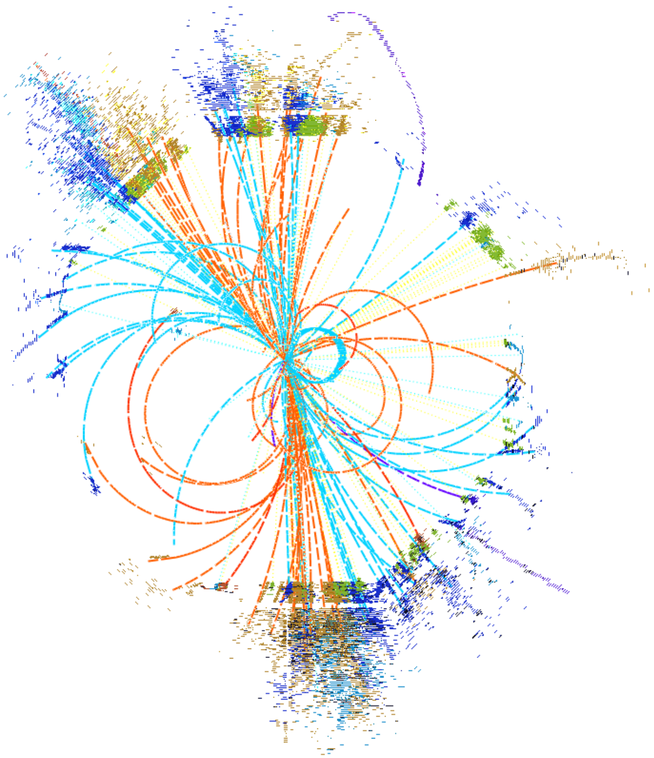
Top physics opportunities at FCC-ee

Philipp Roloff (CERN)
31/05/2022



FCC week 2022
Campus des Cordeliers -
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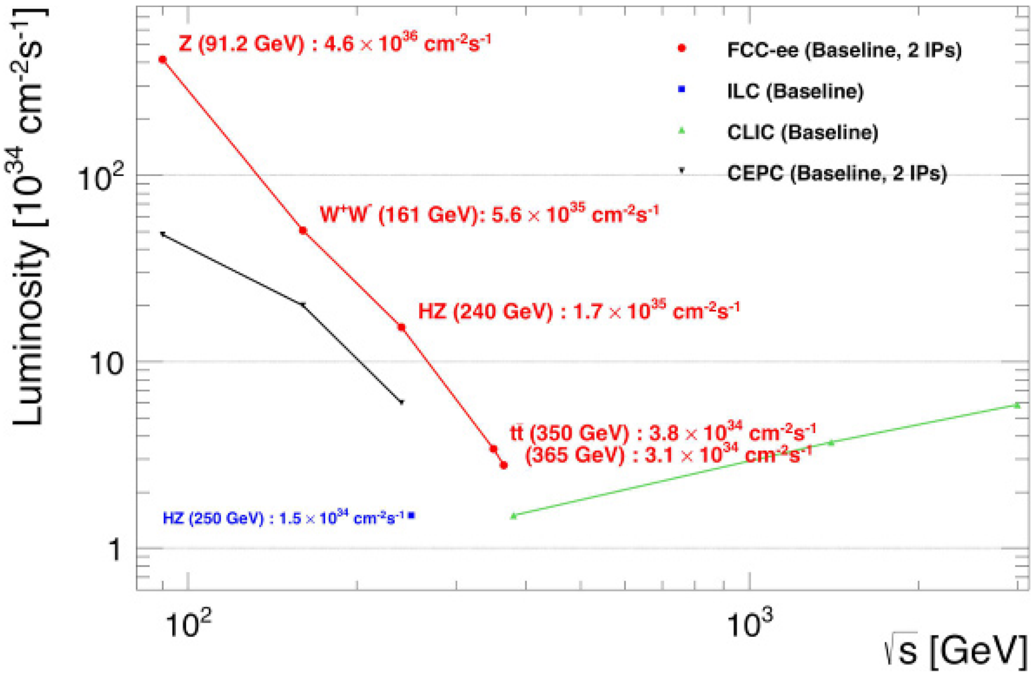
Introduction: FCC-ee energy stages



Relevant for top-quark physics:

240 GeV ("HZ"):
- FCNC using $e^+e^- \to tq$

350 GeV ("$t\bar{t}$"):
- Threshold scan for top-quark mass, width, Yukawa coupling, …

365 GeV:
- O(1 million) top-quark pairs
- Electroweak couplings
- FCNC using $e^+e^- \to tq$ and decays in $e^+e^- \to t\bar{t}$
- Mass from radiative events?

This project is supported from the European Union's Horizon 2020 research and innovation programme under grant agreement No 951754.

→ Large amount of complementarity

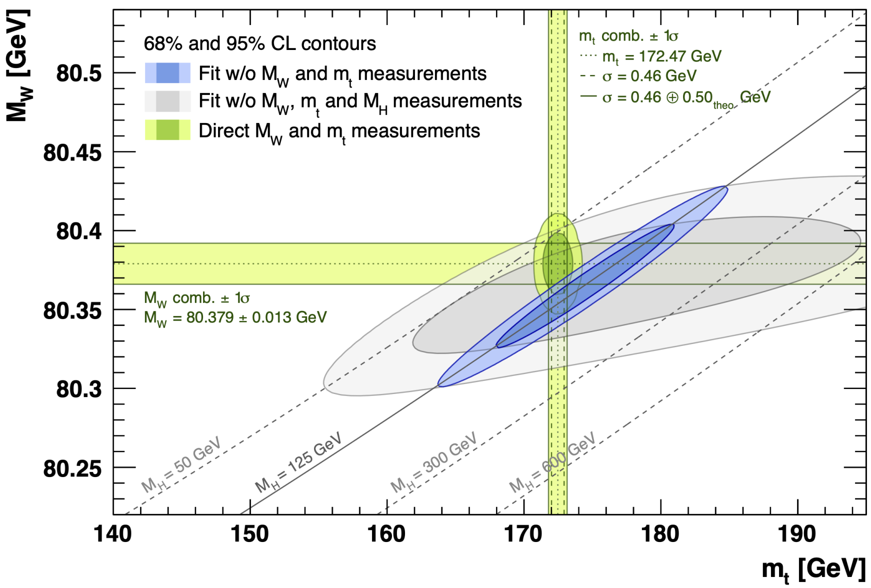
FCC CDR Volume 2

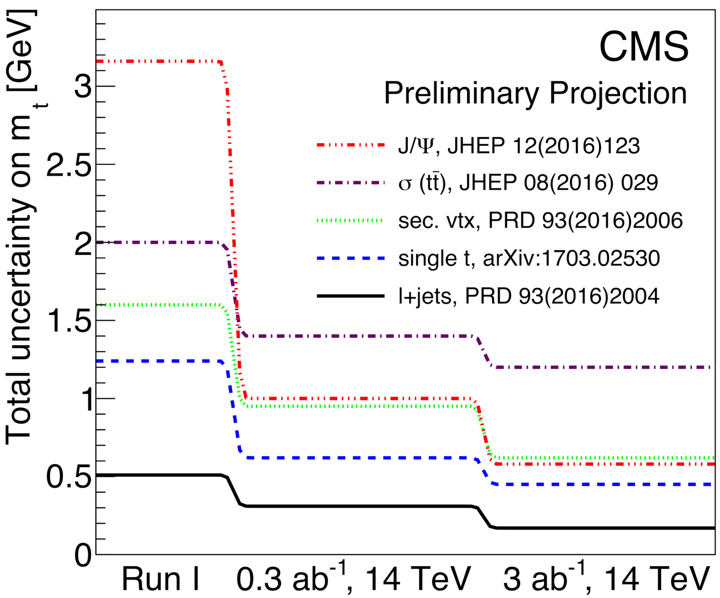
Outline

Top-quark at FCC-ee:

- Mass measurements
- Electroweak couplings
- Top-quark FCNC
- Common reconstruction issues
- EFT interpretations

Top-quark mass



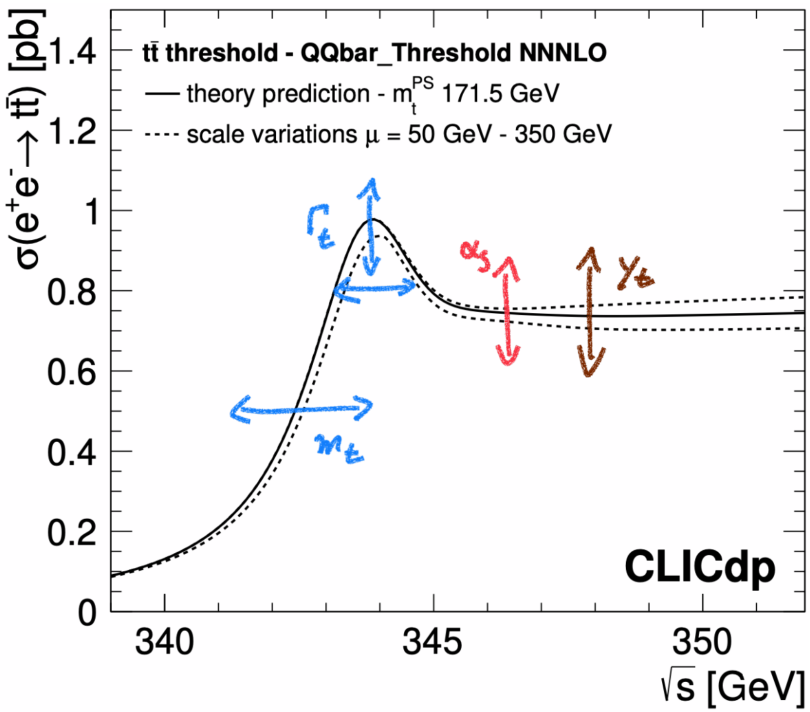


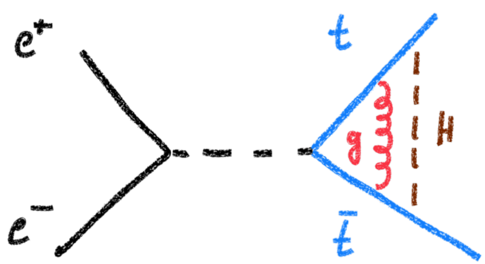
Direct and indirect constraints on top (and W) mass

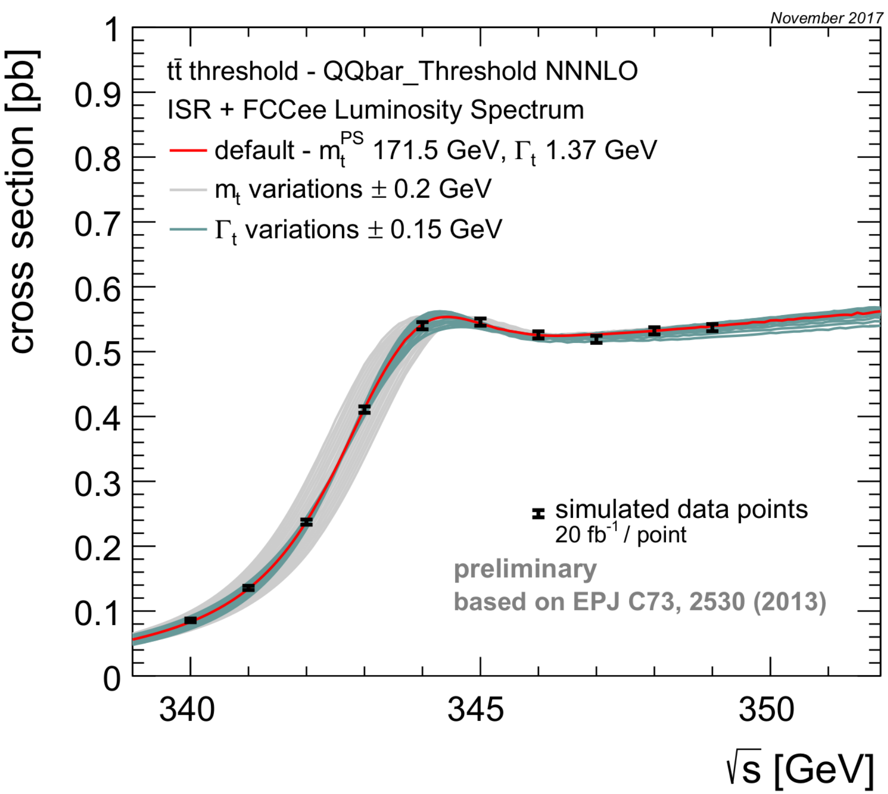
Complementary methods at e^+e^- collider:
- Threshold scan
- Radiative events
- MC mass from direct reconstruction

EPJ **C 78**, 675 (2018)
CERN-LPCC-2018-03

Top-quark pair production at threshold



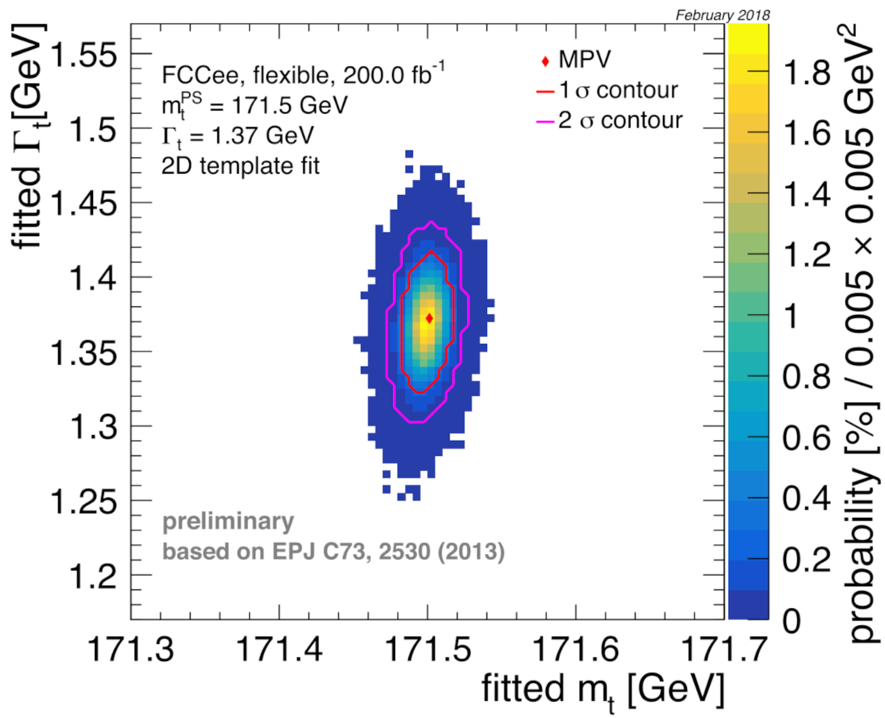


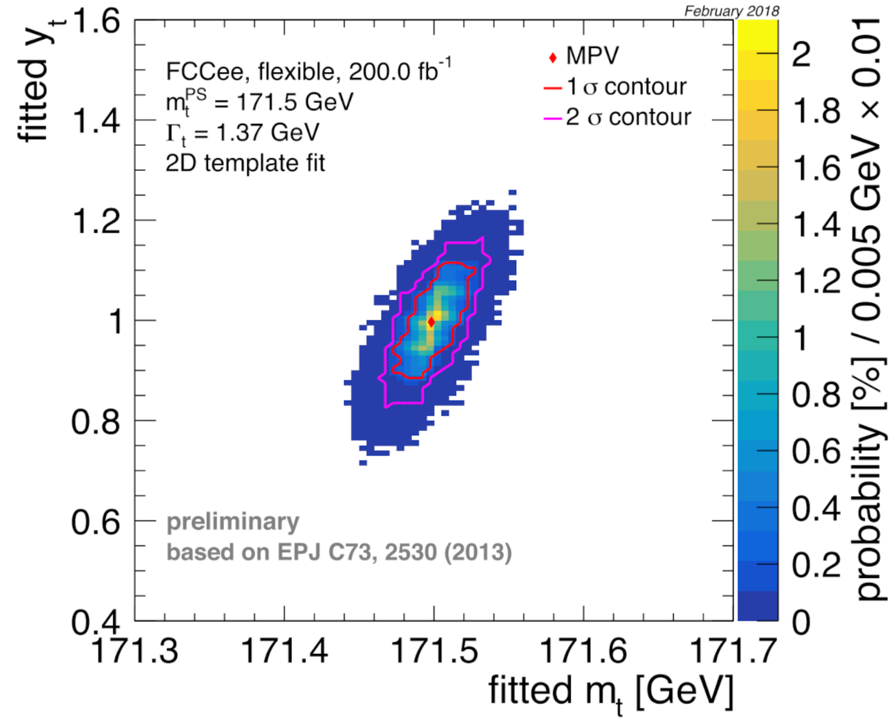


→ Fit to theory predictions in well-defined mass schemes

JHEP 11, 003 (2019)
FCC CDR Volume 3

Measurements at the threshold



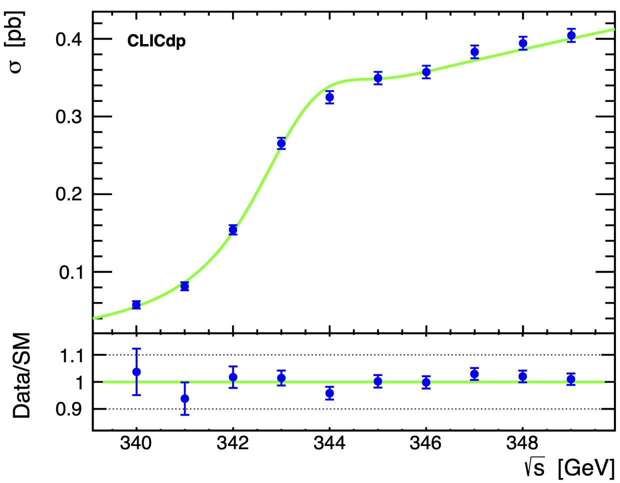


- Statistical uncertainty on m_t (Γ_t) is 17 (45) MeV for 200 fb^{-1}
- Theory uncertainty from current NNNLO calculations: ≈40 MeV
- 3 MeV uncertainty on m_t from centre-of-mass energy (if known with precision better than 10 MeV), 5 MeV from α_s (assuming precision of 2 x 10^{-4} from lower energies)
- 10% precision on the top Yukawa coupling possible
- Potential improvement on top mass from differential distributions → needs further study

FCC CDR Volume 3

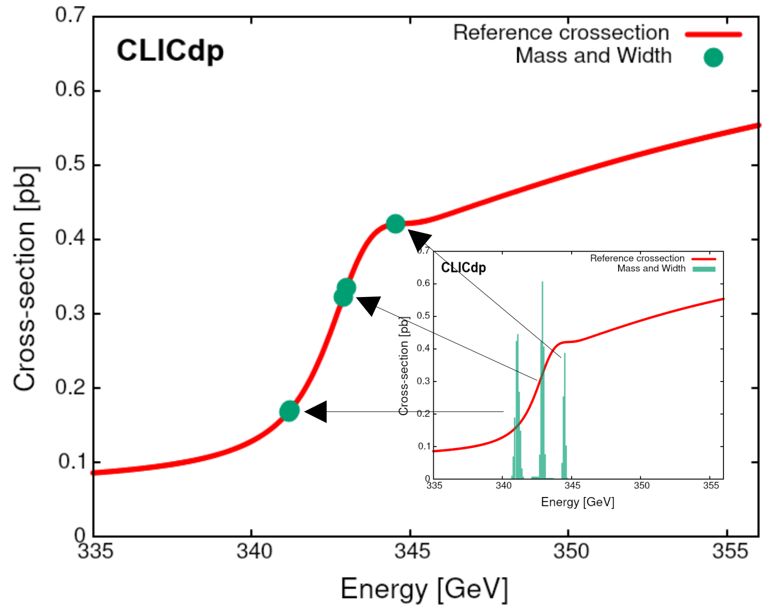
Optimisation of the threshold scan

Baseline scenario:

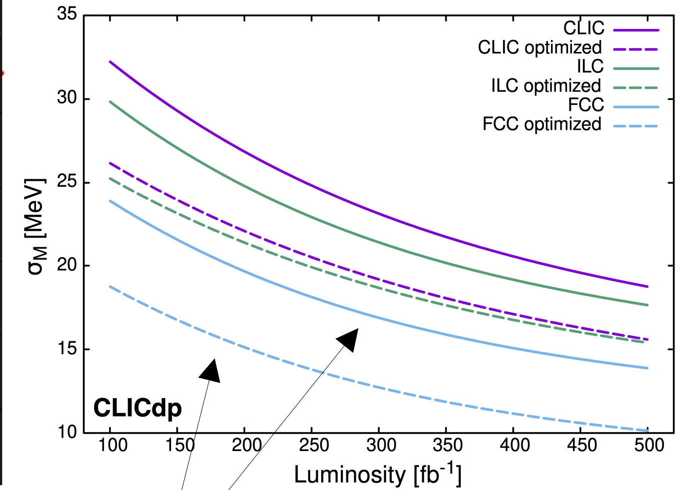


10 points of 10 fb^{-1} each

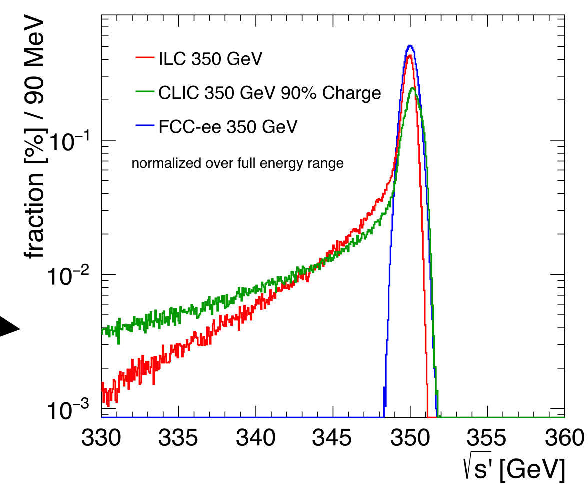
Optimised for mass & width:



Precision on top mass:



FCC-ee



- Optimisation of quantity and centre-of-mass energy for the individual cross section measurements
→ 25% better statistical precision on top mass compared to 10 equidistant measurements

- Main difference between colliders: luminosity spectra

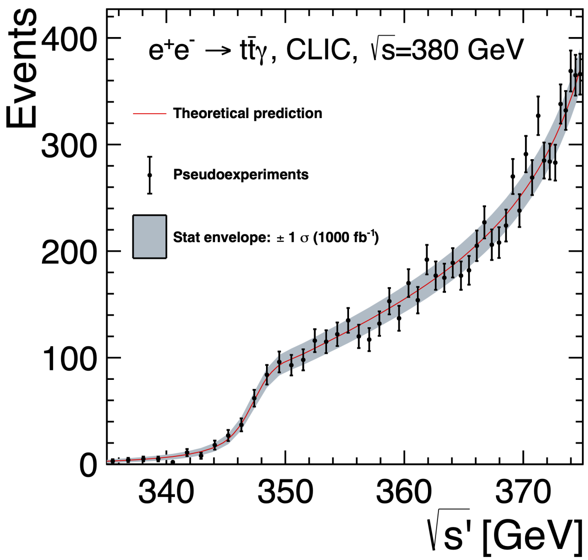
JHEP **07**, 070 (2021)

Radiative events: $e^+e^- \rightarrow t\bar{t}\gamma$

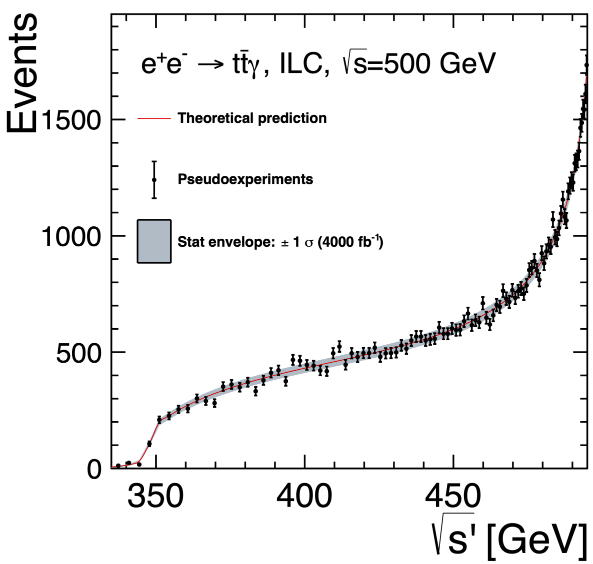
• Radiative events allow to extract the top mass in a well-defined mass scheme above threshold
→ complementary to threshold scan

• **Example:** matched NNLL threshold + N^{3}LO continuum calculation and CLIC/ILC luminosity spectra
→ limited by statistical uncertainty

→ Interesting possibility to explore for FCC-ee as well



cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV



PLB **804**, 135353 (2020)

Outline

Top-quark at FCC-ee:

- Mass measurements
- Electroweak couplings
- Top-quark FCNC
- Common reconstruction issues
- EFT interpretations

Top-quark electroweak couplings

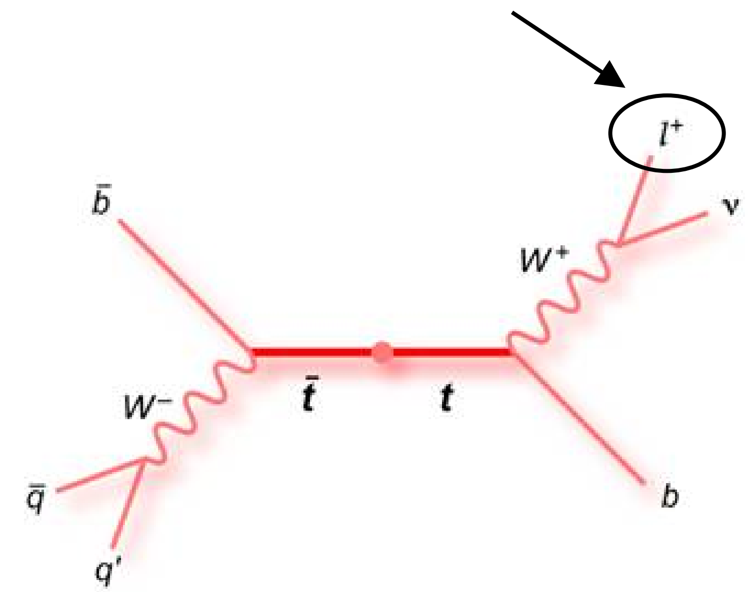
- Top quark pairs are produced via Z/γ* in electron-positron collisions
- The general form of the coupling can be described as:

arXiv:hep-ph/0601112

CP conserving **CPV**

$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$

- The γ and Z contributions can also be separated using the lepton energy and angular distributions in semi-leptonic events
→ Form-factor measurement possible at circular colliders with unpolarised beams



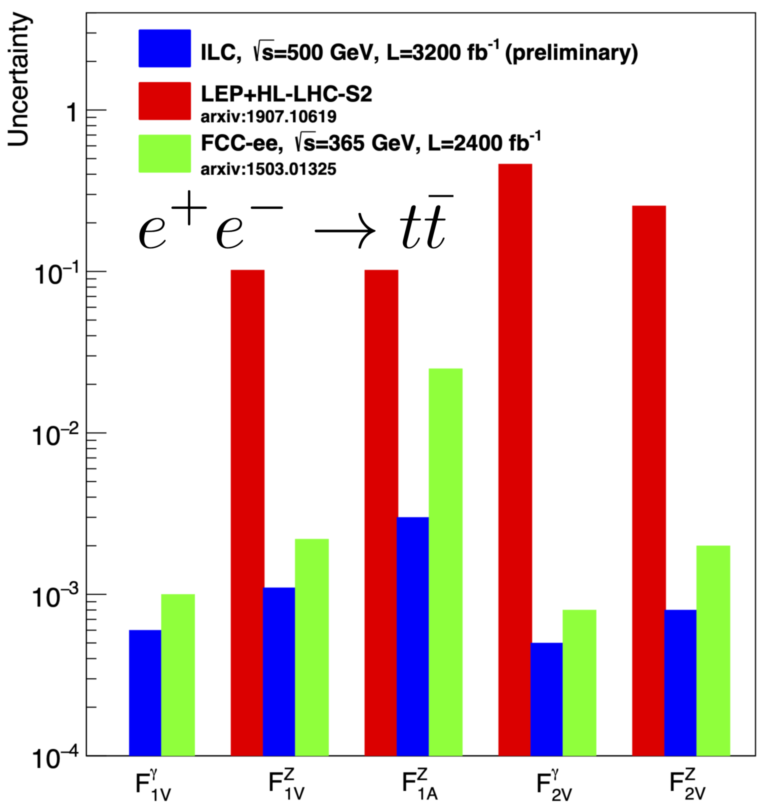
Sensitivity to form factors (1)

- Top quark pairs are produced via Z/γ^* in electron-positron collisions
- The general form of the coupling can be described as:

arXiv:hep-ph/0601112

CP conserving — CPV

$$\Gamma_{\mu}^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_{\mu}\left(F_{1V}^{V}(k^2) + \gamma_5 F_{1A}^{V}(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^{\nu}\left(iF_{2V}^{V}(k^2) + \gamma_5 F_{2A}^{V}(k^2)\right)\right\}$$



→ FCC-ee provides significant improvement compared to HL-LHC

- Generator-level study, results confirmed by full simulation
- For example sensitive to composite Higgs models
- ttZ coupling from FCC-ee needed as input for top-Yukawa measurement at FCC-hh
- Further improvement possible, e.g. from addition of fully hadronic final states

JHEP 04, 182 (2015)
R. Pöschl, EPS-HEP 2021

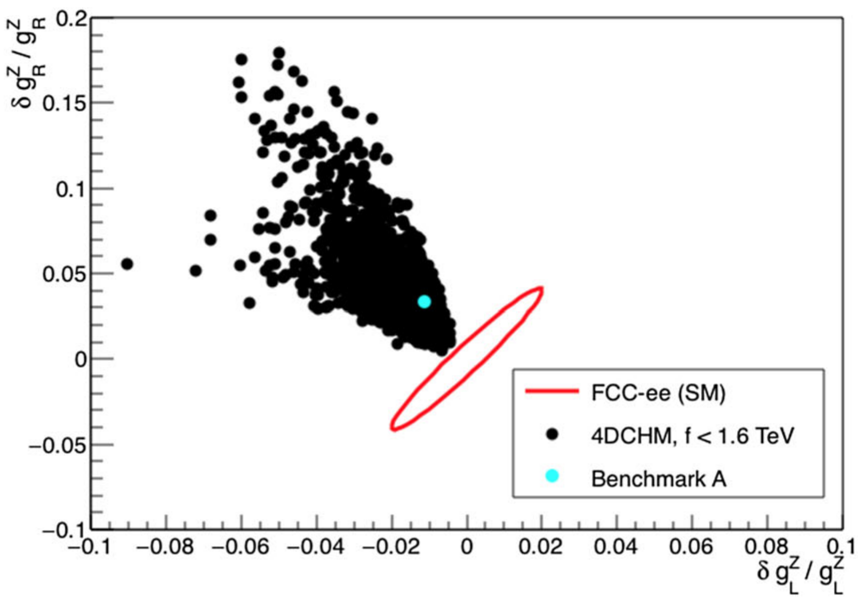
Sensitivity to form factors (2)

- Top quark pairs are produced via Z/γ^* in electron-positron collisions
- The general form of the coupling can be described as:

arXiv:hep-ph/0601112

CP conserving — CPV

$$\Gamma_\mu^{ttV}(k^2, q, \bar{q}) = -ie\left\{\gamma_\mu \left(F_{1V}^V(k^2) + \gamma_5 F_{1A}^V(k^2)\right) + \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu \left(iF_{2V}^V(k^2) + \gamma_5 F_{2A}^V(k^2)\right)\right\}$$



FCC CDR Volume 1

→ FCC-ee provides significant improvement compared to HL-LHC

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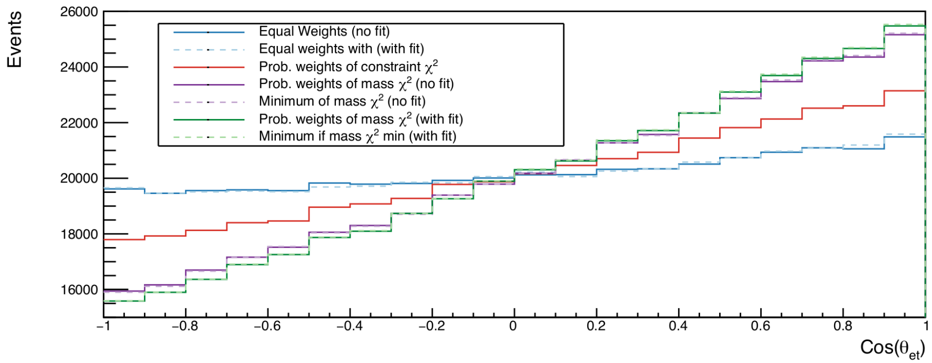
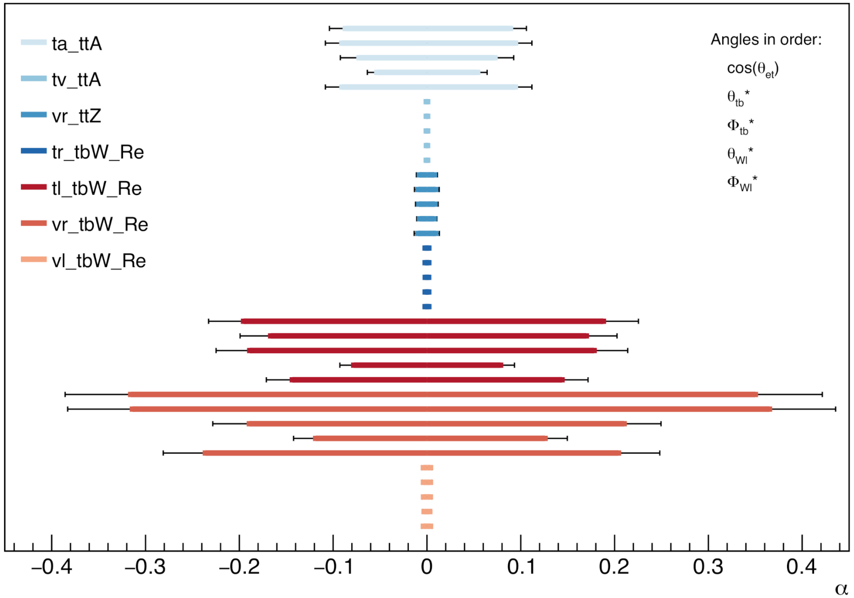
- Further improvement possible, e.g. from addition of fully hadronic final states

Ongoing study





$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(V_L P_L + V_R P_R)tW^{-}_{\mu} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q\nu}{M_W}(g_L P_L + g_R P_R)tW^{-}_{\mu} + H.c.$$

$$\mathcal{L}_{Ztt} = -\frac{g}{2c_W}\bar{t}\gamma^{\mu}(X^L_{tt} P_L + X^R_{tt} P_R - 2s^2_W Q_t)tZ_{\mu} - \frac{g}{2c_W}\bar{t}\frac{i\sigma^{\mu\nu}q\nu}{M_Z}(d^Z_V + i d^Z_A \gamma_5)tZ_{\mu}$$

$$\mathcal{L}_{\gamma tt} = -eQ_t\bar{t}\gamma^{\mu}A_{\mu} - e\bar{t}\frac{i\sigma^{\mu\nu}q\nu}{m_t}(d^{\gamma}_V + i d^{\gamma}_A \gamma_5)tA_{\mu}$$

- Delphes samples
- Comparison of different jet reconstruction algorithms
- Kinematic fit implemented
- Preliminary projections on single anomalous couplings from angular distributions

Julie Munch Torndal
Jorgen Beck Hansen

Outline

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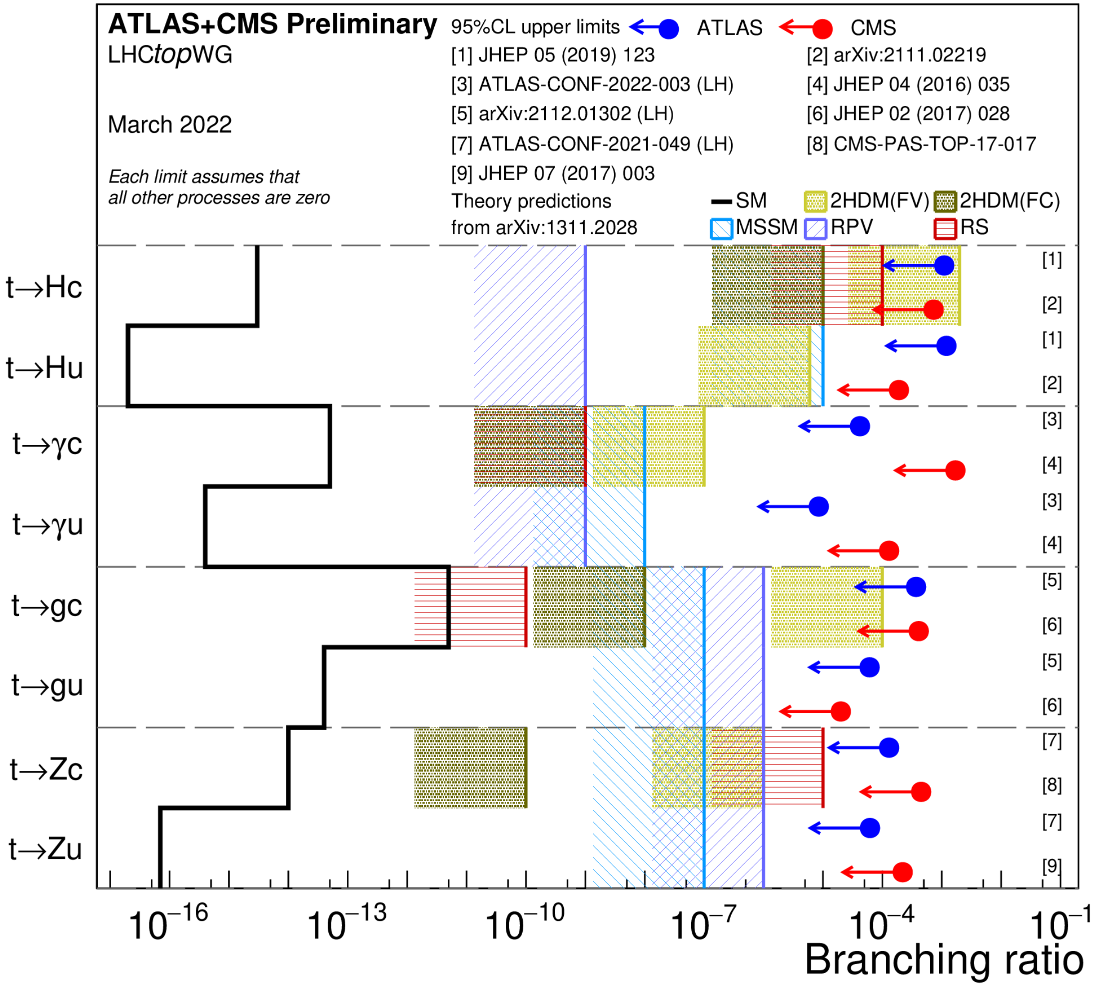
Top-quark FCNC: current status

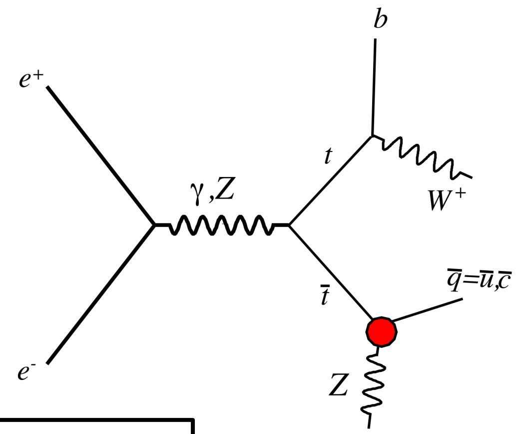


- SM branching ratios strongly suppressed (10^{-16}...10^{-12}) → strong enhancement in certain BSM models possible (update needed?)
- Current 95% CL limits typically at the level of 10^{-5} to 10^{-3}

Top-quark FCNC at FCC-ee

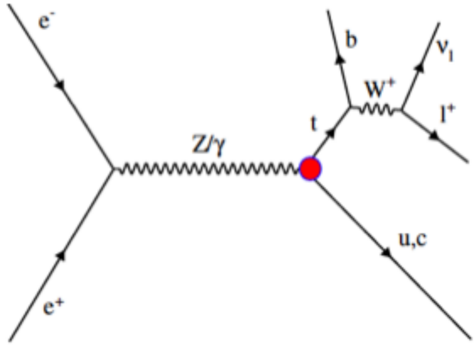
e^+e^- colliders especially competitive for: $t \to cH$, $t \to cZ$, $t \to c\gamma$, $t \to cg$

In top-quark decays:



At 365 GeV

In single top production:

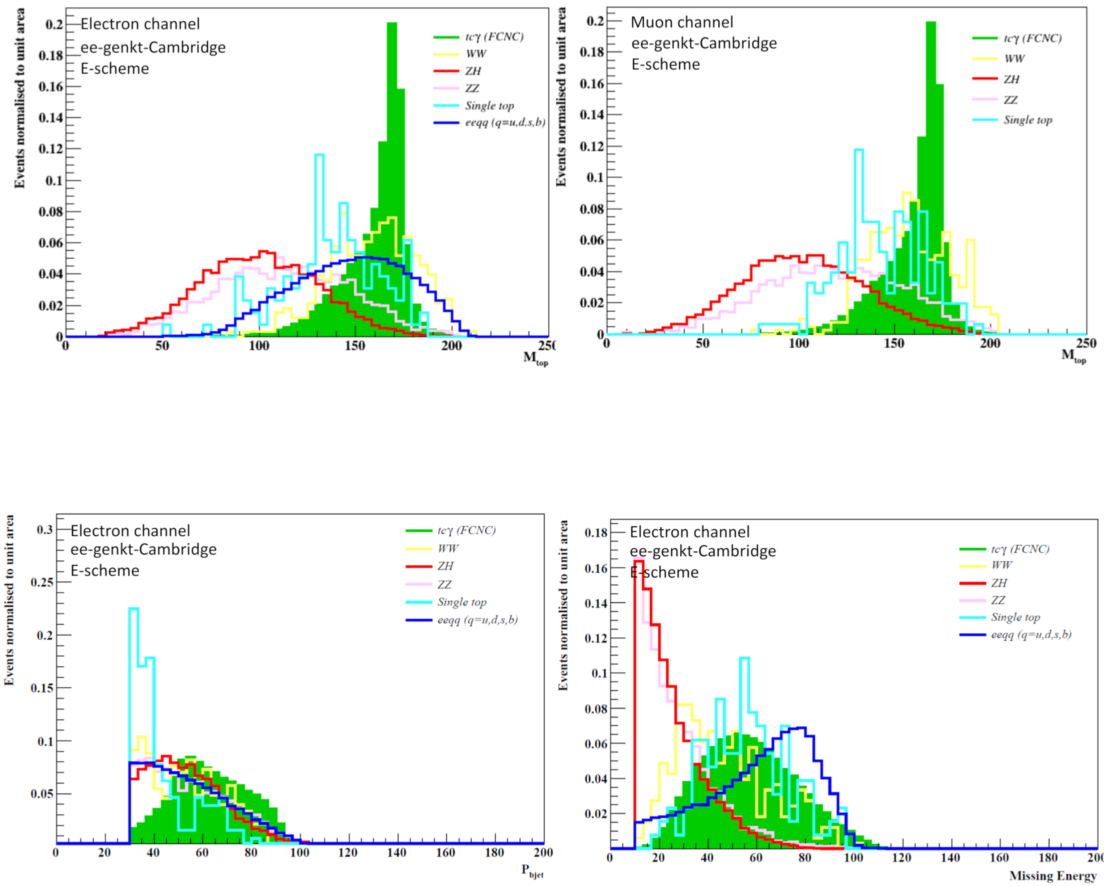


At 240 and 365 GeV

Phys. Lett. **B 755**, 25 (2017)

- Preliminary results indicate that combination of both energies and approaches desirable to improve with respect to HL-LHC
- The ultimate precision will be achieved at FCC-hh

Ongoing study



- Recently started, focussing on single top production at 240 GeV
- Delphes samples, different jet algorithms compared
- First projections from cut-and-count approach, to be improved using multi variate analysis

Hamzeh Khanpour
Seddigheh Tizchang
Mojtaba Mohammadi
Patrizia Azzi
Emmanuel Francois Perez

Outline

Top-quark at FCC-ee:

- Mass measurements
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- Common reconstruction issues
- EFT interpretations

Common reconstruction aspects

- **Jet reconstruction:** all state-of-the-art clustering algorithms available in FastJet (Durham, generalised k_t, Valencia, …) https://fastjet.fr/

- **Flavour tagging:** LCFIPlus (originally developed for linear collider studies), new developments based on ParticleNet very promising in fast simulation
Charm tagging important for FCNC decays
Nucl. Inst. Meth. A 808, 109 (2016)
arXiv:2202.03285

- **Kinematic fits:** MarlinKinFit (from linear collider studies), ABCfit++ (ported from LEP algorithm)
Inclusion of ISR from energy loss can be important above threshold
https://github.com/Torndal/ABCfitplusplus
NIM A 624, 184 (2010)

- **Charged lepton identification:** for semi-leptonic $t\bar{t}$ events

- **Photon identification:** for radiative $t\bar{t}$ events, $t \rightarrow c\gamma$, ...

→ see also talks by Clément Helsens, Valentin Volkl

Outline

Top-quark at FCC-ee:
- Mass measurements
- Electroweak couplings
- Top-quark FCNC
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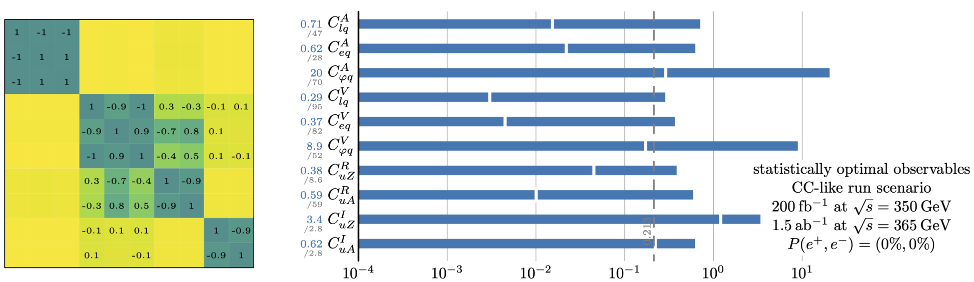
- EFT interpretations

Global EFT interpretations

• Global EFT analyses of EW analyses of $e^+e^- \rightarrow t\bar{t}$ production and $e^+e^- \rightarrow tj$ have been demonstrated in recent years

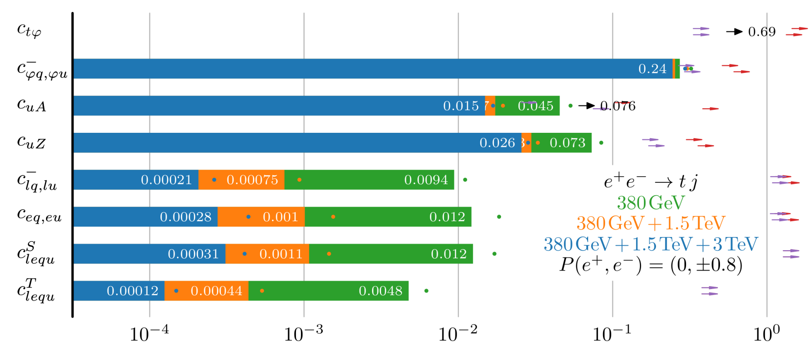
Top-quark electroweak couplings



JHEP **10**, 168 (2018)

NB: This example uses "statistically optimal observables" which make the best use of the fully differential $bW^+\bar{b}W^-$ distributions

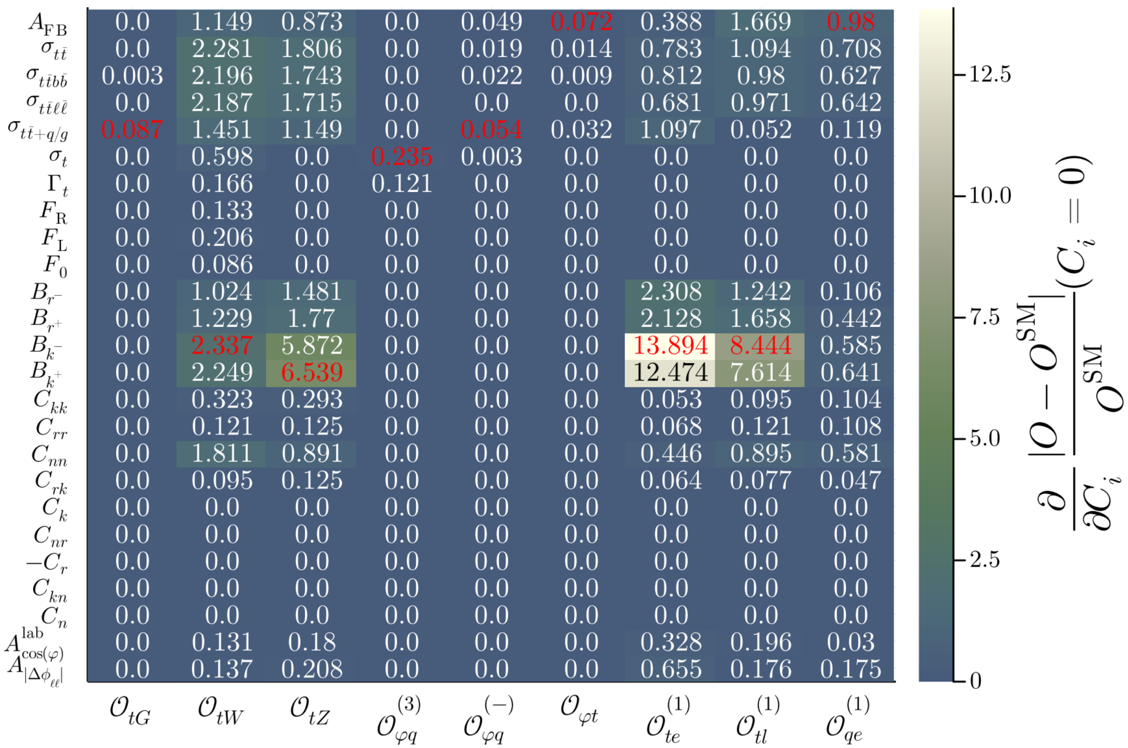
Top-quark FCNC: example from CLIC



CERN-2018-009-M

• To be optimised for FCC-ee conditions (large statistics, but no beam polarisation) and projections
• Combined FCC-ee + FCC-hh EFT analysis would be very interesting (also for comparison with other collider options...)

Ongoing study



Generator-level (MadGraph)

- New study of EFT-sensitive $t\bar{t}$ observables at FCC-ee
- Global fit is final aim
- Transition to Whizard planned
- Started to look at reconstructed observables with Delphes samples

Cornelius Grunwald
Laetitia Guerry
Kevin Kröninger
Romain Madar
Stéphane Monteil
Lars Röhrig

Summary and conclusions

• The top-quark plays a crucial role at FCC-ee below, at and above the pair-production threshold

• Well-defined program:
- A threshold scan is the best possible mass measurement
- Operation well above threshold improves the top-quark EW couplings by at least an order of magnitude
- Top-quark FCNC-effects can be problem in single-top production and in decays

• Interesting reconstruction issues to be studied in ongoing and future physics potential studies, in particular kinematic fitting and jet reconstruction in complex events

• Top-quark production would also be a good detector benchmark channel in full simulation

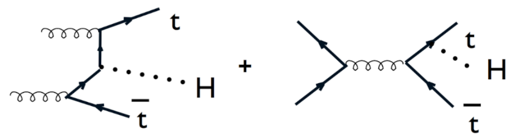
• Global EFT interpretations to be adopted and optimised for FCC-ee

Thank you!

Backup slides

top-Yukawa coupling at FCC-hh

ttH

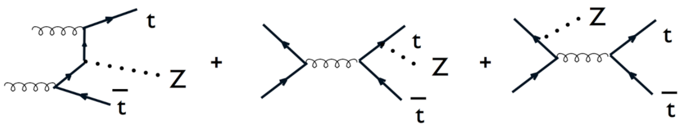


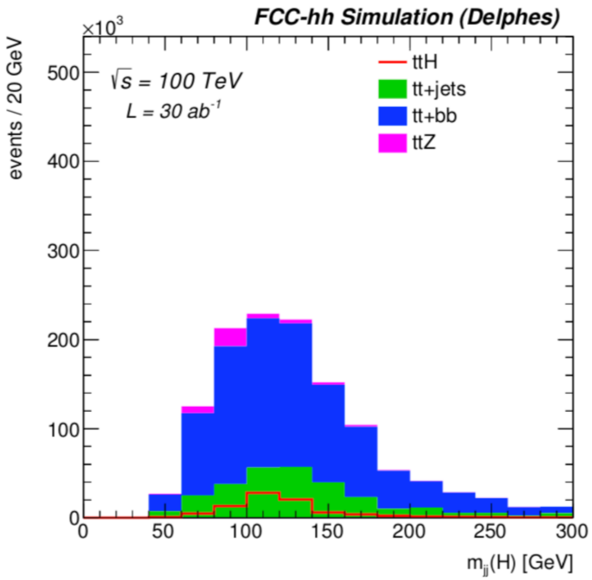
- production ratio **σ(ttH)/σ(ttZ)** ≈ $y_t^2\ y_b^2 /\ g_{ttZ}^{\ 2}$
- measure **σ(ttH)/σ(ttZ)** in **H/Z→bb** mode in the boosted regime, in the **semi-leptonic** channel
- perform **simultaneous fit of double Z and H peak**
- (lumi, scales, pdfs, efficiency) **uncertainties cancel out** in ratio

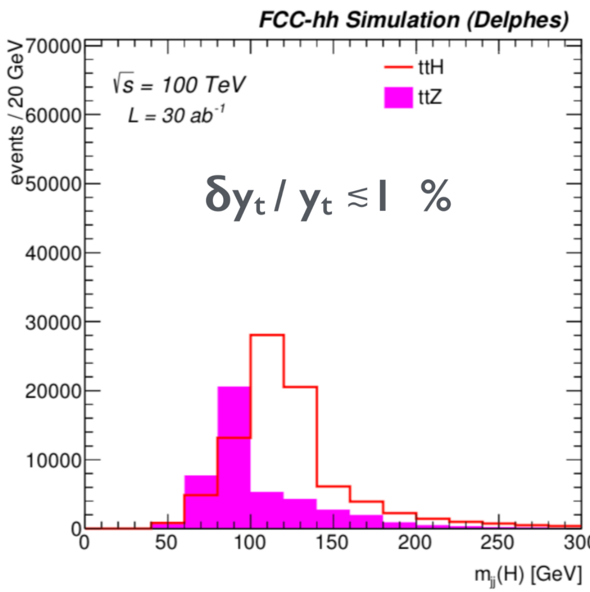
- assuming $\mathbf{g_{ttZ}}$ and $\boldsymbol{\kappa_b}$ known to 1% (from FCC-ee),

   → measure $\mathbf{y_t}$ to 1%

ttZ







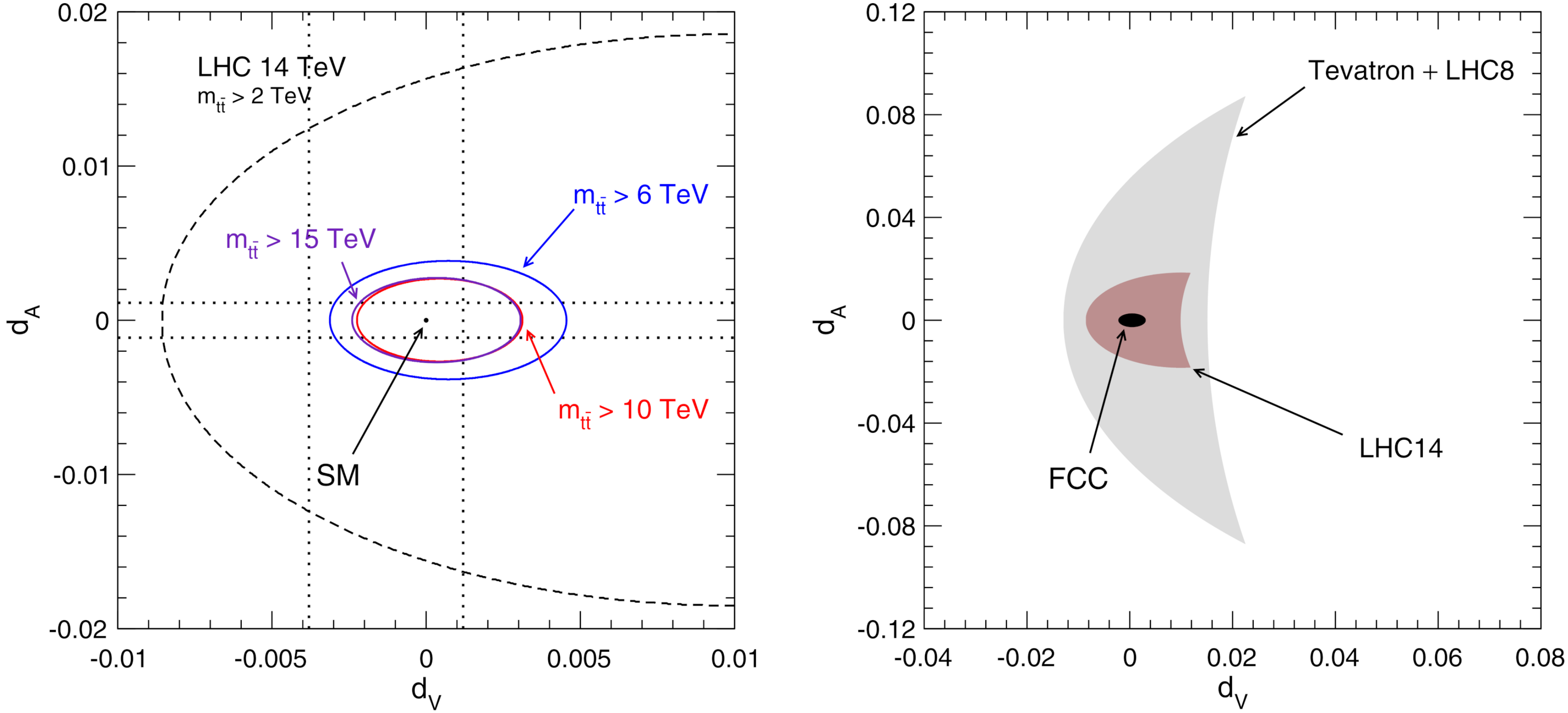
Michele Selvaggi

Anomalous top-gluon couplings from $pp \rightarrow t\bar{t}$

Strongly boosted:
$m_{t\bar{t}} > 10$ TeV is optimal choice from cross section analysis

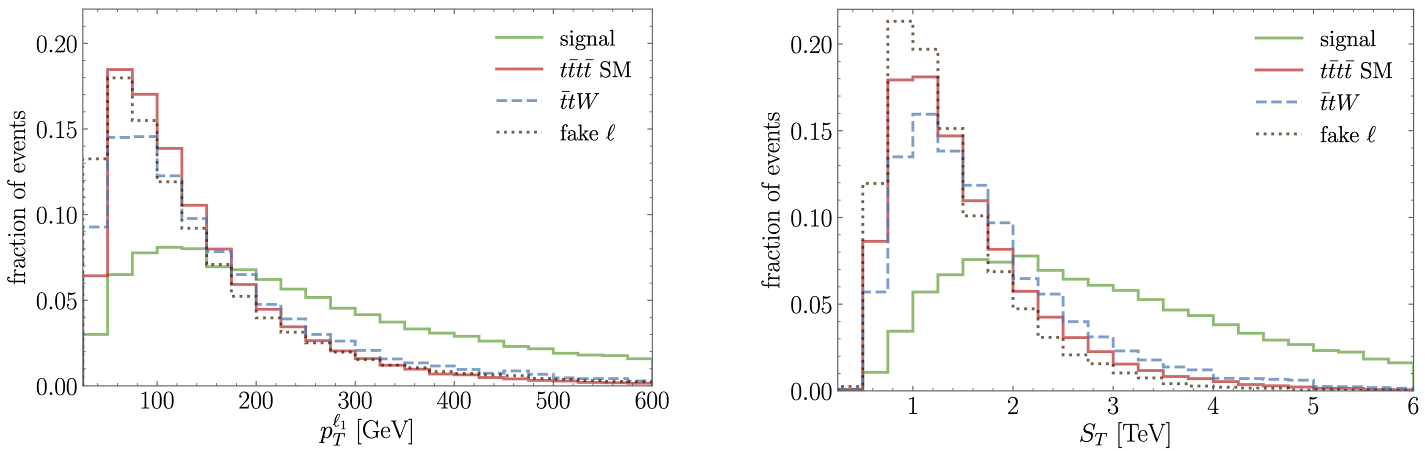
$$\delta\mathcal{L} = \frac{g_s}{m_t}\,\bar{t}\sigma^{\mu\nu}(d_V + i\,d_A\gamma_5)\frac{\lambda_a}{2}\,t\,G^a_{\mu\nu}$$

d_V(d_A): chromomagnetic (chromoelectric) diplole moment



FCC-hh CDR

pp → $t\bar{t}t\bar{t}$ at FCC-hh



Example: same-sign di-lepton final state

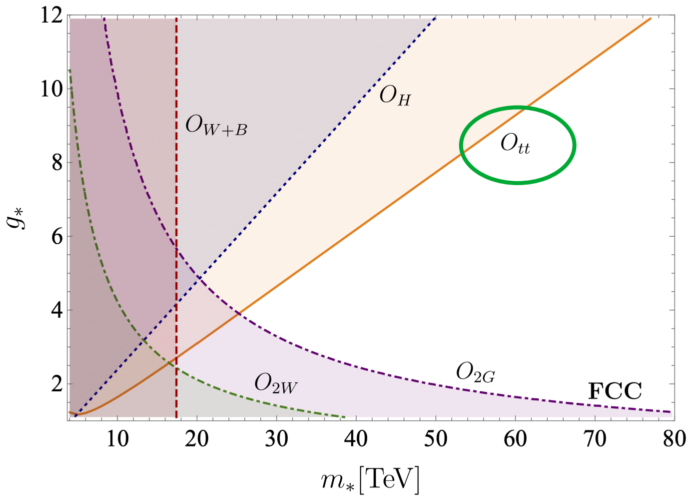
$$\text{FCC-hh}^{\,pp\to t\bar{t}t\bar{t}}_{\,100\,\text{TeV},\ 30\,\text{ab}^{-1}}: \quad \Lambda/\sqrt{|c_{tt}|} > 6.5\,\text{TeV}$$

$$\text{CLIC}^{\,e^+e^-\to t\bar{t}}_{\,3\,\text{TeV},\ 3\,\text{ab}^{-1}}: \quad \Lambda/\sqrt{|c_{tt}|} > 7.7\,\text{TeV}$$

$$\text{ILC}^{\,e^+e^-\to t\bar{t}}_{\,1\,\text{TeV},\ 1\,\text{ab}^{-1}}: \quad \Lambda/\sqrt{|c_{tt}|} > 4.1\,\text{TeV}$$

FCC-hh: same-sign di-lepton and tri-lepton final states combined

Composite Higgs



95% CL limits from individual operators

JHEP **02**, 043 (2021)