

Single Top Quarks Physics at Future Lepton Colliders

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Lepton Colliders vs. Hadron Colliders

- **Clean initial state and well-defined energy**
- **Leptons** are elementary particles with no internal structure; when electrons and positrons collide, the entire energy of the beams goes into the interaction.
- **Precise energy control and scan capability**
- **Lepton** colliders can be tuned to specific resonance energies with high precision.
- **Lower backgrounds and cleaner events**
- **Lepton** collisions produce fewer secondary particles. The final state is easier to reconstruct and interpret.
- **Well-understood theoretical framework**
- Electromagnetic (EM) and weak interactions of leptons are precisely calculable in QED and Electroweak theory.
- **Lepton colliders are ideal for**
 - precision measurements of known particles
 - threshold scans and resonance studies
 - model-independent new physics searches
- **Hadrons** are composite
 - uncertain collision energy for the hard process;
 - large underlying event activity (extra particles from spectator partons).
- **Hadron** collisions have high multiplicity-events due to QCD activity, making it harder to isolate the signal.
- QCD effects in hadron collisions introduce large theoretical uncertainties, especially at low and intermediate energies.
- **Hadron colliders are better for:**
 - direct discovery of heavy new particles (beyond TeV scale)
 - exploring high-energy frontier
 - QCD and heavy-ion physics

Parameters and Characteristics of Future Lepton Colliders

- **FCC-ee**

- circular, 91–365 GeV,
- 10^{34} – 10^{36}
- Z/W/H/t factory
- 2045?

- **ILC**

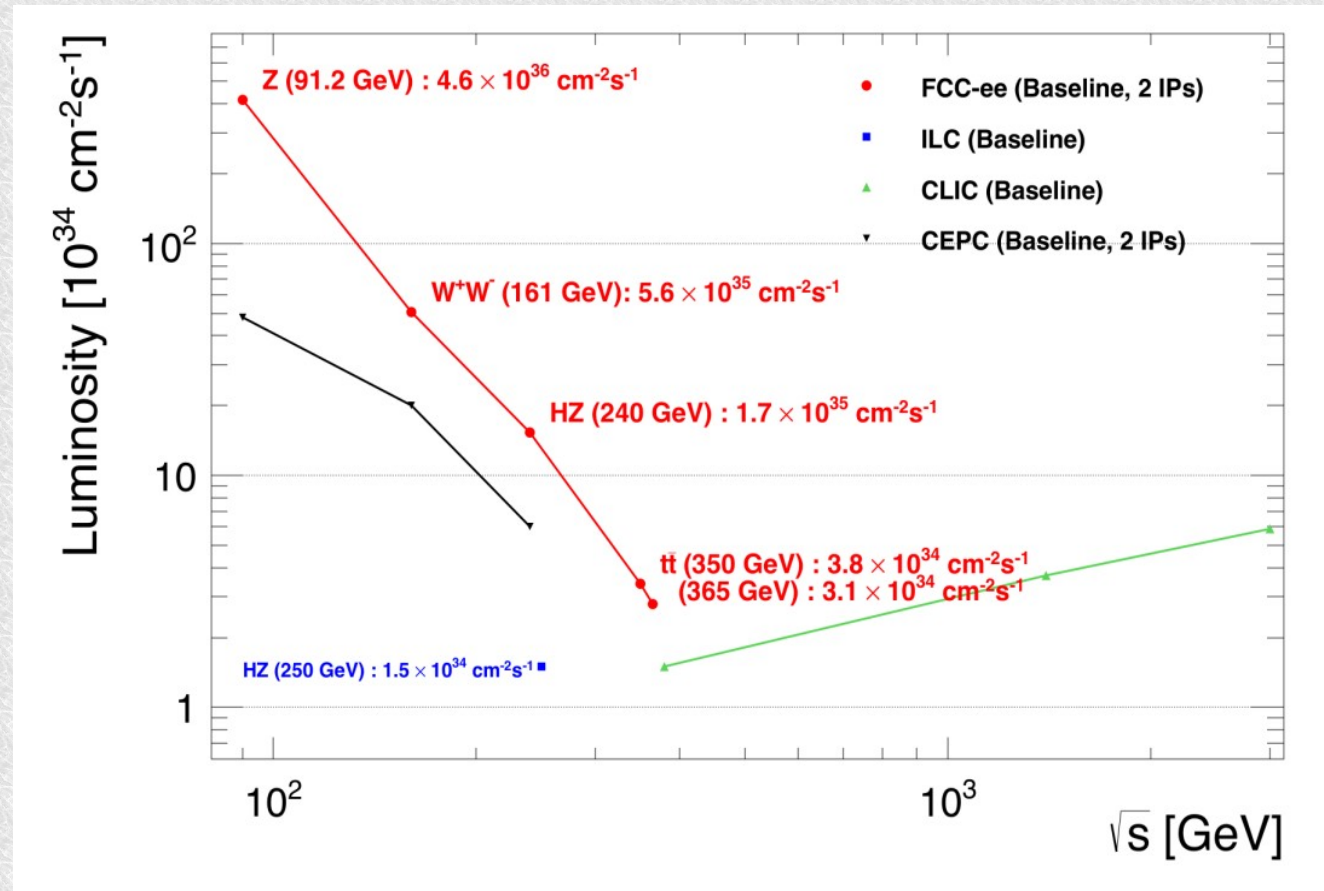
- linear, 250-500 GeV
- 10^{34}
- H/t physics, SUSY
- ?

- **CLIC**

- linear, 250-500 GeV
- 10^{34}
- “new physics”, new resonances
- ?

- **CEPC**

- circular, 91-240 (360?) GeV
- 10^{34} - 10^{35}
- Z/W/H factory and precision measurements
- **2037 (?)**



Studies of Single Top Quarks at Lepton Colliders

[Single Top Production in \$e^+e^-\$, \$e^-e^-\$, \$\gamma e\$ and \$\gamma\gamma\$ Collisions \(Eur.Phys.J.C21:81-91,2001\)](#)

- Evaluations of single top quark CS are performed for energies up to 1 TeV
- The γe mode is the most promising due to its largest CS, lack of tT backgrounds and exceptional sensitivities to ***anomalous Wtb couplings***
- Processes like e^+e^- , $\gamma e \rightarrow e^- \nu_e t B$ are less favorable
- Three processes were chosen to probe their sensitivity to anomalous Wtb couplings, with best bounds found for $\gamma_+ e_L^- \rightarrow e^- t b$ and $e_R^+ e_R^- \rightarrow e^- \nu_e t b$

- On the way to CEPC energies
 - CS for all processes have been validated using widely used generators

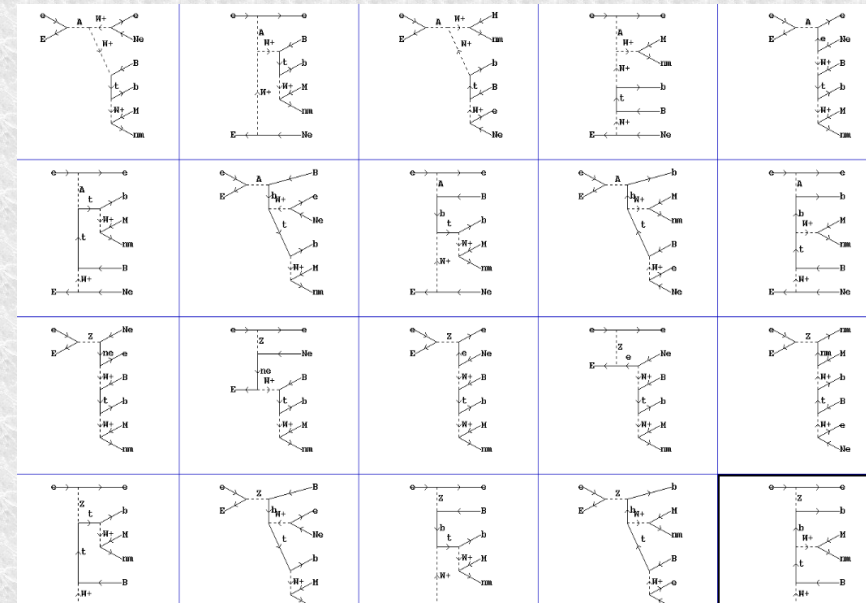
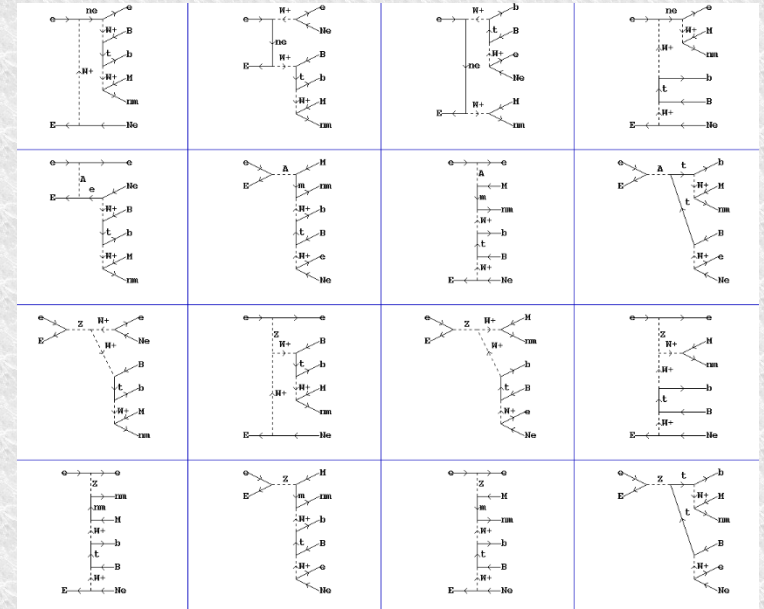
	CS ($e, E \rightarrow e, \nu_e, t, B$) [pb]
CompHEP	2.77e-03
WHIZARD	3.0e-03
Eur.Phys.J.C21: 81-91,2001	3.1e-03

Single Top quarks in e⁺e⁻ processes at CEPC (2)

- **e⁺e⁻**
- CEPC, $\sqrt{s} = 240 \text{ GeV}$
- Below the top-pair production threshold

-	CS (e,E → e,Ne,t,B) [pb]
CompHEP	3.24e-06
WHIZARD	3.0e-06

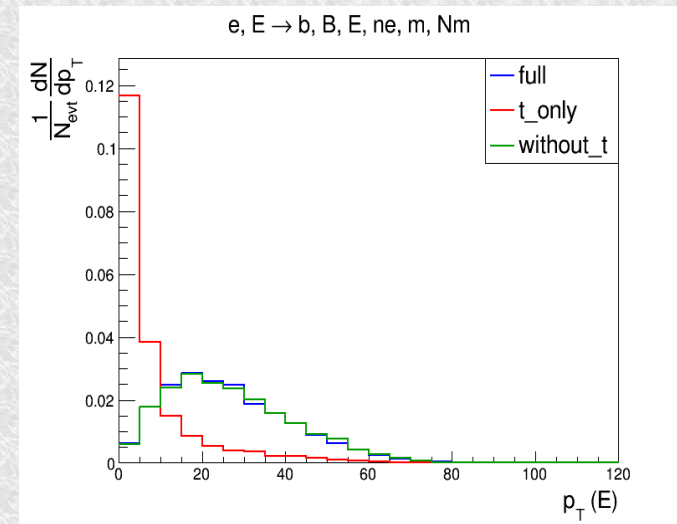
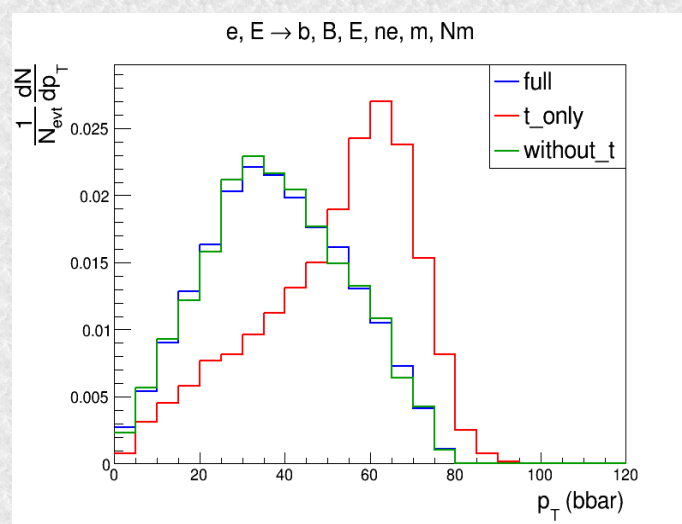
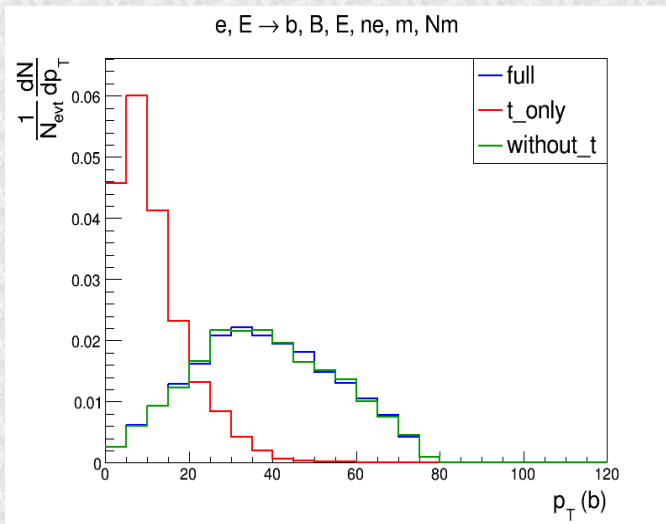
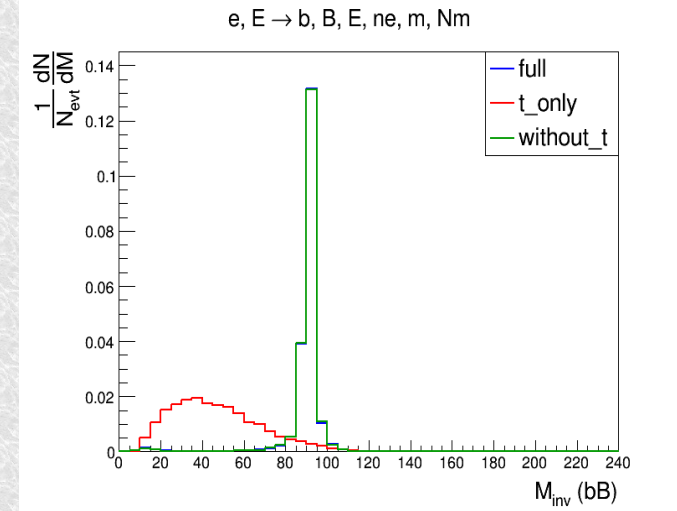
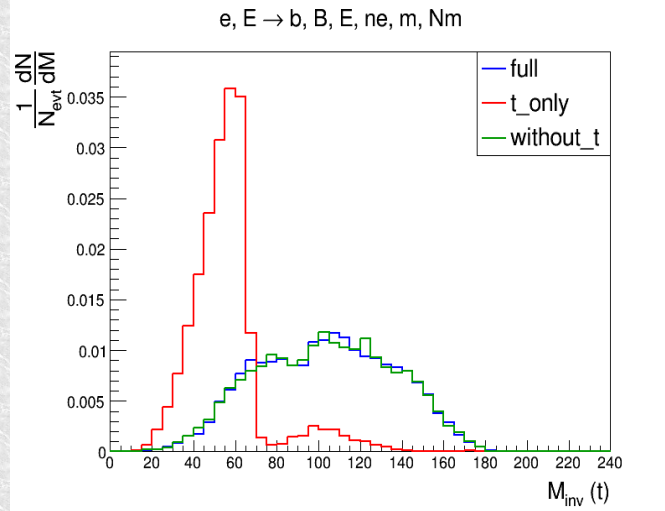
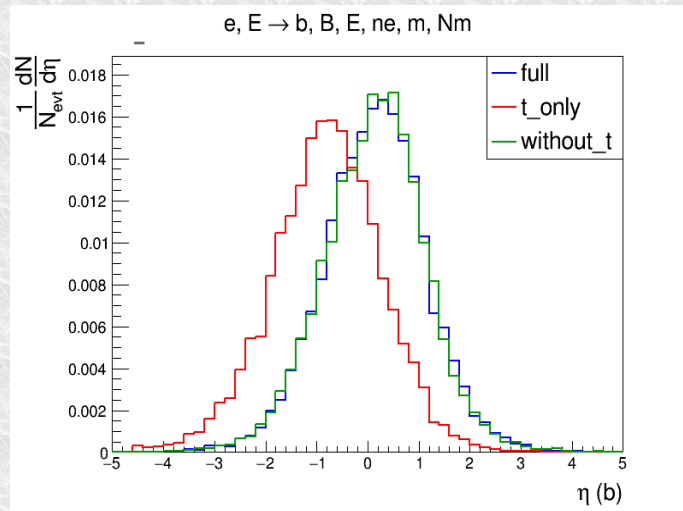
WHIZARD	CS (e,E → e,Ne,M,nm,b,B) [pb]
“t only”	3.7e-07
Full	8.2e-05
without t	8.1e-05



“t only”: M,nm,b come from top quark only
 ”Full”: all diagrams that yield the same final state particles
 “without t”: top quarks excluded

Single Top quarks at CEPC

- **e+e-**



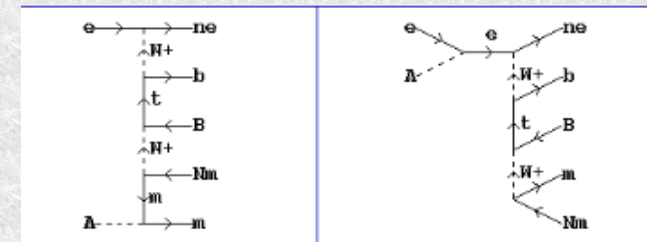
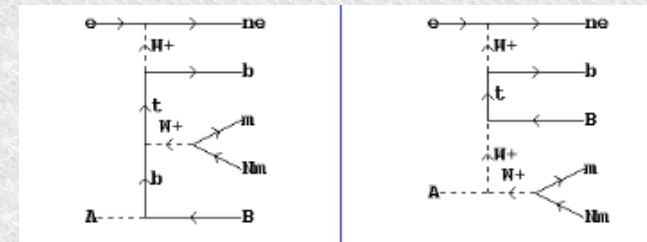
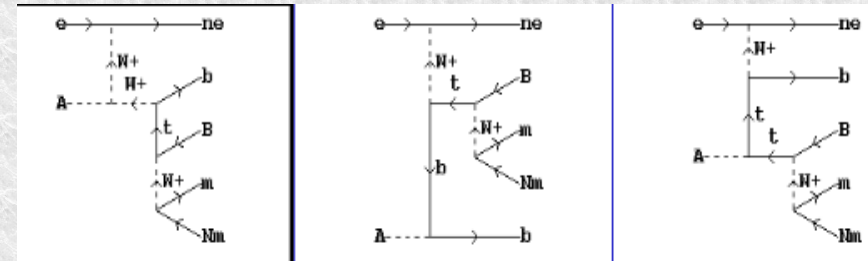
Low-level variables distributions demonstrate distinct signal vs. background behavior

Single Top quarks in e⁺e⁻ processes at CEPC (2)

- **γe**
- CEPC, $\sqrt{s} = 240 \text{ GeV}$
- Below the top-pair production threshold

-	CS (e, $\gamma \rightarrow ne, T, b$) [pb]
CompHEP	1.2e-05
WHIZARD	1.1e-05

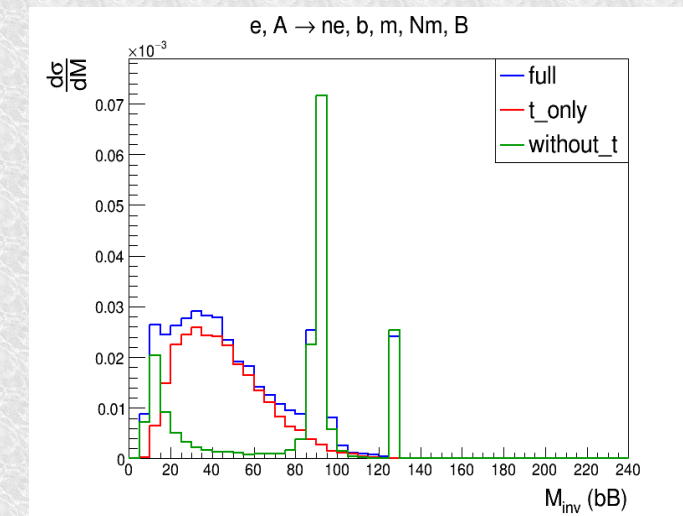
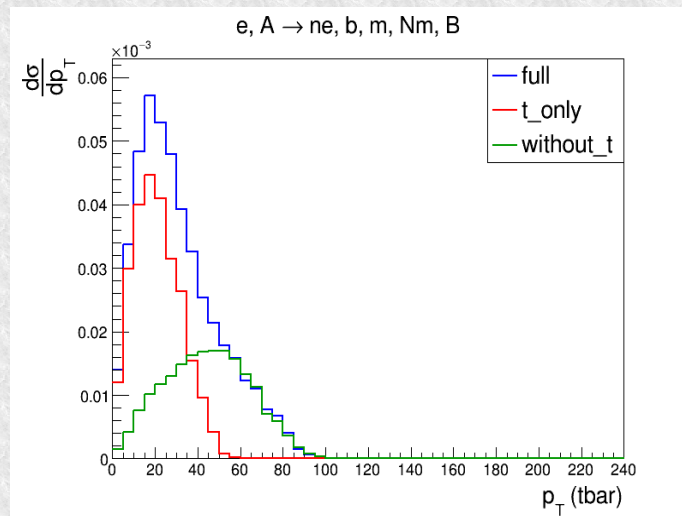
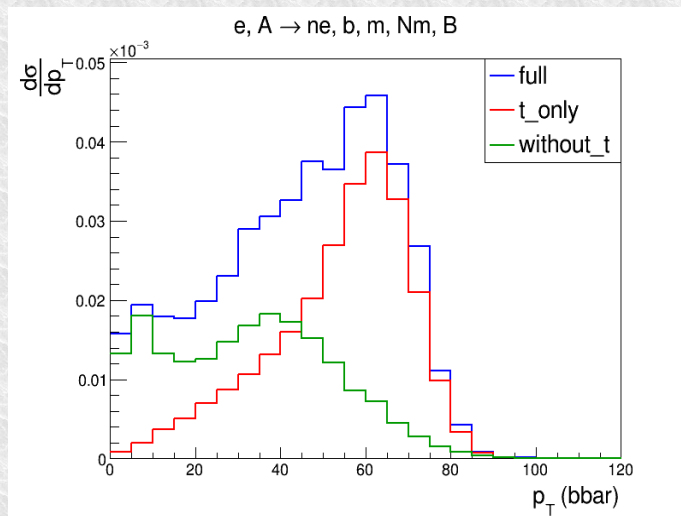
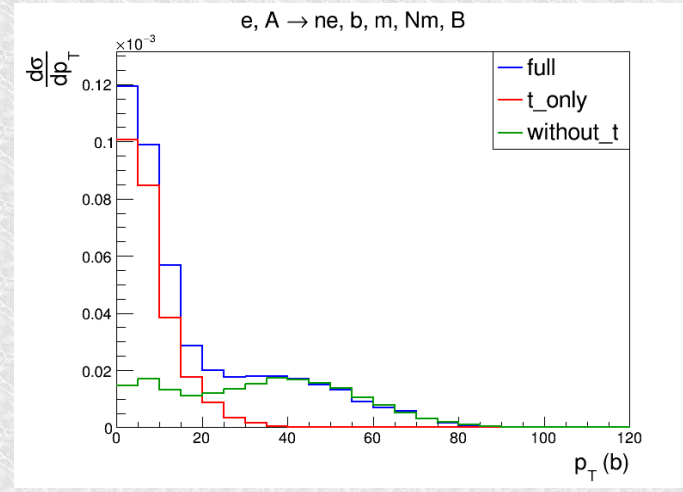
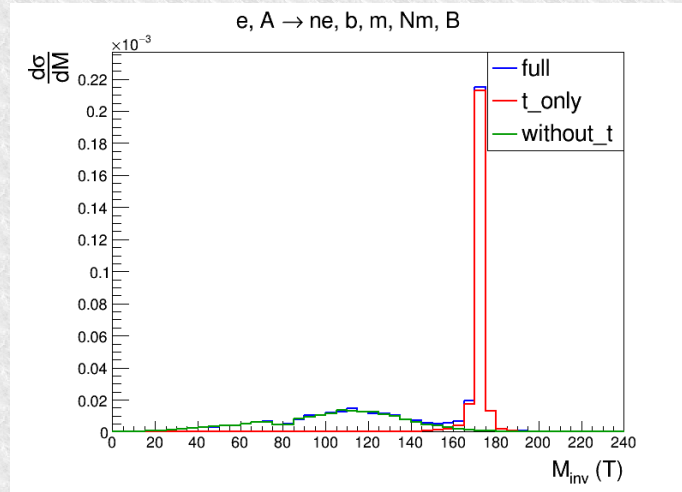
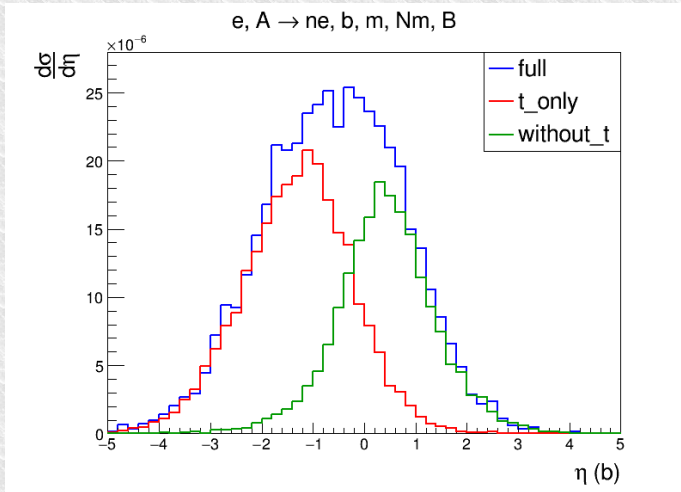
WHIZARD	CS (e, $\gamma \rightarrow ne, m, Nm, b, B$) [pb]
“t only”	1.3e-06
Full	2.3e-06
without t	9.5e-07



- “t only”: M, nm, b come from top quark only
- “Full”: all diagrams that yield the same final state particles
- “without t”: top quarks excluded

Single Top quarks at CEPC

- γe



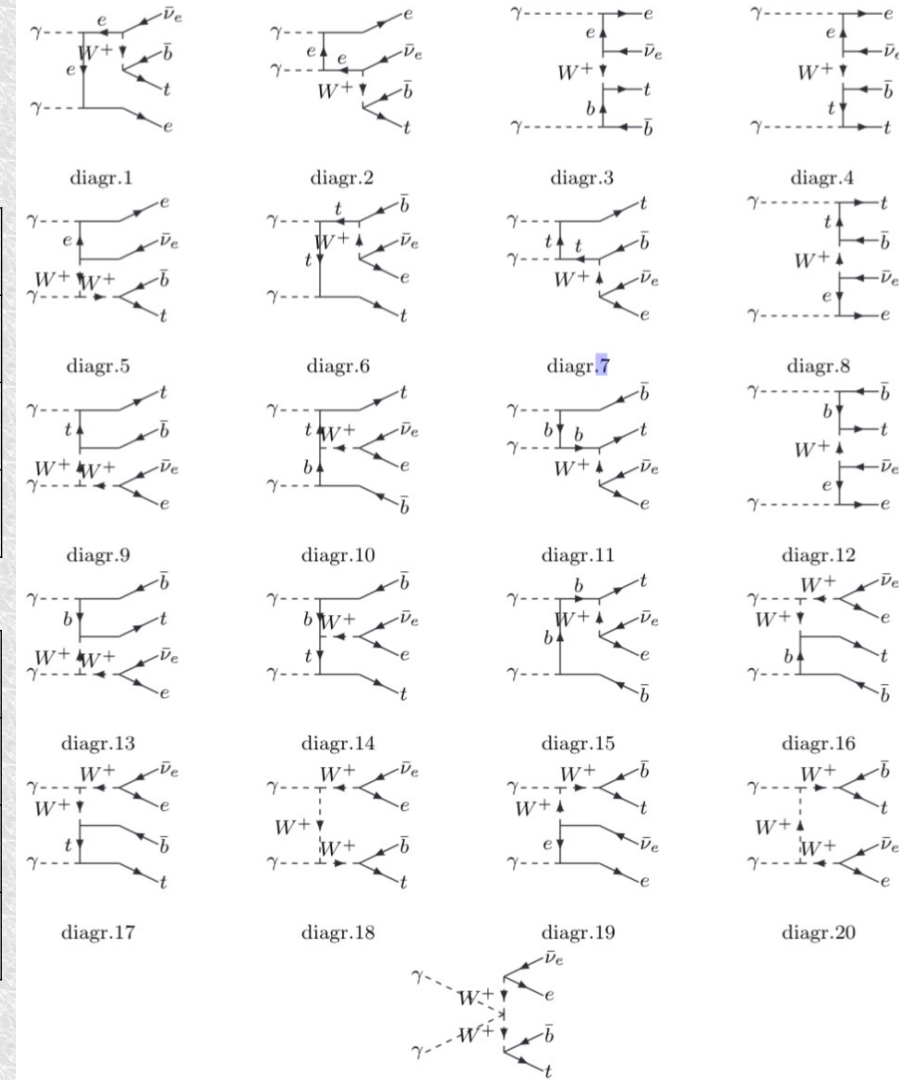
Low level variable distributions demonstrate distinct signal vs. background behavior

Single Top quarks in e⁺e⁻ processes at CEPC (2)

- **$\gamma\gamma$**
- CEPC, $\sqrt{s} = 240 \text{ GeV}$
- Below the top pair production threshold

	CS [pb] COMPHEP
-	
$\gamma, \gamma \rightarrow c, S, T, b$	1.2e-10
$\gamma, \gamma \rightarrow u, D, T, b$	3.9e-10
$\gamma, \gamma \rightarrow ne, E, T, b$	1.0e-10

	CS [pb] WHIZARD
$\gamma, \gamma \rightarrow c, S, T, b$	1.4e-10
$\gamma, \gamma \rightarrow u, D, T, b$	2.9e-10
$\gamma, \gamma \rightarrow ne, E, T, b$	9.2e-11



- Due to its tiny CS the **$\gamma\gamma$** process is not considered promising

EFT and Anomalous Coupling approaches

- **Effective Field Theory** approach:

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i$$

[Nucl.Phys.B 268 \(1986\) 621-653](#)

[Z. Phys. C31 \(1986\) 433-437](#)

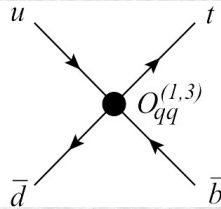
- operators contributing to the Wtb vertex:

$$O_{\phi q}^{(3,3+3)} = \frac{i}{2} \left[\phi^\dagger (\tau^I D_\mu - \overleftarrow{D}_\mu \tau^I) \phi \right] (\bar{q}_{L3} \gamma^\mu \tau^I q_{L3}), \quad O_{\phi\phi}^{33} = i(\tilde{\phi}^\dagger D_\mu \phi)(\bar{t}_R \gamma^\mu b_R),$$

$$O_{dW}^{33} = (\bar{q}_{L3} \sigma^{\mu\nu} \tau^I b_R) \phi W_{\mu\nu}^I, \quad O_{uW}^{33} = (\bar{q}_{L3} \sigma^{\mu\nu} \tau^I t_R) \tilde{\phi} W_{\mu\nu}^I,$$

$$O_{qq}^{(1,3)} = (\bar{q}^i \gamma_\mu \tau^I q^j) (\bar{q} \gamma^\mu \tau^I q)$$

contact four-fermion interactions
(not a part of the Wtb vertex):



- **Anomalous Couplings** approach:

[Phys.Rev.D83:034006,2011](#)

$$\mathcal{L} = \frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_V^L P_L + f_V^R P_R) t W_\mu^-$$

$$- \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu V_{tb}}{M_W} (f_T^L P_L + f_T^R P_R) t W_\mu^- + h.c.$$

order:

$$1/\Lambda^2 \quad 1/\Lambda^4$$

$$f_V^L \quad (f_V^L)^2$$

$$\dots \quad (f_V^R)^2$$

$$\dots \quad (f_T^L)^2$$

$$f_T^R \quad (f_T^R)^2$$

- Translation:

$$|f_V^L| = 1 + |C_{\phi q}| \frac{v^2}{V_{tb} \Lambda^2}$$

$$|f_V^R| = \frac{1}{2} |C_{\phi\phi}| \frac{v^2}{V_{tb} \Lambda^2}$$

$$|f_T^L| = \sqrt{2} |C_{bW}| \frac{v^2}{V_{tb} \Lambda^2}$$

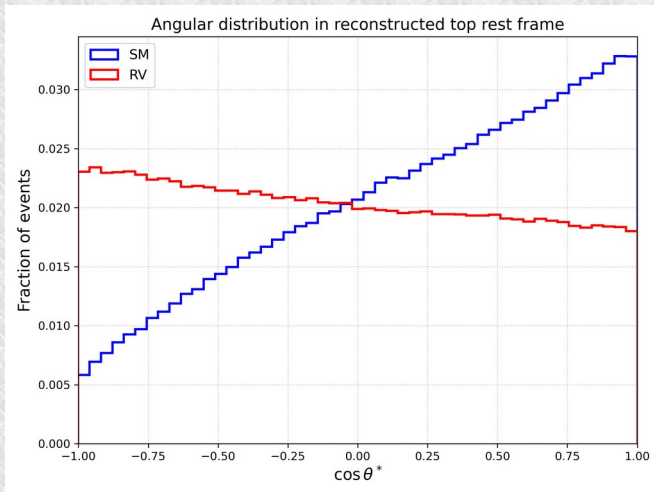
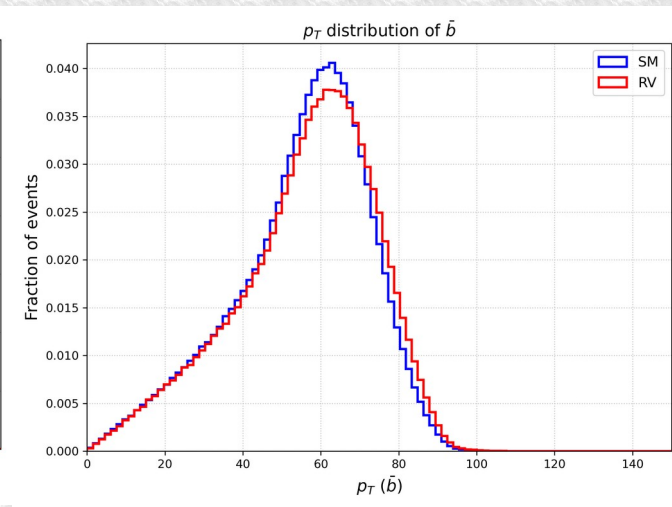
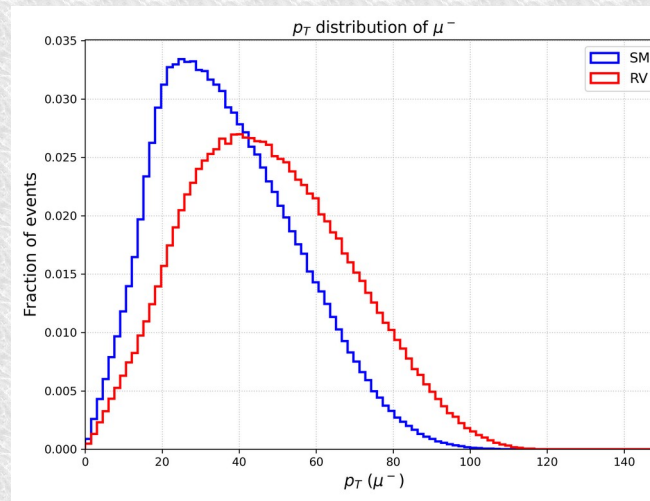
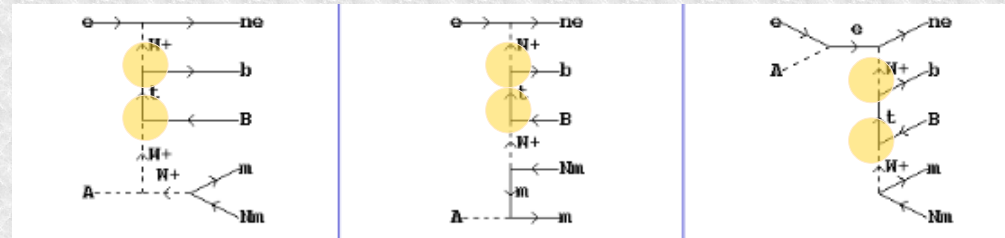
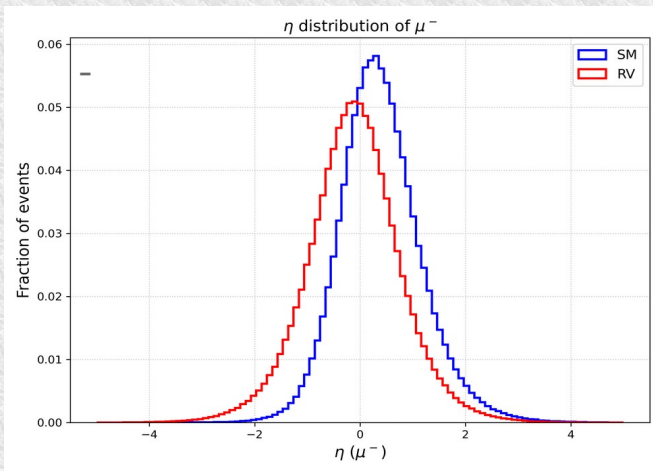
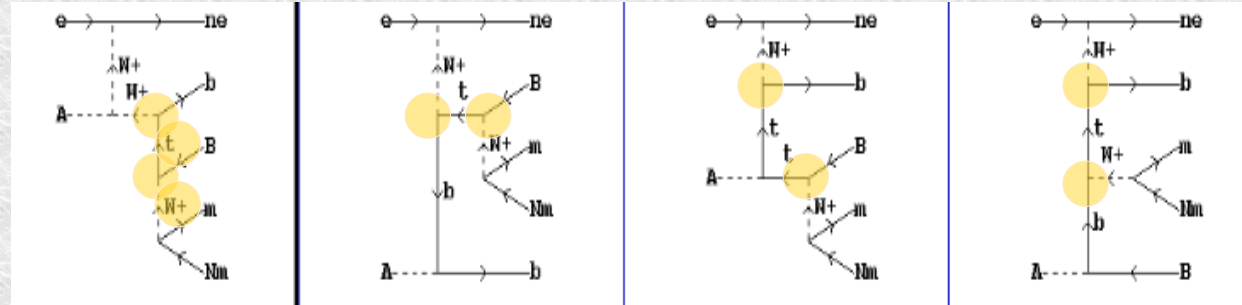
$$|f_T^R| = \sqrt{2} |C_{tW}| \frac{v^2}{V_{tb} \Lambda^2}$$

[Nucl.Phys.B 812 \(2009\) 181-204](#)

[PoS ICHEP2010:378,2010](#)

Anomalous Wtb couplings in νe process for CEPC

- Anom Wtb (LV,RV) scenario
 - First estimation for CEPC energies in the νe process



- Good discrimination for the chosen variables
- These variables, along with new ones can be used for high-level DNN analyses

Conclusion and Future Plans

- Study of the single top quark production in e^+e^- , $e\gamma$ and $\gamma\gamma$ modes at the future CEPC lepton collider have been performed
- $e\gamma$ process is the most promising due to its relatively large CS and reducible background
- A first estimation of the anomalous Wtb contribution to single top quark production in $e\gamma$ mode is provided
- Simulate detector response using DELPHES
- Perform follow-up studies on anomalous Wtb couplings (SMEFT operators, alternative scenarios, subsidiary fields...)
- Other BSM studies (FCNC? DM?)

This study was conducted within the scientific program of the National Center for Physics and Mathematics, section #5 «Particle Physics and Cosmology». Stage 2026-2027