SnowMass2021

EF03 EW Physics: Heavy flavor and top quark physics

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EF workshop at Brown University, March 28-April 1, 2022

Heavy flavor and top quark physics

- Prospects for top quark studies (HL-LHC, FCC, ILC, CLIC, muon collider):
  - top quark properties: mass, width, electroweak top couplings
  - study of rare processes: ttW, ttZ, tZq, tttt, FCNC, compositeness,…
  - precision measurements of a wide variety of observables and in new kinematic regimes: spin correlations, polarization, boosted top, …
- Joined studies:
  - m_{top} in global electroweak fits (input to EF04)
  - Top quark couplings and global EFT fits (with EF04)
  - Top and HF in PDF fits: extraction of gluon PDF, alphas, ... (with EF06)
- Prospects for HF physics (b,c,s) at future colliders
  - Full pattern of quark couplings, running b-quark mass
- Status of predictions and prospects for theory improvements:
  - Interpretation of m_{top}, new ideas for m_{top} measurements
  - Higher order QCD and EW corrections, scale and renormalization scheme uncertainties, PDF uncertainties, parametric uncertainties

Heavy flavor and top quark physics: Contributed Papers

- The ATLAS and CMS collaborations: Physics with the Phase-2 ATLAS and CMS Detectors (Section 4, CERN Yellow report CERN 2019-007)

  New since Yellow report:
  - Projection of top quark spin correlations with CMS at the HL-LHC (in preparation)
  - Sensitivity to measurements of the SM four top quark cross section with ATLAS at the HL-LHC ATL-PHYS-PUB-2022-004
- G. Bernardi *et al.*: The Future Circular Collider: a Summary for the US 2021 Snowmass Process (Section 5) arXiv:2203.06520
- The ILC International Development Team and the ILC Community: The International Linear Collider: Report to Snowmass 2021 (Section 10) arXiv:2203.07622
- International Muon Collider Collaboration: Muon Collider Physics Summary (Sections 4 and 5) arXiv:2203.07256

Covered in EF03 parallel session on Wednesday

Heavy flavor and top quark physics: Contributed Papers (cont.)

- S. Aioli *et al*.: Top-quark mass extraction from ttj+X events at the LHC: theory predictions arXiv:2203.07344
- J. Gombas *et al*.: Dependence of the top-quark mass measured in top-quark pair production on the parton distribution functions at the LHC and future colliders arXiv:2203.08064
- N. Kidonakis: Higher-order corrections for tt production at high energies arXiv:2203.03698
- Z. Yu, C.-P. Yuan: Azimuthal angular correlation as a new boosted top jet substructure arXiv:2203.02760
- K. Nowak, A.F. Zarnecki: Optimising top-quark threshold scan at CLIC using genetic algorithm arXiv:2103.00522
- G. Bevilacqua *et al.*: Modeling uncertainties of ttW multilepton signatures arXiv:2109.15181
- K. Xie *et al*.: Probing heavy flavor PDFs at hadron colliders arXiv:2203.06207

Covered in EF03 (EF06) parallel session on Wednesday

Heavy flavor and top quark physics: Contributed Papers (cont.)

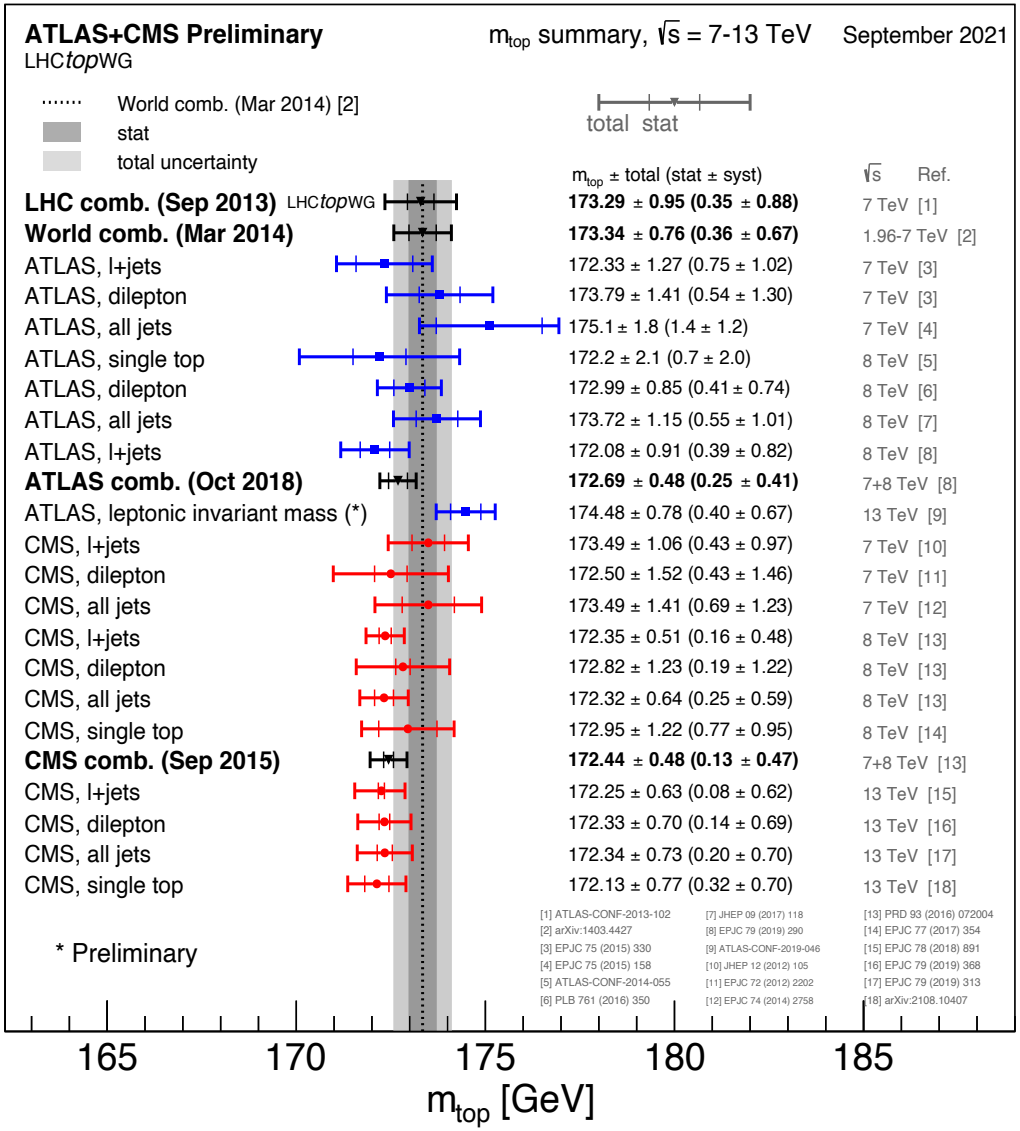
In preparation:

- J. Aparisi *et al*.: m_b at M_H: the running bottom quark mass and the Higgs boson
- K. Agashe *et al*.: A new method for top quark measurements
- M. Vos *et al*.: HL-LHC and Higgs factory projections for top measurements

Covered in EF03 parallel/plenary session on Wednesday

For more highlights see also EF03 talk at the EF Restart workshop on 9/3/2021:
EF03 Highlights

Top-quark mass at the LHC and Tevatron: MC mass



m_{top} from kinematic distributions of reconstructed decay products in top-pair/single top production (MC mass):

ATLAS comb.: 172.69 +- 0.48 GeV

CMS comb.: 172.44+- 0.48 GeV

LHC+Tevatron: 173.34 +- 0.76 GeV

Relation of MC mass to renormalized mass (pole, MSbar, MSR, …) is under discussion (pert.+non-pert.+color rec. etc):

MC mass-pole mass: 570 +- 280 MeV

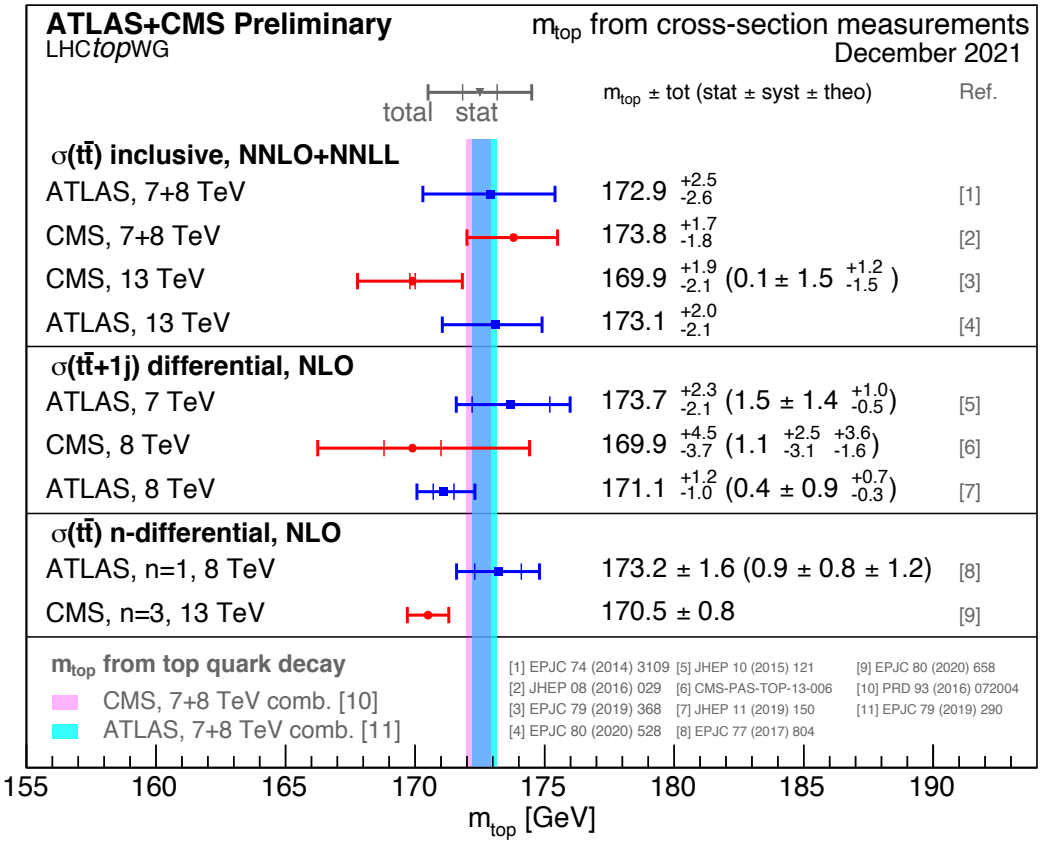
M. Butenschoen *et al.*, arXiv:1608.01318

recent review: A. Hoang, arXiv:2004.12915

New EF03 study:

- K. Agashe *et al.*: A new method for top quark measurements
- TG report will include a discussion of top mass definitions and different sources of uncertainties

Top-quark mass at the LHC: Pole mass



m_{top} from cross section measurements for tt, tt+1j (pole mass); additional theory uncertainty due to use of NLO prediction CMS n=3 [9] in plot is estimated to be 1 GeV

MSbar to pole mass conversion known at 4-loop order; theory uncertainty: 300 MeV (missing h.o.) + 110 MeV (ambiguity)

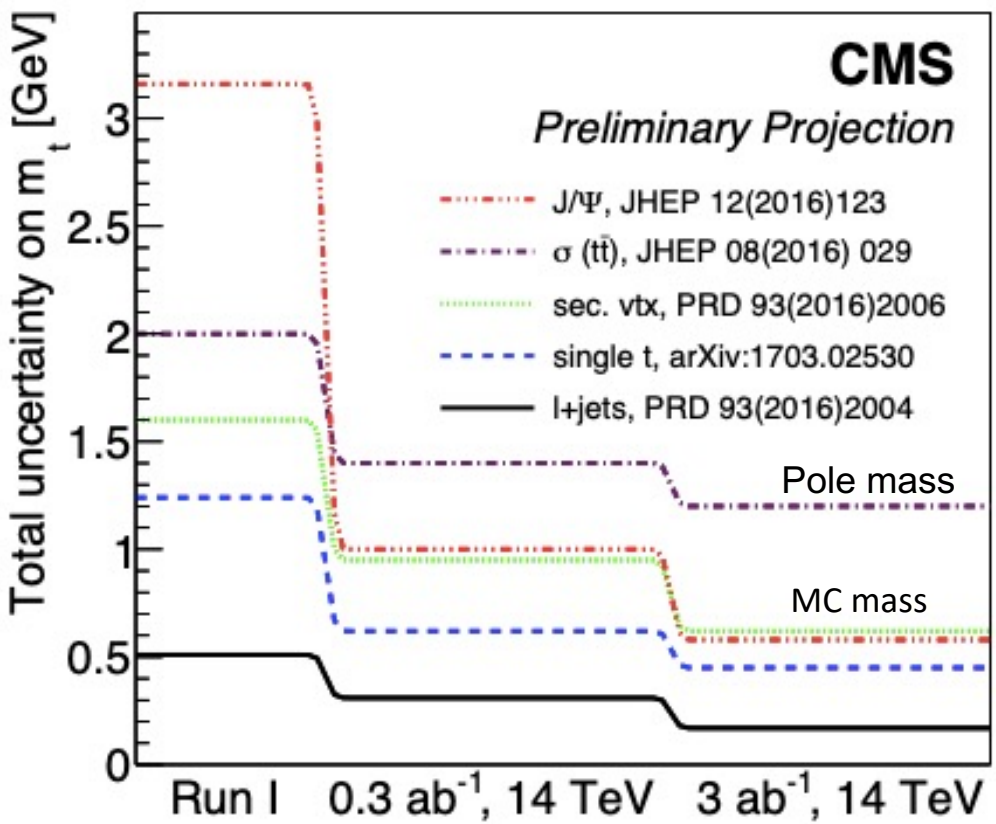
M. Beneke *et al.*, arXiv:1605.03609

New EF03 studies:

- S. Aioli *et al.*: Top-quark mass extraction from ttj+X events at the LHC: theory predictions arXiv:2203.07344
- J. Gombas *et al.*: Dependence of the top-quark mass measured in top-quark pair production on the parton distribution functions at the LHC and future colliders arXiv:2203.08064

Top-quark mass at the HL-LHC

m_{top} measurement uncertainty for different methods as a function of integrated luminosity:



CMS-PAS-FTR-16-006

Projected uncertainty for MC mass measurement in top pair production:

CMS: 20 MeV (stat.)+ 170 MeV (syst.)
(lepton+jets) CMS-PAS-FTR-16-006

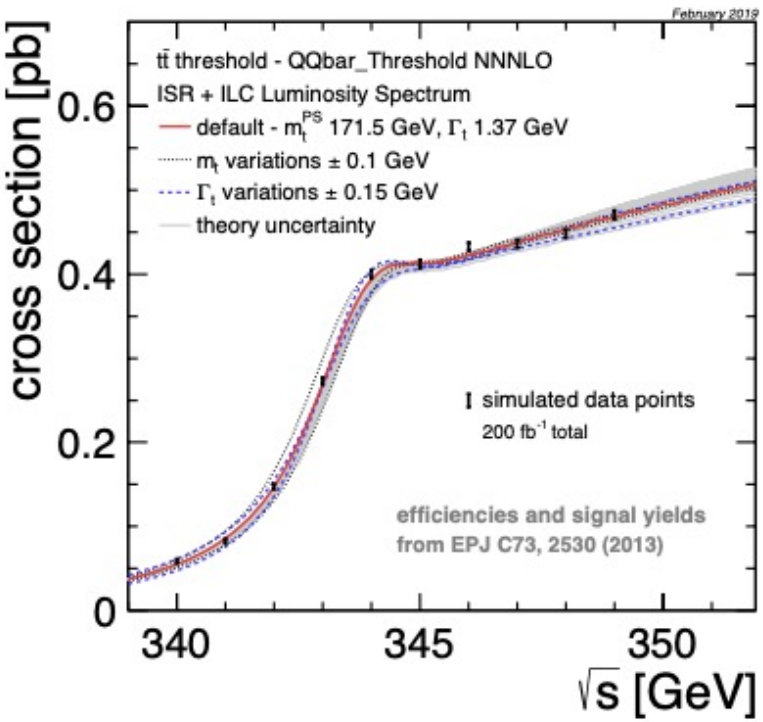
ATLAS: 140 MeV (stat.)+480 MeV (syst.)
(tt → lepton+jets events with J/ψ → μ+μ− in the final state) ATL-PHYS-PUB-2018-042

New EF03 study:

- N. Kidonakis: Higher-order corrections for tt production at high energies arXiv:2203.03698

Top-quark mass: Linear e^+e^- Colliders (ILC, CLIC)

Simulated tt threshold scan showing the dependence on m_{top} in the potential subtraction scheme (PS) and on the top quark width:



F. Simon, arXiv:1902:07246

Projected uncertainty for PS mass measurement from tt threshold scan:

ILC (200 fb^{-1}): 20 MeV (stat.) + 50 MeV (theo. syst.) +30-50 MeV (exp. syst.)

F. Simon, arXiv:1902:07246, Snowmass report arXiv:2203.07622

CLIC (100 fb^{-1}): 23 MeV (stat.) + 30-50 MeV (theo. syst.) + 25-50 MeV (exp. syst.)

(theo. syst: missing higher orders in the prediction and the parametric uncertainty due to the strong coupling constant)

Projected uncertainty at 380 GeV:
MSbar mass from radiative events: 140 MeV (1 ab^{-1})
MC mass from direct reconstruction:
30 MeV (40 MeV) (stat.) in l+jets (all-hadronic) channel at 500 fb^{-1}

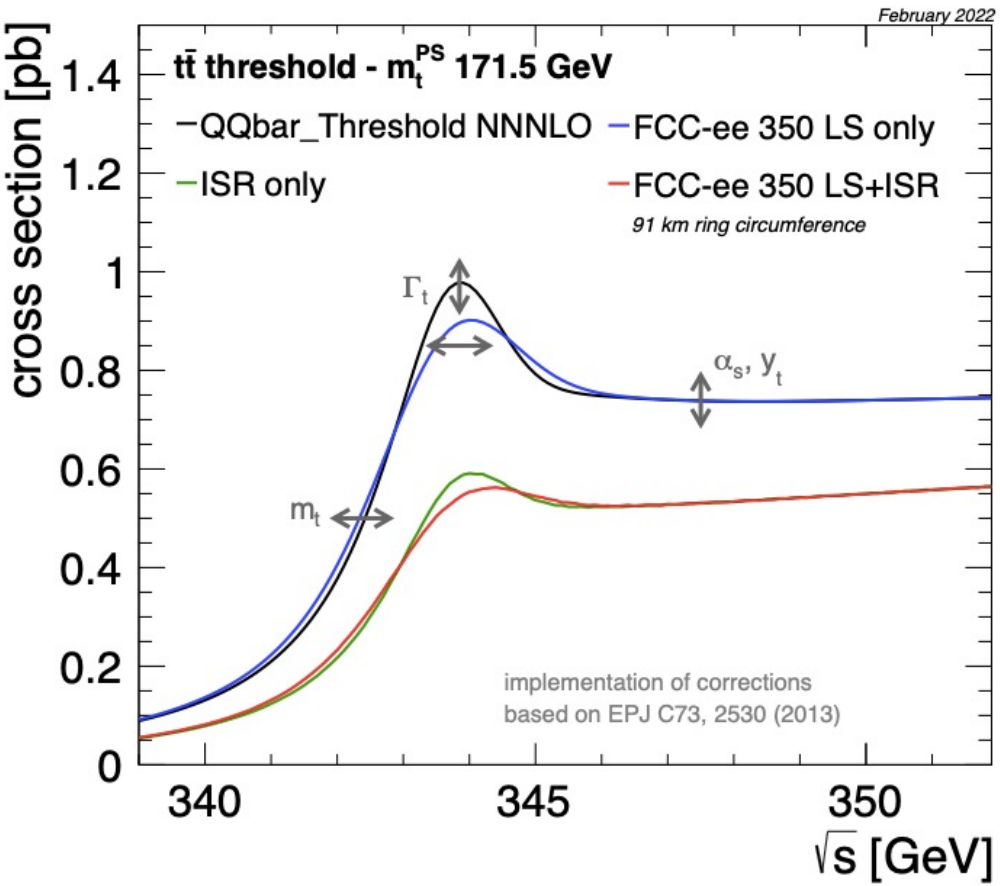
CLICdp collaboration, arXiv:1807.02441

New EF03 study:

- K. Nowak, A.F. Zarnecki: Optimising top-quark threshold scan at CLIC using genetic algorithm arXiv:2103.00522

Top-quark mass: Circular e+e- Colliders (FCC-ee)

tt threshold cross section showing the effects of ISR (green) and the collider luminosity spectrum (LS) (blue):



F. Simon, MPP-2022-25 (2022) and arXiv:2203.06520

Projected uncertainty for PS mass measurement from tt threshold scan:
FCC-ee (200 fb^{-1}): 9 MeV (stat.) + (45 MeV+3.2 MeV) (theo. syst.)
arXiv:2203.06520

(theo. syst: scale uncertainty at N3LO and parametric uncertainty due to the strong coupling constant)

PS to MSbar mass conversion known at 4-loop order; theory uncert.: 23 MeV
P. Marquard et al., arXiv:1502.01030

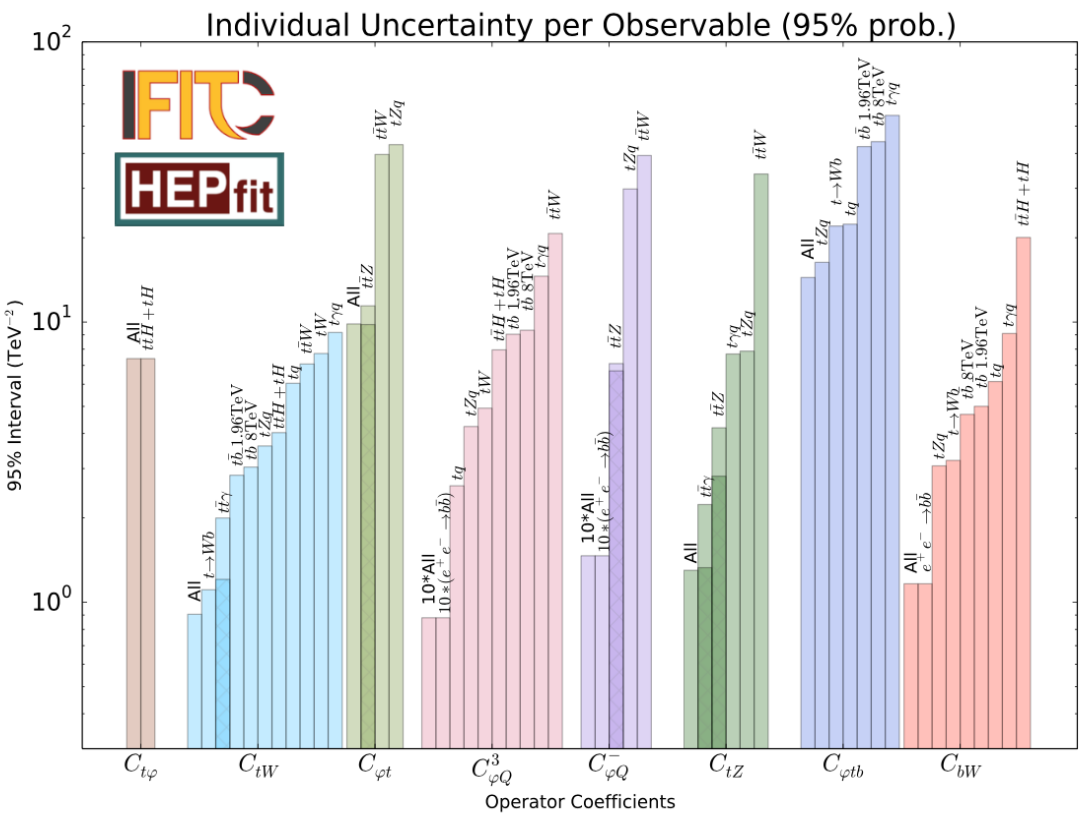
(parametric uncertainty due to the strong coupling constant: O(50) MeV)

New EF03 study:

- G. Bernardi *et al.*: The Future Circular Collider: a Summary for the US 2021 Snowmass Process (Section 5) arXiv:2203.06520

Rare processes: ttV,tVX (V=gamma, Z,W) and EW top couplings

Individual constraints on eight Wilson coefficient resulting from measurements at the LHC, Tevatron and LEP/SLD:



V. Miralles et al., arXiv:2107.13917

Global fit results (ttZ, ttgamma differential cross sections included) with 95% probability bounds on Wilson coefficients that range from ±0.35 to ±8 TeV^{-2}

V. Miralles et al., arXiv:2107.13917

New EF03/EF04 study:

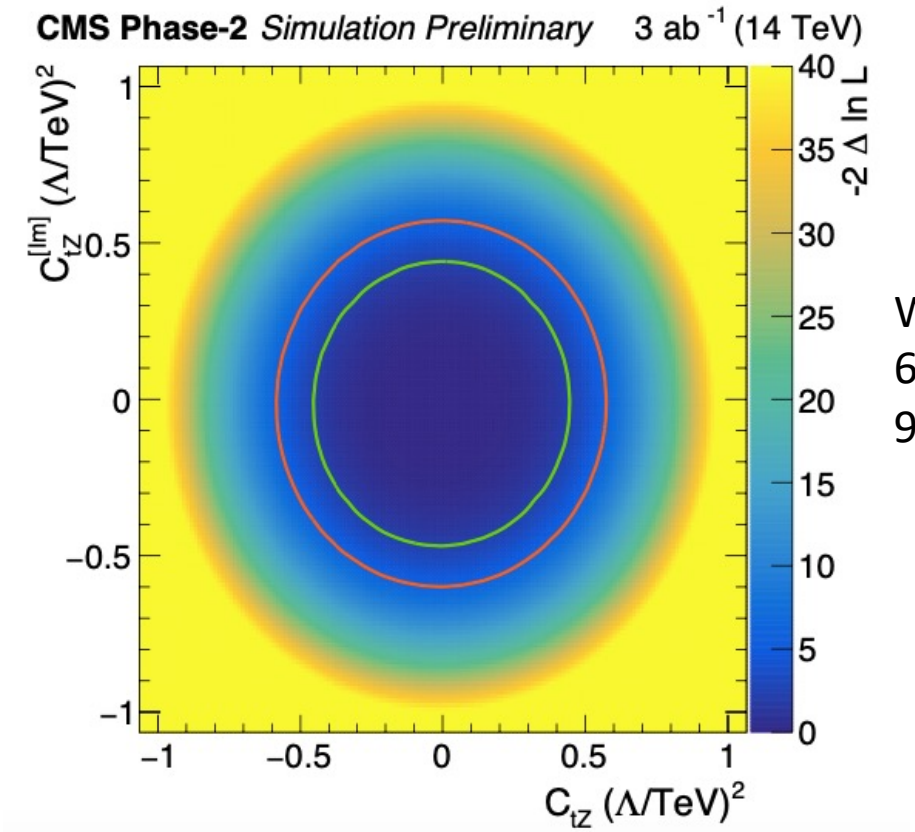
M. Vos *et al.*: HL-LHC and Higgs factory projections for top measurements

New EF03 study:

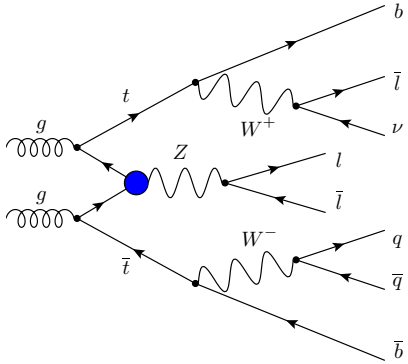
G. Bevilacqua *et al.*: Modeling uncertainties of ttW multilepton signatures arXiv:2109.15181

Rare processes: ttZ and EW top couplings at the HL-LHC

Expected sensitivity to Wilson coefficients of top quark operators C_{tZ} in the ttZ process:



CMS Collaboration, CMS-PAS-FTR-18-036



Wilson coefficient C_{tZ} in SMEFT:
68 % CL $(\Lambda/\text{TeV})^2$: [-0.37, 0.36]
95 % CL $(\Lambda/\text{TeV})^2$: [-0.52, 0.51]

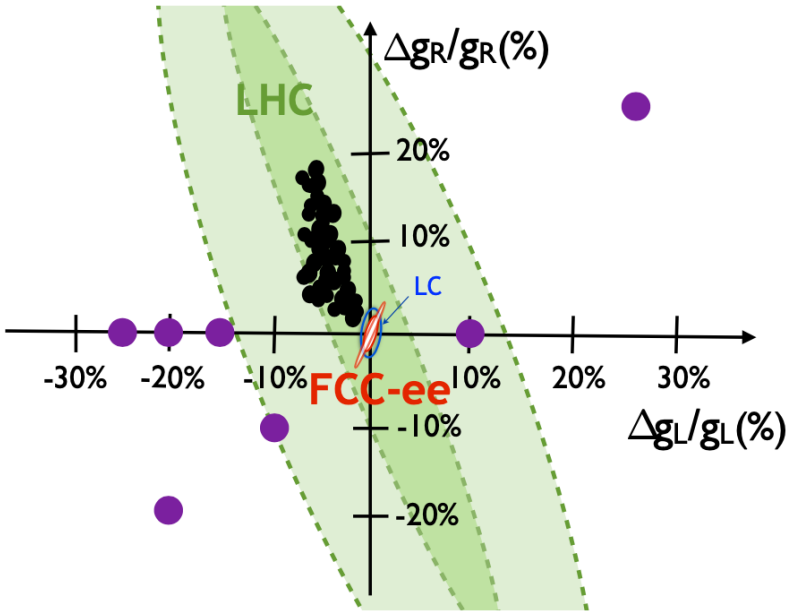
CMS Collaboration, CMS-PAS-FTR-18-036

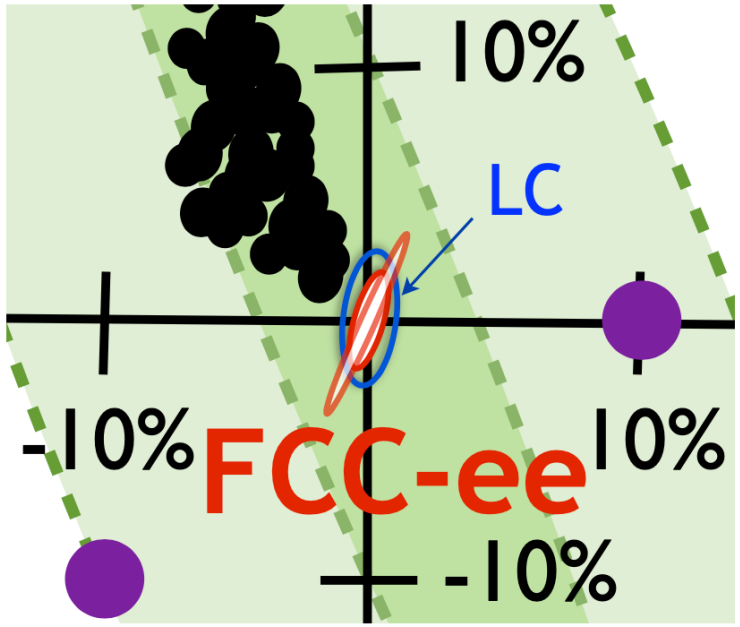
New EF03/EF04 study:

- M. Vos *et al.*: HL-LHC and Higgs factory projections for top measurements

EW top couplings at e+e- colliders

Projected relative precision on the Zt_Lt_L and Zt_Rt_R couplings at the LHC (lighter green), HL-LHC (darker green), ILC (blue) and the FCC-ee (orange, red):

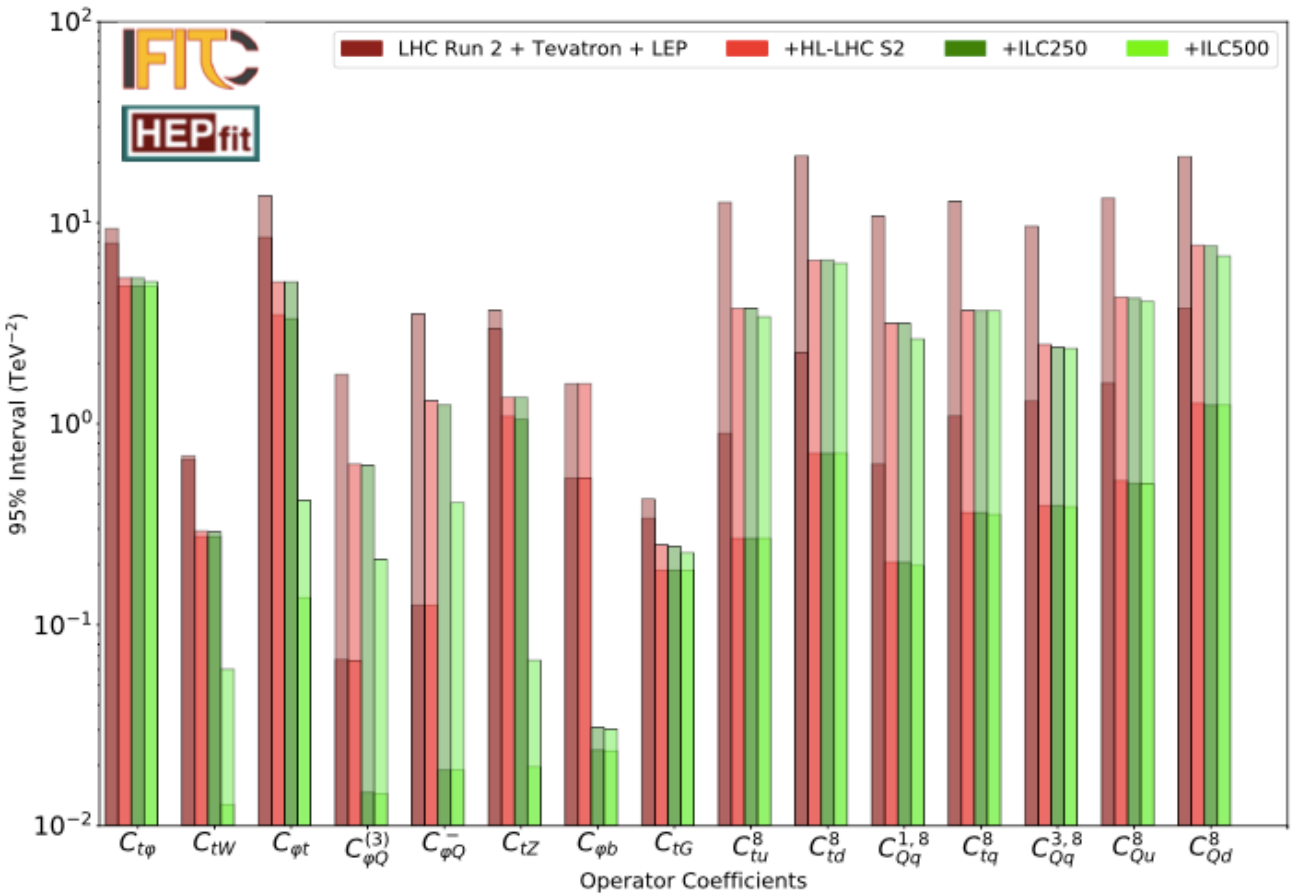




P.Janot, arXiv:1510.09056 arXiv:1510.09056

EW top and bottom quark couplings at LHC, HL-LHC, ILC

Comparison of current 95% CL bounds and HL-LHC and ILC prospects for 95% CL bounds on Wilson coefficients of two-fermion SMEFT operators that affect the top and bottom quark EW couplings and the four-fermion operators qqtt:

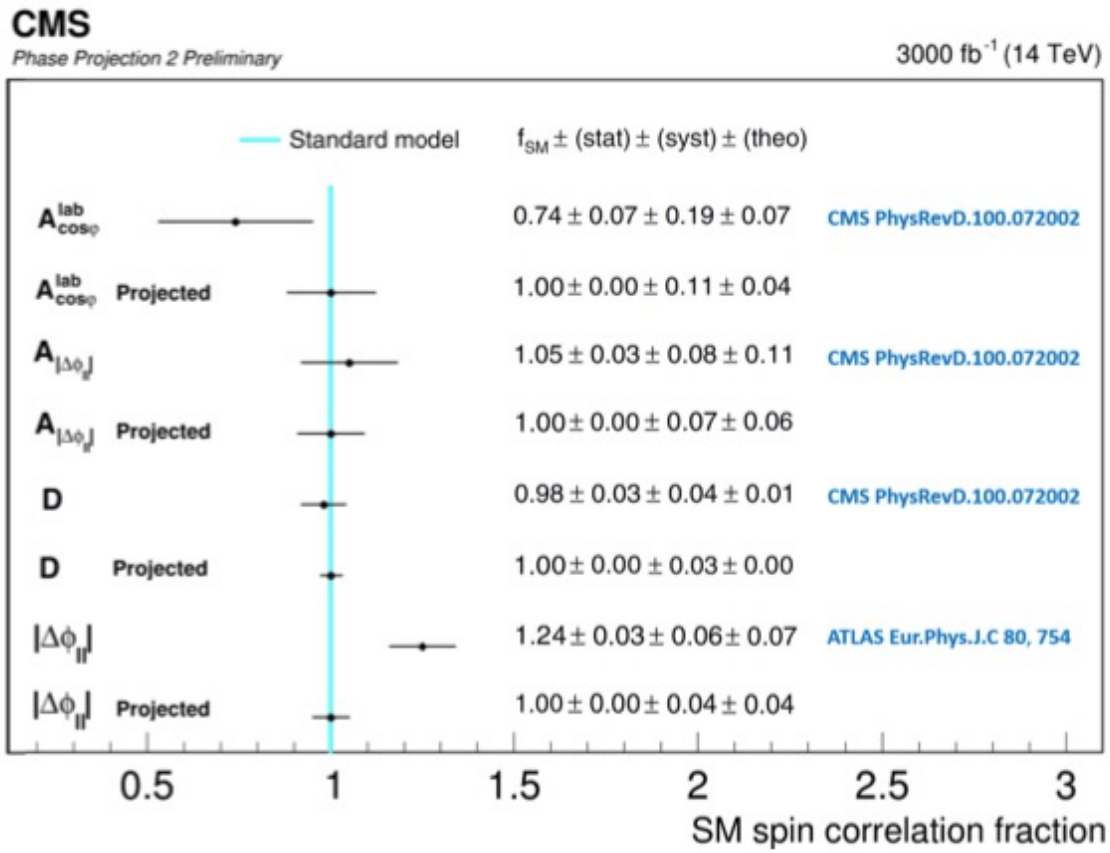


The ILC International Development Team and the ILC Community: The International Linear Collider: Report to Snowmass 2021 (Section 10) arXiv:2203.07622

New EF03/EF04 study:
M. Vos *et al.*: HL-LHC and Higgs factory projections for top measurements

Top-quark spin correlations at the LHC and HL-LHC

Extracted values of SM spin correlation fraction from CMS and ATLAS spin correlation variables and projected values at the LH-LHC:



The ATLAS and CMS collaborations: Physics with the Phase-2 ATLAS and CMS Detectors (Section 4, CERN Yellow report CERN 2019-007)

New EF03/EF04 study:

- Top spin correlations

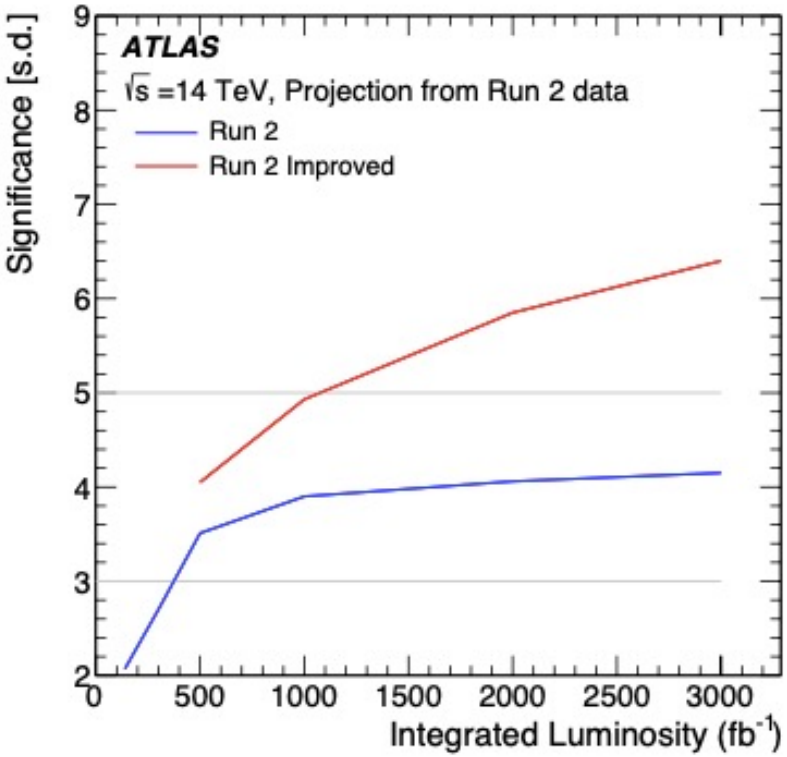
as input for global EFT fits (in progress)

New EF03 study:

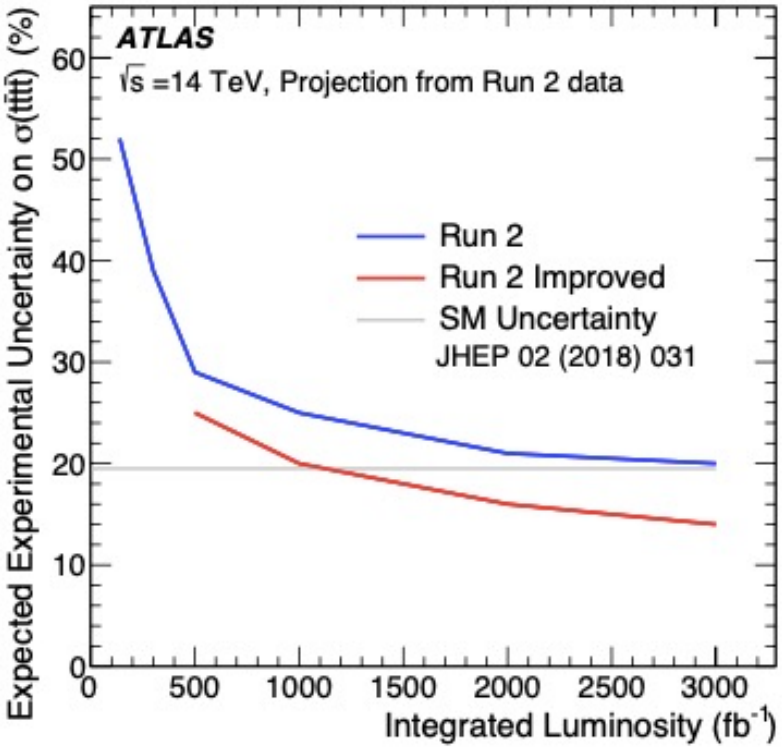
- Projection of top quark spin correlations with CMS at the HL-LHC
- Z. Yu, C.-P. Yuan: Azimuthal angular correlation as a new boosted top jet substructure arXiv:2203.02760

Rare processes: Four top production at the HL-LHC

Expected significance for the measured four top cross section for two scaling scenarios for the systematic uncertainties:



Expected experimental uncertainty for two scaling scenarios for the systematic uncertainties:



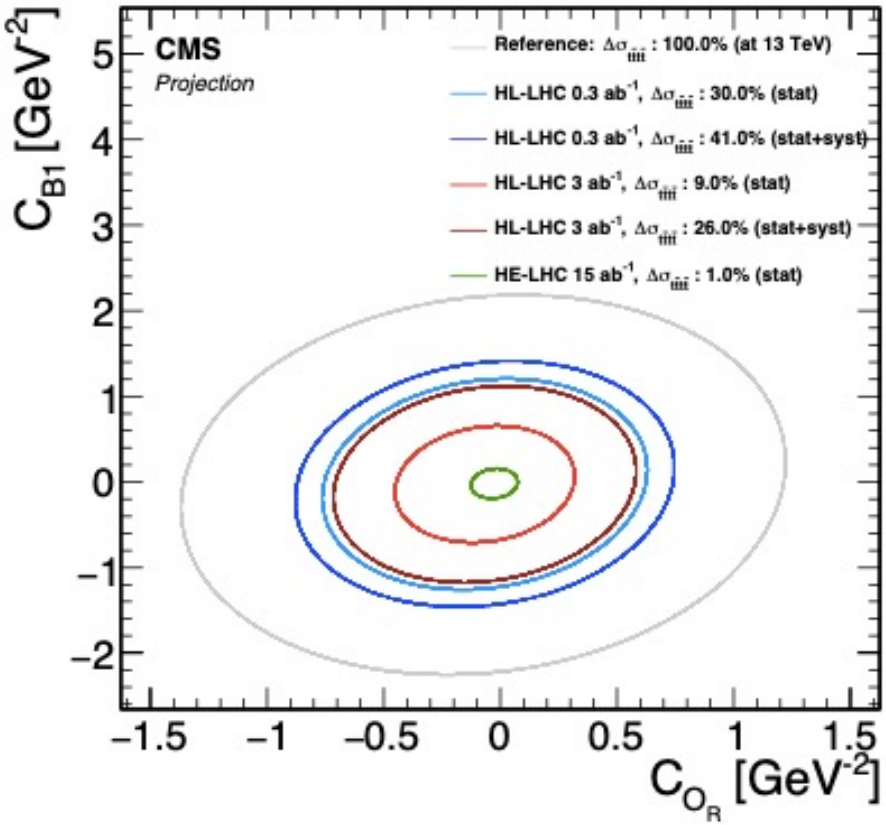
ATL-PHYS-PUB-2022-004

New EF03 study:

- The ATLAS and CMS collaborations: Physics with the Phase-2 ATLAS and CMS Detectors (Section 4, CERN Yellow report CERN 2019-007)

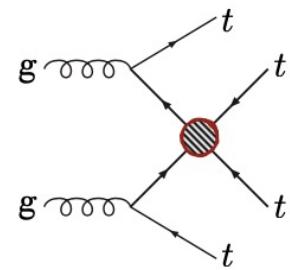
Rare processes: Four top production at the HL-LHC

Expected limits on EFT contact interaction operators for four top production:



CMS PAS FTR-22-0014

Top compositeness:



$$\sim \frac{g_*^2}{m_*^2} s$$

$$\frac{c_{tt}}{\Lambda^2}(\bar{t}_R\gamma_\mu t_R)(\bar{t}_R\gamma^\mu t_R)$$

$$\frac{c_{tt}}{\Lambda^2} \sim \frac{g_*^2}{m_*^2}$$

HL-LHC:

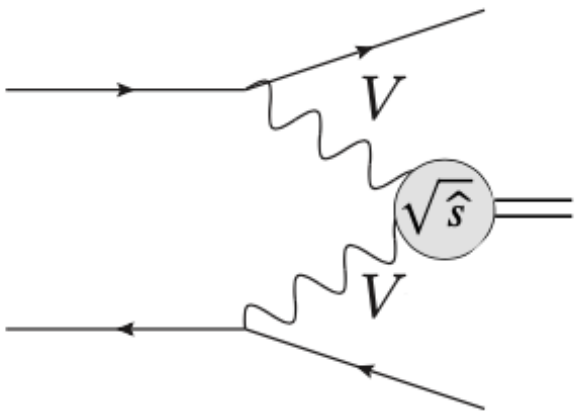
$$\Lambda/\sqrt{|c_{tt}|} > 1.3\,\text{TeV} \quad (\text{no syst.: } 1.4\,\text{TeV})$$

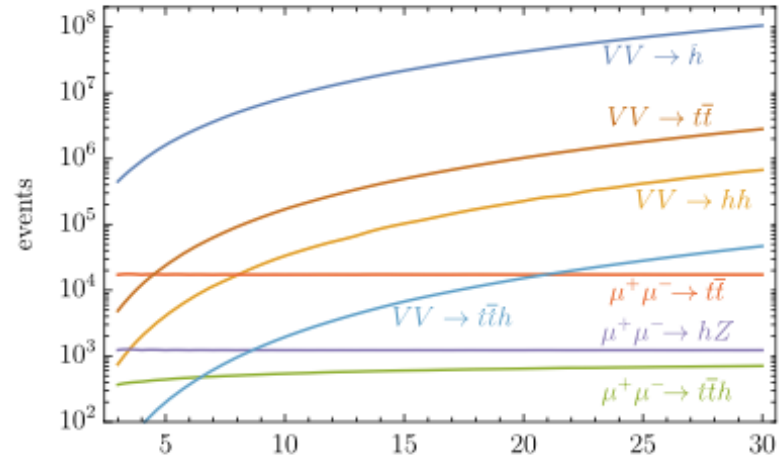
Banelli *et al.*, arXiv:2010.05915

New EF03 study:

- The ATLAS and CMS collaborations: Physics with the Phase-2 ATLAS and CMS Detectors (Section 4, CERN Yellow report CERN 2019-007)

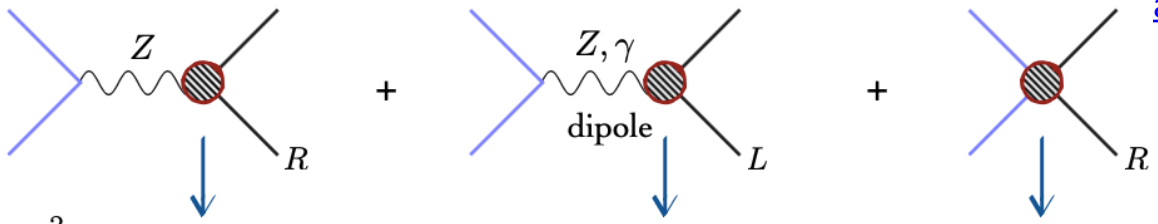
Top-pair production at a muon collider





arXiv:2203.07256

$\mathcal{M}_{\ell^+\ell^- \to t\bar{t}} \sim$



$$\frac{g_*^2}{m_*^2}(H^\dagger D_\mu H)(\bar{t}_R\gamma^\mu t_R) \qquad \frac{y_t g}{m_*^2}\bar{q}_L H \sigma_{\mu\nu} W^{\mu\nu} t_R \qquad \frac{c_{te}}{m_*^2}(\bar{e}_R\gamma_\mu e_R)(\bar{t}_R\gamma^\mu t_R)$$

$$\sim \frac{g_*^2}{m_*^2} m_W^2 \qquad \sim \frac{g^2}{m_*^2} m_t\sqrt{s} \qquad \sim \frac{g_*^2}{m_*^2} s$$

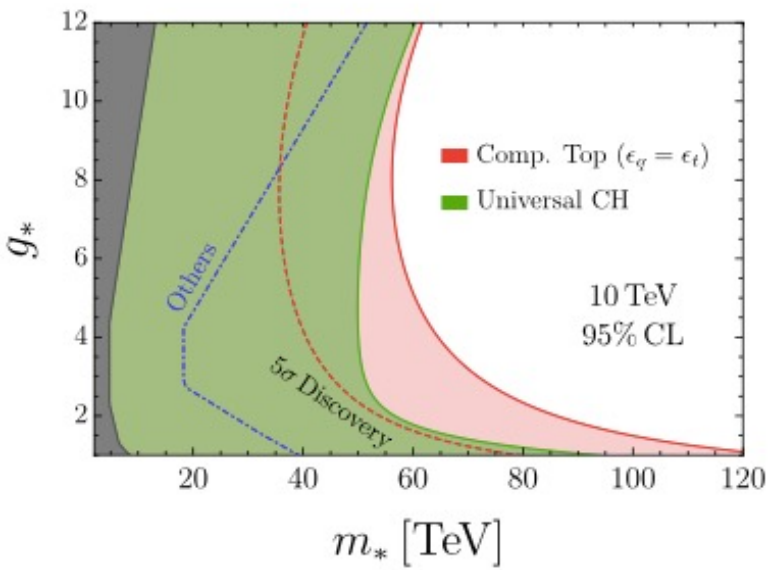
New EF03 study:

- International Muon Collider Collaboration: Muon Collider Physics Summary (Sections 4 and 5) arXiv:2203.07256

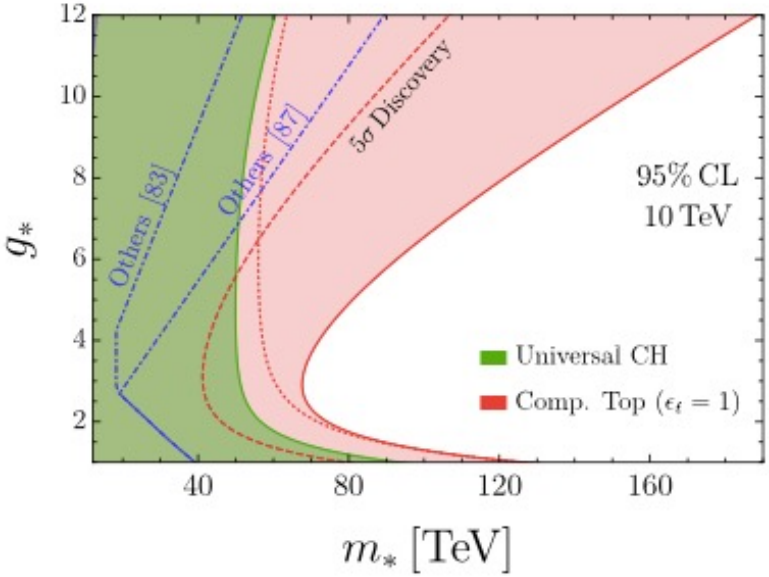
From talk given by T. Theil at the EF Restart Workshop

Top compositeness: ILC, CLIC, muon collider

95% exclusion reach for the two compositeness scenarios:



Also includes the stronger CLIC sensitivity estimate (Others [87]):



Top quark compositeness produces additional signatures that extend the muon collider sensitivity up to the red contour.

S.Chen et al., arXiv:2202.10509

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

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

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

Banelli *et al.*, arXiv:2010.05915

New EF03 study:

- International Muon Collider Collaboration: Muon Collider Physics Summary (Sections 4 and 5) arXiv:2203.07256

This workshop…

- Presentation of contributed papers on Wednesday, 10am-12am EDT and 1pm-1:30pm EDT.
- Discussion of EF03 TG report on Wednesday, 1pm-2pm EDT:
  - We are looking for the experts of certain topics to volunteer to help writing the relevant sections:
    - Top-quark mass: Theory issues and challenges: Andre Hoang
    - ttV production processes (Theory): Manfred Kraus
    - …