CP Violation
- Chien-Shung Wu and the Wu experiment
  - Parity Violation
- Goal and Motivation

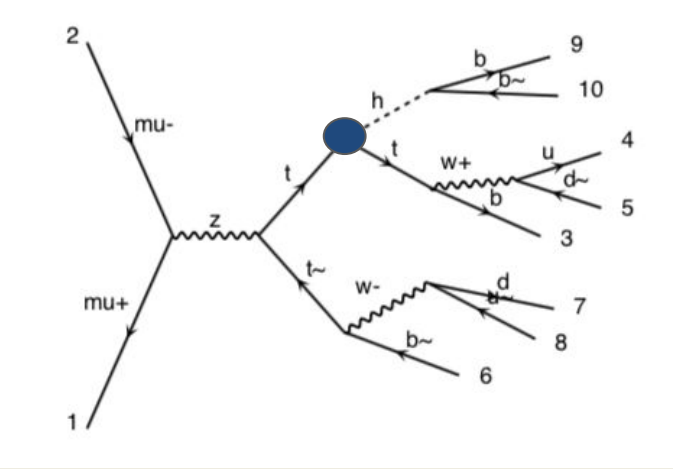
Top Yukawa Coupling

- Aim to explore CP tth violating coupling via tth, tth$\nu\nu$,and tbh$\mu\nu$. The tth interaction Lagrangian term modeled by:

$$\mathcal{L} = -\frac{m_t}{v}\kappa_t \bar{t}(cos\alpha + i\gamma_5 sin\alpha)th$$

- Where alpha is the CP violating phase.





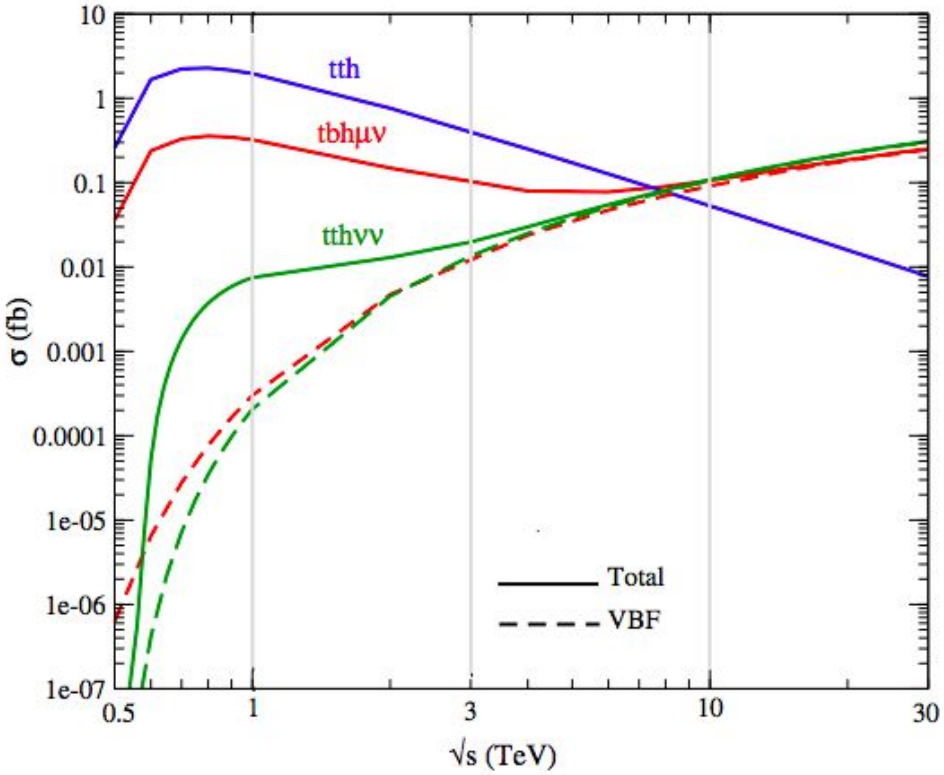
Representative Feynman diagrams for signal process tth with decay. The left diagram does not contain tth coupling. The right diagram tth coupling is marked in red.

Cross Section versus √s for the Standard Model

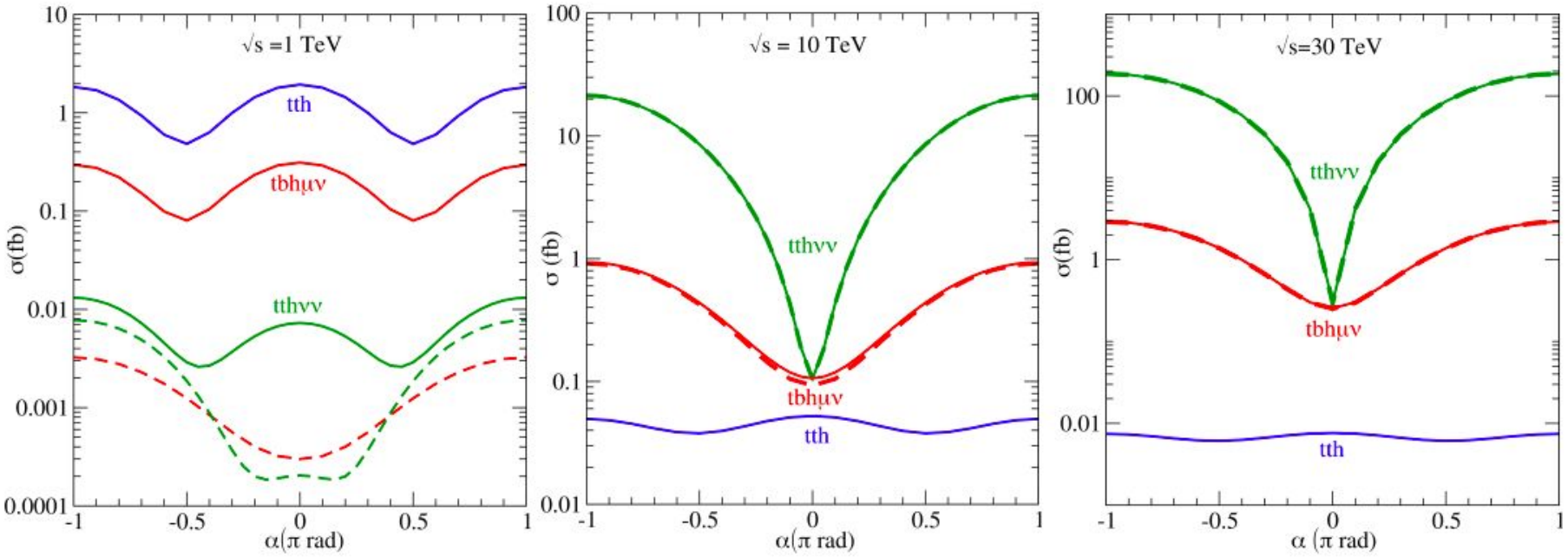
- XS versus c.o.m. energy from 500 GeV to 30 TeV for processes:

$$\mu^+\mu^- \to t\bar{t}h$$
$$\mu^+\mu^- \to t\bar{t}h\nu_\ell\bar{\nu}_\ell$$
$$\mu^+\mu^- \to tbh\mu\nu$$

- All processes generated through MadGraph5_aMC@NLO.



Cross Section versus CP Phase



- Cross section varying with cp phase from -π to π for signal processes at 1, 10 and 30 TeV. Dashed lines show VBF contributions for tth$\nu\nu$ and tbh$\mu\nu$.

- CP values are introduced in MadGraph5_aMC@NLO by incorporating a CPV model via FeynRules.

Benchmark Luminosities

- Using an estimated cross section at 10 TeV of 1 fb

$$L \gtrsim \frac{5\,\text{years}}{\text{time}} \left(\frac{\sqrt{s}_{\mu}}{10\,\text{TeV}} \right)^2 2 \cdot 10^{35} \text{cm}^{-2} \text{s}^{-1}$$

$\sqrt{s}\ \ (TeV)$	$L\ \ (fb^{-1})$
1	100
10	10,000
30	10,000

Table: Corresponding luminosities for each of the three benchmark energies.

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

2σ Exclusion & 5σ Discovery

- Log likelihood ratio used to determine 5σ discovery and 2σ exclusion.
- Likelihood function following Poisson distribution: $L(x|n) = \frac{x^n}{n!}e^{-x}$

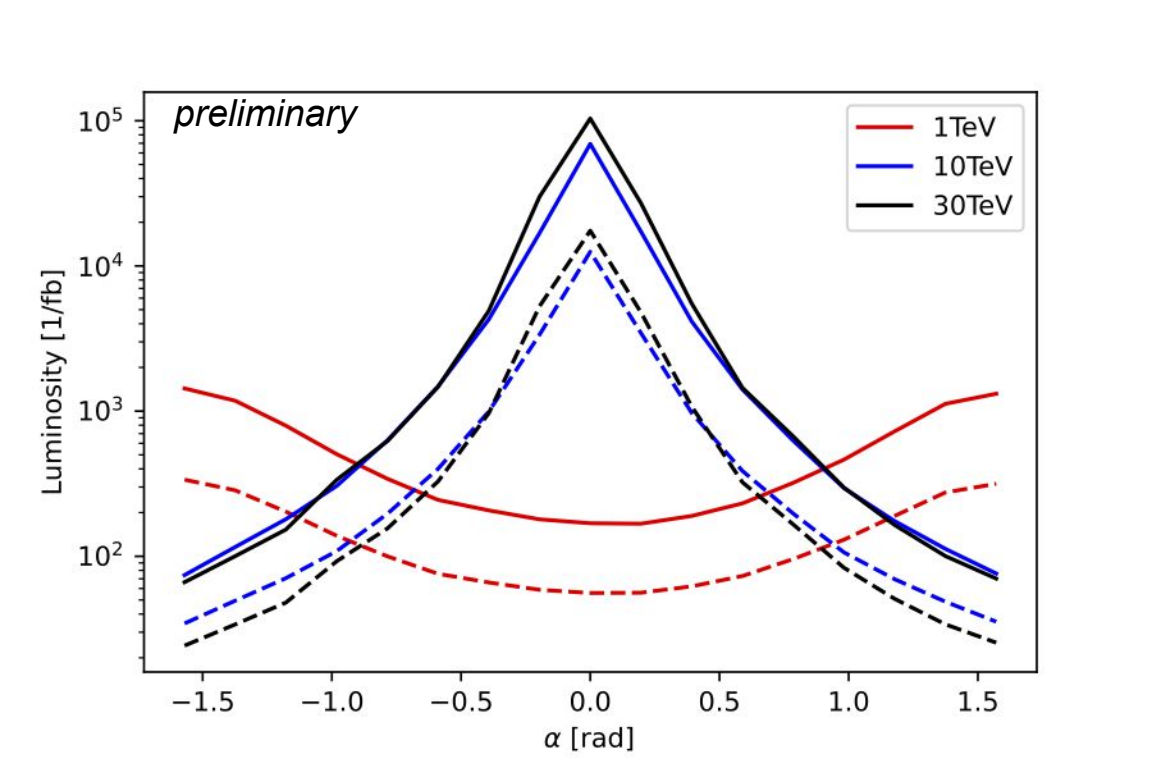
$$\sigma_{dis} \equiv \sqrt{-2\ \ln\left(\frac{L(B|Sig+B)}{L(Sig+B|Sig+B)}\right)}$$

$$\sigma_{exc} \equiv \sqrt{-2\ \ln\left(\frac{L(Sig+B|B)}{L(B|B)}\right)}$$

Top: formula used to calculate 5σ significance

Bottom: formula used to calculate 2σ significance

Luminosity versus CP phase



Solid Lines:
Corresponding luminosity required to achieve 5σ discovery for a particular α value.

Dashed Lines:
Luminosity required for 2σ exclusion of particular α value.

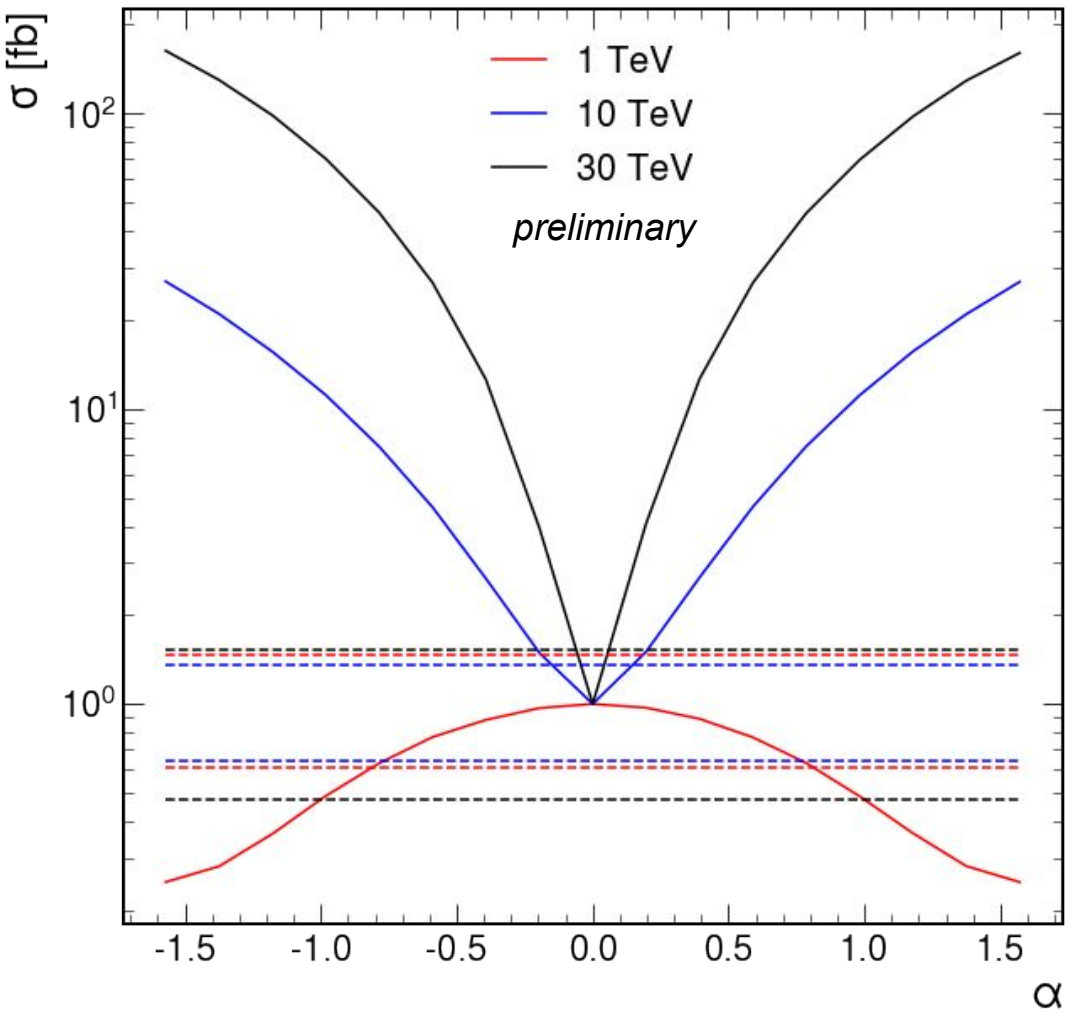
2σ Exclusion on CP phase

Bands give 2σ exclusion on α using benchmark luminosities

Solid Lines:
Combined signal cross section before cuts normalized to SM.

Dashed Bands:
Projected bounds at 95% CL normalized to SM.

Approximate values:
$|\alpha| \lesssim 47°$ at 1 TeV
$|\alpha| \lesssim 9°$ at 10 TeV
$|\alpha| \lesssim 3°$ at 30 TeV



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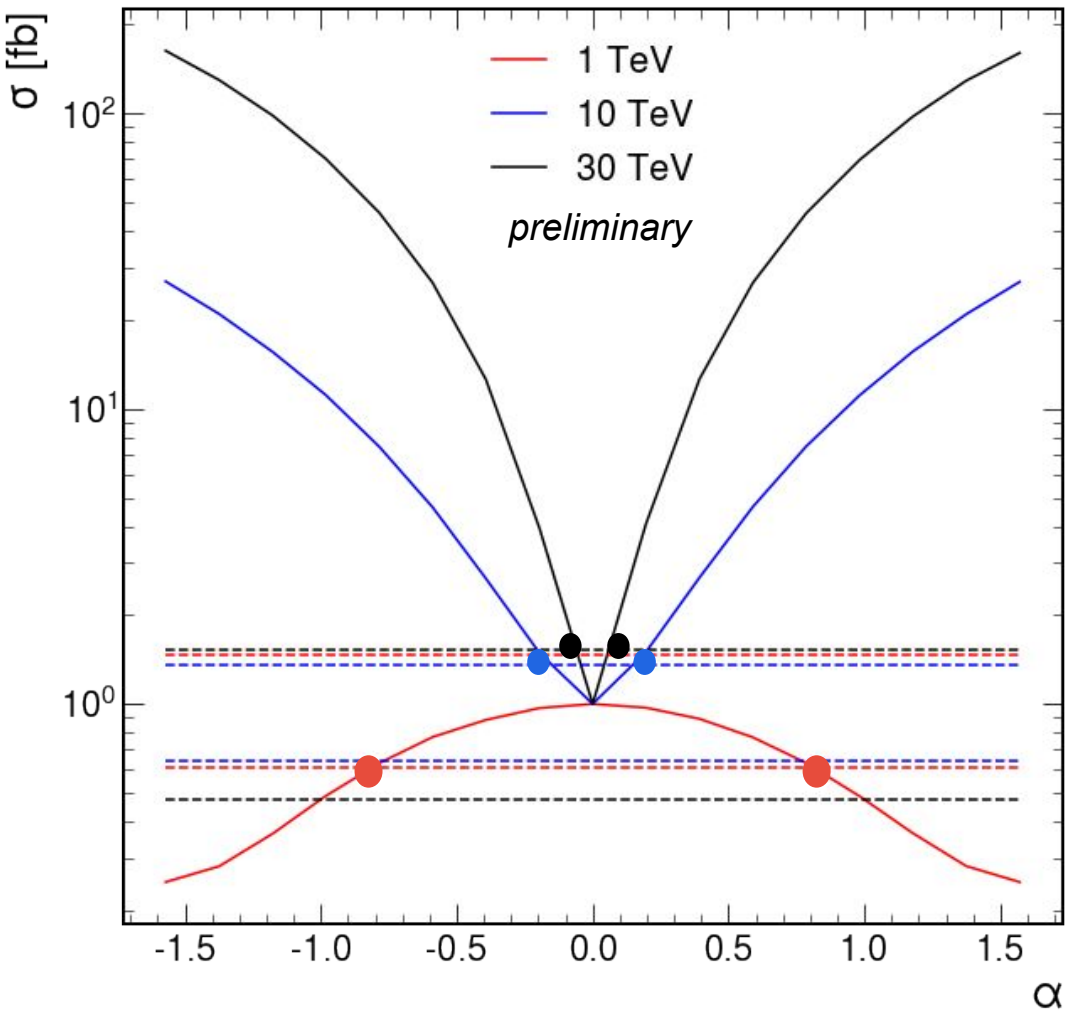


2σ Exclusion on CP phase cont.

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

Table: bounds at 95% CL for α at different colliders.

Directly Probing the CP-structure of the Higgs-Top Yukawa at HL-LHC and Future Colliders
R. K. Barman, et.al .http://arxiv.org/abs/2203.08127

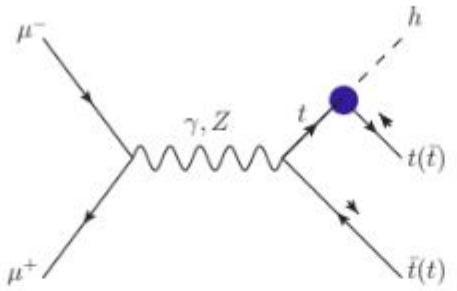
Questions?

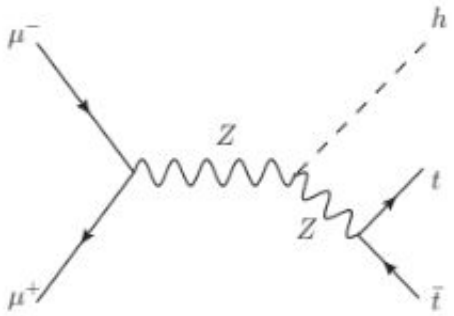
Backups

tth diagrams

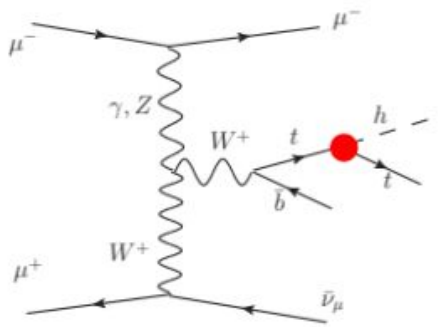
- Diagrams independent of alpha:
- Can parameterize tth cross section as:

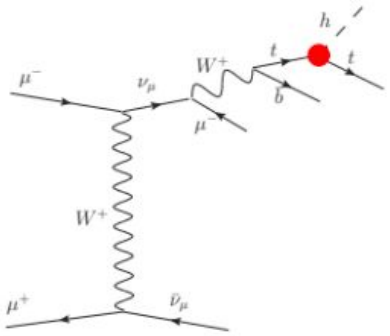
$$\sigma_{t\bar{t}h}(\alpha) = C^2 cos^2\alpha + C^1 cos\alpha + C^0$$

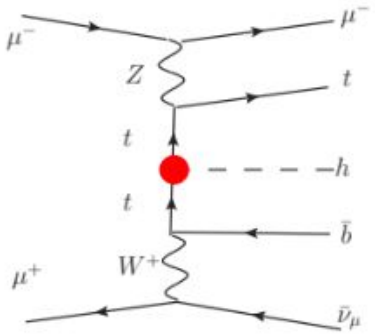


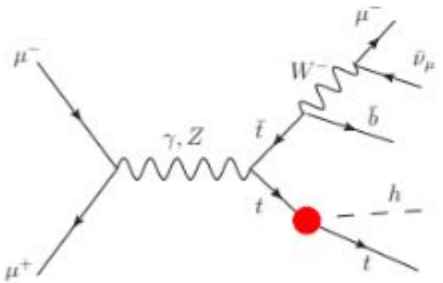


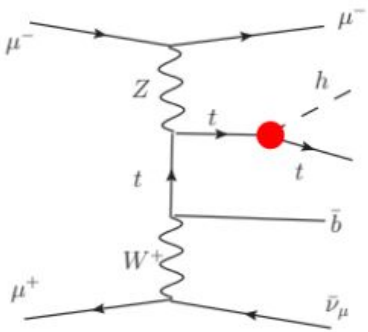
tbh$\mu\nu$ diagrams

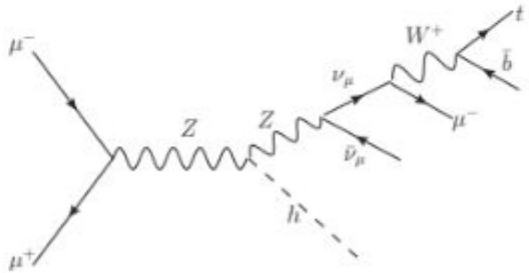




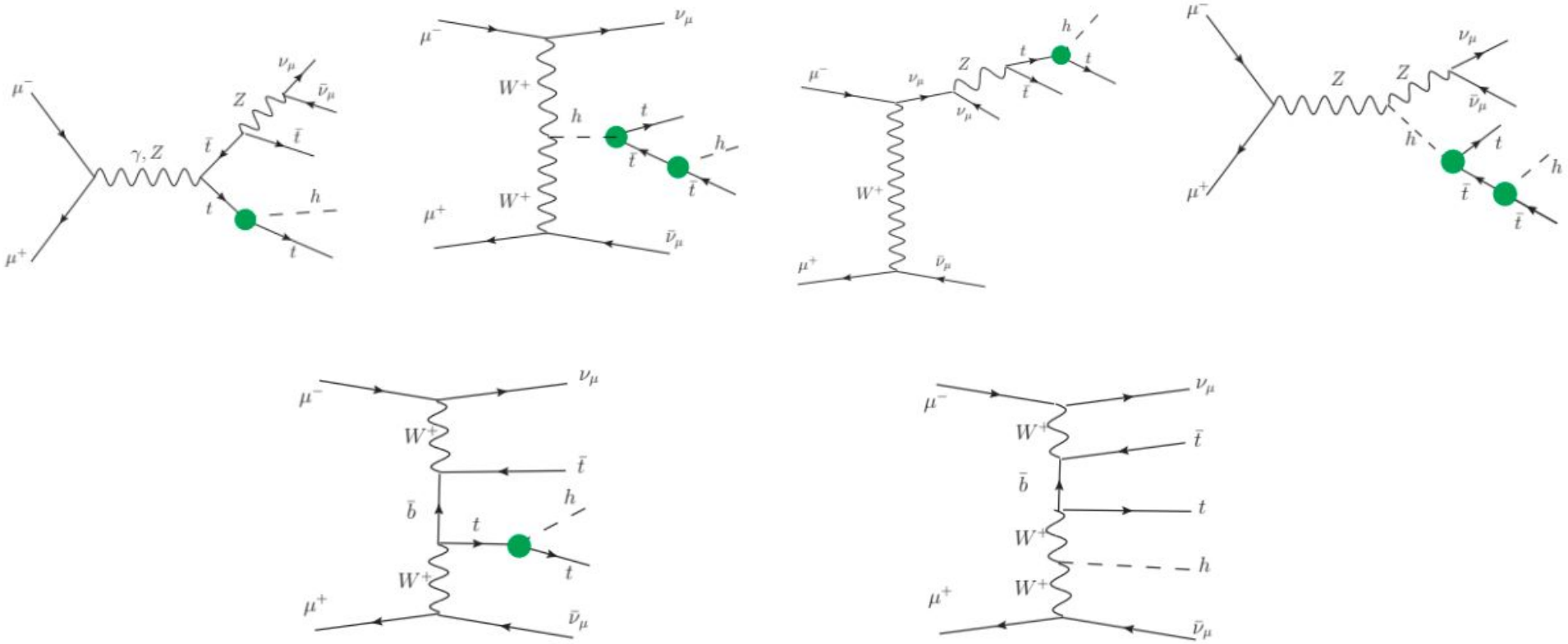








tth$\nu\nu$ diagrams



tth$\nu\nu$

- for fixed √s can determine which contributions dominate

	$t\bar{t}h\nu\bar{\nu}$			
$\sqrt{s}$ (TeV)	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	$7.44 \cdot 10^{-3}$	0.24	2.16	8.09
C^1	$-3.00 \cdot 10^{-3}$	-0.58	−10.43	−93.23
C^0	$2.89 \cdot 10^{-3}$	0.38	8.53	86.00

$$\sigma_{t\bar{t}h\bar{\nu}\nu}(\alpha) = C^4 cos^4\alpha + C^3 cos^3\alpha + C^2 cos^2\alpha + C^1 cos\alpha + C^0$$