The third-generation quarks from the LHC to the Higgs factory and beyond

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The bottom and top quark

$Z \rightarrow b\bar{b}$ vertex (g_L) characterized precisely at LEP/SLC, but top escaped scrutiny at previous e^+e^-

Close connections to the Higgs: $H \rightarrow b\bar{b}$ is the largest branching fraction and top has O(1) Yukawa coupling

Somewhat forgotten in our excitement about the Higgs boson

LHC and HL-LHC prospects

LHC has an impressive top quark physics programme

→ boosted top and rare processes (ttX, tXj,tttt) provide genuinely new probes

HL-LHC prospects: from somewhat gloomy 3-pager in 2005 HL-LHC primer..,

4.4 Top-quark physics

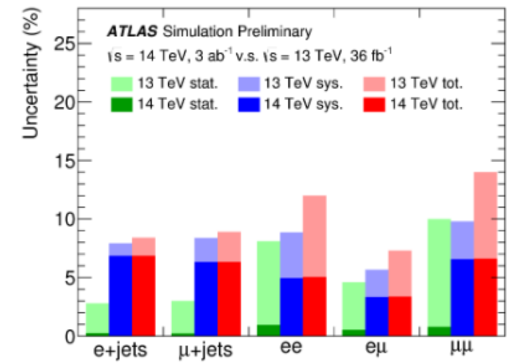
Given the large top quark cross-section, most of the top physics programme should be completed during the first few years of LHC operation [32]. In particular, the $t\bar{t}$ and the single-top production cross-sections should be measured more precisely than the expected theoretical uncertainties, and the determination of the top mass should reach an uncertainty (dominated by systematics) of ~ 1 GeV, beyond which more data offer no obvious improvement.

hep-ph/0204087

… to optimism (and 40 pages) in yellow report arXiv:1902.04070

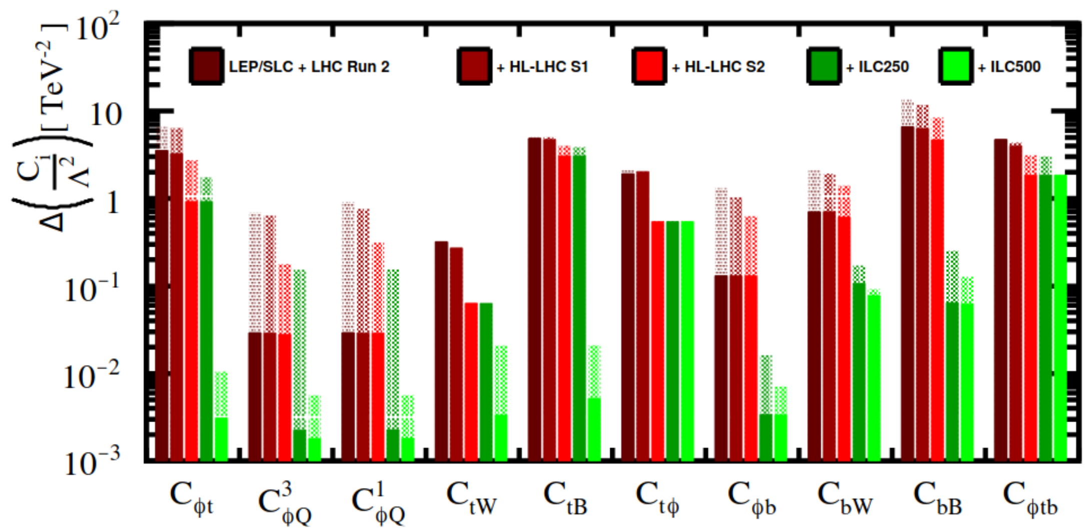
→ *See talk by Clement Helsens in EF03 meeting on 25th of June*

Can we predict the potential of a hadron collider?



Too many analyses to perform explicit prospect studies. And results tend to be too pessimistic!

Solution: adopt S1, S2 scenarios of the Higgs group?



JHEP 12 (2019) 098, arXiv:1907.10619 [hep-ph]

Can we predict the potential of a hadron collider?

S2: data makes us smarter!

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S2: data makes us smarter!

How quickly? And how smart exactly?

The answer depends on how smart we were before data came

Corrolaries: smart, existing analyses improve less than new, first-time analyses
theorists get smarter less quickly than experimentalists

Can we predict the potential of a hadron collider?

S2: Exp. systematics are reduced as 1/sqrt(N)

Examples of hard-to-predict analyses:

- top mass: ~500 MeV today, CMS HL-LHC prospects ~200 MeV?
- $t\bar{t}$ cross section: 3-4% today, limited by 1% luminosity at HL-LHC?
- Any FCChh/SPPC scenario...

Any attempt to define a simple “scaling” in these cases is futile

Discuss main issues (Jet Energy Scale, PDF, modelling uncertainties, theory) and ways to improve them instead?

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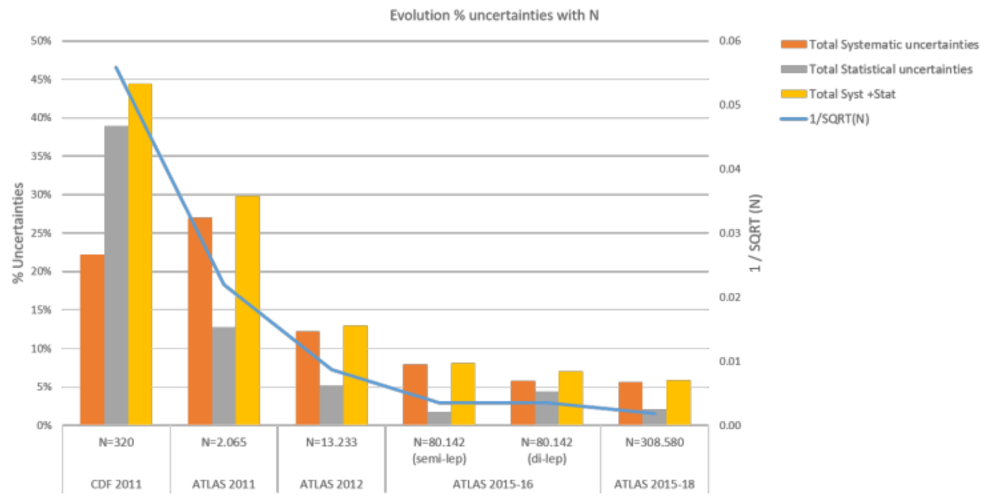
Can we predict the potential of a hadron collider?

Meta-analysis of ttγ cross section measurements

(Estanis Utrilla, U. Valencia 2020)

- stat. uncertainty lags behind 1/sqrt(N) as we move towards cleaner di-lepton channels
- syst. uncertainty from jets, modelling, etc. improve rapidly at first, but stabilize soon



We'll need to work very hard to get close to S2 experimental predictions, using the full potential of the HL-LHC programme, including differential analyses

Perform meta-analyses systematically? Identify and discuss major bottle necks?

Everyone (including European strategy ‘13+’20):

“the highest-priority next collider is an e^+e^- Higgs factory”

Bottom, top and the Higgs factory

The “Higgs factory” idea is a simplification to explain the e^+e^- collider to the general public. Remember there is a bit more to it.

An e^+e^- collider can (and must) push SM precision to the per mille level all across the board, from EWPO to WW, $t\bar{t}$ and Higgs-boson pair production.

Linear machines struggle at the Z-pole, 100 km circular colliders cannot reach far beyond the $t\bar{t}$ threshold.

What is the optimal program? If we build multiple e^+e^- colliders, can we optimize the global programme – beyond the initial race to 250 GeV?

See: M. Peskin et al., ILC Study Questions for Snowmass 2021, arXiv:2007.XXXXX

Grand, global SM EFT fits

Interplay between Higgs and EW sectors well recognized: standard Higgs fit includes all operators (LO-complete, Barklow et al., arXiv:1708.08912) and relies on precision EW data and W-pair production data.

Effect of top and bottom mass acknowledged, if not always accounted for

How does one interpret a prospect study vs. extrapolation?
(i.e. ILC top mass analysis vs. CMS projection)

How precisely do we need to measure these SM parameters?
(Repeat EW, Higgs fits in different α_s, m_W, m_Z m_t, m_b scenarios)

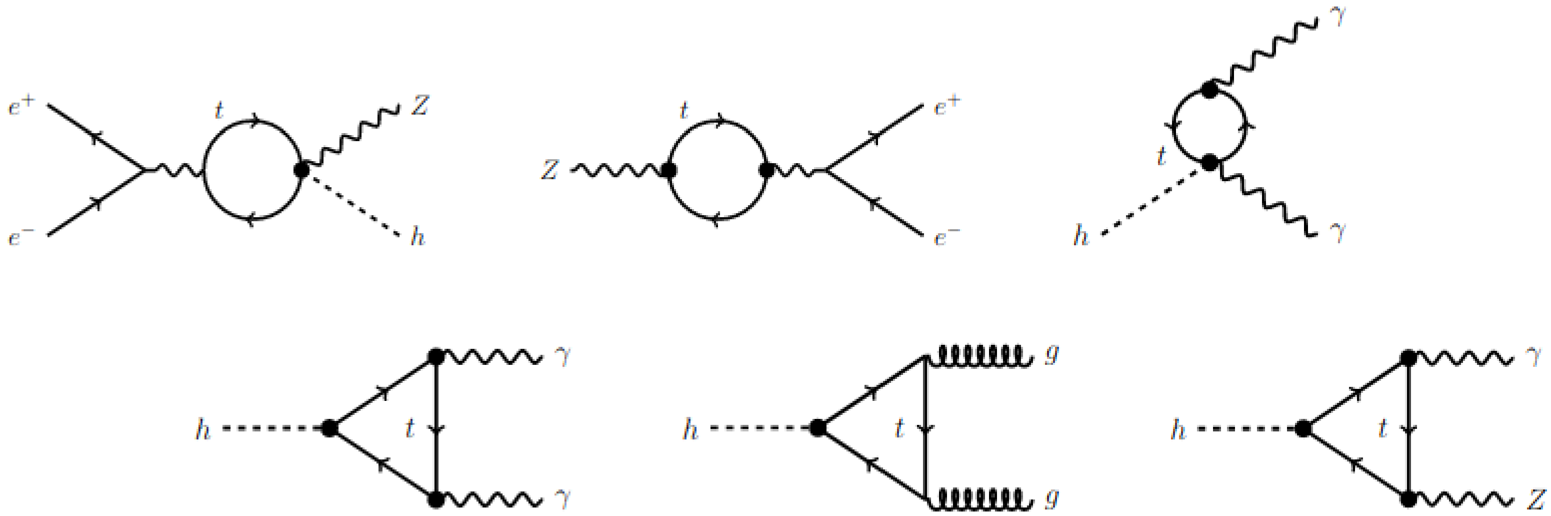
How precisely can we measure all SM parameters together?
(fit α_s, m_t, Γ_t, y_t at threshold scan + add other data)

What added value is there in measurements of the scale evolution of α_s, m_t, m_b ?
(see CMS, arXiv:1909.09193, and arXiv:1912.01275 [hep-ph]).

Grand, global SM EFT fits

Interplay between Higgs and EW sectors well recognized: standard Higgs fit includes all operators (LO-complete, Barklow et al., arXiv:1708.08912) and relies on precision EW data and W-pair production data.

In practice, top and bottom enter in several ways, through top and bottom EW couplings (see Durieux et al.)…



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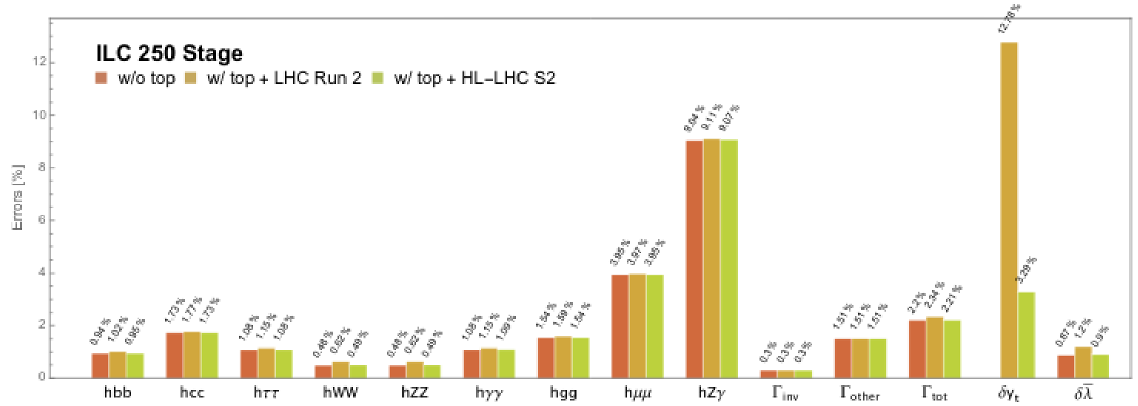
Grand, global SM EFT fits

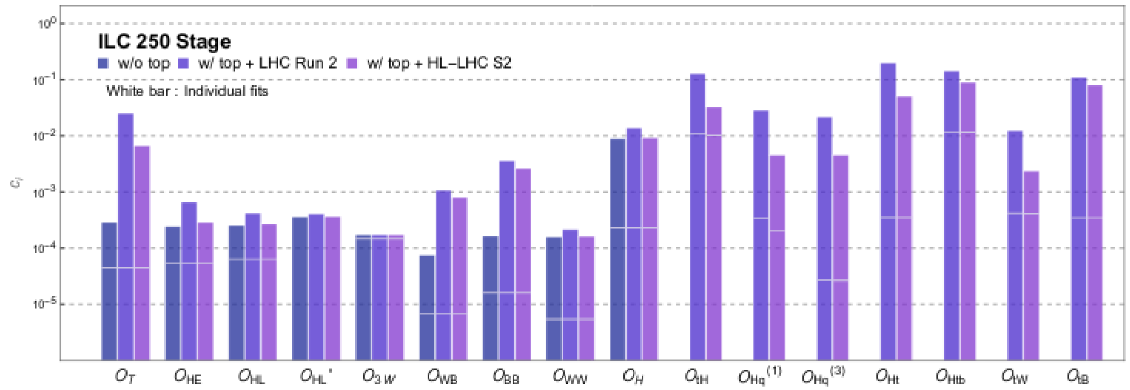
S. Jung. J. Lee, M. Perelló, J. Tian, M.V., arXiv:2006.14631

Top and bottom EW couplings affect Higgs fit considerably

Physical Higgs couplings largely shielded from extra degrees of freedom



Limits on Wilson coefficients affected even with HL-LHC prospects



Summary

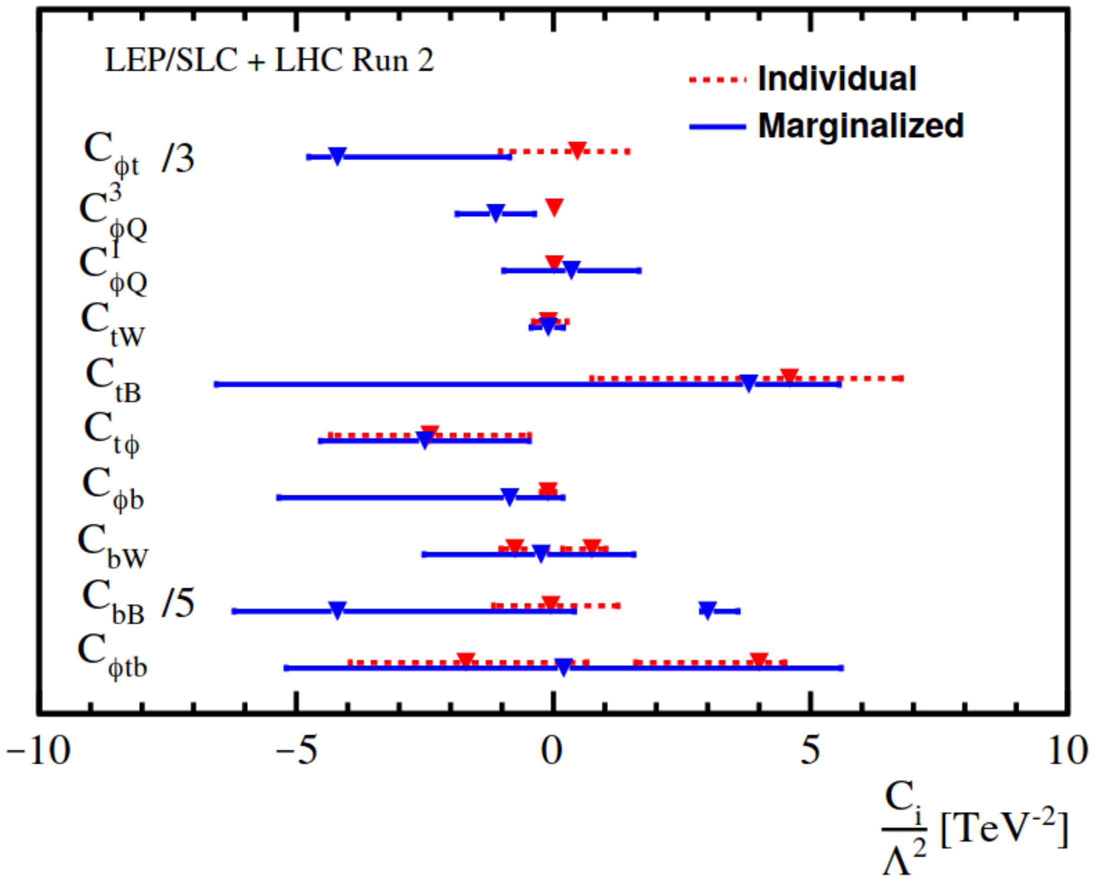
Don’t forget the 3rd generation quarks!

Studies for European strategy update are not the end of the story; use as a starting point to gain a deeper understanding

Snowmass process may point us towards a global, optimal program for HEP

Dedicated fit to top EW operators

Dedicated fit to top and bottom EW operators [M. Perelló et al.]



Current constraints are order(few TeV^{-1})

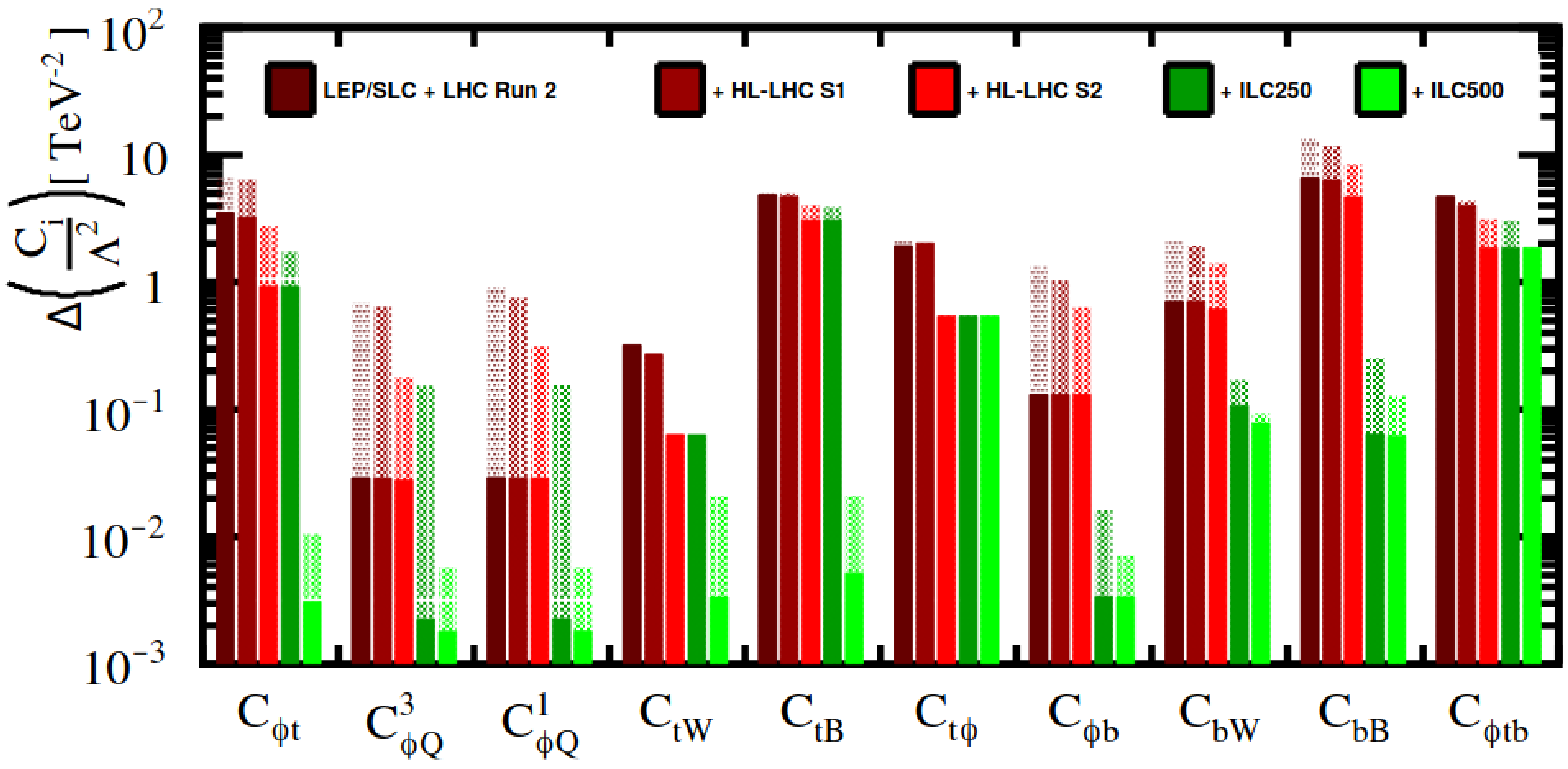
R^b, A_{FB} @ LEP/SLC

Associated ttX @ LHC

Single top & top decay

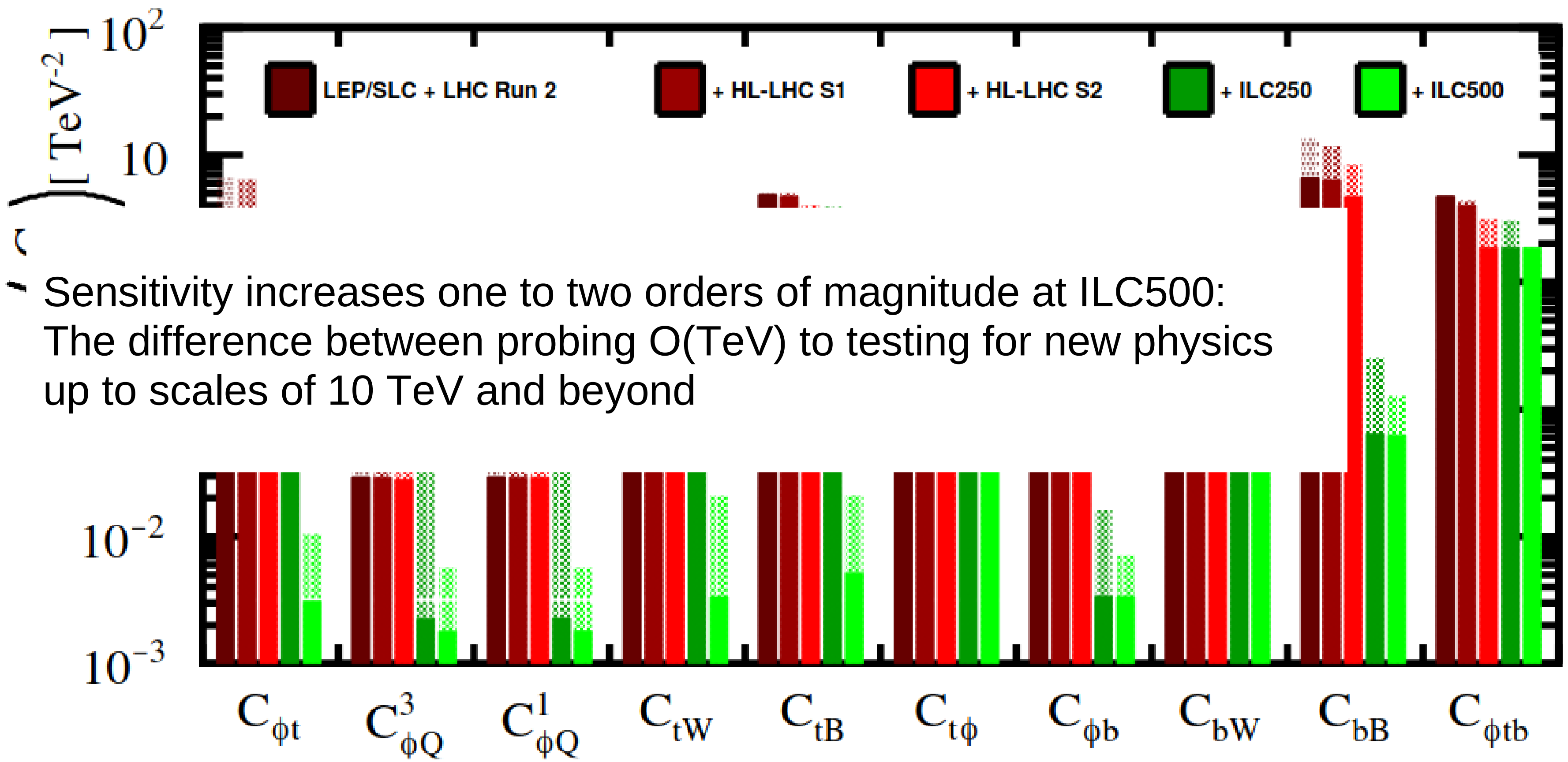
→ HepFit implementation with IFIC theory (A. Peñuelas, V. Miralles)

Comparison to prospects



HL-LHC S2: theory → 1/2, experiment ∝ 1/√L
ILC250: e+e- → bb (Irles et al., 1709,04289)
ILC500: e+e- → tt (1807.02441, 1807.02121, 1505.06020)

Comparison to prospects



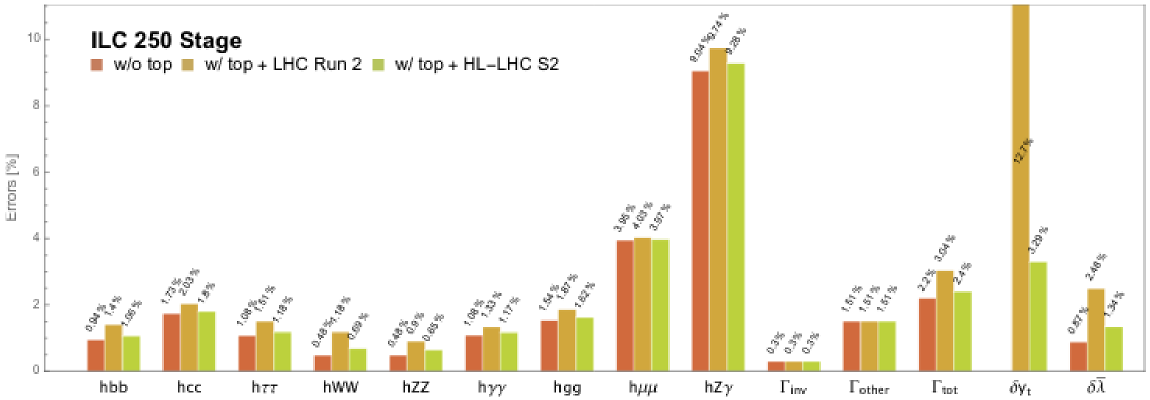
Sensitivity increases one to two orders of magnitude at ILC500:
The difference between probing O(TeV) to testing for new physics up to scales of 10 TeV and beyond

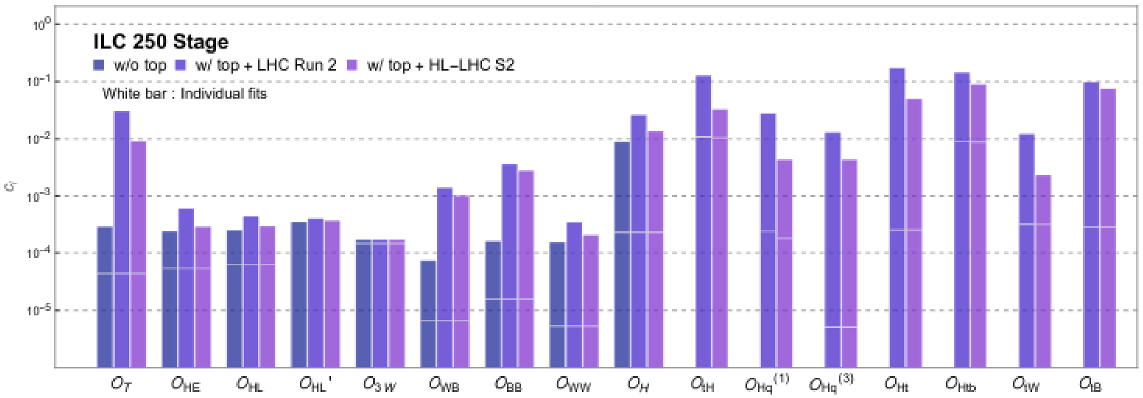
HL-LHC S2: theory → 1/2, experiment ∝ 1/√L
ILC250: e+e- → bb (Irles et al., 1709,04289)
ILC500: e+e- → tt (1807.02441, 1807.02121, 1505.06020)

Feeding into a global fit

Global top/Higgs/EW fit

Ph.D. Martín Perelló, UV, abr. 2020





Ongoing work: S. Jung, J. Lee, M. Perelló, J. Tian

Threat: “top” degrees of freedom can degrade “Higgs” fit considerably, even with HL-LHC S2 projection

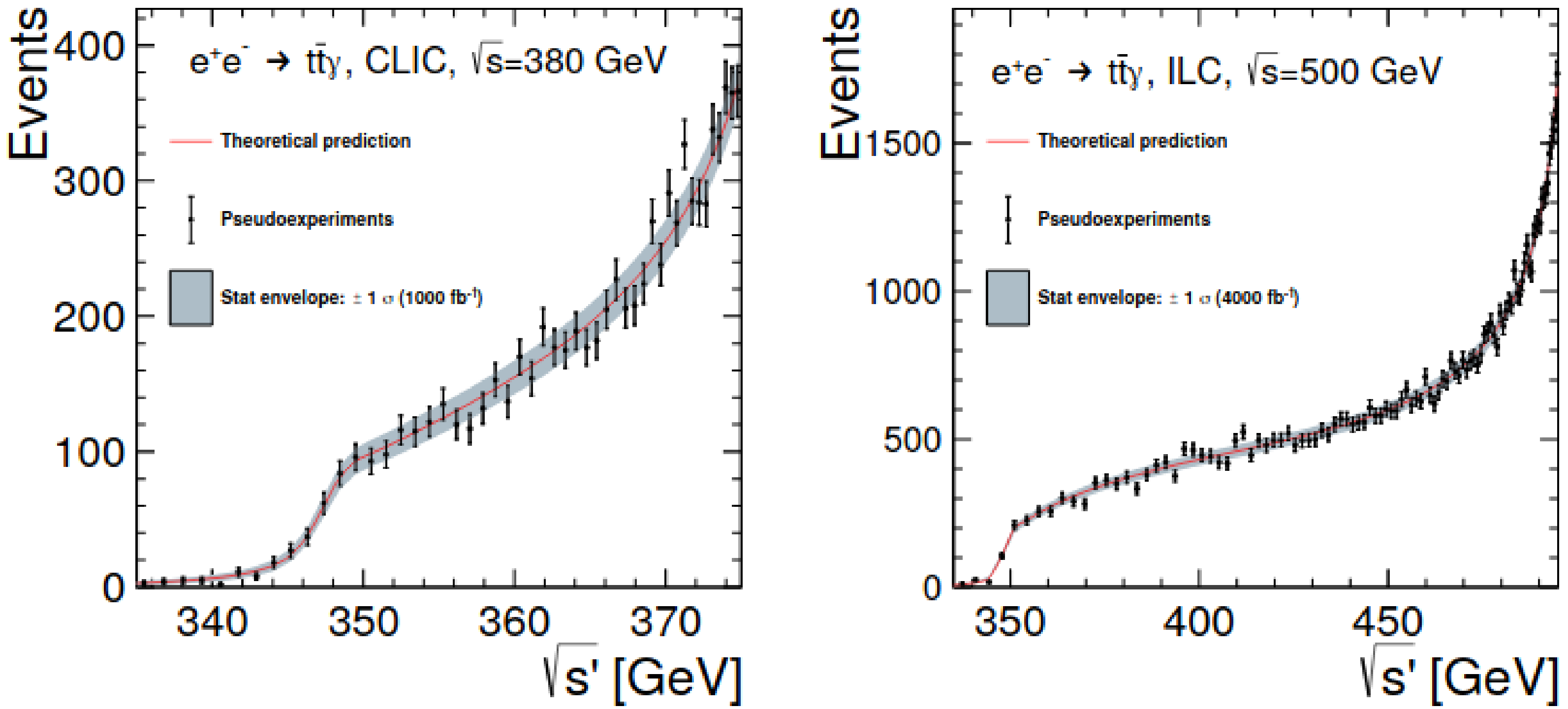
Opportunity: indirect sensitivity to top EW operators (+Yukawa) yields tight single-parameter limits already at 250 GeV

HL-LHC + ILC250 + ILC550 (+ Z-pole) provides very robust bounds on extended Higgs/EW/top operator basis

Top quark mass

Top quark mass from radiative events

Ph.D. Pablo Gomis, UV, jan. 2020



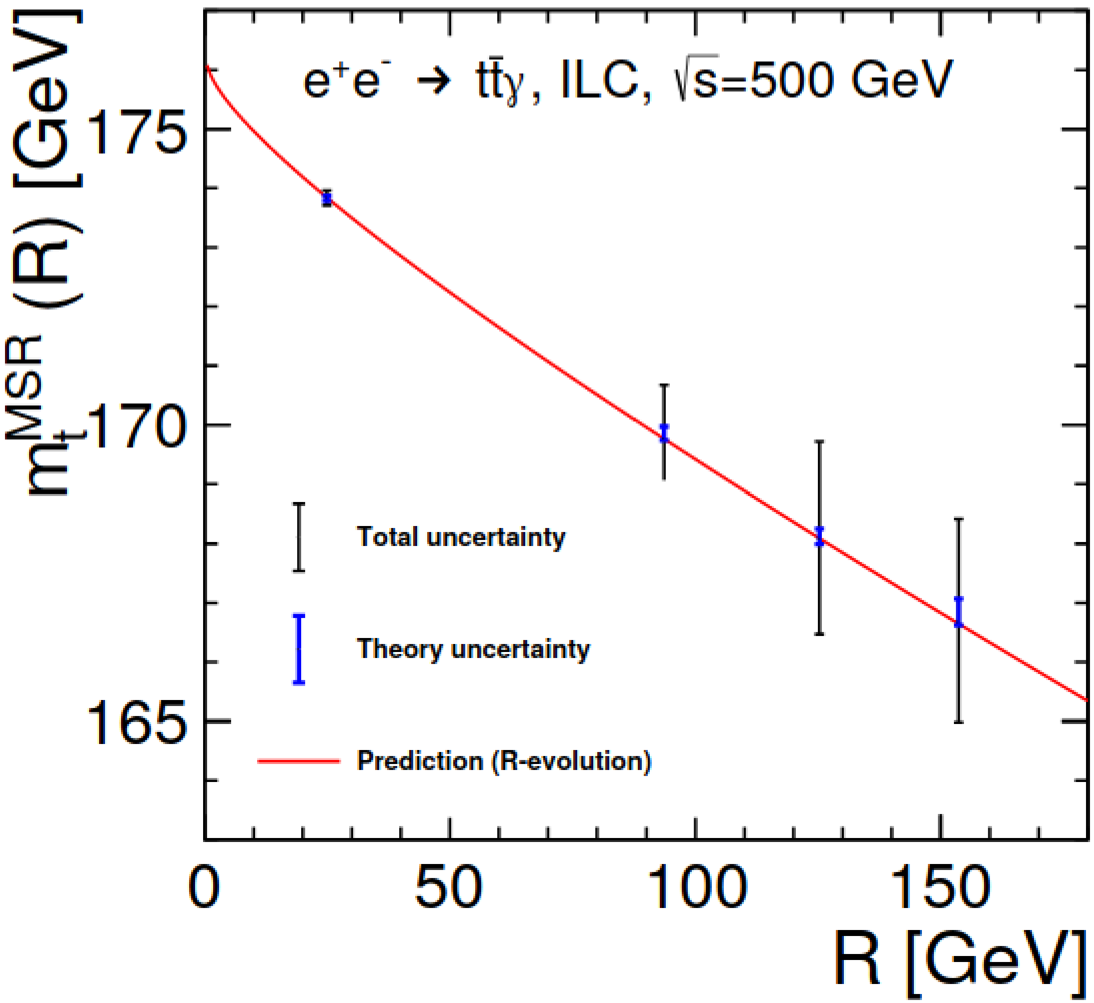
Radiative "return to threshold" in e+e- → ttγ events

Extract short-distance MSR 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

Top quark mass from radiative events



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