

Snowmass EF03: Heavy flavor and top quark physics

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The many facets of heavy flavor and top quark physics



Need to measure top-quark mass precisely

 Theoretical W boson mass uncertainty has large contribution from top quark loops

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

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

hep-ph/0311148

- Stability of the electroweak vacuum hinges on top mass
 - Higgs mass and α_s uncertainties smaller



Current top mass measurements at the LHC

- Large experimental program
 - Mass from decay (MC mass) has additional uncertainty for interpretation in well-defined scheme (less than ~500 MeV)

ATLAS+CMS Preliminary LHC <i>top</i> WG	m _{top} summary, √s = 7-13 TeV	June 2022						
World comb. (Mar 2014) [2] stat	I + ∓ I total stat							
total uncertainty	$m_{top} \pm total (stat \pm syst)$	vs Ref.						
LHC comb. (Sep 2013) LHCtopWG HITH	173.29 ± 0.95 (0.35 ± 0.88)	7 TeV [1]						
World comb. (Mar 2014)	173.34 \pm 0.76 (0.36 \pm 0.67)	1.96-7 TeV [2]						
ATLAS, I+jets	$172.33 \pm 1.27 \ (0.75 \pm 1.02)$	7 TeV [3]						
ATLAS, dilepton	173.79 ± 1.41 (0.54 ± 1.30)	7 TeV [3]						
ATLAS, all jets	 175.1 ± 1.8 (1.4 ± 1.2)	7 TeV [4]						
ATLAS, single top	$172.2 \pm 2.1 (0.7 \pm 2.0)$	8 TeV [5]						
ATLAS, dilepton	$172.99 \pm 0.85 (0.41 \pm 0.74)$	8 TeV [6]						
ATLAS, all jets	- 173.72 ± 1.15 (0.55 ± 1.01)	8 TeV [7]						
ATLAS, I+jets	172.08 ± 0.91 (0.39 ± 0.82)	8 TeV [8]						
ATLAS comb. (Oct 2018) HTH	172.69 \pm 0.48 (0.25 \pm 0.41)	7+8 TeV [8]						
ATLAS, leptonic invariant mass (*)	174.48 ± 0.78 (0.40 ± 0.67)	13 TeV [9]						
CMS, I+jets	173.49 ± 1.06 (0.43 ± 0.97)	7 TeV [10]						
CMS, dilepton	$172.50 \pm 1.52 \; (0.43 \pm 1.46)$	7 TeV [11]						
CMS, all jets	173.49 ± 1.41 (0.69 ± 1.23)	7 TeV [12]						
CMS, I+jets	$172.35 \pm 0.51 (0.16 \pm 0.48)$	8 TeV [13]						
CMS, dilepton	$172.82 \pm 1.23 \ (0.19 \pm 1.22)$	8 TeV [13]						
CMS, all jets	$172.32 \pm 0.64 \; (0.25 \pm 0.59)$	8 TeV [13]						
CMS, single top	$172.95 \pm 1.22 \; (0.77 \pm 0.95)$	8 TeV [14]						
CMS comb. (Sep 2015)	172.44 \pm 0.48 (0.13 \pm 0.47)	7+8 TeV [13]						
CMS, I+jets	$172.25 \pm 0.63 \; (0.08 \pm 0.62)$	13 TeV [15]						
CMS, dilepton	$172.33 \pm 0.70 \; (0.14 \pm 0.69)$	13 TeV [16]						
CMS, all jets	172.34 ± 0.73 (0.20 ± 0.70)	13 TeV [17]						
CMS, single top	$172.13 \pm 0.77 \; (0.32 \pm 0.70)$	13 TeV [18]						
CMS, I+jets (*)	171.77 ± 0.38	13 TeV [19]						
CMS, boosted (*)	$172.76 \pm 0.81 (0.22 \pm 0.78)$	13 TeV [20]						
* Preliminary	[1] ATLAS-CONF-2013-102 [8] EPJG 79 (2019) 280 [2] arXiv:160.4427 [9] ATLAS CONF-2016-046 [3] EPJG 75 (2015) 330 [10] //EPT (2 (2017) 610- [4] EPJG 75 (2015) 158 [11] EPJG 72 (2017) 2022 [5] ATLAS-CONF-2014-055 [12] EPJG 72 (2017) 2022 [6] ELL3 761 (2016) 350 [12] EPJG 72 (2017) 361 [7] //EP (92 (2017) 158 [13] PFD 93 (2016) 72004 [7] //EP (92 (2017) 158 [14] EPJG 72 (2017) 361	[15] EPJC 78 (2018) 891 [16] EPJC 79 (2019) 368 [17] EPJC 79 (2019) 313 [18] arXiv:2108.10407 [19] CMS-PAS-TOP-20-008 [20] CMS-PAS-TOP-21-012						
165 170 1	175 180	185						
m _{top} [GeV]								

Mass from decay

Pole mass



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Top quark mass measurement from top decays at the LHC

• Comparison to projections from Snowmass 2013



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Mass from decay and pole mass at the LHC and HL-LHC

- Measurements at 13 TeV have not yet been combined between channels
- Mass from decay has additional ~500 MeV interpretation uncertainty

<u>arXiv:</u>1712.02796, <u>arXiv</u>:2004.12915



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

- Threshold scan around 350 GeV to determine PS mass
- Fit mass, width, Yukawa and α_s simultaneously
- Theory systematics dominate
 - missing higher orders
 - parametric uncertainty due to α_s
- Conversion of PS to MSbar mass known at 4-loop



Top-quark MSbar mass

- Mass from decay has ~500 MeV interpretation uncertainty
- Pole mass has ~200 MeV translation uncertainty (renormalon)
- PS mass has ~10 MeV translation uncertainty (fixed order calculation)



Top-quark mass summary



Top quark production at hadron colliders

- important for measurements of properties, direct searches for BSM, interpretations in EFTs, as background to other processes
- HL-LHC requires improved parton shower modeling, reduced PDF uncertainties, higher order theory calculations



EFT fits, top and bottom quark measurements

- Top-quark-specific EFT fits
- Include data from LEP/SLC, Tevatron, LHC
- HL-LHC: top pair and single top cross-sections, differential cross-sections, helicities
- FCC, ILC, CLIC: exploit full information in top production and decay
 - At multiple CM energies
- Bottom quark pair production at FCC, ILC, CLIC
 - Exploit full information at multiple CM energies

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



BSM top:

Four-top production, contact interaction and compositeness

Contact interaction operators are manifestation of composite top at lower scales



	$ \text{HL-LHC}(pp \rightarrow tttt) $	FCC-ee	ILC	CLIC	FCC-hh		
2	$(pp \rightarrow tttt)$	$(e^+e^- \rightarrow tt)$	$(e^+e^- \rightarrow tt)$	$(e^+e^- \rightarrow tt)$	$(pp \rightarrow tttt)$		
\sqrt{s} [TeV]	14	0.365	1	3	100		
$\mathcal{L}[\mathrm{ab}^{-1}]$	3	1.5	1	3	30		
$\Lambda/\sqrt{ c_{tt} }$ [TeV]	1.3	1.6	4.1	7.7	6.5		

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

_CMS-PAS-FTR-18-031 arXiv:2010.05915



Examples of BSM physics in top

- Cross section measurements as inputs to EFT fits
 - See Electroweak report
- Spin correlation in top pair events
 - SUSY limit in compressed regime
- Flavor-changing neutral currents
- More top BSM in BSM report



Example top-quark measurements

Parameter	HL-LHC	ILC 500	FCC-ee	FCC-hh
$\sqrt{s} [\text{TeV}]$	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}	_

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 EF06, TF06, TF07 and CompF2 reports.

Conclusions

- 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.

Thanks to everyone who contributed

- Thanks to the white paper contributors, summary writers, reviewers, everyone who helped put the Top and HF production report together
- We look forward to your feedback: <u>Report</u> and <u>Feedback form</u>