Study of Top Yukawa Coupling Deviations in High Energy Muon Colliders

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- Muon Colliders
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Motivation

Objective

- Precise measurement of top Yukawa coupling

Method

- The effective Lagrangian we consider:

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

- Such $\mathscr{L}_{eff}$ 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 $W^+W^- \to t\bar{t}$ Process

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

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

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

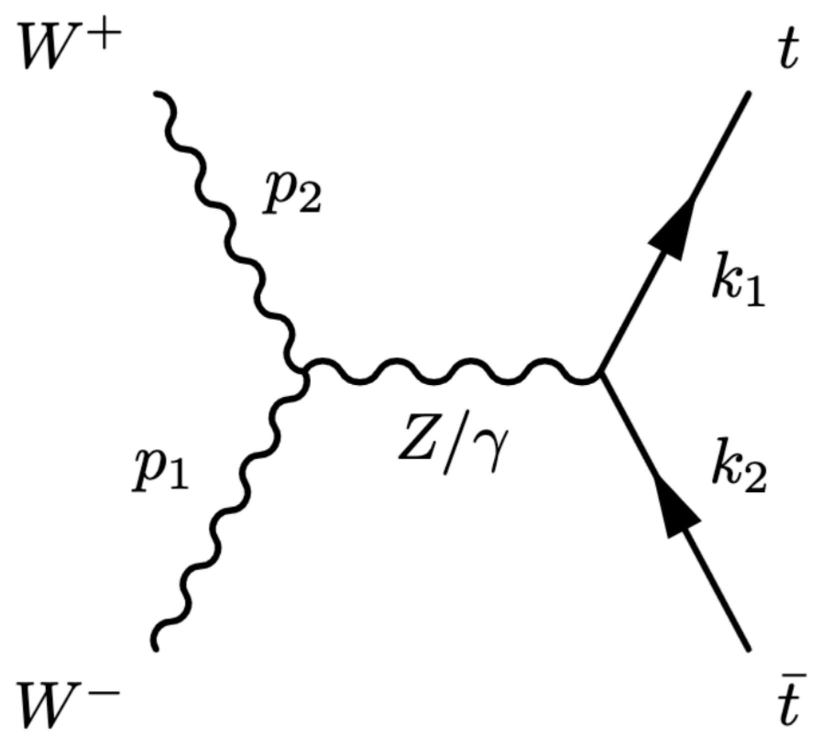
$$y_t \to y_t(1 + \delta_{yt})$$

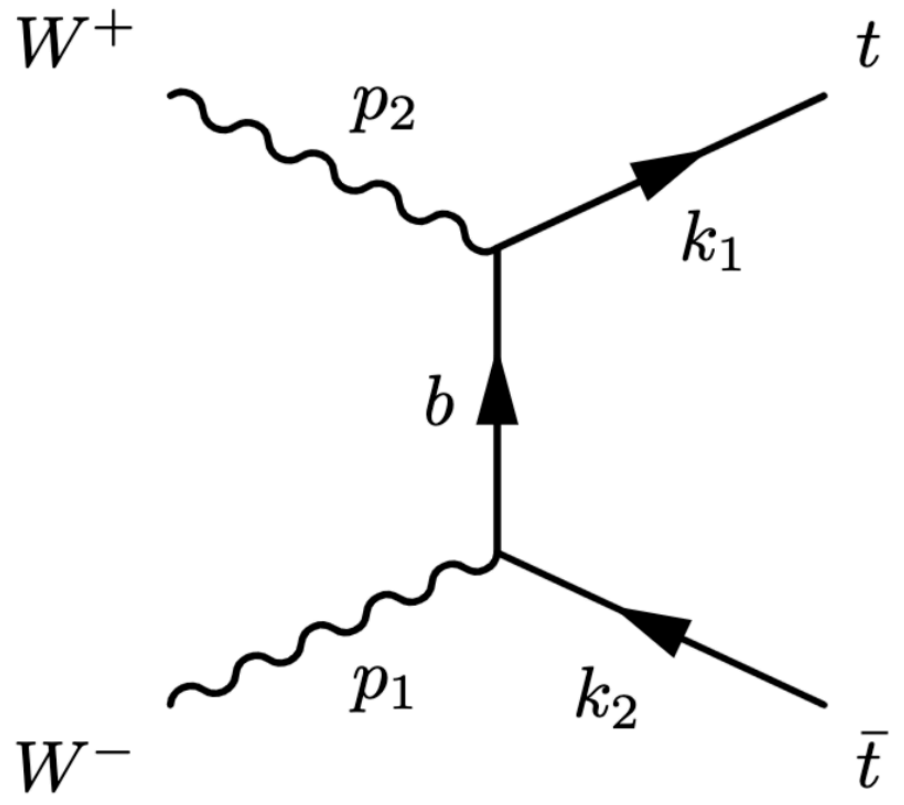
The scattering amplitude will scale as:

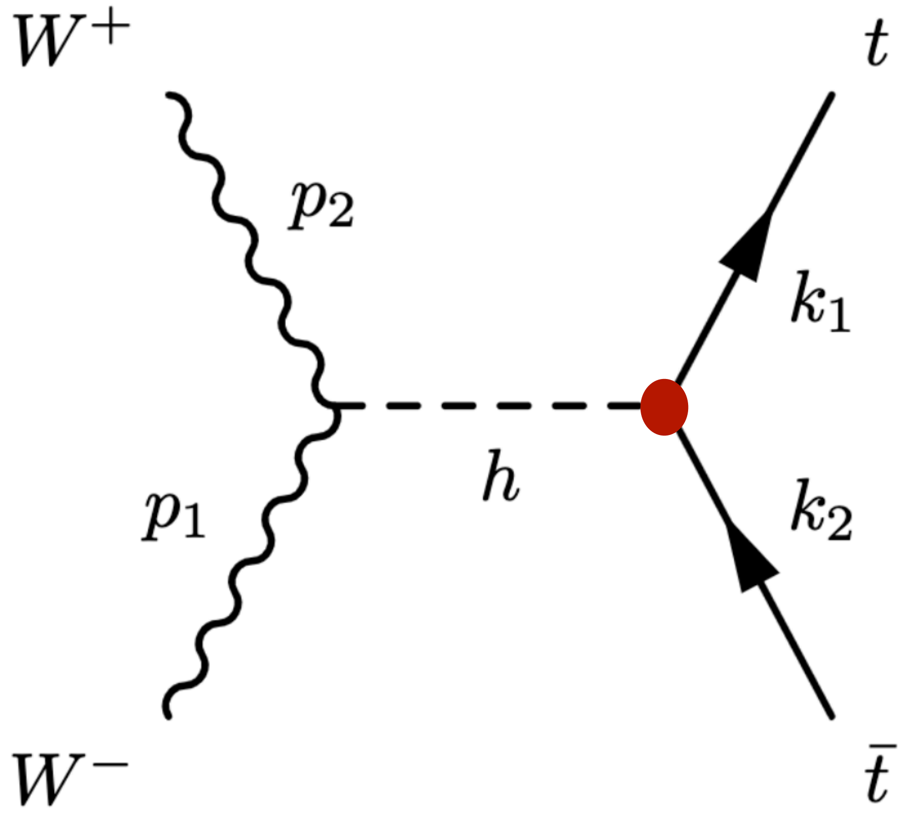
$$\mathcal{M}(W_L^+W_L^- \to t\bar{t}) \;=\; \frac{m_t}{v^2}\sqrt{s}\delta_{yt} \;\; ; \;\; \sqrt{s} >> m_t$$

Then Perturbative unitarity will be broken at some scale:

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



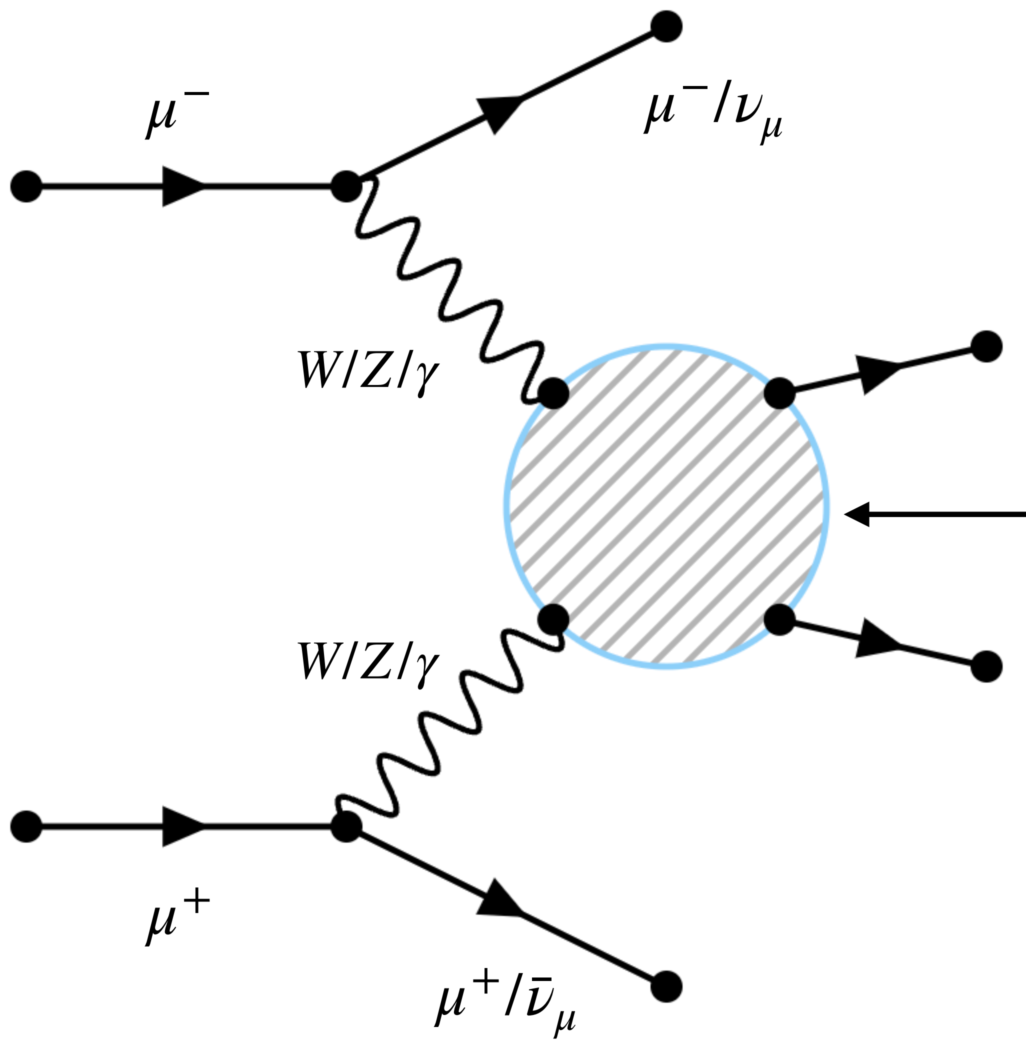




Muon Collider

- 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 unstability 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



Partonic Process: $W^+W^- \to t\bar{t}$,$ZZ \to t\bar{t}$
$\gamma\gamma \to t\bar{t}$, $Z\gamma \to t\bar{t}$ etc.

Production Cross-section

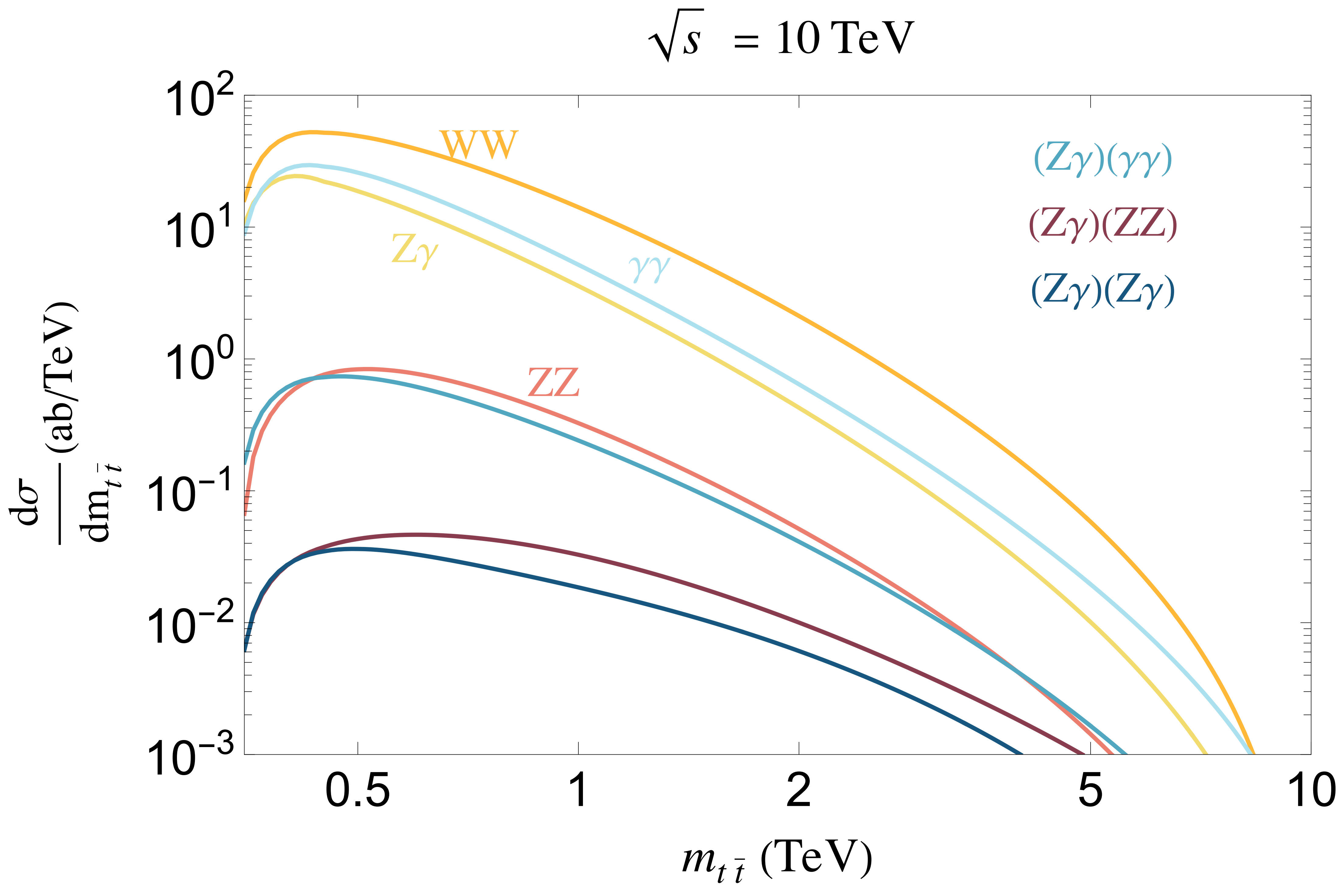
$$\sigma(\mu^+\mu^- \to F + X) = \int_{\tau_{\min}}^{\tau_{\max}} d\tau \sum_{ij} \frac{\mathscr{L}_{ij}}{d\tau} \hat{\sigma}(ij \to F)$$

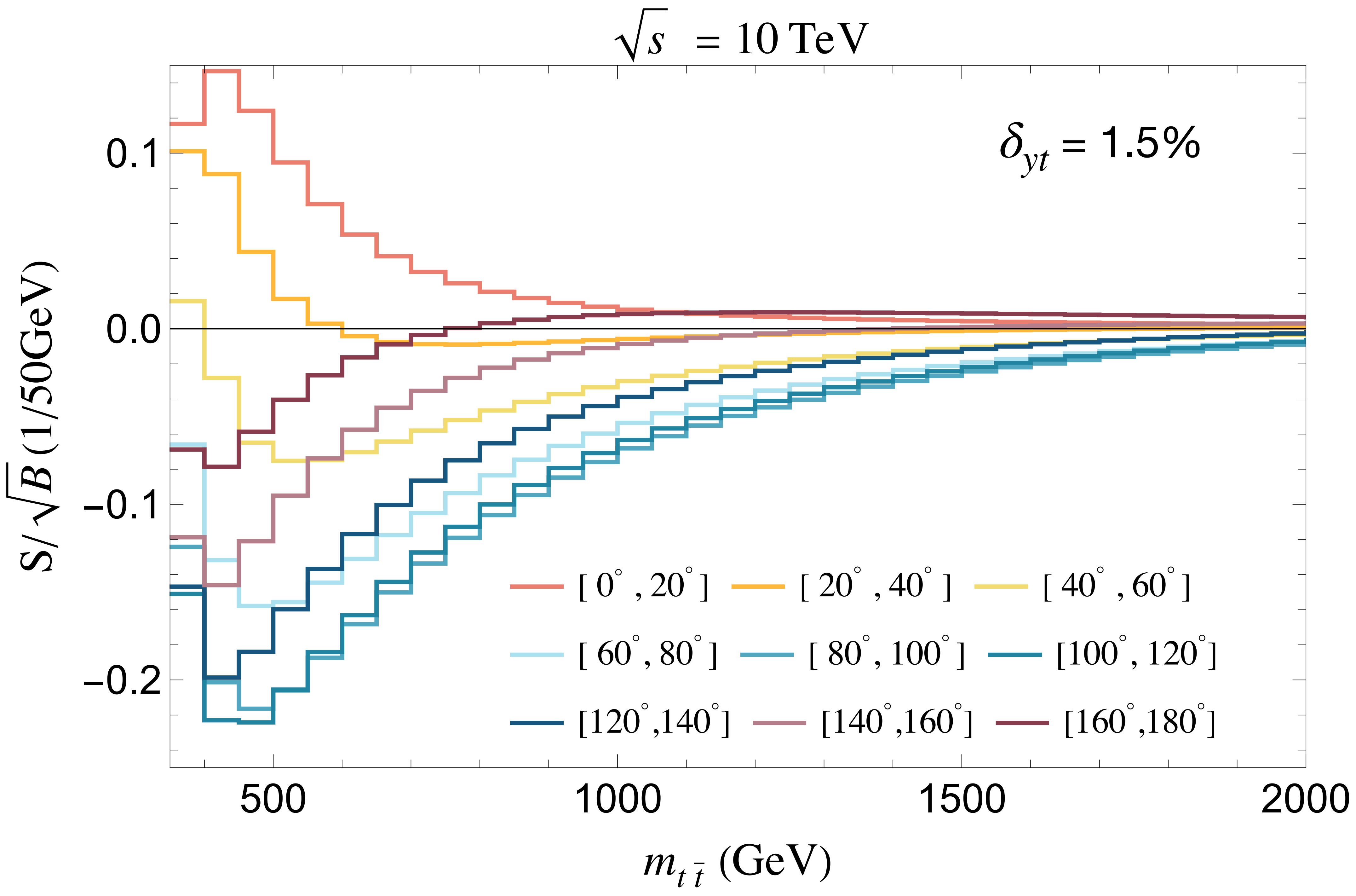
Luminosity Function is given by:

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

[T. Han, Y. Ma, K. Xie , arXiv:2007.14300v4]

Cross-section for $\mu^+\mu^- \to t\bar{t} + X$
10 TeV 10 ab^{-1} Muon Collider

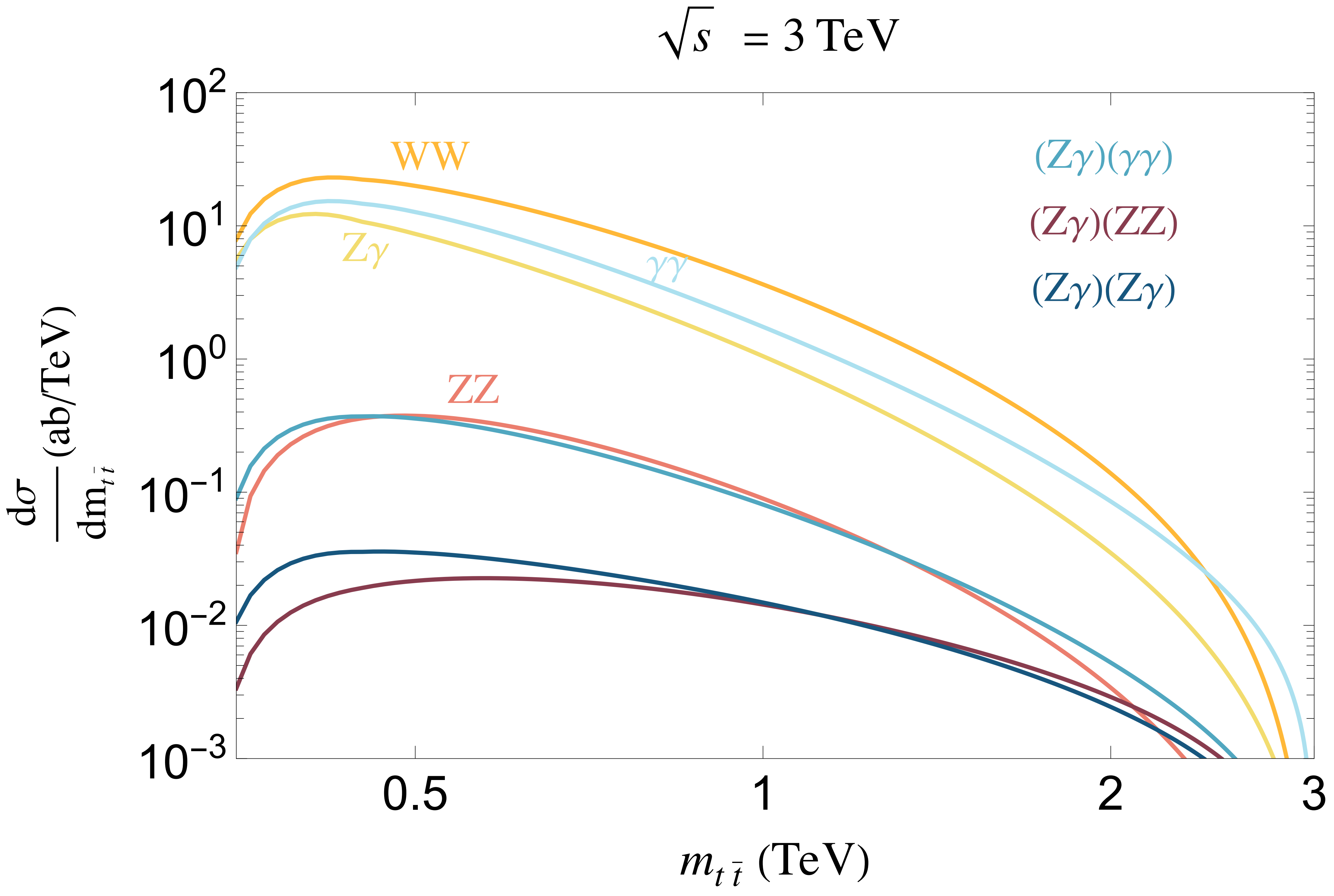




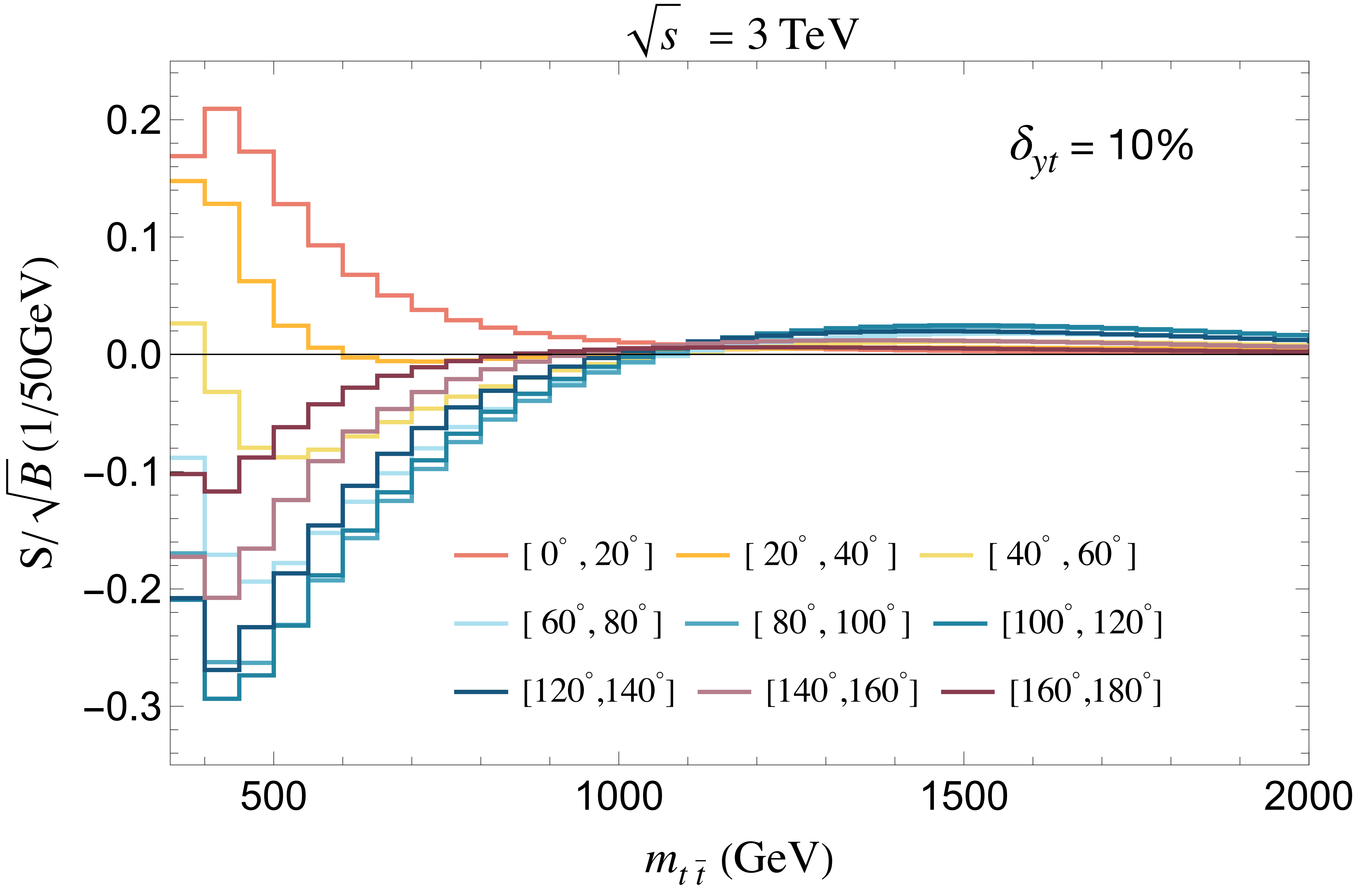
- W-Channel dominates the cross-section where we have the δ_{yt} signal
- $(Z\gamma)(\gamma\gamma)$, $(ZZ)(\gamma\gamma)$, $(Z\gamma)(Z\gamma)$ are subtle interference effects

- Signal referes to $|\mathscr{M}_{SM} + \mathscr{M}_{\delta_{yt}}|^2 - |\mathscr{M}_{SM}|^2$
- Signal dominated by interference between $\mathscr{M}_{SM}$ and $\mathscr{M}_{\delta_{yt}}$

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

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

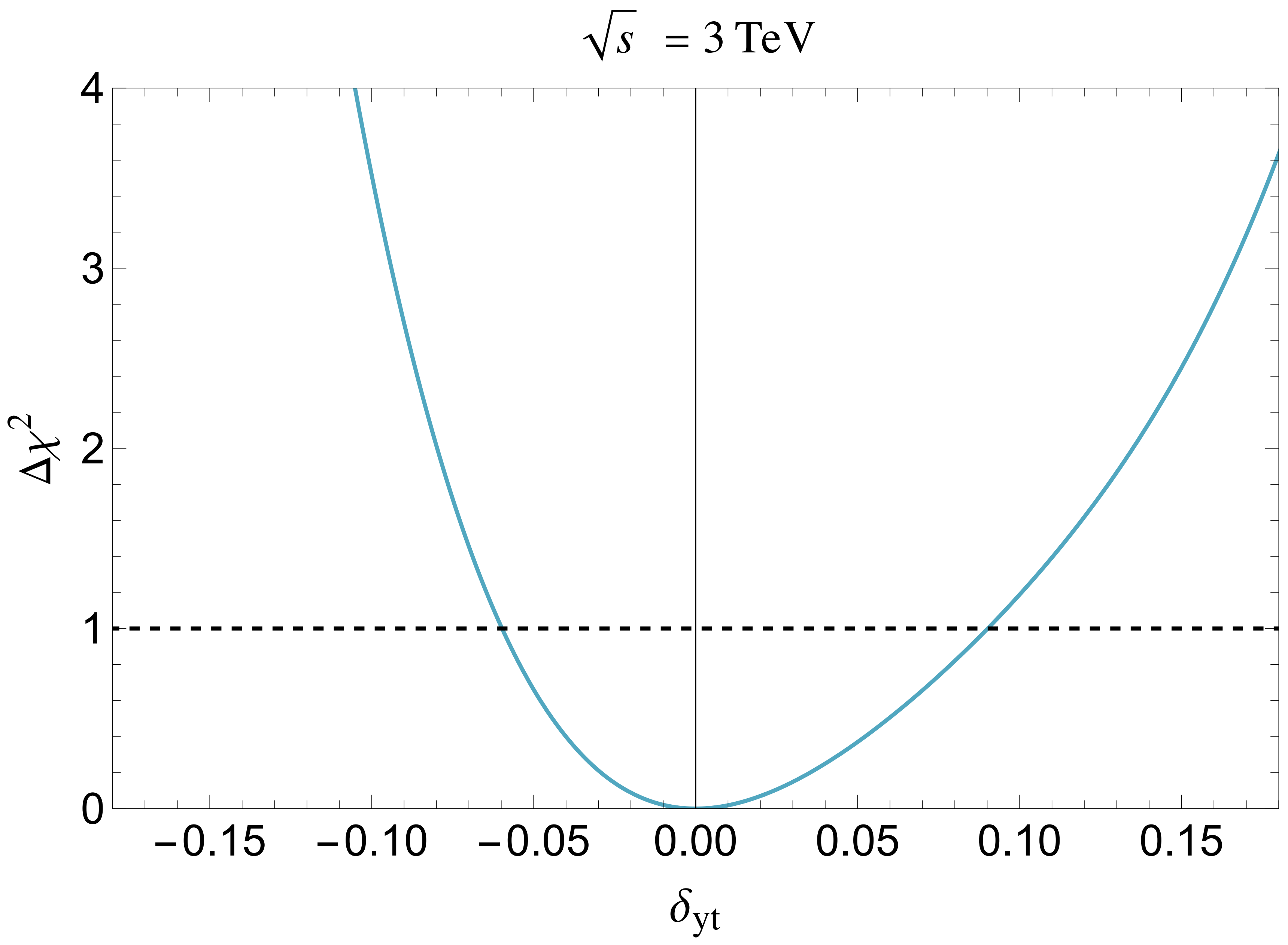
Comparison:

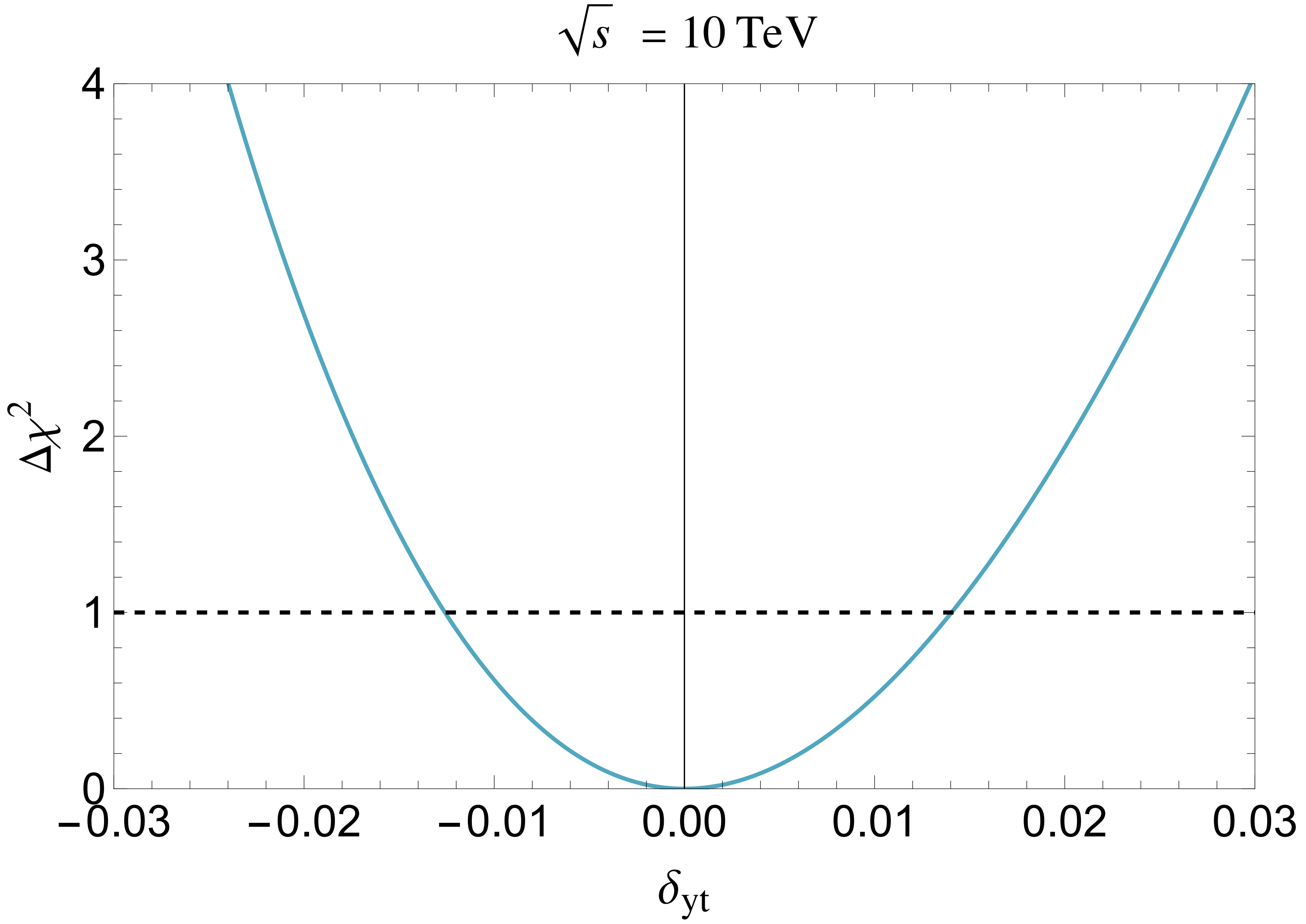
Direct measurement @MuC using $t\bar{t}h$ channel for 3 TeV is 53% and for 10 TeV 34%

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

14 TeV HL-LHC @ 3 ab^{-1} is 6.9%

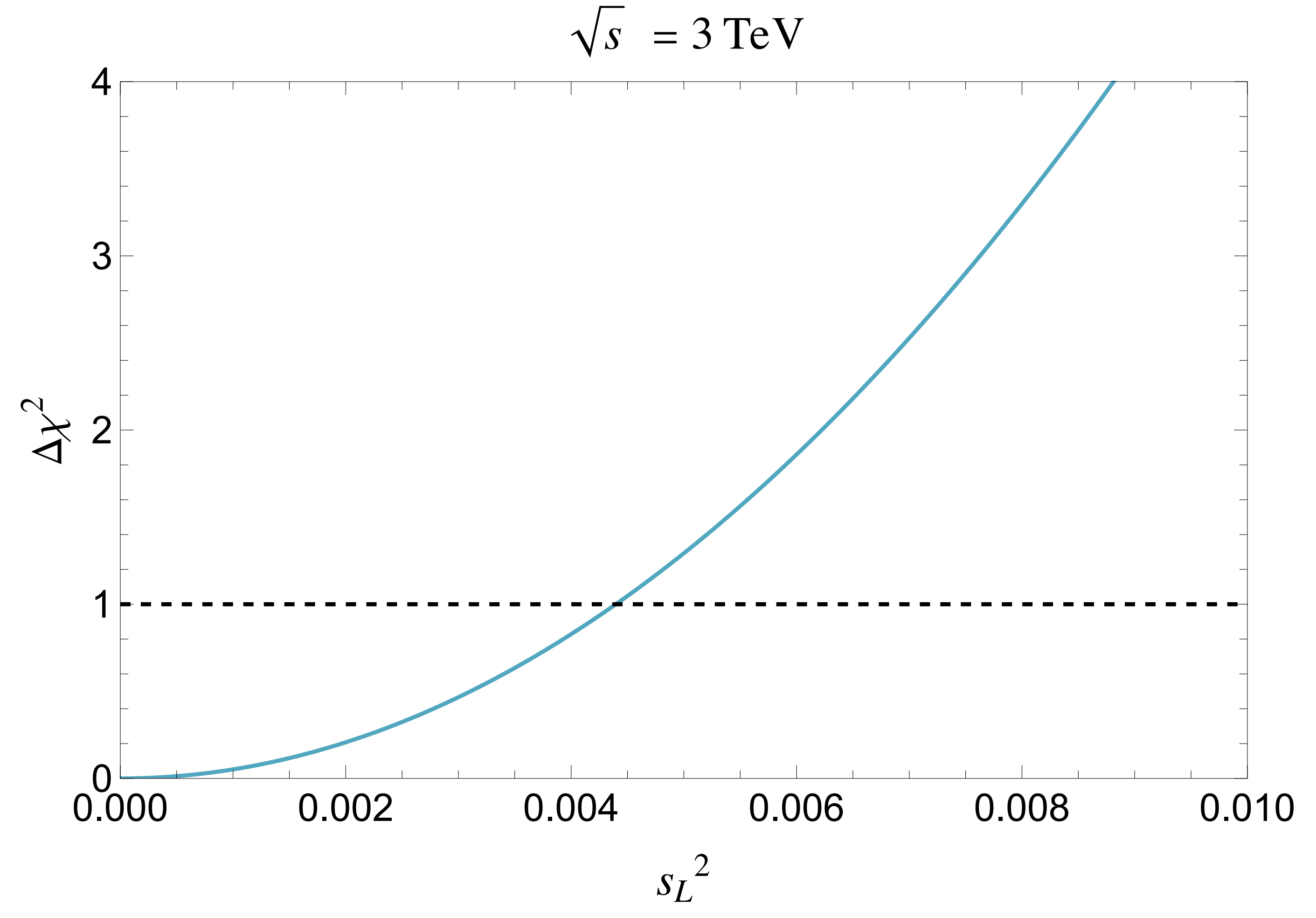
[M. Cepeda *et al.*, arXiv:1902.00134]

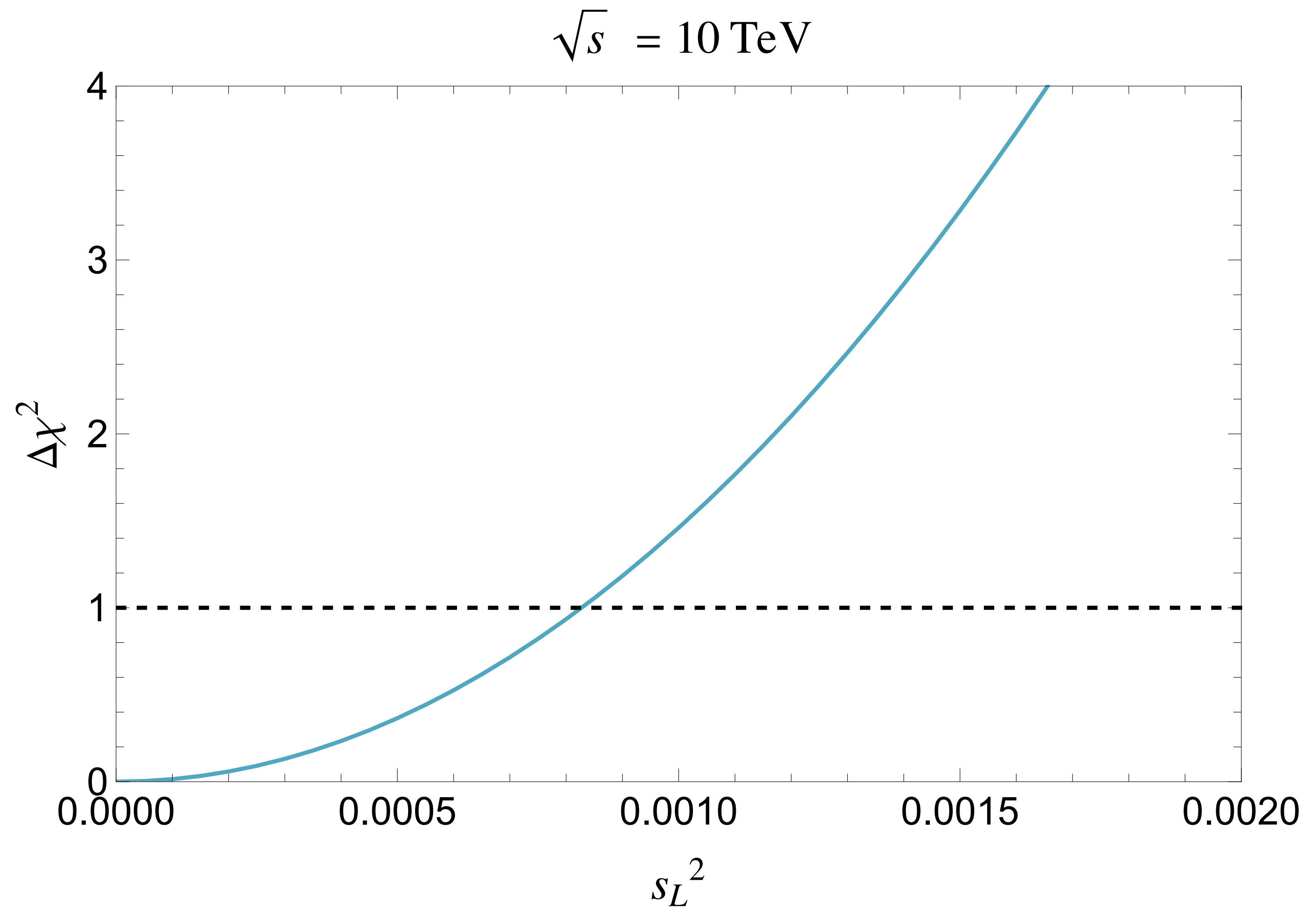




Summary and Outlook

- 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