SnowMass2021

Snowmass EF03: Heavy flavor and top quark physics

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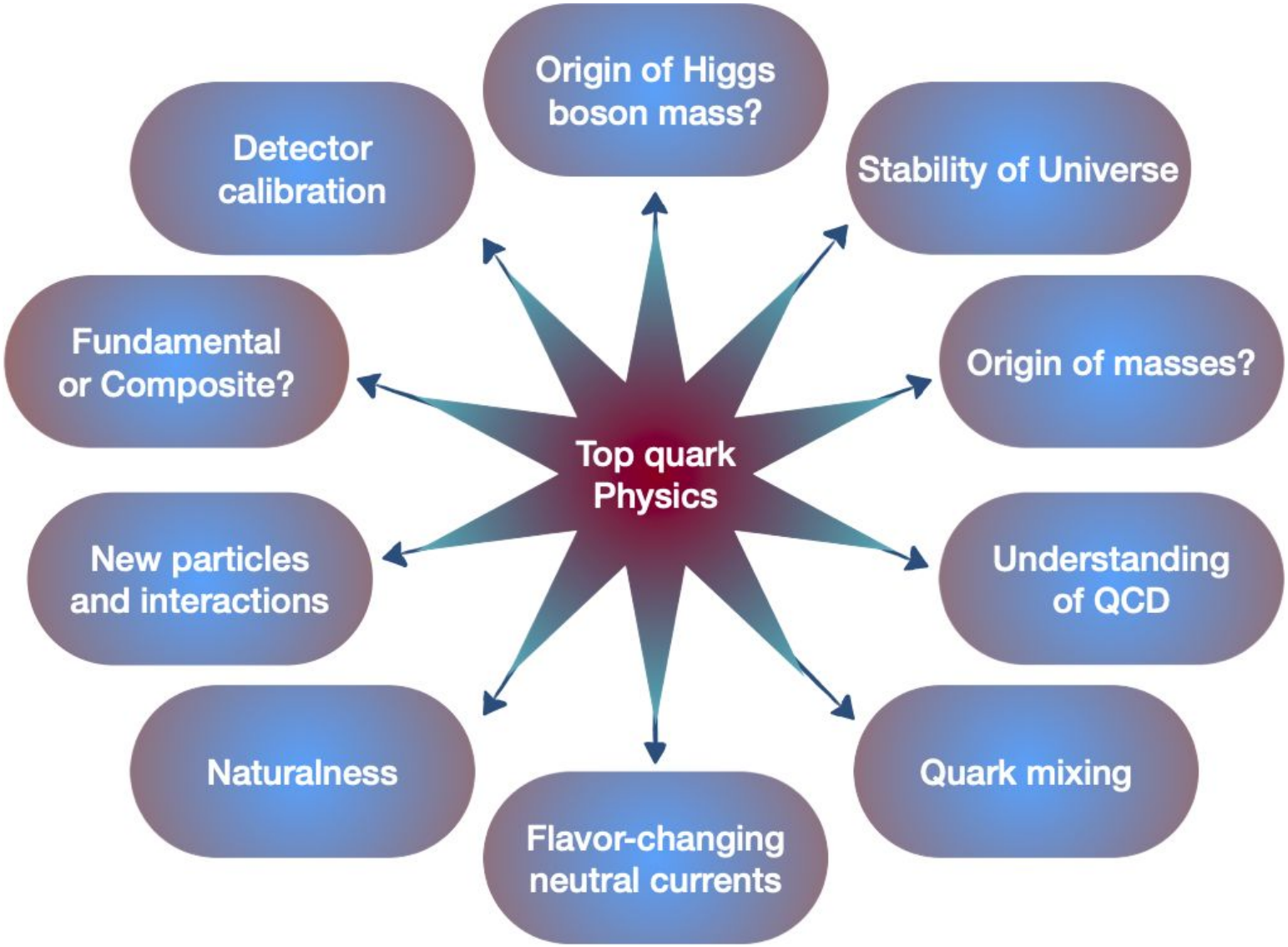
The many facets of heavy flavor and top quark physics



Need to measure top-quark mass precisely

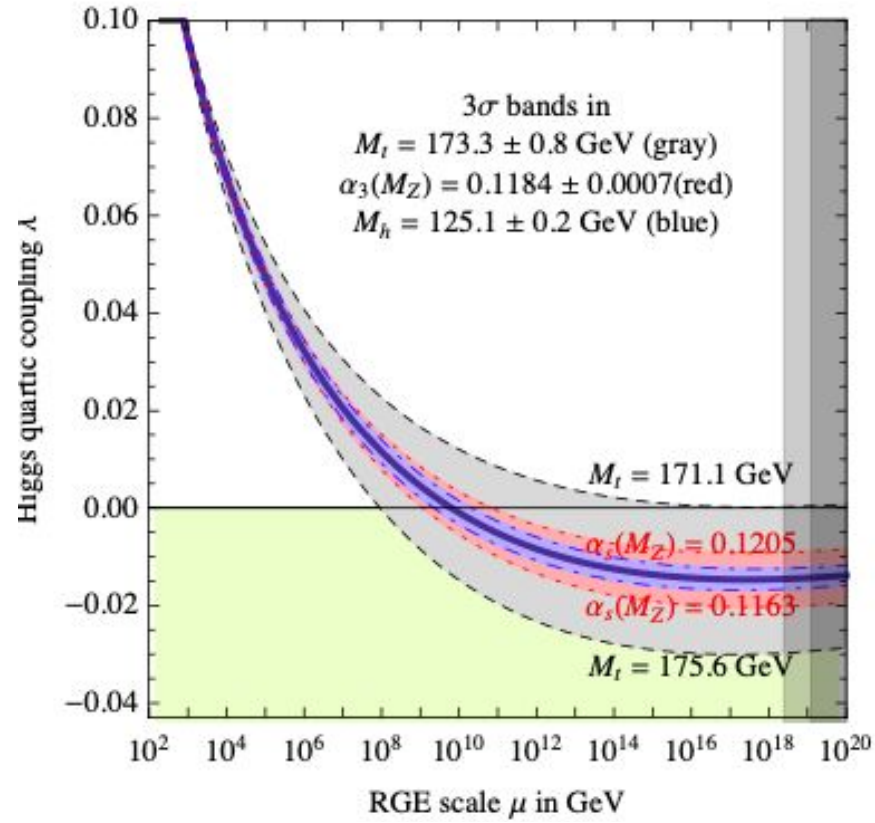
- Theoretical W boson mass uncertainty has large contribution from top quark loops

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

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

hep-ph/0311148

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

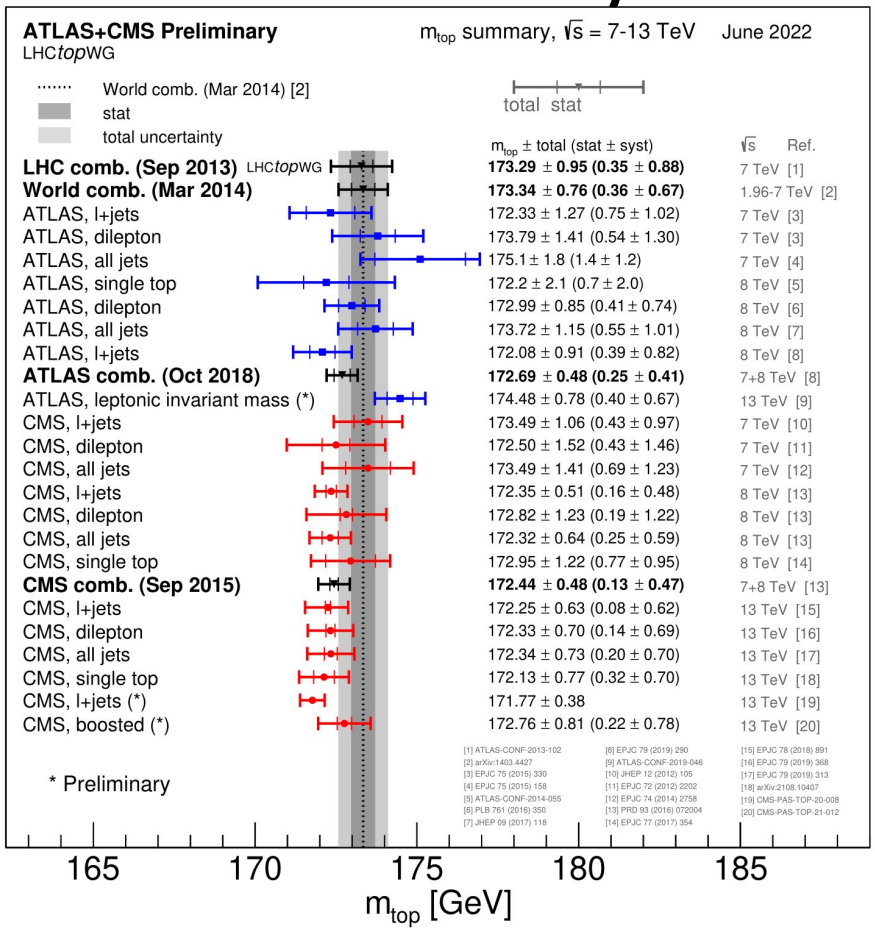


arXiv:1307.3536

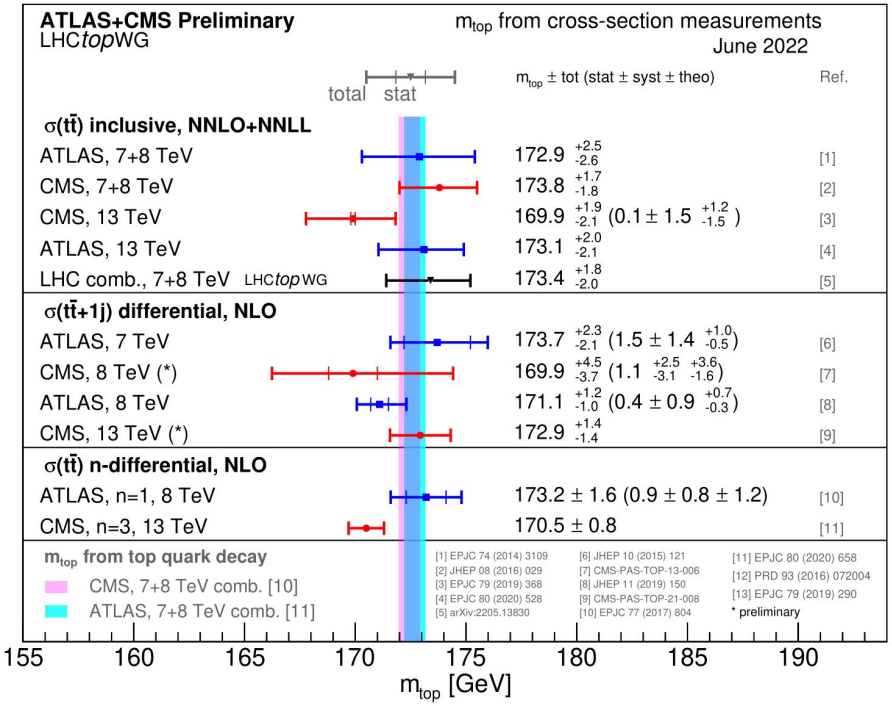
Current top mass measurements at the LHC

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

Mass from decay

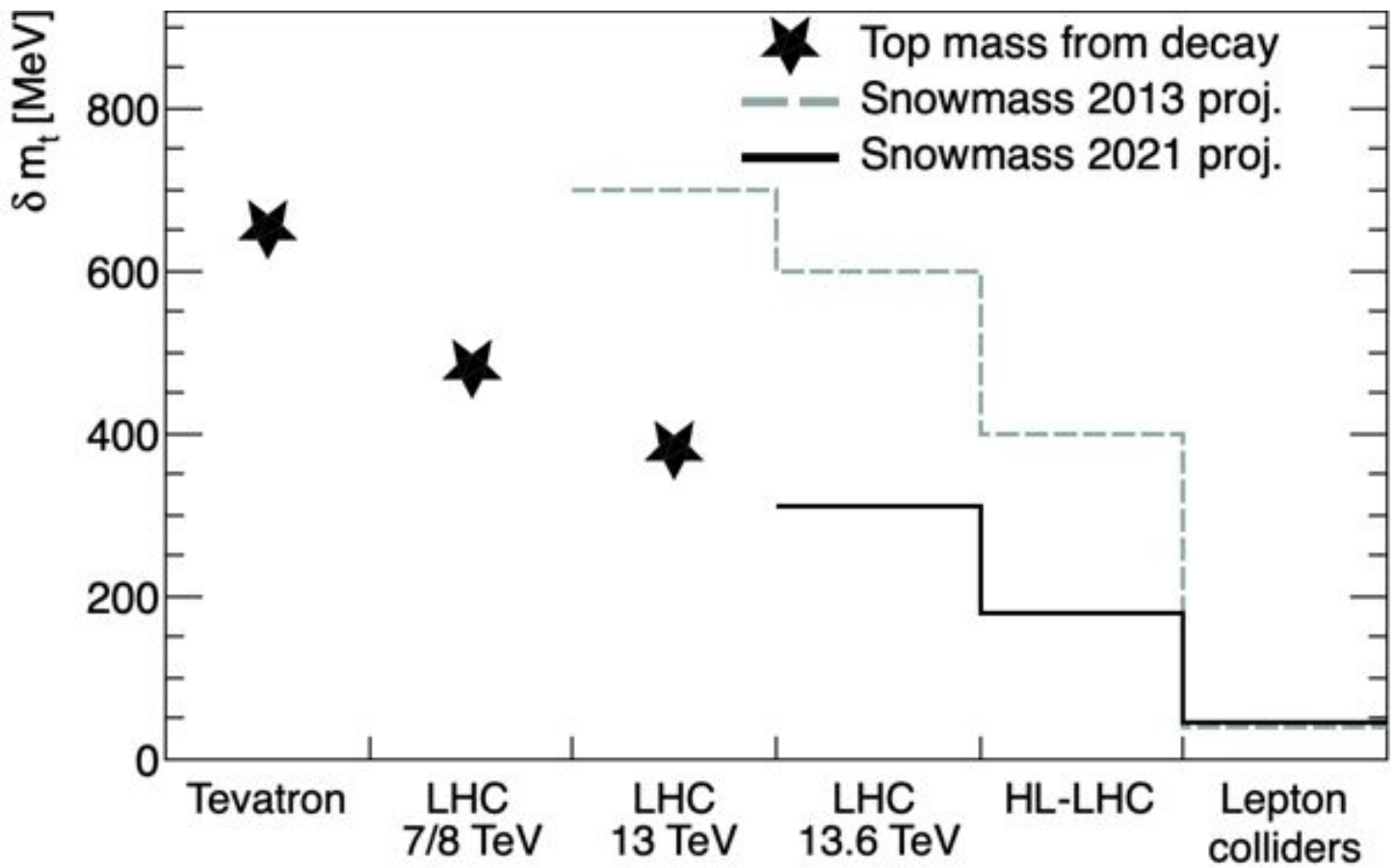


Pole mass



Top quark mass measurement from top decays at the LHC

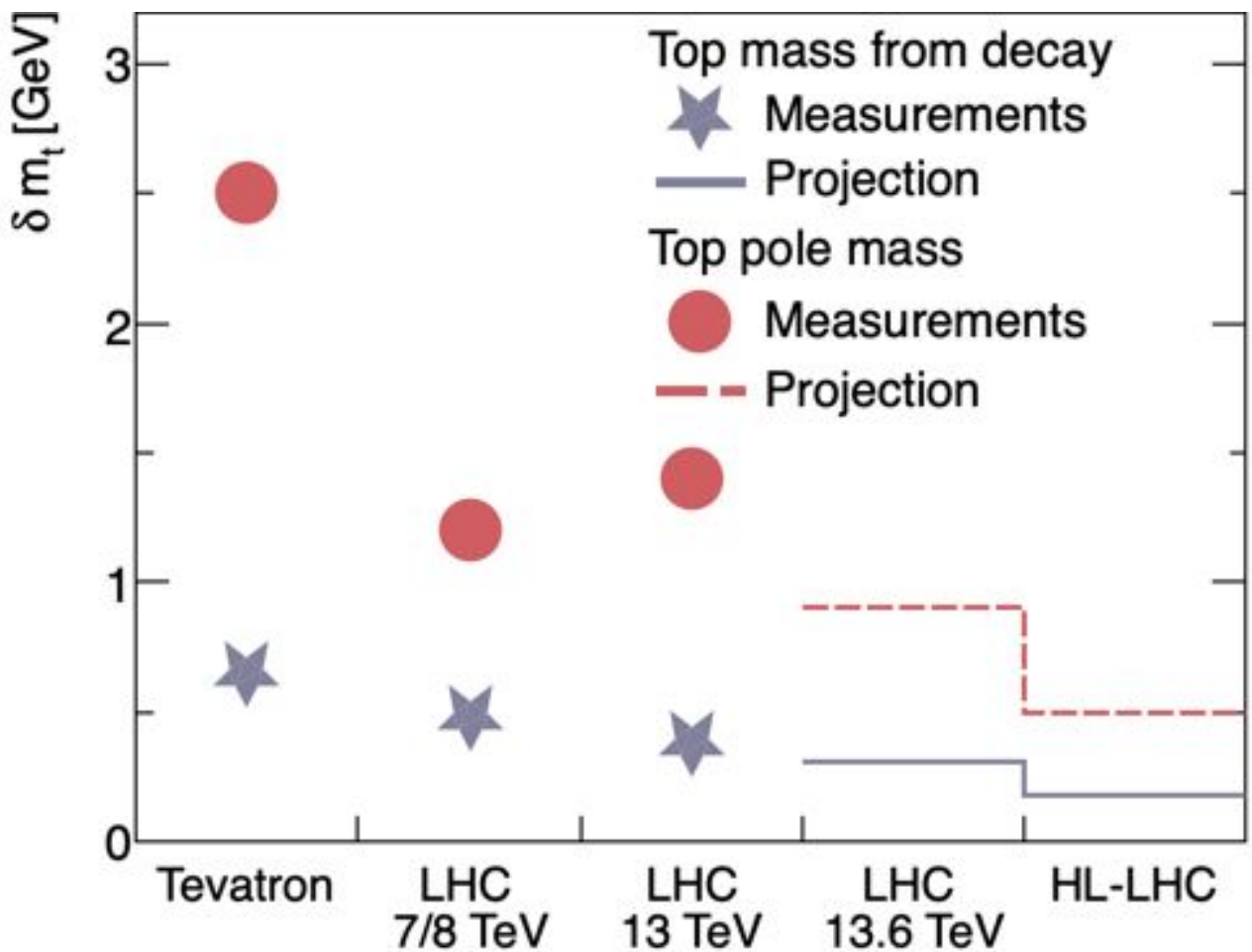
- Comparison to projections from Snowmass 2013



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

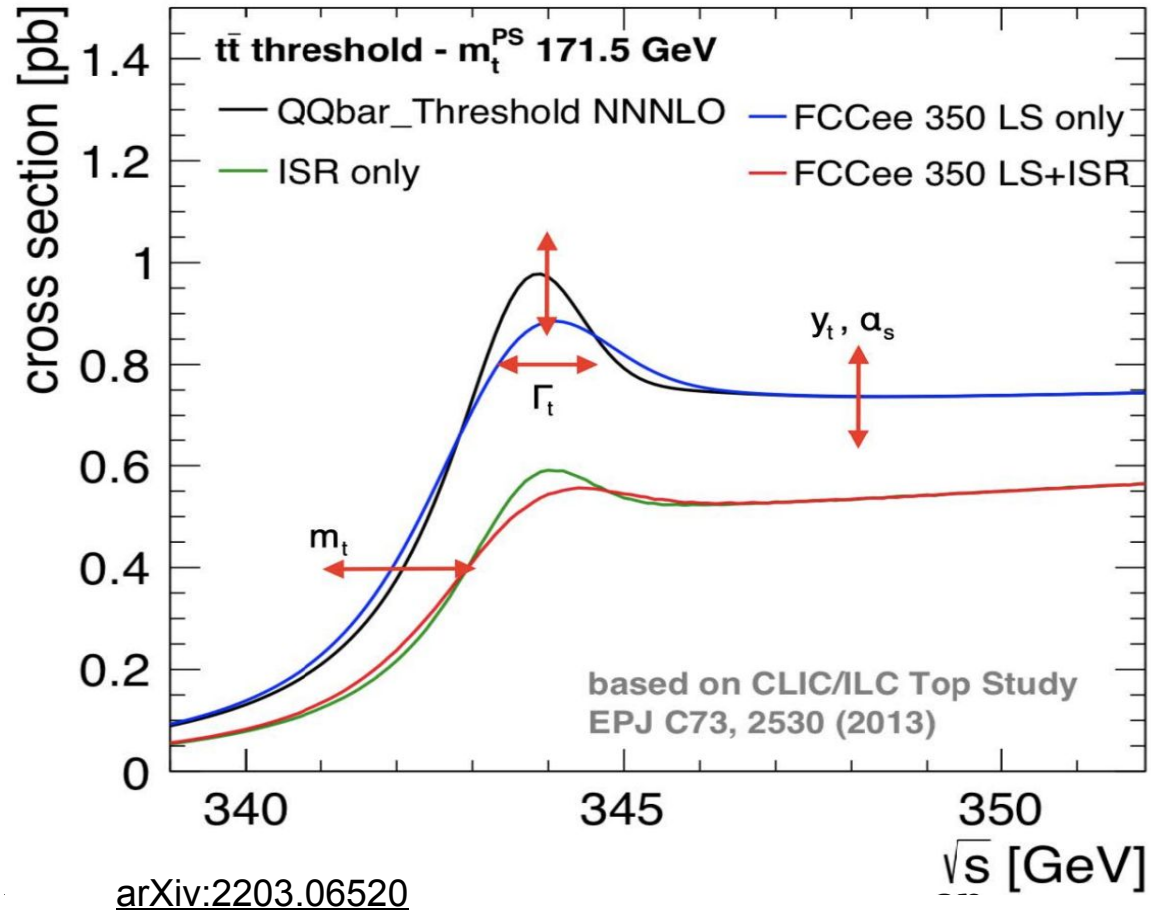
- Measurements at 13 TeV have not yet been combined between channels
- Mass from decay has additional ~500 MeV interpretation uncertainty

arXiv:1712.02796, arXiv:2004.12915



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

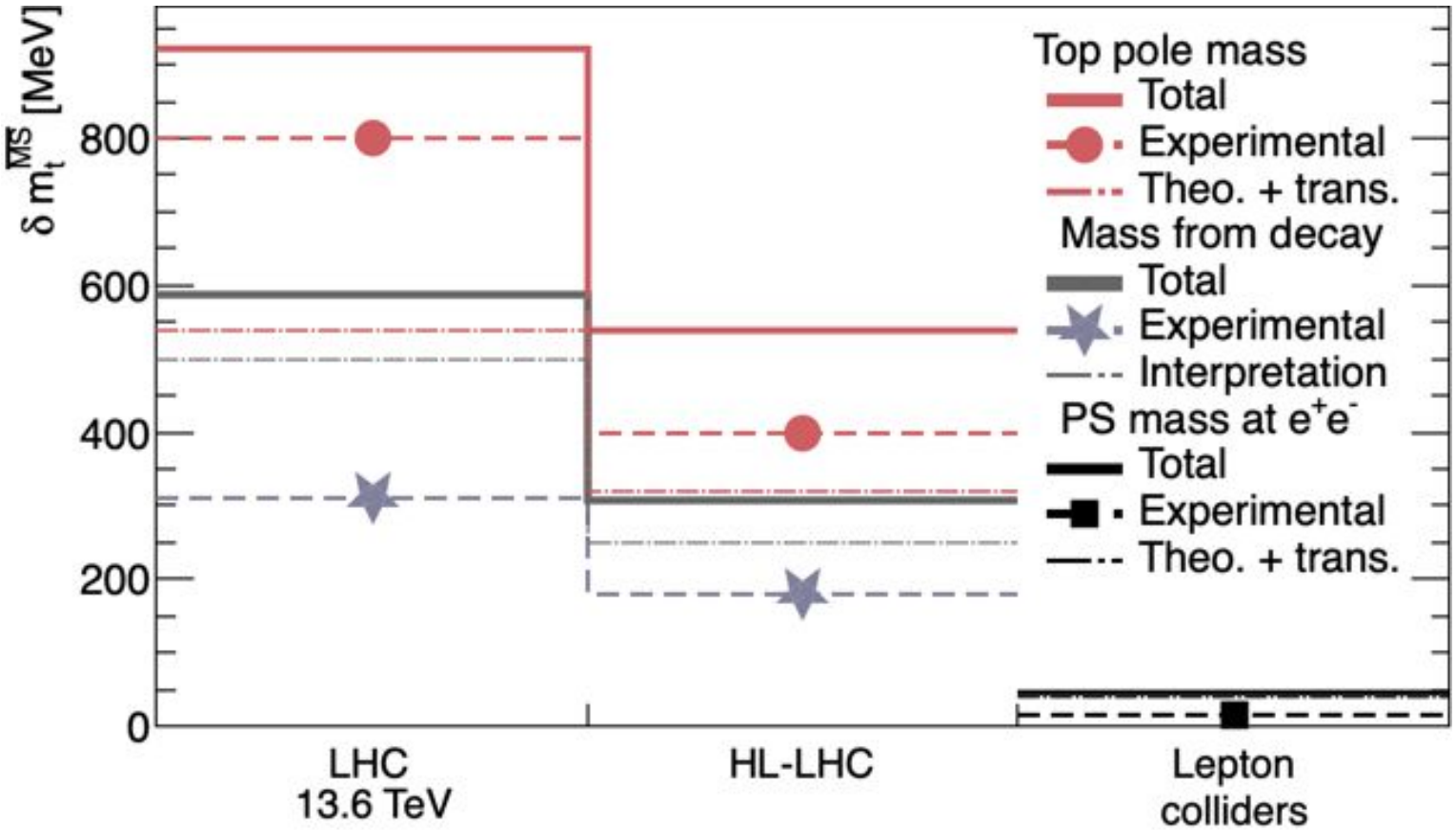
- Threshold scan around 350 GeV to determine PS mass
- Fit mass, width, Yukawa and α_S simultaneously
- Theory systematics dominate
  - missing higher orders
  - parametric uncertainty due to α_S
- Conversion of PS to MSbar mass known at 4-loop



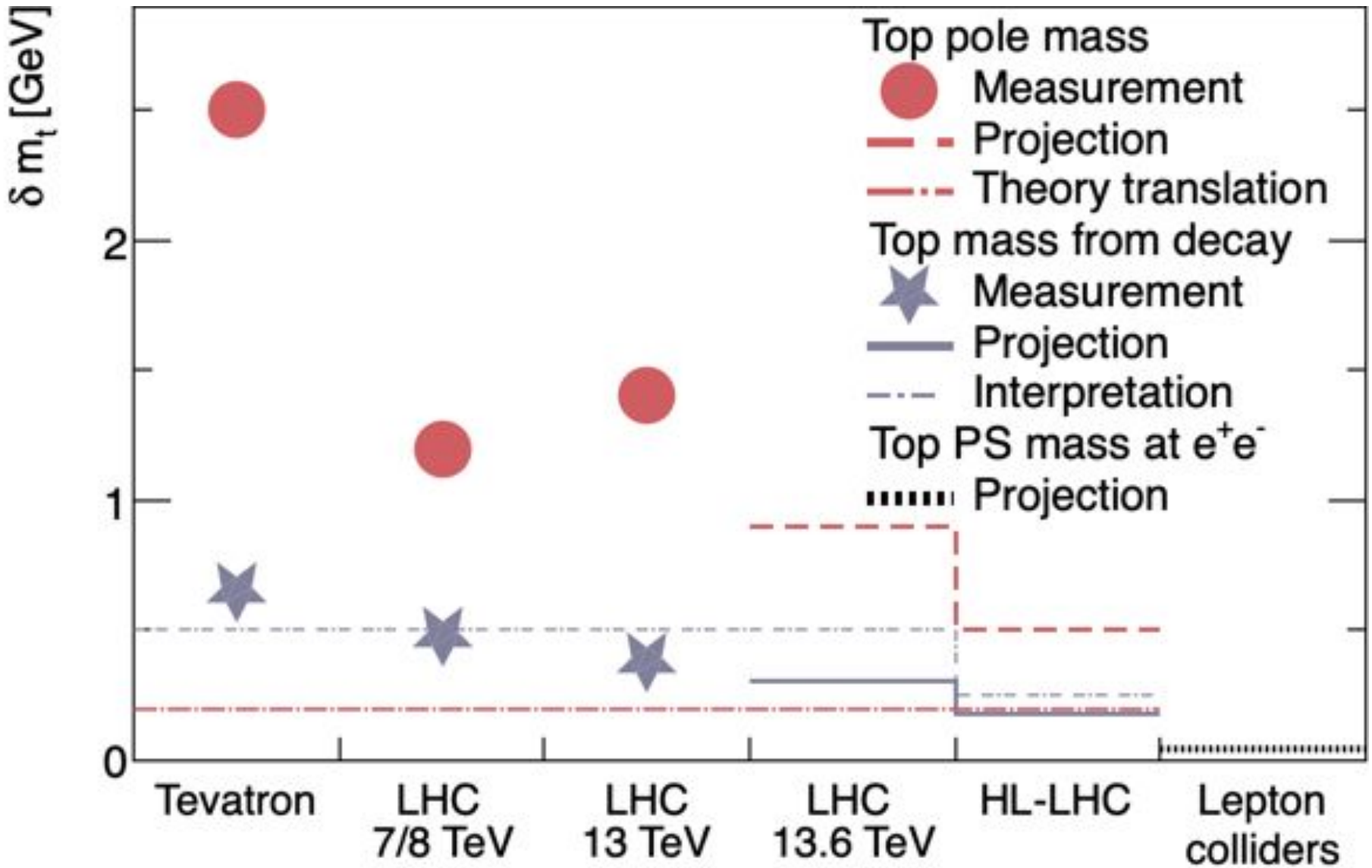
arXiv:2203.06520

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)

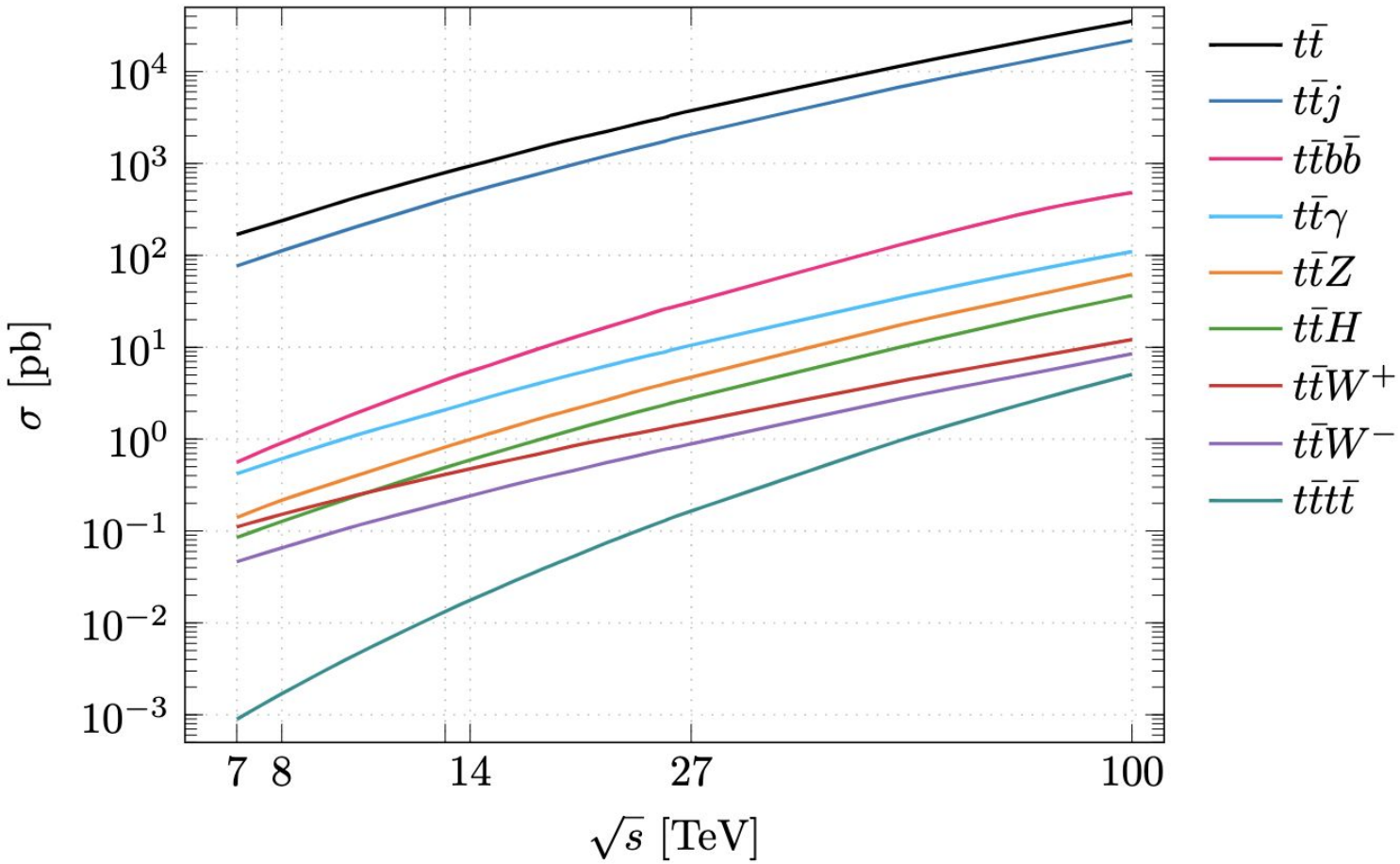


Top-quark mass summary



Top quark production at hadron colliders

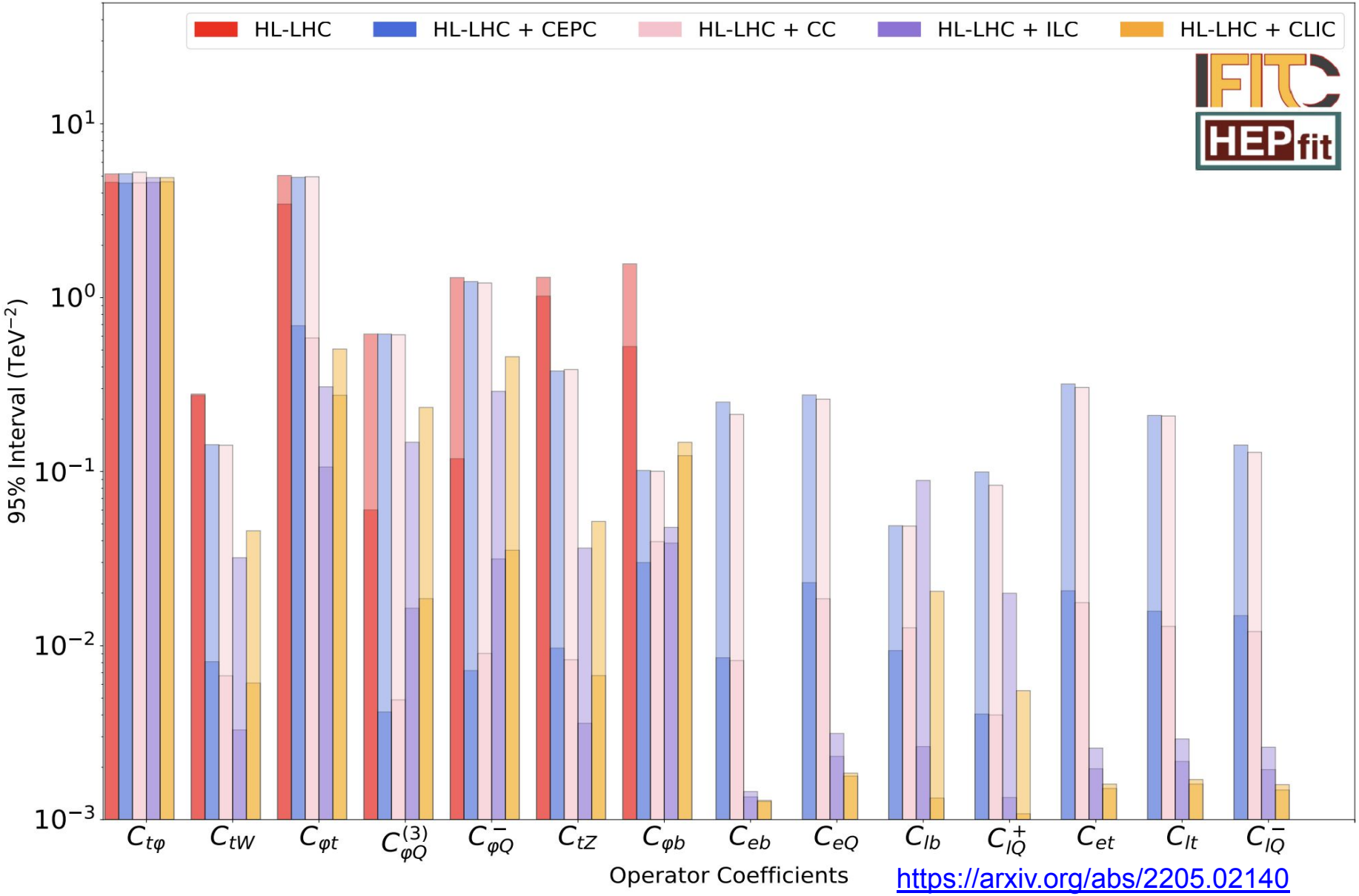
- important for measurements of properties, direct searches for BSM, interpretations in EFTs, as background to other processes
- HL-LHC requires improved parton shower modeling, reduced PDF uncertainties, higher order theory calculations



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

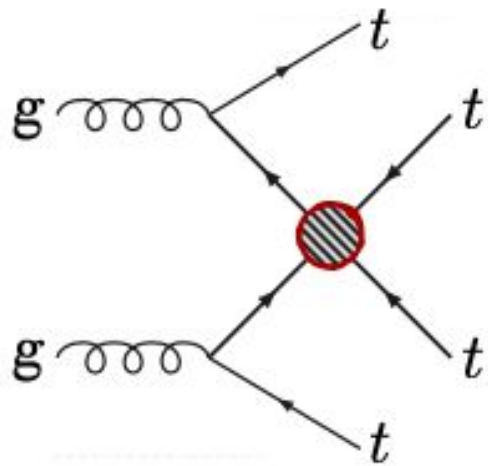


https://arxiv.org/abs/2205.02140

BSM top:
Four-top production, contact interaction and compositeness

Contact interaction operators are manifestation of composite top at lower scales

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



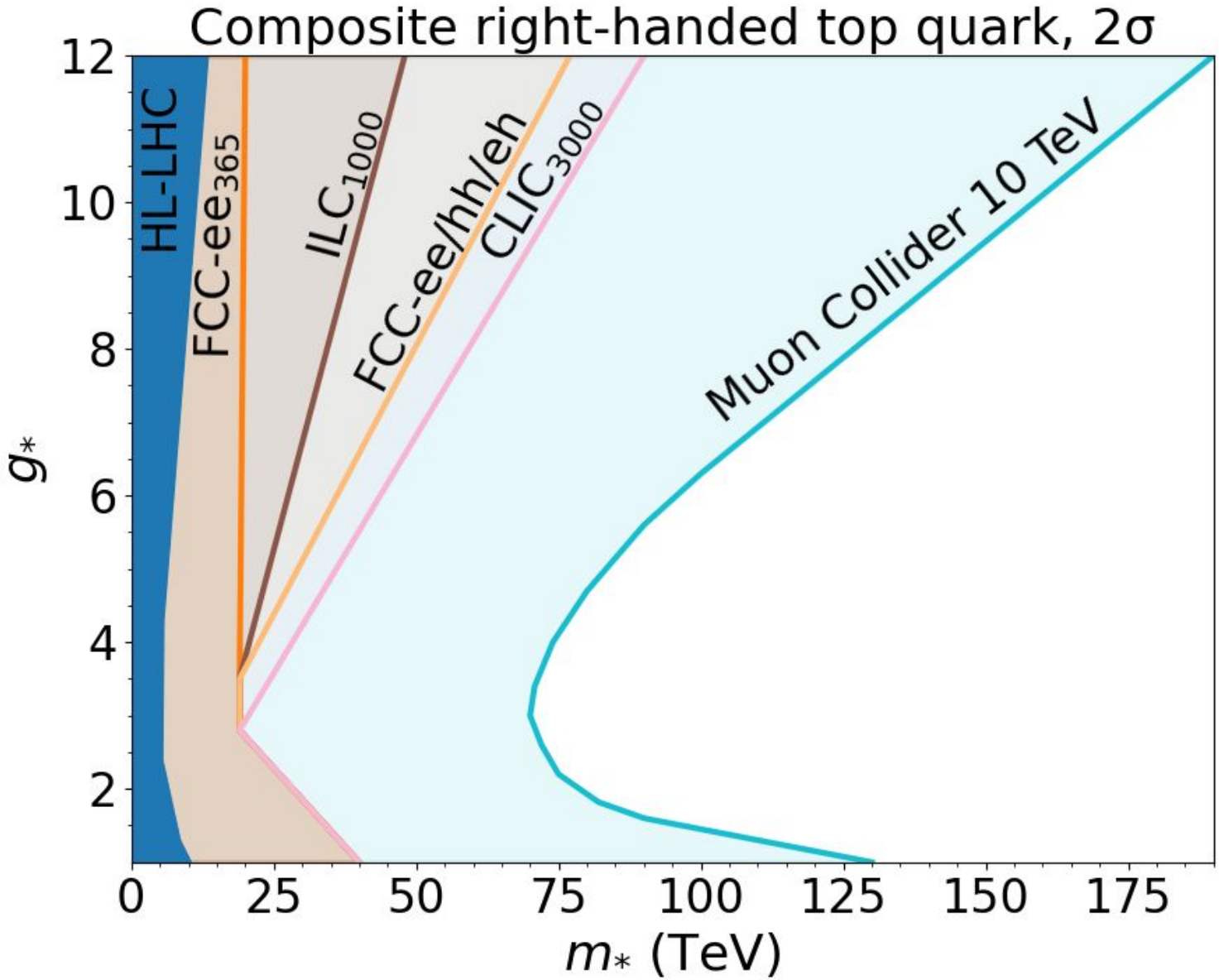
$$\sim \frac{g_*^2}{m_*^2}s$$

	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
$\mathcal{L}[\mathrm{ab}^{-1}]$	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]*

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

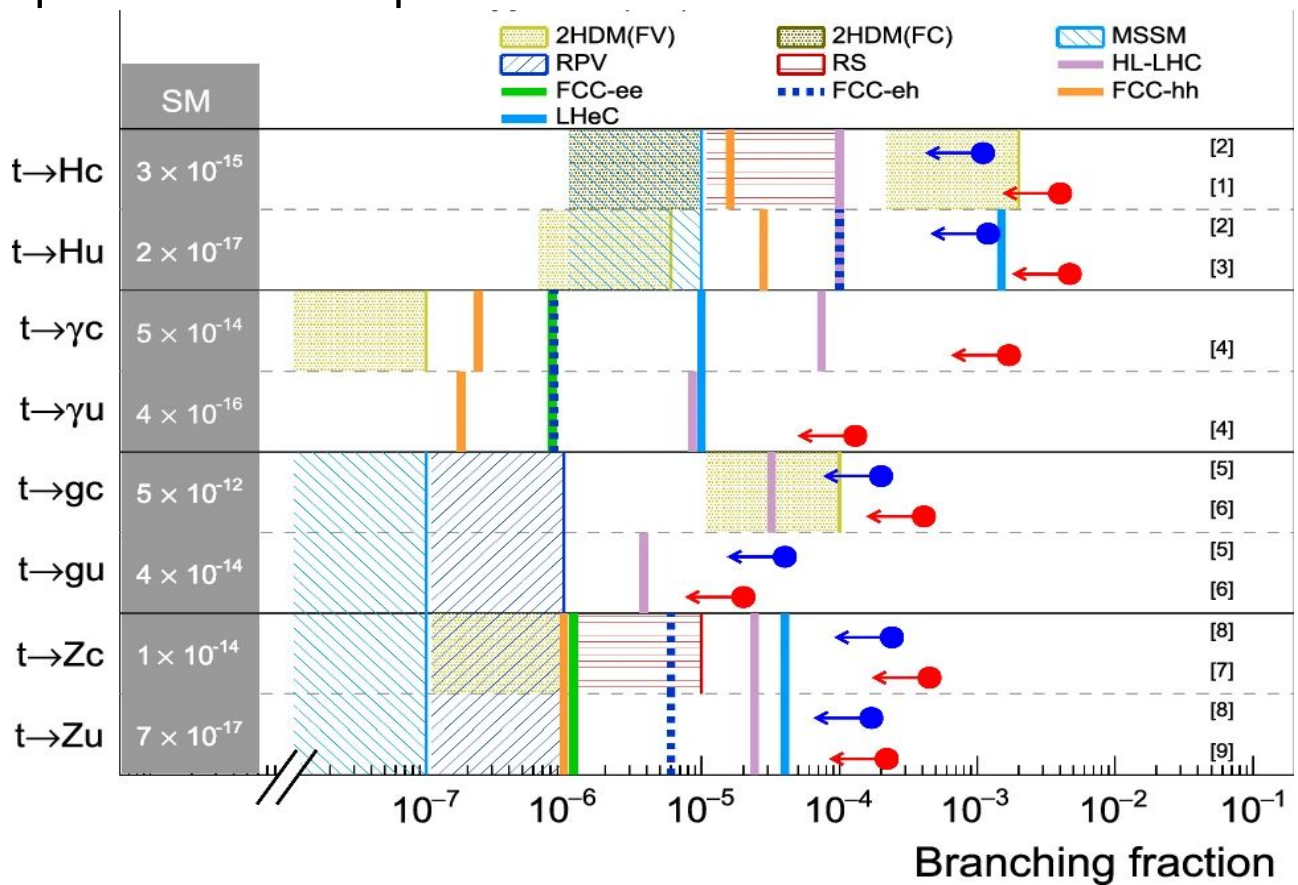
Bounds on Compositeness models



Based on arXiv:2202.10509 and 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
$\sqrt{s}$ [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:

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