SnowMass2021

Snowmass EF03: Heavy flavor and top quark physics

Discussion of our Vision

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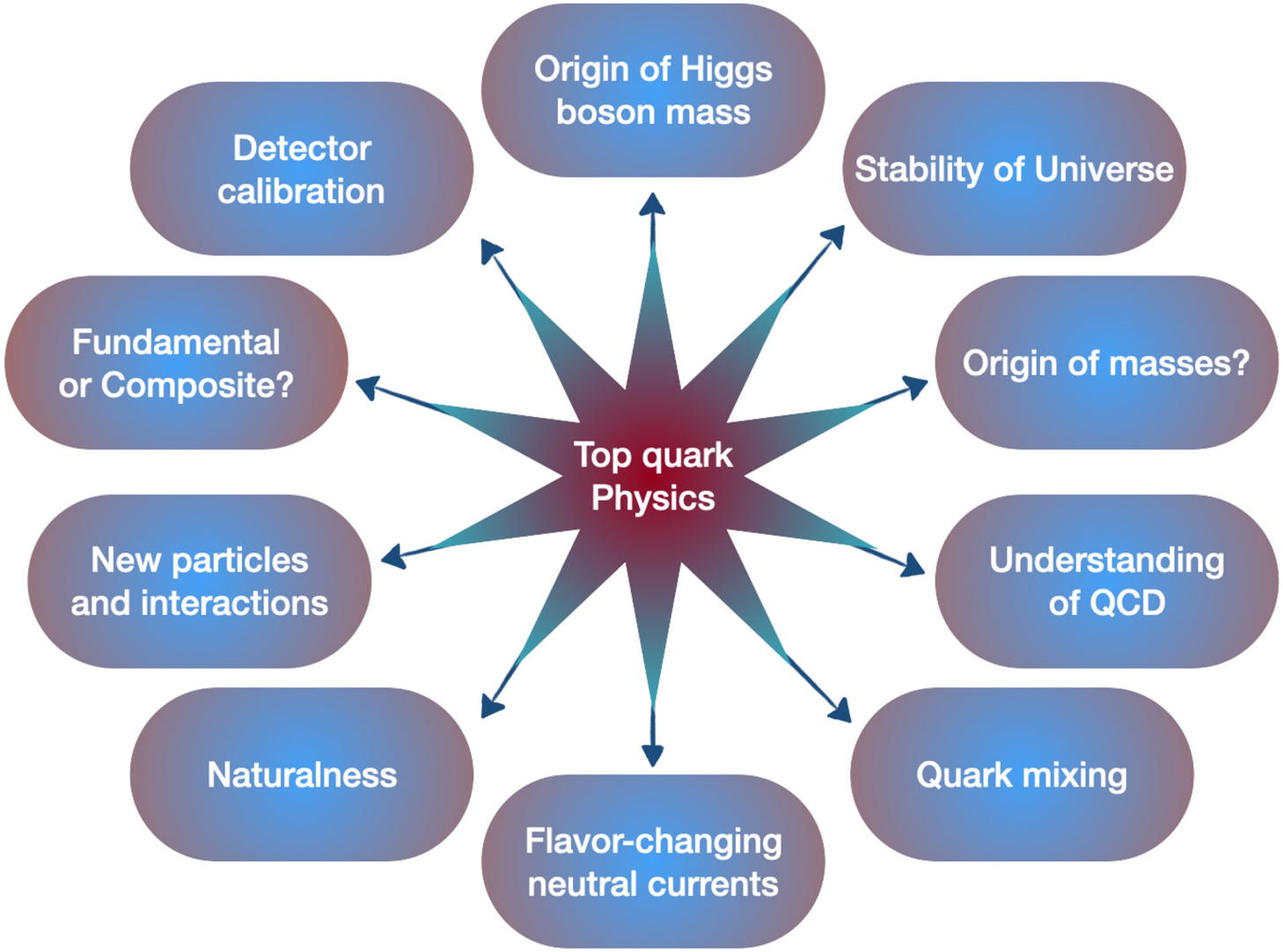
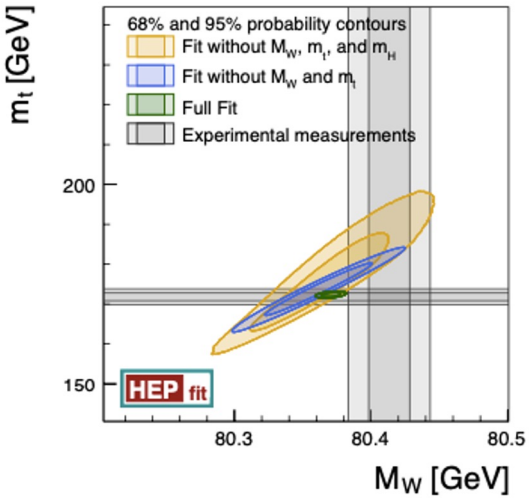
The many facets of heavy flavor and top quark physics



Top-quark physics at the energy frontier

- Top quarks play a central role in the exploration of the energy frontier, second only to the Higgs boson.
- The plethora of studies performed for Snowmass 2021 underlines the breadth of topics and the multitude of challenges.
- Of particular importance is the top quark mass, e.g., it is a key ingredient in EW precision fits.
- Top-quark pair and rare ttX (X=Z,H,…) production processes probe all aspects of the top-quark couplings to the SM bosons.
- Searches for new physics in top-quark final states focus on the third-generation coupling of BSM particles, indirectly through EFT fits or searches for FCNC, and directly through searches for SUSY and other new particles.
- Contact interaction and searches for compositeness are examples of BSM physics that top-quark production is sensitive to at TeV energies and above.

Top-quark mass



arXiv:2204.04204

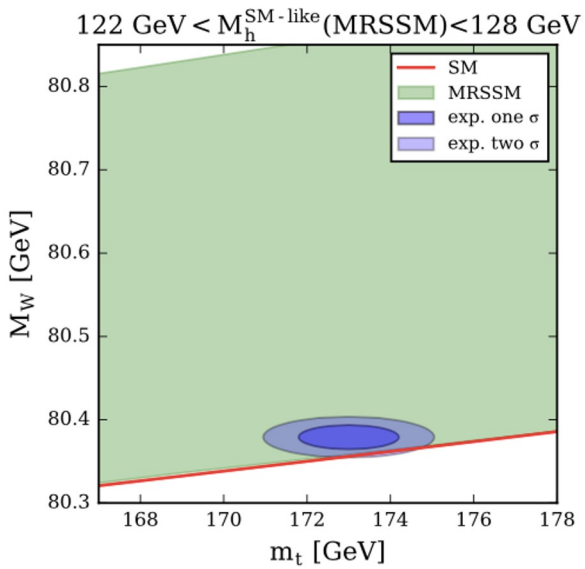
Top mass uncertainty introduces largest parametric uncertainty in W boson mass prediction:

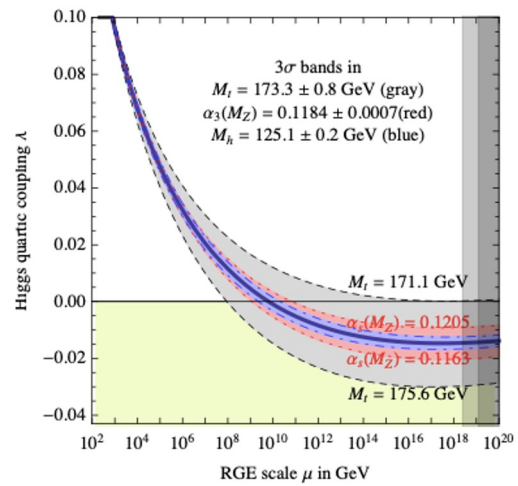
$$\delta m_t = 500\,\mathrm{MeV} \rightarrow \delta M_W^{theo.} \approx 3\,\mathrm{MeV}$$

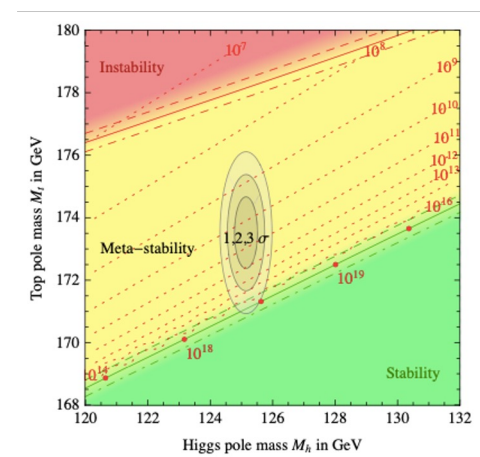
$$\delta m_t = 100\,\mathrm{MeV} \rightarrow \delta M_W^{theo.} \approx 0.6\,\mathrm{MeV}$$

$$\delta m_t = 50\,\mathrm{MeV} \rightarrow \delta M_W^{theo.} \approx 0.3\,\mathrm{MeV}$$

hep-ph/0311148



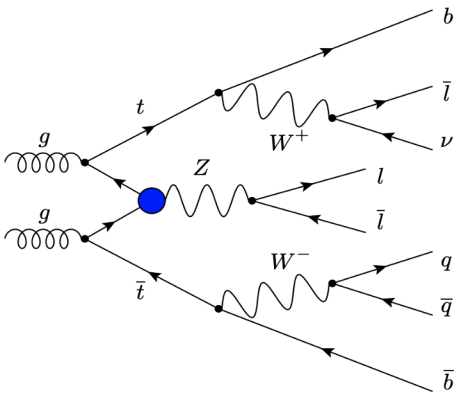


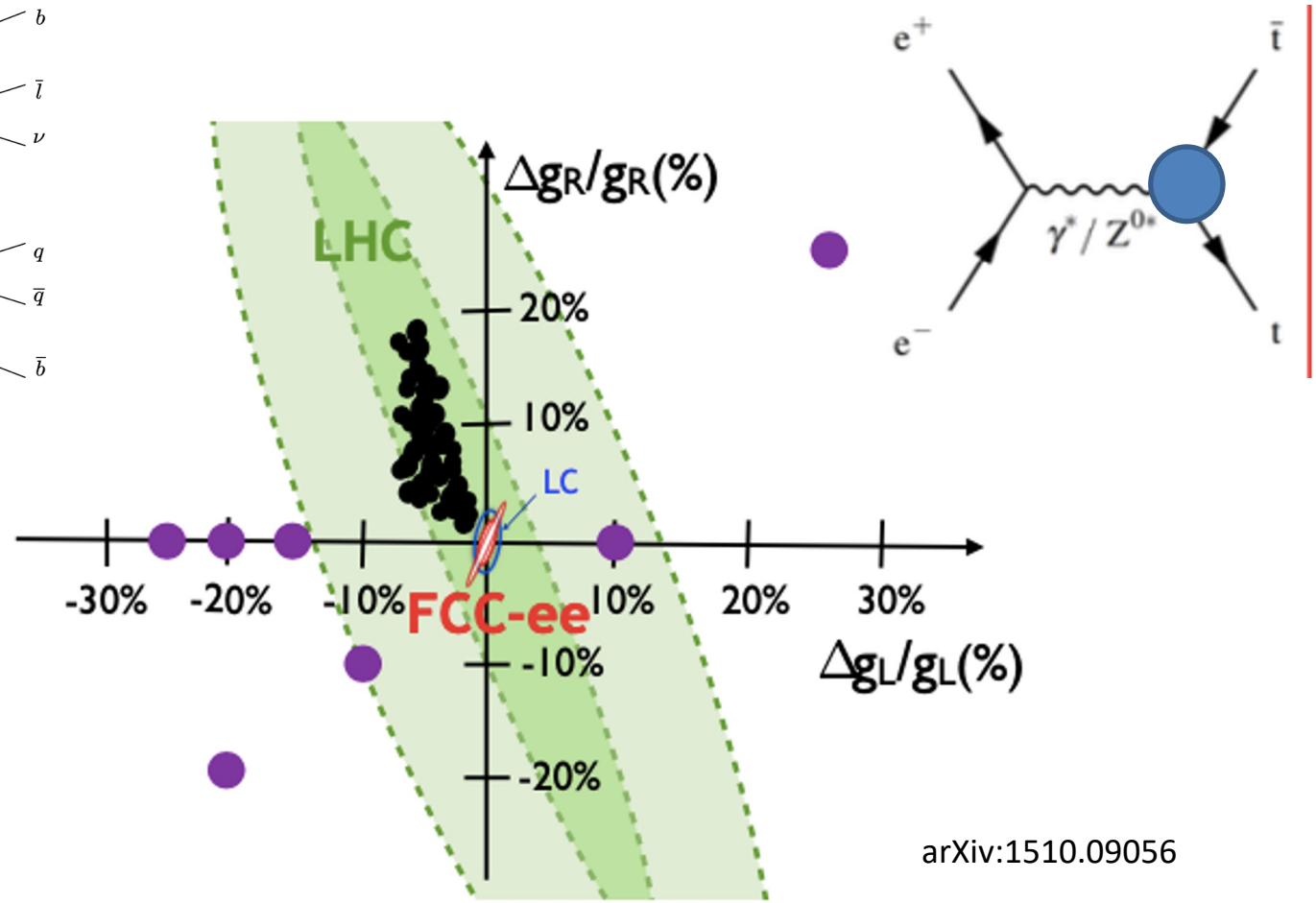


arXiv:1307.3536

arXiv:1904.03634

EW top-quark couplings: a window to BSM physics

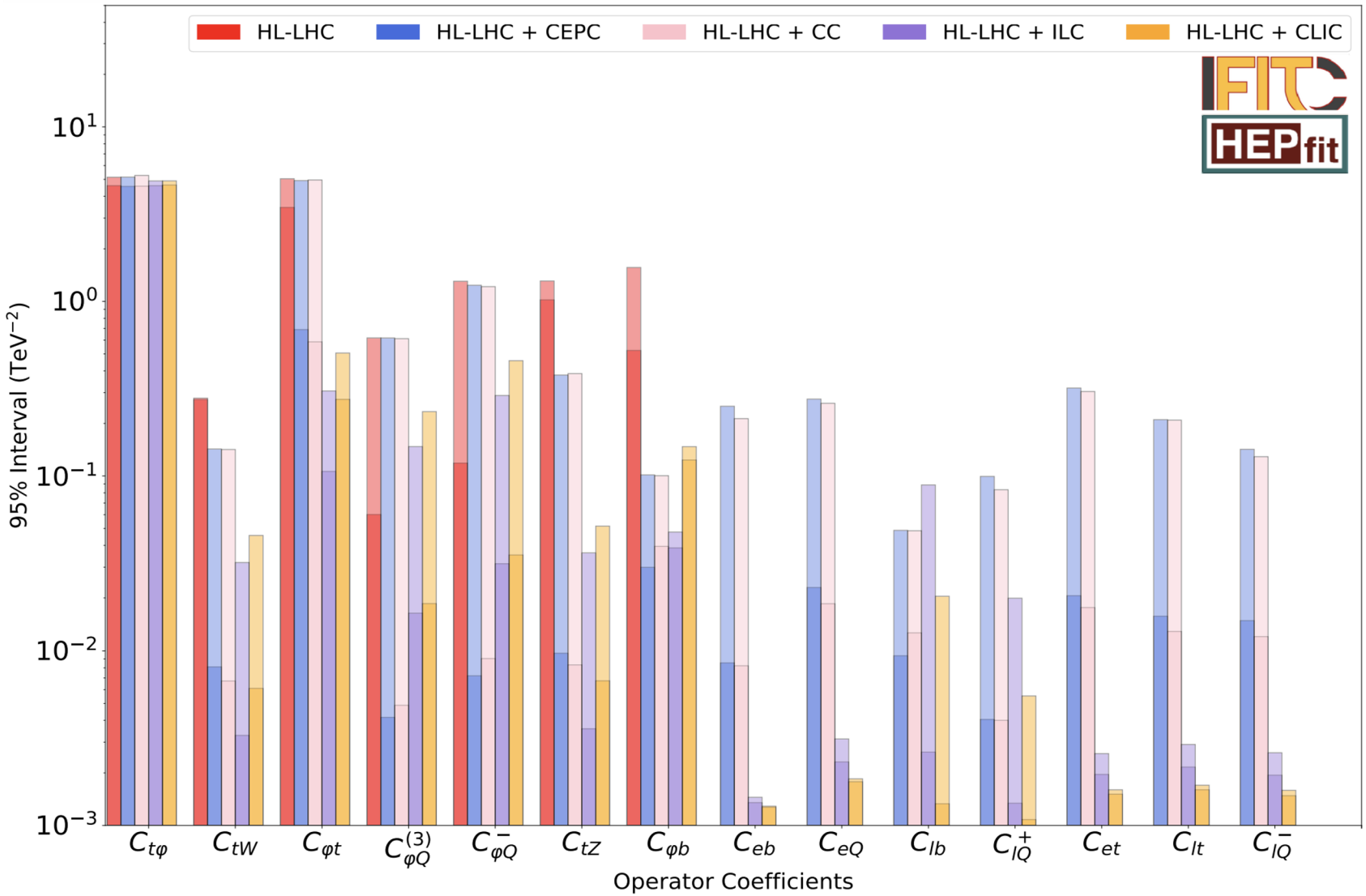




arXiv:1510.09056

Figure 1-22. *Expected relative precision on the Zt_Lt_L and Zt_Rt_R couplings at the LHC (lighter green), the HL-LHC (darker green), the ILC (blue) and the FCC-ee (orange, red). The black dots indicate the deviations expected for different parameter choices of 4D composite Higgs models, with $f < 2$ TeV (purple dots: examples for typical deviations in various BSM models). From [478].*

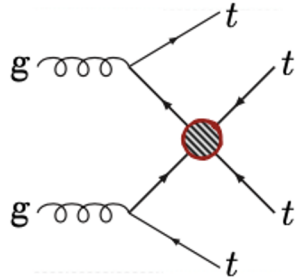
EFT fits: HL-LHC and ILC and FCC-ee and CLIC



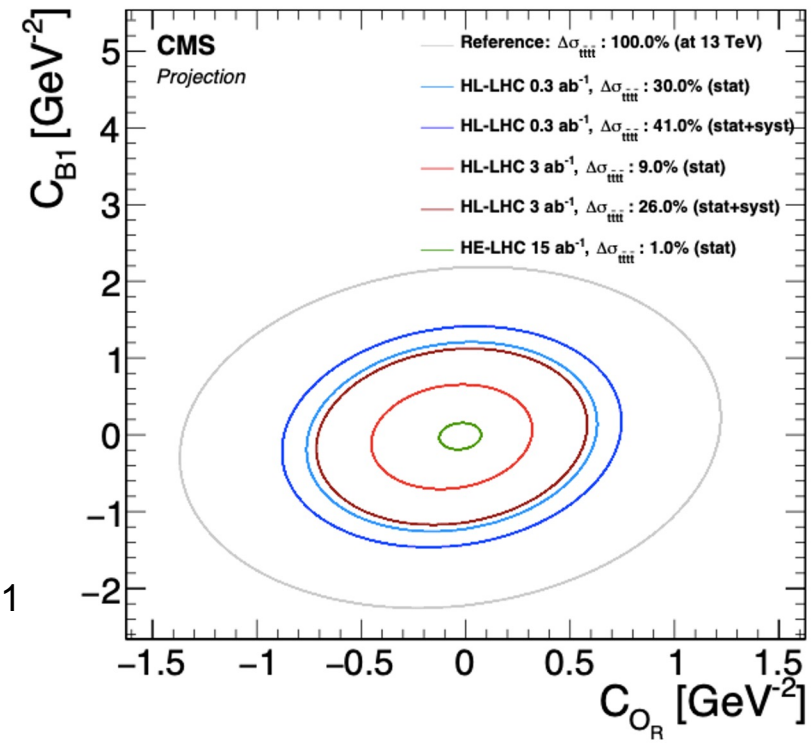
https://arxiv.org/abs/2205.02140

Four-top operators, contact interaction and compositeness

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



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



CMS-PAS-FTR-18-031

Figure 1-21. *Expected limits on EFT contact interaction operators for the $t\bar{t}t\bar{t}$ process. Taken from Ref [437].*

	HL-LHC($pp \to tttt$) ($pp \to tttt$)	FCC-ee ($e^+e^- \to tt$)	ILC ($e^+e^- \to tt$)	CLIC ($e^+e^- \to tt$)	FCC-hh ($pp \to tttt$)
$\sqrt{s}$ [TeV]	14	0.365	1	3	100
$\mathcal{L}$[ab^{-1}]	3	1.5	1	3	30
$\Lambda/\sqrt{\lvert c_{tt}\rvert}$ [TeV]	1.3	1.6	4.1	7.7	6.5

Table 1-7. *Bounds on the four-top operator. Taken from [430]*

arXiv:2010.05915

Bounds on Composite Higgs/Top-quark models

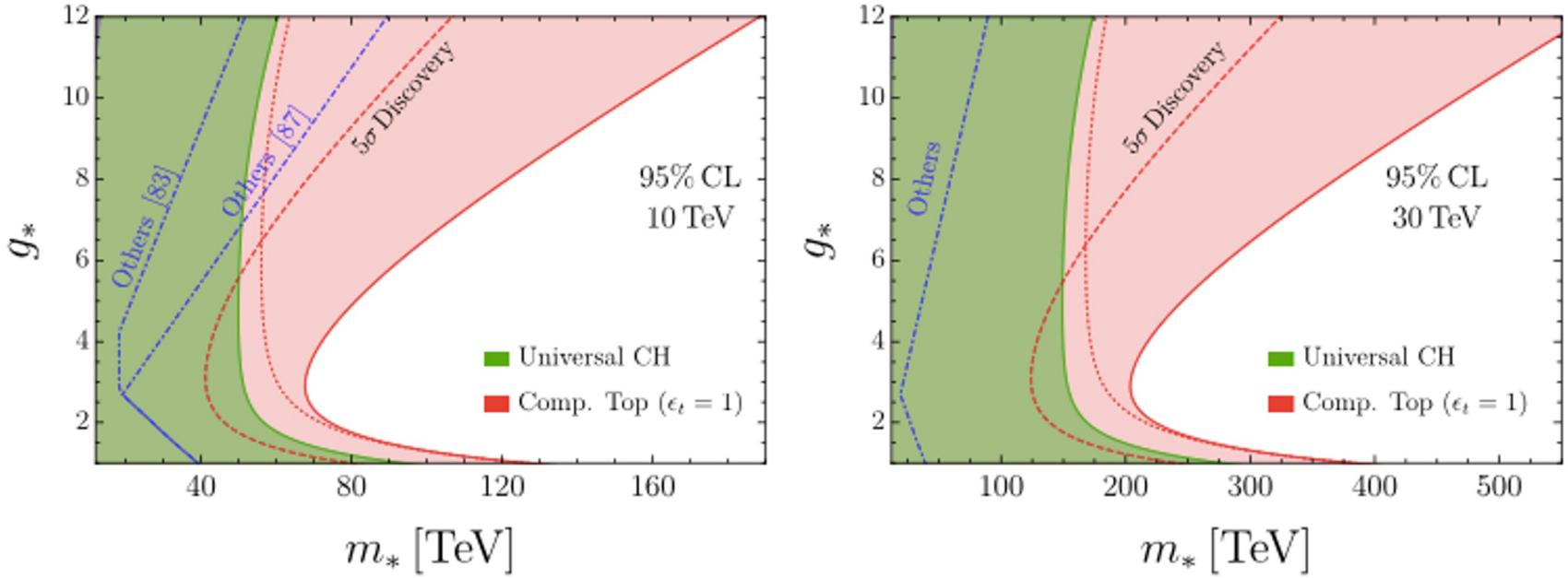
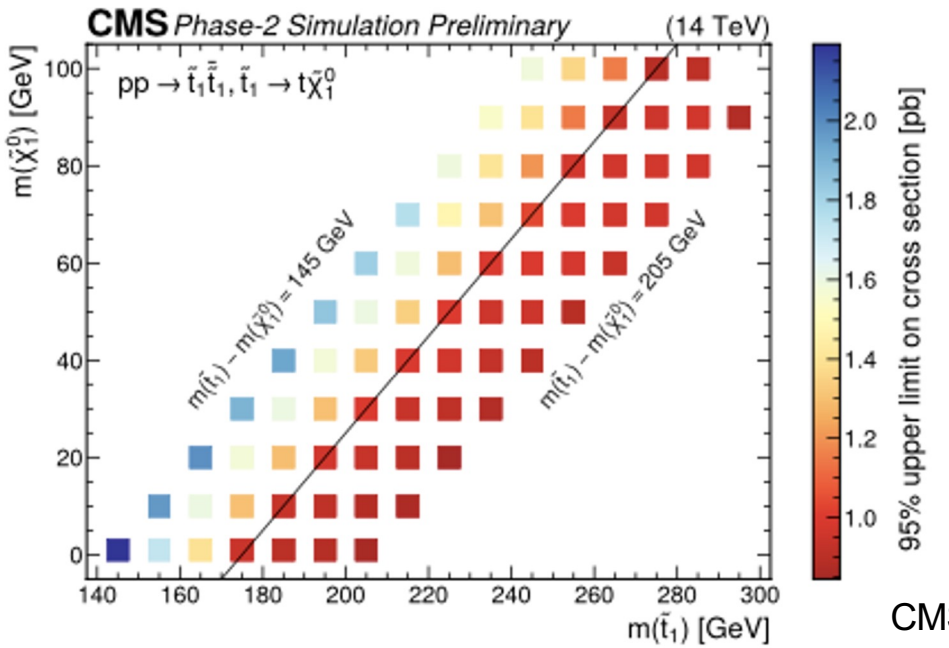


Figure 1-28. *Projected 95% exclusion reach at a 10 TeV (left) and 30 TeV (right) muon collider when including $t\bar{t}$ (and $b\bar{b}$) production (red shaded area) in a top compositeness model where the right-handed top quark is considered fully composite. Also shown are projections obtained for the HL-LHC (labeled as 'Others [83]') [497] and for CLIC (labeled as 'Others [87]') [430]. From [496].*

arXiv:2202.10509

Top-quark spin correlations: Bounds on SUSY top squark production

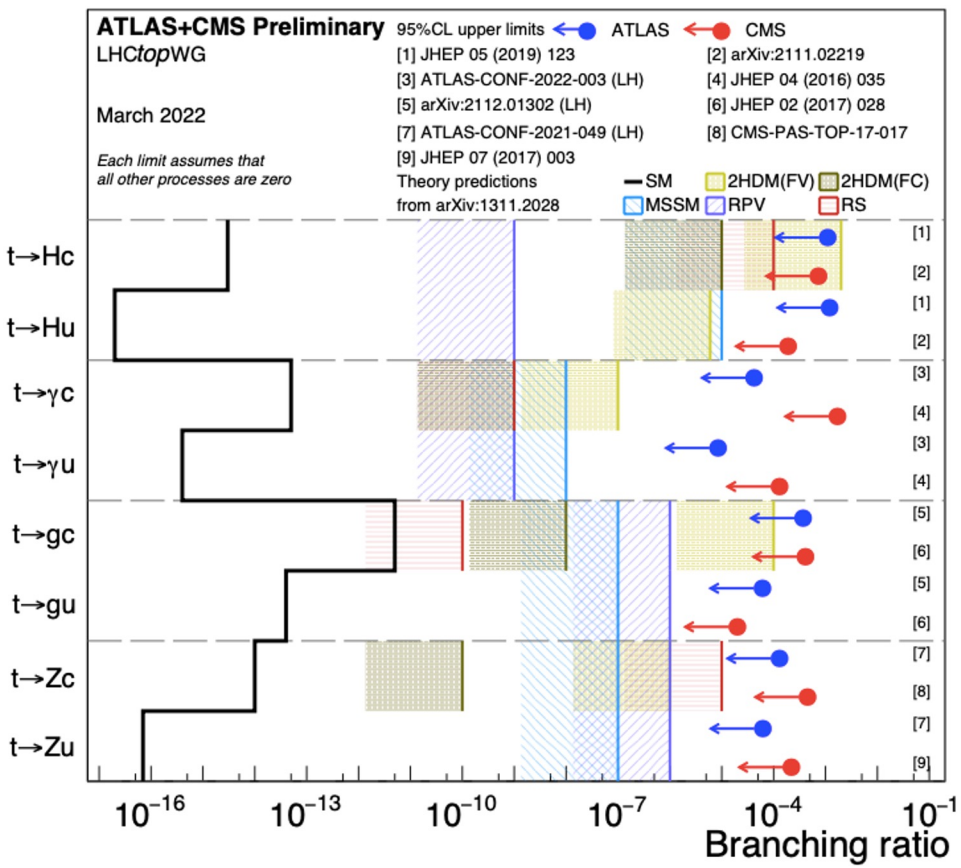


CMS-PAS-FTR-18-034

Figure 1-23. *Limit on the cross-section for SUSY stop production in the compressed region where the stop mass ($m(\tilde{t})$) is close to the neutralino mass ($m(\chi_0)$), $m(\tilde{t}) - m(\chi_0) = 175$ GeV. From Ref. [479].*

FCNC at the LHC and HL-LHC

- Top quark interactions are an excellent probe of flavor-changing neutral currents (FCNC).



Prospects for the HL-LHC:

B(t->ug)< 3.8 10^{-6}

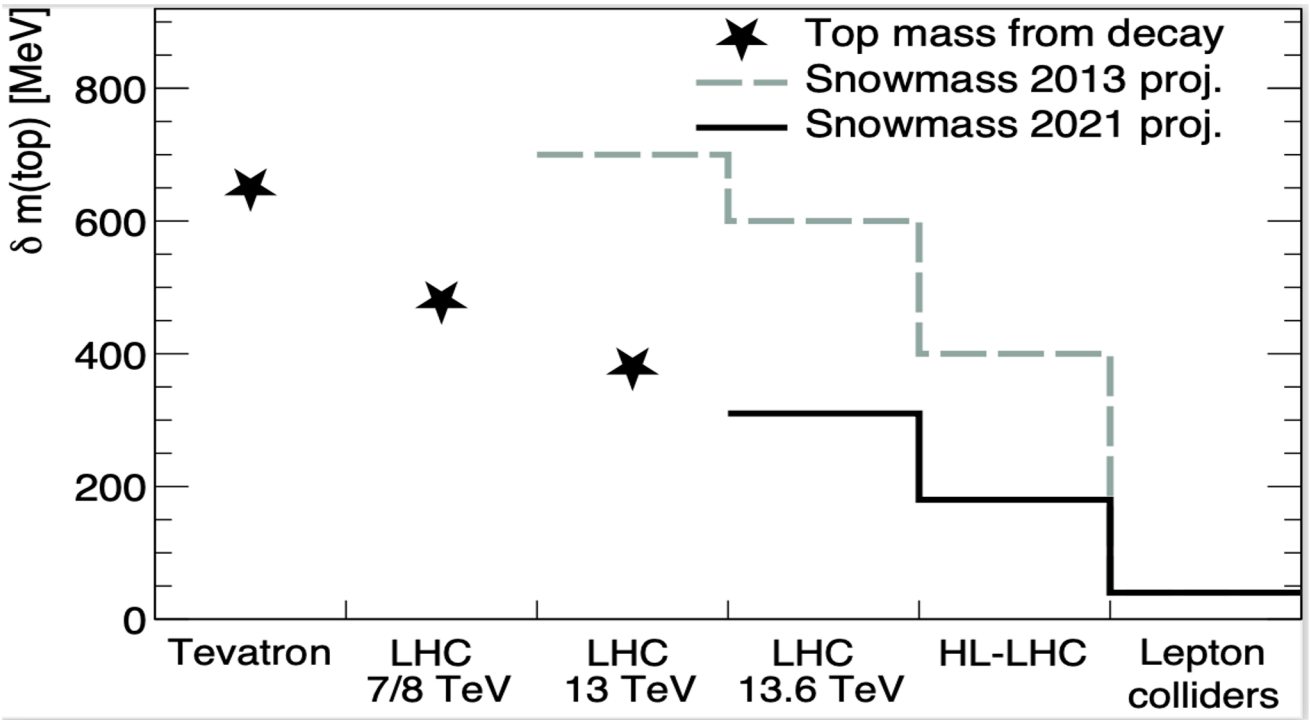
B(t->cg) < 32 10^{-6}

B(t->Zc,Zu) < 4-5 10^{-5}

B(t->Hc,Hu) < 10^{-4}

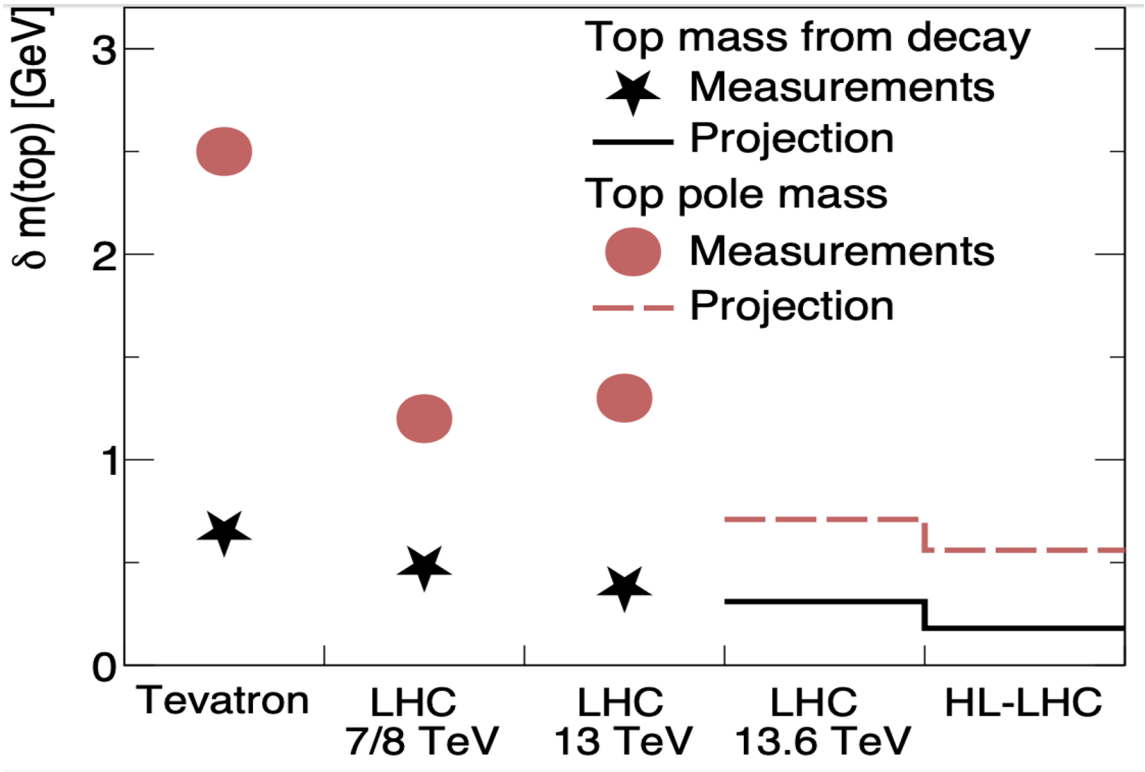
Top quark mass measurement from top decays at the LHC

- Mass is extracted from detector-level kinematic distributions by comparing to MC event generator predictions (MC mass or *direct measurement*)
- Comparison to projections from Snowmass 2013



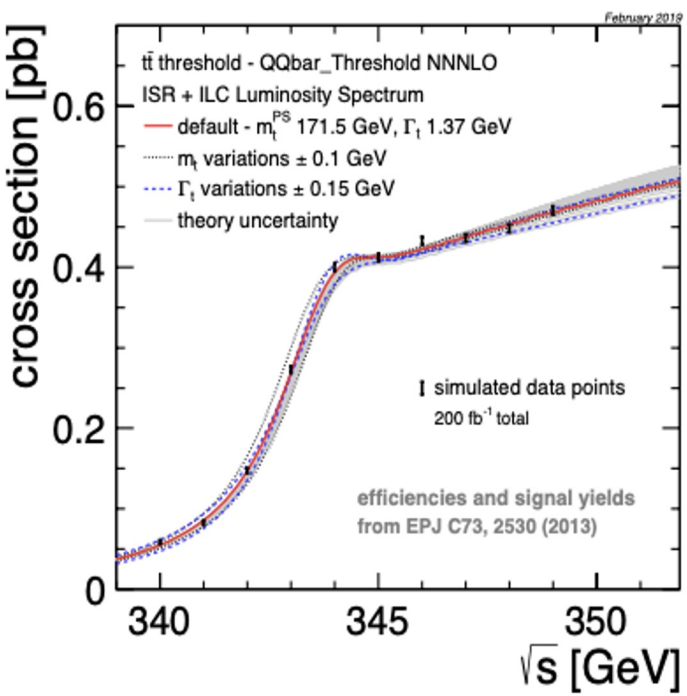
Top quark MC and pole mass at the LHC and HL-LHC

- Measurement in well-defined scheme is based on measured cross sections unfolded to parton level and compared to theory predictions at least at NLO QCD (from tt production and from ttj) in,e.g., MSbar or pole scheme (*indirect measurement*)
- Note: Measurements at 13 TeV have not yet been combined between channels

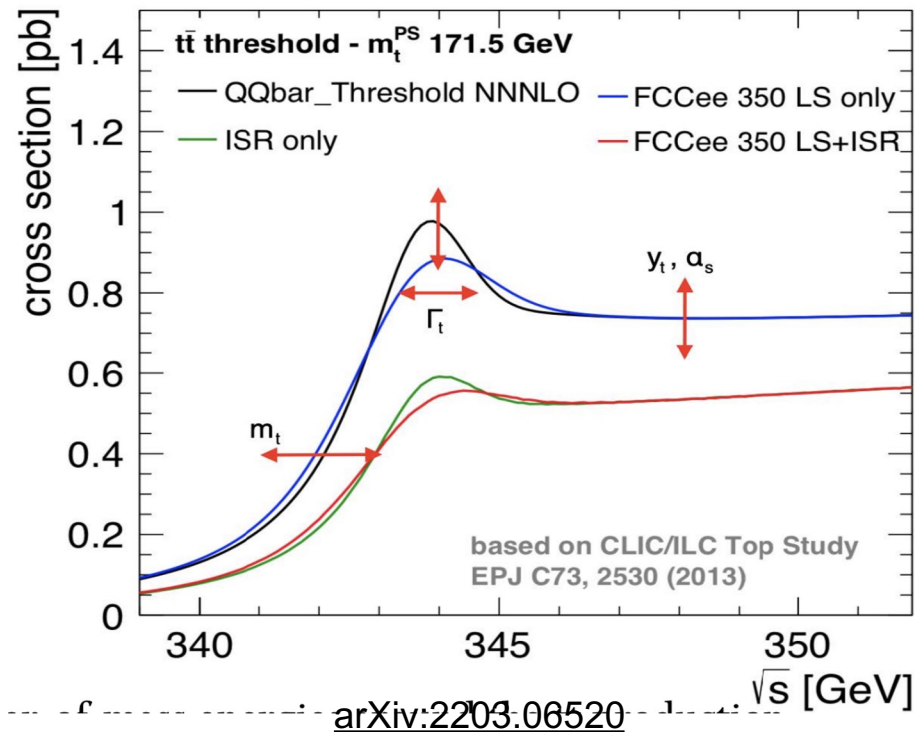


Top-quark mass at e^+e^- Colliders (ILC, CLIC, FCC-ee)

- Threshold scan around 350 GeV to determine PS mass
- Can also fit mass, width, Yukawa and α_S simultaneously
- Theory systematics include missing higher orders, parametric uncertainty due to α_S
- Conversion of PS to MSbar mass known at 4-loop, uncertainty: 23 MeV



arXiv:2203.07622



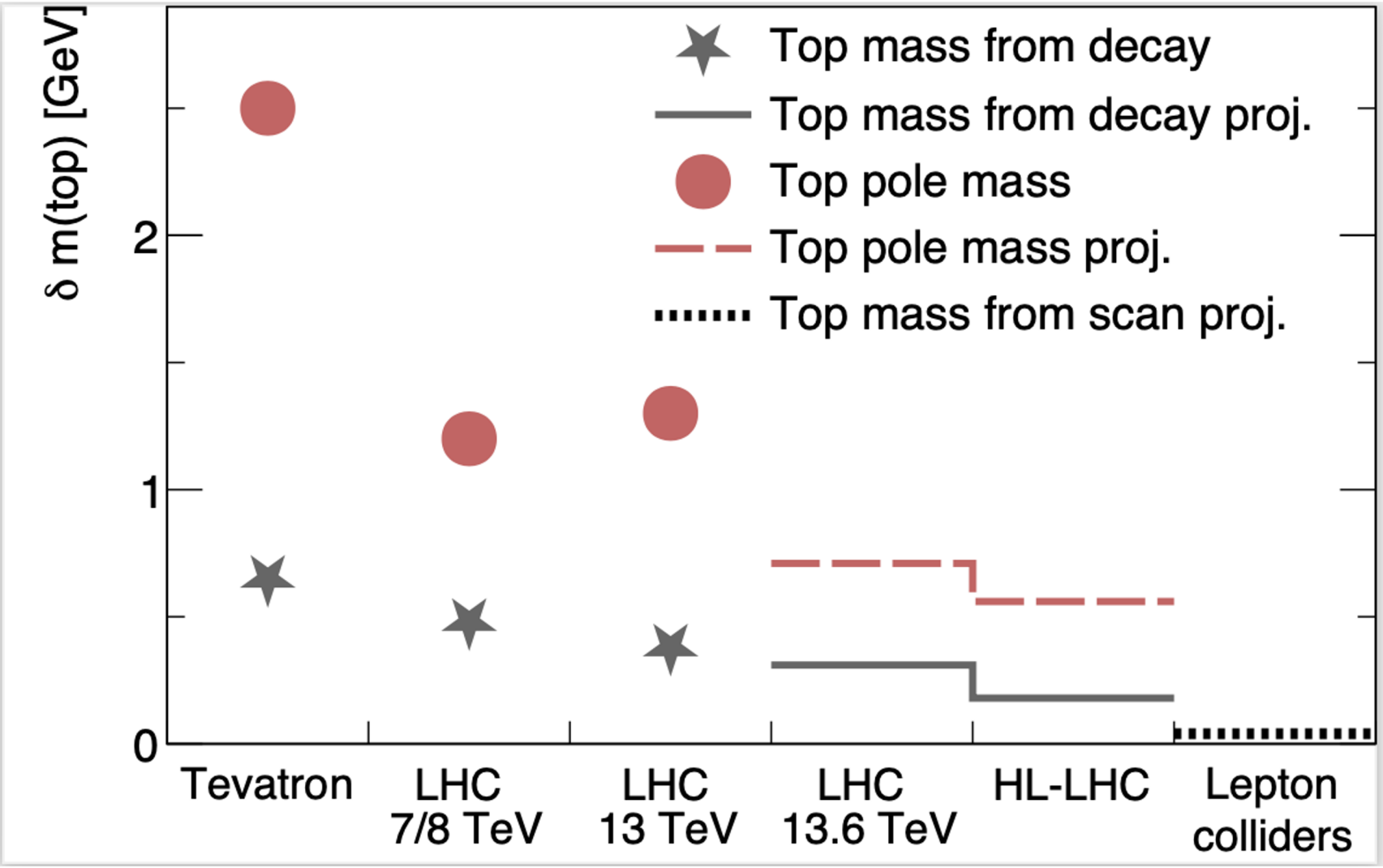
arXiv:2203.06520

PS top quark mass: ILC, CLIC, FCC-ee

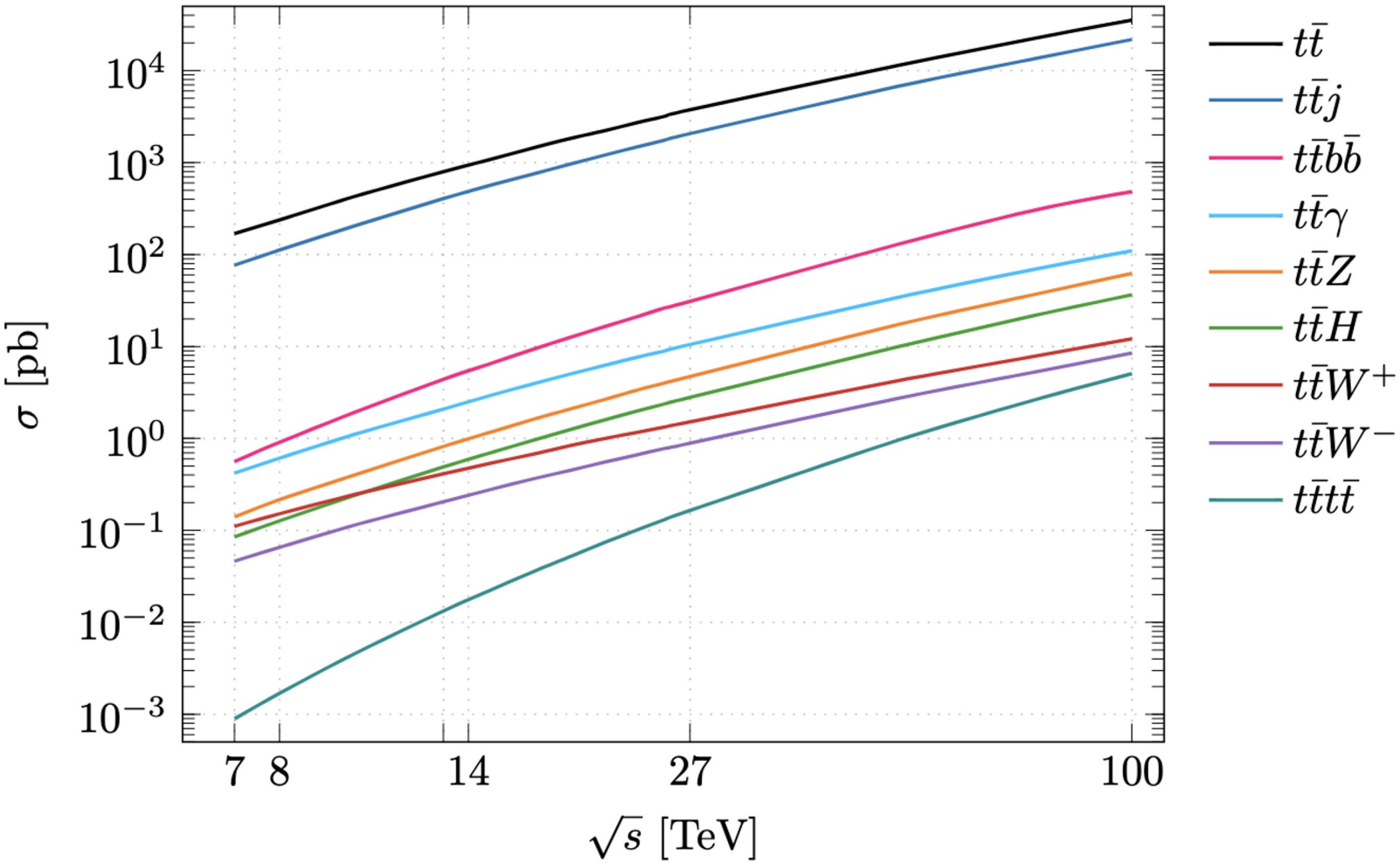
- Top mass from threshold scan at a lepton collider
- Experimental uncertainties should be similar
  - Circular colliders have larger samples, better energy calibration
  - Current uncertainty on α_s leads to 26 MeV top mass uncertainty
  - Terra-Z running at FCC-ee will reduce this significantly

δm_t^{PS} [MeV]	ILC	CLIC	FCC-ee
$\mathcal{L}[\mathrm{fb}^{-1}]$	200	100 [200]	200
Statistical uncertainty	10	20 [13]	9
Theoretical uncertainty (QCD)		40 – 45	
Parametric uncertainty α_s	26	26	3.2
Parametric uncertainty y_t HL-LHC		5	
Non-resonant contributions		< 40	
Experimental systematic uncertainty		20 – 30	11 – 20
Total uncertainty		40 – 75	

Top quark mass projection summary



Top quark production processes at hadron colliders

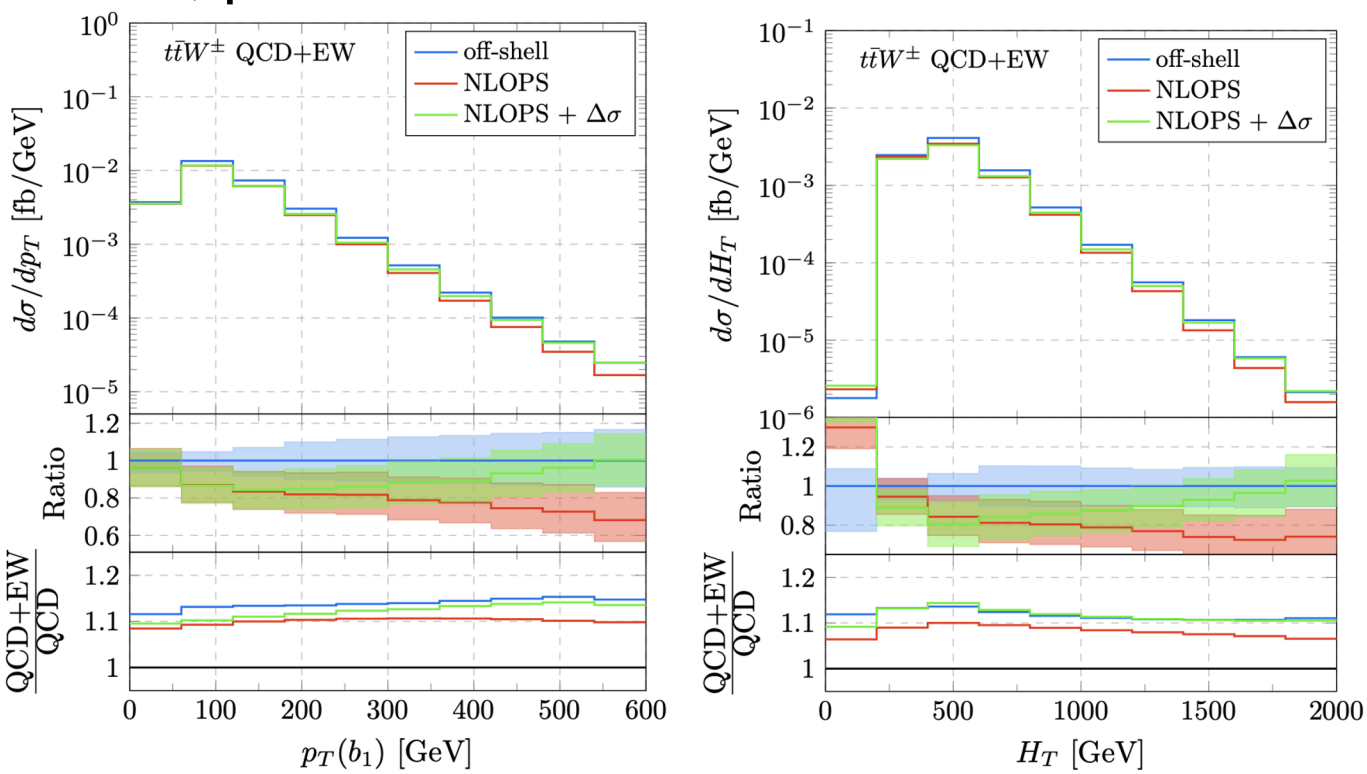


ttX, X = γ, Z, W , H, tt: theory predictions for LHC and HL-LHC

- ttj: NLO scale uncertainties estimated to be of the order of 10 – 20% at the differential level. First steps have been taken towards NNLO QCD.
- tt γ: NNLO QCD corrections for pp → ttγ become necessary in order to exploit the full potential of future data sets, including in EFT fits
- ttZ: ±8% can be obtained for integrated fiducial cross sections and of the order of ±10% at the differential level (NLO+NNLL), same level as exp. unc: needs further improvements.
- ttW: HL-LHC: factor of 2 improvement needs NNLO.
- ttH: HL-LHC again needs NNLO QCD.
- tttt: Currently, NLO scale uncertainties amount to +- 20% (and 5% PDF unc.), HL-LHC measurement of tttt will be limited by signal modeling. Again further theory improvements are needed (e.g., matching to PS).

An example: Modeling uncertainties in pp -> ttW

- ttW is background to many measurements and searches (Higgs, SUSY, 4-top, etc.)
- Improved theory calculations, including off-shell tops
- Study of modeling uncertainties: NWA vs full off-shell, generators, parton showers



arXiv:2109.15181

EFT fits, top quark measurements

Process	Observable	$\sqrt{s}$	L_{int}	Experiment	SM	Ref.
$pp \to t\bar{t}$	$d\sigma/dm_{t\bar{t}}$ (15+3 bins)	13 TeV	140 fb^{-1}	CMS	[34]	[189]
$pp \to t\bar{t}$	$dA_C/dm_{t\bar{t}}$ (4+2 bins)	13 TeV	140 fb^{-1}	ATLAS	[34]	[418]
$pp \to t\bar{t}H + tHq$	σ	13 TeV	140 fb^{-1}	ATLAS	[419]	[420]
$pp \to t\bar{t}Z$	$d\sigma/dp_T^Z$ (7 bins)	13 TeV	140 fb^{-1}	ATLAS	[307]	[421]
$pp \to t\bar{t}\gamma$	$d\sigma/dp_T^\gamma$ (11 bins)	13 TeV	140 fb^{-1}	ATLAS	[250, 251]	[422]
$pp \to tZq$	σ	13 TeV	77.4 fb^{-1}	CMS	[423]	[424]
$pp \to t\gamma q$	σ	13 TeV	36 fb^{-1}	CMS	[425]	[425]
$pp \to t\bar{t}W$	σ	13 TeV	36 fb^{-1}	CMS	[419, 348]	[426]
$pp \to t\bar{b}$ (s-ch)	σ	8 TeV	20 fb^{-1}	LHC	[196, 427]	[428]
$pp \to tW$	σ	8 TeV	20 fb^{-1}	LHC	[168]	[428]
$pp \to tq$ (t-ch)	σ	8 TeV	20 fb^{-1}	LHC	[196, 427]	[428]
$t \to Wb$	F_0, F_L	8 TeV	20 fb^{-1}	LHC	[429]	[430]
$p\bar{p} \to t\bar{b}$ (s-ch)	σ	1.96 TeV	9.7 fb^{-1}	Tevatron	[431]	[432]
$e^-e^+ \to b\bar{b}$	R_b , A^{bb}_{FBLR}	$\sim$ 91 GeV	202.1 pb^{-1}	LEP/SLD	-	[433]

Table 1-8. *Measurements included in the EFT fit of the top-quark electroweak sector. For each measurement, the process, the observable, the centre-of-mass energy, the integrated luminosity and the experiment/collider are given. The last two columns list the references for the predictions and measurements that are included in the fit. LHC refers to the combination of ATLAS and CMS measurements. In a similar way, Tevatron refers to the combination of CDF and D0 results, and LEP/SLD to different experiments from those two accelerators.*

A selection of top-quark measurements

Comparison of a few top-quark measurements between different future collider options:

Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s}$ [TeV]	14	0.5	0.36	100
Yukawa coupling y_t (%)	3.4	2.8	3.1	1.0
Top mass m_t (%)	0.10	0.031	0.025	–
Left-handed top-W coupling $C^3_{\phi Q}$ (TeV^{-2})	0.08	0.02	0.006	–
Right-handed top-W coupling C_{tW} (TeV^{-2})	0.3	0.003	0.007	–
Right-handed top-Z coupling C_{tZ} (TeV^{-2})	1	0.004	0.008	–
Top-Higgs coupling $C_{\phi t}$ (TeV^{-2})	3	0.1	0.6	
Four-top coupling c_{tt} (TeV^{-2})	0.6	0.06	–	0.024
FCNC $t\gamma u$, tZu BR	10^{-5}	10^{-6}	10^{-5}	–

Table 1-10. *Anticipated precision of top quark Yukawa coupling and mass measurements, and of example EFT Wilson coefficient for the top quark coupling to W, Z and Higgs bosons, as well as a four-top Wilson coefficient. The expected reach of the CEPC should mirror that of the FCC-ee.*

Theory Challenges

Significant theoretical effort is required to exploit the full potential of future colliders:

- Calibration of the top quark MC mass to a well-defined scheme with a precision comparable to the experimental uncertainty.
- Computing cross-sections, inclusively and differentially at higher orders in perturbation theory, going to N3LO in QCD for top pair production plus resummation, going to NNLO in QCD for associated production processes, and computing EW higher order corrections.
- Reducing the PDF uncertainties, which are already now the largest theory uncertainties for several processes, most importantly top-pair production.
- Improving the modeling of the full event at hadron and lepton colliders and at hadron colliders reducing parton shower uncertainties.

A sustained and dedicated effort on the theory side is needed already in the LHC/HL-LHC era.

See also TF06, TF07 and CompF2 reports.

We look forward to your feedback:

Report and Feedback