Top Yukawa Coupling determination at High Energy Muon Colliders

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Reference: *arXiv:2308.06323v1*

Outline

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

Motivation

Objective

- Precise measurement of top Yukawa coupling using Muon Colliders

Motivation

- The Top Yukawa coupling is one of the least constrained parameters in the SM and holds significance for Higgs research
- Recent LHC measurement for Top Yukawa is $y_t = 1.16^{+0.24}_{-0.35}$ [CMS Collaboration, ArXiv:2009.07123]
- Precision measurement at hadron collider face constrains due to QCD background
- High Energy Muon Collider (MuC) can be used for precision Higgs measurement.

Theoretical Framework

- Top Yukawa can be directly probed from final states $ht\bar{t}$
- One can indirectly probe Top Yukawa in $VV \to t\bar{t}$ process

- The effective Lagrangian we consider:

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

- Partial wave unitarity then bounds the domain of validity of the effective theory

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

- At Large Energies, for $(\pm, \mp)$ the contribution from the γ, Z and t-channel contribution grows as $\mathcal{O}(E^2/m_W^2)$, which cancels off due to gauge invariance

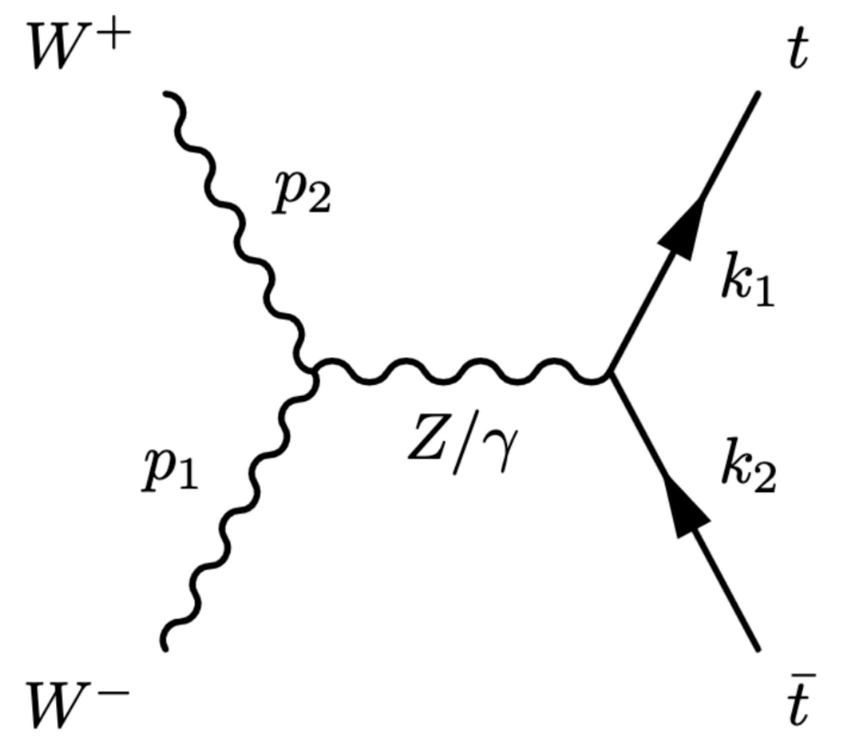
- Contribution from $(\pm, \pm)$ grows as $\mathcal{O}(E/m_W)$

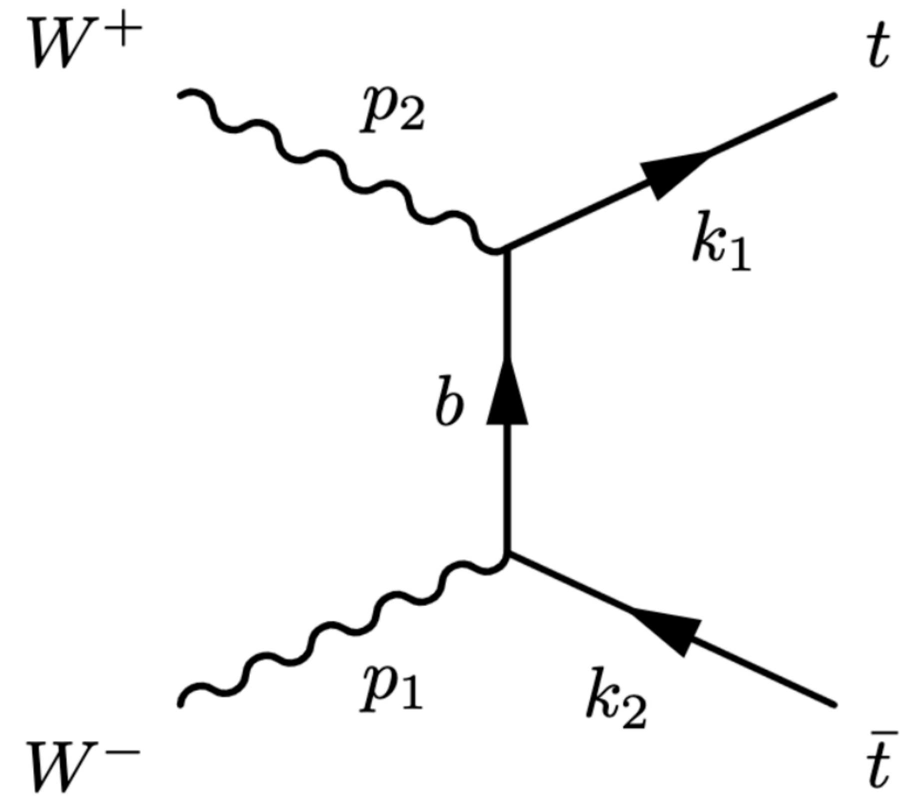
$$\mathcal{M}^{\gamma+Z+b}(W_L^+W_L^- \to t\bar{t}) \;=\; \frac{m_t}{v^2}\sqrt{s} \qquad ;\sqrt{s} >> m_t$$

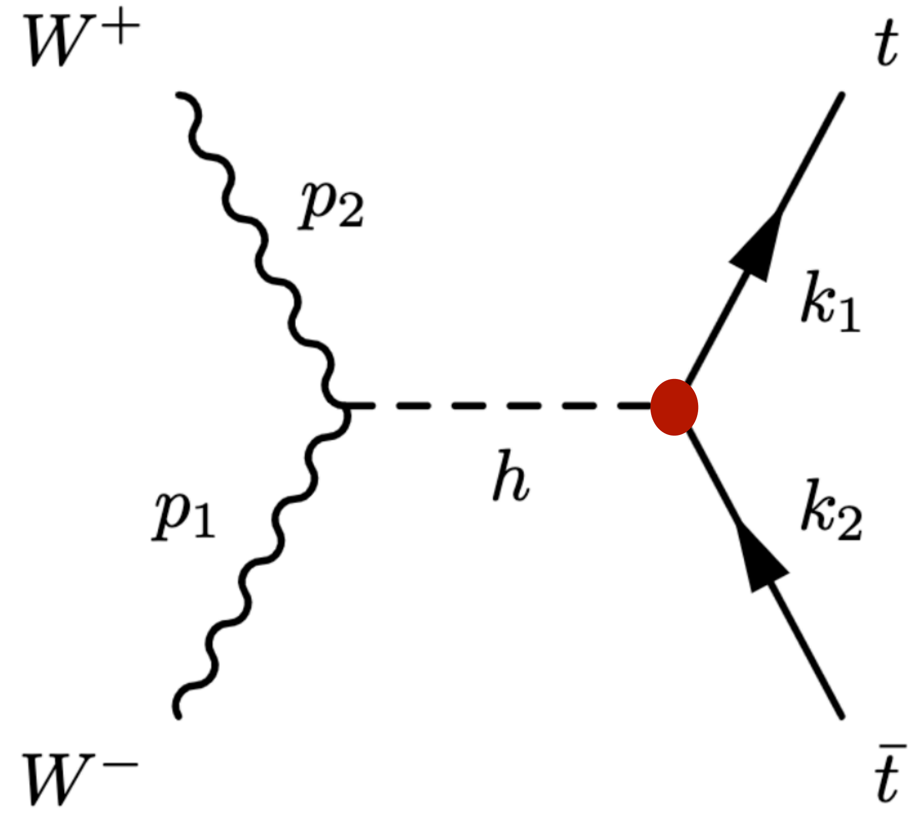
- Higgs channel precisely cancels this growing energy behavior

- Can be understood from Goldstone boson equivalence theorem

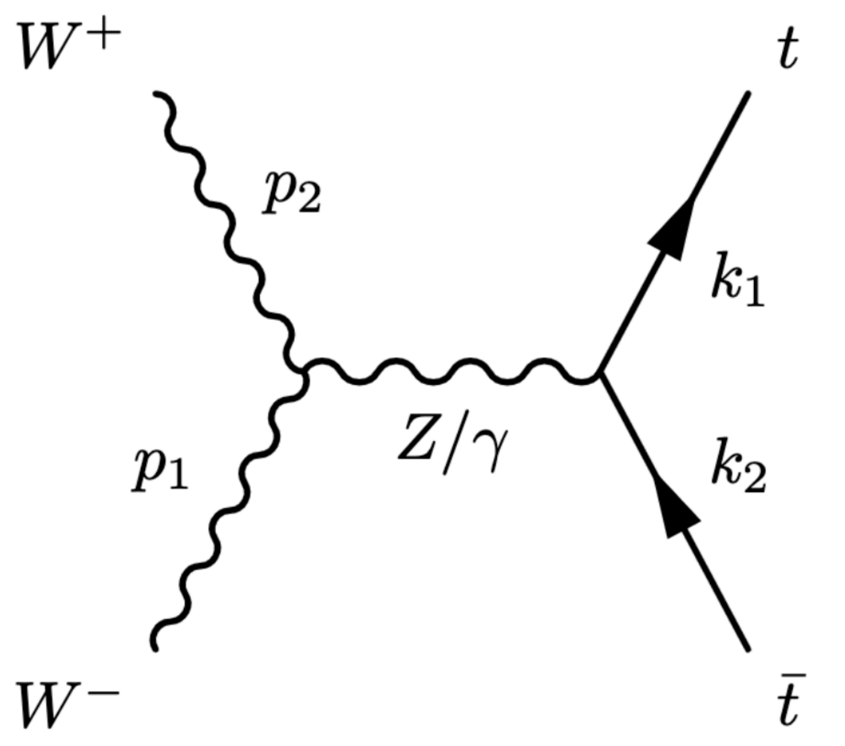
$$\mathcal{M}_{W_L^+W_L^- \to t\bar{t}} = \mathcal{M}_{\phi^+\phi^- \to t\bar{t}}\left[1 + O\left(\frac{m_W^2}{E^2}\right)\right]$$





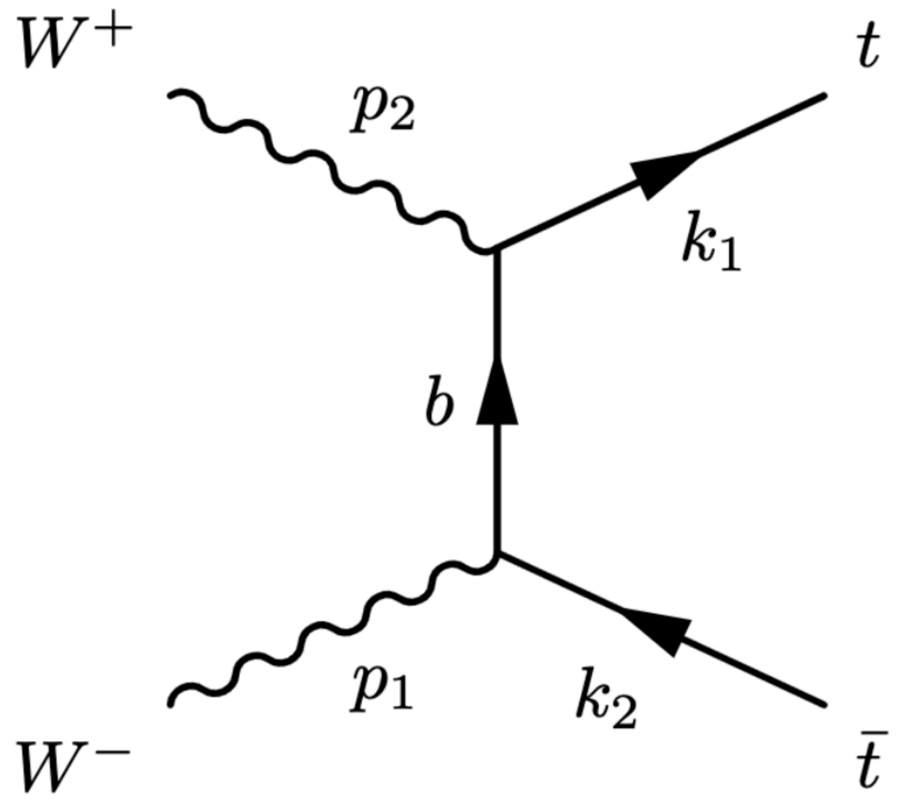


Unitarity in the $W^+W^- \rightarrow t\bar{t}$ Process



If the top yukawa-coupling deviates from Standard Model value by δ_{yt} :

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

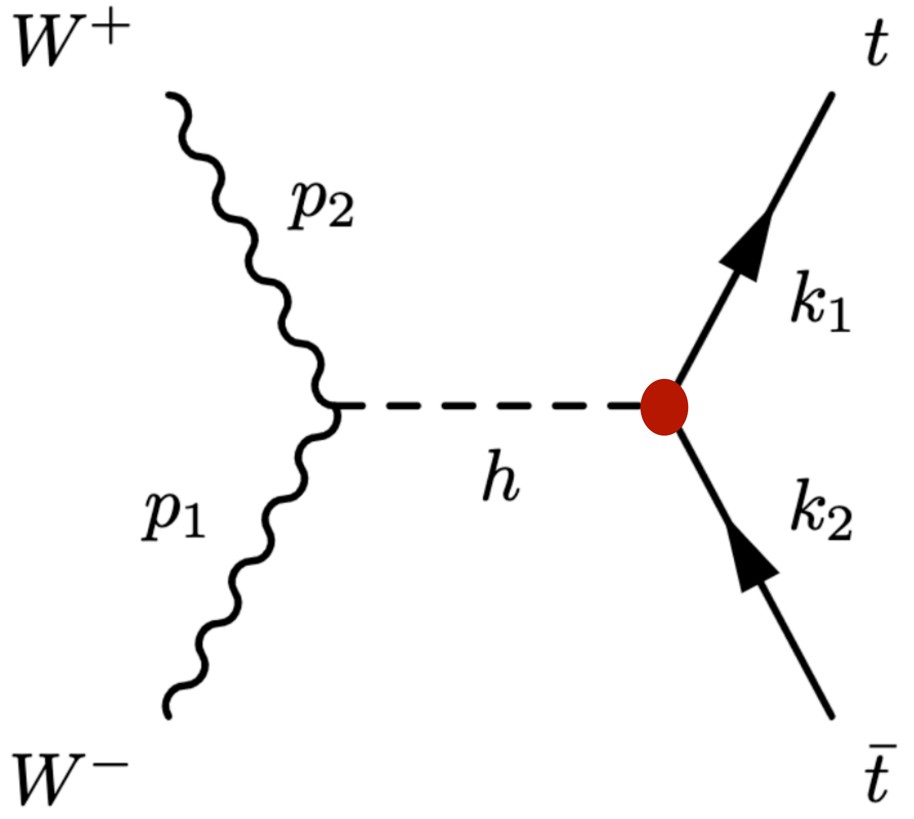


The scattering amplitude will scale as:

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

Then Perturbative unitarity will be broken at some scale:

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



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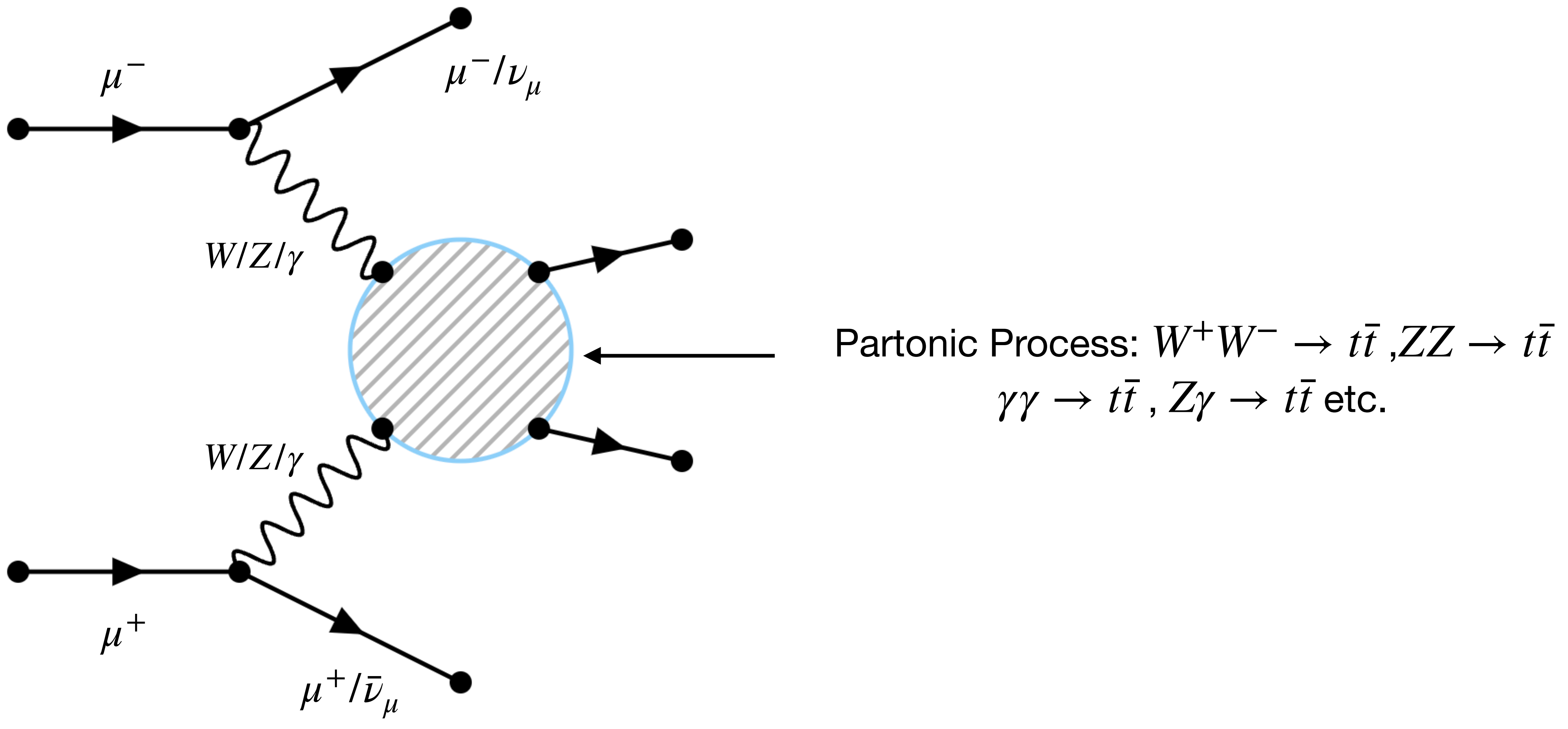
Muon Collider

- 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



Production Cross-section

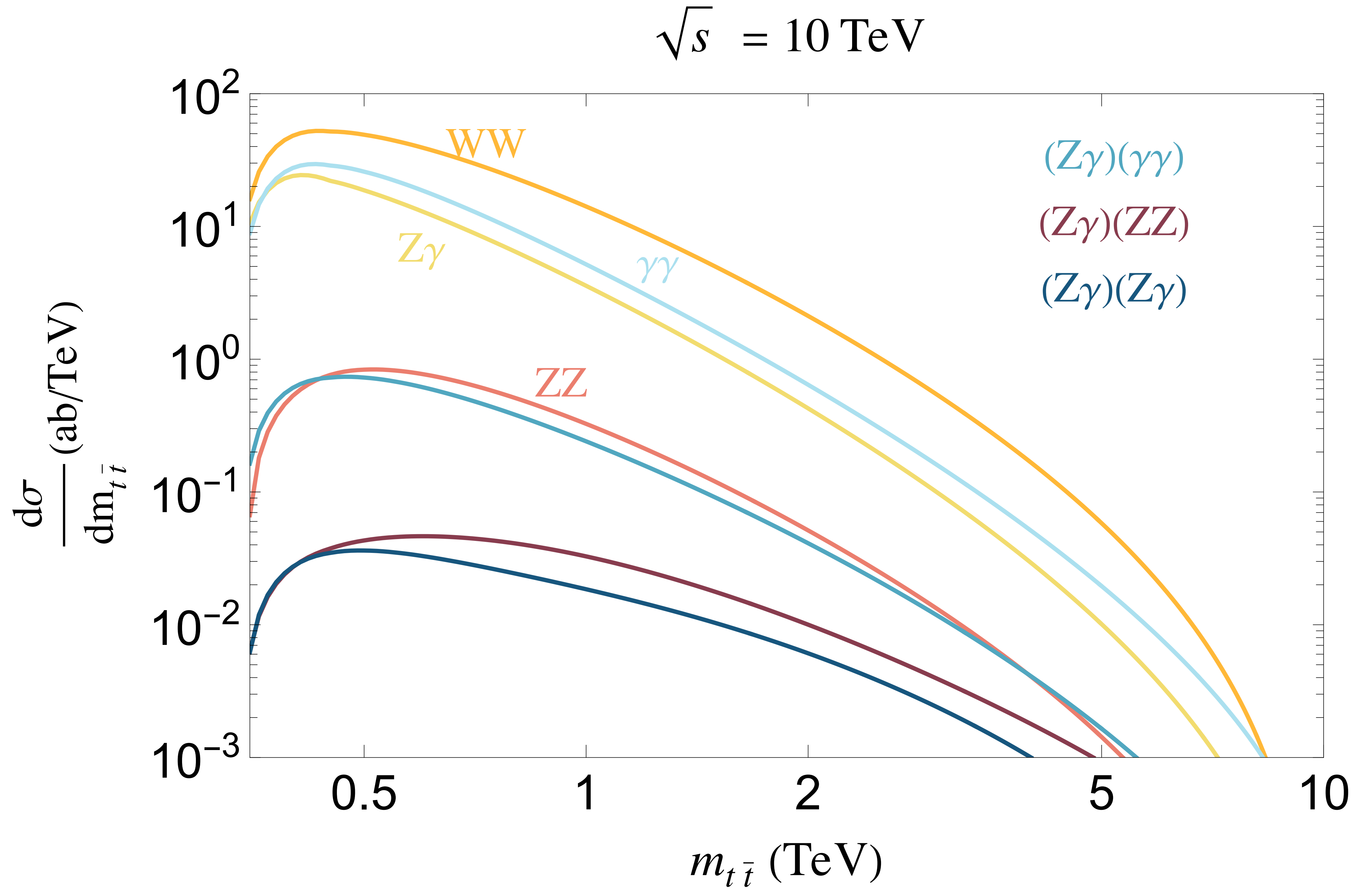
$$\sigma(\mu^+\mu^- \to F + X) = \int_{\tau_{\min}}^{\tau_{\max}} d\tau \sum_{ij} \frac{\mathscr{L}_{ij}}{d\tau} \hat{\sigma}(ij \to F)$$

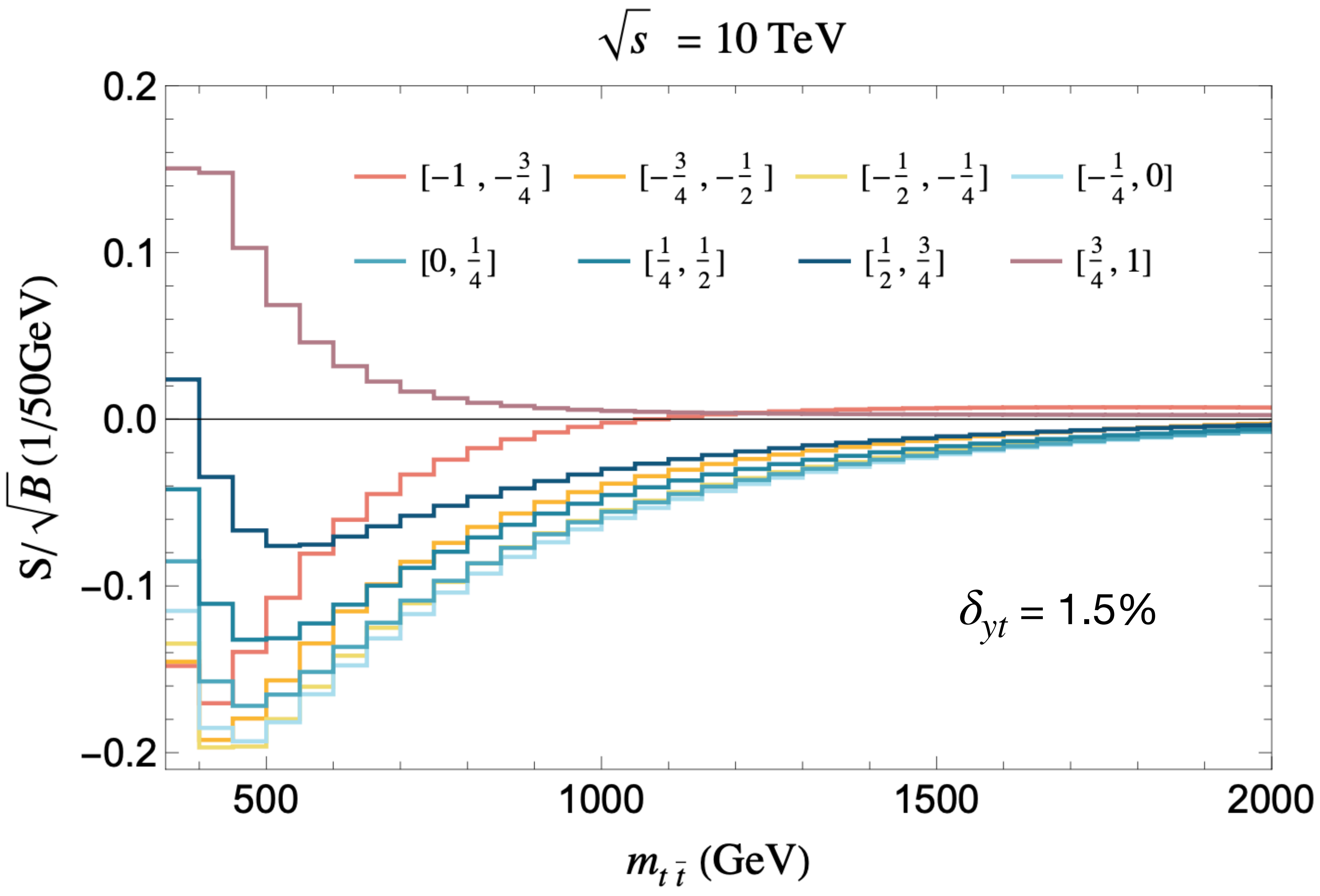
Luminosity Function is given by:

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

[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

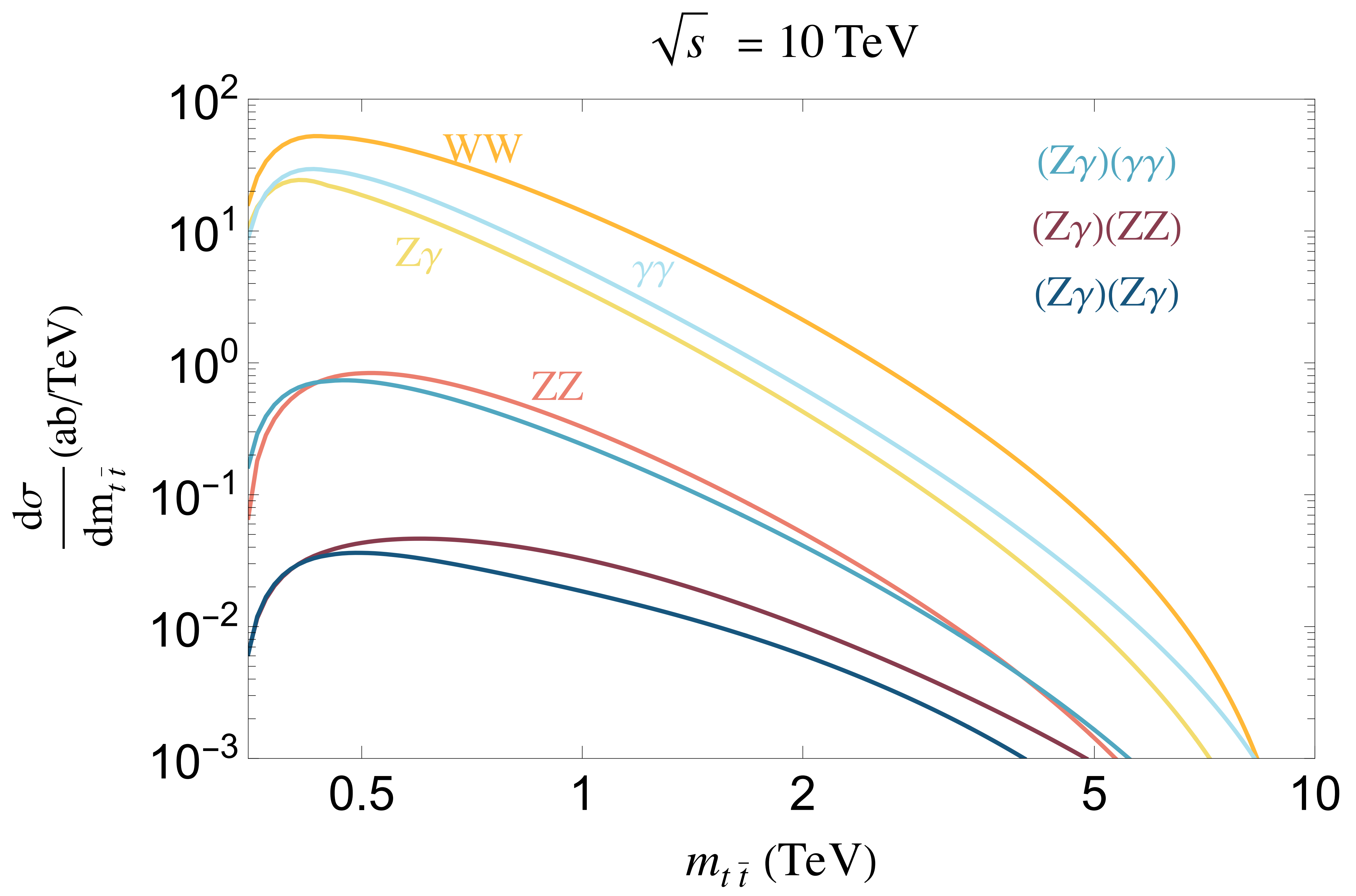


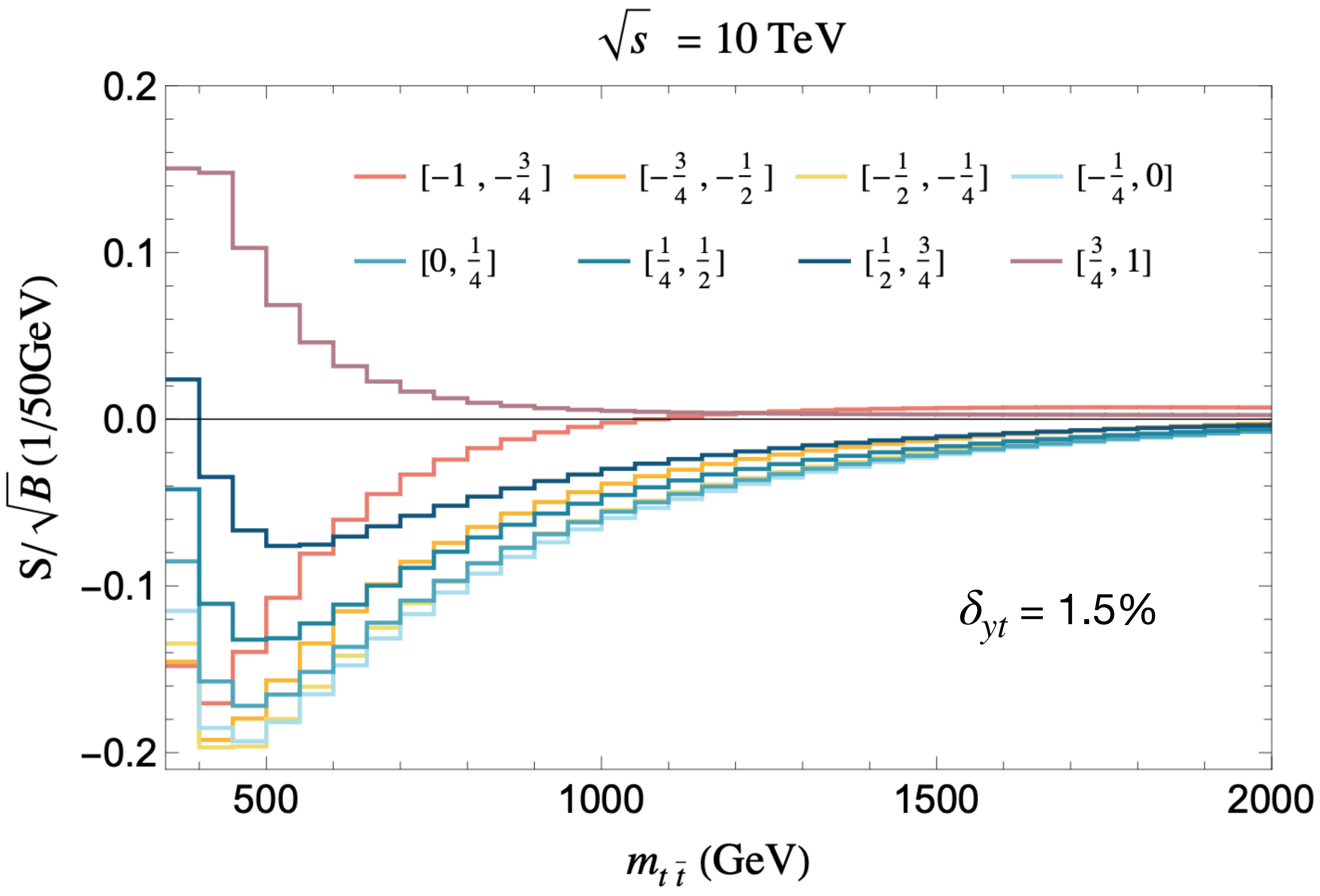


- W-Channel dominates the cross-section where we have the δ_{yt} signal

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

Interference Effects

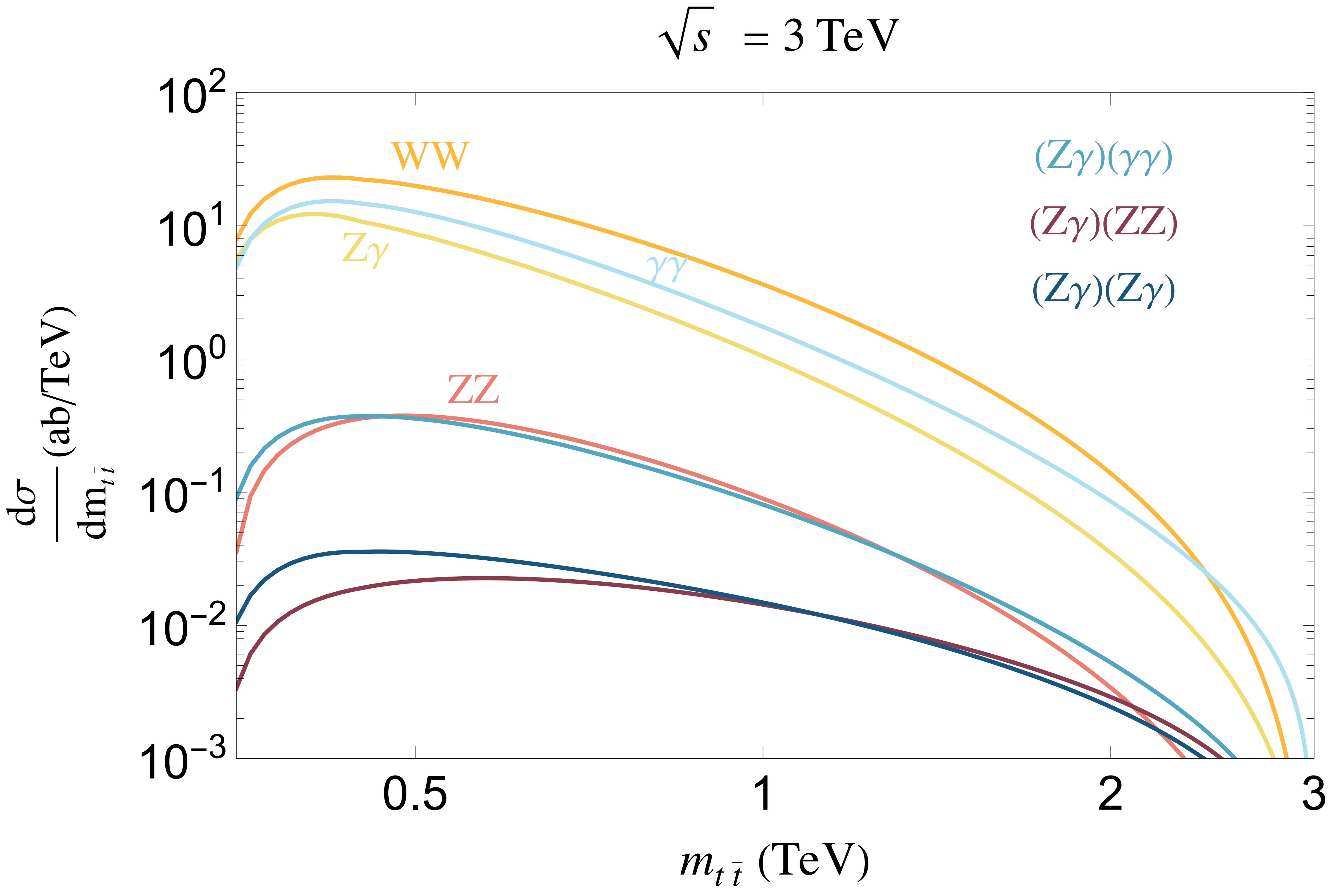


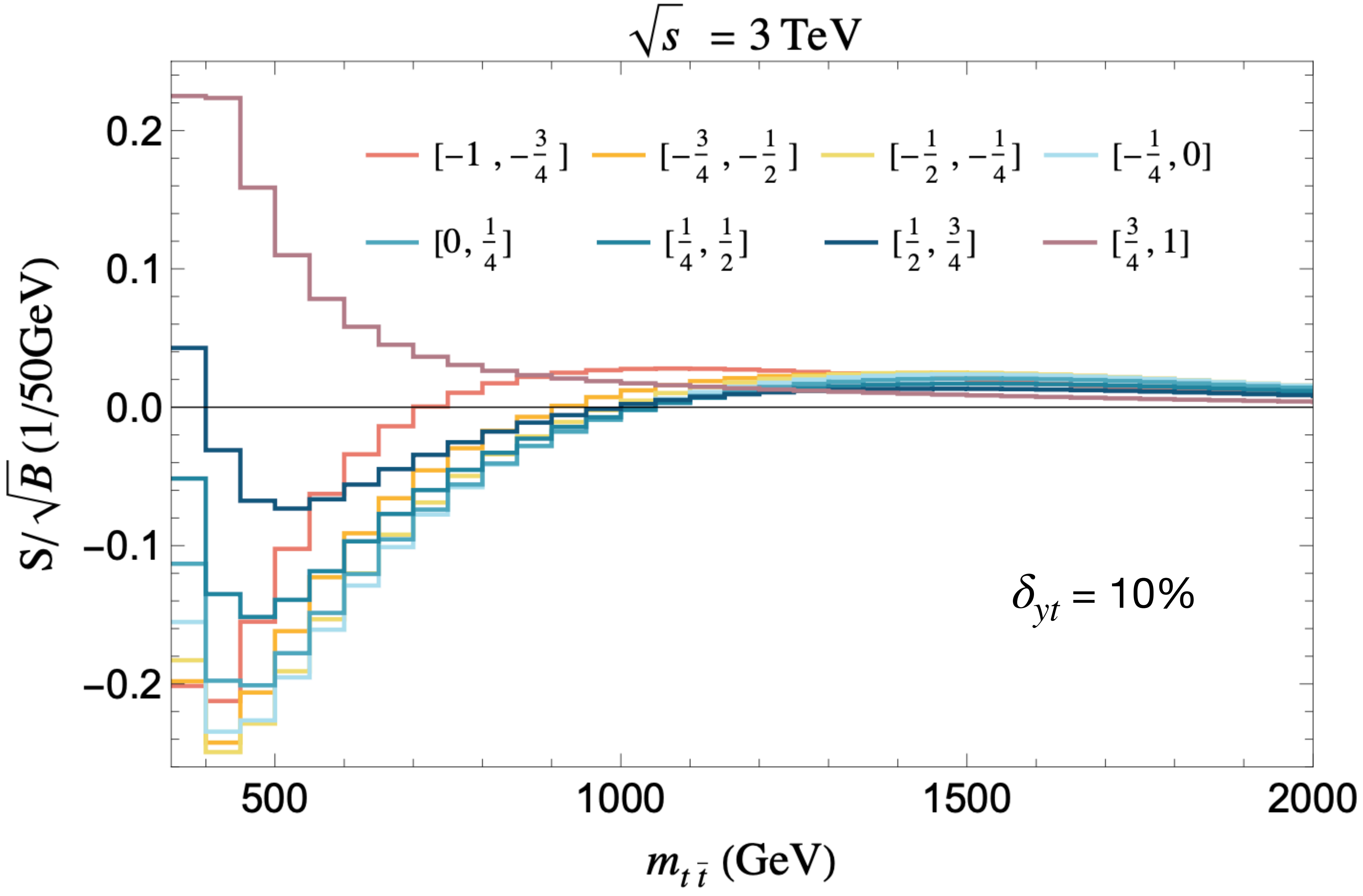


For $\mu^+\mu^- \to \mu^+\mu^- t\bar{t}$, one cannot distinguish the intermediate neutral vector boson:

$$\mathcal{M} = \sum_{i,j} \mathcal{M}_{V_{+,i}V_{-,j}} = \mathcal{M}_{ZZ} + \mathcal{M}_{\gamma\gamma} + \mathcal{M}_{Z\gamma} + \mathcal{M}_{\gamma Z}$$

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 8 bins

$\Delta\chi^2$ Analysis

Event Selection:

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

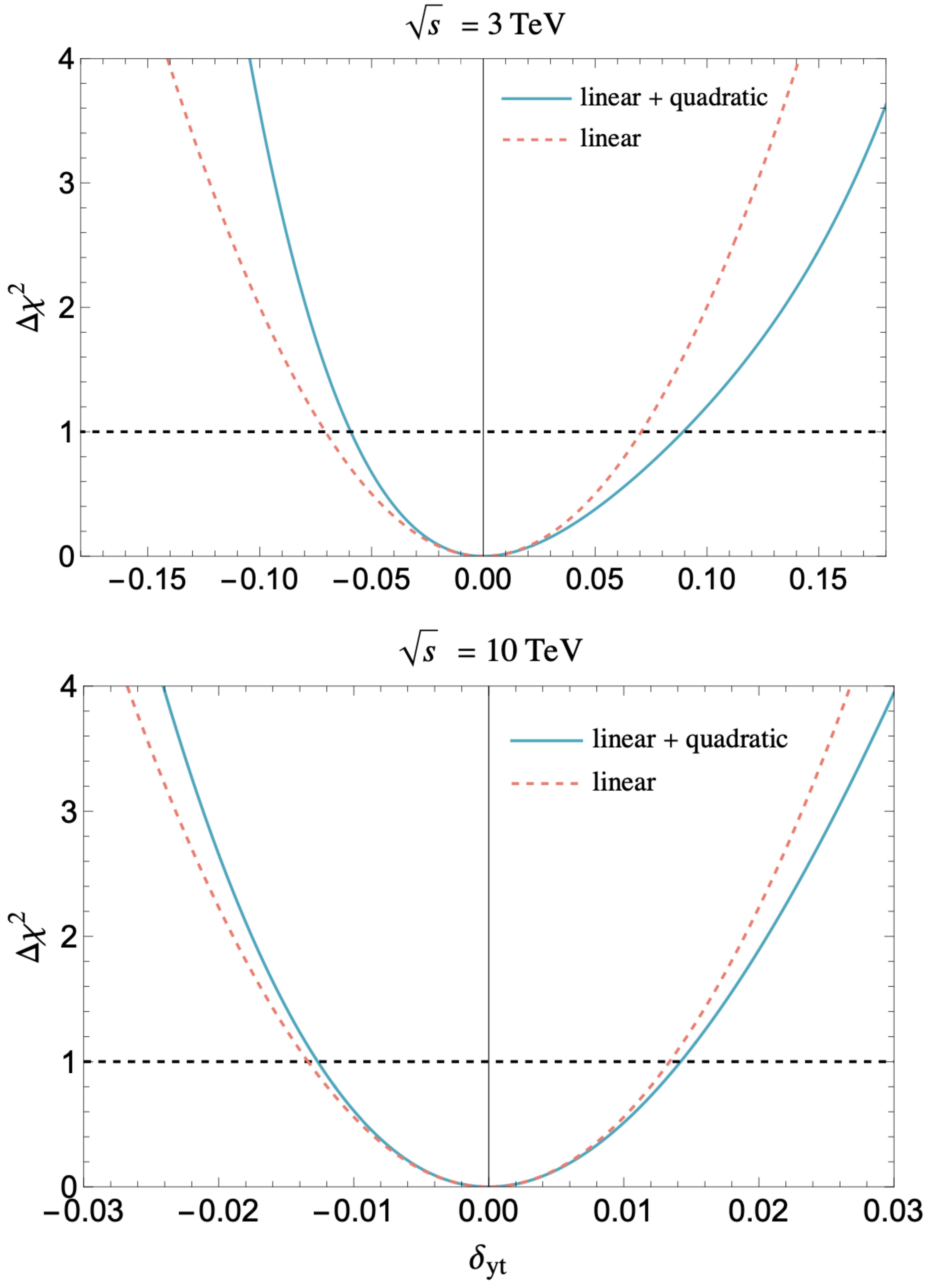
Results:

@68% C.L.

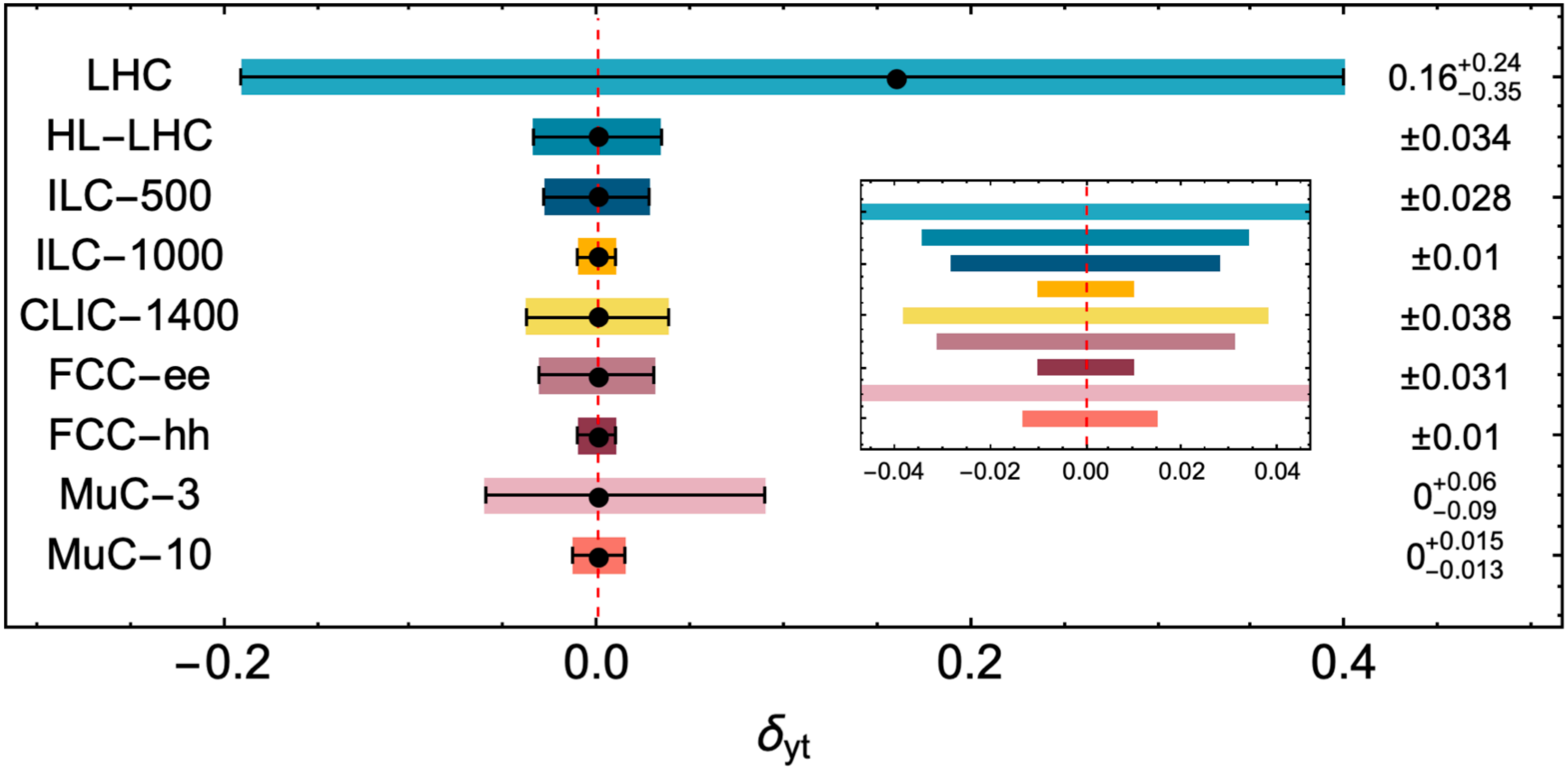
	δ_{yt}	δ_{yt}
$\sqrt{s}$ = 3 TeV	-6%	9%
$\sqrt{s}$ = 10 TeV	-1.3%	1.5%

$$\Delta\chi^2 = 2.0\times10^2\delta_{yt}^2 - 1.2\times10^3\delta_{yt}^3 + 3.9\times10^3\delta_{yt}^4 \quad (3\text{TeV})$$

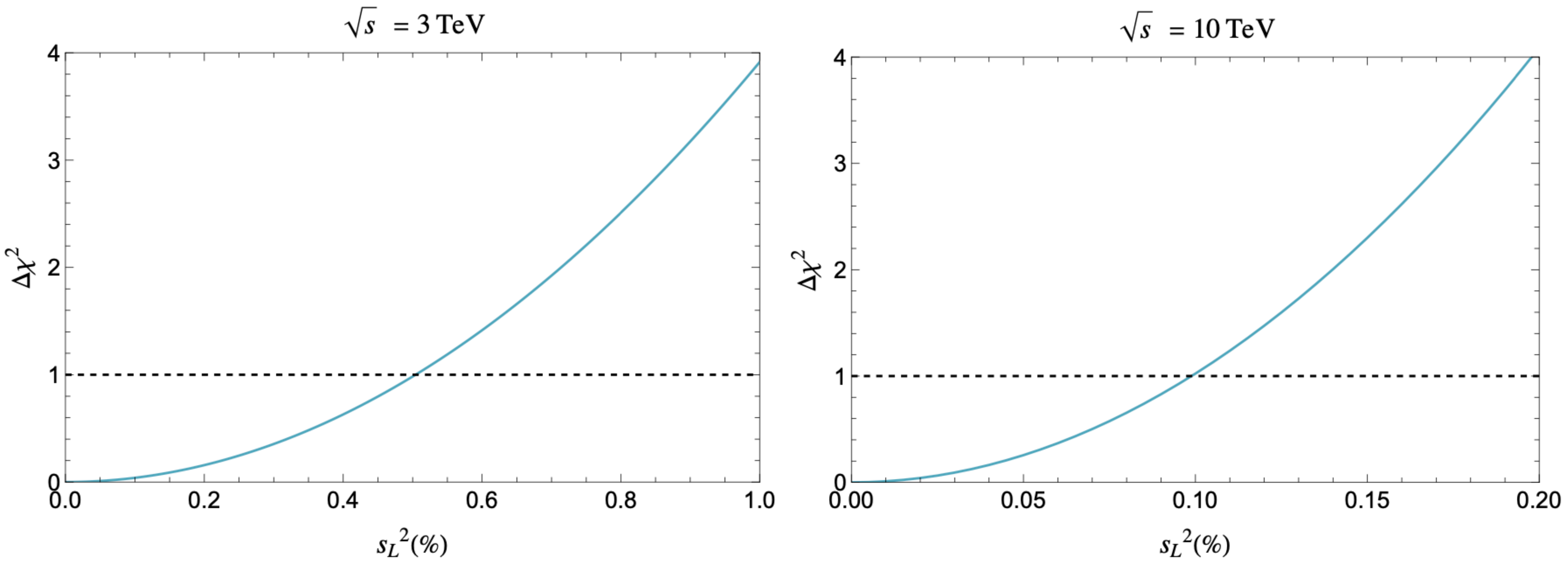
$$\Delta\chi^2 = 5.6\times10^3\delta_{yt}^2 - 4.8\times10^4\delta_{yt}^3 + 2.6\times10^5\delta_{yt}^4 \quad (10\text{TeV})$$



The Reach Plot for δ_{yt}



VLQ Model



- Introduce single Top partner which is singlet under electroweak SU(2)
- Fermion field rotation of the form $t_L \to c_L t_L - s_L T_L$ would modify gauge coupling and relative shift to Top Yukawa:

$$\delta_{yt} = -s_L^2 = -\frac{\left(\lambda_t^2 + \lambda_0^2\right) v^2/2 - m_t^2}{m_T^2 - m_t^2}.$$

@68% C.L.

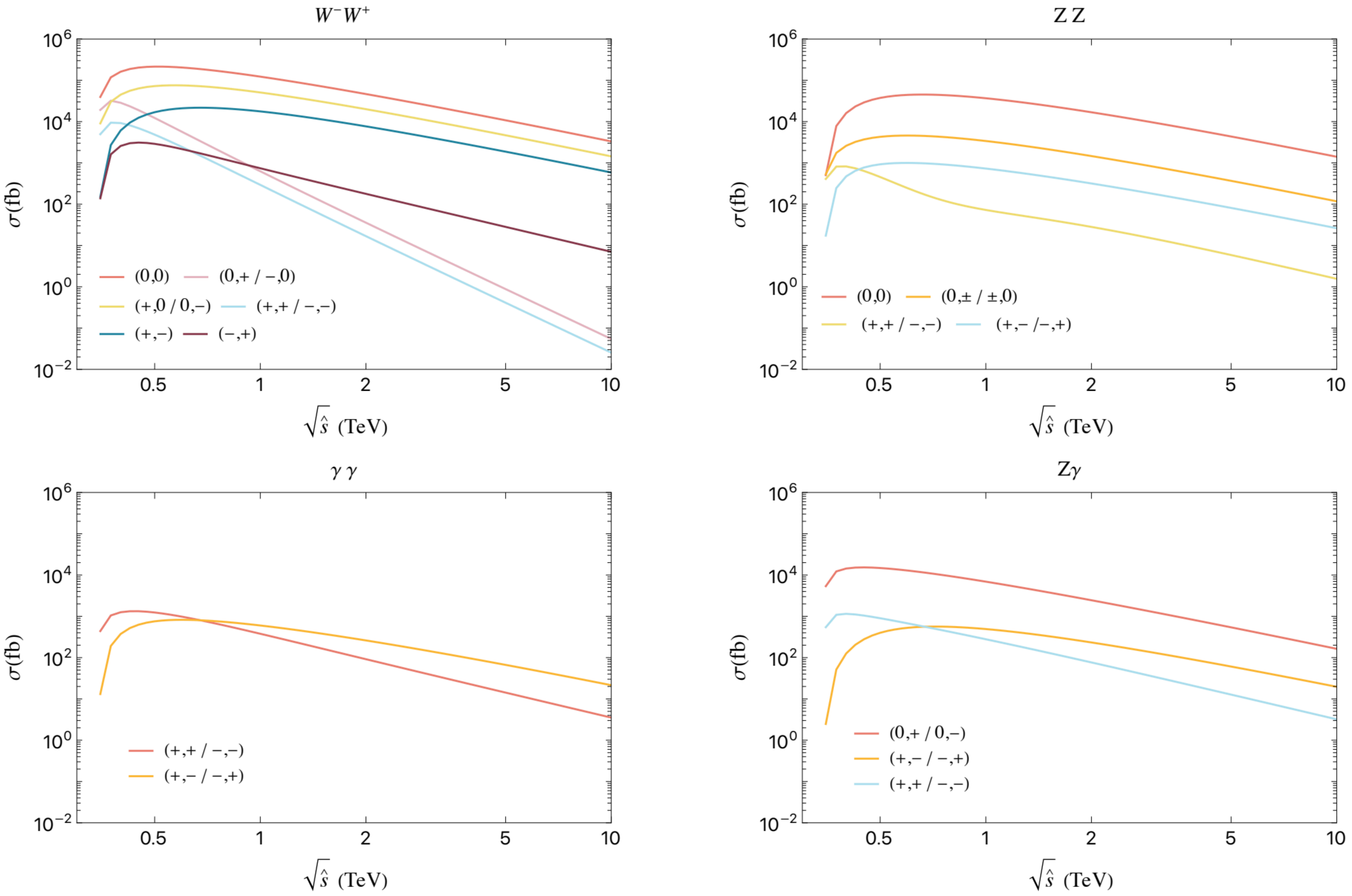
	s_L^2
$\sqrt{s}$ = 3 TeV	0.5%
$\sqrt{s}$ = 10 TeV	0.1%

Summary and Outlook

- Using indirect method presented, muon collider shows promising bounds on precision Top Yukawa measurement
- Detector based study
- Future study of SMEFT operators for High Energy Muon Collider

THANK YOU!

Backup


W^-W^+
ZZ
$\gamma\gamma$
$Z\gamma$
σ(fb)
$\sqrt{\hat{s}}$ (TeV)
(0,0)
(0,+ / −,0)
(+,0 / 0,−)
(+,+ / −,−)
(+,−)
(−,+)
(0,± / ±,0)
(+,− / −,+)
(0,+ / 0,−)

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