

Study of Top Yukawa Coupling in High Energy Muon Colliders

Ishmam Mahbub
University of Minnesota

In Collaboration with Zhen Liu and Kunfeng Lyu

Pheno 2023 Symposium, May 9th, 2023

Outline

- Motivation
- Unitarity in the $W_L^+ W_L^- \rightarrow t\bar{t}$ process
- Muon Colliders
- Measurement
- Results
- Summary and Outlook

Motivation

Objective

- Precise measurement of top Yukawa coupling

Method

- The effective Lagrangian we consider:

$$\mathcal{L}_{eff} \subset (1 + \delta_{yt}) y_t \bar{t} t h$$

- Such \mathcal{L}_{eff} is expected to appear in BSM models like vector like quark (VLQ) models, composite Higgs models , top quark condensation models.
- LHC measurement uncertainty high due to jet background

Unitarity in the $W^+W^- \rightarrow t\bar{t}$ Process

At Large Energies, the contribution from the γ , Z and t-channel contribution grows as:

$$\mathcal{M}^{\gamma+Z+b}(W_L^+W_L^- \rightarrow t\bar{t}) = \frac{m_t}{v^2}\sqrt{s} \quad ; \sqrt{s} > > m_t$$

So, the Higgs diagram is needed to unitarize this contribution. But, if the top yukawa-coupling deviates from Standard Model value by δ_{yt} :

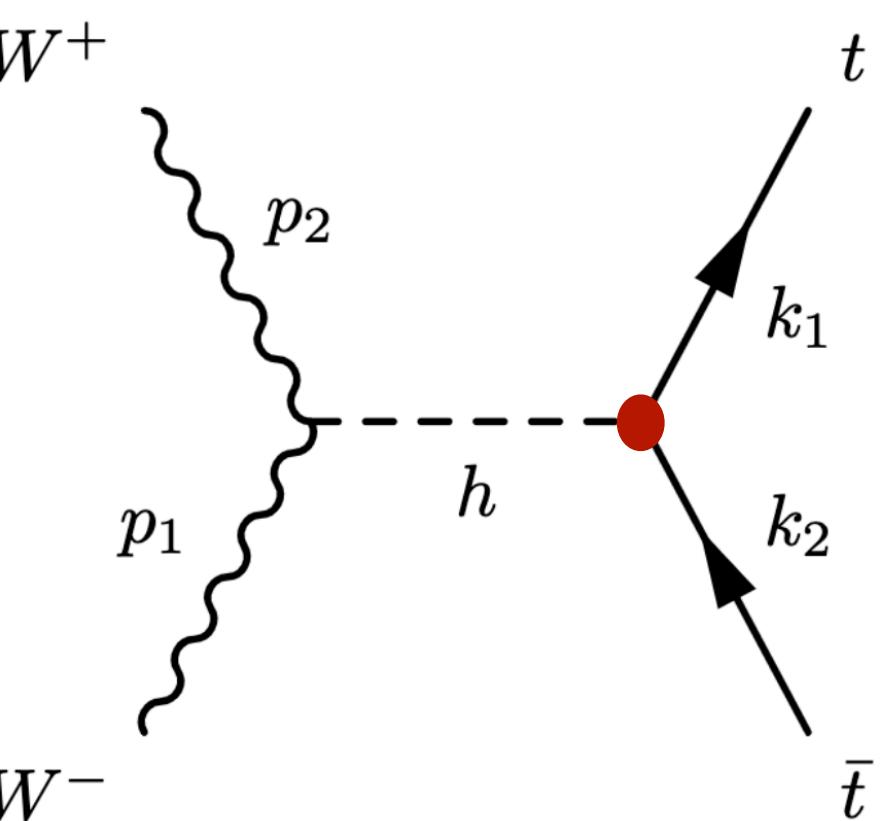
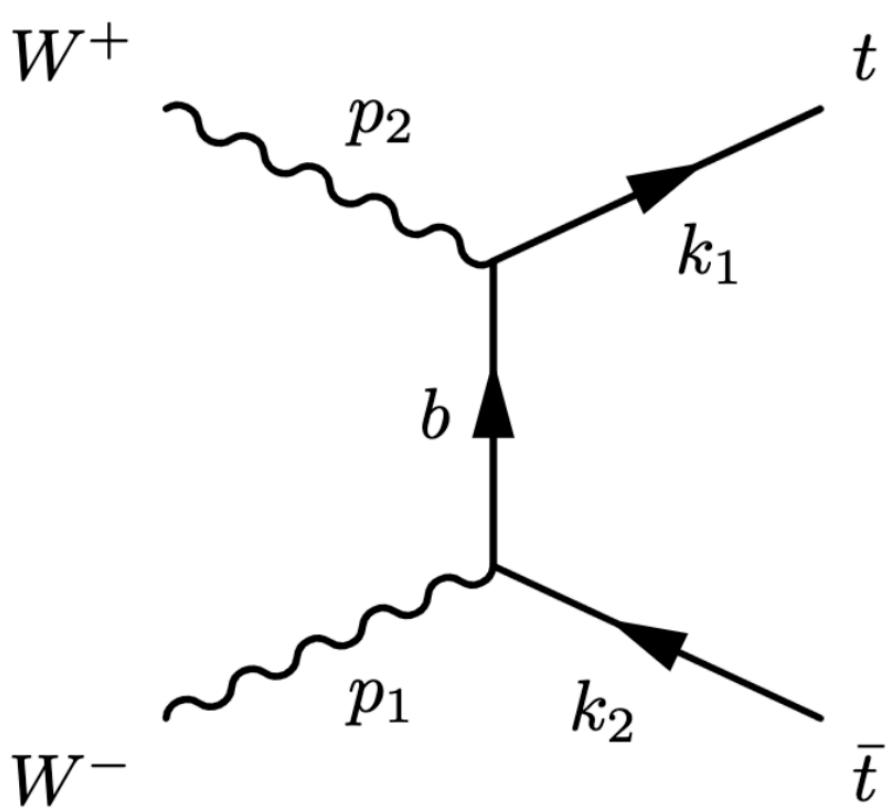
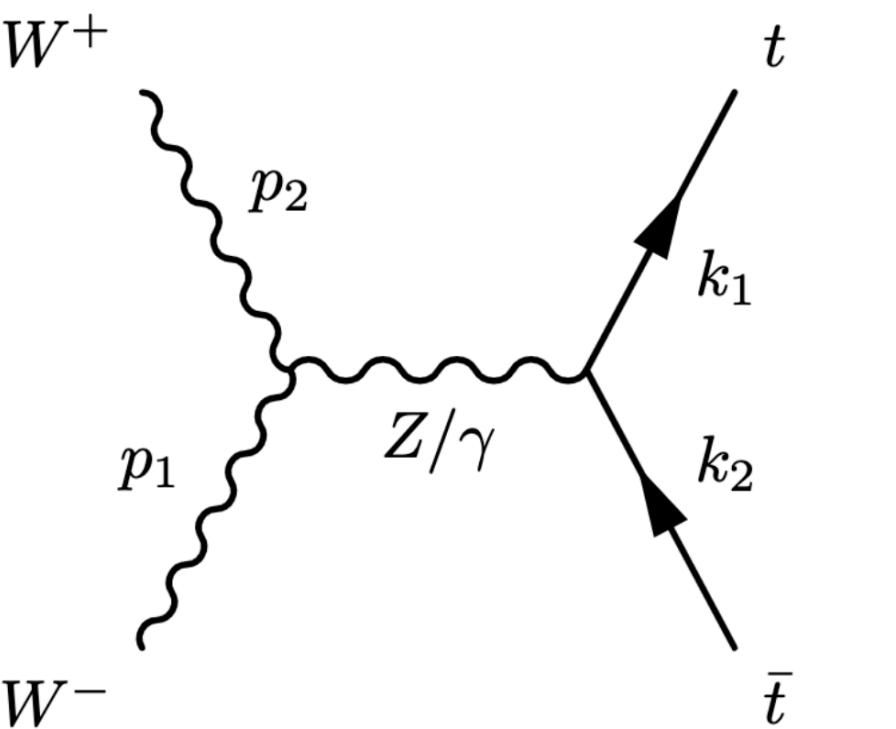
$$y_t \rightarrow y_t(1 + \delta_{yt})$$

The scattering amplitude will scale as:

$$\mathcal{M}(W_L^+W_L^- \rightarrow t\bar{t}) = \frac{m_t}{v^2}\sqrt{s}\delta_{yt} \quad ; \quad \sqrt{s} > > m_t$$

Then Perturbative unitarity will be broken at some scale:

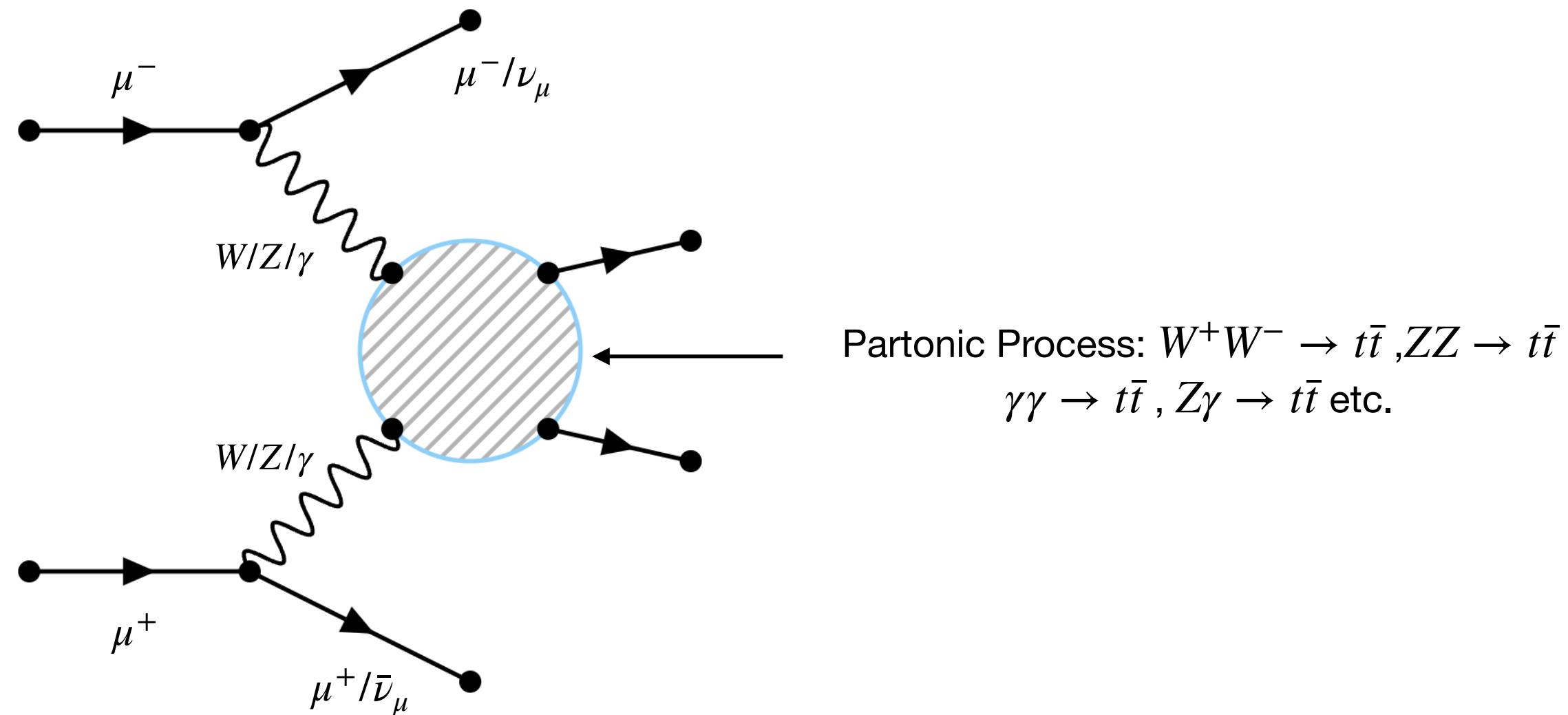
$$\Lambda < \frac{10\text{TeV}}{\delta_{yt}}$$



Muon Collider

- Can provide high precision and high energy
 - Muon being fundamental particle, full energy available in collision
 - Cleaner background
 - High mass suppresses synchrotron radiation
- The price to pay is the instability of muons leading to neutrino radiation, beam induced background
 - Progress to overcome spearheaded by US Muon Accelerator Program (MAP), the Muon Ionization Cooling Experiment (MICE)

$t\bar{t}$ production at muon colliders



Production Cross-section

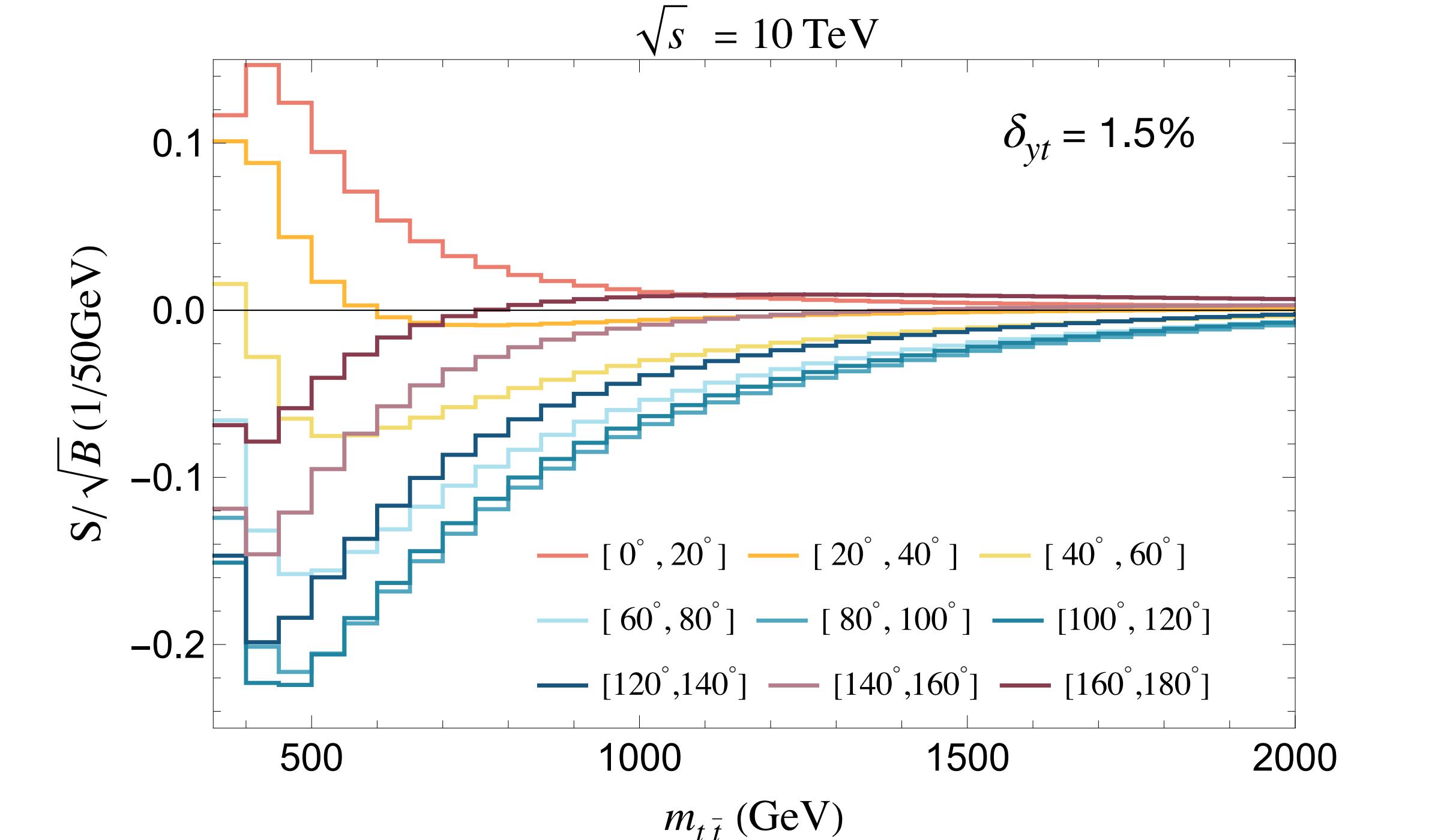
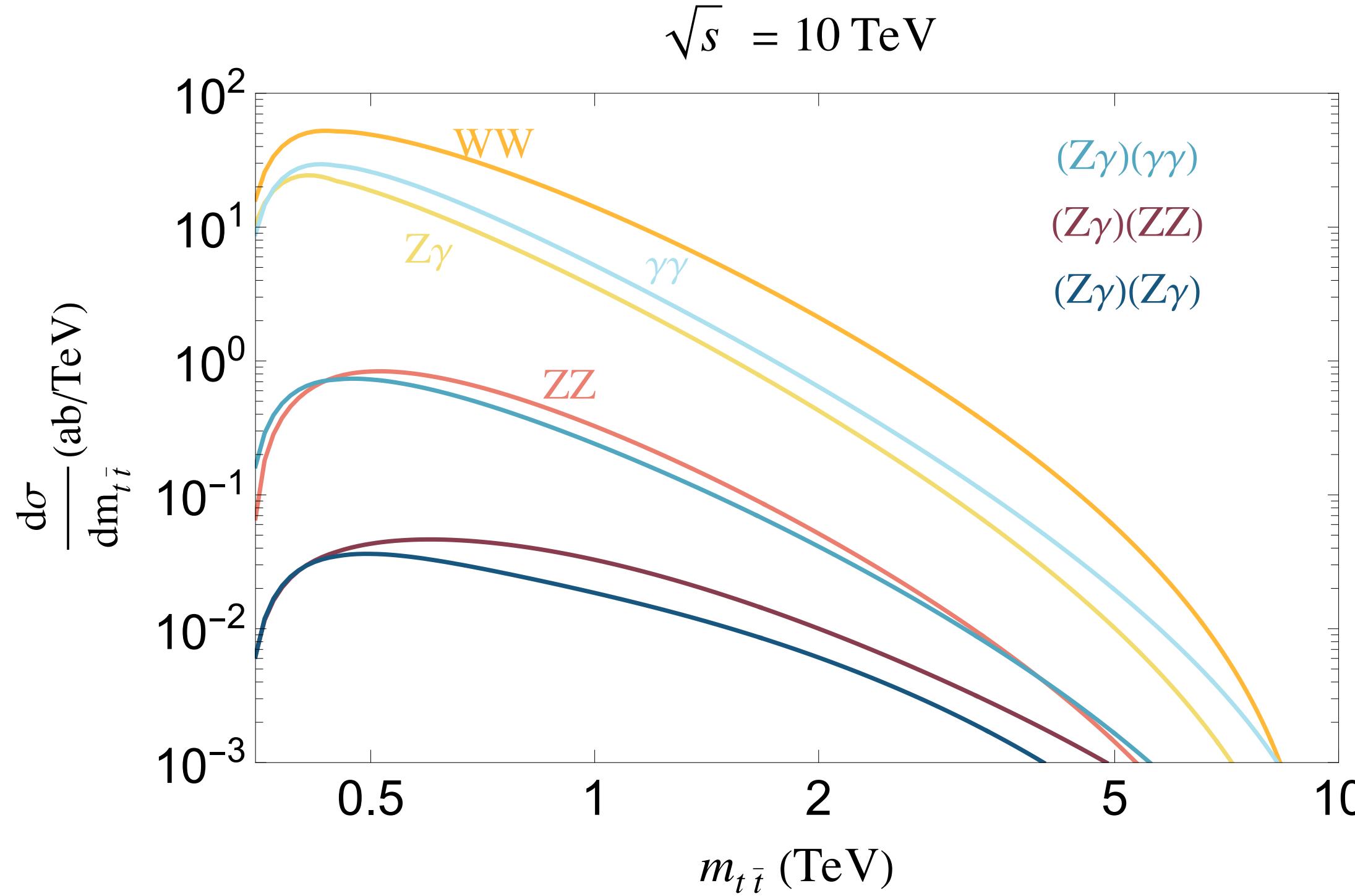
$$\sigma(\mu^+\mu^- \rightarrow F + X) = \int_{\tau_{\min}}^{\tau_{\max}} d\tau \sum_{ij} \frac{d\mathcal{L}_{ij}}{d\tau} \hat{\sigma}(ij \rightarrow F)$$

Luminosity Function is given by:

$$\frac{d\mathcal{L}_{ij}}{d\tau} = \frac{1}{1 + \delta_{ij}} \int_{\tau}^1 \frac{d\xi}{\xi} [f_i(\xi, \mu_f) f_j(\frac{\tau}{\xi}, \mu_f) + i \leftrightarrow j]$$

Cross-section for $\mu^+\mu^- \rightarrow t\bar{t} + X$

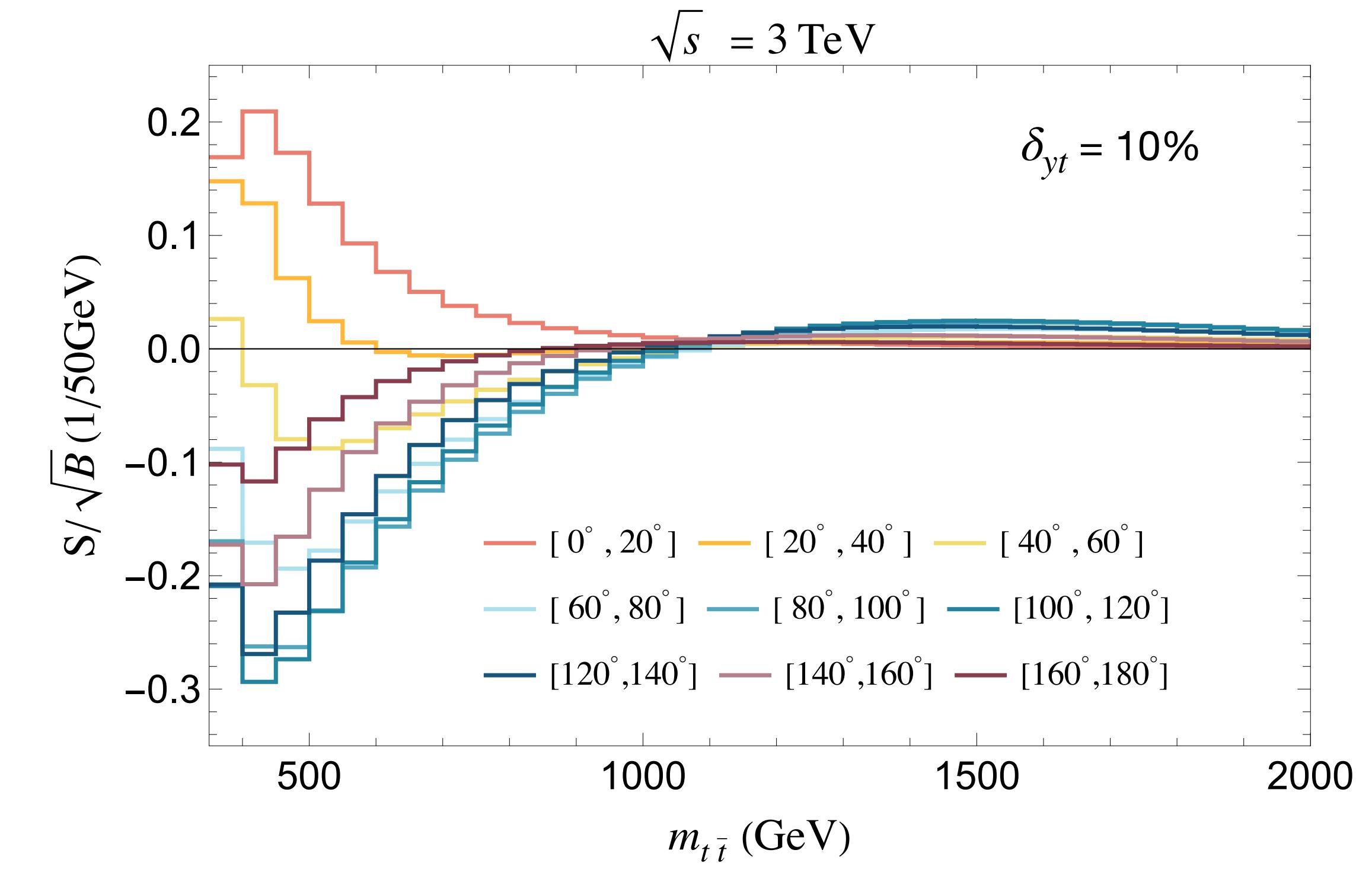
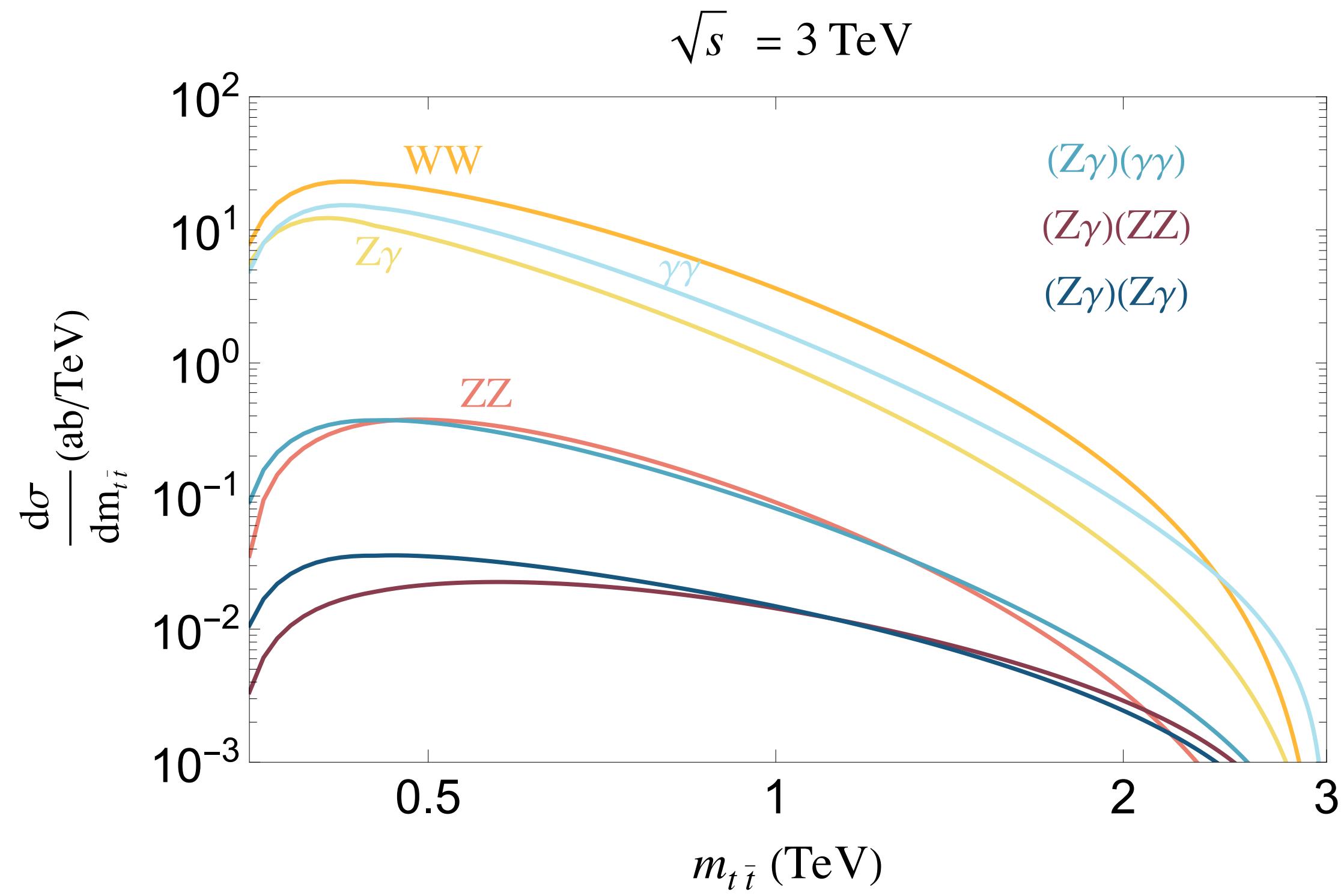
10 TeV 10 ab^{-1} Muon Collider



- W-Channel dominates the cross-section where we have the δ_{yt} signal
- $(Z\gamma)(\gamma\gamma)$, $(ZZ)(\gamma\gamma)$, $(Z\gamma)(Z\gamma)$ are subtle interference effects
- Signal refers to $|\mathcal{M}_{SM} + \mathcal{M}_{\delta_{yt}}|^2 - |\mathcal{M}_{SM}|^2$
- Signal dominated by interference between \mathcal{M}_{SM} and $\mathcal{M}_{\delta_{yt}}$

Cross-section for $\mu^+\mu^- \rightarrow t\bar{t} + X$

3 TeV 1 ab^{-1} Muon Collider



- W-Channel dominates the cross-section

- Reduced significance at 3 TeV

$\Delta\chi^2$ test is performed by binning $m_{t\bar{t}}$ with 50 GeV bins and angular distribution into 9 bins

$\Delta\chi^2$ Analysis

Event Selection:

- Dilepton events are discarded after $t\bar{t}$ decay
- Angle Cut: $10^\circ < \theta < 170^\circ$

Results:

@68% C.L.

	δ_{yt}	δ_{yt}
$\sqrt{s} = 3 \text{ TeV}$	-6%	8%
$\sqrt{s} = 10 \text{ TeV}$	-1.25%	1.4%

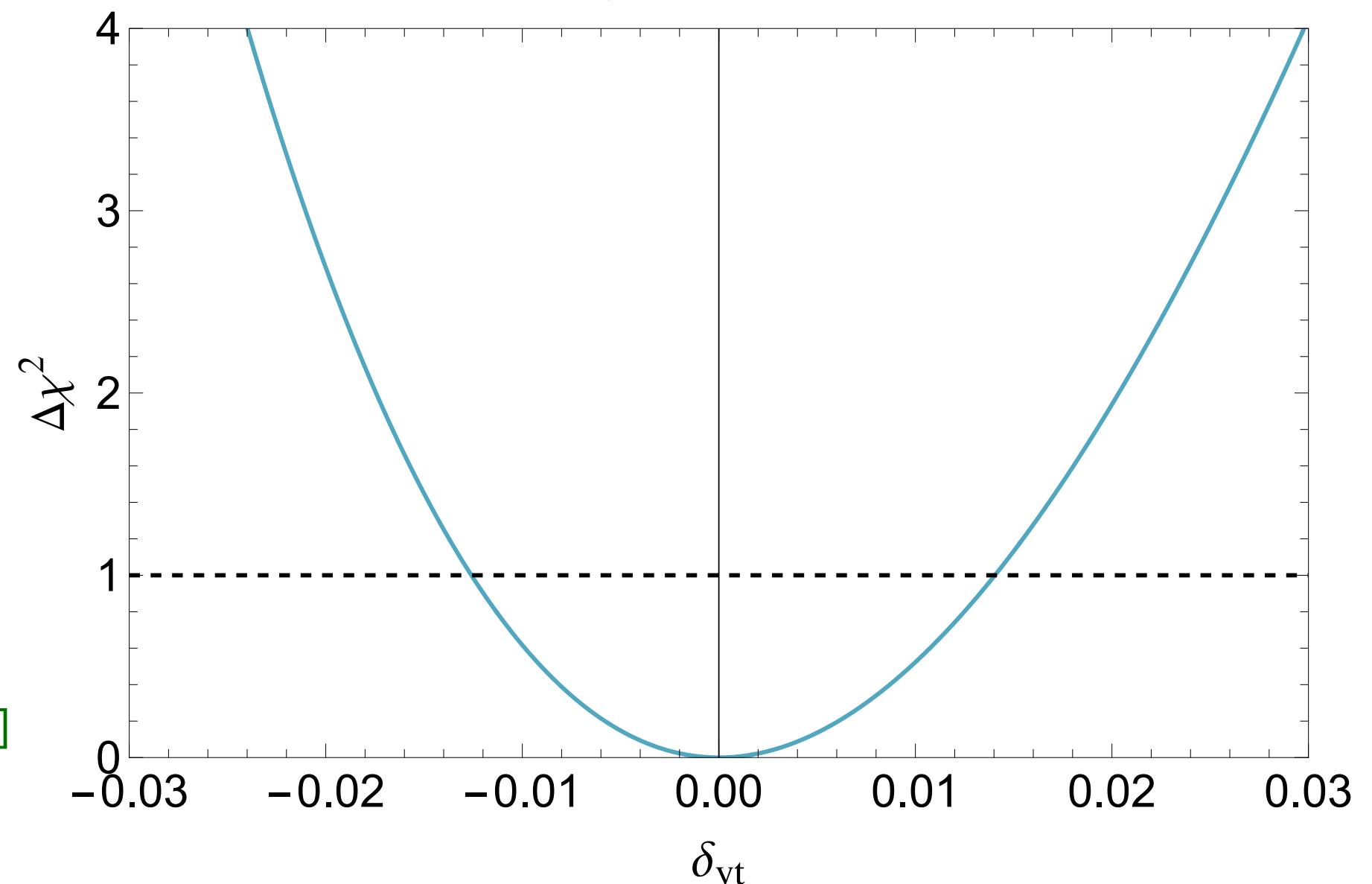
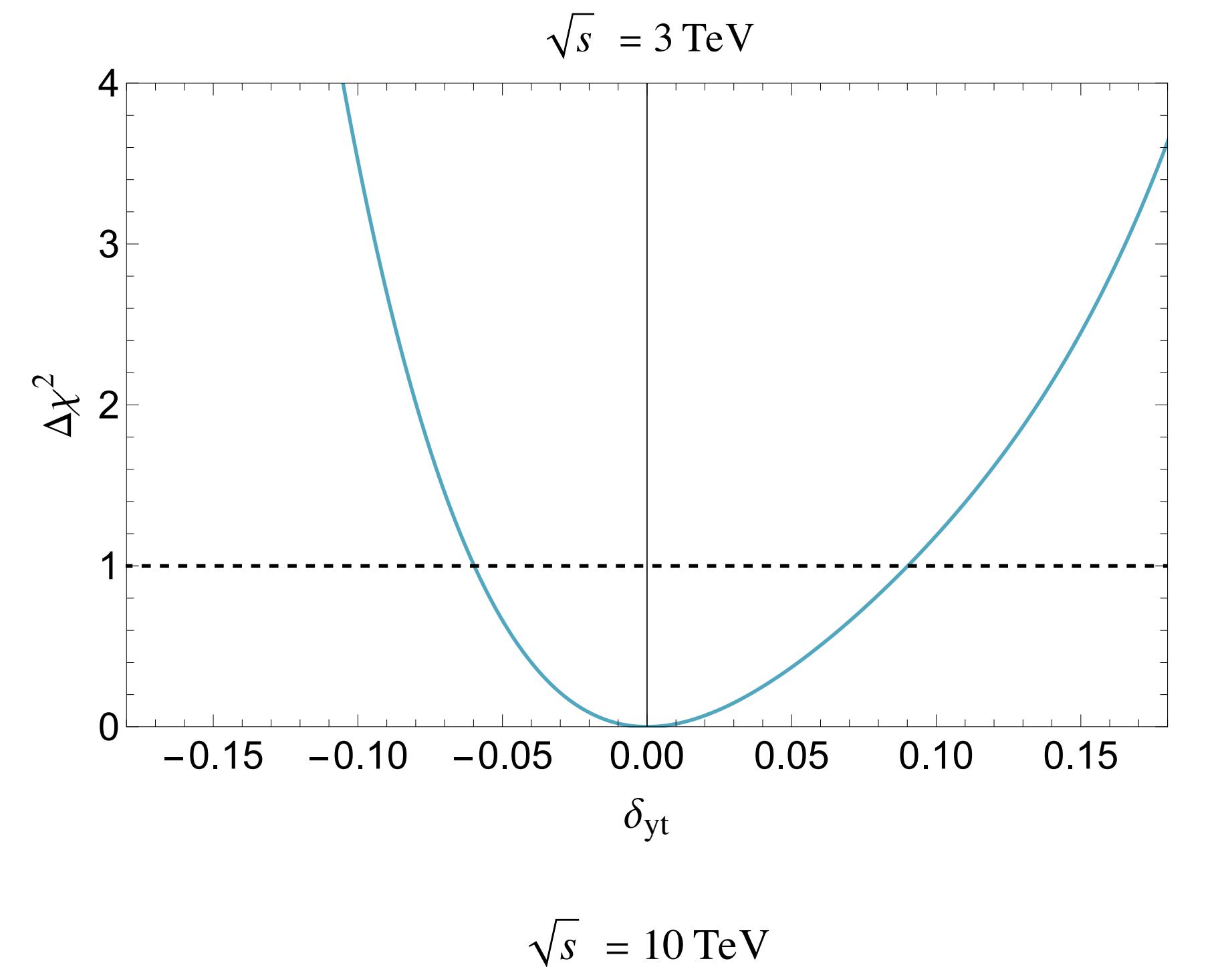
Comparison:

Direct measurement @MuC using $t\bar{t}h$ channel for 3 TeV is 53% and for 10 TeV 34%

14 TeV HL-LHC @ $3 ab^{-1}$ is 14%

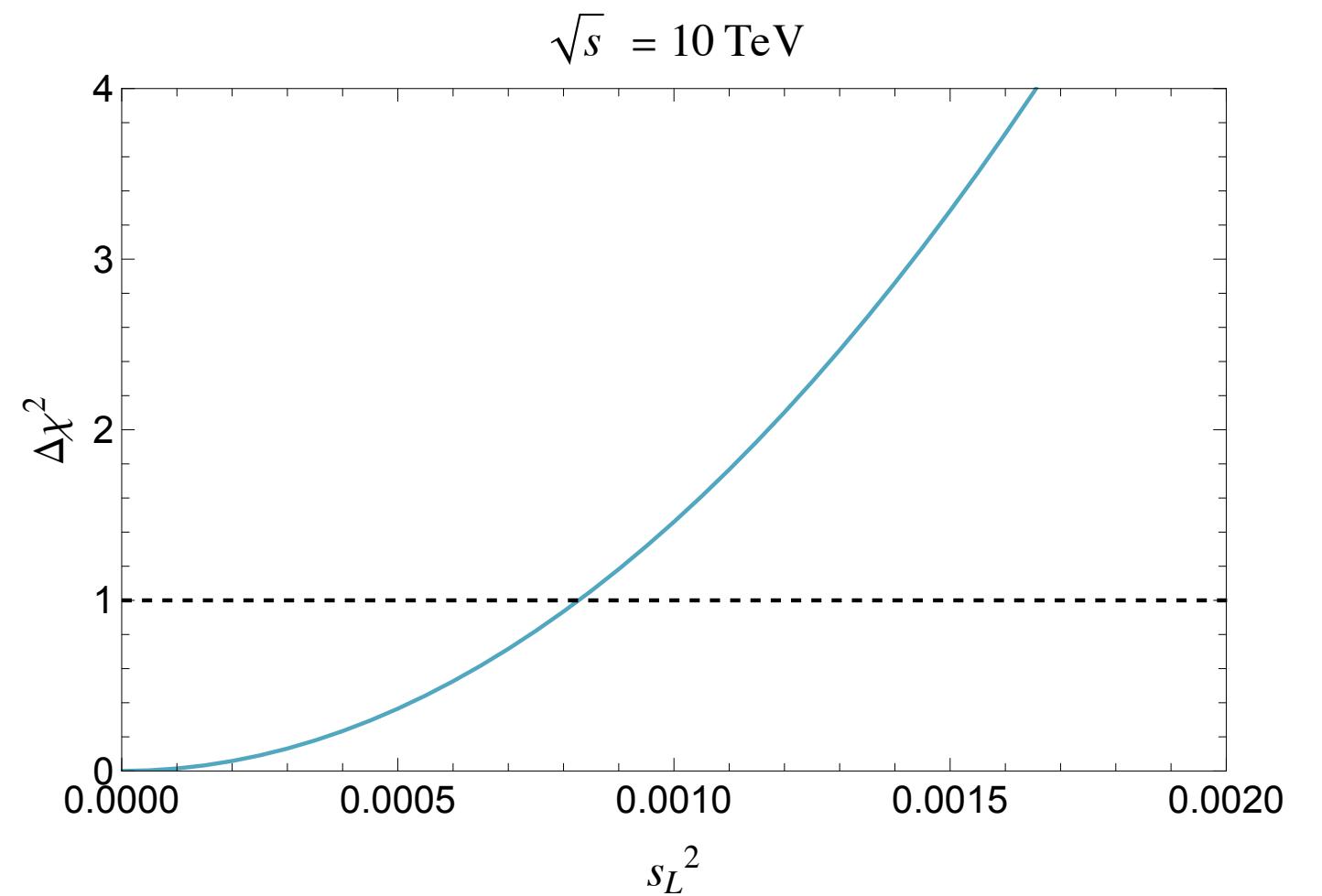
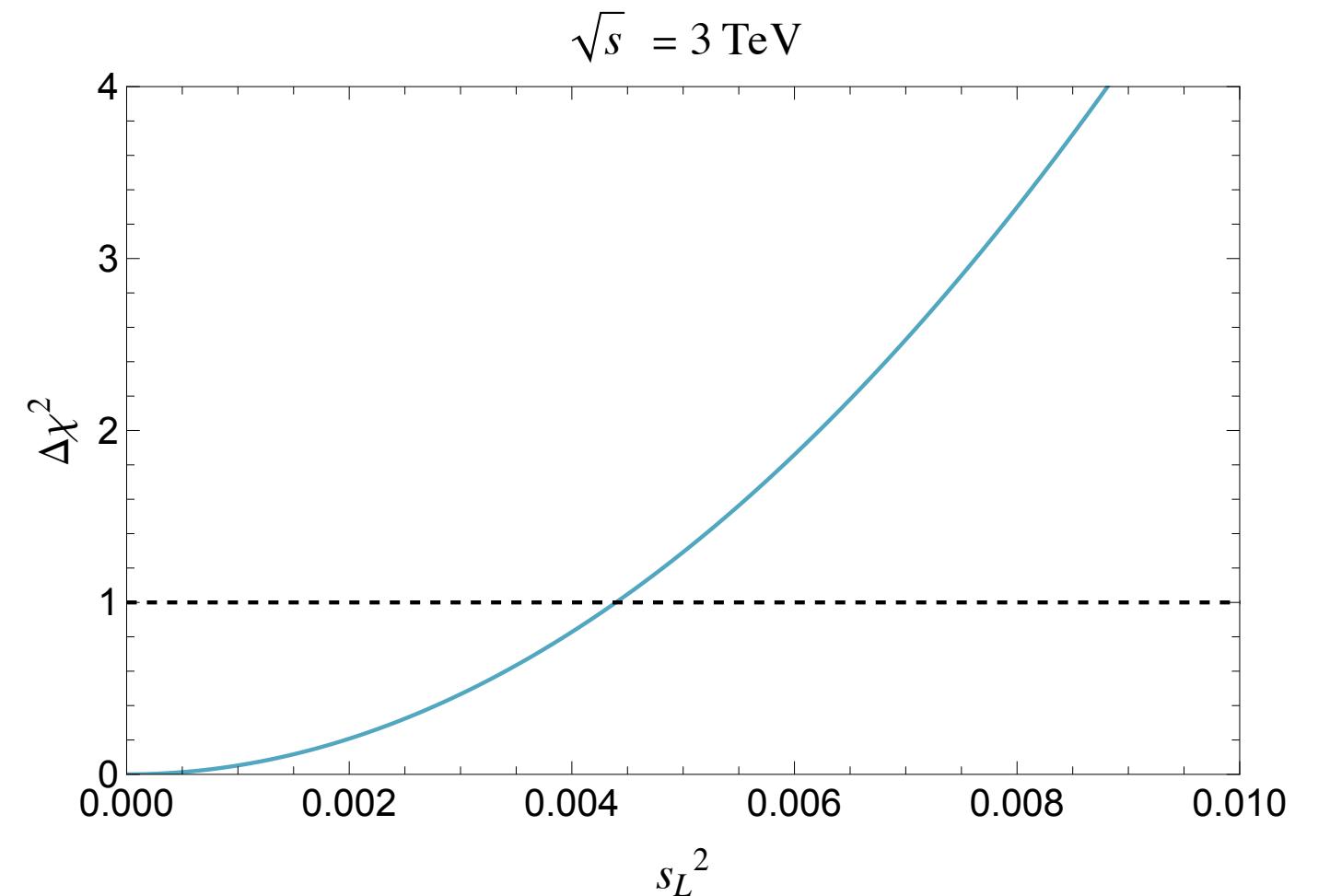
[M. Forslund, P. Meade, arXiv:2203.09425]

[A. M. Sirunyan et. al., arXiv:1809.10733]



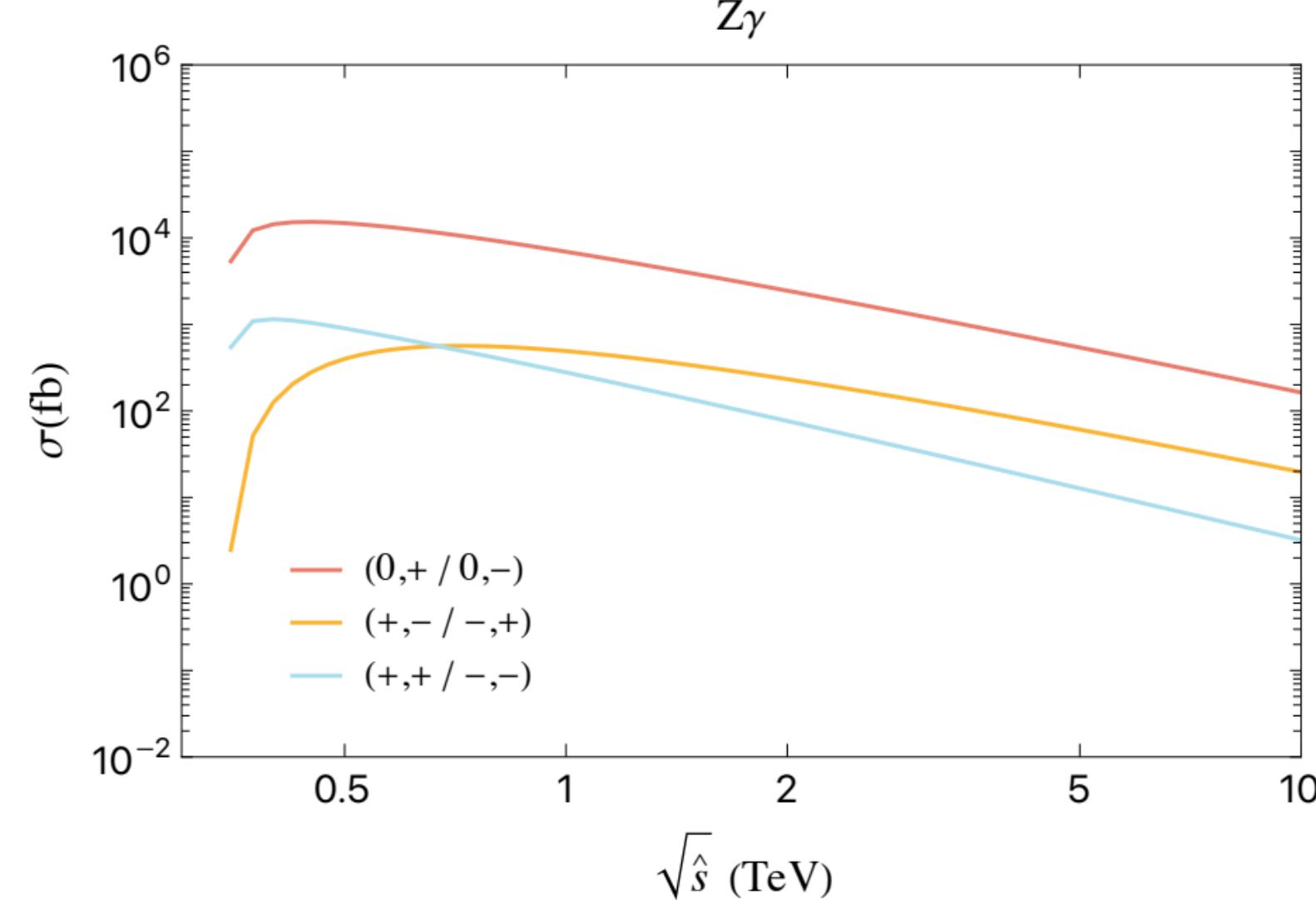
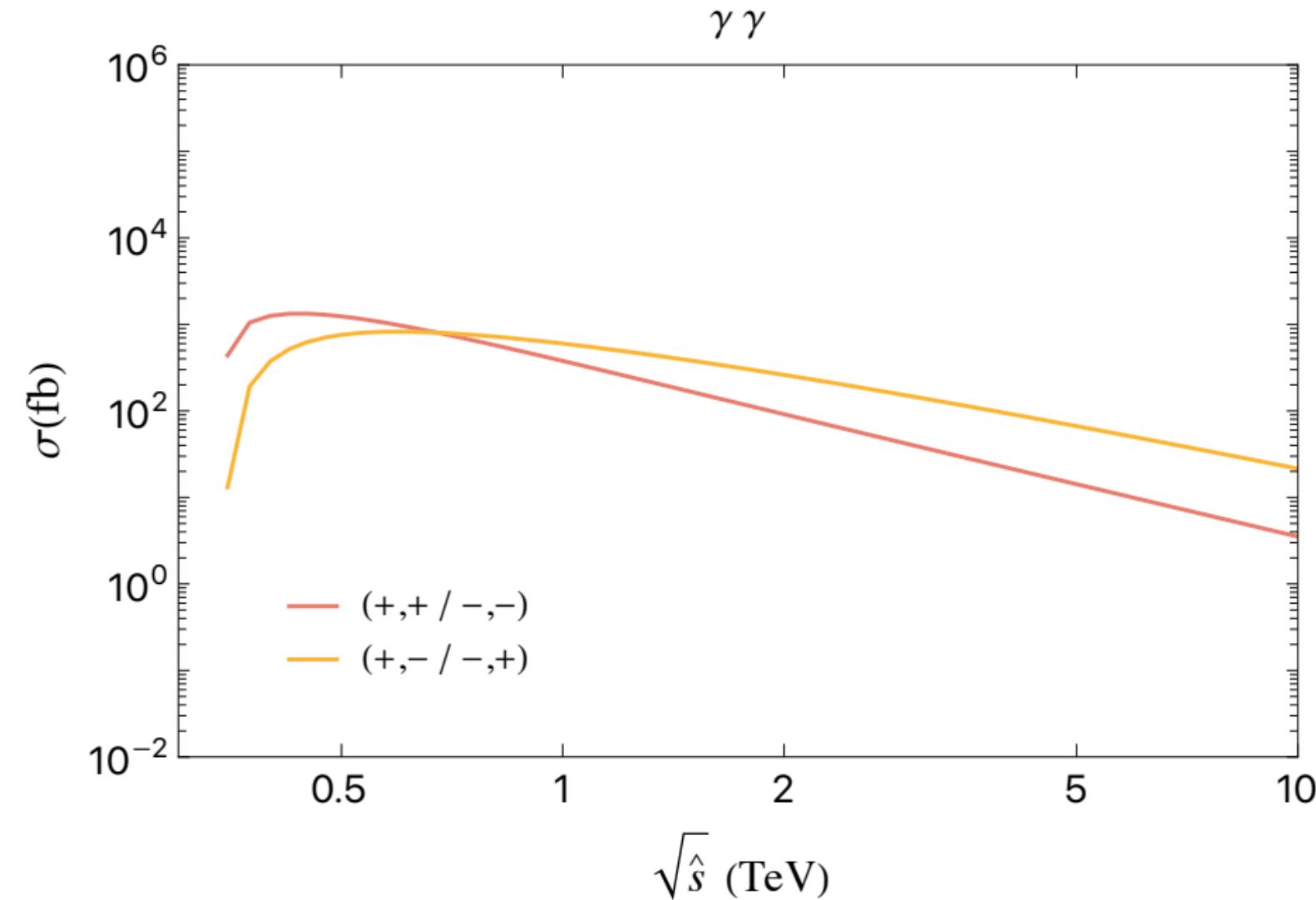
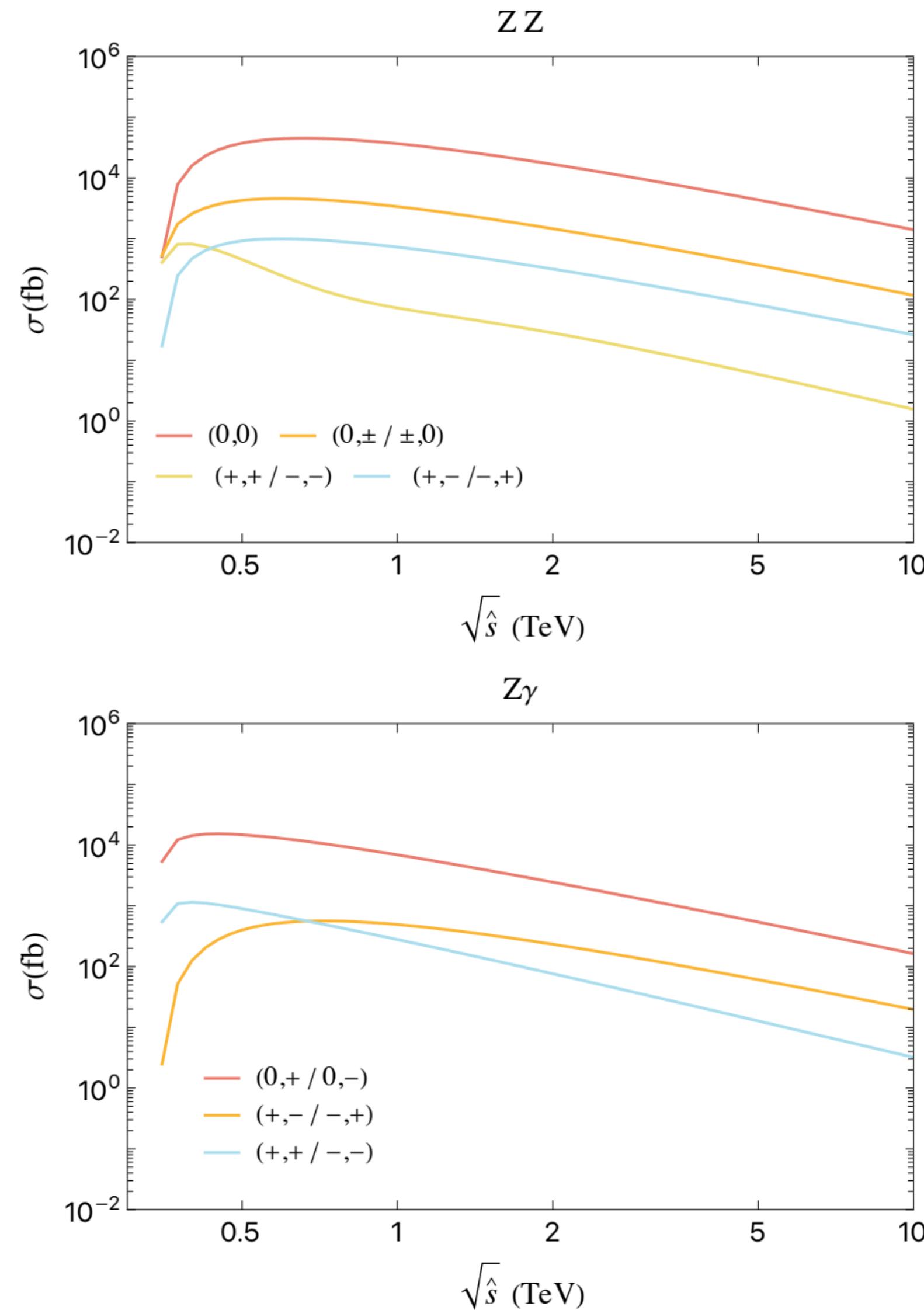
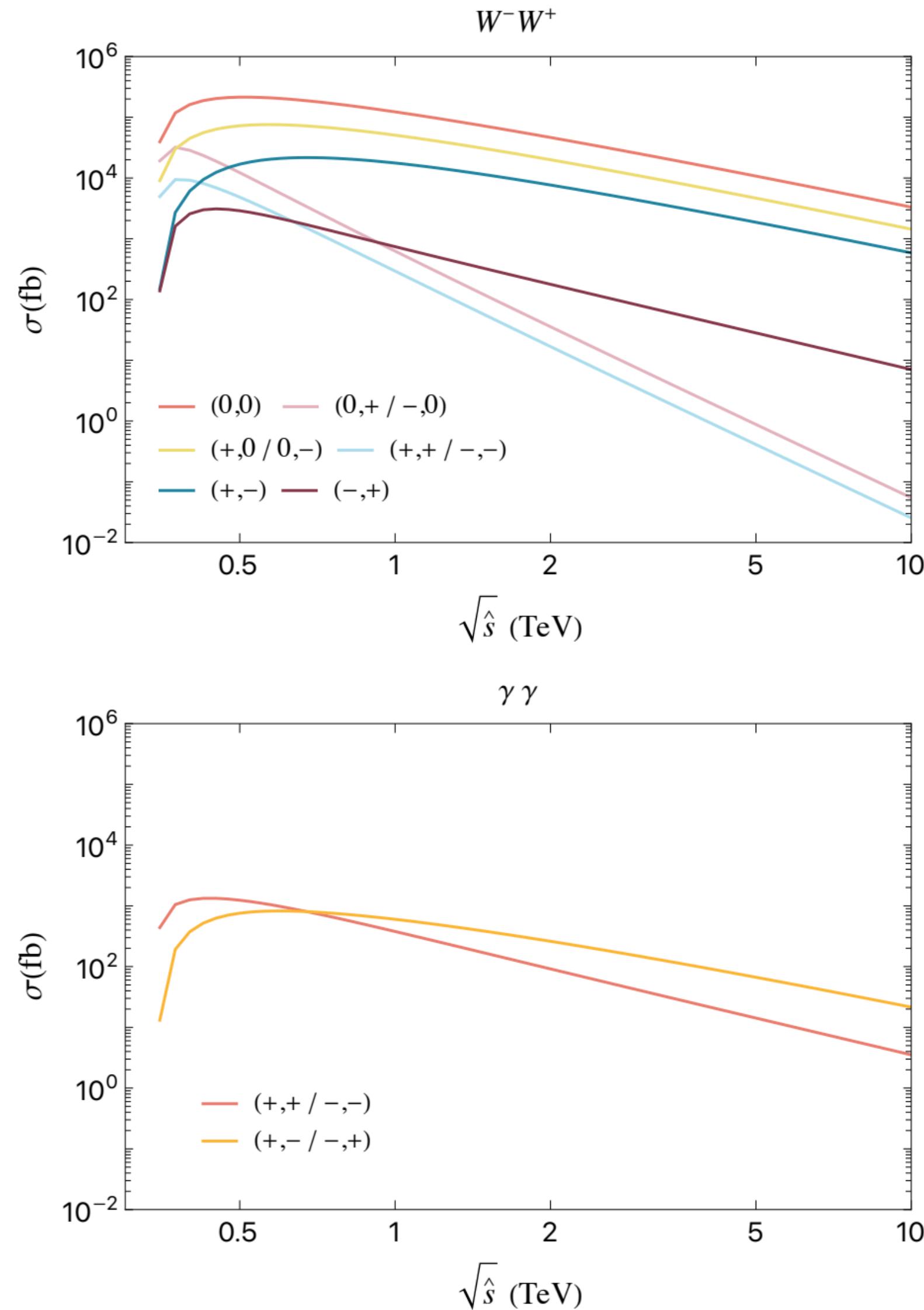
Summary and Outlook

- Consideration of various UV complete models
 - Promising results for VLQ model with one heavy top partner
 - Study other models
- Detailed consideration of detector effects and reconstruction



Results for VLQ model with one top partner

Backup



Sensitivity of $W^+W^- \rightarrow t\bar{t}$ partonic process

