Top quark Electroweak Couplings at the CEPC

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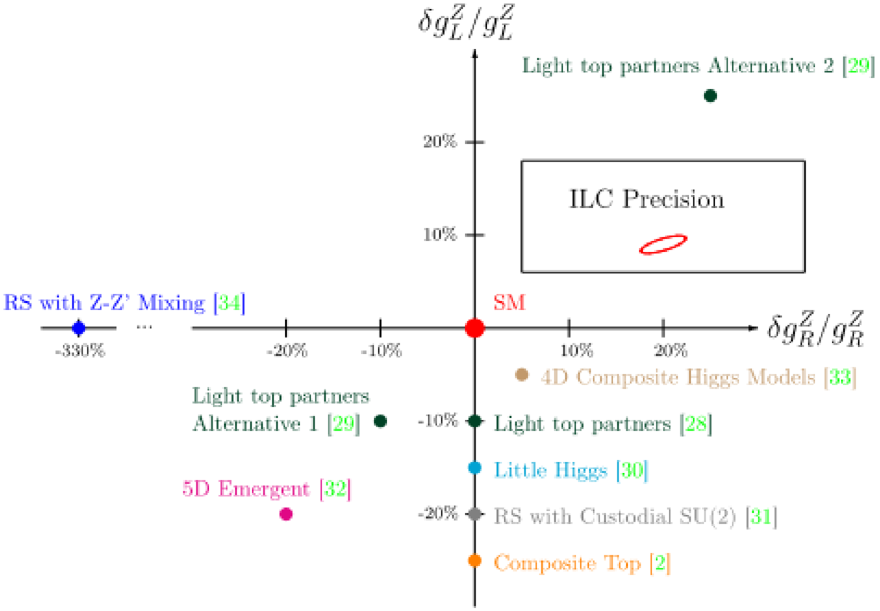
Introduction/Motivation

- As the heaviest known elementary particle, the top quark has a Yukawa coupling close to unity, making it uniquely sensitive to EW symmetry breaking.

- Precision measurements of the top quark's coupling to neutral EW gauge bosons provide a unique probe of the electroweak sector and a sensitive test for deviations from the SM.

- *Lepton colliders (i,e CEPC) offer clean e+e− → $t\bar{t}$ environment, enabling per-mil level precision on these form factors, far beyond LHC reach!*



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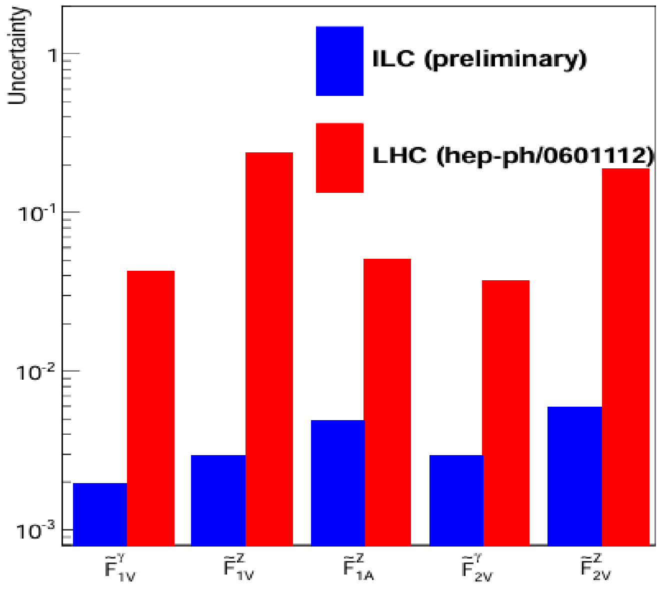

Sensitive Observables

- *The top-quark EW couplings can be probed through different observables in e+e− → tt̄, sensitive to different combinations of form factors:*

- **Total cross section σ:**

$$\sigma = \int \frac{d^2\sigma}{d\cos\theta_{top}\, d\cos\psi}\, d\cos\theta_{top}\, d\cos\psi$$

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- **Forward-backward asymmetry:**

$$A^{l}_{FB} = \frac{\sigma(\cos\theta_{top} > 0) - \sigma(\cos\theta_{top} < 0)}{\sigma(\cos\theta_{top} > 0) + \sigma(\cos\theta_{top} < 0)}$$

- **At CEPC/FCC (unpolarized beams), we use the double-differential distribution :**

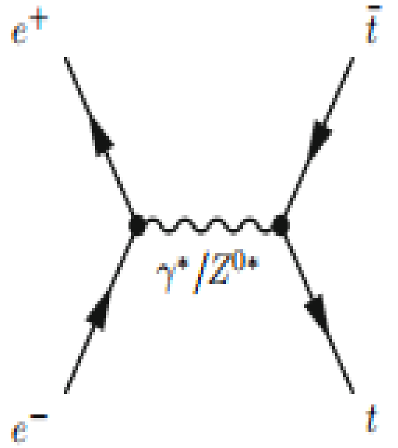
  Depends on the final top quark decay products, namely, leptons and b-quarks.

$$\frac{d^2\sigma}{dx_f\, d\cos\theta_f}$$

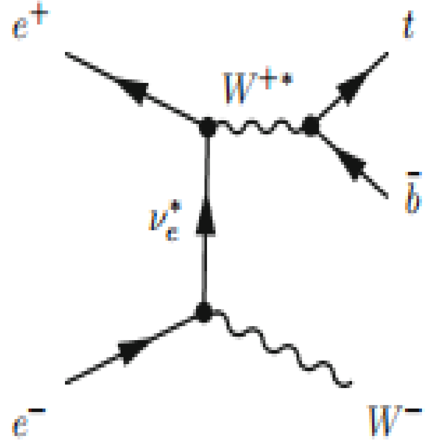
Signal and Background Processes

- ☐ The signal and background processes were generated with MG5 and simulated using the CEPC full simulation, at a center-of-mass energy of 360 GeV:

Channel	σ (pb)	$\Delta\sigma$ (pb)	Process
$t\bar{t}$	0.4	0.000619	Signal
WW	10.94	0.020	background
ZZ	0.657	0.001	background
ZWW	0.0148	2.2×10^{-5}	background
ZZZ	7.32×10^{-4}	7.6×10^{-7}	background
$\mu^+\mu^-$	0.816	0.0005	background
$\sum q\bar{q}$	4.27	0.003	background
$b\bar{b}$	0.767	0.0006	background



top-pair-production



single top-production

❖ Single-top background was not considered in this study, given that it is indistinguishable from top-pair production at centre-of-mass energies below *500 GeV.*

Lepton Isolation

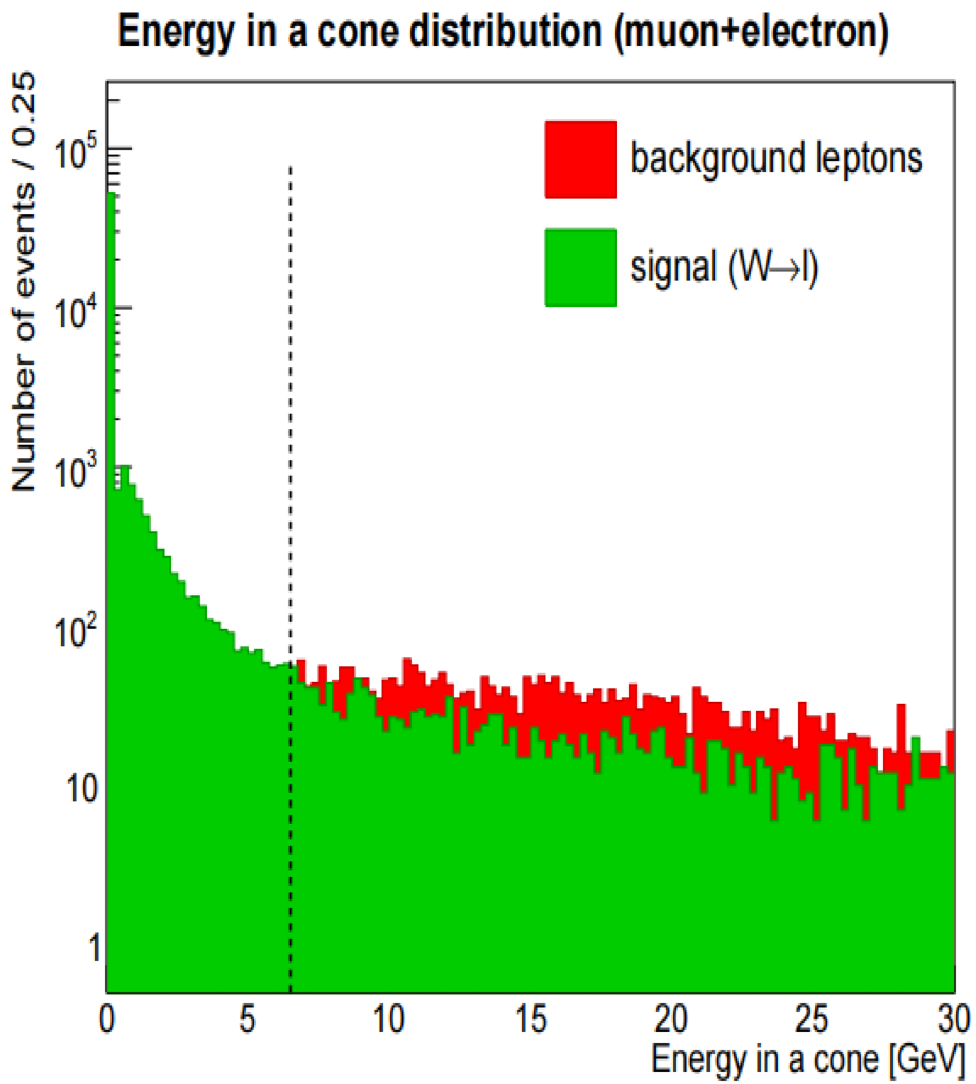
- ***In $t\tilde{t}$ semi-leptonic channel*** **:**

Lepton final states originating from W-boson decays are isolated using a cone-energy method.

Signal leptons (W→ℓ) are distinguished from background leptons(heavy-flavor (b/c) hadron decays), by exploiting both lepton energy and surrounding cone activity.

The cone energy is defined by the requirement

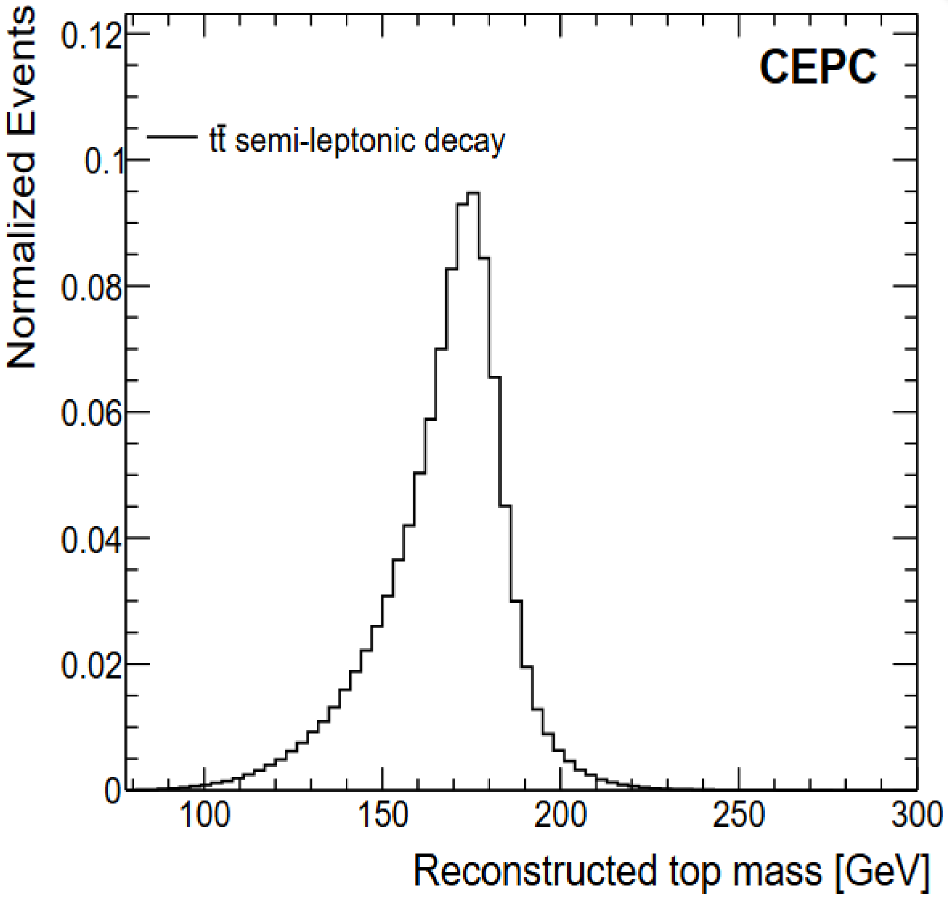
$$cos_{\theta} \geq 0.98$$



- **The thresholds on the lepton energy and cone energy were optimized using truth-level information.**

Top mass Reconstruction

- **Top mass reconstruction is done using two methods: one based on kinematic fitting, and a chi-squared minimization method.**



$$\chi^2 = \frac{(M_{jj} - m_W^{\text{had}})^2}{\sigma^2_{W,\text{had}}} + \frac{(M_{bjj} - m_t^{\text{had}})^2}{\sigma^2_{t,\text{had}}} + \frac{(M_{l\nu} - m_W^{\text{lep}})^2}{\sigma^2_{W,\text{lep}}} + \frac{(M_{bl\nu} - m_t^{\text{lep}})^2}{\sigma^2_{t,\text{lep}}}$$

❖ **Accurate hadronic top mass reconstruction is essential for the determination of the top-quark direction which is subsequently used for top quark electroweak couplings determination. (DOI 10.1140/epjc/s10052-015-3746-5r)**

Top Coupling Parameterization

- ***The $t\bar{t}$ EW couplings are parameterised through the following **vertex function** (v=γ,Z):***

$$\Gamma^{\mu}_{t\bar{t}v} = \frac{g}{2}\left[\gamma^{\mu}\left\{(A_v + \delta A_v) - \gamma_5(B_v + \delta B_v)\right\} + \frac{(p_t - p_{\bar{t}})^{\mu}}{2m_t}(\delta C_v - \delta D_v\gamma_5)\right],$$

- A_v and B_v are the SM couplings, and $\delta A_v, \delta B_v, \delta C_v, \delta D_v$ represent the anomalous form factors (i.e vanishes at SM).

➢ ***The angular and energy distributions of the lepton arising from the $t\bar{t}$ semileptonic decays:***

$$\frac{d^2\sigma}{dx\, d\cos\theta} = \frac{3\pi\beta\alpha^2(s)}{2s} B_\ell S_\ell(x, \cos\theta)$$

$$x_f = \frac{2E_f}{m_{top}}\sqrt{\frac{1-\beta}{1+\beta}}$$

Why using lepton/b-jet energy and dirercion? Top decays before hadronizing ($\Gamma_t >>> \Lambda_{QCD}$), The full spin state is preserved and transferred to the decay products.

differential Cross Section

- ***The differential cross section decomposes into two parts: the SM and the non-standard contributions:***

$$S(x,\theta) = S^0(x,\theta) + \sum_{i=1}^{8} \delta_i f_i(x, \cos\theta)$$

- **Assuming the anomalous form factors δ_i to be small, only terms linear in δ_i are kept. This can be written explicitly as:**

$$S(x,\cos\theta) = \underbrace{S^0(x,\cos\theta)}_{\substack{\text{SM: all couplings}\\ \text{at SM values}}} + \underbrace{\delta A_\gamma \cdot F_{A\gamma}(x,\cos\theta)}_{\substack{\text{shift in}\\ F^\gamma_{1V}\text{ only}}} + \underbrace{\delta A_Z \cdot F_{AZ}(x,\cos\theta)}_{\substack{\text{shift in}\\ F^Z_{1V}\text{ only}}} + \underbrace{\delta B_Z \cdot F_{BZ}(x,\cos\theta)}_{\substack{\text{shift in}\\ F^Z_{1A}\text{ only}}}$$
$$+ \underbrace{\delta C_\gamma \cdot F_{C\gamma}(x,\cos\theta)}_{\substack{\text{shift in}\\ F^\gamma_{2V}\text{ only}}} + \underbrace{\delta C_Z \cdot F_{CZ}(x,\cos\theta)}_{\substack{\text{shift in}\\ F^Z_{2V}\text{ only}}} + \underbrace{\delta D_\gamma \cdot F_{D\gamma}(x,\cos\theta) + \delta D_Z \cdot F_{DZ}(x,\cos\theta)}_{\text{set to 0 (CP-odd terms)}}$$

Parameter	Form Factor	CP	Physical meaning
δA_γ	δF^γ_{1V}	even	Anomalous photon vector coupling to top
δA_Z	δF^Z_{1V}	even	Anomalous Z vector coupling to top
δB_Z	δF^Z_{1A}	even	Anomalous Z axial coupling to top
δC_γ	δF^γ_{2V}	even	Anomalous photon chromo-electric moment
δC_Z	δF^Z_{2V}	even	Anomalous Z chromo-electric moment
δD_γ	--	odd	CP-violating electric dipole (set to 0)
δD_Z	--	odd	CP-violating dipole (set to 0)

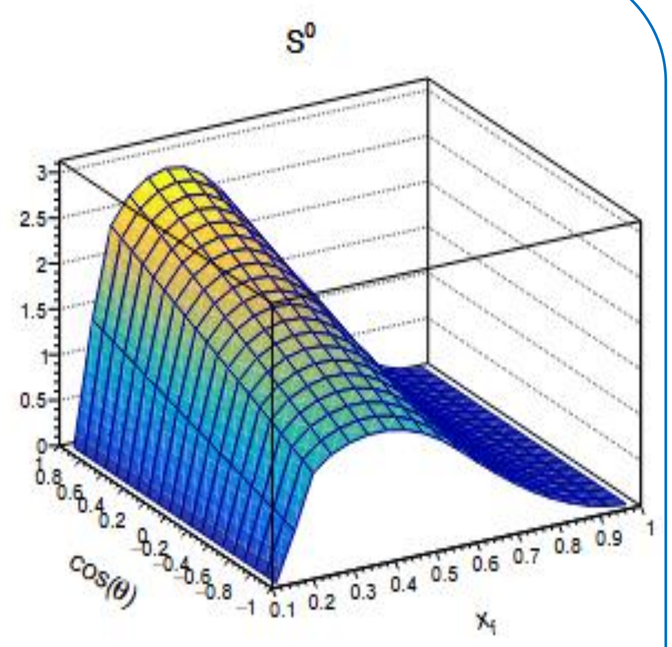
Where F(x,cos_θ) are *<u>kinematic shape functions</u>*, each encodes the unique signature of its corresponding form factor.

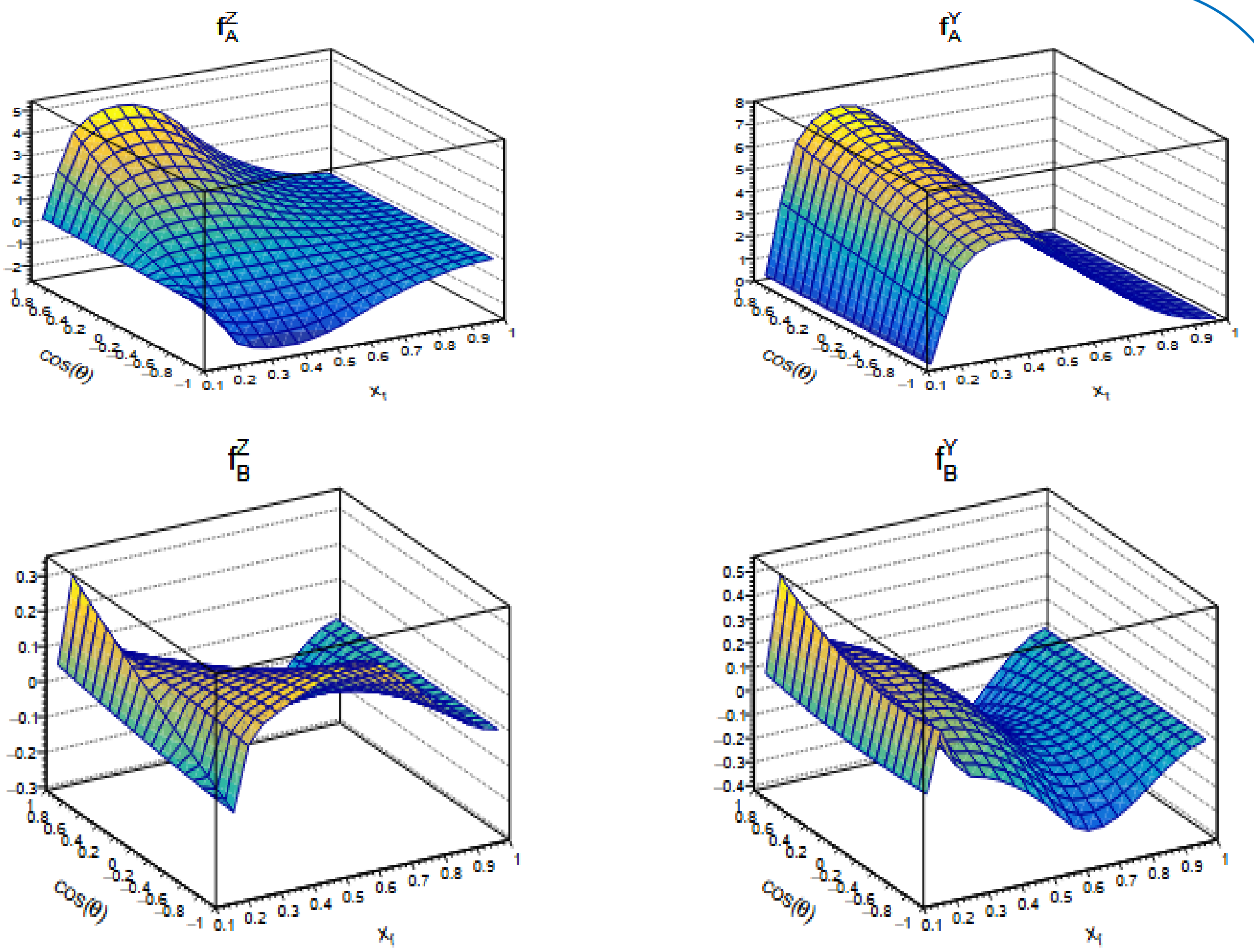
SM and non-standard contributions:

- The shapes of the SM contribution i.e, S^0, and the associated distribution to the non-standard form factors:

Non-Standard contribution

SM contribution





Binned Likelihood

❖ There are eight form factors to determine simultaneously δ_i:

$$S(x,\theta) = S^0(x,\theta) + \sum_{i=1}^{8} \delta_i f_i(x, \cos\theta)$$

❖ The likelihood to evaluate for the different form factors:

$$L = \frac{\mu^N}{N!} \mathrm{e}^{-\mu} \times \prod_{k=1}^{N} p(k)$$

❖ For a straightforward comparison with other projected sensitivities, we consider two form factor configurations:

$$S(x,\theta) = S^0(x,\theta) - 2i\sin\theta_W \delta F_{1V}^{\gamma} f_A^{\gamma} - 2i\sin\theta_W \delta F_{1V}^{Z} f_A^{Z} + -2i\sin\theta_W \delta F_{1A}^{Z} f_B^{Z}$$

$$S(x,\theta) = S^0(x,\theta) - 2i\sin\theta_W \delta F_{2V}^{\gamma} (f_A^{\gamma} + f_C^{\gamma}) - 2i\sin\theta_W \delta F_{2V}^{Z} (f_A^{Z} + f_C^{Z})$$

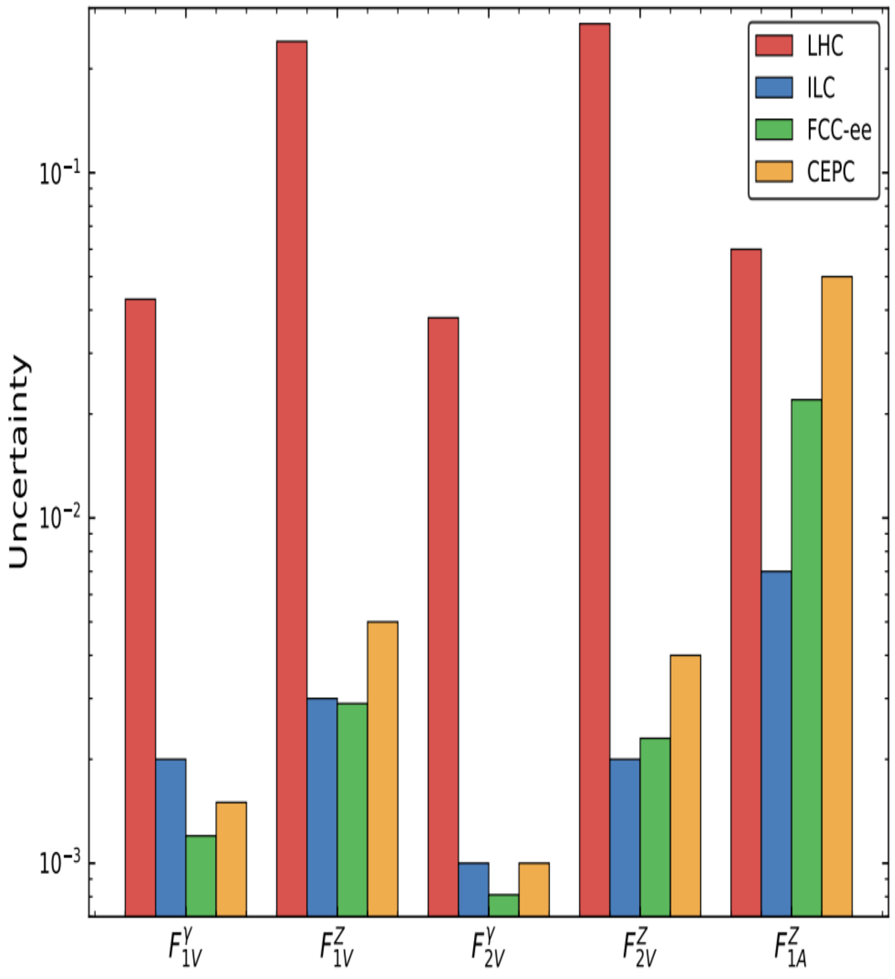
- ❑ First Configuration: 3 parameters to fit simultaneously : δF_1^{γ}, δF_{1V}^{Z}, δF_{1A}^{Z}.
- ❑ Second Configuration: 2 parameters to fit simultaneously: δF_2^{γ}, δF_{2V}^{Z}

Binned Likelihood

- As a first step, a binned likelihood fit is performed directly on the double-differential distributions, with all δ_i floated.

- Following the two-form factor configuration:

Form Factor	Projected Sensitivity
F_{1V}^{γ}	0.002
F_{1V}^{Z}	0.005
F_{2V}^{γ}	0.001
F_{2V}^{Z}	0.004
F_{1A}^{Z}	0.05



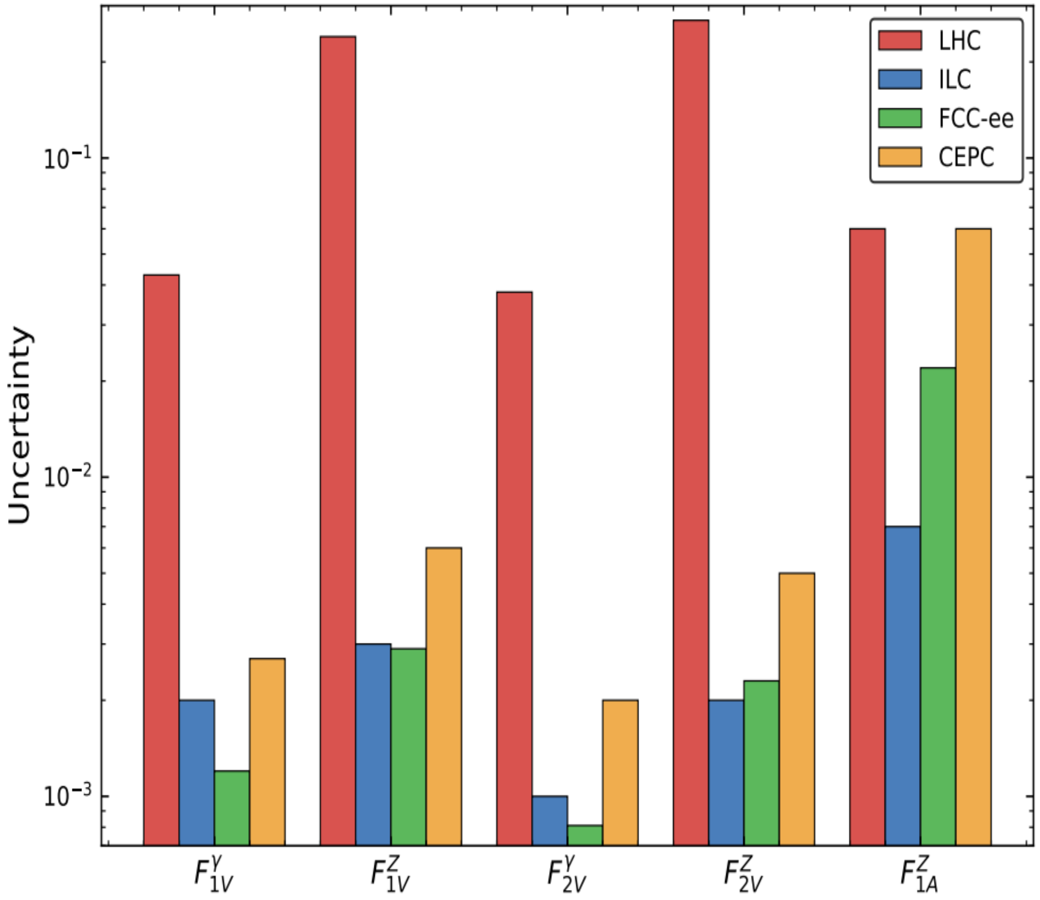
✓ Theoretical projection at CEPC@360GeV and $1ab^{-1}$ integrated luminosity.

✓ Compared to other projections such as FCC-ee ,which assumes $2.4\ ab^{-1}$ of integrated luminosity (Better Precision).

Binned Likelihood

- To validate these sensitivities against CEPC-Full simulation:
- We use the reconstructed observables (energy and direction of the final-state lepton).
- Residual background is suppressed, and a lepton isolation efficiency $\varepsilon(x, cos_{\theta})$ is incorporated into the likelihood function to account for efficiency variation across lepton energy and direction.

Form Factor	Full-Simulation Sensitivity
F_{1V}^{γ}	0.003
F_{1V}^{Z}	0.006
F_{2V}^{γ}	0.002
F_{2V}^{Z}	0.005
F_{1A}^{Z}	0.06



❖ Per-mille to percent-level precision is achieved across the form factors, competitive with other projections, and validating the theoretical predictions.

Theoretical uncertainty :

- **Theoretical uncertainties on the predicted cross-section affect the precision of the form factor determination.**

$$\frac{d^2\sigma}{dx\, d\cos\theta} = \frac{3\pi\beta\alpha^2(s)}{2s} B_\ell\, S_\ell(x, \cos\theta).$$

- **Allow the normalization to vary by incorporating a shift δ^{th} in the predicted cross section.**

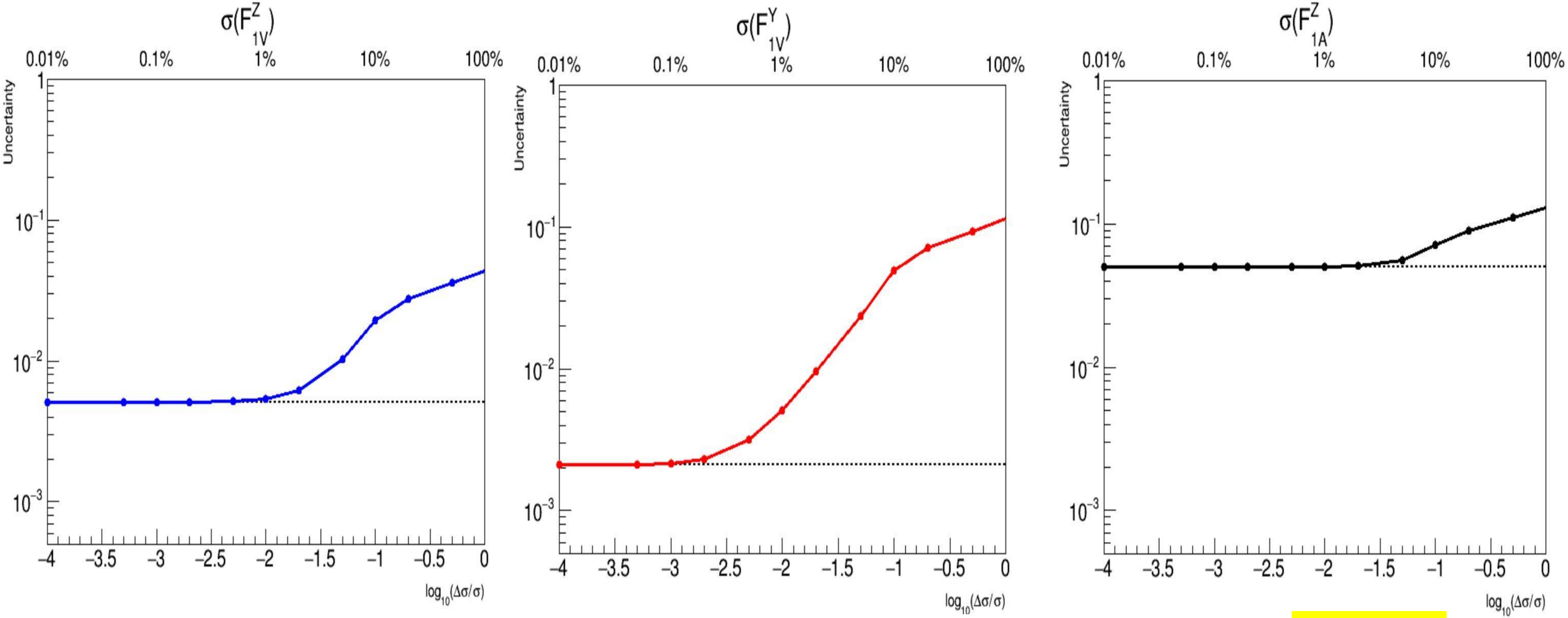
$$\mu_{ij} \to \mu_{ij} * (1 + \delta^{th})$$

- **Scanned the theory uncertainty σ_{th} (Δσ/σ): from 0.01% to 100%, by profiling a Gaussian nuisance parameter $\delta^{th} \sim$ N(0, $\sigma_{th}{}^2$).**

- **The fit is reapted 11 times, once per scan point, where δ^{th} is fitted alongside with the anomalous form factors.**

Theoretical uncertainty :

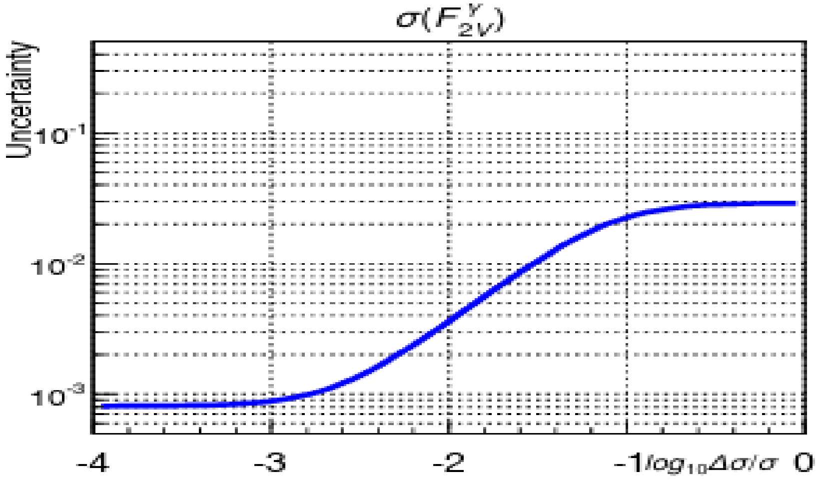
- *Simultaneous fit of the three parameters as a function of the theoretical uncertainty (first configuration):*

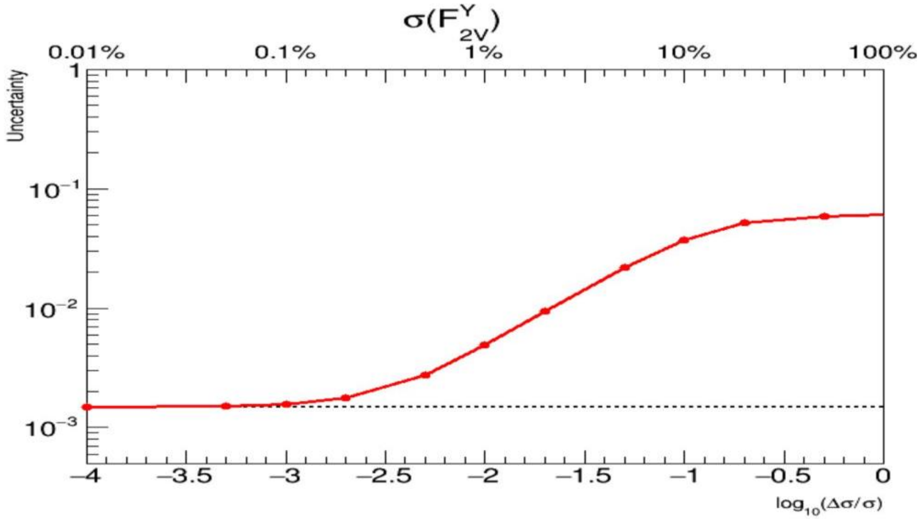


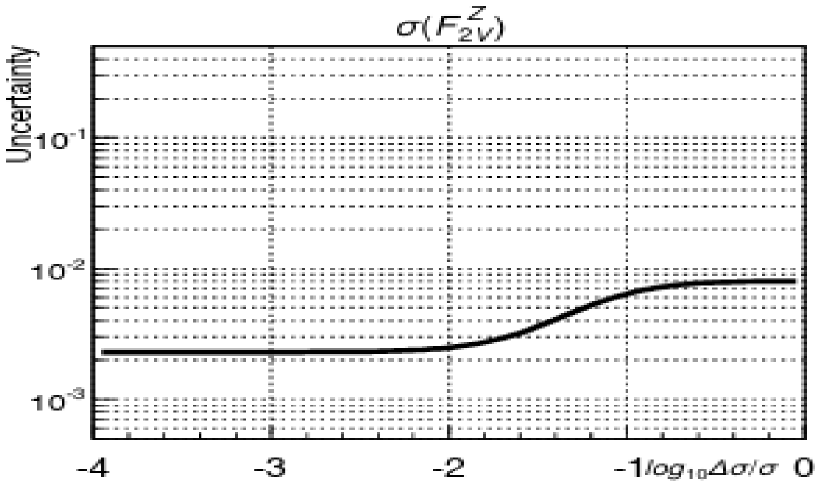
- The uncertainty on the form factors (except F^{Z}_{1A}) remains below a few per-mille if the cross section can be predicted with a precision of ~ 3%.

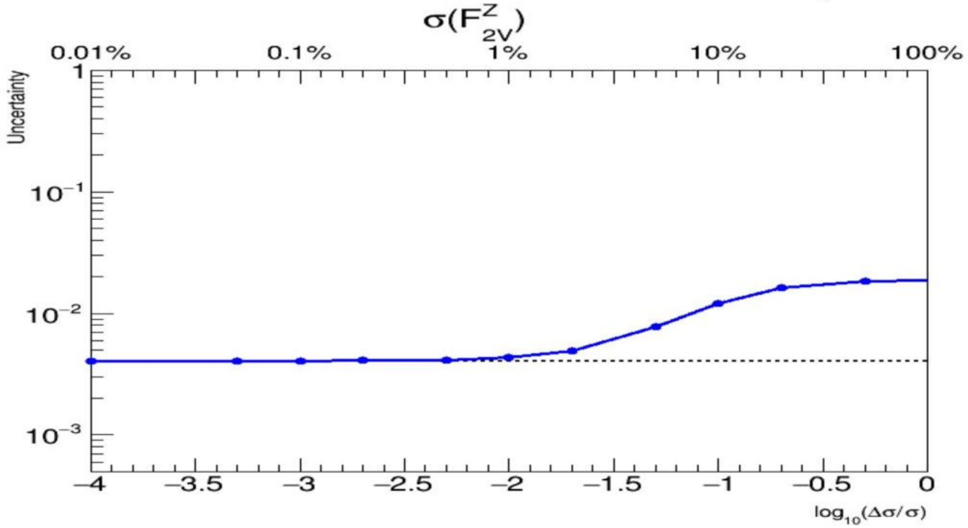
Theoretical uncertainty :

- <u>***A comparison of FCC-ee (left) and CEPC (right) expected uncertainties for the second configuration:***</u>









Other Uncertainties:

Compared to ILC:

- **Beamstrahlung effects & *Beam polarisation*:** CEPC is expected to be largely unaffected by beamstrahlung effects. The beamstrahlung parameter ε_{av}~ 4.5 at CEPC, while ILC@500GeV is expected to reach ε_{av}~ 620 (arXiv:1505.01270).

- ***Lepton energy resolution*** of *1GeV* and a lepton angular resolution of 20 mrad (theoretical assumptions) have no impact on the extarction of the form factors, CEPC provides much precise energy/angular resolutions than these assumptions! (arXiv:1811.10545).

$$\sigma(\frac{1}{p^T}) = \sqrt{(2\times 10^{-5})^2 + (\frac{10^{-3}}{P sin\theta^{\frac{3}{2}}})^2}$$

$$\sigma(E) \sim \frac{3\%}{\sqrt{E(GeV)}} < 1GeV$$

- ***Luminosity:*** known to per-mille level, safely neglected.

Operating at High Energies

- **The dependence of the expected statistical uncertainties on the center-of-mass energy was investigated by performing an energy scan:**

$\sqrt{s}$ [GeV]	β	$\sigma(\delta F_{1A}^{\gamma})$	$\sigma(\delta F_{1V}^{Z})$	$\sigma(\delta F_{1A}^{Z})$
355	0.2357	0.0019	0.0046	0.0643
360	0.2857	0.0018	0.0044	0.0437
365	0.3265	0.0017	0.0043	0.0325
380	0.4192	0.0018	0.0044	0.0206
400	0.5061	0.0019	0.0050	0.0153
450	0.6420	0.0024	0.0067	0.0115
480	0.6953	0.0026	0.0078	0.0108
500	0.7238	0.0028	0.0086	0.0105
700	0.8701	0.0038	0.0139	0.0093
900	0.9236	0.0042	0.0165	0.0089
1000	0.9386	0.0045	0.0177	0.0091

Increasing the center-of-mass energy does not improve the sensitivity for most of the form factors. The only exception is δF_1^Z.

The best centre-of-mass energy for top-quark EW coupling measurements is *360–365 GeV*.

Summary

- **CEPC demonstrate a strong potential for probing the top quark electroweak couplings, with projected sensitivities reaching the level of $O(10^{-3})$,$O(10^{-2})$.**

- **Operating at energies above 360 GeV does not significantly improve the expected sensitivity to the form factors.**

- **A key result from this analysis is that the top-quark coupling to neutral bosons, γ and Z can be extracted simultaneously, even in the absence of polarized beams, free of any systematic associated with beam polarization.**

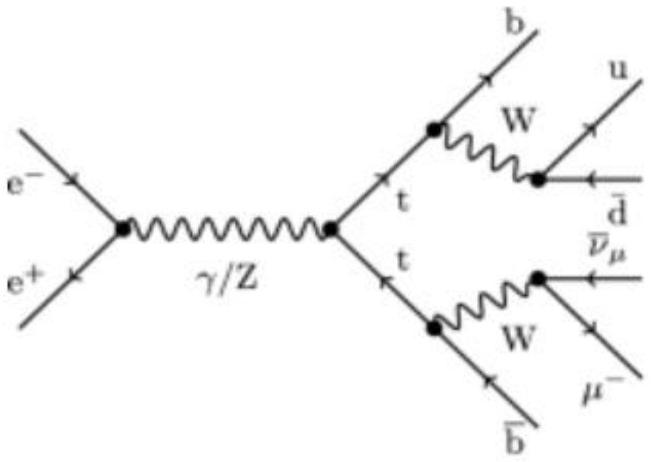
- **A draft paper has been prepared for this analysis.**

Backup slides

Semi-Leptonic channel

The are three differents channels for ttbar study :

- Semileptonic
- Dileptonic
- Hadronic

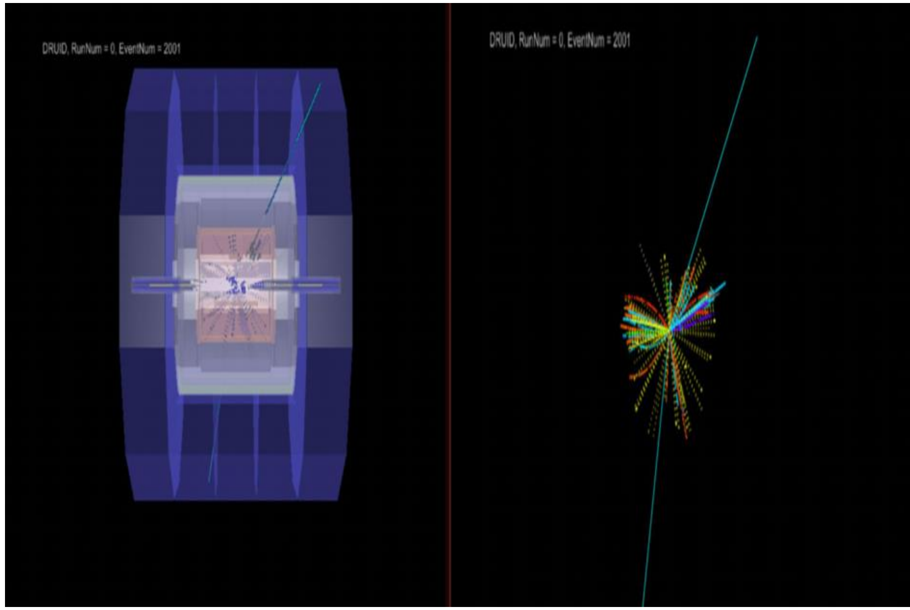


- For the **semi-leptonic channel :**

The samples are generated using MG5 and passed through Pythia8 for showering and hadronization.

- CEPC_v4 ($\sqrt{s}$ =360GeV, B-field = 3.0 T)
- Luminosity is 1.0ab-1.

- Generated Events are then passed through CEPC reco & sim.



- **There are two simulation methods for CEPC detector:**

  - Fast Simulation : uses Delphes to perform a fast multipurpose detector response simulation.

  - Full Simulation is a method using Geant4-based tools to simulate the particle transport and the detector response and then reconstruct the responses back to original signals.

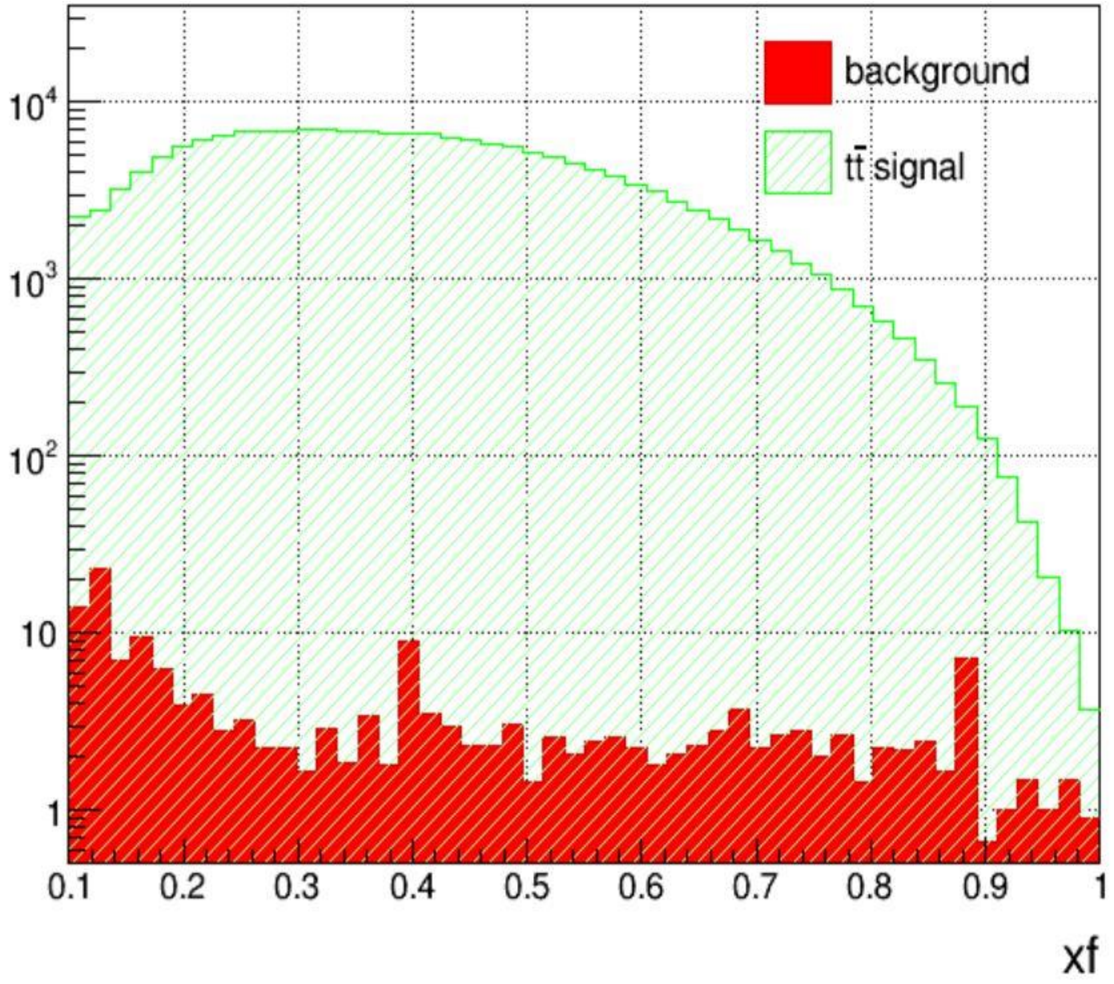
Event Selection

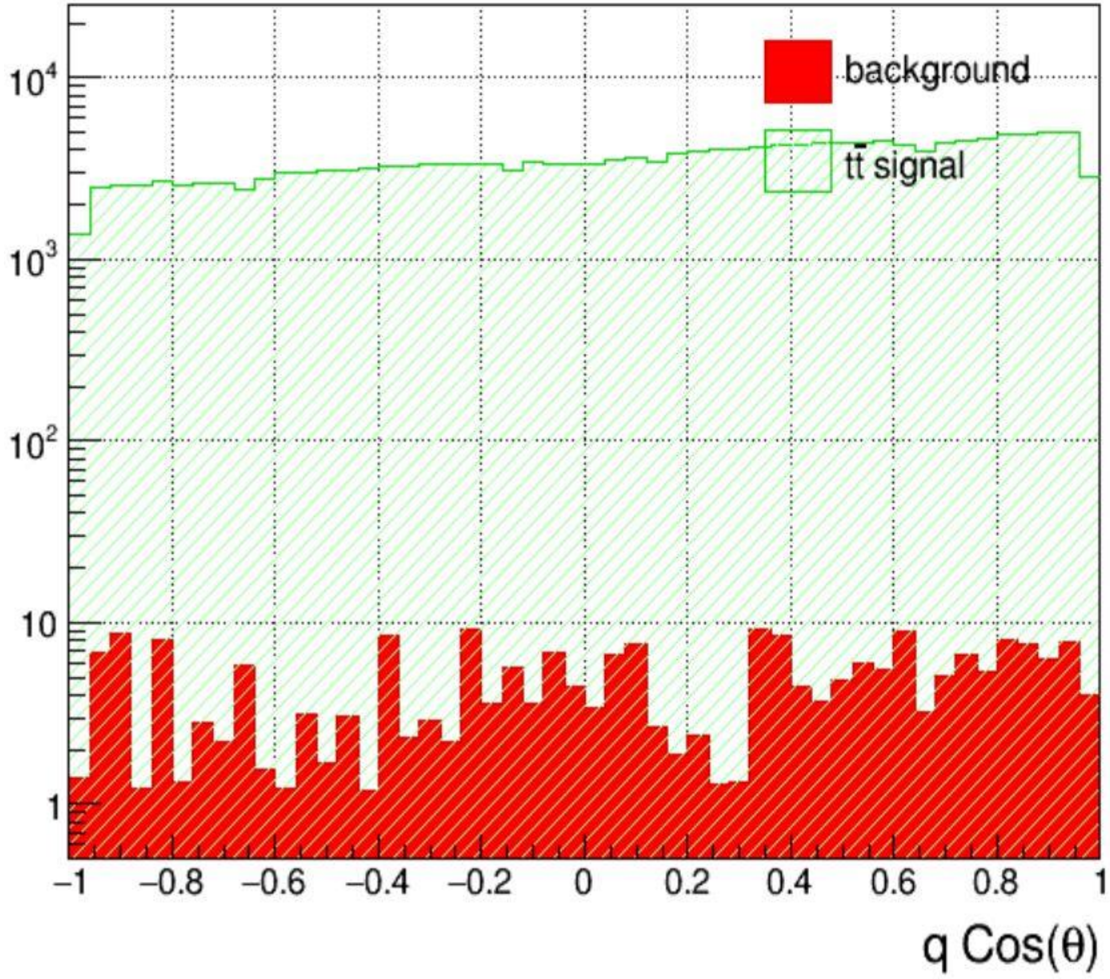
- Considering the $t\bar{t}$ semileptonic final-state channel, we require the following event selection:

Selection Criterion	Requirement
Final State	4-jets + single lepton
Thrust	< 0.83
Sphericity	> 0.35
Number of PFOs (n_{PFOs})	> 60
Maximum b-tagging score (max(b-tag))	> 0.85
Maximum particle momentum (P_{max})	< 50 GeV
Cone energy (E_{cone})	< 7 GeV
Lepton energy (E_{lep})	> 10 GeV

Reconstructed Observables

- The lepton energy and direction are the sensitive observables for probing the top-quark electroweak couplings.
- SM backgrounds are suppressed through a cut-based selection.





❑ The Explicit Formula describing the energy-dependent coefficients for the angular and energy distributions :

arxiv.org/pdf/hep-ph/9911505

$$
\begin{aligned}
\Theta_0^f(x) \;=\; & \Big[\frac{1}{2}(3-\beta^2)D_V - \frac{1}{2}(1-3\beta^2)D_A - (1+\beta^2)\mathrm{Re}(G_1) \\
& -\alpha^f\big[\,(1-\beta^2)\mathrm{Re}(D_{VA}) - \mathrm{Re}(F_1) + (2-\beta^2)\mathrm{Re}(G_3)\,\big]\Big]\, F^f(x) \\
& +\alpha^f \mathrm{Re}(2D_{VA} - F_1 - G_3)\, G^f(x) \\
& +\Big[\, D_V + D_A + 2\,\mathrm{Re}(G_1) + \alpha^f \mathrm{Re}(2D_{VA} - F_1 + 3G_3)\Big]\, H_1^f(x) \\
& -\frac{1}{2}\Big[\, D_V + D_A + 2\,\mathrm{Re}(G_1) + 2\alpha^f\, \mathrm{Re}(D_{VA} + G_3)\Big]\, H_2^f(x), \\
\Theta_1^f(x) \;=\; & 2\Big[\, 2\mathrm{Re}(E_{VA}) + \alpha^f\big[\,(1-\beta^2)E_A - \mathrm{Re}(F_4 - G_2)\,\big]\Big] F^f(x) \\
& +2\alpha^f \Big[\, E_V + E_A - \mathrm{Re}(F_4 - G_2)\Big]\, G^f(x) \\
& -2\Big[\, 2\mathrm{Re}(E_{VA}) + \alpha^f\big[\, E_V + E_A - \mathrm{Re}(F_4 - G_2)\,\big]\Big]\, H_1^f(x), \\
\Theta_2^f(x) \;=\; & \Big[\frac{1}{2}(3-\beta^2)(D_V + D_A) + (3-\beta^2)\mathrm{Re}(G_1) \\
& +3\alpha^f\big[\,(1-\beta^2)\mathrm{Re}(D_{VA}) - \mathrm{Re}(F_1) + (2-\beta^2)\mathrm{Re}(G_3)\,\big]\Big]\, F^f(x) \\
& +\alpha^f \mathrm{Re}(2D_{VA} - F_1 + 3G_3)\, G^f(x) \\
& -3\Big[\, D_V + D_A + 2\,\mathrm{Re}(G_1) + \alpha^f \mathrm{Re}(2D_{VA} - F_1 + 3G_3)\Big]\, H_1^f(x) \\
& +\frac{3}{2}\Big[\, D_V + D_A + 2\,\mathrm{Re}(G_1) + 2\alpha^f\, \mathrm{Re}(D_{VA} + G_3)\Big]\, H_2^f(x),
\end{aligned}
$$

arxiv.org/pdf/hep-ph/9710358

$$
\begin{aligned}
D_V \equiv\; & C\big[A_\gamma^2 - 2A_\gamma A_Z v_e d' + A_Z^2(1+v_e^2)d'^2 + 2(A_\gamma - A_Z v_e d')\mathrm{Re}(\delta A_\gamma) \\
& -2\{A_\gamma v_e d' - A_Z(1+v_e^2)d'^2\}\mathrm{Re}(\delta A_Z)\big], \\
D_A \equiv\; & C\big[B_Z^2(1+v_e^2)d'^2 - 2B_Z v_e d' \mathrm{Re}(\delta B_\gamma) + 2B_Z(1+v_e^2)d'^2\mathrm{Re}(\delta B_Z)\big], \\
D_{VA} \equiv\; & C\big[-A_\gamma B_Z v_e d' + A_Z B_Z(1+v_e^2)d'^2 - B_Z v_e d'(\delta A_\gamma)^* \\
& +(A_\gamma - v_e d' A_Z)\delta B_\gamma + B_Z(1+v_e^2)d'^2(\delta A_Z)^* \\
& -\{A_\gamma v_e d' - A_Z(1+v_e^2)d'^2\}\delta B_Z\big], \\
E_V \equiv\; & 2C\big[A_\gamma A_Z d' - A_Z^2 v_e d'^2 + A_Z d' \mathrm{Re}(\delta A_\gamma) + (A_\gamma d' - 2A_Z v_e d'^2)\mathrm{Re}(\delta A_Z)\big], \\
E_A \equiv\; & 2C\big[-B_Z^2 v_e d'^2 + B_Z d' \mathrm{Re}(\delta B_\gamma) - 2B_Z v_e d'^2 \mathrm{Re}(\delta B_Z)\big], \\
E_{VA} \equiv\; & C\big[A_\gamma B_Z d' - 2A_Z B_Z v_e d'^2 + B_Z d'(\delta A_\gamma)^* + A_Z d' \delta B_\gamma \\
& -2B_Z v_e d'^2(\delta A_Z)^* + (A_\gamma d' - 2A_Z v_e d'^2)\delta B_Z\big], \\
F_1 \equiv\; & C\big[-(A_\gamma - A_Z v_e d')\delta D_\gamma + \{A_\gamma v_e d' - A_Z(1+v_e^2)d'^2\}\delta D_Z\big], \\
F_2 \equiv\; & C\big[-A_Z d' \delta D_\gamma - (A_\gamma d' - 2A_Z v_e d'^2)\delta D_Z\big], \\
F_3 \equiv\; & C\big[B_Z v_e d' \delta D_\gamma - B_Z(1+v_e^2)d'^2 \delta D_Z\big], \\
F_4 \equiv\; & C\big[-B_Z d' \delta D_\gamma + 2B_Z v_e d'^2 \delta D_Z\big], \\
G_1 \equiv\; & C\big[(A_\gamma - A_Z v_e d')\delta C_\gamma - \{A_\gamma v_e d' - A_Z(1+v_e^2)d'^2\}\delta C_Z\big], \\
G_2 \equiv\; & C\big[A_Z d' \delta C_\gamma + (A_\gamma d' - 2A_Z v_e d'^2)\delta C_Z\big], \\
G_3 \equiv\; & C\big[-B_Z v_e d' \delta C_\gamma + B_Z(1+v_e^2)d'^2 \delta C_Z\big], \\
G_4 \equiv\; & C\big[B_Z d' \delta C_\gamma - 2B_Z v_e d'^2 \delta C_Z\big],
\end{aligned}
$$

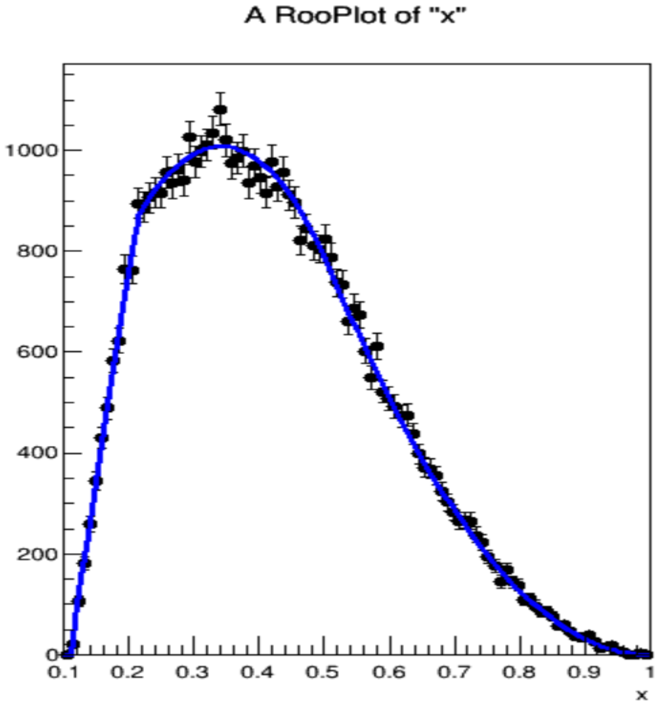
❑ ***Dv, DA, DVA, EV, EVA, Fi, Gi {i=1,2,3,4} , which are related to the Form factors in ttZ/γ Couplings !***

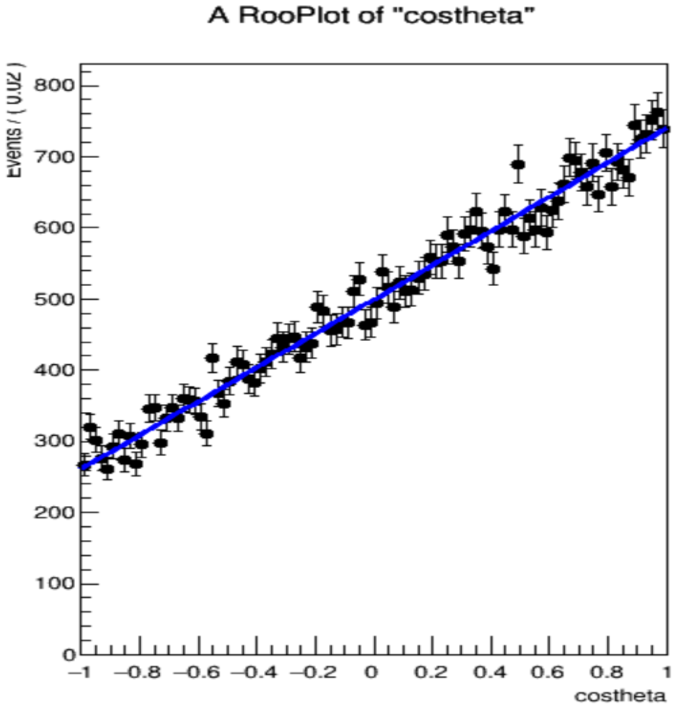
SM Contribution

- **The Standard Model contribution is given by the following term with a normalisation factor:**

$$S_f^{(0,*)}(x_f,\theta_f) = \Theta_0^{f(0,*)}(x_f) + \cos\theta_f \Theta_1^{f(0,*)}(x_f) + \cos^2\theta_f \Theta_2^{f(0,*)}(x_f)$$

- **Shape of the scaled Lepton energy and Polar Angle by fitting the data:**

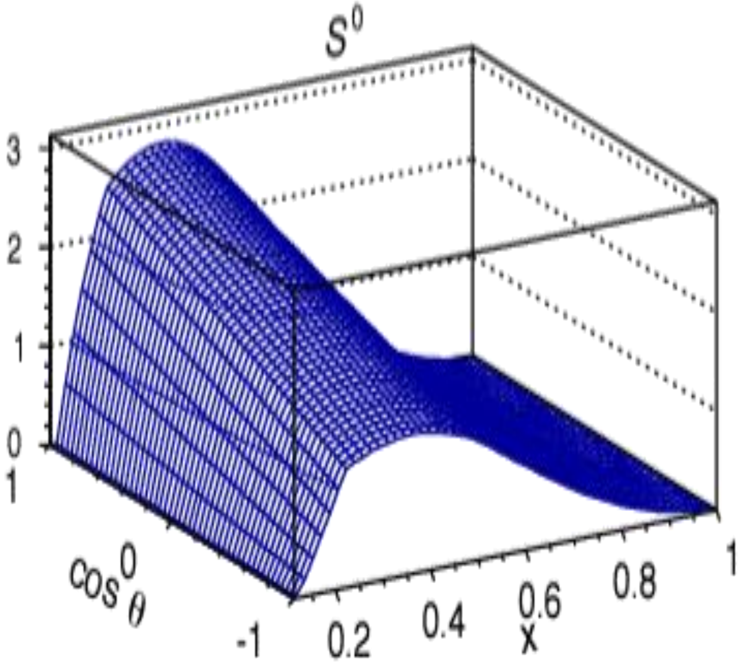




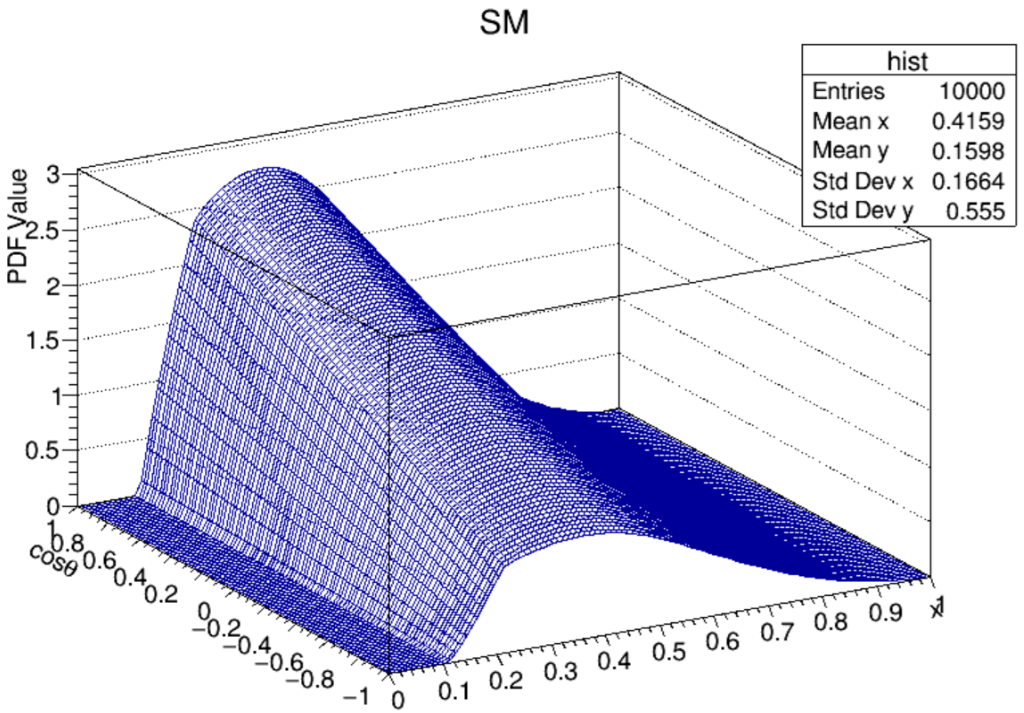
SM Contribution

- **The Standard Model contribution was fitted using RooFit :**

FCC@365 GeV



CEPC@360 GeV

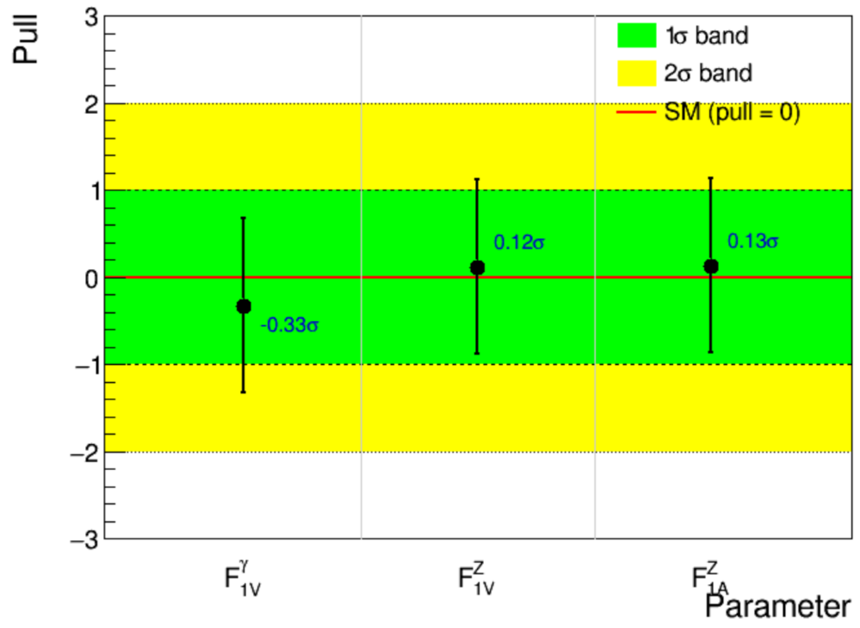


- **The obtained SM shape is similar to what was obtained for FCC-ee at 365 GeV Validating the Procedure.**

Result: First Configuration

- The obtained uncertainties of the floating form factors :
- Compared to FCC-ee Results :
- Considering a simultaneous fit of the form factors (First Sector):

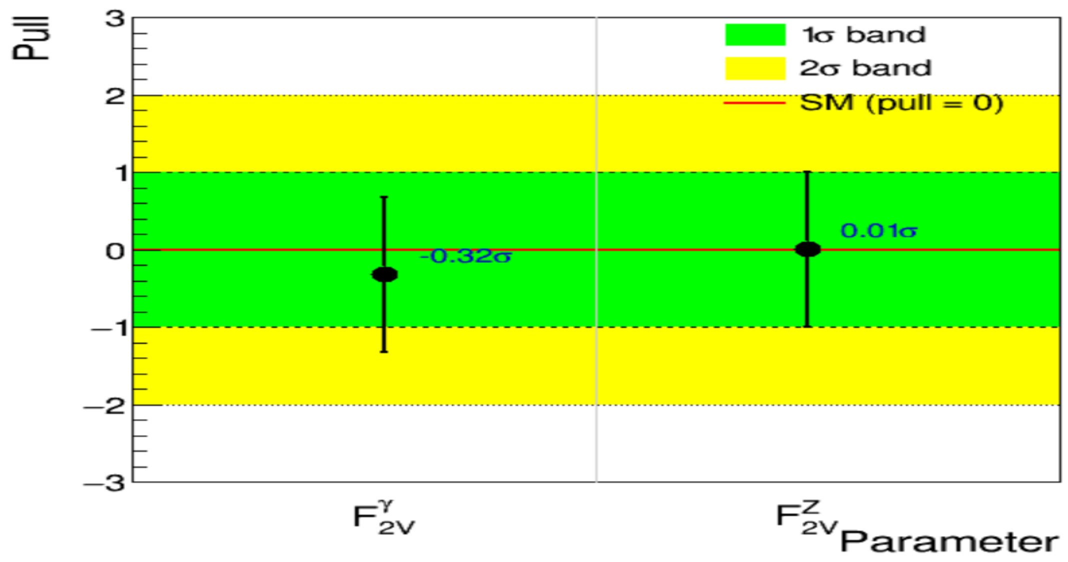
Precision on	F_{1V}^{γ}	F_{1V}^{Z}	F_{1A}^{γ}	F_{1A}^{Z}
FCC-ee $(2.4\,\text{ab}^{-1}, \sqrt{s} = 365\,\text{GeV})$	1.2×10^{-3}	2.9×10^{-3}	0.0×10^{-2}	2.2×10^{-2}
CEPC $(1.0\,\text{ab}^{-1}, \sqrt{s} = 360\,\text{GeV})$	1.80×10^{-3}	4.38×10^{-3}	0.0	4.28×10^{-2}



Result: Second Configuration

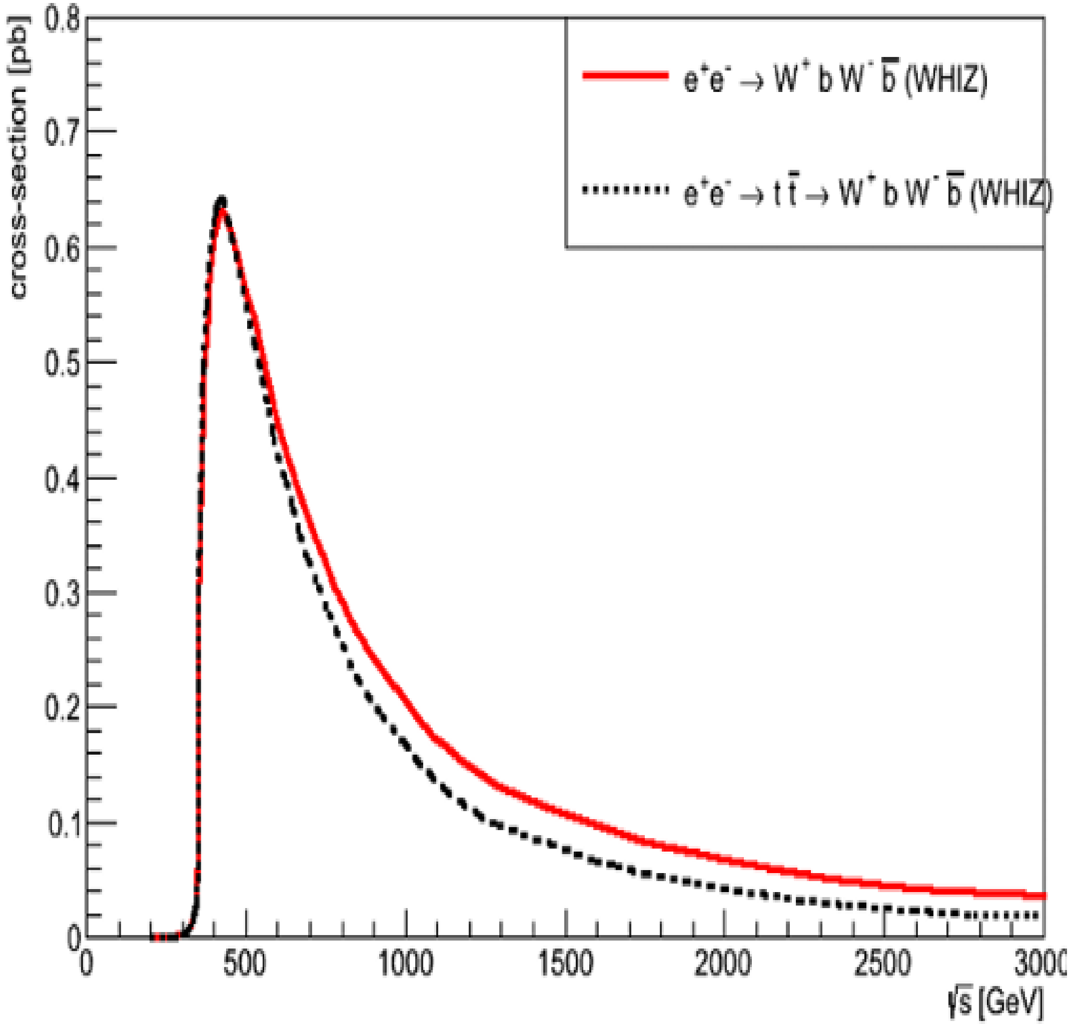
- The obtained uncertainties of the floating form factors :
- Compared to FCC-ee Results :
- Considering a simultaneous fit of the form factors (Second Sector):

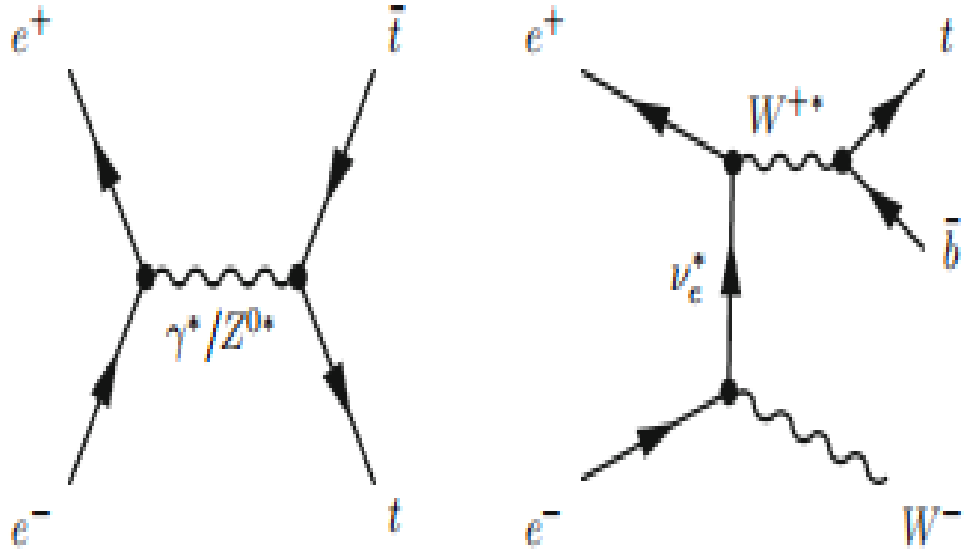
Precision on	F_{2V}^{γ}	F_{2V}^{Z}
FCC-ee ($2.4\,\mathrm{ab}^{-1}$, $\sqrt{s} = 365\,\mathrm{GeV}$)	8.1×10^{-4}	2.3×10^{-3}
CEPC ($1.0\,\mathrm{ab}^{-1}$, $\sqrt{s} = 360\,\mathrm{GeV}$)	1.33×10^{-3}	3.64×10^{-3}



❖ **The fit converges and the Hessian matrix was successfully computed.**

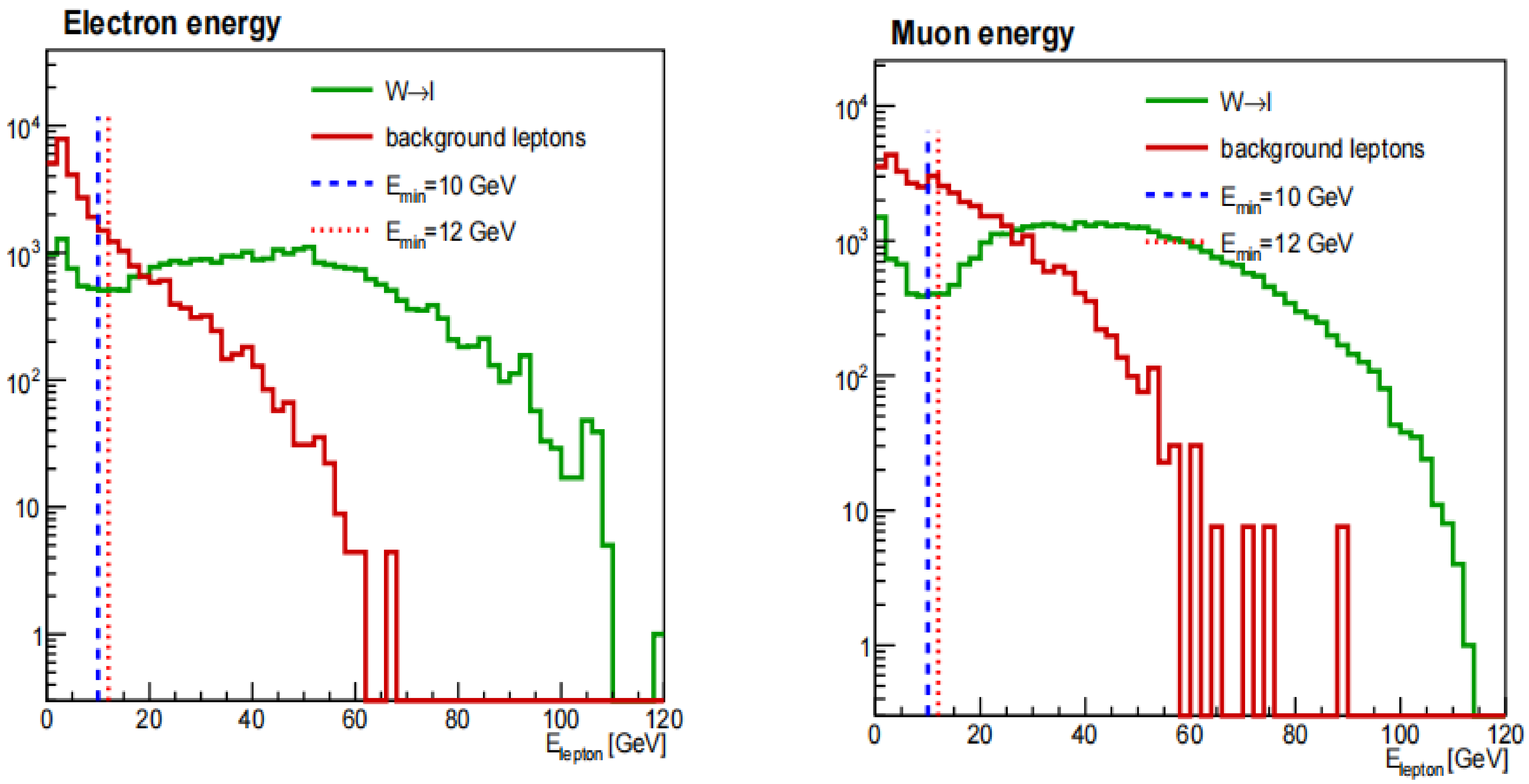
Single top Background





- **<u>Single-top is indistinguishable from top-pair production at centre-of-mass energies below 500 GeV.</u>**

Lepton Isolation



Jet-Tagging

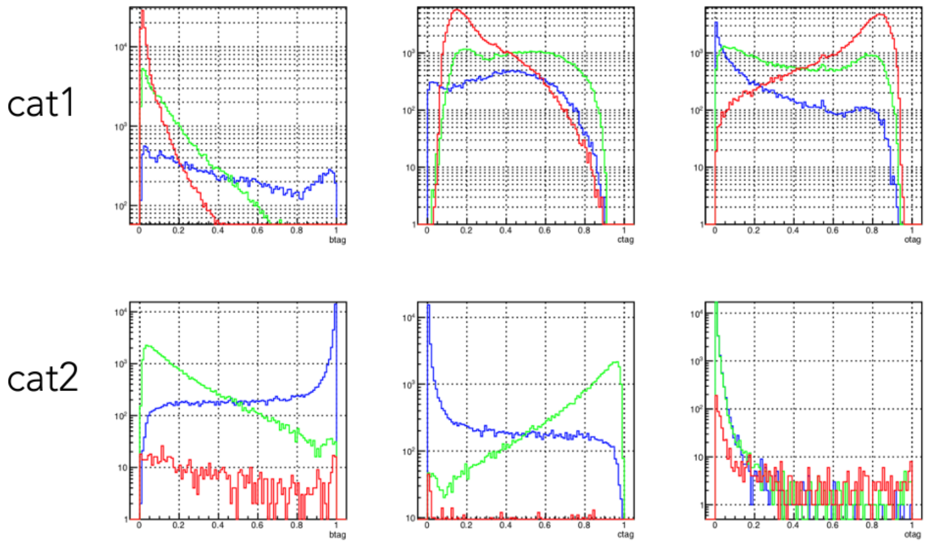
LCFIplus :

- Use of BDT for multi-class classification
- 3 classes: b, c, o(uds, g assumed as same as uds)
- 4 categories: #vtx = 0, 1, 1+single, 2
- 20-30 variables for each category

- 2 independent outputs: b-likeliness, c-likeliness

btag+ctag+otag=1: 2 outputs

Output b, c, and o likeliness



❑ Receiver Operating Characteristic Curve (ROC):

❖ 80% b-tagging eff : Reject 90% c and 99% o jets
❖ 80% c-tagging eff. : Reject 75% b and 75% o jets