top physics opportunities at the threshold

Marcel Vos, IFIC, CSIC/UV, Valencia, Spain

ECFA Higgs/top/EW factory studies, Paestum (IT), October 2023

Expert team: M. Beneke (TUM, theory), F. Cornet (Case Western, theory), M. Defranchis (CERN, CMS), G. Durieux (Louvain, theory), A. Hoang (U. Vienna, theory), A. Jafari (DESY, CMS), Y. Kiyo (theory), V. Miralles (Manchester, theory), M. Moreno (IFIC, ATLAS), L. Pintucci (Trieste, ATLAS), R. Schwienhorst (Michigan State, ATLAS), F. Simon (KIT, e+e-), F. Zarnecki (Warsaw, e+e-)

R. Franceschini, A. Irles J. de Blas (related focus topics), P. Azzi (liaison FCCee)

One meeting:

Group met once in June 2023 to agree on scope:
https://indico.cern.ch/event/1300081/

Focus topics: subjects chosen by relevance and by common interest
— top physics is definitely important to us!
— all e+e- projects envisage a run at the pair production threshold

Original proposal: link
Recent list: link

Focus Topics

1. H->ss
2. ZH angular distributions / CP studies
3. Higgs self-coupling
4. W mass at threshold and continuum
5. Full studies of WW and evW processes, aTGCs
6. Top threshold detector-level sim study & scan optimisation ← That's us!
7. Luminosity measurement
8. New exotic scalars
9. Long-lived particles
10. Exotic top decays ← Roberto
11. CKM matrix elements with on-shell & boosted W decays
12. B → $K^{0*}\tau+\tau-$
13. EWK precision: 2-fermion final states
14. Measurement of b- and c-fragmentation functions / hadronisation
15. Measurement of gluon splitting to bb / cc & interplay with separating h → gluons from h →bb/cc

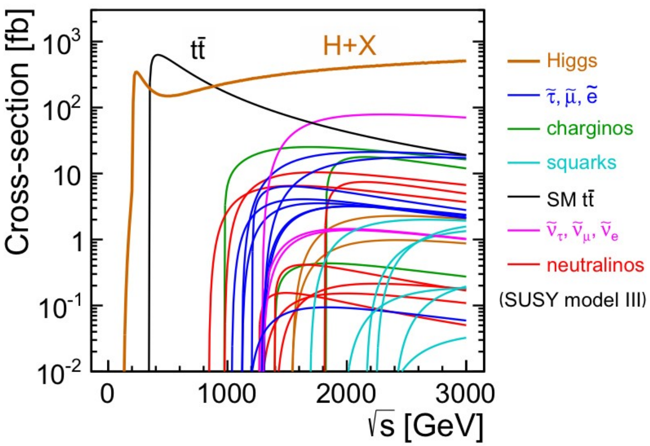
	relevant $\sqrt{s}$			
	91 GeV	161 GeV	240/250 GeV	350-380 GeV
1			X	X
2			X	X
3			X	X
4		X	X	X
5			X	X
6				X
7	X	x	x	x
8	x	x	x	x
9	x	x	x	x
10				x
11		x	X	x
12	X			
13	X	X	X	X
14	X	x	X	X
15	X	x	X	X

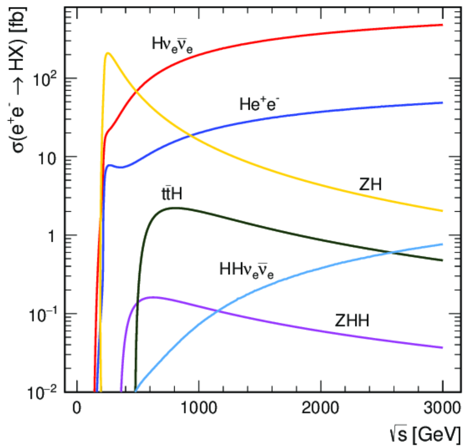
All containing many aspects, e.g. theory calculations / MC generators / reconstruction techniques / EFT interpretation / detector-level studies / interface to detector requirements / …

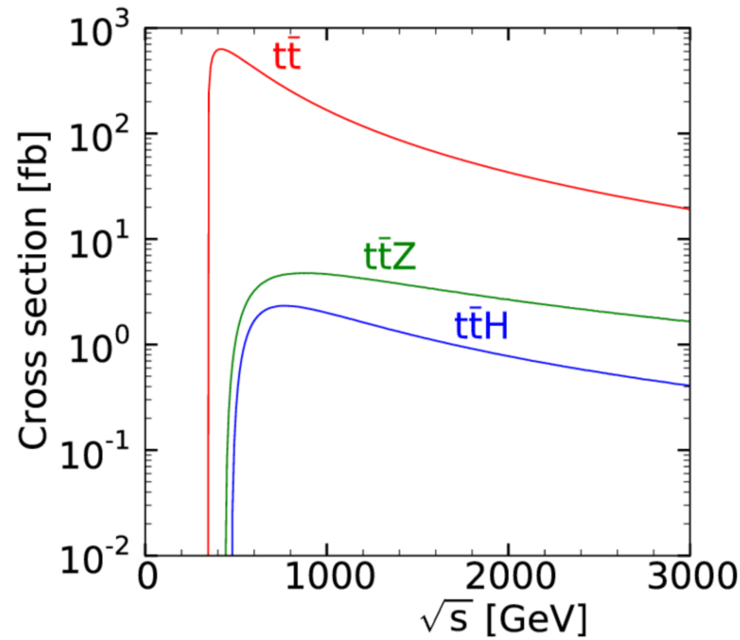
Individual conversations have continued over summer
Some actual personpower to work out expert ideas may have appeared
M.V. “retired” as ATLAS top WG convener and have time now!

Energy reach: top production thresholds

The ideal facility covers a broad energy range.





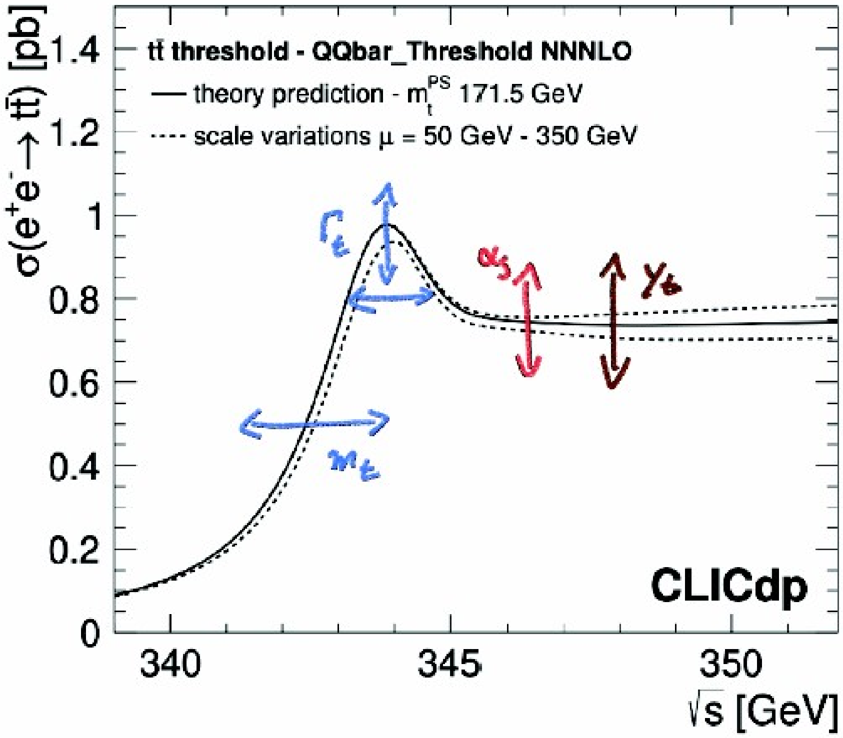


Direct BSM searches benefit from high energy

Higgs programme not limited to 250 GeV (VBF, di-Higgs production)

Top physics thresholds: ~ 350 GeV for pair production
~ 550 GeV for ttH
~ few TeV for VBF tt production, single top

The $t\bar{t}$ threshold scan



Top mass at LHC & HL-LHC, interpretation

+ Snowmass report
arXiv:2209.11267
arXiv:2203.08064

Direct mass measurements are experimentally the most precise

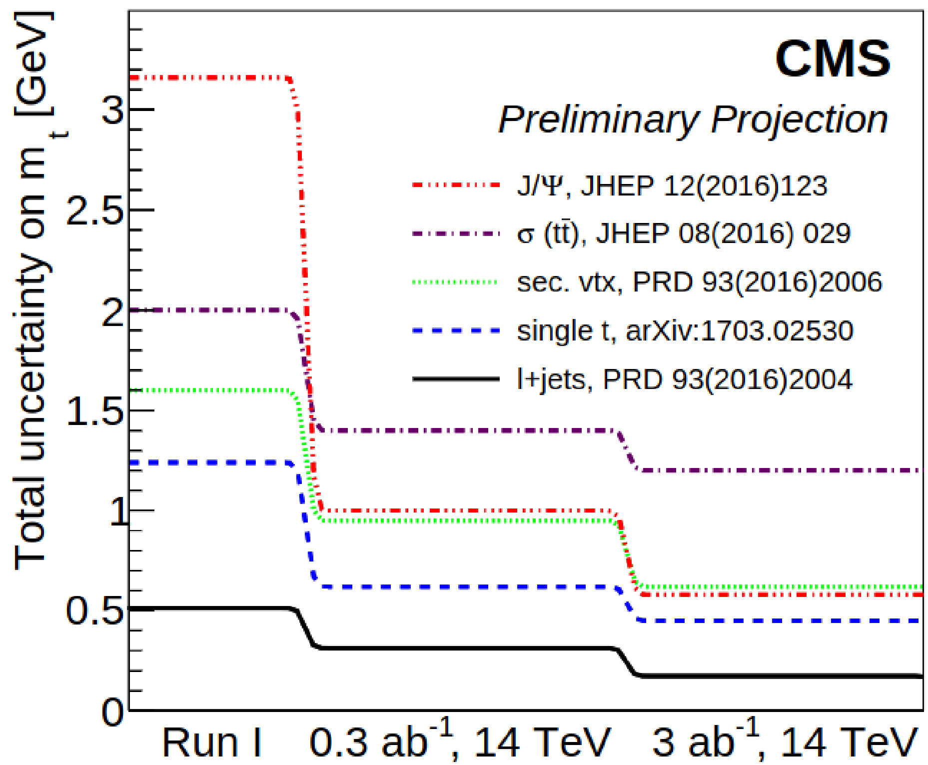
m_t ~ 172.52 ± 0.33 GeV

(ATLAS+CMS run 1 **combination***)*

J/psi and **sec. vertex** methods are starting to deliver (CMS sec. Vtx., ATLAS soft-muon)

Boosted top mass improving rapidly
CMS 2.5 GeV in 2020 → 0.8 GeV in 2023

Cross-section-based mass extractions achieve O(1 GeV) precision/measurement. Theorist's combined fit yields 400 MeV (Zenaiev & Moch, preliminary).

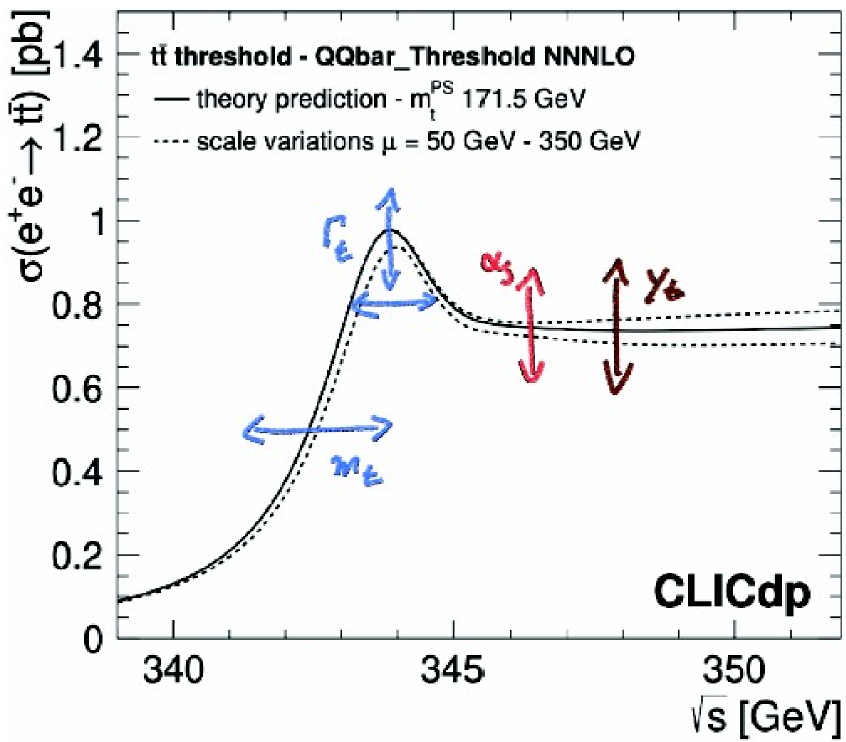


Status quo interpretation: "the difference between the top mass in direct measurements and the top pole mass is of the order of few hundred MeV", Corcella, Nason, Hoang, Yokoya, arXiv:1902.04070

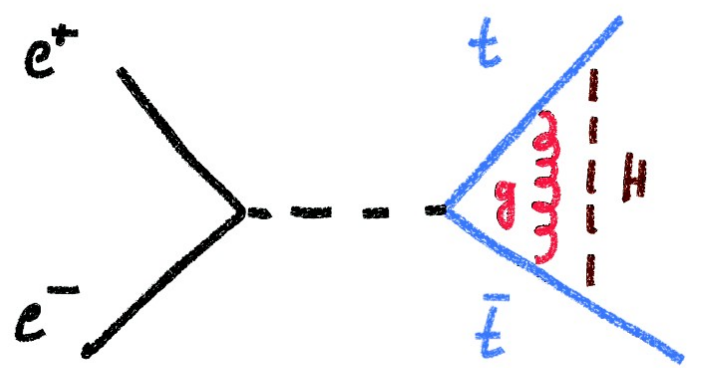
Combination of direct measurements: **200 MeV (exp.) + ?? (theo.)**
Combination of x-sec-based extractions: **500 MeV (theo.+exp.)**

e+e- threshold scan

A scan of the e^+e^- center-of-mass energy through the pair production threshold allows for the ultimate mass measurement *(Gusken & Kuhn ‘85, Peskin & Strassler ‘91)*
Experimental studies: Martinez & Miquel, hep-ph/020735, Seidel et al., arXiv:1303.3758
Part of the operation plan for all e+e- collider projects: Higgs & top factory!



Art-work: Frank Simon



The threshold position is sensitive to the top quark mass, the shape to the width
The normalization is sensitive to strong coupling and top quark Yukawa coupling
Just measure the cross section vs. sqrt(s) shape and derive all parameters

Precision measurements of cross sections

The LHC is a precision machine

Top quark pair production cross section to 2% uncertainty!!

Possible thanks to new luminosity calibration (0.8%!, arXiv:2212.09379)

Main bottle neck: NNLO+NNLL theory (scales, PDFs)

At an e+e- collider experimental systematic uncertainties can be controlled to O(few ‰) level → *e.g. CLIC top paper, arXiv:1807.02441*

→ *for mass & width measure a shape vs. sqrt(s): no need to control the absolute tt acceptance*

Theory very advanced: **N3LO in NRQCD** *by Beneke et al., PRL 115 (2015) corrections from P-wave production, non-resonant production, Higgs effects, and further EW interactions are known*

Code available in QQthreshold, CPC219 (2016)

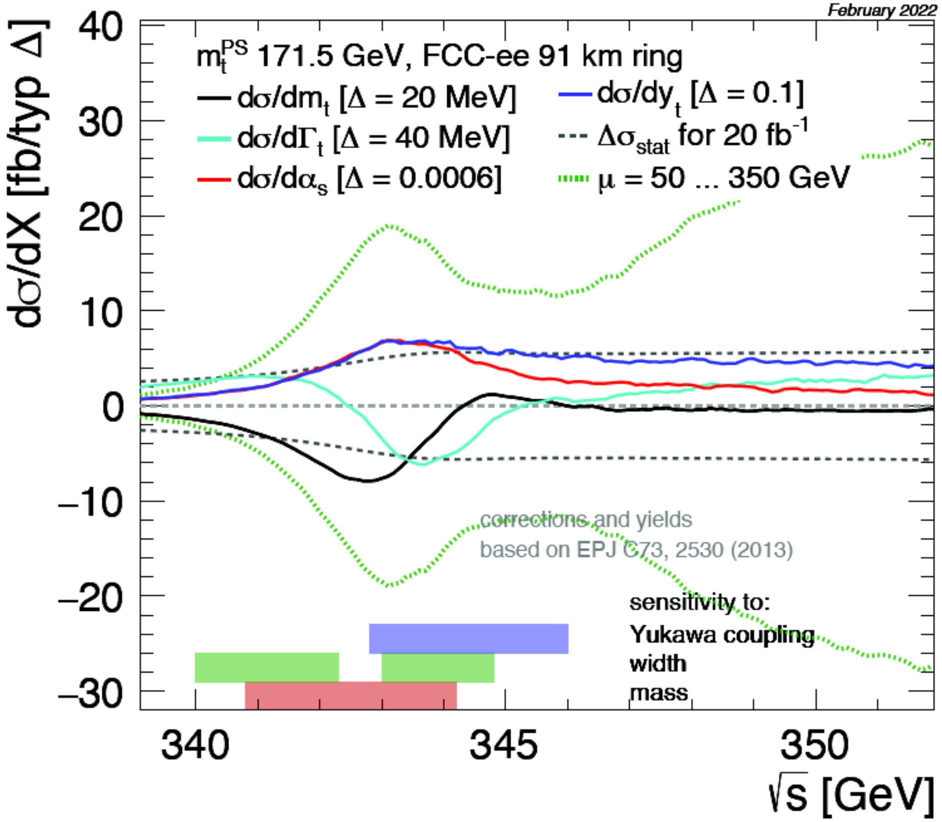
RGE-resummed NNLL results in Hoang, Stahlhofen arXiv:1309.6323

See also N3LO for e+e → γ^* → tt in the continuum

X. Chen et al., Heavy-quark pair production at lepton colliders at NNNLO in QCD, arXiv:2209.14259

Top quark mass

Frank Simon's seminar
Snowmass top physics report



Statistical uncertainty - - - - can be made small with 1-2 years of operation

Theory uncertainty …… requires calculation beyond NNNLO (QCD) + NNLO (EW). Resummation is available and can be added.

Note: interpretation unambiguous, translation to MS scheme with O(10 MeV) QCD scale uncertainty, parametric uncertainty from α_s requires care, as well as EW corrections

Top quark mass to **approx. 50 MeV**, limited by theory uncertainty and to first order independent of collider design (luminosity spectrum has 2nd order effect)

Top quark width to 45 MeV → bounds on invisible decays+SMEFT arXiv:1907.00997
Precision for α_s ~ 0.001 and y_t ~ 12% not competitive, but good cross-checks

 marcel.vos@ific.uv.es

Future directions

Exp: Full-simulation study to revisit and harmonize experimental systematic uncertainties

Theo: Fully differential predictions at adequate precision

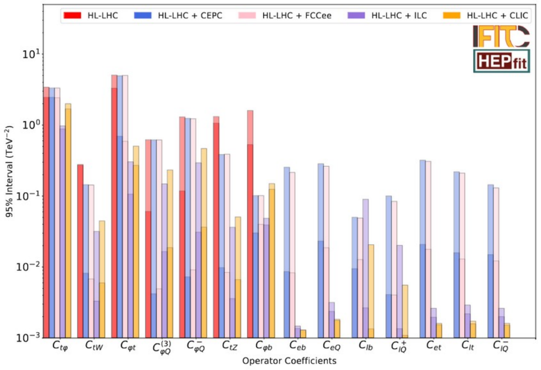
Specify procedure for comparison of data and theory (i.e. treatment of ISR?)

Study width prospects in more detail (i.e. comparison LHC, interpretation in NP scenarios)

Embed top mass prospect in global EW fit environment

Find a way to make top Yukawa and strong coupling results more competitive

Above the threshold:
a broad precision programme

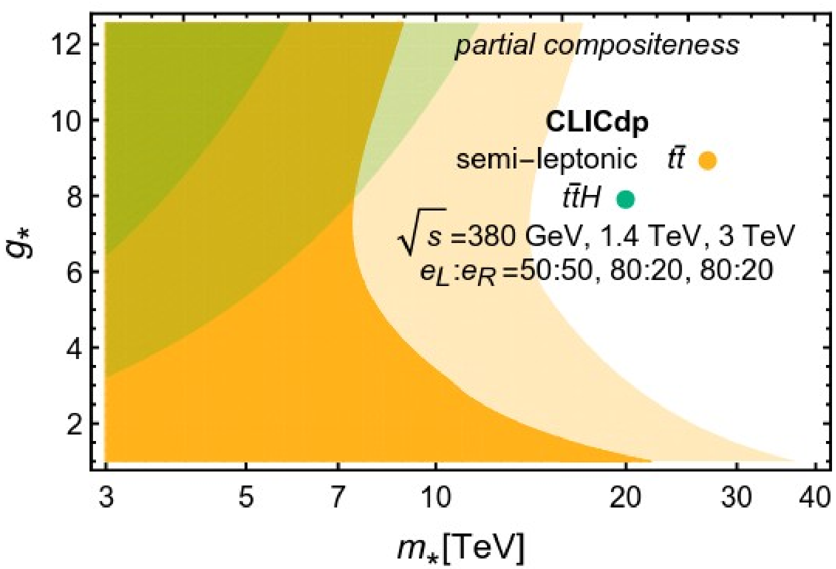


Top (and its couplings) are special in many BSM scenarios
Precision coupling measurements ARE a sensitive BSM search

Snowmass top physics report, https://arxiv.org/pdf/2209.11267.pdf

D. Top-quark compositeness

High-energy lepton colliders are sensitive probes of top-quark compositeness. For example, Fig. 30 shows the reach in the composite sector confinement scale m_* and the composite coupling strength parameter g_* of a partial top compositeness scenario at a multi-TeV e^+e^- collider [61] (see also [542]).



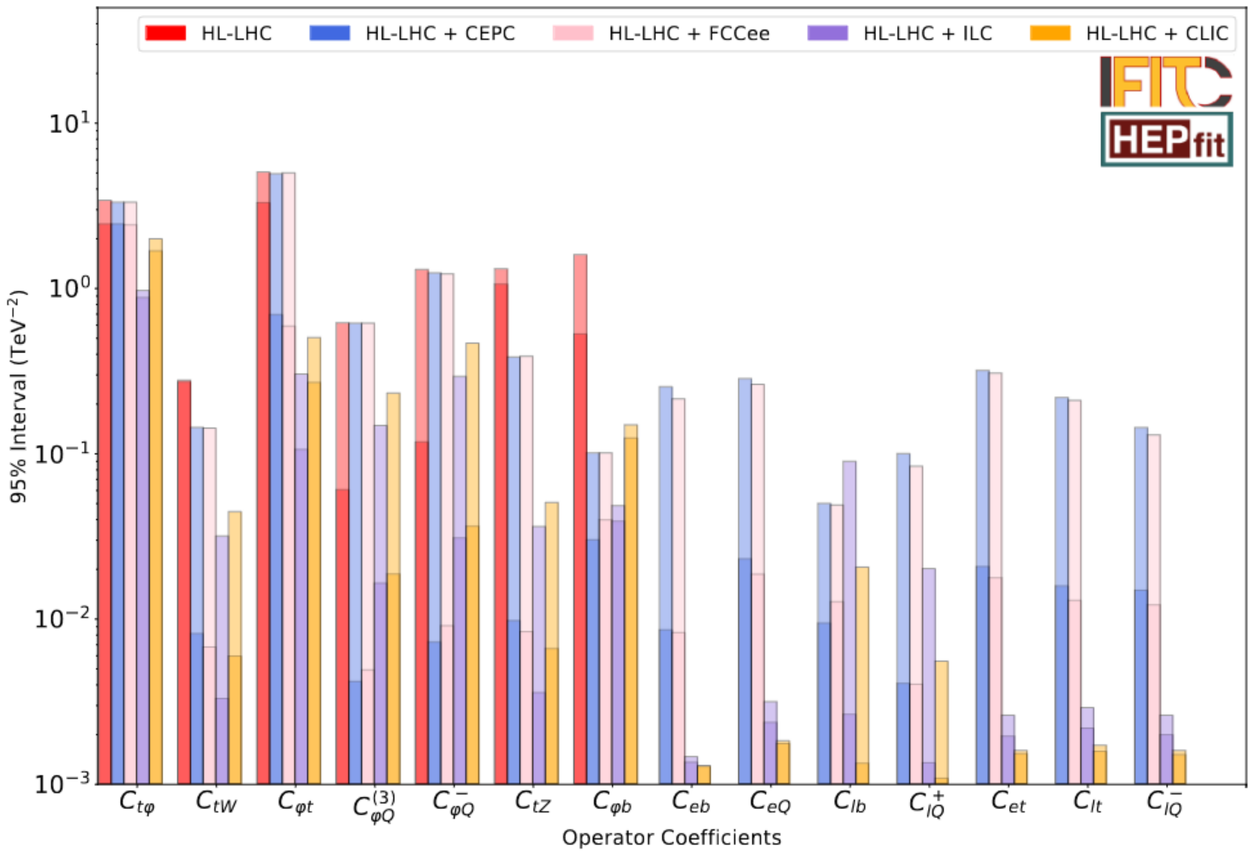
energy & precision!

marcel.vos@ific.uv.es

SMEFT fit HL-LHC + e+e- collider

EFT for e+e-: Durieux et al. , arXiv:1807.02121
top EW fit HL-LHC/e+e-: Durieux et al., arXiv:1907.10619
Snowmass top couplings, arXiv:2205.02140
Global SMEFT fit, J. De Blas et al., arXiv:2206.08326
Snowmass report, Schwienhorst et al., arXiv:2209.11267

four-quark operators (qqtt):	no progress
two-fermion top-boson:	O(1) → O(0.1)
Two-lepton-two-top (lltt):	XXX → O(10^{-1} - 10^{-3})



Snowmass SMEFT fit based on Durieux et al., with updated operating scenarios

Future improvements

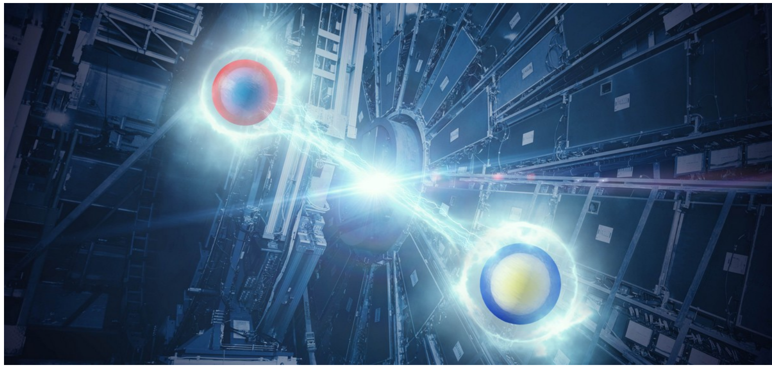
Complete and update LHC/HL-LHC fit at NLO (work in progress)
Add imaginary parts that are left out (and compare to low-energy observables)
Merge with Higgs/EW fit (major project!)

marcel.vos@ific.uv.es

Entanglement?

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2023-069/

LHC: an established top QI lab since Sep. 2023.
Great statistics, complex “mixed-state” production



Future e+e-: carefully prepared initial state
(including tunable beam polarization)

marcel.vos@ific.uv.es

Summary

The next large-scale e+e- facility in HEP can (should) do a lot of top physics!

An energy scan through the pair production threshold yields the ultimate top quark mass measurement + width, strong coupling, top quark Yukawa

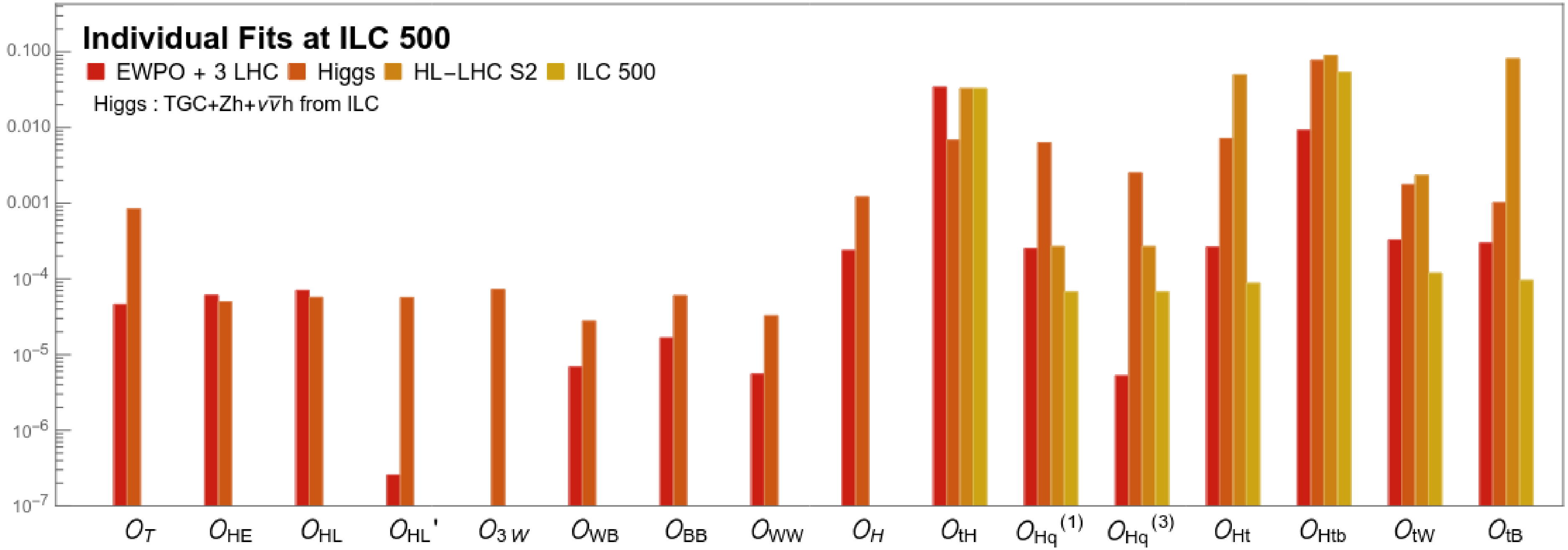
A broad precision programme of top measurements unfolds above threshold including many processes (tt, ttγ, ttg, single top, ttZ, ttH, VBF tt production) and many measurements (σ, A_{FB}, polarization, CP-odd observables…).

There is a **strong case to reach 500-550 GeV** (direct Yukawa from ttH, running top quark mass, constraints on eett operators) and for beam polarization.

Complementary strengths in comparison to **hadron colliders**

SMEFT fit – future work

With just the “single” energy (threshold + 360/365 GeV) the challenge is to constrain all directions in SMEFT coefficient space. EWPO and Higgs data have



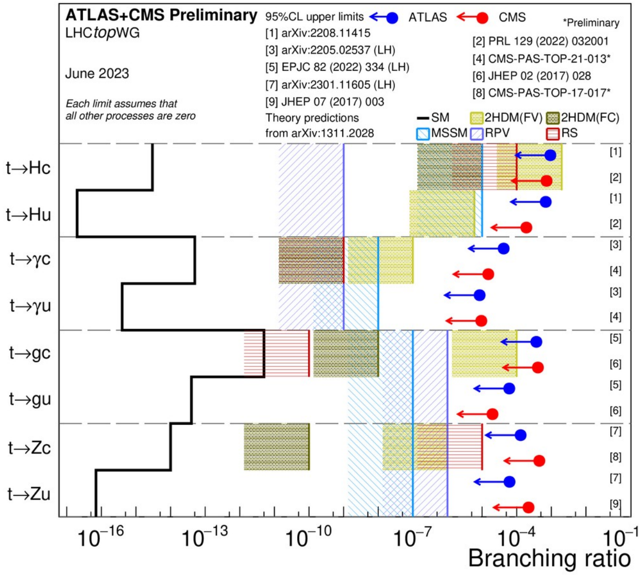
S. Jung et al., arXiv:2006. (see also work by Vryonidou et al.)

Possible next steps in ECFA Higgs/top/EW factory studies:

– merge Higgs/EW and top EFT fits on prospects

– find further exp. inputs to enable “single-energy” fit

FCNC interactions:
top physics below the $t\bar{t}$ threshold



FCNC searches are HL-LHC territory, aren't they?

Most recent prospects: CERN YR 7 (2019), arXiv:1902.04070
+ Matteo Defranchis, this morning

LHC: excellent sensitivity. BR($t \to qX$)@95%CL from 10^{-3} to 10^{-5}

Note: production pp $\to$ tX is as important as decay t $\to$ qX

HL-LHC: expect to improve more than an order of magnitude

$\mathcal{B}$ limit at 95%C.L.	3 ab^{-1}, 14 TeV	15ab^{-1}, 27 TeV	Ref.
$t \to gu$	3.8×10^{-6}	5.6×10^{-7}	[721]
$t \to gc$	32.1×10^{-6}	19.1×10^{-7}	[721]
$t \to Zq$	$2.4 - 5.8 \times 10^{-5}$		[733]
$t \to \gamma u$	8.6×10^{-6}		[724]
$t \to \gamma c$	7.4×10^{-5}		[724]
$t \to Hq$	10^{-4}		[733]

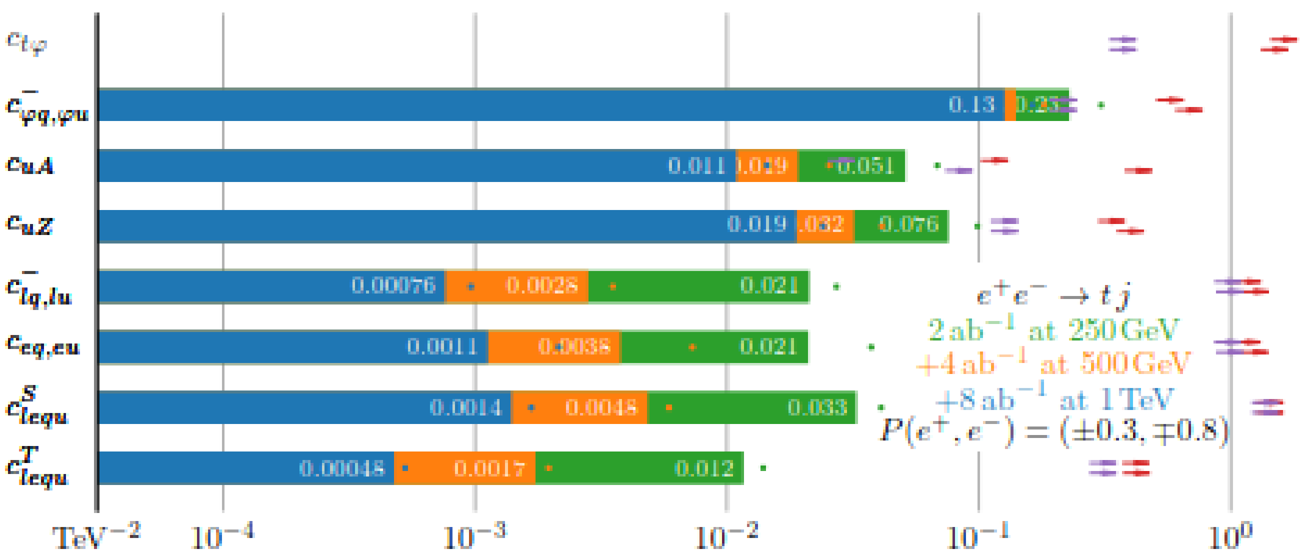
Well, e+e- colliders aren't that bad, either.

Lepton collider is both competitive and complementary

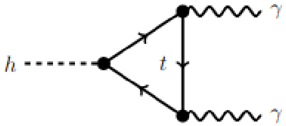
First top physics: e+e- → tj searches at 250 GeV

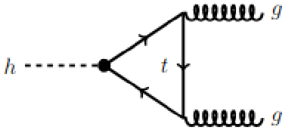
More full-simulation work needed!

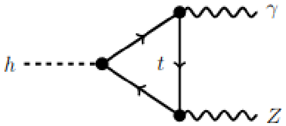
H. Hesari et al., arXiv:1412.8572
G. Durieux et al., arXiv:1412.7166
Shi & Zhang, arXiv:1906.04573
ILC white paper, arXiv:2203.07622
M. Arroyo et al.,arXiv:2202.04572



Top and Higgs

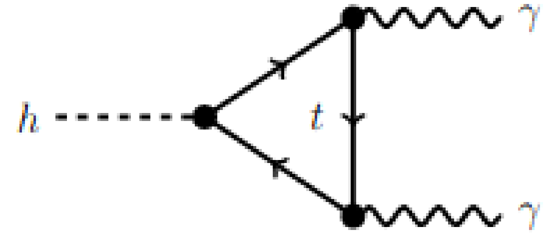


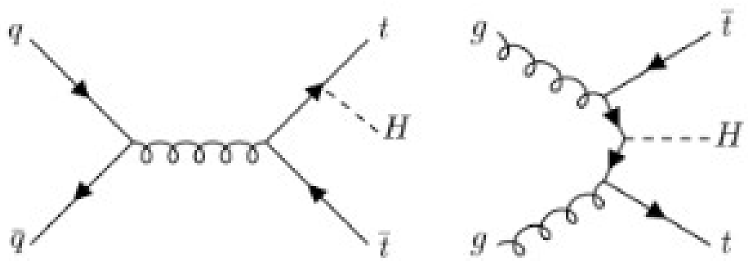




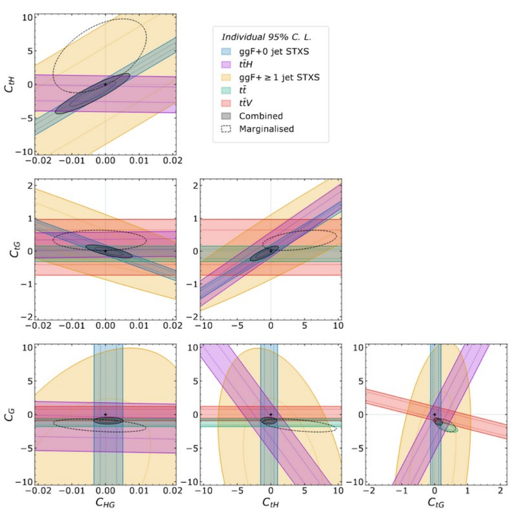
The top Yukwa coupling at the LHC

H(125) observation in **2012** in gg → H, H→ γγ implicitly establishes Higgs-top coupling





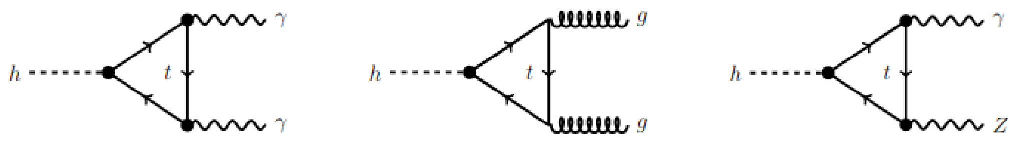
Explicit confirmation in **2018** with the observation of pp → ttH production



Global fit to LHC data in **2021** (Ellis et al.) finds correlations among SMEFT coefficients prevent a robust determination of y_t from gg → H or H → γγ.

Global limit on C_phit is dominated by ttH.

The top Yukawa coupling at a lepton collider



250 GeV run offers "indirect" sensitivity to the top Yukawa

$\Delta y/y < 1\%$ from $H \to gg$ *Mitov et al., arXiv:1805.12027*

$\Delta y/y < 1\%$ from $H \to \gamma\gamma$ *Jung et al., arXiv:2006.14631*

Assuming the SM for all other couplings

500+ GeV run offers a "direct" measurement in ttH production

1-2% precision *Price et al., arXiv:1409.7157*

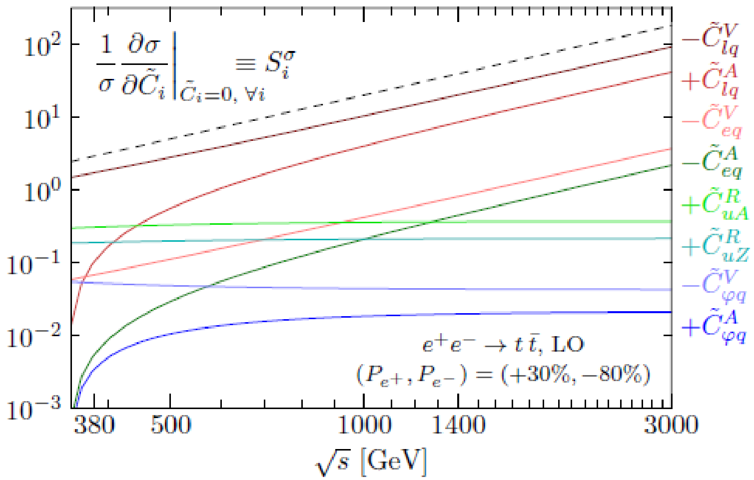
robust in global analysis *Jung et al.,arXiv:2006.14631*

Values in % units		LHC	HL-LHC	ILC500	ILC550	ILC1000	CLIC
δy_t	Global fit	12.2	5.06	3.14	2.60	1.48	2.96
	Indiv. fit	10.2	3.70	2.82	2.34	1.41	2.52

Top-SMEFT fit on prospects, de Blas et al., 2206.08326

Energy: BSM sensitivity

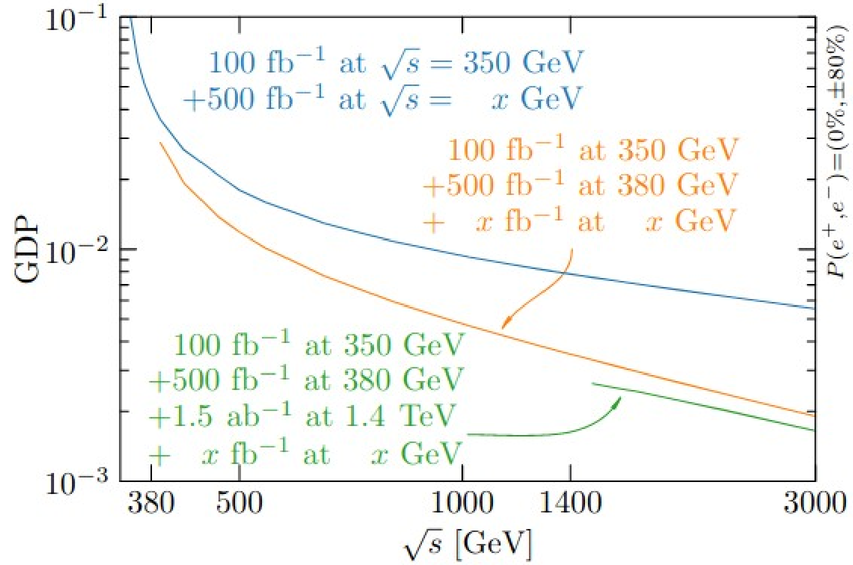
Durieux, Perello, Zhang, Vos, arXiv:1807.02121
CLIC top paper, arXiv:1807.02441
CLIC New Physics paper, arXiv:1812.02093



Effect of four-fermion operators felt most strongly at high energy

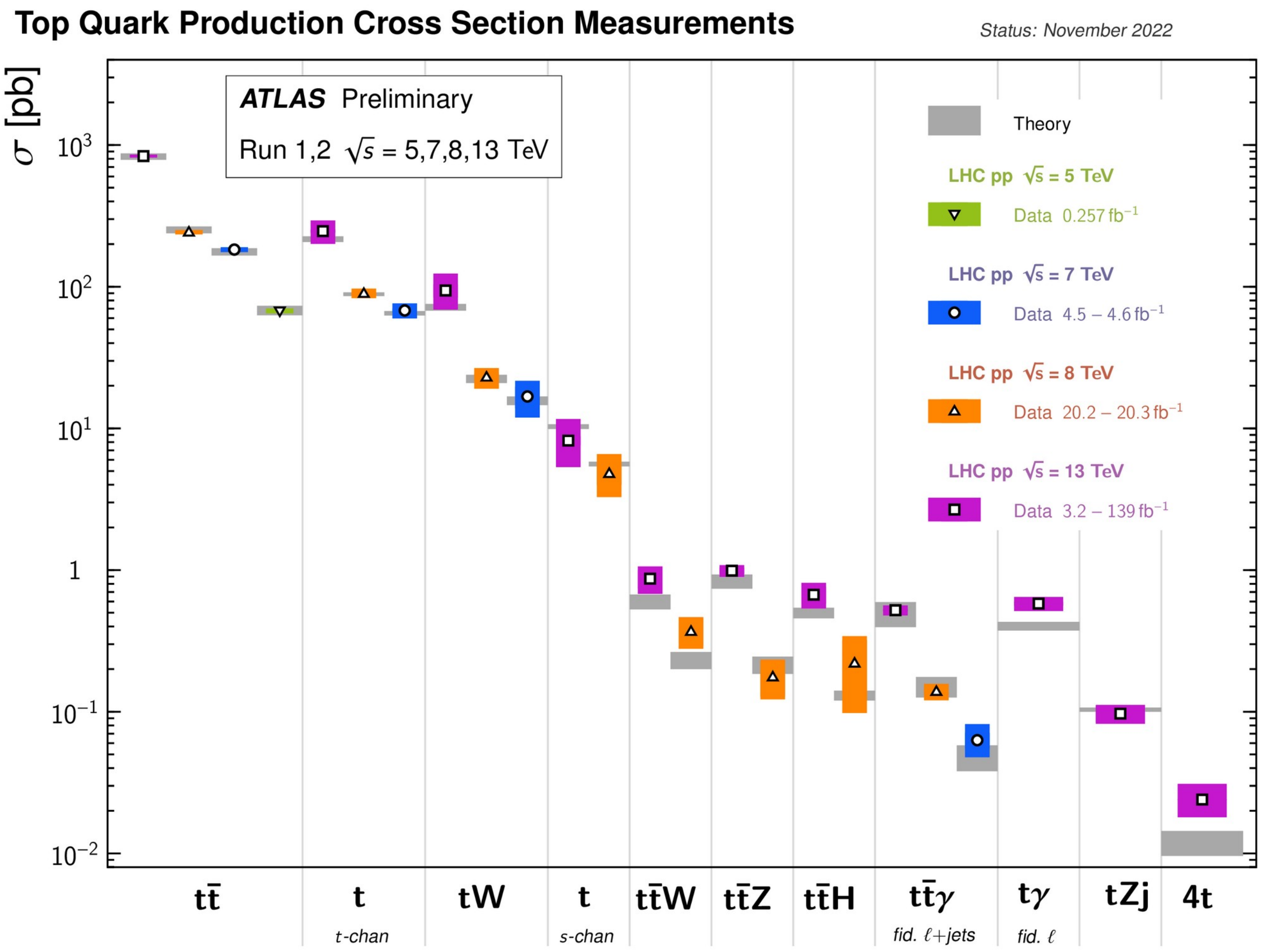
Effect of two-fermion operators best probed at ~400-500 GeV

Ideal facility to characterize top EFT:
– take data at two energies
– maximize lever arm of high-energy



(See also Fiolhiais et al., arXiv:1206.1033)

The LHC top couplings programme



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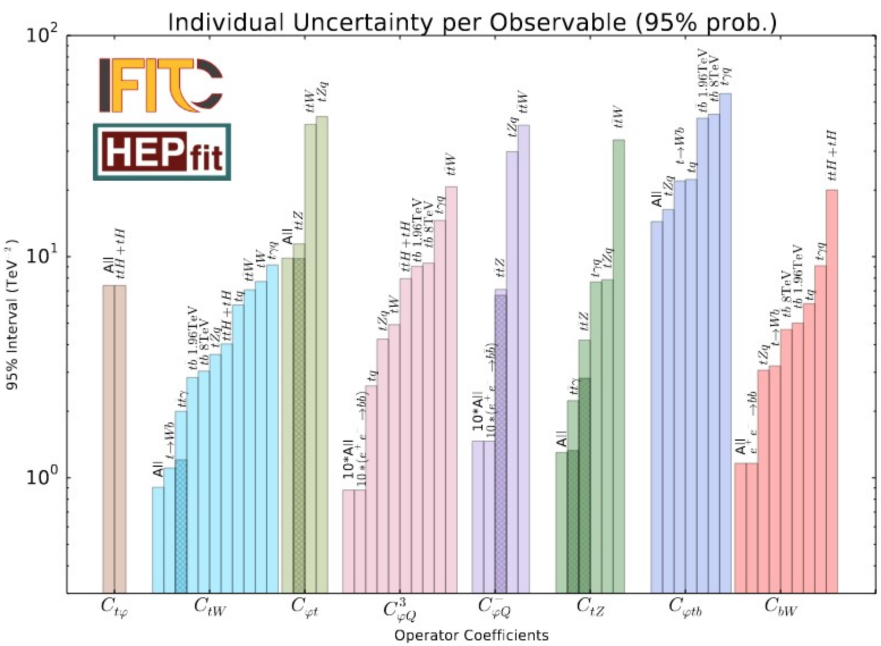
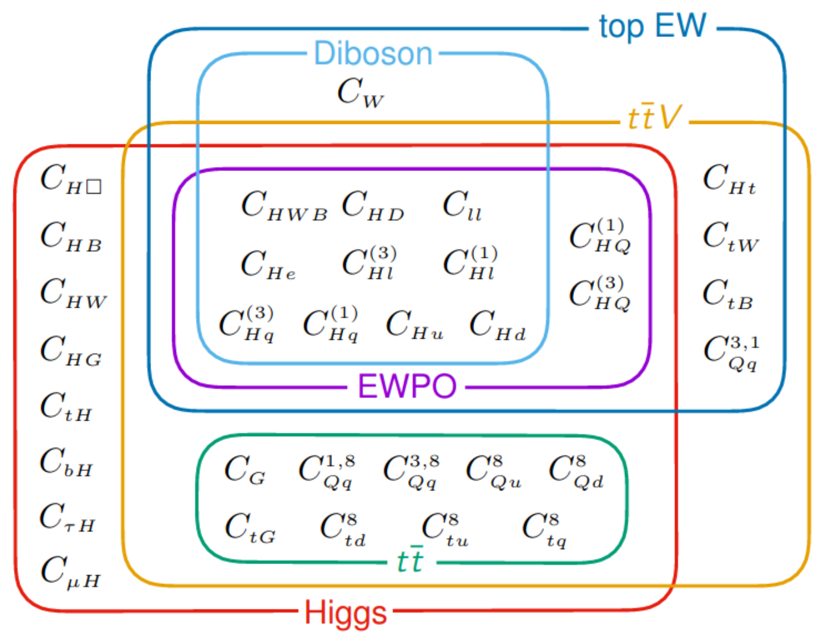
LHC top physics programme

Tevatron+LHC $t\bar{t}$ measurements characterize top QCD couplings precisely
Charged-current tWb interaction constrained by single top and W-helicity
Couplings with γ/Z/H probed in t+X (top quark escaped scrutiny at LEP
Measurements of tttt and ttbb characterize 4-heavy-quark vertices

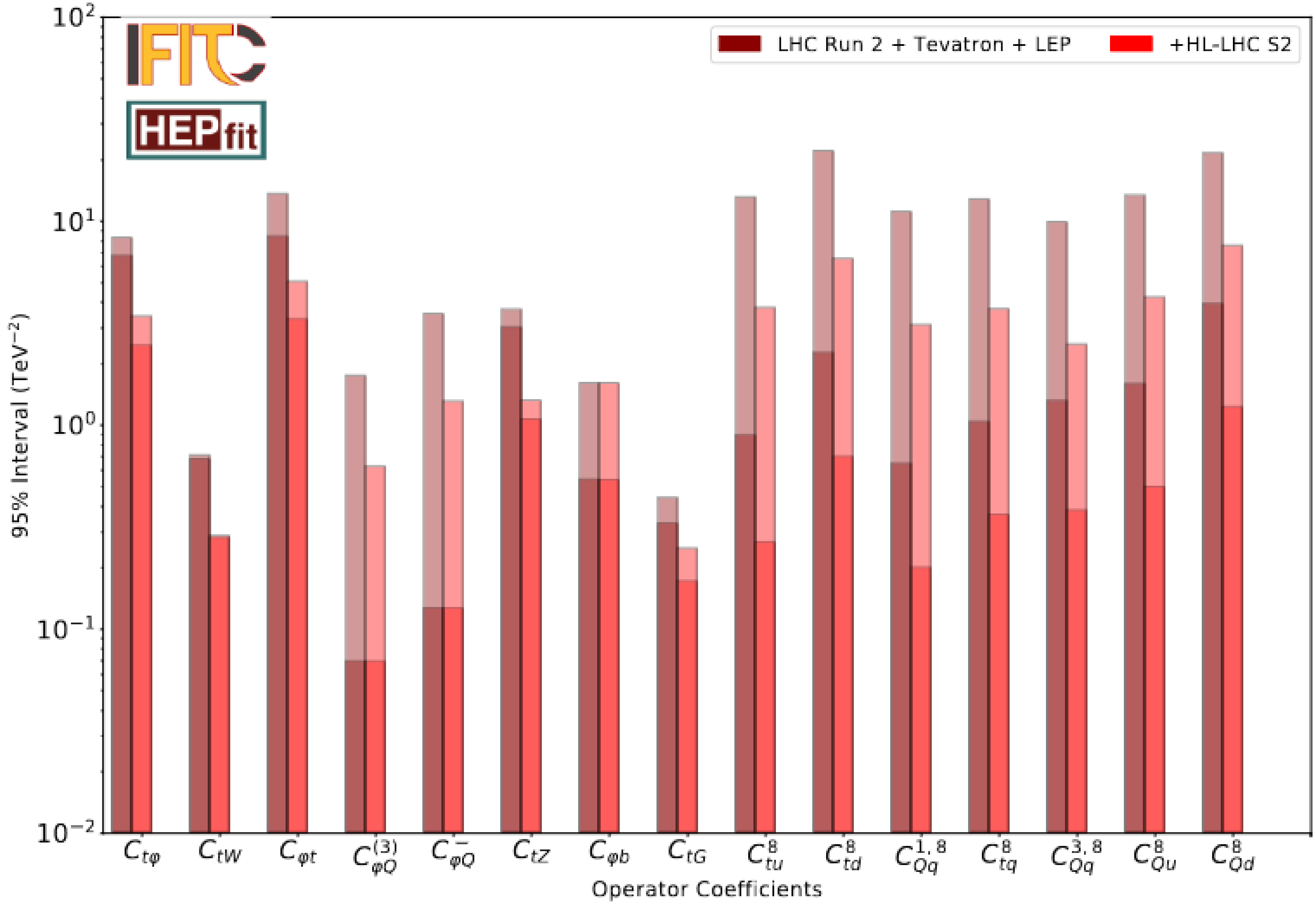




tttt, ttbb

ArXiv:2107.13917

HL-LHC projections



The e+e- programme

A broad programme above the $t\bar{t}$ threshold

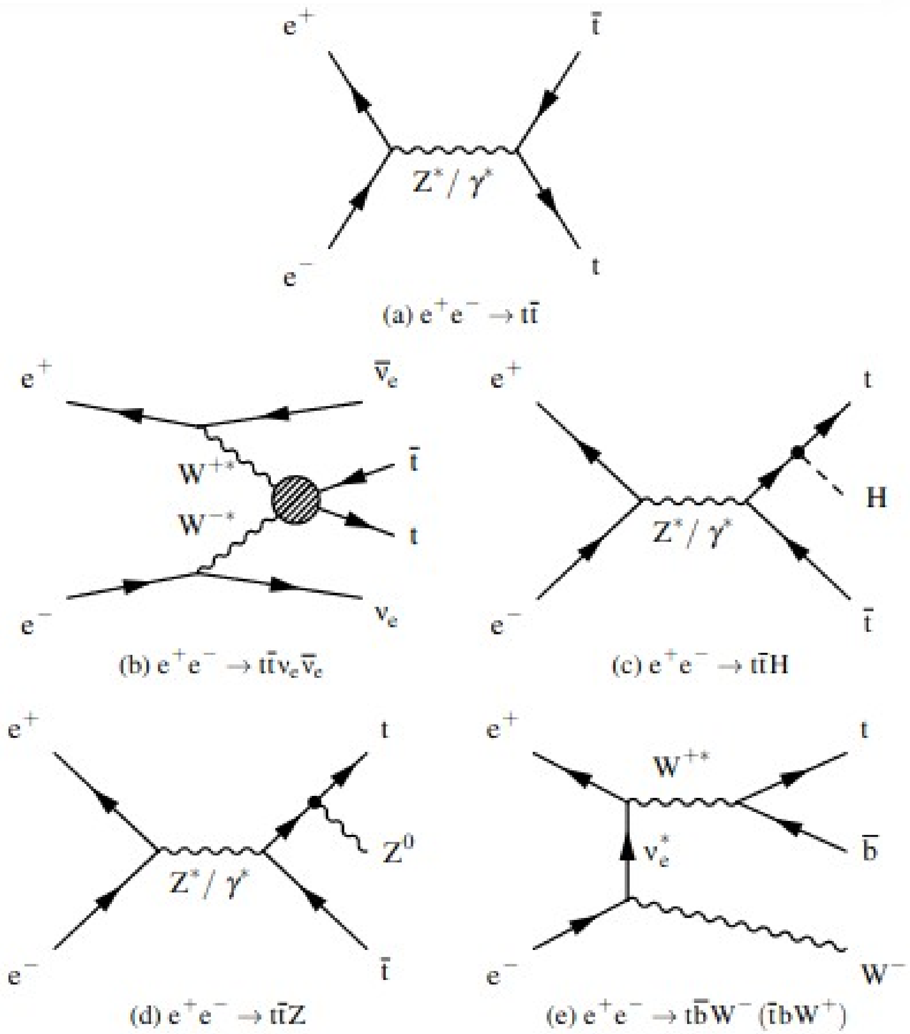
– pair production (a)
– single top production (b)

High energy enables further processes

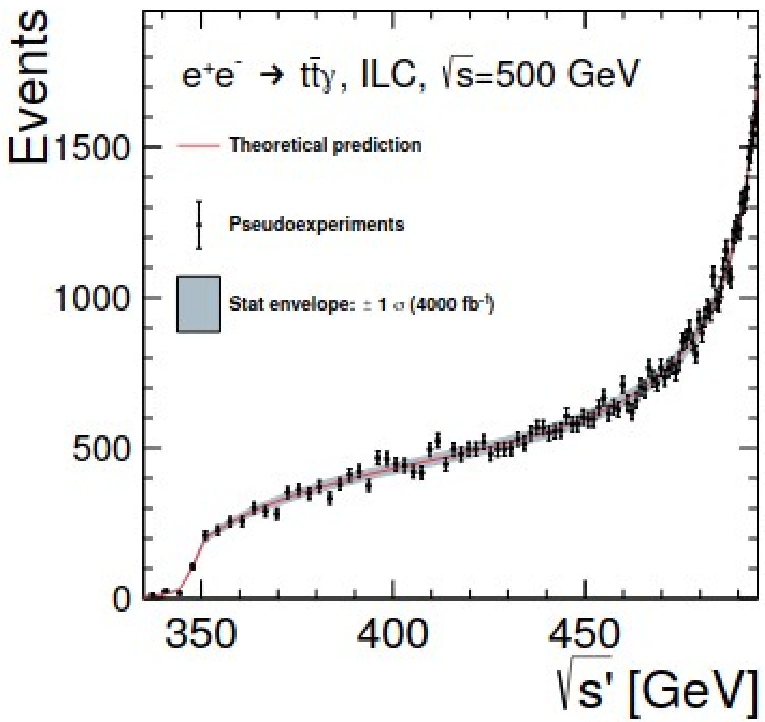
– ttZ & ttH (c,d)
– VBF top production (b)

Measurements of cross section, forward-backward asymmetry, polarization, CP-odd observables

Durieux et al. *(arXiv:1807.02121)* *define* ***optimal observables*** *on e+e- → WbWb production*



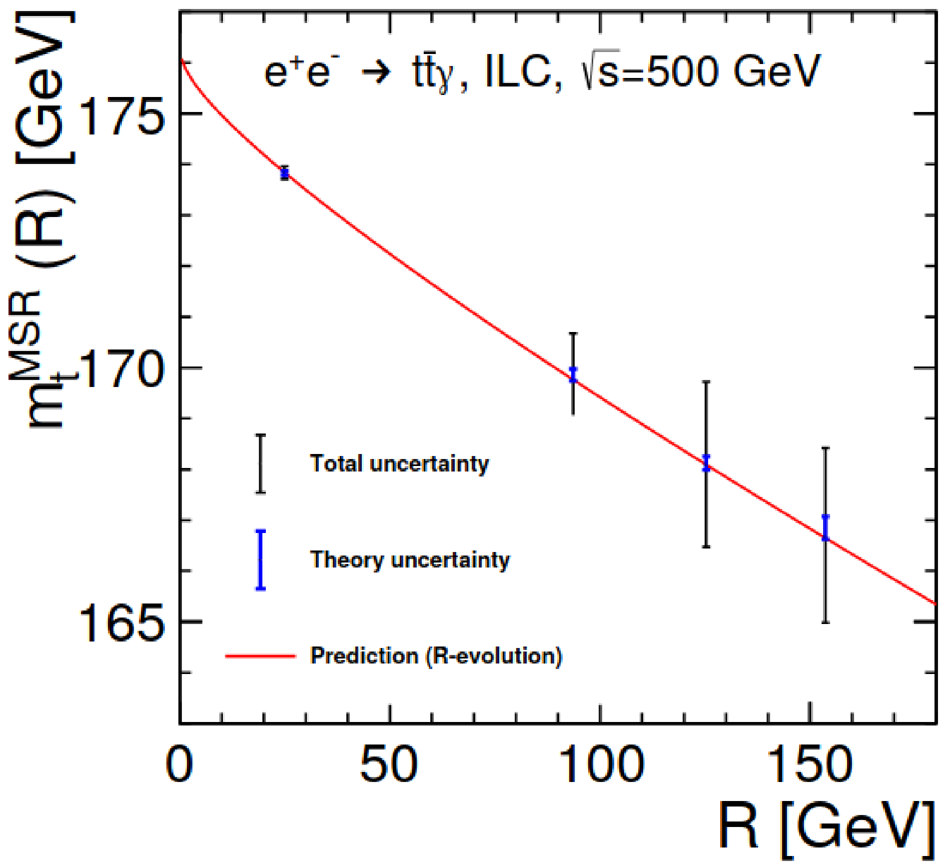
Higher-energy colliders: top quark mass from radiative events



Radiative "return to threshold" in e+e- → ttγ events

Extract short-distance mass with rigorous interpretation and competitive precision:

CLIC380 (1/ab): 50 MeV (theory), 110 MeV total
ILC500 (4/ab): 50 MeV (theory), 150 MeV total

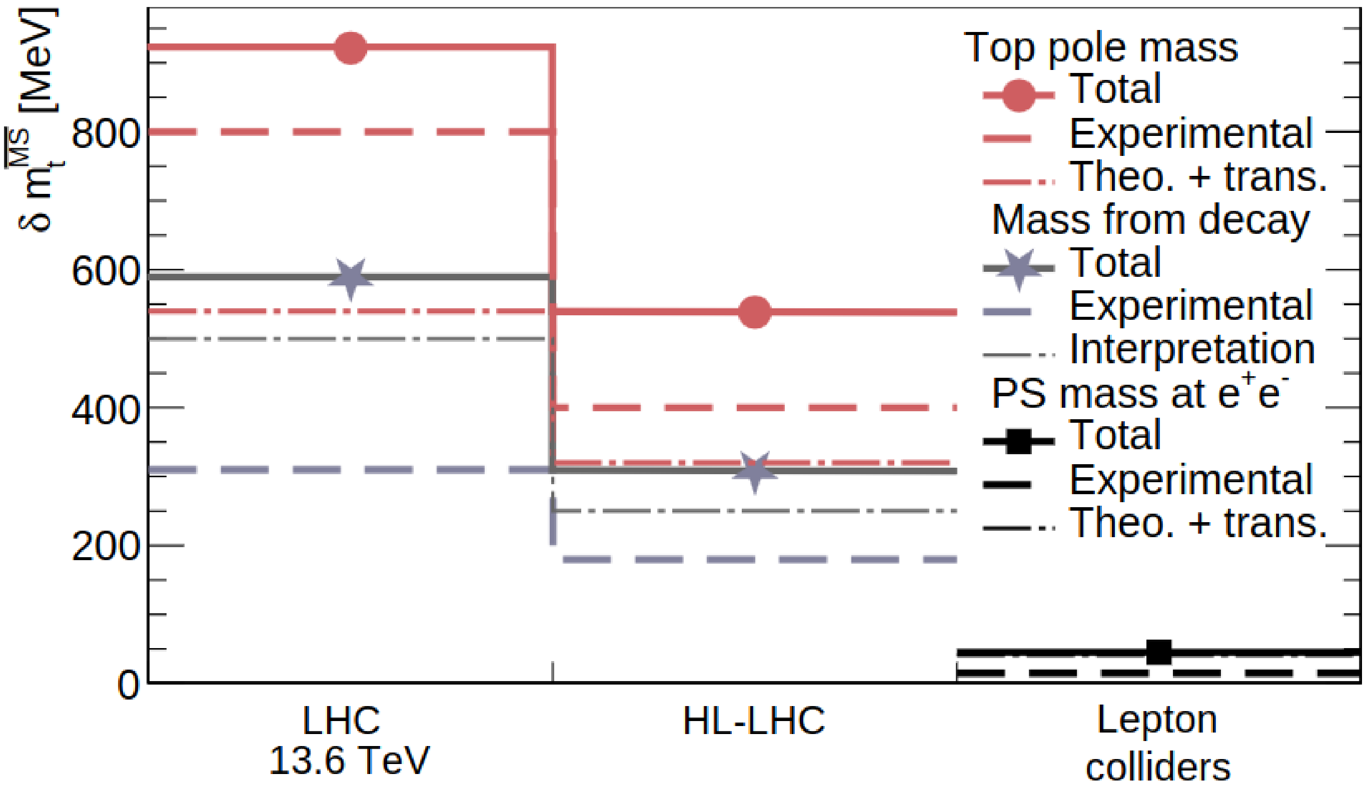


5σ evidence for scale evolution ("running") of the top quark MSR mass from ILC500 data alone

Boronat et al., arXiv:1912.01275

Top mass summary

Snowmass report, arXiv:2209.11267



marcel.vos@ific.uv.es