Top physics at the FCC-ee

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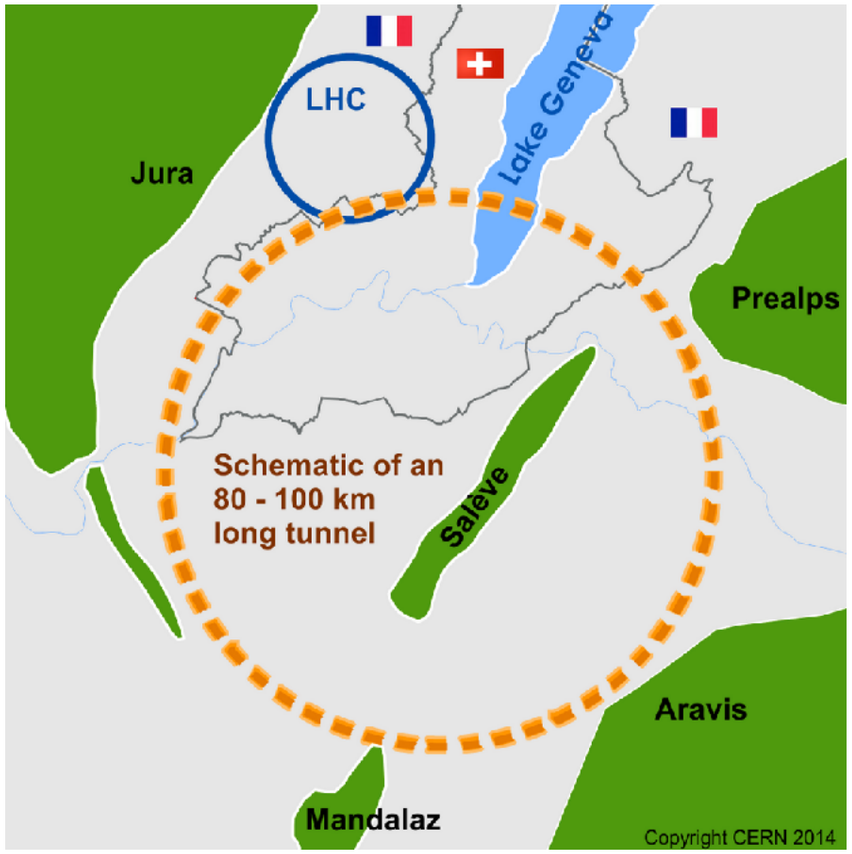
1st FCC France workshop

Virtually @ LPNHE, 15 May 2020

Outline

✦ A future electron-positron circular collider at CERN

- ✤ A new 80/100 km tunnel in the Geneva area
- ✤ Precision measurements
  - ★ Study of Z, W, Higgs and top properties
  - ★ $\sqrt{s}$ energies: 91.2, 161, 240, 340 – 350/365 GeV
- ✤ SM top physics
  - ★ 1.5 ab^{-1} @ 365 GeV → 1 million $t\bar{t}$ pairs
  - ★ 200 fb^{-1} @ 340 – 350 GeV ($t\bar{t}$ threshold scan)
- ✤ BSM
  - ★ Indirect and direct probes at all $\sqrt{s}$
  - ★ 5 ab^{-1} @ 240 GeV (single top)



Top pair production close to threshold (I)

✦ The top quark mass @ ee colliders

- ✤ Threshold position → m_t
- ✤ The slope of the rise → Γ_t
- ✤ Extra dependence on y_t (and α_s)

Threshold scan: access to these parameters

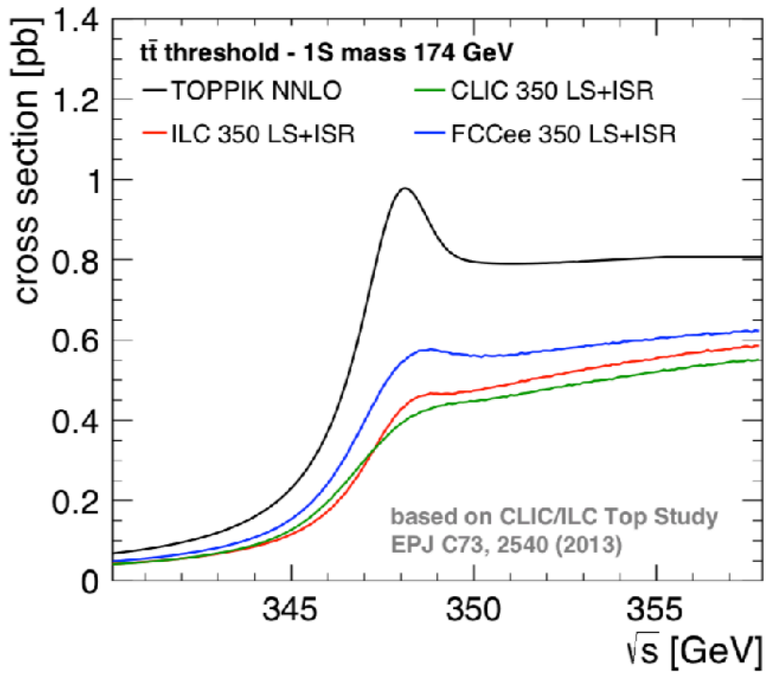
✦ The cross section dependence

- ✤ $\sqrt{s} \approx 342.5$ GeV: independent of Γ_t
- ✤ $\sqrt{s} \approx 344$ GeV: maximally sensitive to Γ_t

Relevance of a multipoint scan

[Simon (2019)]

[Vos *et al.* (2016)]



Top pair production close to threshold (2)

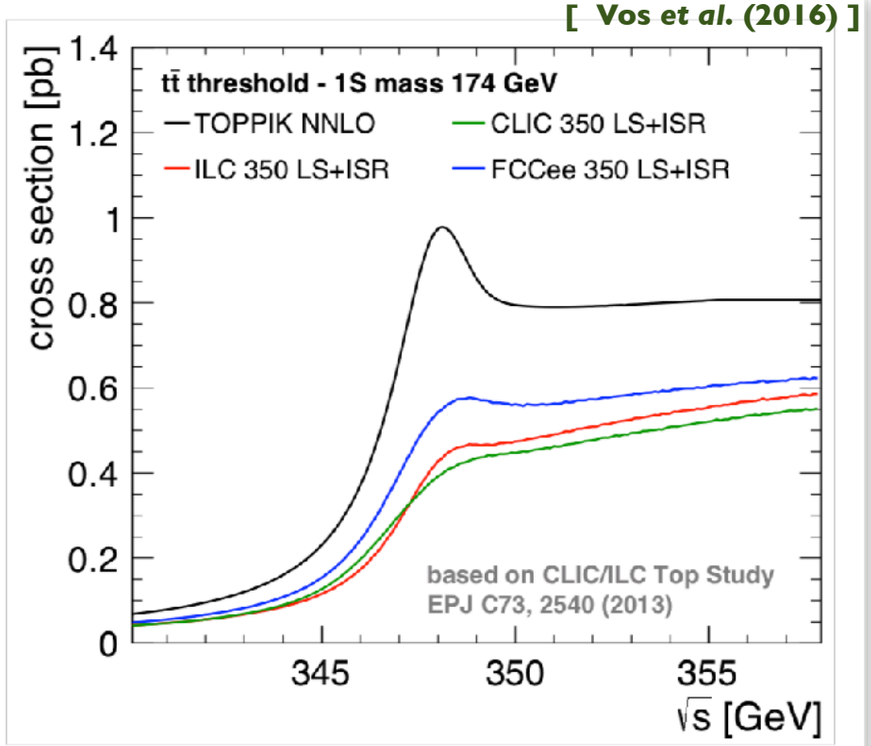
✦Need for precision predictions

$$\sigma_{t\bar{t}} = \sigma_0 \sum_n \left[\frac{\alpha_s}{v}\right]^n \sum_j \left[\alpha_s \log v\right]^j \left(\mathrm{LL} + \mathrm{NLL}(\alpha_s, v) + \mathrm{N^2LL}(\alpha_s^2, \alpha_s v, v^2) + \dots\right)$$

✦Theory calculations

- ✤ Higgs-boson exchange
- ✤ Bound state effects large
- ✤ N³LO corrections in NRQCD [Beneke *et al.* (PRL`15)]
- ✤ N²LL (velocity logs)
  - ★ Threshold: $\alpha_s \approx v \approx 0.1$ [Hoang & Stahlhofen (JHEP`14)]
- ✤ Matching with the *WbWb* continuum [Bach *et al.* (JHEP`18)]

[Vos *et al.* (2016)]

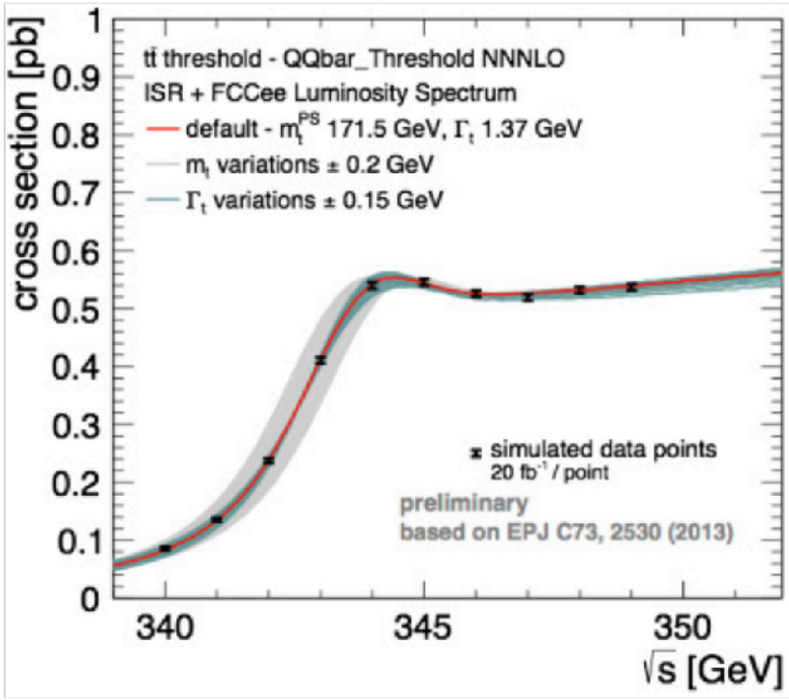


✦More realistic predictions

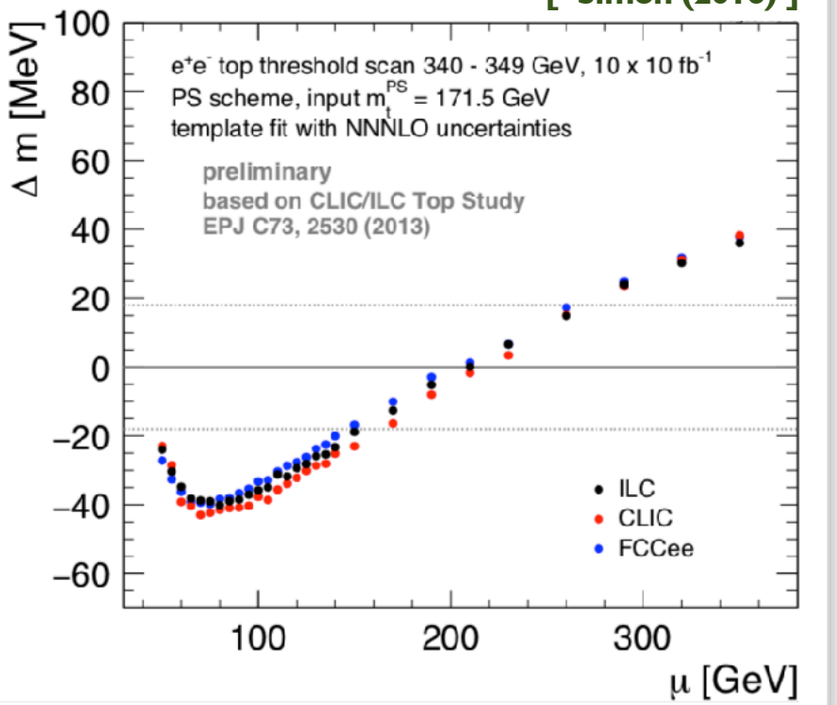
- ✤ ISR profile to include
- ✤ Broadening of the peak
- ✤ Taming of the tail

Top pair production close to threshold (3)

[Abada *et al.* (EPJST`19)]



[Simon (2016)]



✦ Multipoint scan: 8 x 25 fb^{-1} for $\sqrt{s}$ in [340, 350] GeV

- ✤ Stat.: 17 MeV on m_t
- ✤ Stat.: 45 MeV on Γ_t
- ✤ Systematics of 50 MeV
  - ★ Beam energy, luminosity spectrum, *etc.*
  - ★ Theory (scales, non-res.)
  - ★ α_s negligible from other FCC runs

✦ Top Yukawa coupling

- ✤ 9% effect on the cross section [Horiguchi *et al.* (2013)]
- ✤ Multidimensional fit → 10%-level [Beneke *et al.* (NPB`15); Simon (2019)]

Anomalous top gauge couplings (I)

✦ Generic parameterisation of the top electroweak couplings

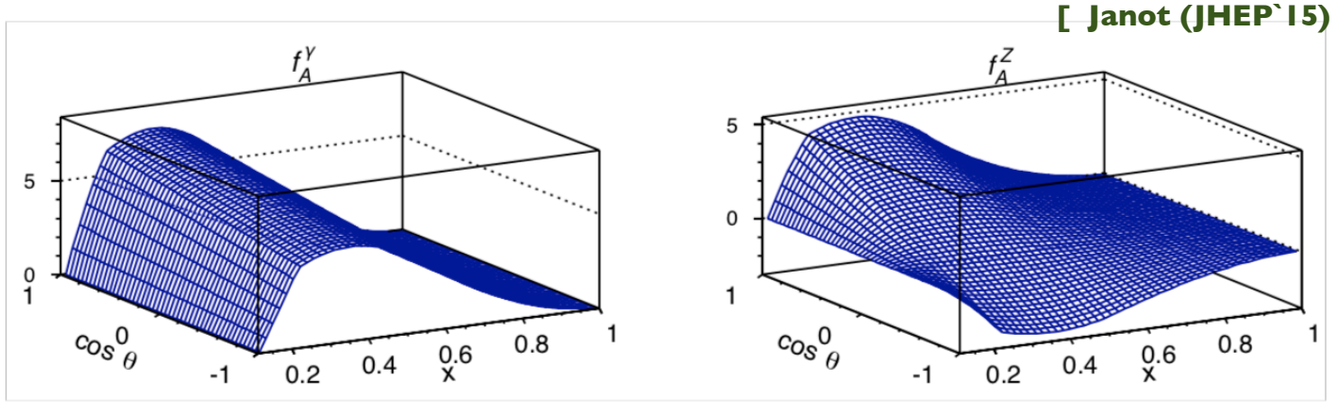
$$\mathcal{L} = ie\,\bar{t}\gamma^{\mu}\Big[F_{1L}^{V}P_L + F_{1R}^{V}P_R\Big]tV_{\mu} - \frac{1}{2\Lambda}\bar{t}\sigma^{\mu\nu}\Big[F_{2L}^{V}P_L + F_{2R}^{V}P_R\Big]tV_{\mu\nu}$$
$$+ i\frac{g}{\sqrt{2}}\,\bar{b}\gamma^{\mu}\Big[F_{1L}^{W}P_L + F_{1R}^{W}P_R\Big]tW_{\mu} - \frac{1}{2\Lambda}\bar{b}\sigma^{\mu\nu}\Big[F_{2L}^{W}P_L + F_{2R}^{W}P_R\Big]tW_{\mu\nu} + \text{h.c.}$$

- ✤ Top quark polarisation (as transferred into the decay products)
  - → Distribution measurements (FB asymmetries, *etc.*)
- ✤ Correlations in 2D distributions

✦ Example: neutral currents

- ✤ Lepton angular and energy spectra in semi-leptonic top-antitop systems

[Janot (JHEP`15)]



→ 2D dependence on x, θ

Anomalous top gauge couplings (2)

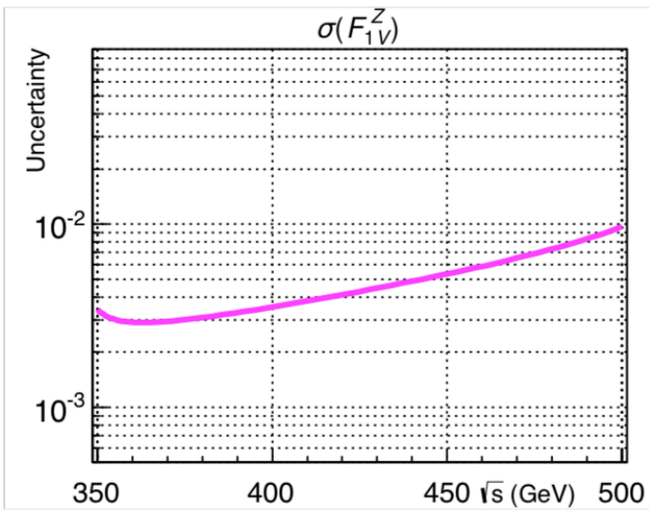
Example: neutral currents

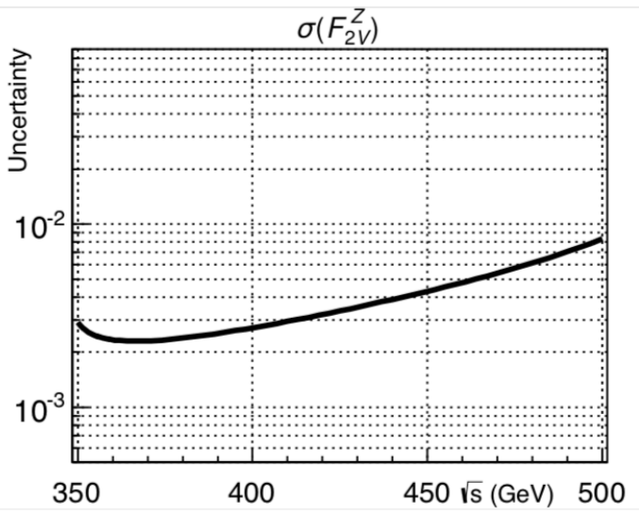
- $e^+e^- \to t\bar{t} \to \ell\nu b\bar{b}q\bar{q}$
- Lepton angular and energy spectra
- Percent/sub-percent level precision
- Large improvement wrt LHC

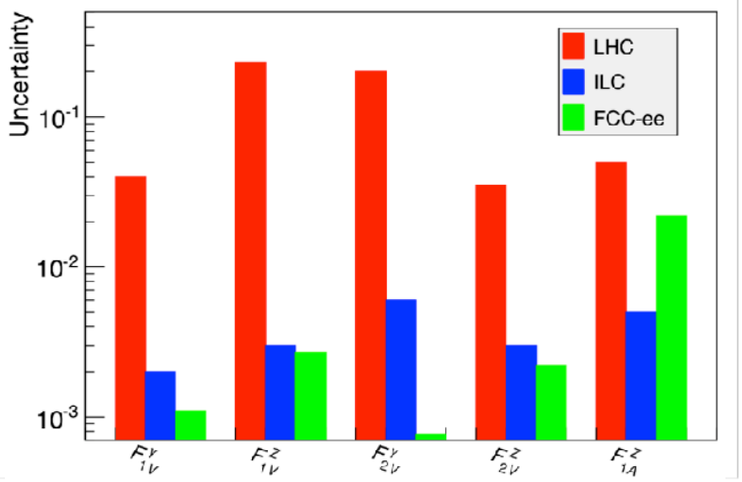
Optimal precision at 365 GeV

- For most couplings
- Improvements: other observables

[Janot (JHEP`15)]







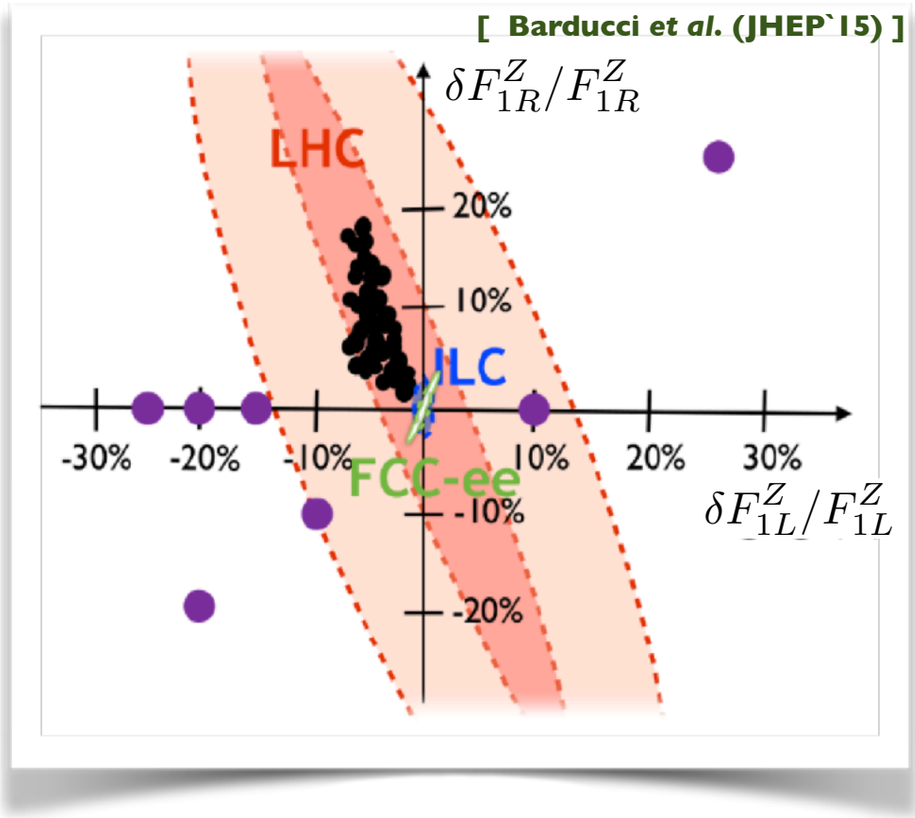
Top couplings as handles on new physics

BSM: deviations in the top neutral EW couplings

- At tree or loop level, via mixings
- Example:
  - ★ Compositeness (black)
  - ★ Extra dimensions (purple)

$$\mathcal{L} = ie\,\bar{t}\gamma^{\mu}\left[F_{1L}^{V}P_L + F_{1R}^{V}P_R\right]tV_{\mu}$$

[Barducci *et al.* (JHEP`15)]



Constraints on the allowed deviations

- LHC sensitivity: flat directions
- FCC-ee: disentangling BSM and SM

Strong constraints on a lot of models

The EFT paradigm

✦ Improvement on the anomalous coupling descriptions: EFT operators

- ✤ Gauge invariant (W, Z and γ are not independent)
- ✤ Can be matched to any heavy new physics model

$$
\begin{array}{llll}
O^1_{\varphi q} \equiv \frac{y_t^2}{2} & \bar{q}\gamma^\mu q & \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi & O_{uG} \equiv y_t g_s \quad \bar{q}T^A\sigma^{\mu\nu}u \quad \epsilon\varphi^* G^A_{\mu\nu} \\
O^3_{\varphi q} \equiv \frac{y_t^2}{2} & \bar{q}\tau^I\gamma^\mu q & \varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi & O_{uW} \equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu}u \quad \epsilon\varphi^* W^I_{\mu\nu} \\
O_{\varphi u} \equiv \frac{y_t^2}{2} & \bar{u}\gamma^\mu u & \varphi^\dagger i\overleftrightarrow{D}_\mu \varphi & O_{dW} \equiv y_t g_W \quad \bar{q}\tau^I\sigma^{\mu\nu}d \quad \epsilon\varphi^* W^I_{\mu\nu} \\
O_{\varphi ud} \equiv \frac{y_t^2}{2} & \bar{u}\gamma^\mu d & \varphi^T\epsilon\, iD_\mu \varphi & O_{uB} \equiv y_t g_Y \quad \bar{q}\sigma^{\mu\nu}u \quad \epsilon\varphi^* B_{\mu\nu}
\end{array}
$$

Gauge interaction modifiers

✦ Four-fermion operator relevant (after decays)

$$
\begin{array}{llll}
O^1_{lq} \equiv \frac{1}{2} & \bar{q}\gamma_\mu q & \bar{l}\gamma^\mu l & \\
O^3_{lq} \equiv \frac{1}{2} & \bar{q}\tau^I\gamma_\mu q & \bar{l}\tau^I\gamma^\mu l & \\
O_{lu} \equiv \frac{1}{2} & \bar{u}\gamma_\mu u & \bar{l}\gamma^\mu l & O^T_{lequ} \equiv \bar{q}\sigma^{\mu\nu}u\ \epsilon\ \bar{l}\sigma_{\mu\nu}e \quad O^S_{lequ} \equiv \bar{q}u\ \epsilon\ \bar{l}e \\
O_{eq} \equiv \frac{1}{2} & \bar{q}\gamma_\mu q & \bar{e}\gamma^\mu e & O_{ledq} \equiv \bar{d}q\ \ \bar{l}e \\
O_{eu} \equiv \frac{1}{2} & \bar{u}\gamma_\mu u & \bar{e}\gamma^\mu e &
\end{array}
$$

✦ 10 relevant combinations for top physics at 365 GeV

$$
\begin{array}{lllll}
C^A_{lq}, & C^A_{eq}, & C^A_{\varphi q}, & C^R_{uZ}, & C^R_{uA}, \\
C^V_{lq}, & C^V_{eq}, & C^V_{\varphi q}, & C^I_{uZ}, & C^I_{uA}.
\end{array}
$$

✤ 8 CP-even + 2 CP-odd

The SMEFT @ lepton colliders

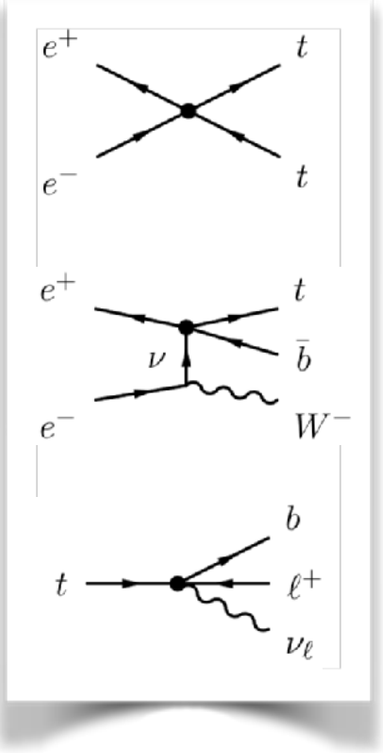
✦ A global approach to constrain top-induced new physics

- ✤ Top pair production modifications
- ✤ Single top processes
- ✤ New top decay modes

$$|\mathcal{M}|^2 = |\mathcal{M}_{\rm SM}|^2 \left(1 + \alpha \frac{CE^2}{\Lambda^2} + \beta \left[\frac{CE^2}{\Lambda^2} \right]^2 + \dots \right)$$

dim6; small

dim8; smaller (neglected)



✦ Allows for a global approach

- ✤ Percent-level measurements to combine as percent-level constraints
- ✤ Suppressions (and thus reduced sensitivities) possible → dim 8 terms

Example of observables

✦ Inclusion of various observables

[Durieux *et al.* (JHEP`18)]

✤ Top-antitop production: combining total rates and A_{FB}

$$A_{\mathrm{FB}} = \frac{1}{\sigma}\int_{-1}^{+1} \mathrm{d}c_\theta \frac{\mathrm{d}\sigma}{\mathrm{d}c_\theta}$$

θ: angle between the positron and the top quark momentum in the CMS frame

✤ Top polarisation (transferred to the decay product *i*)

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}c_{\theta_i}} = \frac{1}{2}\left[1 + \alpha_i P c_{\theta_i}\right]$$

P not independent of A_{FB} in the presence of EFT operators

★ Normal and transverse polarisations (to the *t*/*e* plane)

✤ W-boson helicity fractions (and top width)

$$\frac{1}{\Gamma}\frac{\mathrm{d}\Gamma}{\mathrm{d}c_{\theta_\ell}} = \frac{3}{8}F_+\left[1 + c_{\theta_\ell}\right]^2 + \frac{3}{4}F_0 s^2_{\theta_\ell} + \frac{3}{8}F_+\left[1 - c_{\theta_\ell}\right]^2$$

θ: angle between the lepton in the W-frame and the W in the top-frame

✤ Single top production (*Wtb* modifiers)

✤ Bottom production

✤ Statistically optimal observables

★ Maximal exploitation of the differential rates

★ Ratio of the EFT to the SM predictions

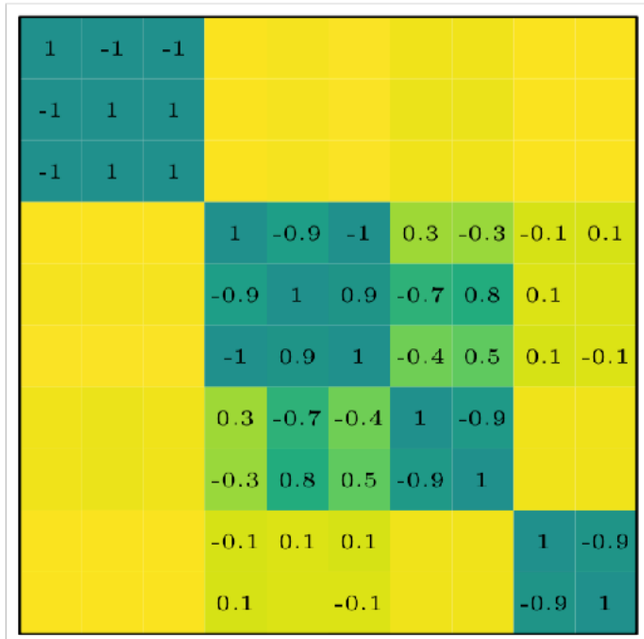
$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\mathrm{SM}} + \sum_i \mathrm{d}\sigma_i C_i \rightarrow \mathrm{d}\mathcal{O}_i \propto \frac{\mathrm{d}\sigma_i}{\mathrm{d}\sigma_{\mathrm{SM}}}\,\mathrm{d}\sigma$$

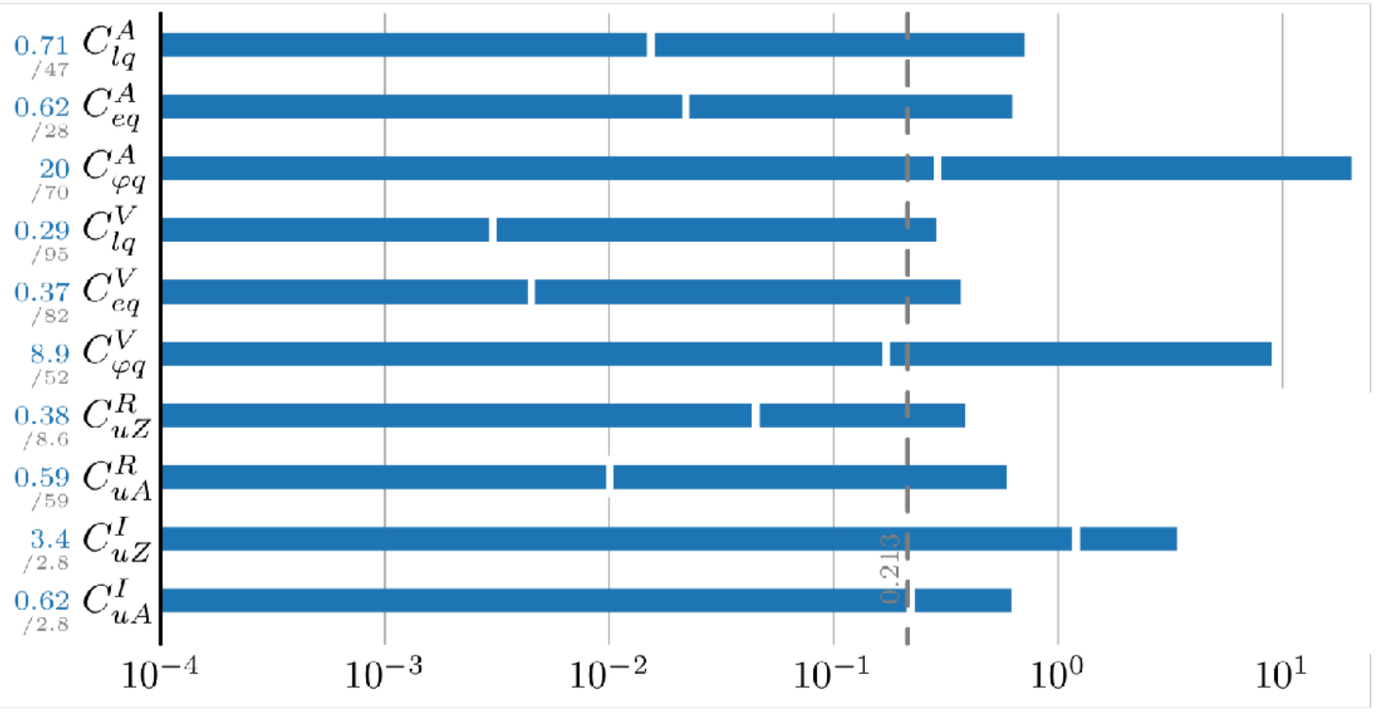
$$S_j^{\mathcal{O}_i} \Rightarrow \frac{1}{\sigma_i}\int \frac{\mathrm{d}\sigma_i \mathrm{d}\sigma_j}{\mathrm{d}\sigma_{\mathrm{SM}}}$$

A global approach for the top properties

✦ Statistically optimal observables only

[Durieux *et al.* (JHEP`18)]





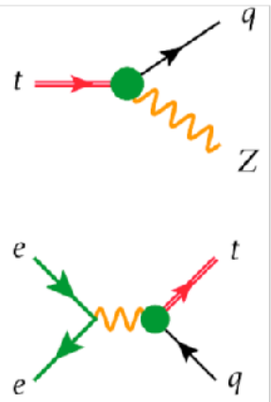
✦ Correlations

- ✤ Many operators lead to identical Lorentz structures
- ✤ White vertical lines: *one operator at a time* paradigm

Top FCNCs

✦Anomalous couplings

$$\mathcal{L} = \sum_{q=u,c} \Bigg[\sqrt{2} g_s \frac{\kappa_{gqt}}{\Lambda} \, \bar{t} \sigma^{\mu\nu} T_a (f_q^L P_L + f_q^R P_R) q \; G^a_{\mu\nu} + \frac{g}{\sqrt{2} c_W} \frac{\kappa_{zqt}}{\Lambda} \, \bar{t} \sigma^{\mu\nu} (\hat{f}_q^L P_L + \hat{f}_q^R P_R) q \; Z_{\mu\nu} + \frac{g}{4 c_W} \frac{\zeta_{zqt}}{\Lambda} \, \bar{t} \gamma^{\mu} (\tilde{f}_q^L P_L + \tilde{f}_q^R P_R) q \; Z_{\mu} \Bigg] + \text{h.c.}$$

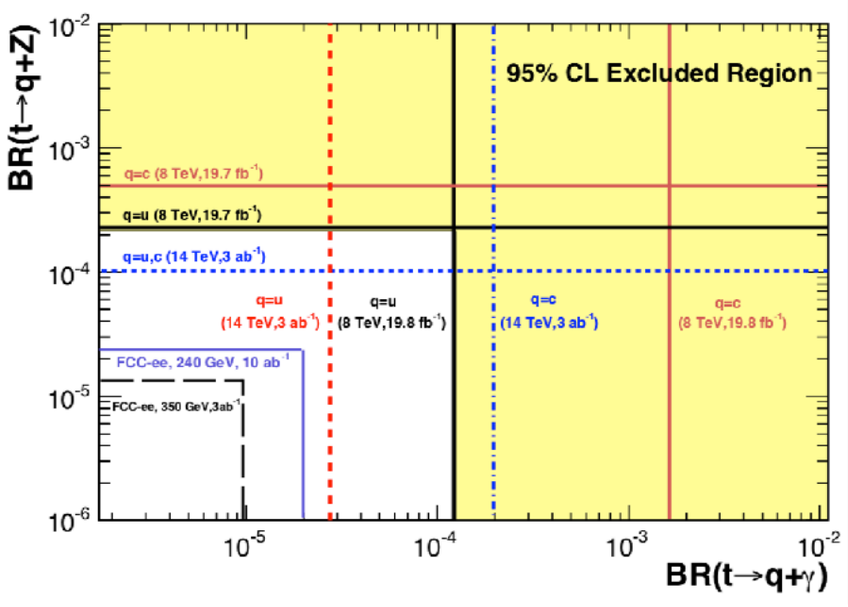


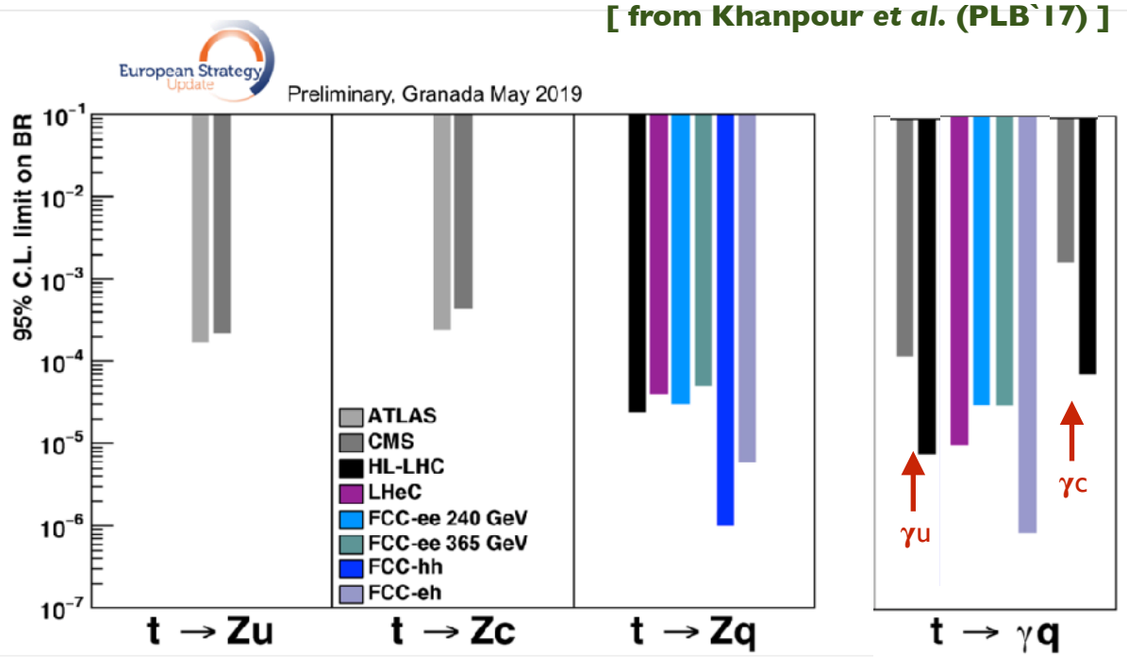
✦Two handles

- ✤ Rare top decays
- ✤ Single top production
  - ★ 5 ab^{-1} @ 240 GeV
  - ★ 1.5 ab^{-1} @ 365 GeV

✦Translations in terms of BR: improvement over the LHC

[from Khanpour *et al.* (PLB`17)]



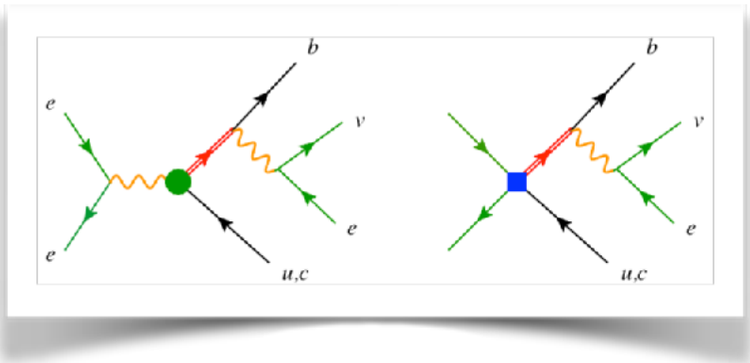


FCNC in the effective field theory

✦Four-fermionic interactions to be included

✤ 56 degrees of freedom!

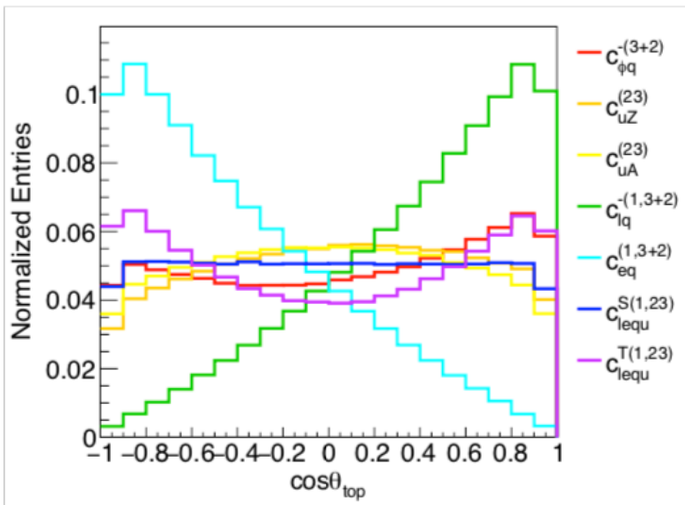
$$
\begin{array}{lllllll}
c_{\varphi q}^{-(3+a)} & c_{uZ}^{(a3)} & c_{uA}^{(a3)} & c_{lq}^{-(1,3+a)} & c_{eq}^{(1,3+a)} & c_{lequ}^{S(1,a3)} & c_{lequ}^{T(1,a3)} \\
c_{\varphi u}^{(3+a)} & c_{uZ}^{(3a)} & c_{uA}^{(3a)} & c_{lu}^{(1,3+a)} & c_{eu}^{(1,3+a)} & c_{lequ}^{S(1,3a)} & c_{lequ}^{T(1,3a)} \\
c_{\varphi q}^{-I(3+a)} & c_{uZ}^{I(a3)} & c_{uA}^{I(a3)} & c_{lq}^{-I(1,3+a)} & c_{eq}^{I(1,3+a)} & c_{lequ}^{SI(1,a3)} & c_{lequ}^{TI(1,a3)} \\
c_{\varphi u}^{I(3+a)} & c_{uZ}^{I(3a)} & c_{uA}^{I(3a)} & c_{lu}^{I(1,3+a)} & c_{eu}^{I(1,3+a)} & c_{lequ}^{SI(1,3a)} & c_{lequ}^{TI(1,3a)}
\end{array}
$$

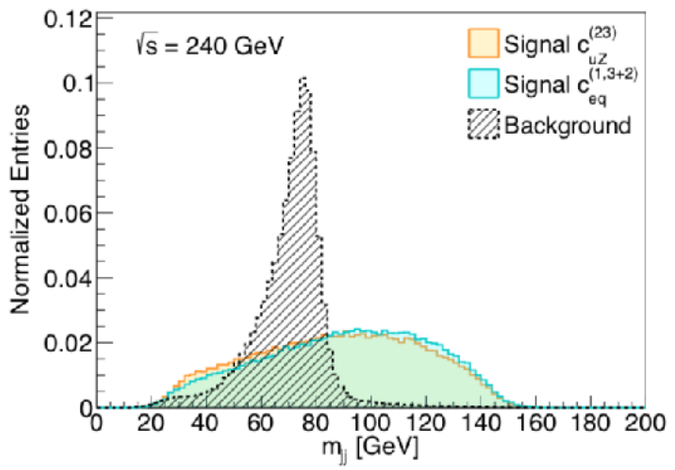


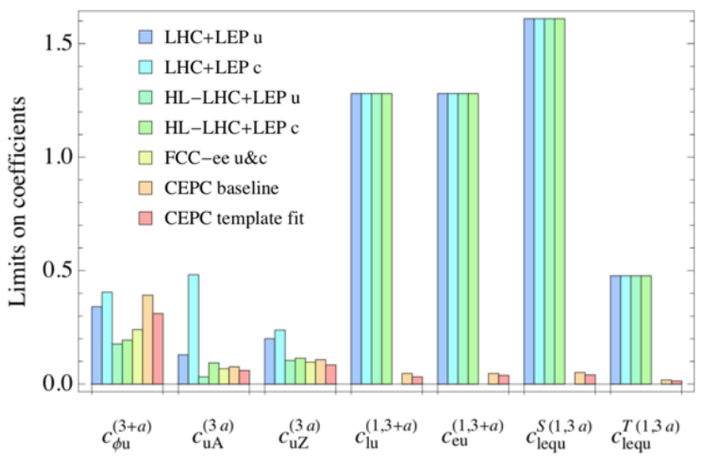
✦Classes of operators → different Lorentz structures → various observables

✤ Exploiting single top at 240 GeV

[Shi & Zhang (CP`19)]







Very few studies so far → more is coming

A rich top physics program at the FCC

✤ Plans
- ★ 1.5 ab^{-1} @ 365 GeV → 1 million $t\bar{t}$ pairs
- ★ 200 fb-1 @ 340 – 350 GeV ($t\bar{t}$ threshold scan)

✤ Precision measurements at threshold
- ★ Top mass, width and Yukawa
- ★ Top couplings
- ★ Rare decays