Single Top Quarks Physics at Future Lepton Colliders

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Lepton Colliders vs. Hadron Colliders

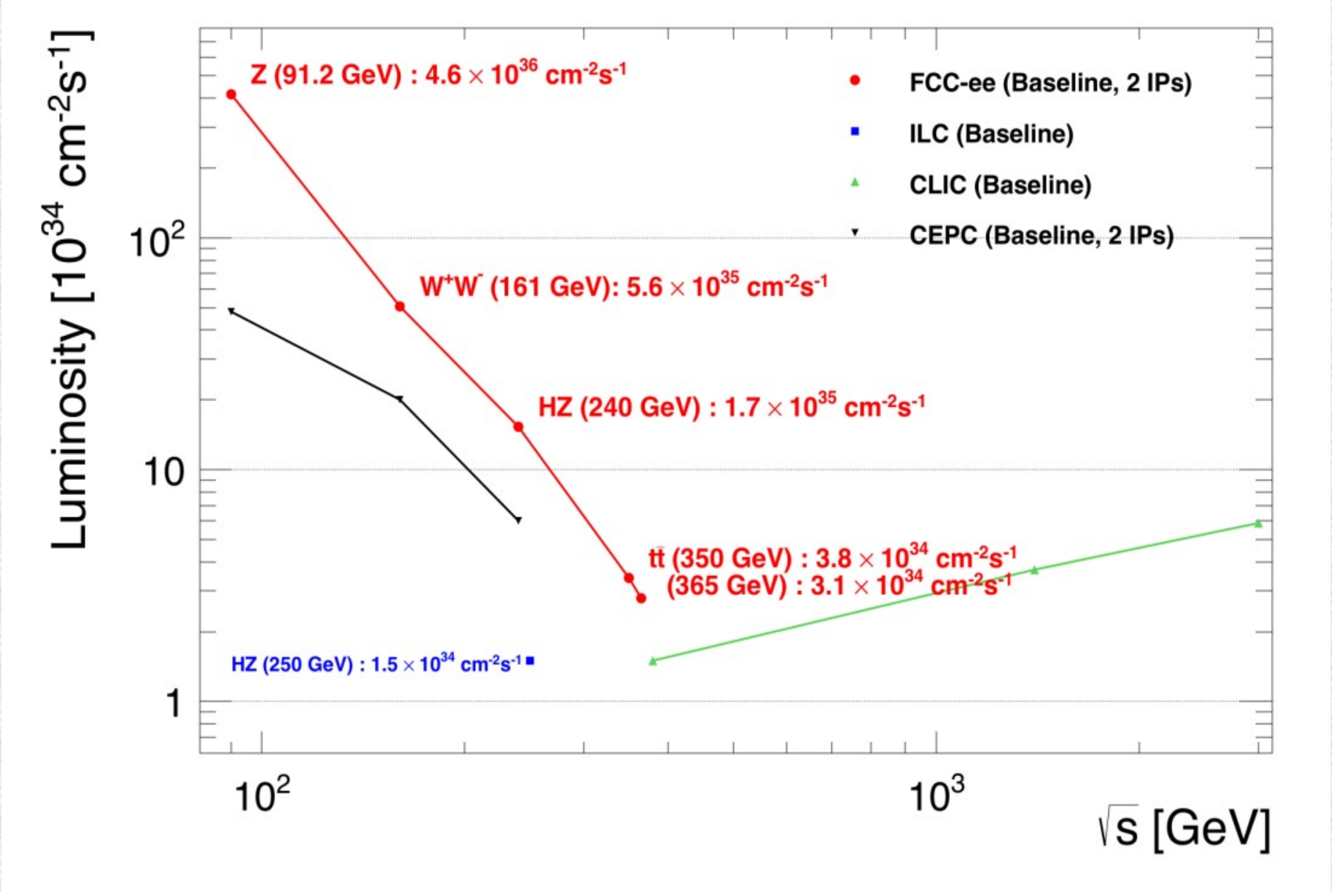
- Clean initial state and well-defined energy
- **Leptons** are elementary particles with no internal structure; when electrons and positrons collide, the entire energy of the beams goes into the interaction.
- **Hadrons** are composite
  - uncertain collision energy for the hard process;
  - large underlying event activity (extra particles from spectator partons).
- 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.
- **Hadron** collisions have high multiplicity-events due to QCD activity, making it harder to isolate the signal.
- Well-understood theoretical framework
- Electromagnetic (EM) and weak interactions of leptons are precisely calculable in QED and Electroweak theory.
- QCD effects in hadron collisions introduce large theoretical uncertainties, especially at low and intermediate energies.

- **Lepton colliders are ideal for**
- precision measurements of known particles
- threshold scans and resonance studies
- model-independent new physics searches

- **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−, γe and γγ 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-, **γe → e- νe t B** are less favorable
- Three processes were chosen to probe their sensitivity to anomalous Wtb couplings,with best bounds found for $\gamma_+ e^-_L \to e^- t\bar{b}$ $e^+_R e^-_R \to e^- \nu_e t\bar{b}$

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

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

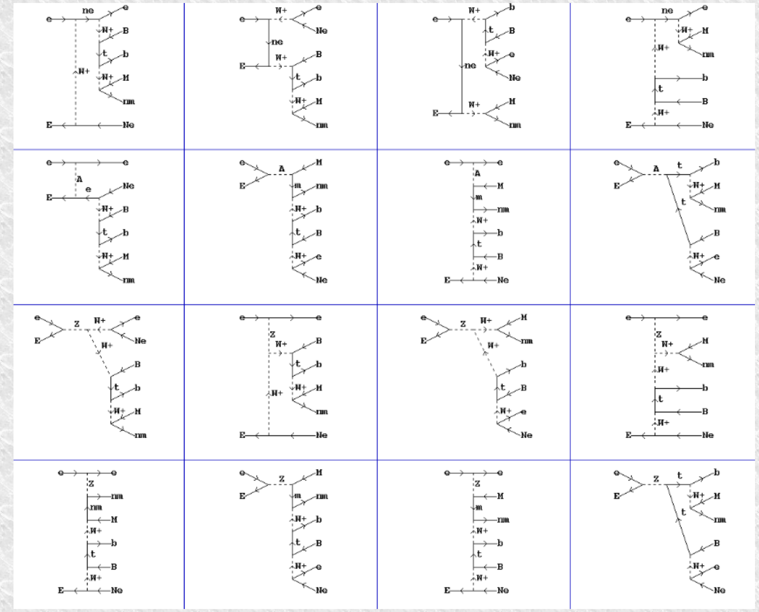
Single Top quarks in e+e- processes at CEPC (2)

- e+e-
- CEPC, **√s = 240 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



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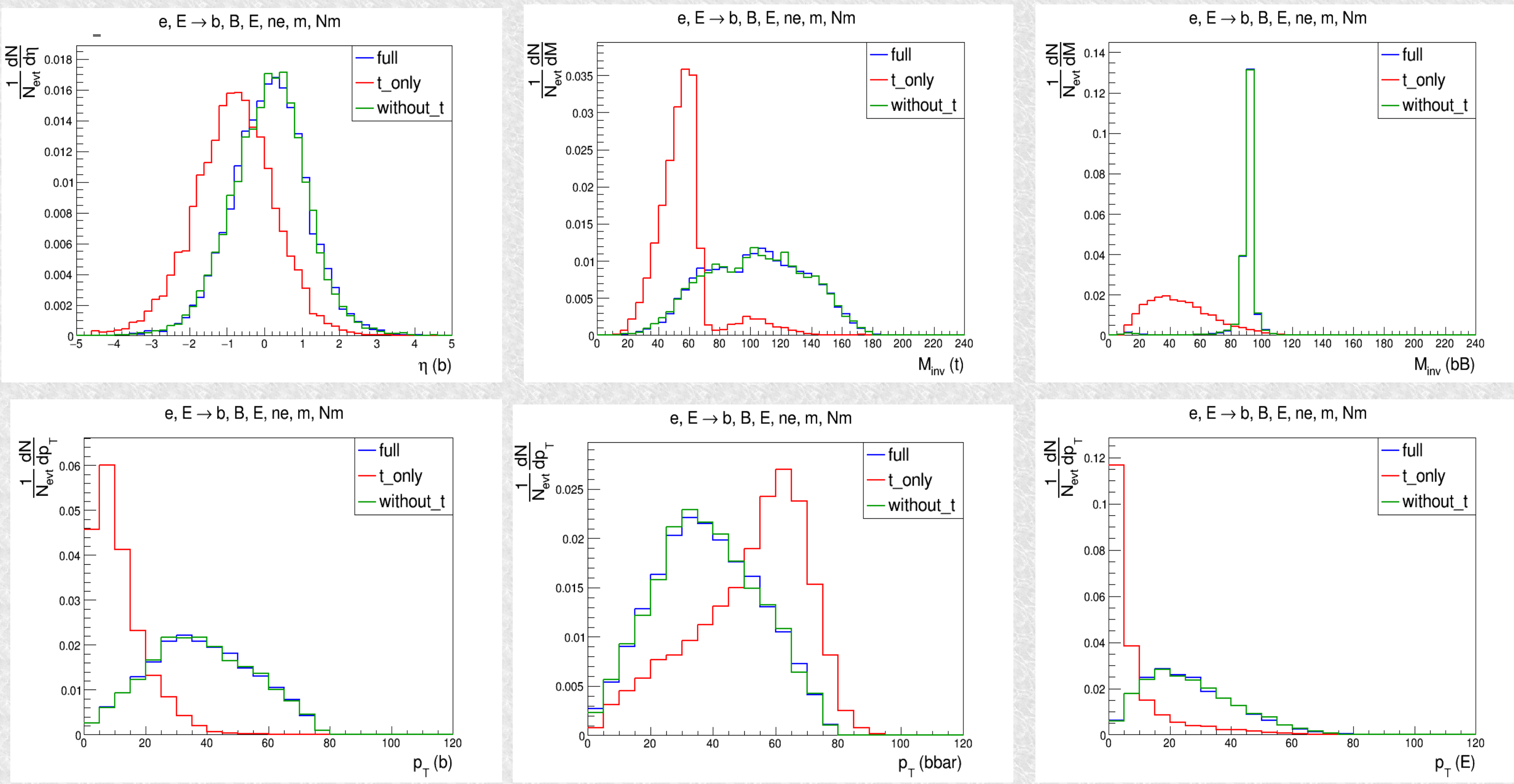
Single Top quarks at CEPC

- **e+e-**



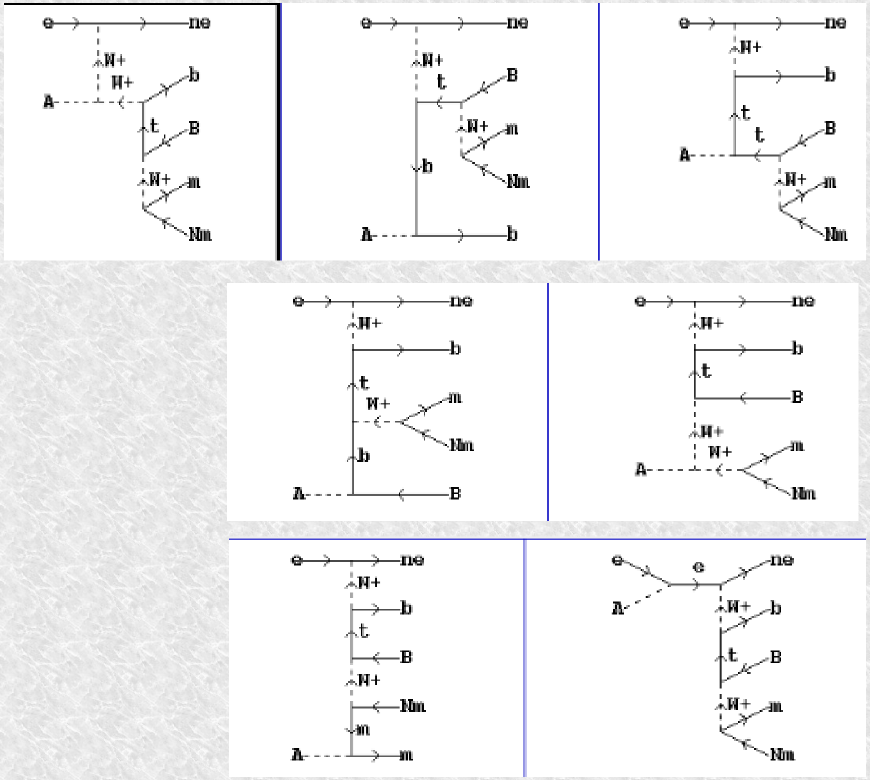
Low-level variables distributions demonstrate distinct signal vs. background behavior

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

- **γe**
- CEPC, **√s = 240 GeV**
- Below the top-pair production threshold

-	CS (e,γ → ne,T,b) [pb]
CompHEP	1.2e-05
WHIZARD	1.1e-05

WHIZARD	CS (e,γ → 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
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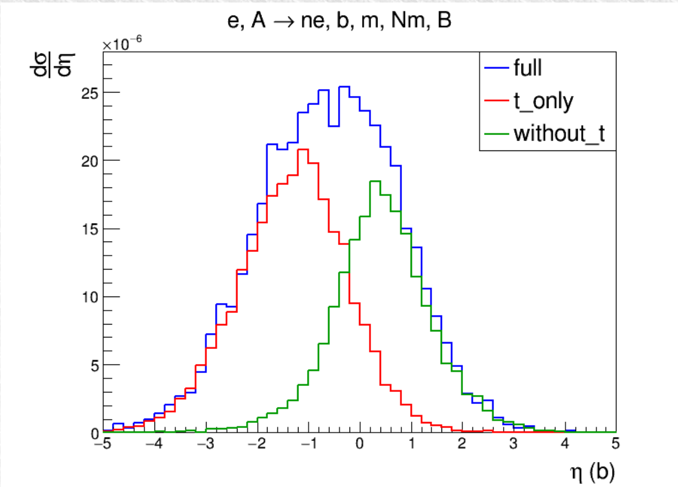
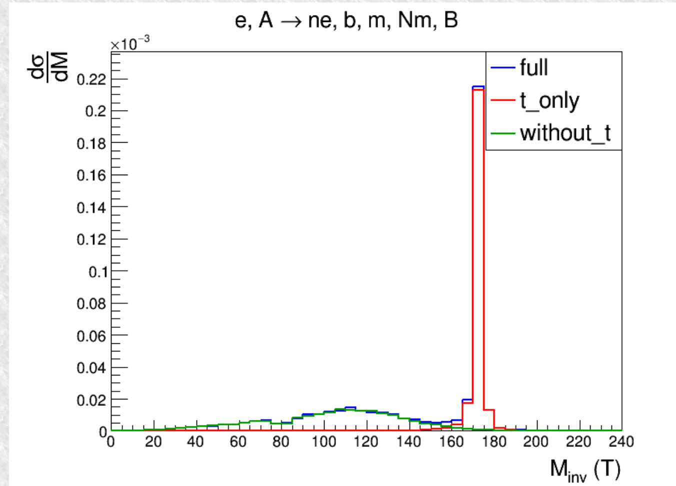
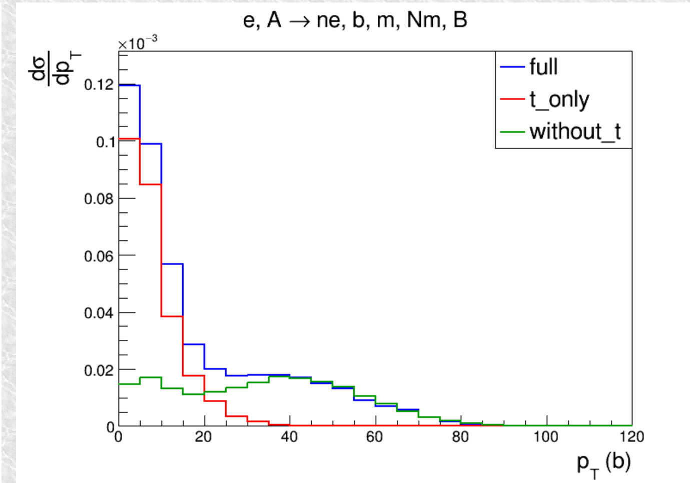
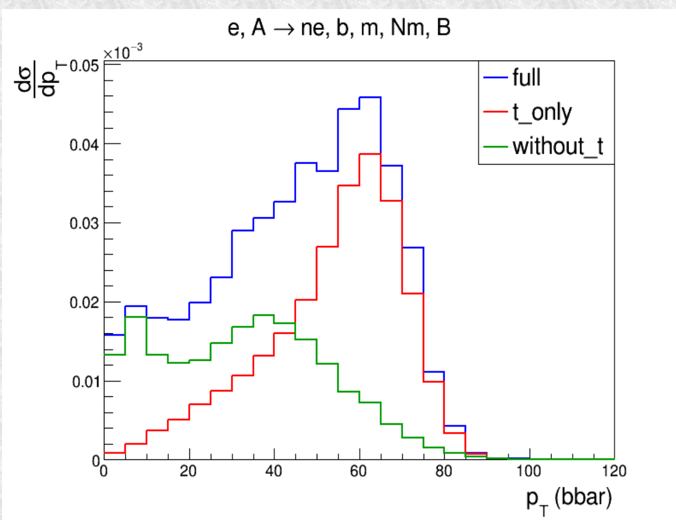
Single Top quarks at CEPC

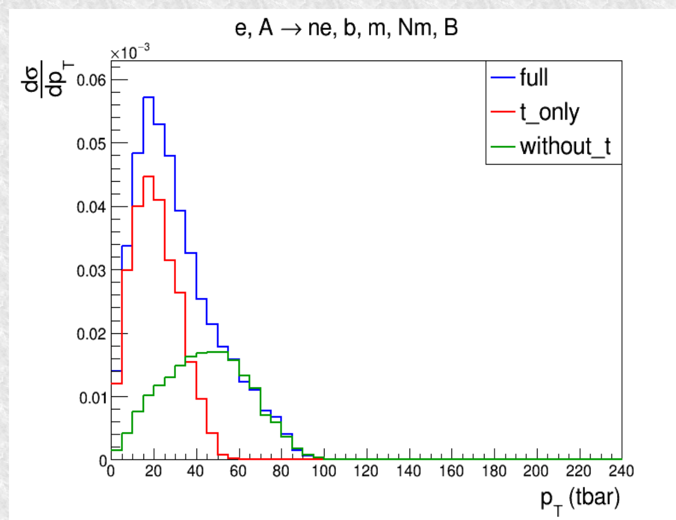
- **γe**

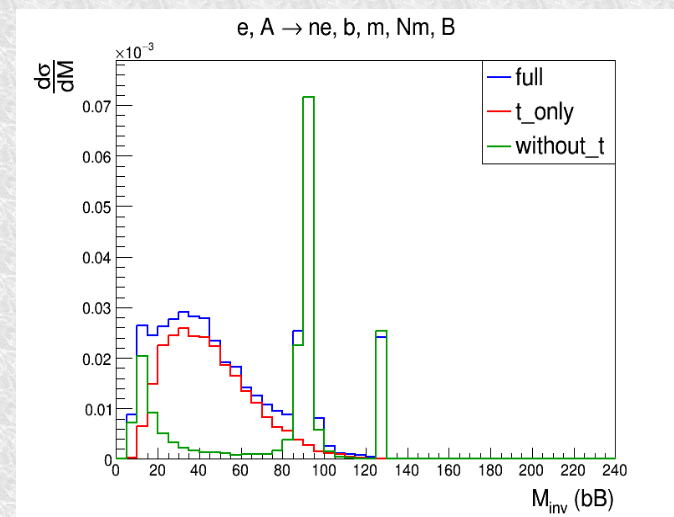












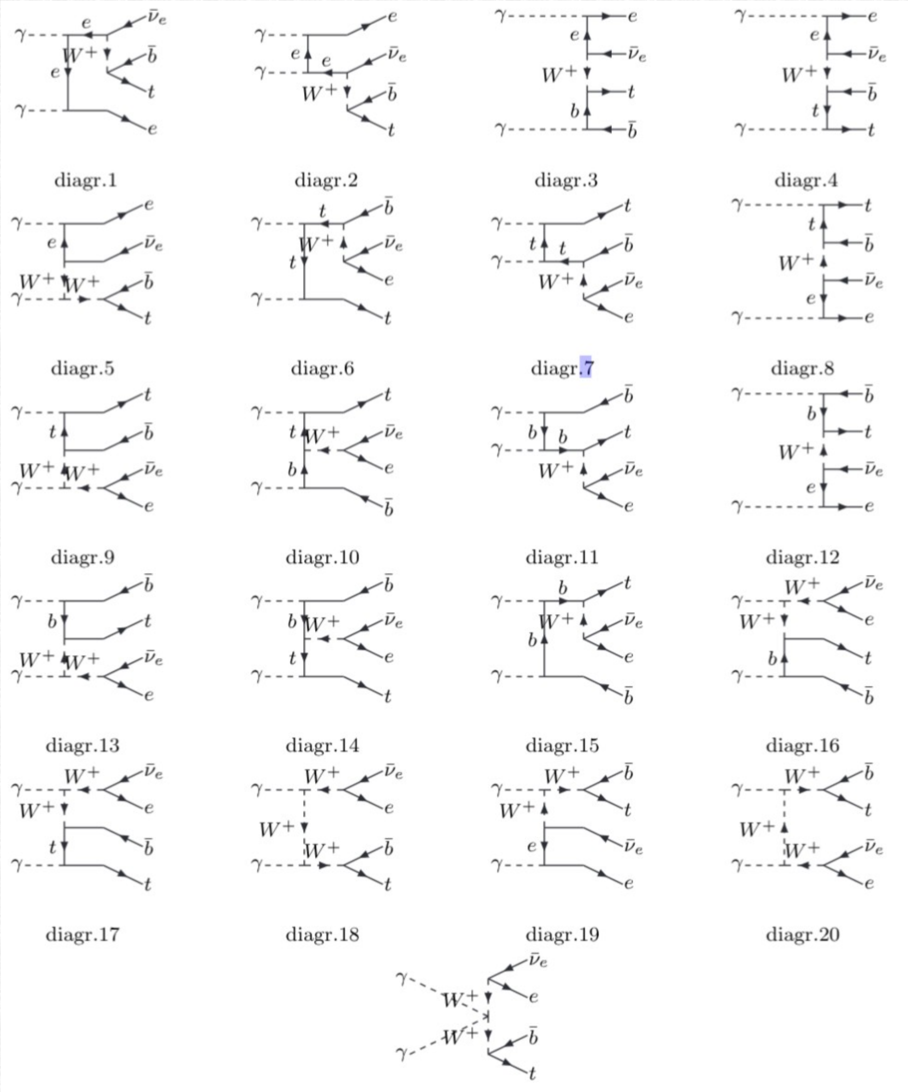
Low level variable distributions demonstrate distinct signal vs. background behavior

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

- **γγ**
- CEPC, **√s = 240 GeV**
- Below the top pair production threshold

-	CS [pb] COMPHEP
γ,γ → c,S,T,b	1.2e-10
γ,γ → u,D,T,b	3.9e-10
γ,γ → ne,E,T,b	1.0e-10

	CS [pb] WHIZARD
γ,γ → c,S,T,b	1.4e-10
γ,γ → u,D,T,b	2.9e-10
γ,γ → ne,E,T,b	9.2e-11



- Due to its tiny CS the **γγ** process is not considered promising

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EFT and Anomalous Coupling approaches

- **Effective Field Theory** approach:

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

Nucl.Phys.B 268 (1986) 621-653

Z. Phys. C31 (1986) 433-437

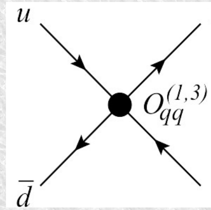
- operators contributing to the Wtb vertex:

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

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

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

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: $1/\Lambda^2$	$1/\Lambda^4$
f_V^L	$(f_V^L)^2$
...	$(f_V^R)^2$
...	$(f_T^L)^2$
f_T^R	$(f_T^R)^2$

- Translation:

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

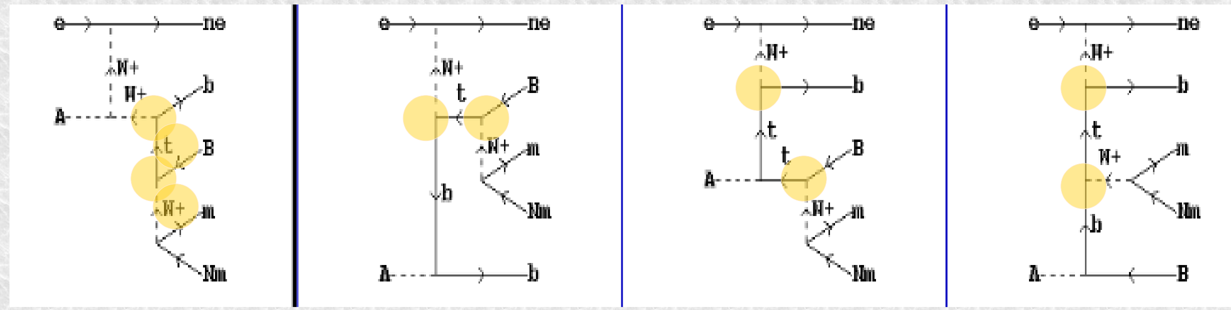
$$|f_T^L| = \sqrt{2}|C_{bW}|\frac{v^2}{V_{tb}\Lambda^2} \qquad |f_T^R| = \sqrt{2}|C_{tW}|\frac{v^2}{V_{tb}\Lambda^2}$$

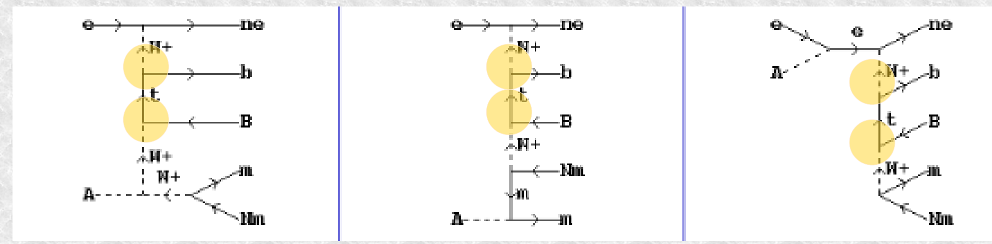
Nucl.Phys.B 812 (2009) 181-204

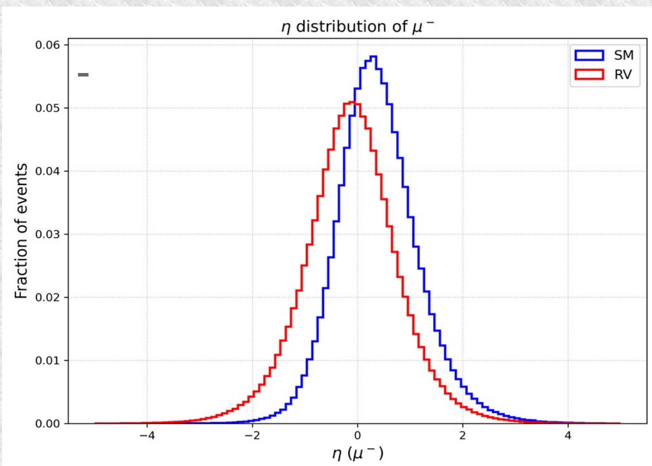
PoS ICHEP2010:378,2010

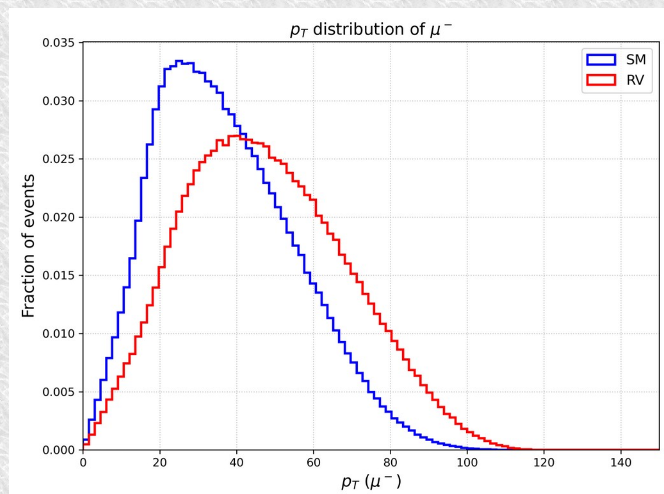
Anomalous Wtb couplings in **γe** process for CEPC

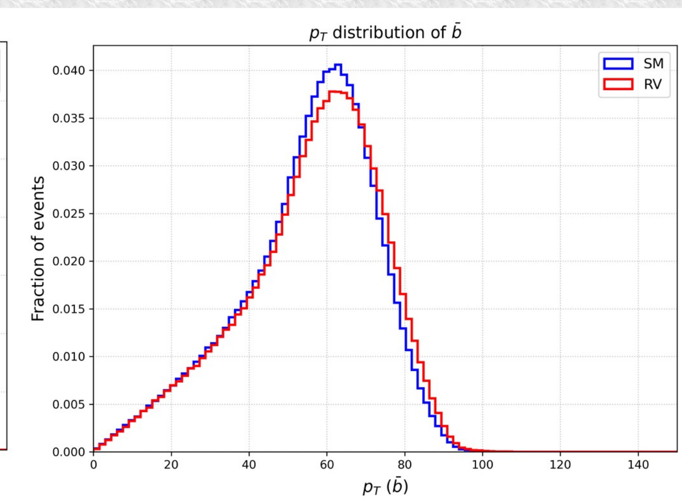
- AnomWtb (LV,RV) scenario
  - First estimation for CEPC energies in the **γe** process

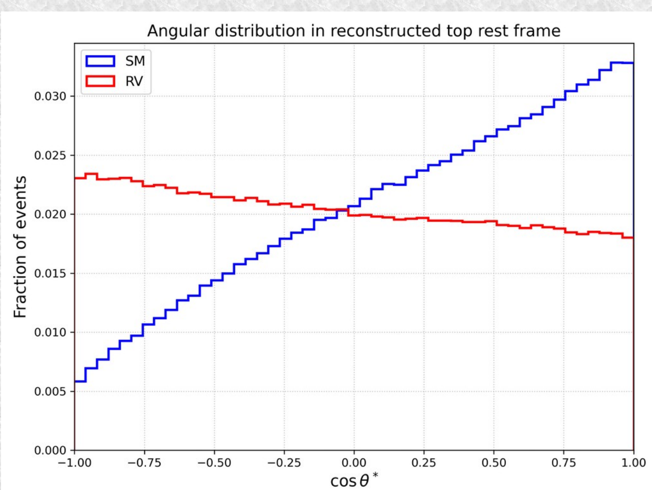












- Good discrimination for the chosen variables
- These variables, aling with new ones can be used for high-level DNN analyses

E.E. Boos, A.V. Sherstnev PLB 534 1-4 97-105

Conclusion and Future Plans

- Study of the single top quark production in ***e+e-***, **eγ** and **γγ** modes at the future CEPC lepton collider have been performed
- **eγ** 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 **eγ** 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?)

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