SnowMass2021

EF03 EW Physics: Heavy flavor and top quark physics

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Heavy flavor and top quark physics

- Prospects for precision measurements (HL-LHC, FCC, ILC, CLIC, muon collider):
  - top quark properties: mass, width, electroweak 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 (with 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 and The physics case of a 3 TeV muon collider stage, arXiv:2203.07256
- M.Vos et al.: HL-LHC and Higgs factory projections for top measurements (in preparation)

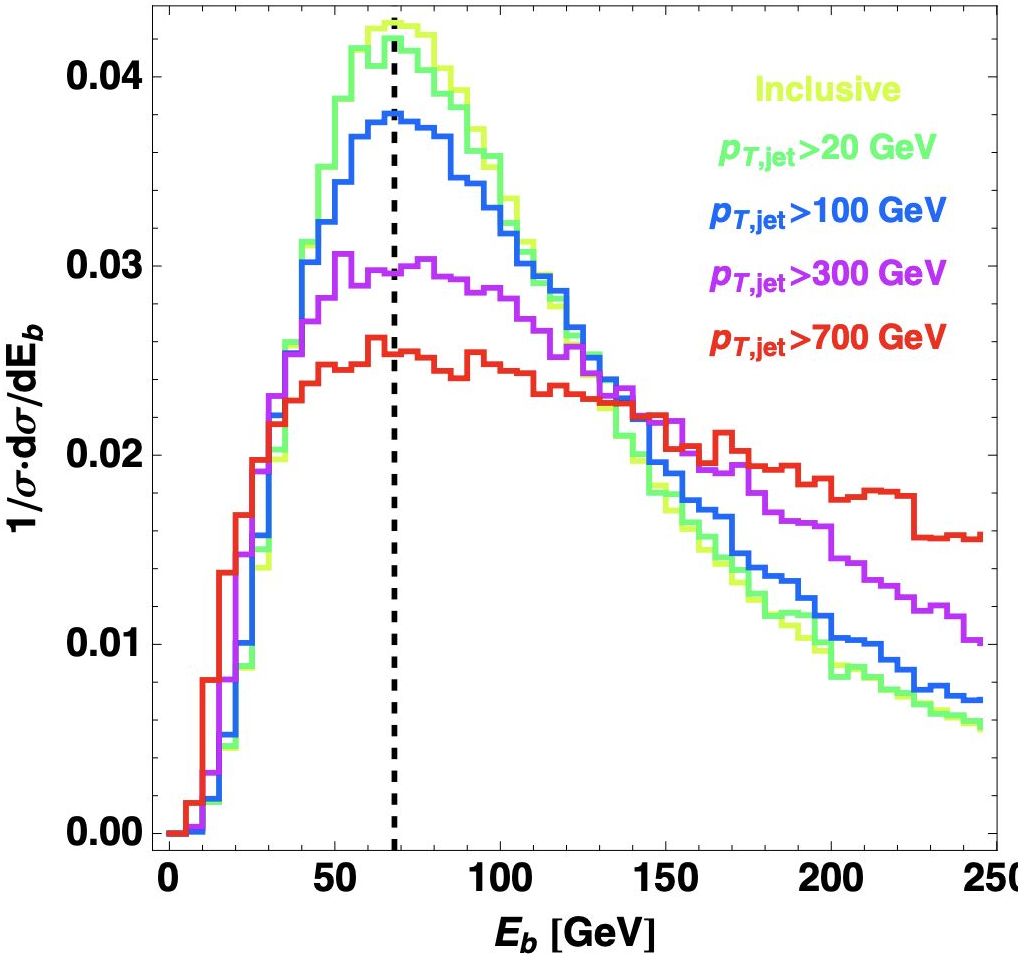
Heavy flavor and top quark physics: Contributed Papers (cont.)

- 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 PDF at the LHC and future colliders, arXiv:2203.08064
- N.Kidonakis: Higher-order corrections to tt production at high energies, arXiv:2203.03698
- Z.Yu, C-P Yuan: Azimuthal angle correlations 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
- J.Aparisi et al: Prospects for measurements of the bottom quark mass arXiv:2203.16994
- K.Agashe et al: A new method for top quark measurements arXiv:2204.02928

For more highlights see also EF workshop in 2022 and EF workshop in 2021

Top-quark MC mass: LHC and HL-LHC

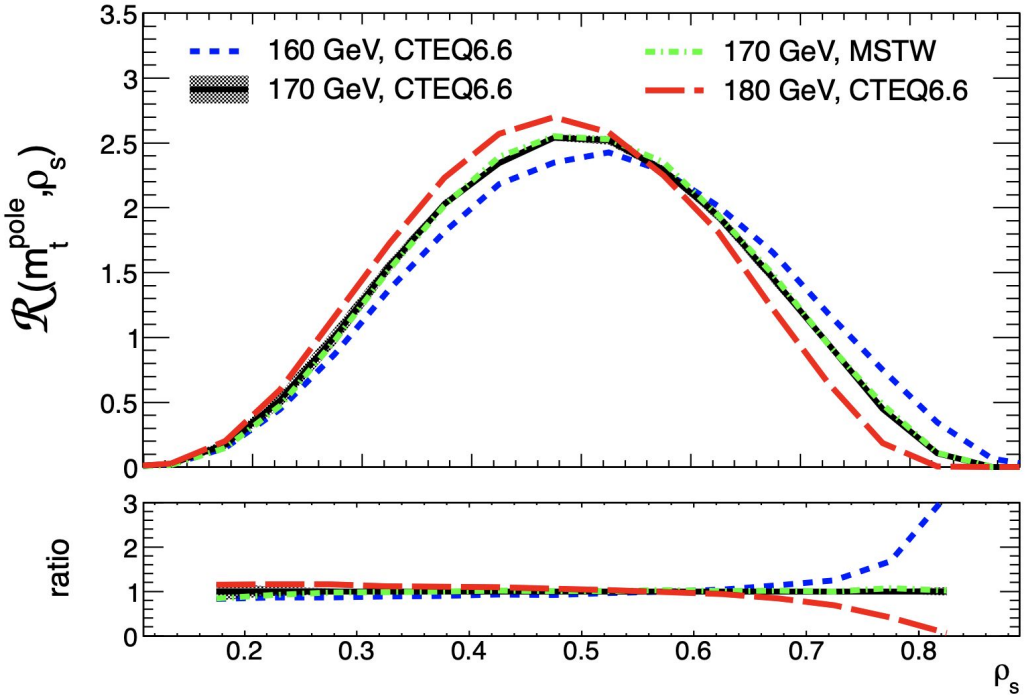
- New ideas for MC mass measurements
  - Bottom jet energy, from B meson decay length
  - Reduce dependence on top production modeling
  - Independent of top p_T
  - Reduce dependence on JES
  - Residual uncertainties from fragmentation



arXiv:2204.02928

Top-quark Pole mass: LHC and HL-LHC

- Pole mass from tt+jet
- Sensitive to top mass at turn-on, sensitive variable $\rho_s = 2m_0/m_{t\bar{t}j}$ with $m_0 = 170\,\text{GeV}$
- Unfold to parton level
- compare to NLO theory predictions
- Study scale, PDF, top mass scheme dependence

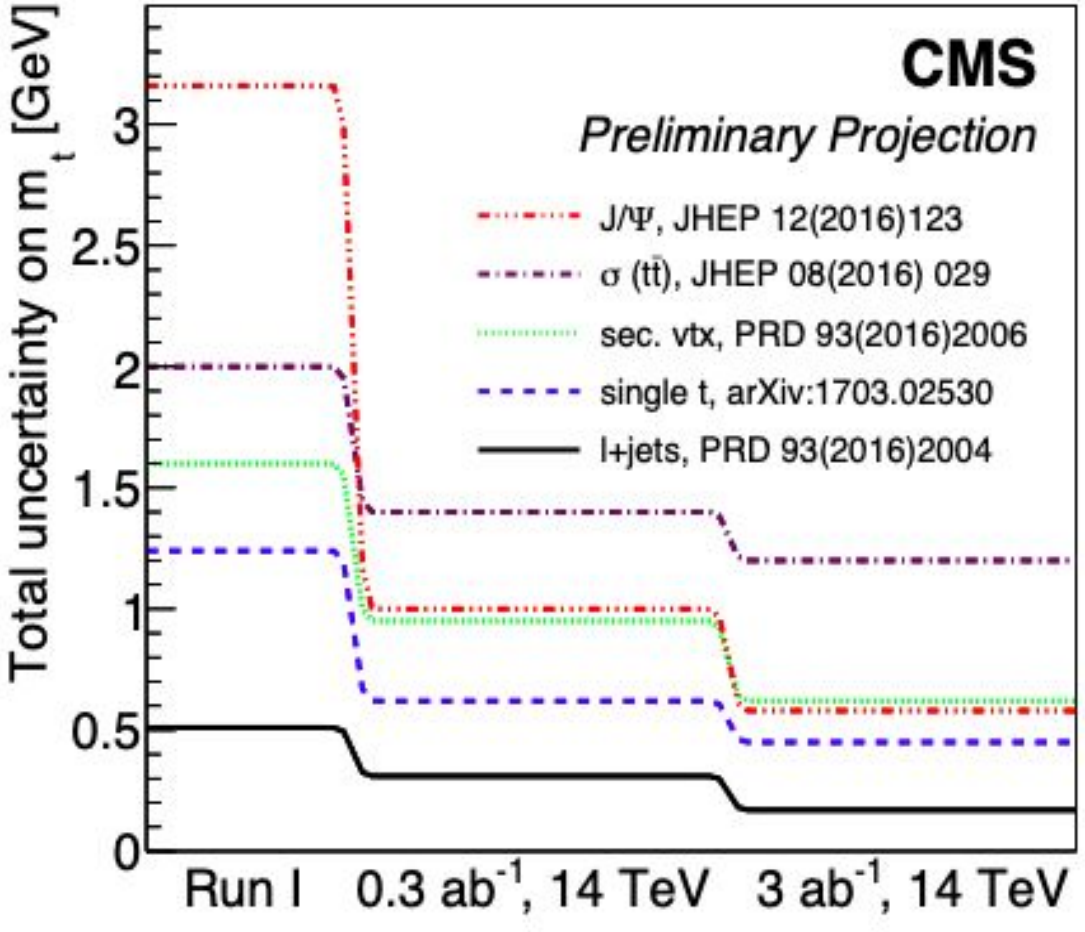


https://arxiv.org/abs/2203.07344

Top-quark mass: LHC and HL-LHC

- Projection to HL-LHC from different measurement methods
- Projected uncertainty in lj:
  20 MeV (stat.)
  + 170 MeV (syst.)
- J/Psi production also studied by ATLAS:
  500 MeV unc

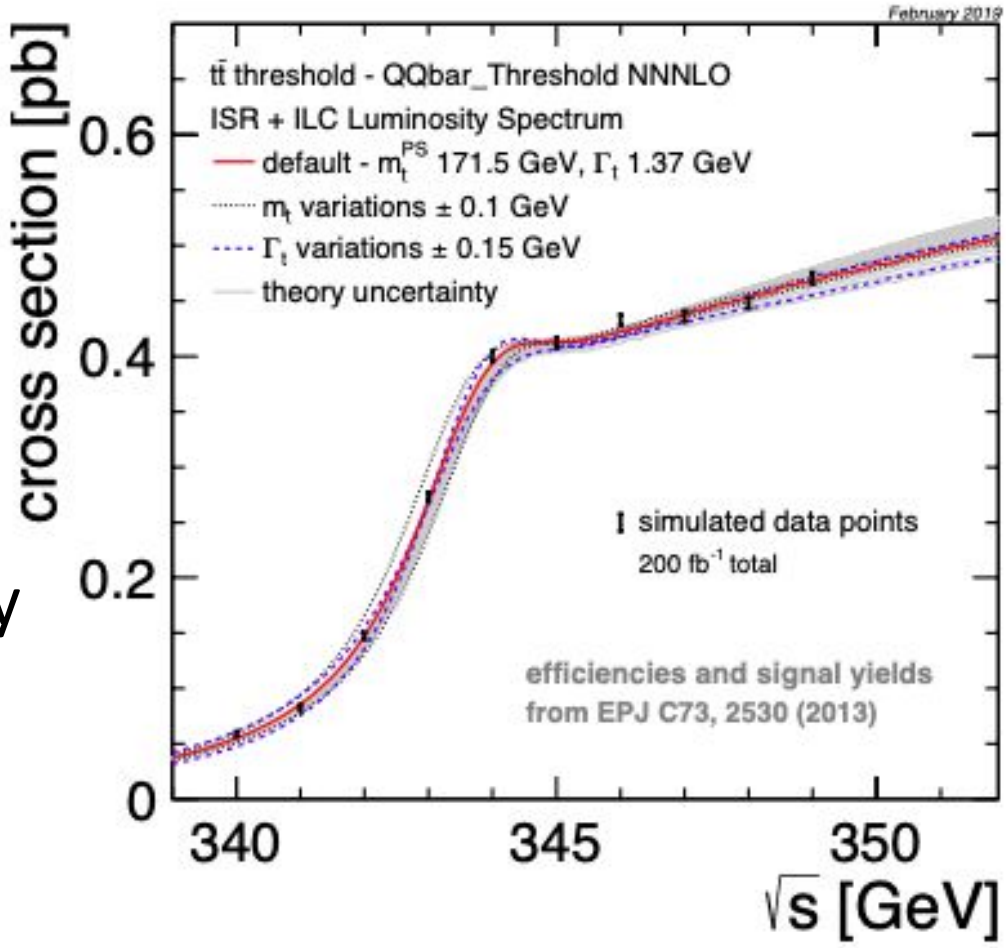
http://cdsweb.cern.ch/record/2649882



CMS-PAS-FTR-16-006

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

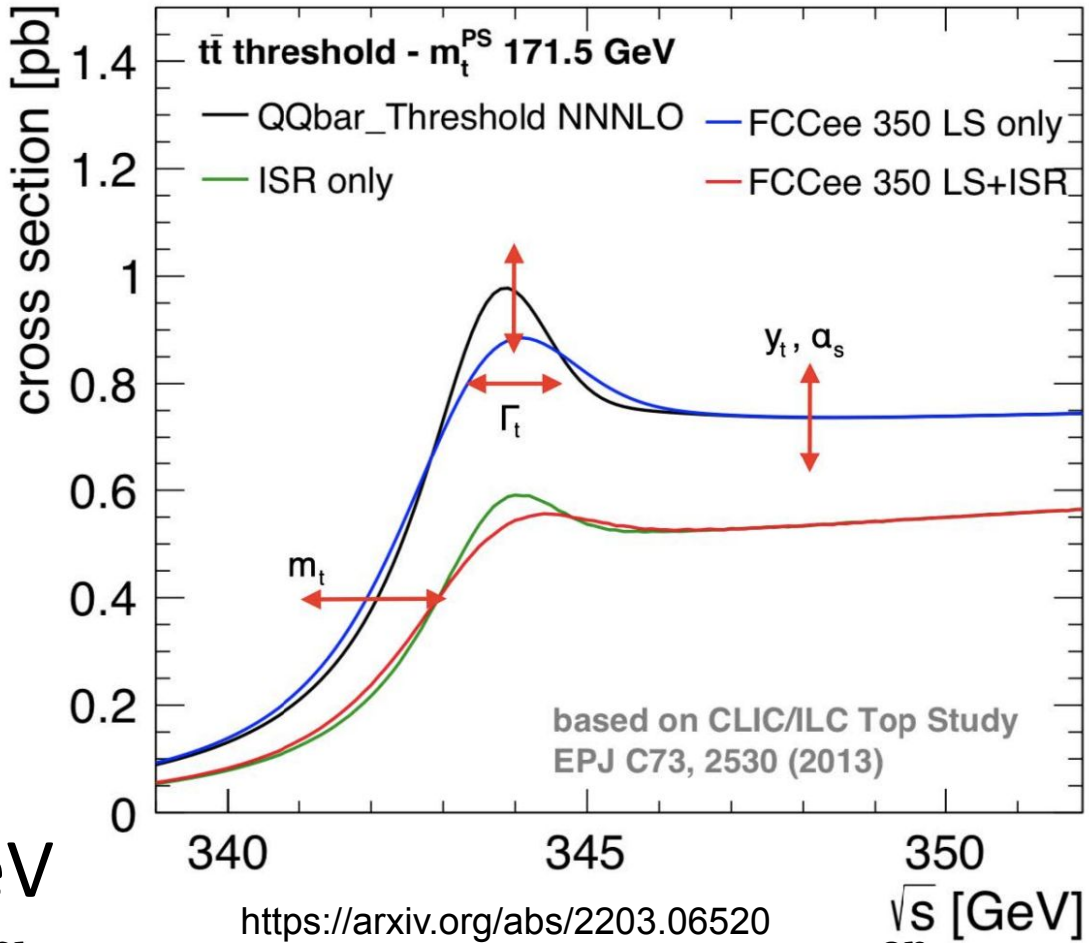
- Threshold scan to determine PS mass
- ILC (200 fb-1):
  20 MeV (stat.)
  + 50 MeV (theo. syst.)
  + 30-50 MeV (exp.)
- Theo syst include
  - missing higher orders
  - parametric uncertainty due to α_s



https://arxiv.org/abs/2203.07622

Top-quark mass: FCC-ee

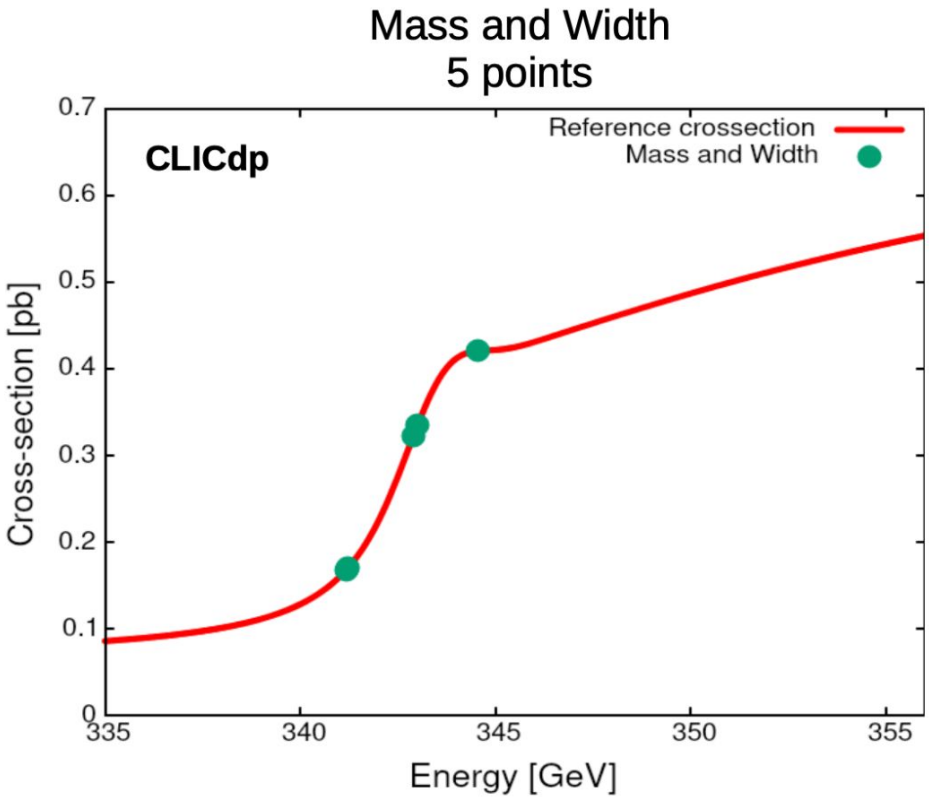
- Expected stat uncertainty of 9 MeV
- Assume SM values for top width and Yukawa
- Can also fit mass, width, Yukawa and α_s simultaneously
- Theo syst 45 + 3.2 MeV
  - N3LO scale
  - parametric error due to α_s
- PS to MSbar mass at 4-loop, err 23 MeV

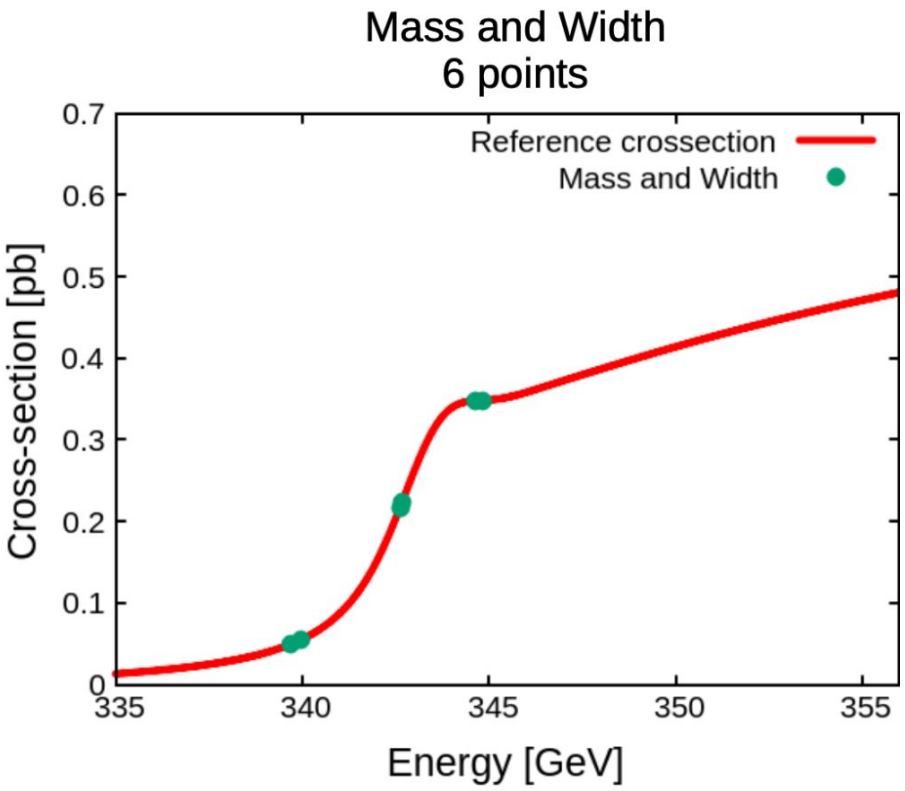


https://arxiv.org/abs/2203.06520

Top-quark mass: threshold scan

- Optimize mass scan parameters with genetic algorithm
- Less data to reach same precision (25 MeV)

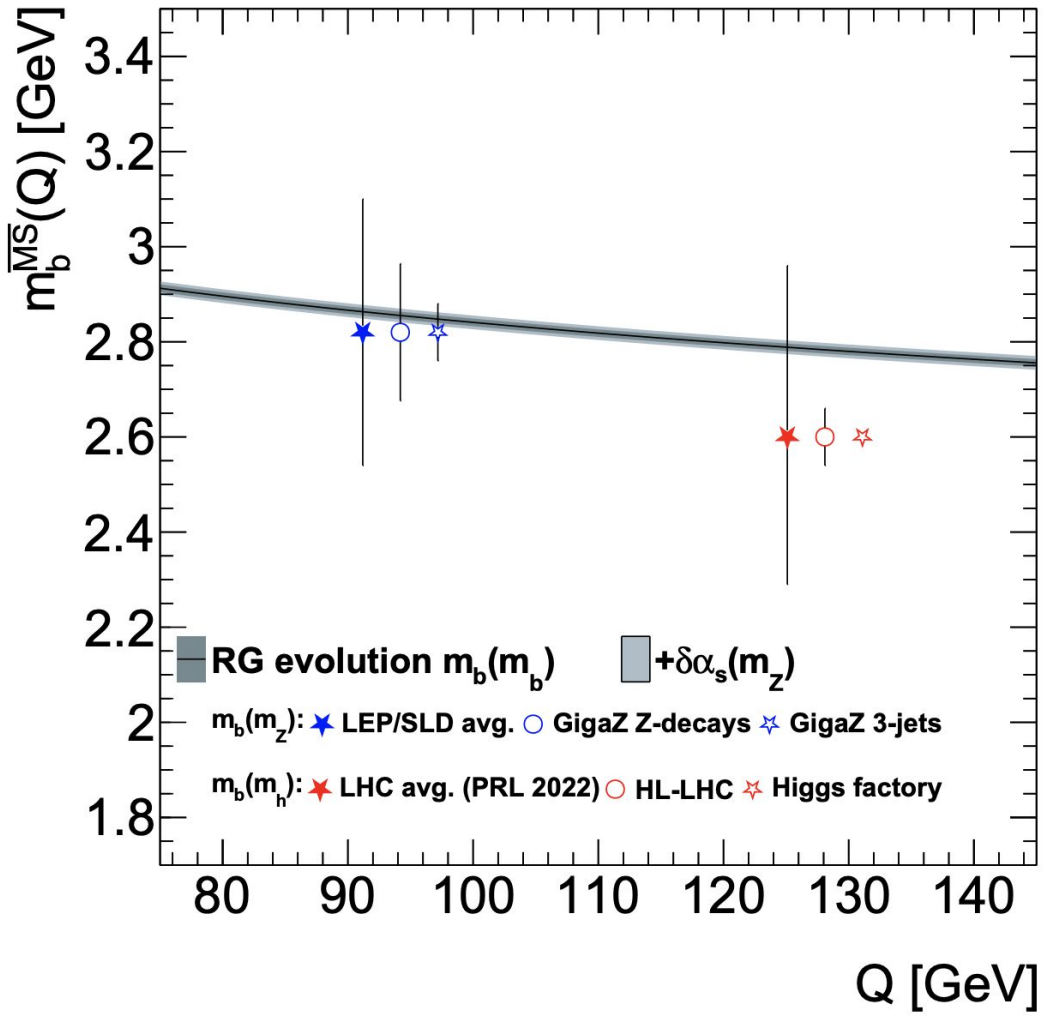




https://arxiv.org/abs/2203.06520

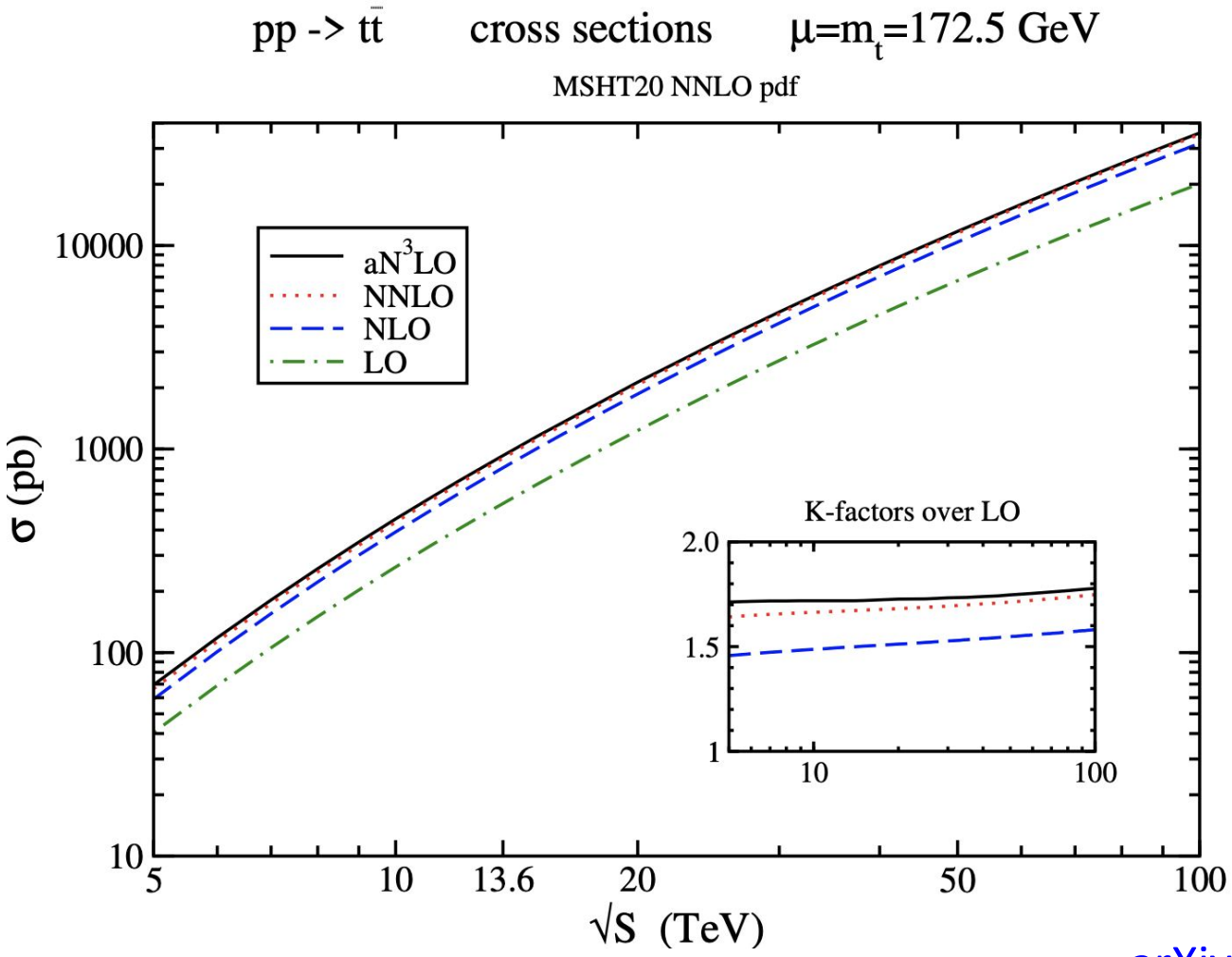
Bottom quark mass

- Bottom quark mass measurements from Z boson decays, Higgs boson decays
- Theory evolution at 5 loops



Cross-section at LHC: top pairs

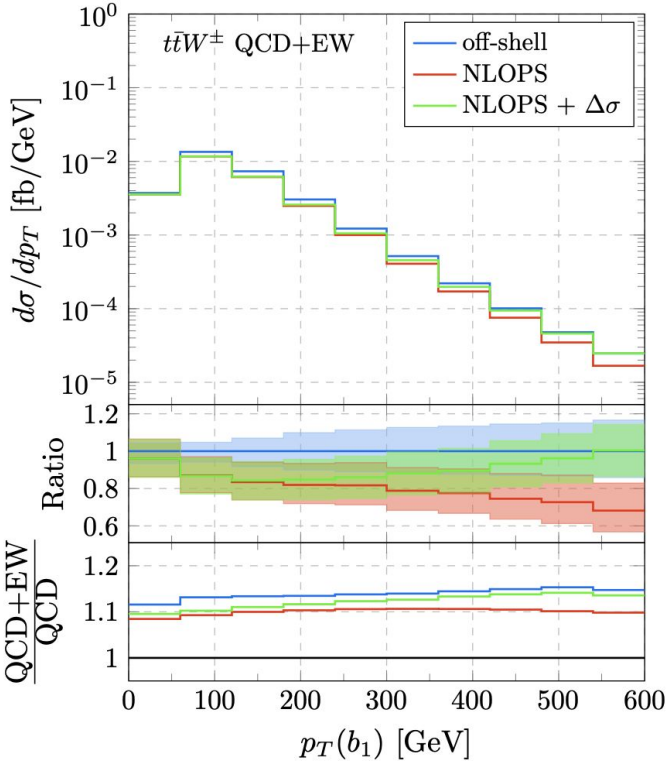
- Resummation of logs, XS at approx N3LO

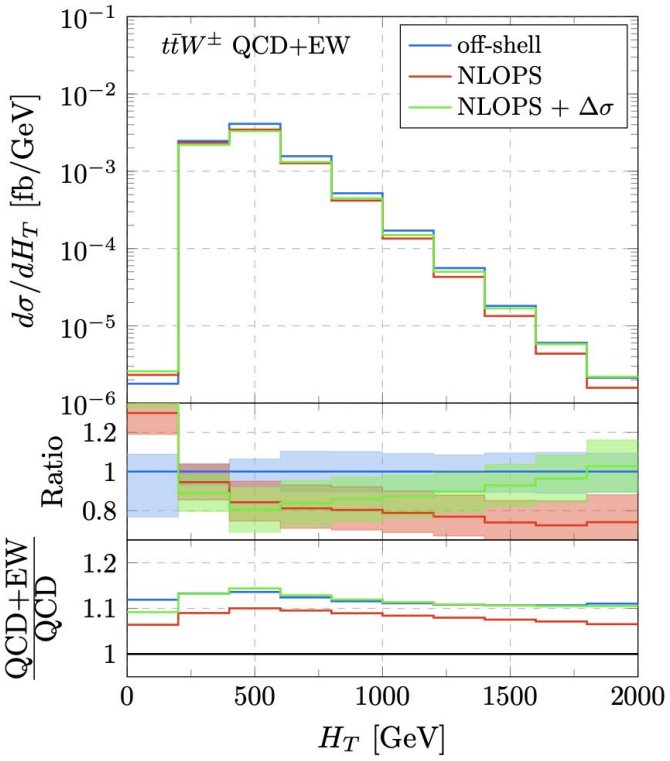


arXiv:2203.03698

Cross-section at LHC: ttW

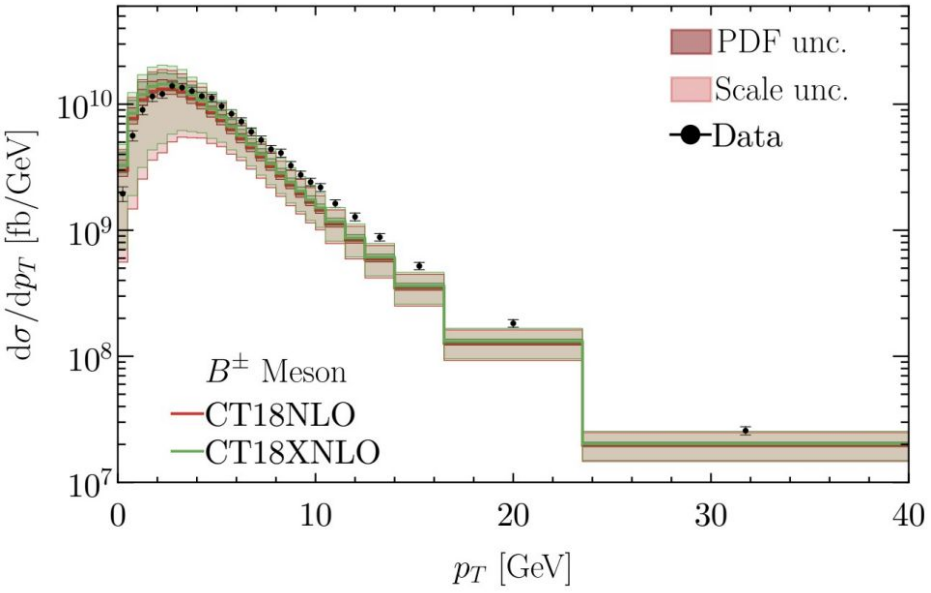
- ttW is background to many measurements and searches (Higgs, SUSY, 4-top, etc.)
- Improved theory calculations, including off-shell tops
- Study generators, parton showers

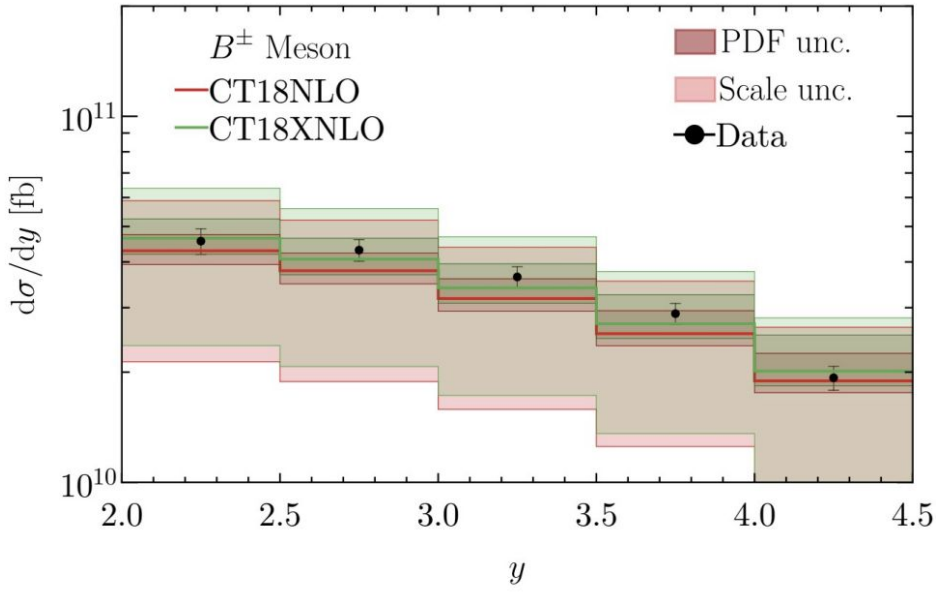




Heavy flavor PDFs

- Study HF PDFs in forward region
  - probe very small and very large x
- New scheme: S-ACOT-MPS, for charm and bottom
  - Currently at NLO, extend to NNLO to reduce scale unc



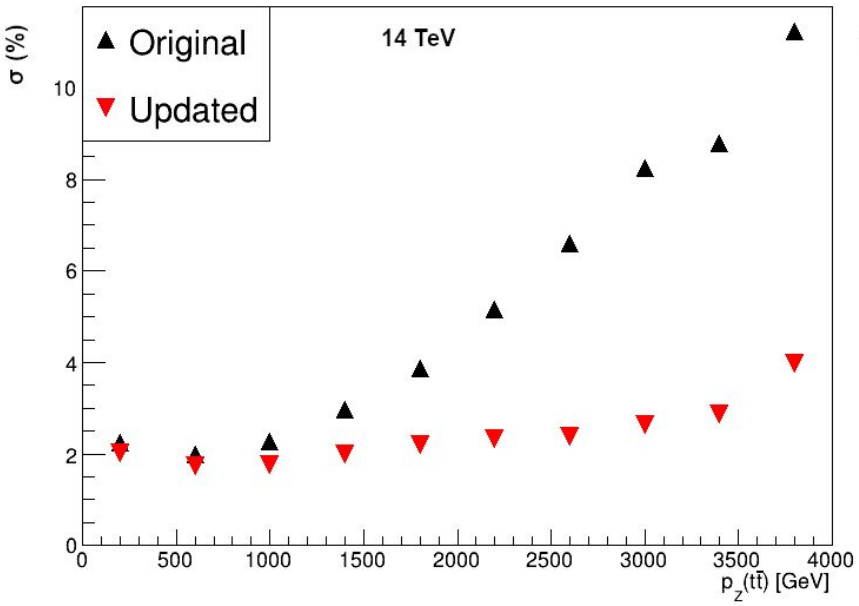


- arXiv:2203.16994

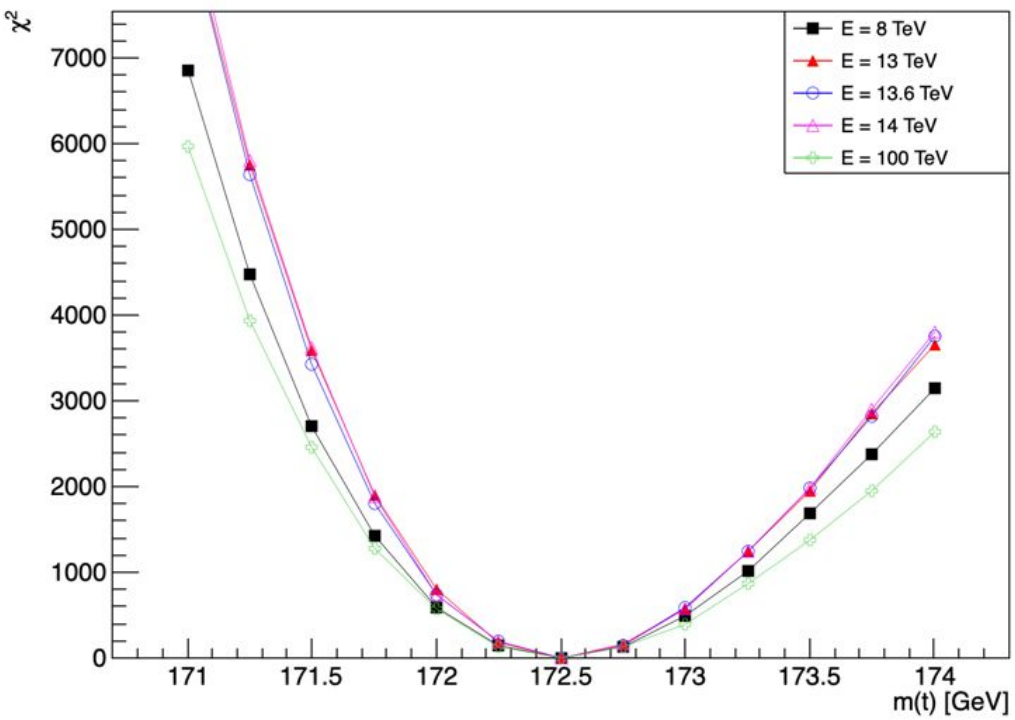
Top pole mass and PDFs

- Analysis of differential cross-sections in top-pair production
- Fit top-quark pole mass to m(ttbar), consider uncertainty from PDFs (CT18)
- Constrain PDF uncertainties from pZ(ttbar), assuming 1% uncertainty
- Top mass PDF uncertainty reduced by ~ factor 2

PDF uncertainty constraint

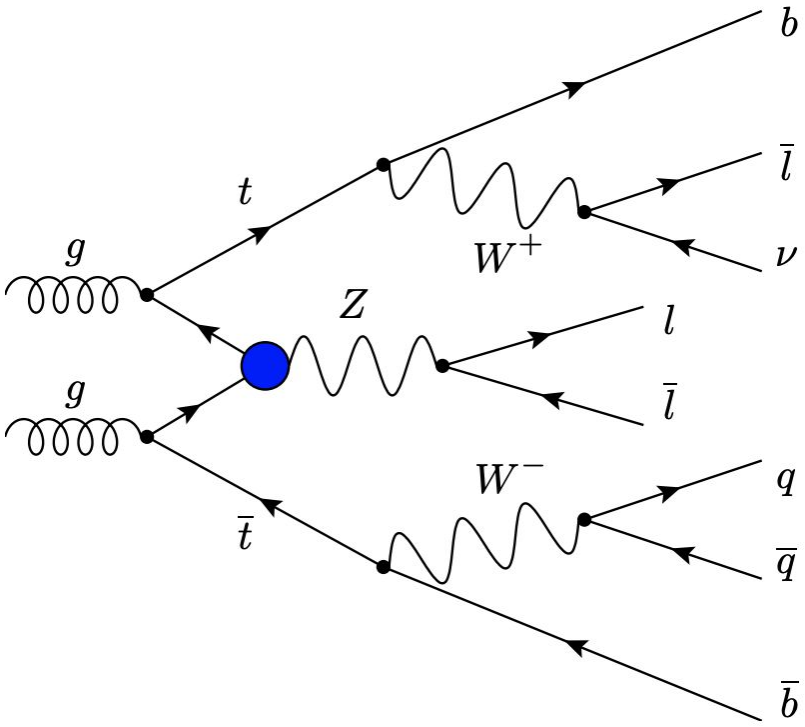


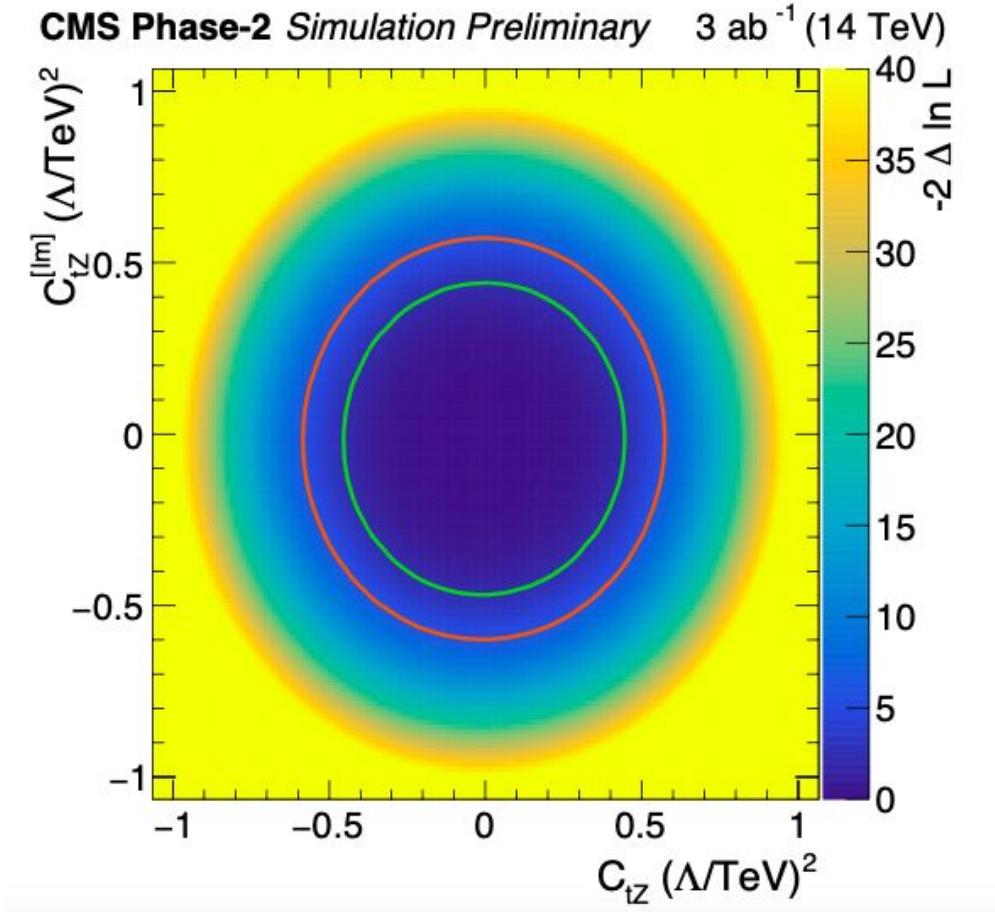
Top quark mass fit



Rare processes: ttZ and EW top couplings

- HL-LHC study of ttZ production and EFT operators

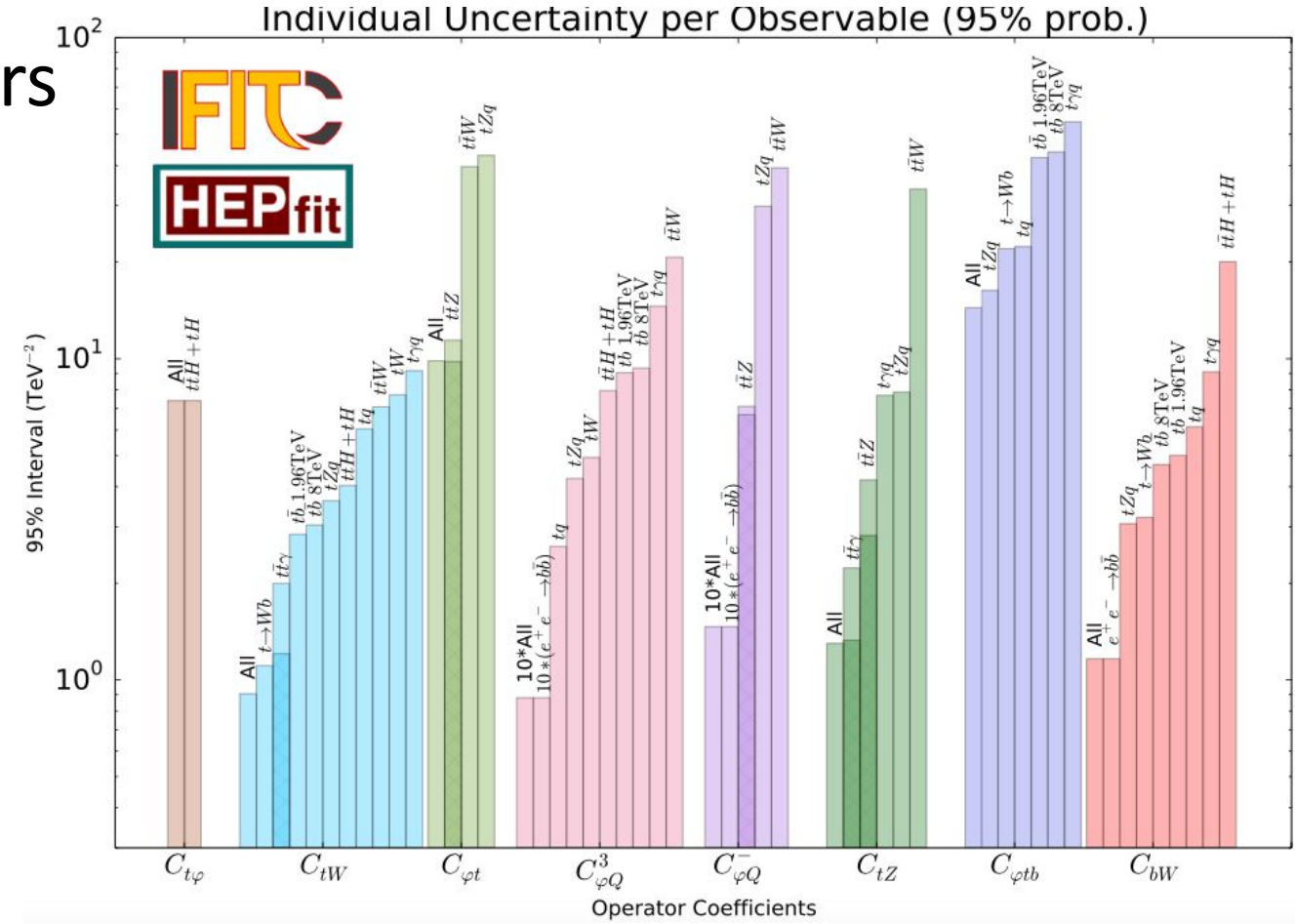




http://cds.cern.ch/record/2652018

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

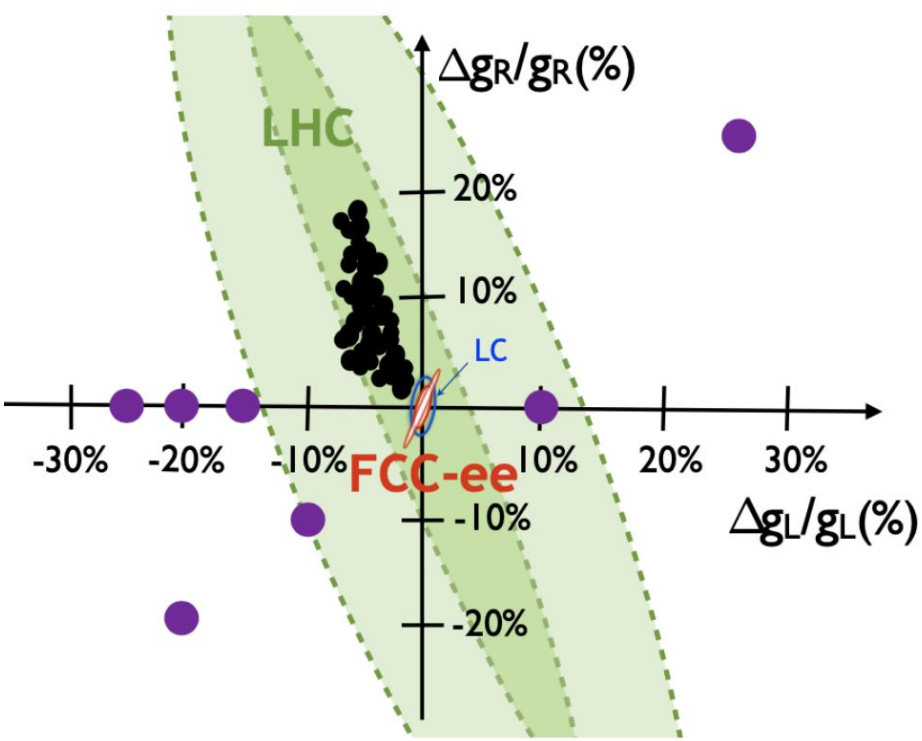
- Simultaneous fit to LEP/SLD, Tevatron, LHC
- Constrain
  8 EFT operators

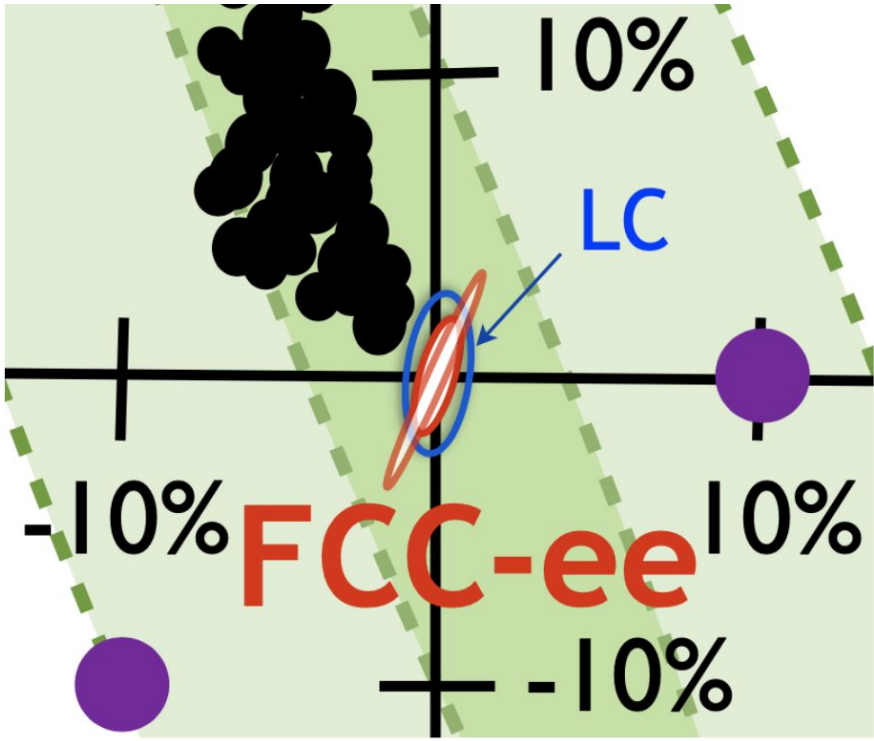


https://arxiv.org/abs/2107.13917

Top-Z couplings

- Compare LHC to FCC-ee for left-handed and right-handed top quark to Z boson couplings





https://arxiv.org/abs/1510.09056

EFT fits, top quark measurements

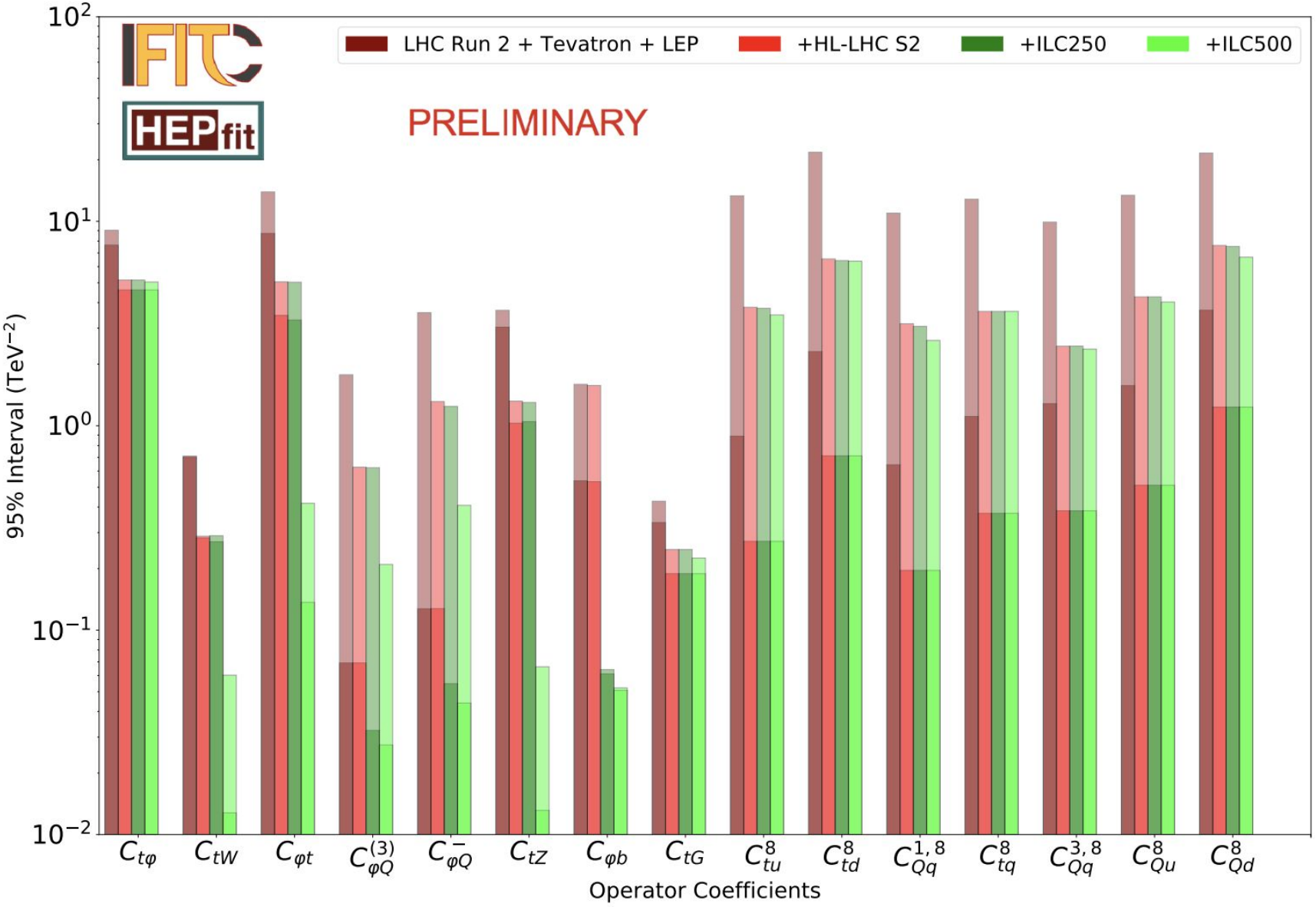
- Top-quark-specific EFT fits
  - Also integrate into global fits
- LEP/SLC, Tevatron, LHC: cross-sections, differential cross-sections, helicities
- FCC, ILC, CLIC: exploit full information in top production and decay

Machine	Polarisation	Energy	Luminosity	Observable
ILC	$P(e^+, e^-)$:(−30%, +80%) $P(e^+, e^-)$:(+30%, −80%)	500 GeV	$4\ ab^{-1}$	Optimal Observables
		1 TeV	$8\ ab^{-1}$	
CLIC	$P(e^+, e^-)$:(0%, +80%) $P(e^+, e^-)$:(0%, −80%)	380 GeV	$2\ ab^{-1}$	Optimal Observables
		1.5 TeV	$2.5\ ab^{-1}$	
		3 TeV	$5\ ab^{-1}$	
FCC	Unpolarised	350 GeV	$0.2\ ab^{-1}$	Optimal Observables
		365 GeV	$1.5\ ab^{-1}$	

Bottom quark measurements for EFT fit

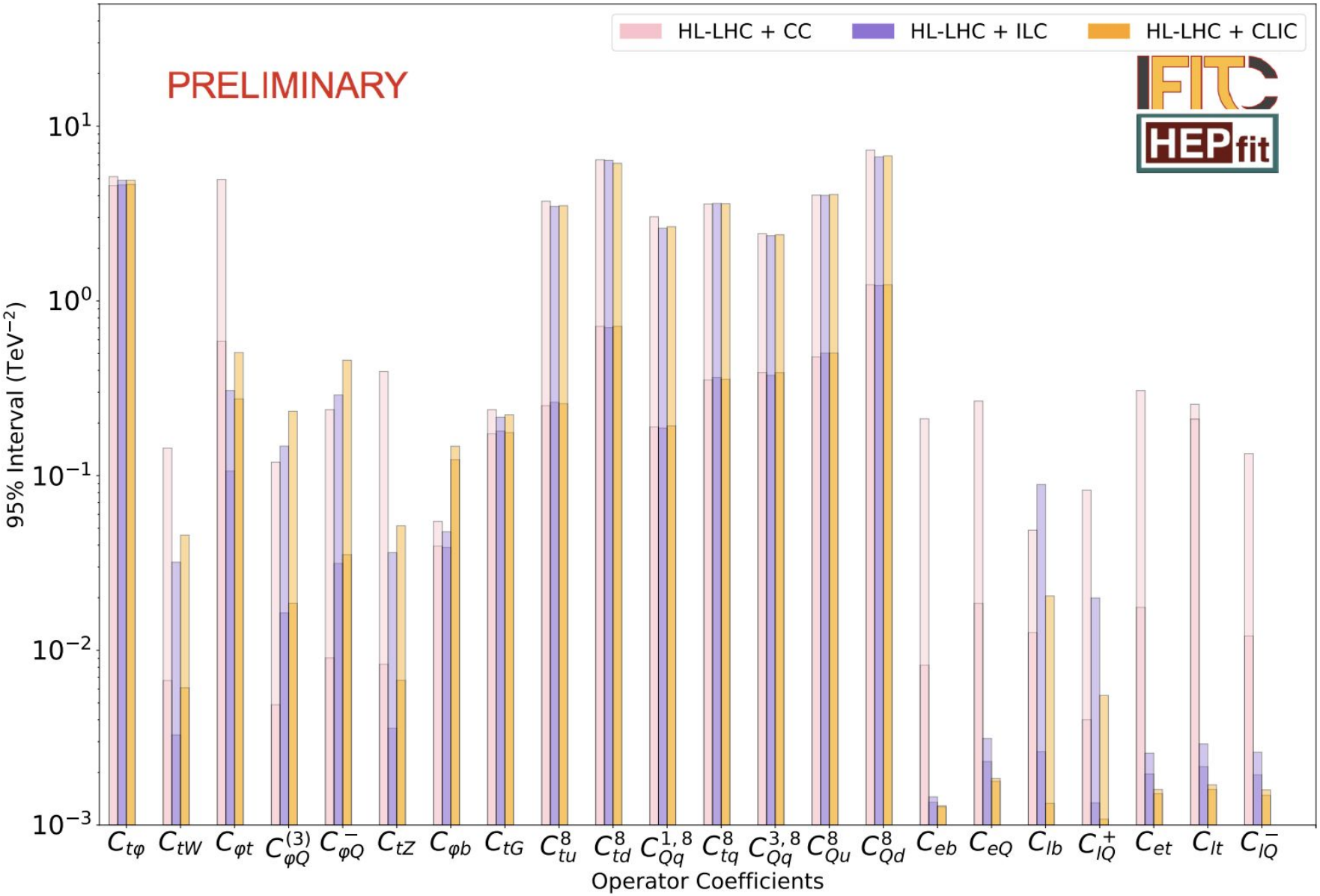
Machine	Polarisation	Energy	Luminosity	Observable
ILC	$P(e^+, e^-)$:$(-30\%, +80\%)$ $P(e^+, e^-)$:$(+30\%, -80\%)$	250 GeV	$2\ ab^{-1}$	$\sigma_{b\bar{b}}$ $A_{FB}^{b\bar{b}}$
		500 GeV	$4\ ab^{-1}$	
		1 TeV	$8\ ab^{-1}$	
CLIC	$P(e^+, e^-)$:$(0\%, +80\%)$ $P(e^+, e^-)$:$(0\%, -80\%)$	380 GeV	$2\ ab^{-1}$	$\sigma_{b\bar{b}}$ $A_{FB}^{b\bar{b}}$
		1.5 TeV	$2.5\ ab^{-1}$	
		3 TeV	$5\ ab^{-1}$	
FCC	Unpolarised	Z-pole	$150\ ab^{-1}$	$\sigma_{b\bar{b}}$ $A_{FB}^{b\bar{b}}$
		240 GeV	$5\ ab^{-1}$	
		365 GeV	$1.5\ ab^{-1}$	

EFT fits HL-LHC and ILC



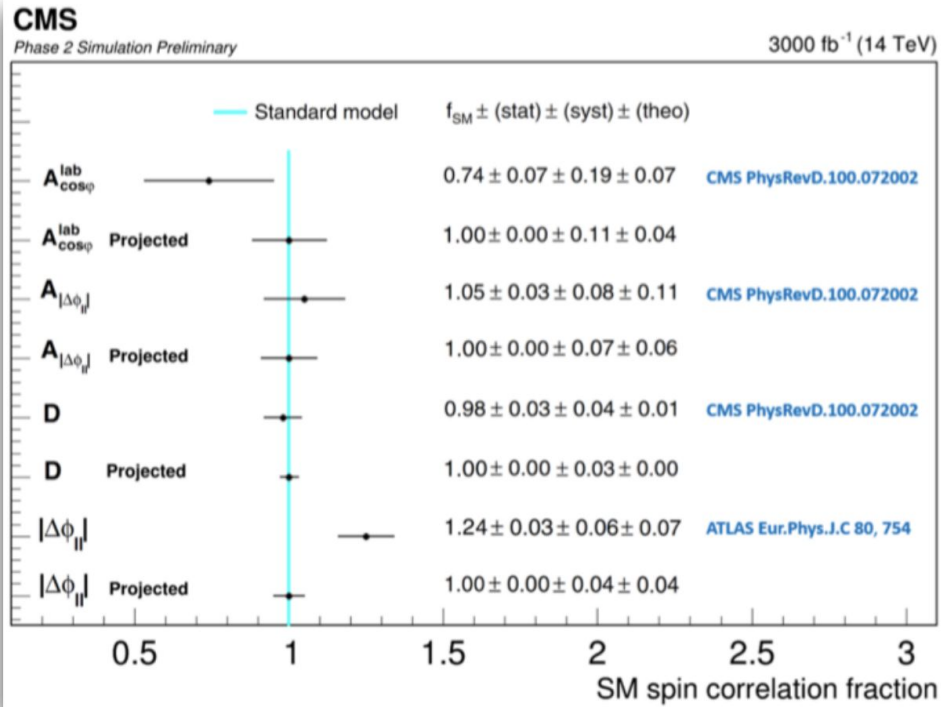
https://arxiv.org/abs/2203.07622

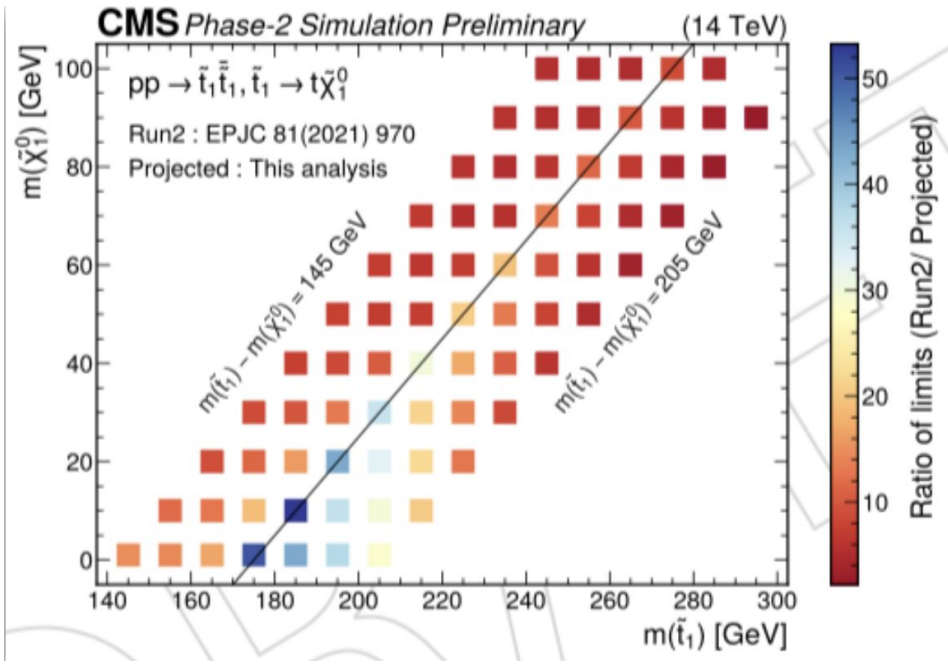
EFT fits HL-LHC and ILC and FCC-ee and CLIC



HL-LHC top quark spin correlation

- Measure correlation of top-quark spins in tt production (see next talk by Andy)
- Project current measurements to HL-LHC
- And set limits on SUSY compressed region

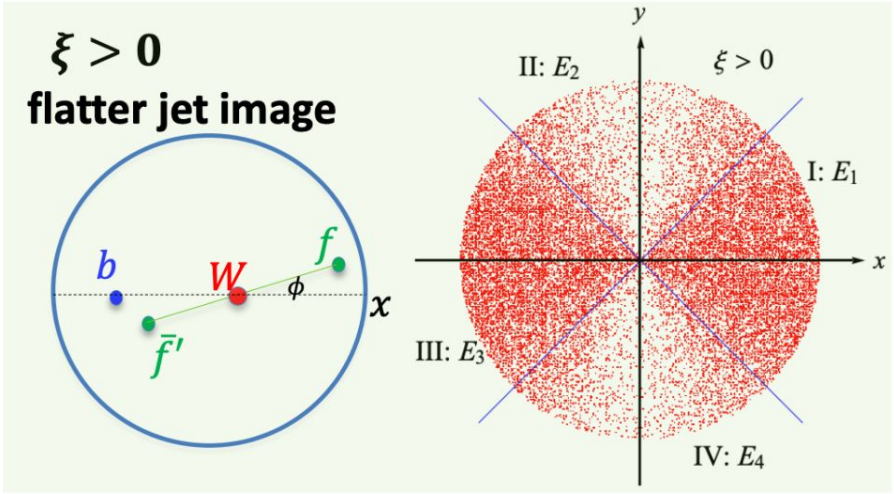


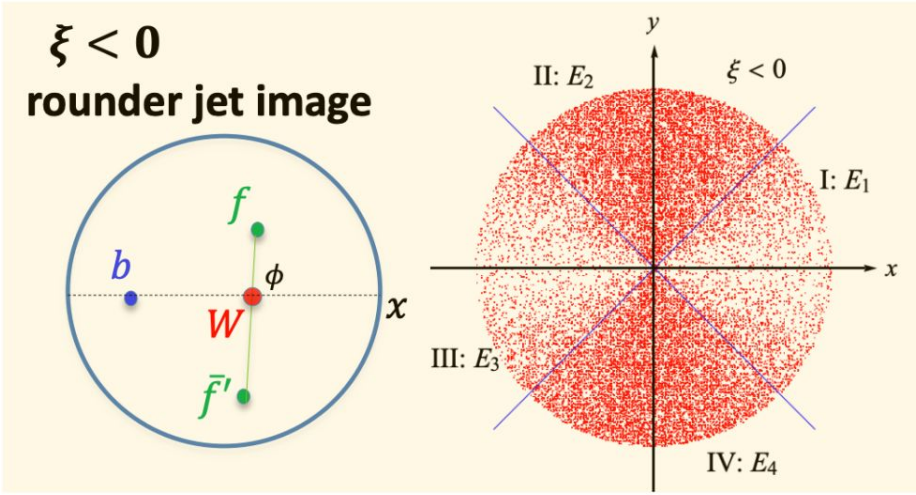


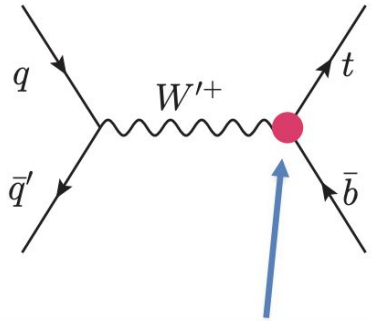
Top quark helicity in boosted top jets

- b-tagged jet compared to plane of light quark jets

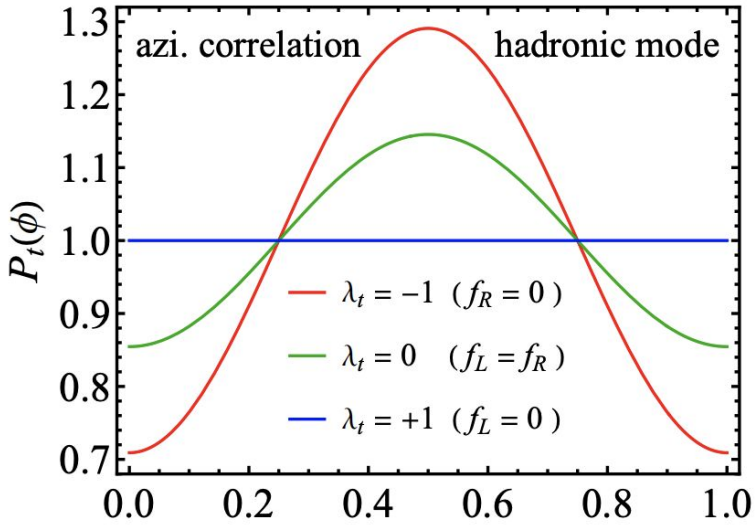
$$\frac{1}{\Gamma_t}\frac{d\Gamma_t}{d\phi} = \frac{1}{\pi}\,[1 + \xi\cos 2\phi], \qquad \phi \in [0, \pi]$$





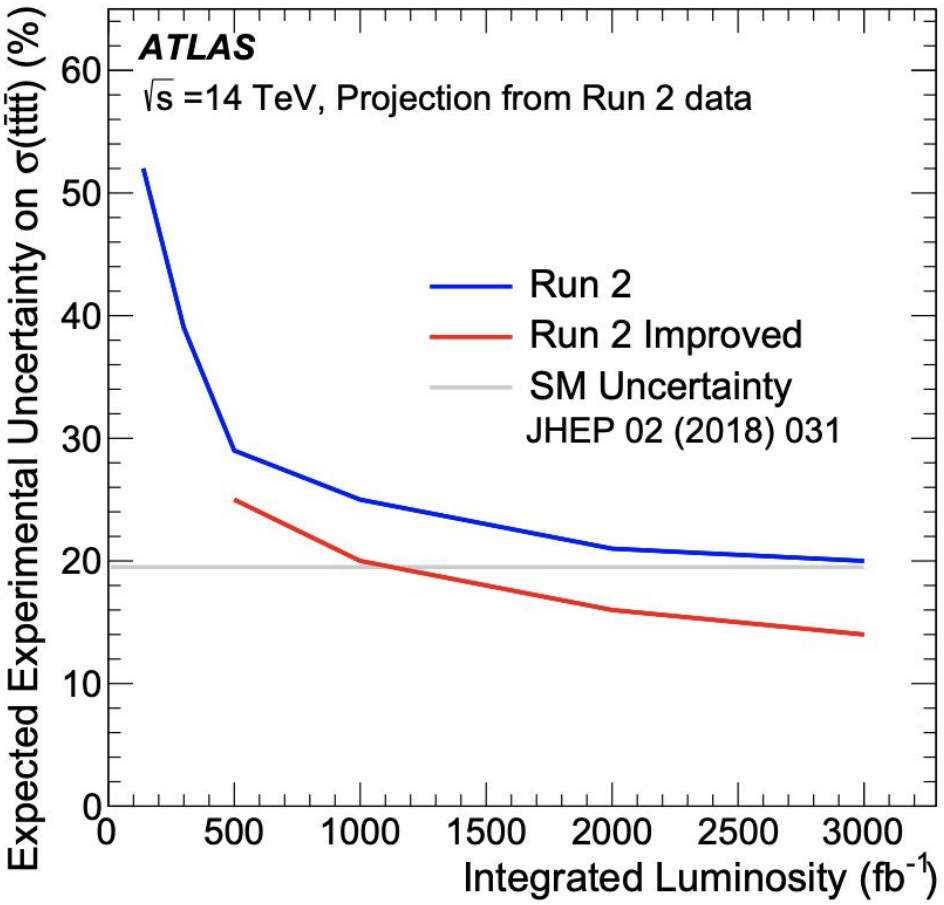


$$\bar{t}\gamma^{\mu}\,(f_L P_L + f_R P_R)\,b\,W'_{\mu} + \text{h.c.}$$



Rare processes: Four top production at the HL-LHC

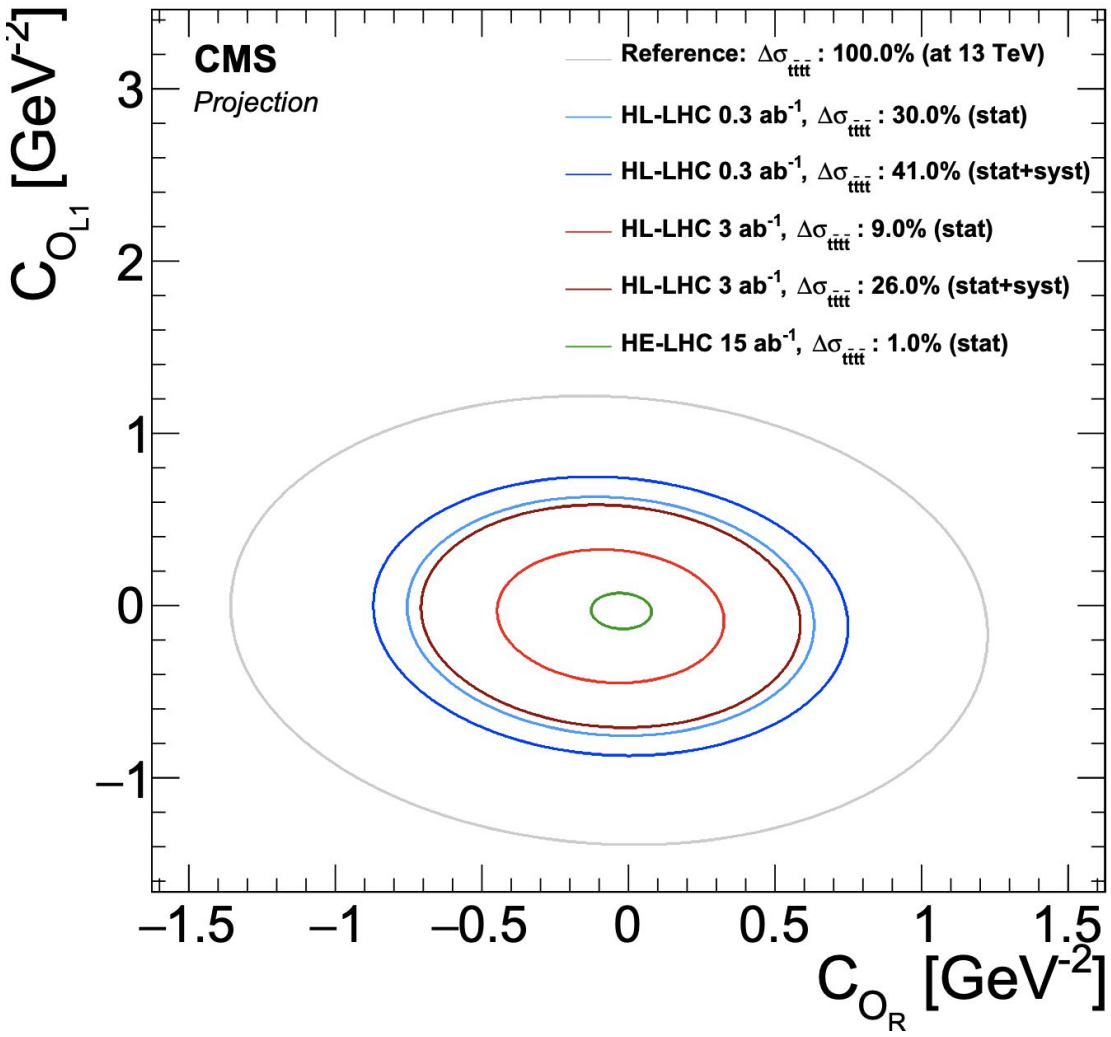
- Extrapolate from existing ATLAS analysis
- Same-sign dilepton, 3-lepton final states
- Measured XS about 2 sigma above SM
- Extrapolate syst:
  - ½ or scale by lumi



ATL-PHYS-PUB-2022-004

Rare processes: Four top production at the HL-LHC

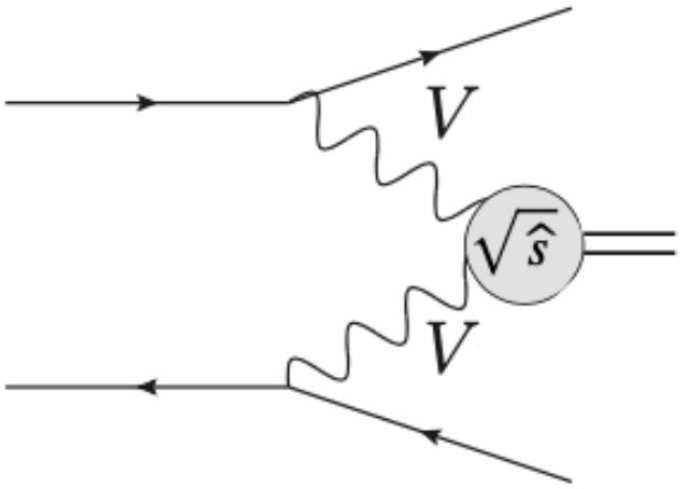
- Extrapolate from existing CMS analysis
- Same-sign dilepton, 3-lepton final states
- EFT operators limits, 4-fermion operators

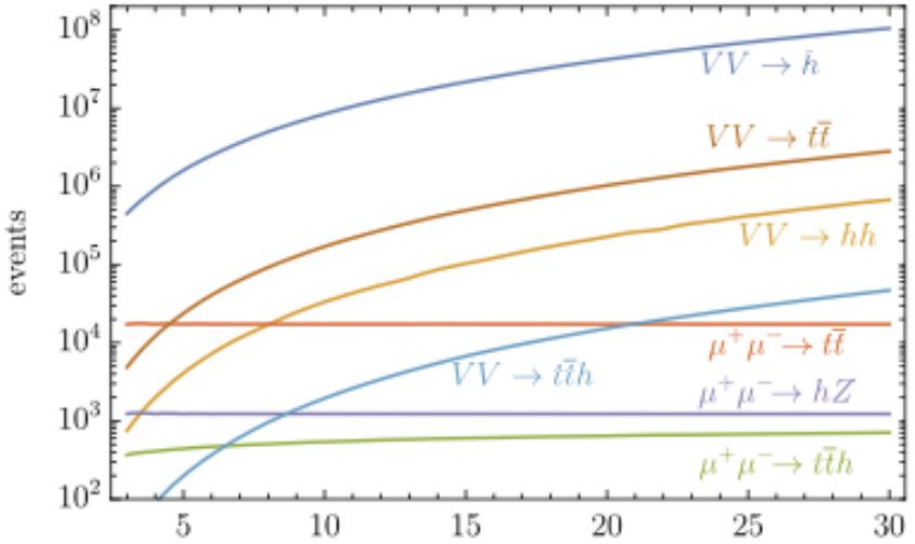


CMS PAS FTR-22-001

Muon collider

- Top pair production at a muon collider
- Several production modes
- Sensitive to EFT operators at very high energies
- Sensitive to Higgs/top compositeness

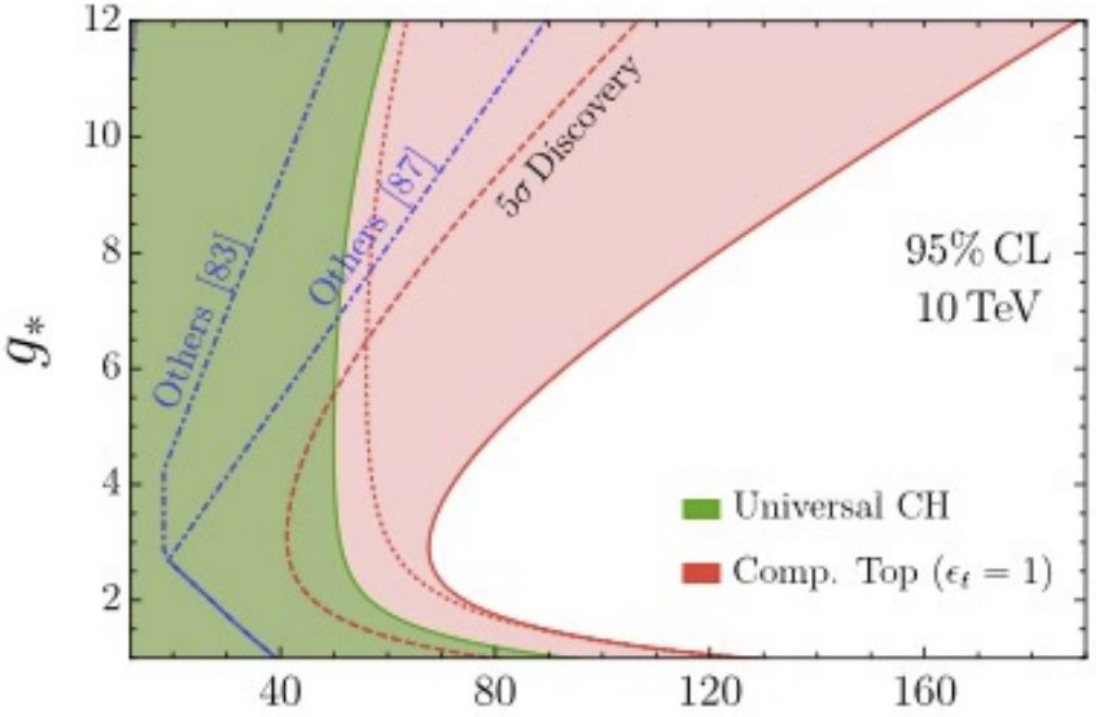




https://arxiv.org/abs/2203.07256

Muon collider: compositeness

- Top quark final states at muon collider sensitive to compositeness
- Also at CLIC



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

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

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

https://arxiv.org/abs/2202.10509

https://arxiv.org/abs/2010.05915

Conclusions

- Top quark and heavy flavor production will be important at all future collider options
  - Top quark mass, width, couplings
- EFT fits including top and bottom
- EF03 report writing in progress
  - We are looking for experts to help write sections and paragraphs