top physics
opportunities at
a linear e^+e^- collider

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The top quark

The top quark causes SM “instability”

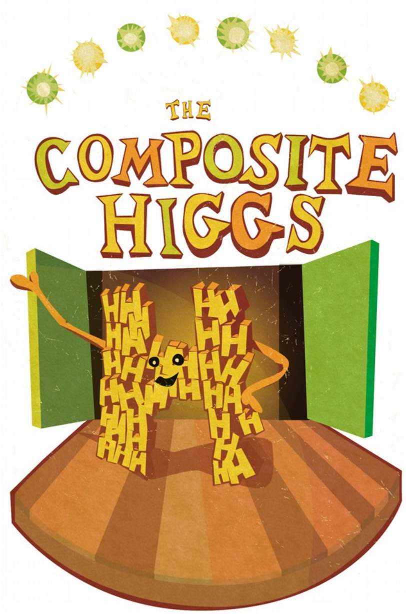
→ provides leading radiative contributions to Higgs mass

→ instability of SM vacuum at high scale

Extensions of the SM have “special” top partners

→ the stop is the lightest squark in “natural” SUSY

→ top is close to IR brane/Higgs profile in RS/Comp. Higgs models



Images: sandbox study for symmetry magazine

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The top quark

One of two SM particles to escape scrutiny at LEP

→ precise constraints on top (EW) couplings are missing

The SM particle with the closest connection to the Higgs

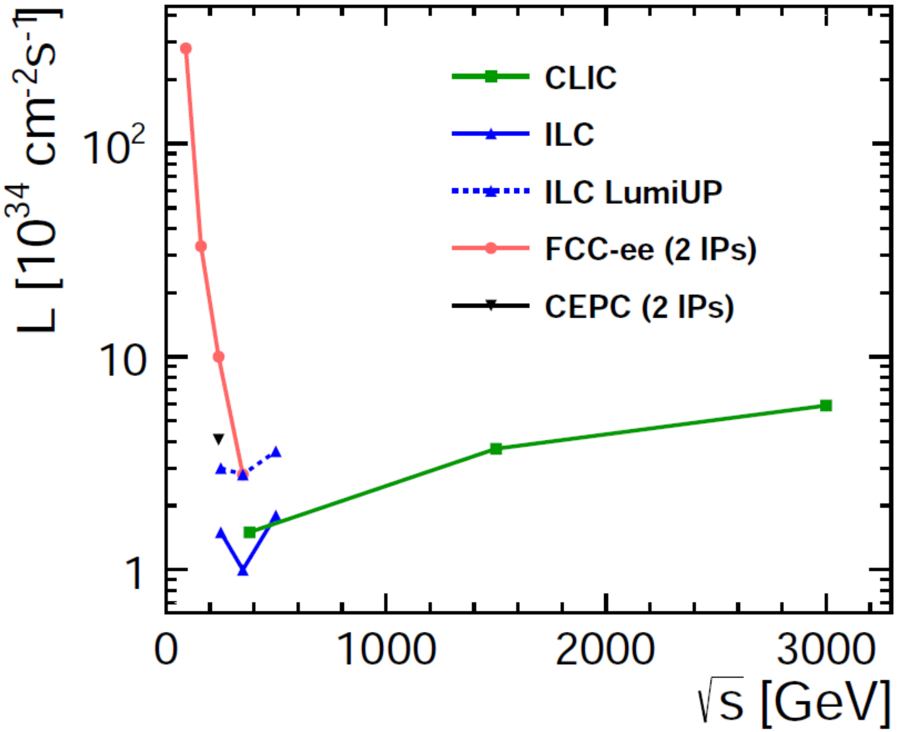
→ top Yukawa coupling is a key target of HEP

A friendly quark

→ decay gives access to sign, polarization, etc.

Lepton collider projects:

- ILC (TDR):
  250, 550, 1000 GeV
- CLIC (CDR):
  380, 1500, 3000 GeV
- CEPC (CDR 2018):
  90, 160, 250 GeV → no $t\bar{t}$
- FCC-ee (CDR 2018):
  90, 160, 240, 350, 370 GeV



A linear collider is the obvious choice above the top threshold

Lepton collider projects

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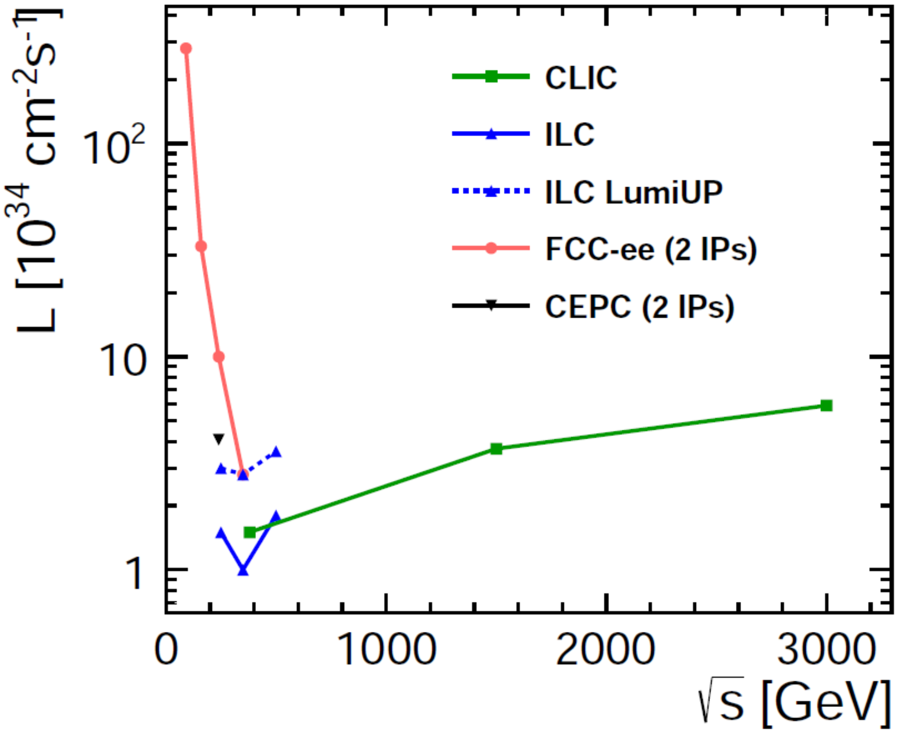


High energy is the obvious choice once you have a linear collider

Top production at e^+e^- colliders

Thresholds:

160 GeV WW

240 GeV ZH

350 GeV $t\bar{t}$

500 GeV ZHH

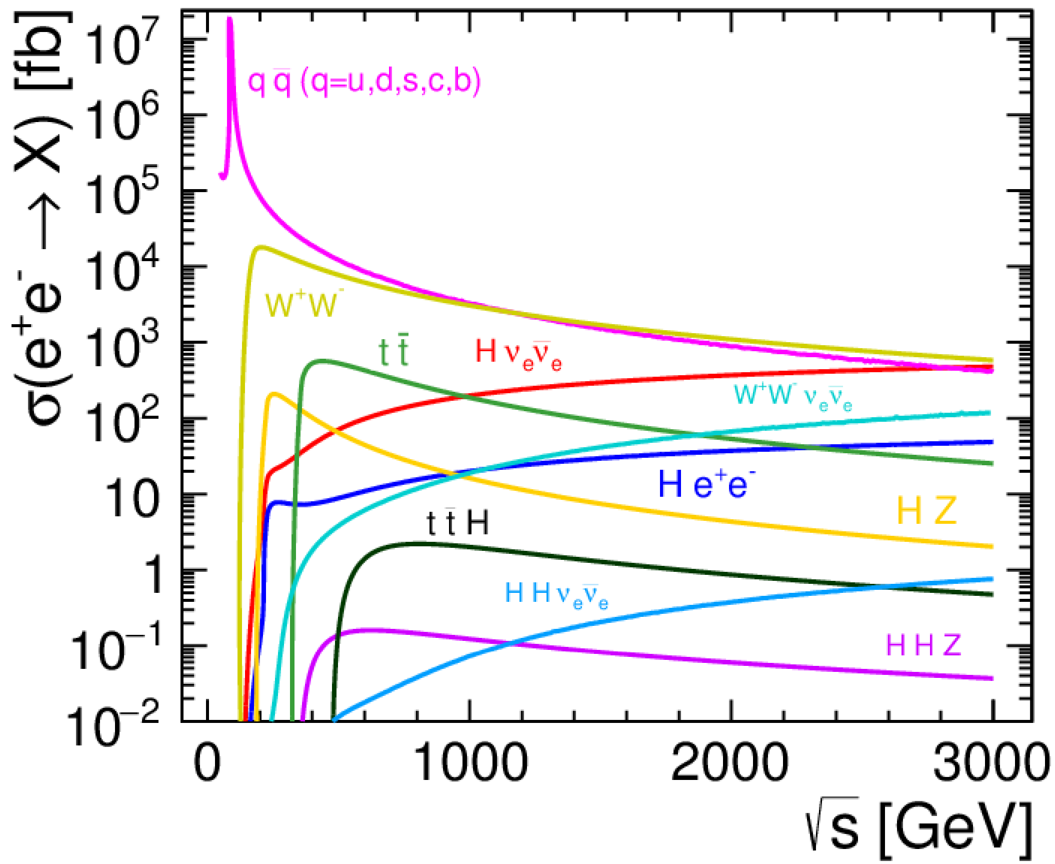
550 GeV $t\bar{t}$H

t-channel processes:

Vector-boson fusion

H$\nu\nu$, HH$\nu\nu$

WW$\nu\nu$, **$t\bar{t}\nu\nu$**



Higher c-o-m energy gives access to new SM processes

Direct sensitivity: searches

The LHC pushes direct search limits up to several TeV

$Sp\bar{p}S$ (540 GeV) discovered W, but not top (173 GeV)

Tevatron (1.96 TeV) discovered top, but not Higgs (125 GeV)

LHC (13 TeV) has discovered the Higgs boson, but not SUSY (?)

Indirect sensitivity: precision

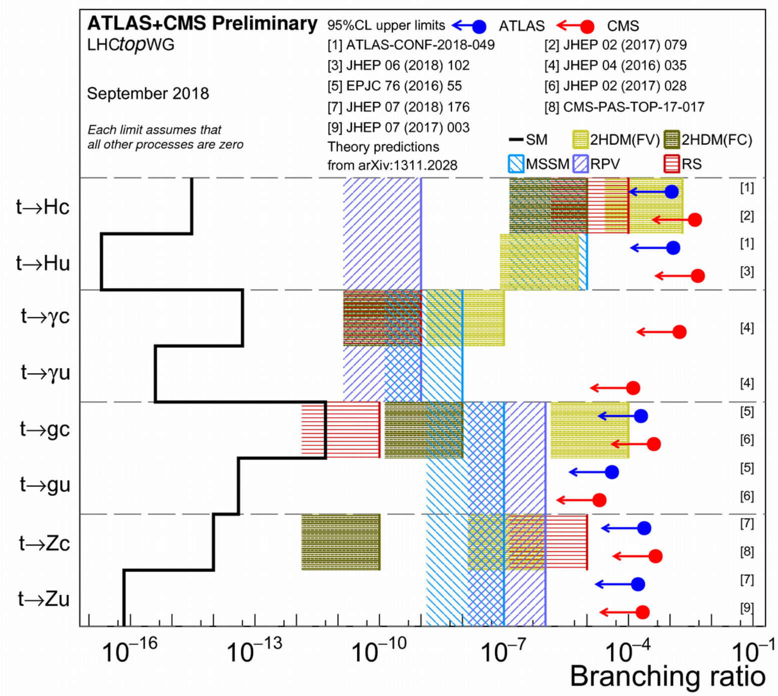
A new lepton collider to push the precision frontier

EW fit of LEP/SLC data is sensitive to top and Higgs

ILC or CLIC can discover new physics well beyond $\sqrt{s}$

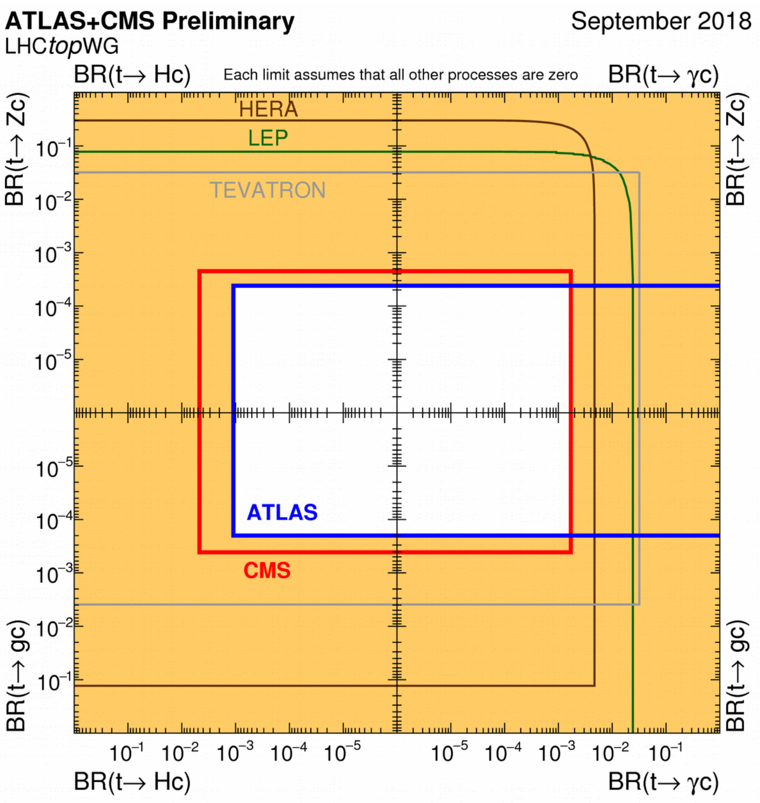
Top and FCNC

The ultimate rare process in the SM,
Strongly enhanced in popular extensions
A signal is direct evidence of new physics



Not covered: lepton-flavour violating top decays → arXiv:1507.07163

FCNC interactions



pp → t (CDF/ATLAS)
pp → tj (D0/CMS)
pp → tγ/ll (CMS)
e^+e^- → tj (LEP2)
ep → et (HERA)
t → jγ/ll (CDF/D0/ATLAS/CMS)
t → jh (ATLAS/CMS)

t → Xc limits

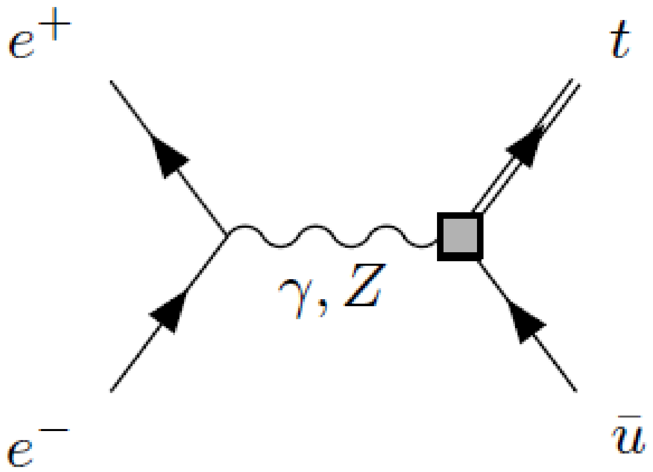
Current limits on BR(t → Zc) and BR(t → Hc) surpass 10^{-3}

Hadron collider prospects range from hopeful to pessimistic
- stat only limits on BR could reach 10^{-7} at FCChh
- actual limits soon saturated by systematics (ATLAS-PHYS-PUB-2016-019, arXiv:1709.03975)

Official prospects to be included in HL-LHC/HE-LHC Yellow Report (soon)

FCNC at lepton colliders

Lepton colliders can provide competitive constraints:
Clean environment and charm-tagging performance



$e^+e^- \to tj$ production <u>below $t\bar{t}$ threshold</u>
sensitive to $t \to Zq$ and $t \to \gamma q$

limits from LEP2: 10^{-2} - 10^{-1} arXiv:1412.7166

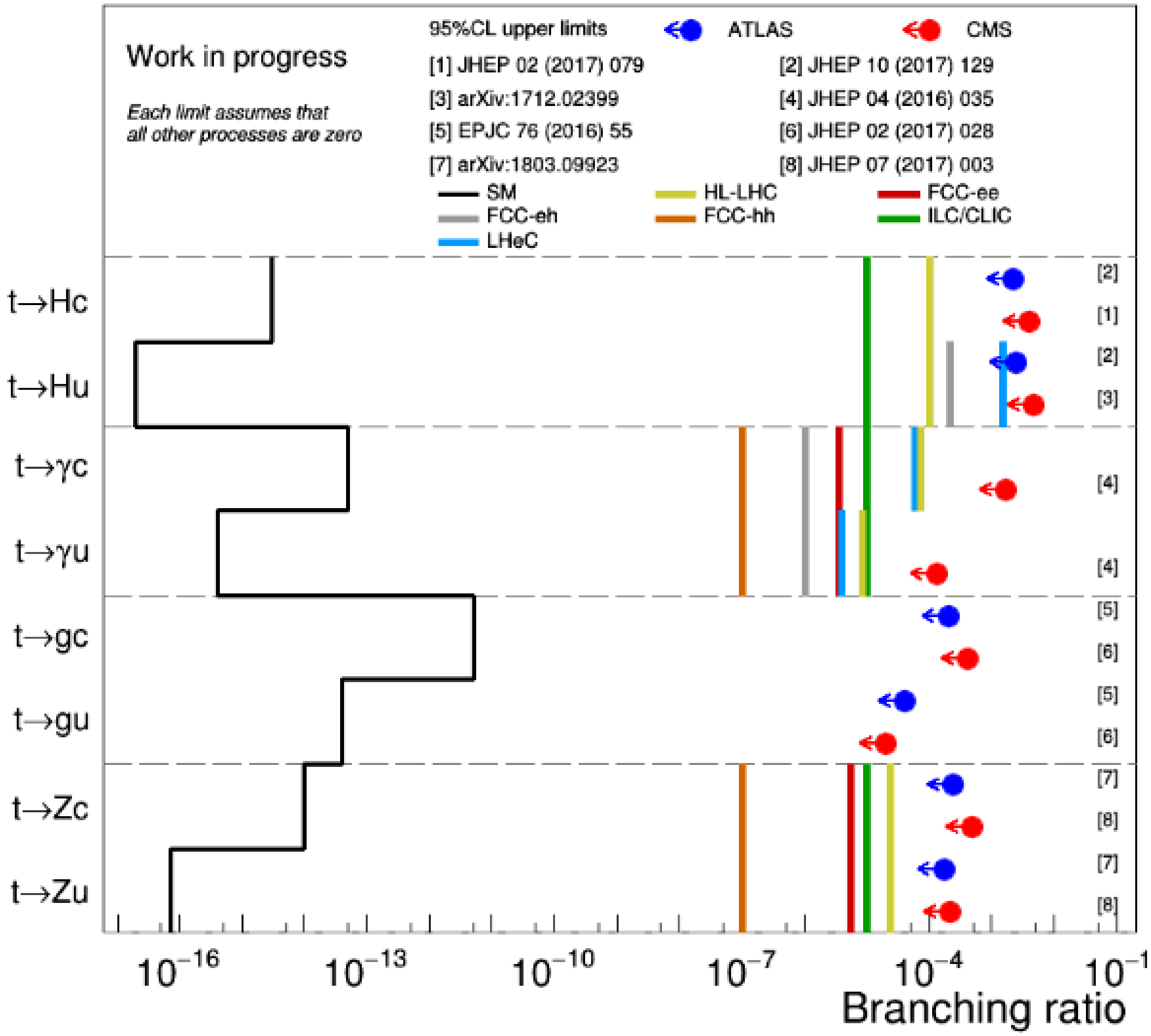
Prospect studies for ILC (hep-ph/0102197) and FCC-ee (arXiv:1408.2090) indicate **potential well beyond equivalent BR < 10^{-4}**

top decay above $t\bar{t}$ threshold, particularly interesting for $t \to Zc$ and $t \to hc$
CLIC380 limits on BR ($t \to c\gamma$) and BR($t \to ch$) × BR($h \to b\bar{b}$) ~ 10^{-5}
arXiv:1807.02441, CLICdp-Conf-2018-001

e^+e^- is competitive with Snowmass expectation for HL-LHC in some channels, even <u>below the $t\bar{t}$ threshold</u>

LC prospects urgently needed!!

FCNC: the rarest processes of all



First attempt to prepare a comprehensive comparison

From:
Freya Blekman, TOP2018

Direct sensitivity: energy reach

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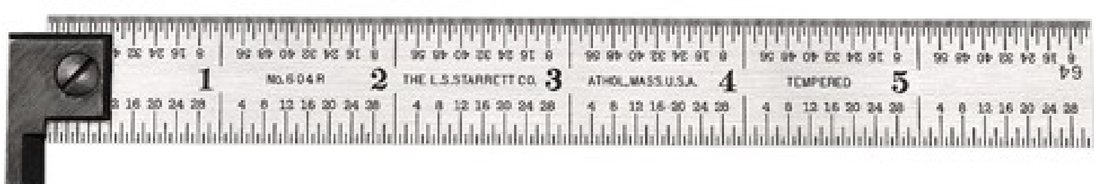


Indirect sensitivity

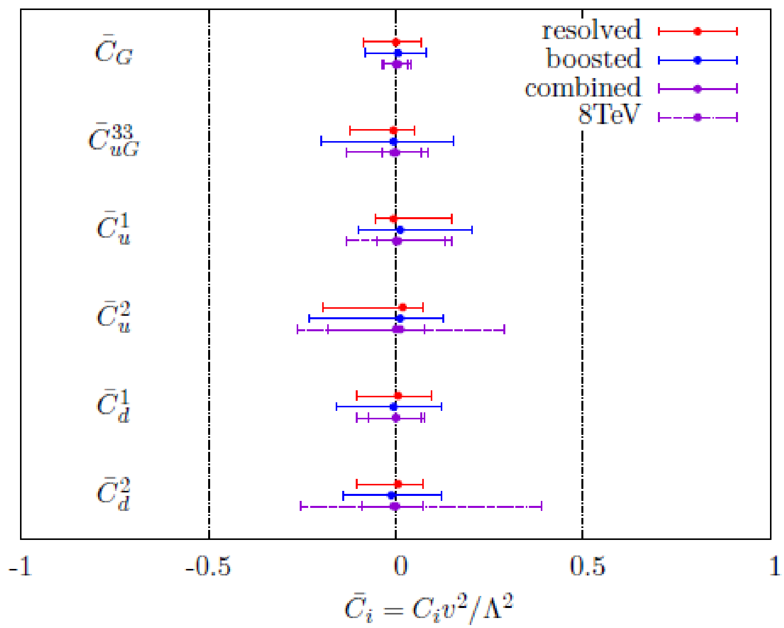
Quantify BSM sensitivity in a model-agnostic way with limits on anomalous D6 operator coefficients in Effective Field Theory

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + \mathcal{O}\left(\Lambda^{-4}\right)$$

EFT analyses "by sector" are in full swing at the LHC. A linear collider can deliver the solid, and precise constraints that are crucial for a global SM EFT fit.

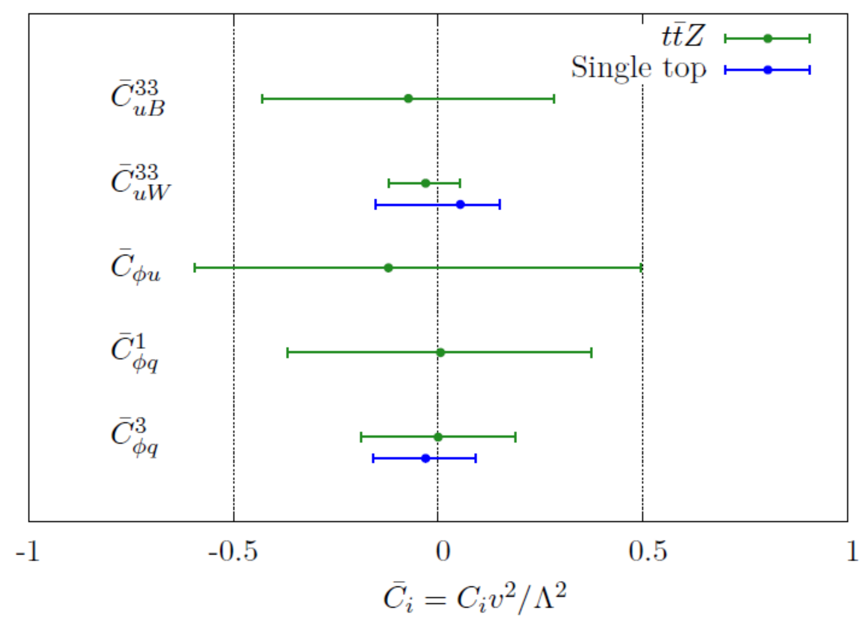
EFT constraints on top quark operators

The LHC has produced millions of top quarks. The “standard program” is nearly done, as inclusive measurements are mostly systematics-limited. Semi-global EFT fit to Tevatron+LHC8 data yields O(1) constraints on the Wilson coefficients of the relevant top operators.

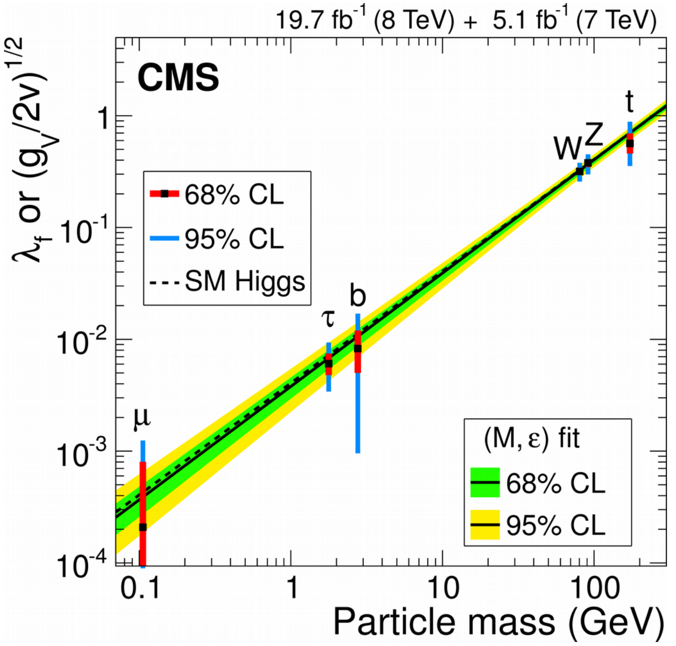


Boosted measurements are surpassing precise inclusive measurements
Englert et al., arXiv:1607.04304

Rare associated production processes yield limits on top quark EW couplings
arXiv:1506.08845, arXiv:1512.03360



Further progress to come from the exploration of regions with enhanced sensitivity and new SM processes (ttH, ttZ, ttW, ttγ, tZ, tγ,...)



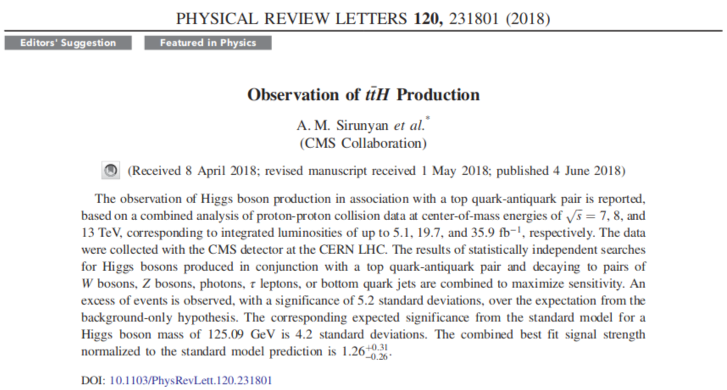
Top and Higgs

In my biased opinion, the top Yukawa coupling is the most exciting SM parameter (maybe after the Higgs trlinear coupling)

Rare processes: LHC establishes $t\bar{t}H$ production!

$t\bar{t}H$ production observed with >5 σ in both ATLAS and CMS

"New SM physics". A process that has never been observed before. Experimental evidence that the Yukawa coupling is responsible for the mass of third-generation fermions.



PHYSICAL REVIEW LETTERS **120,** 231801 (2018)

Editors' Suggestion | Featured in Physics

Observation of $t\bar{t}H$ Production

A. M. Sirunyan *et al.**
(CMS Collaboration)

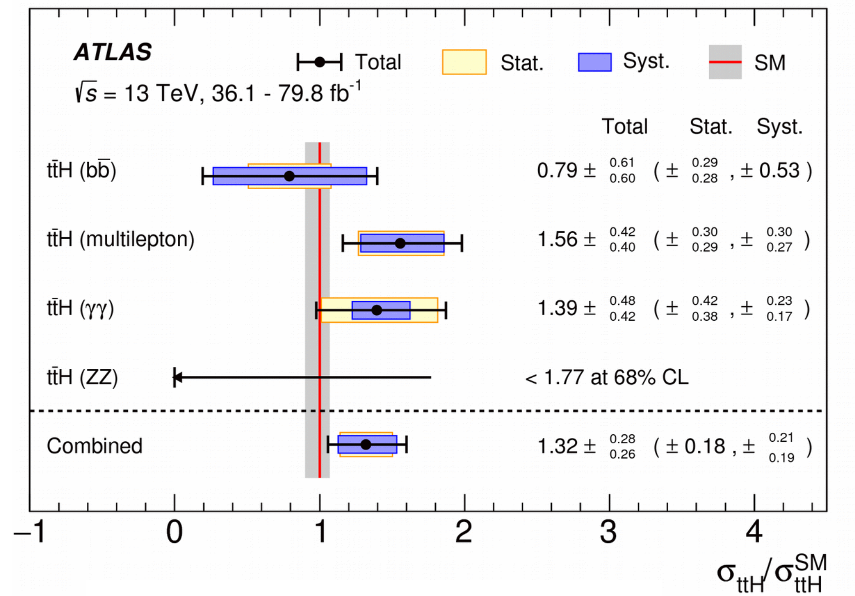
(Received 8 April 2018; revised manuscript received 1 May 2018; published 4 June 2018)

The observation of Higgs boson production in association with a top quark-antiquark pair is reported, based on a combined analysis of proton-proton collision data at center-of-mass energies of $\sqrt{s} = 7$, 8, and 13 TeV, corresponding to integrated luminosities of up to 5.1, 19.7, and 35.9 fb^{-1}, respectively. The data were collected with the CMS detector at the CERN LHC. The results of statistically independent searches for Higgs bosons produced in conjunction with a top quark-antiquark pair and decaying to pairs of W bosons, Z bosons, photons, τ leptons, or bottom quark jets are combined to maximize sensitivity. An excess of events is observed, with a significance of 5.2 standard deviations, over the expectation from the background-only hypothesis. The corresponding expected significance from the standard model for a Higgs boson mass of 125.09 GeV is 4.2 standard deviations. The combined best fit signal strength normalized to the standard model prediction is $1.26^{+0.31}_{-0.26}$.

DOI: 10.1103/PhysRevLett.120.231801

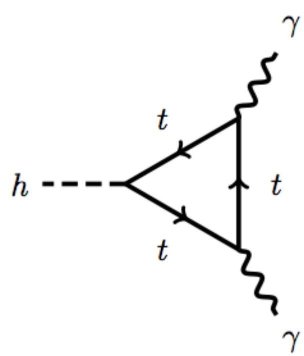
CMS, PRL 120, 231801 (2018)

ATLAS, PLB 784, 173-191 (2018)



indirect 8 TeV

Run I: $k_t = 1.43 \pm 0.23$



direct 13 TeV

CMS: $\mu_{ttH} = 1.26 \pm 0.3$
ATLAS: $\mu_{ttH} = 1.32 \pm 0.3$

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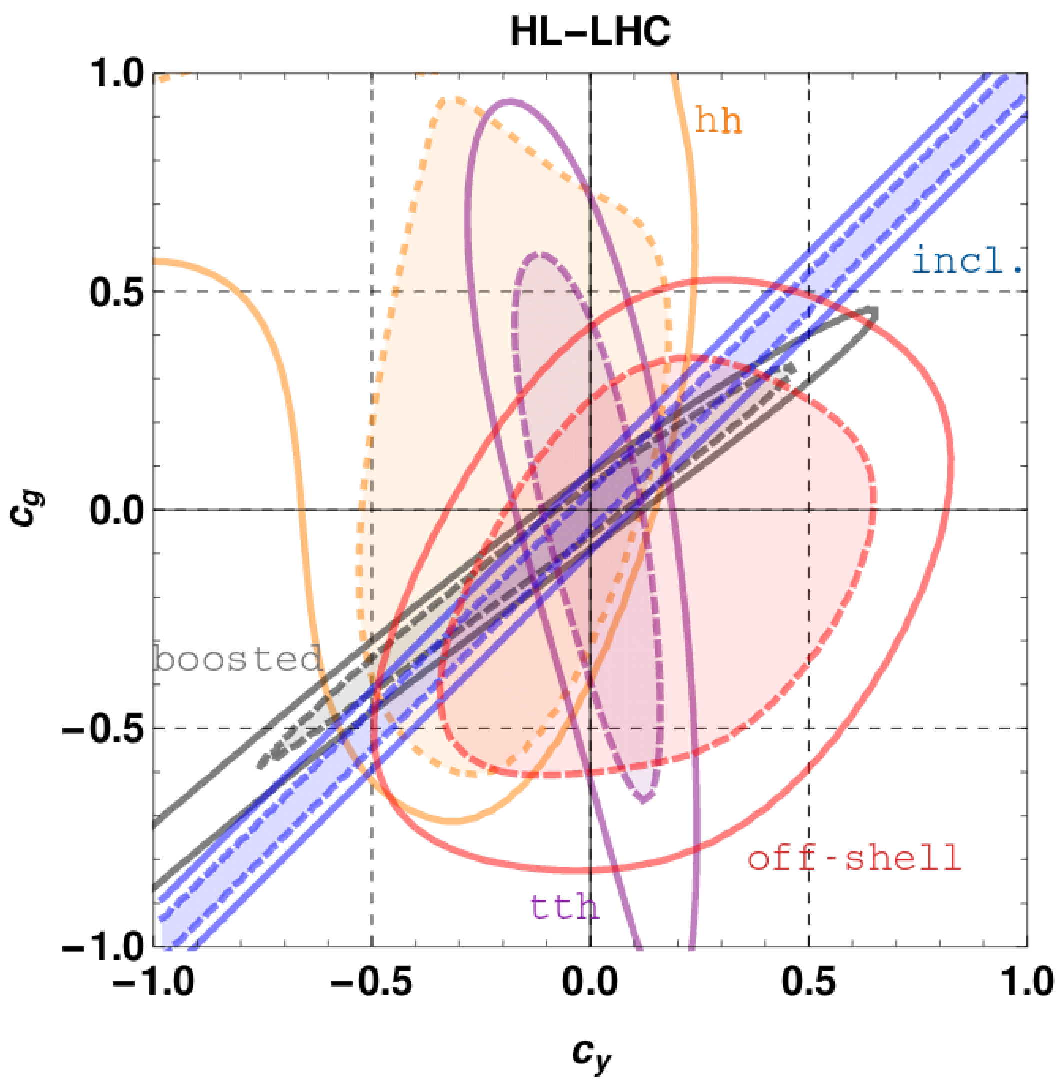
The top Yukawa coupling: global analysis

The indirect constraint on the top Yukawa coupling from top loops in gg → H (and H → γγ) is quite powerful

In a global EFT analysis it is very hard to distinguish the effect of a direct Hgg coupling (c_g) from that of the operator that modifies the top Yukawa coupling (c_y)

Direct measurement in tt̄H is necessary in a global analysis

Azatov et al., arXiv:1608.00977



Top quark Yukawa coupling at hadron colliders

Cancel systematic uncertainties in a ratio:

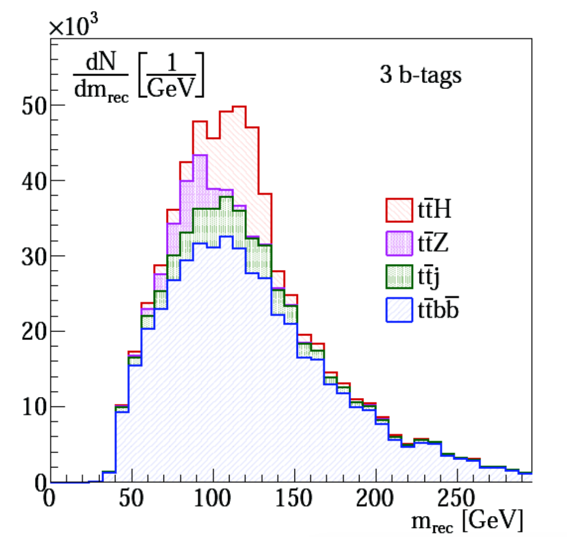
	$\sigma(t\bar{t}H)$[pb]	$\sigma(t\bar{t}Z)$[pb]	$\frac{\sigma(t\bar{t}H)}{\sigma(t\bar{t}Z)}$
13 TeV	$0.475^{+5.79\%+3.33\%}_{-9.04\%-3.08\%}$	$0.785^{+9.81\%+3.27\%}_{-11.2\%-3.12\%}$	$0.606^{+2.45\%+0.525\%}_{-3.66\%-0.319\%}$
100 TeV	$33.9^{+7.06\%+2.17\%}_{-8.29\%-2.18\%}$	$57.9^{+8.93\%+2.24\%}_{-9.46\%-2.43\%}$	$0.585^{+1.29\%+0.314\%}_{-2.02\%-0.147\%}$

Mangano, Plehn, Reimitz, Schell, Shao, 2015

LHC, HL-LHC and HE-LHC can - and will - take advantage of this strategy
(yellow report to be published soon)

FCChh prospect study :

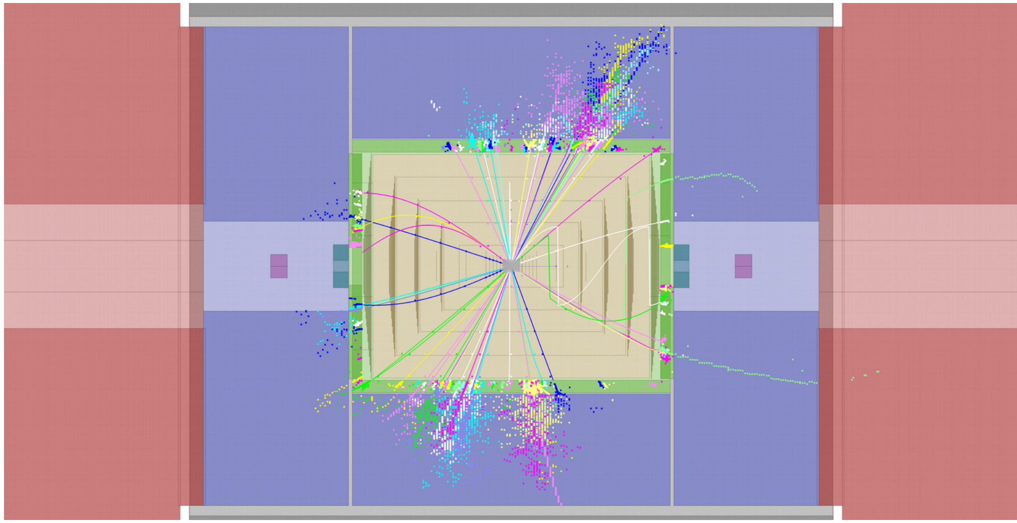
→ boost H and t → reconstruct "fat" jets
→ distinguish Z and H with jet mass
→ S/B ~ 1/3



1% precision on the top Yukawa coupling!

FCChh 20/ab, 100 TeV, *Mangano, Plehn, Reimitz, Schell, Shao, 2015*
Fast simulation: detailed study required to make solid claim

Top quark Yukawa coupling



Challenges:

Small signal sample
Large (x100) background rejection
Jet reconstruction and pairing

ILC : 3% with 4 ab^{-1} at 550 GeV *arXiv:1506.05992*

ILC : 4% with 1 ab^{-1} at 1 TeV *arXiv:1409.7157*

CLIC : 3.8% with 1.5 ab^{-1} at 1.4 TeV *arXiv:1807.02441*

Bonus: CP properties of the Higgs
arXiv:1809.07127, arXiv:1807.02441

Indirect top Yukawa coupling

Mitov et al., arXiv:1805.12027

$$\mu_{h\to gg} = \frac{\Gamma_{h\to gg}}{\Gamma^{\rm SM}_{h\to gg}} = 1 + 2\Delta y_t \, ,$$

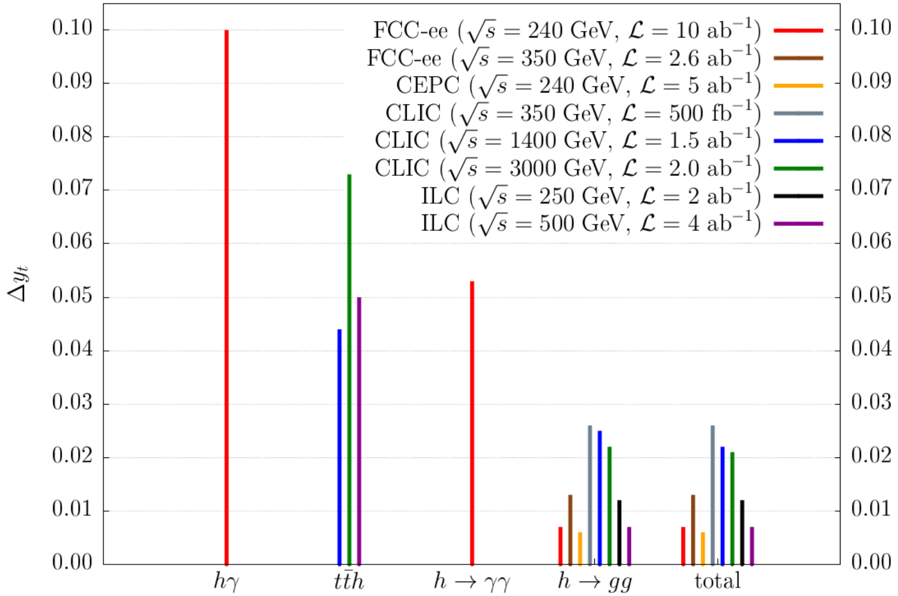
$$\mu_{h\to\gamma\gamma} = \frac{\Gamma_{h\to\gamma\gamma}}{\Gamma^{\rm SM}_{h\to\gamma\gamma}} = 1 - 0.56\Delta y_t \, .$$

One-paramteter fit of H → gg rate measured at 250 GeV yields

1% precision on top Yukawa coupling

Confirmed in preliminary ILC fit by S. Jung, J. Tian, M. Perelló

They also show that H → $\gamma\gamma$ can be as powerful as H → gg



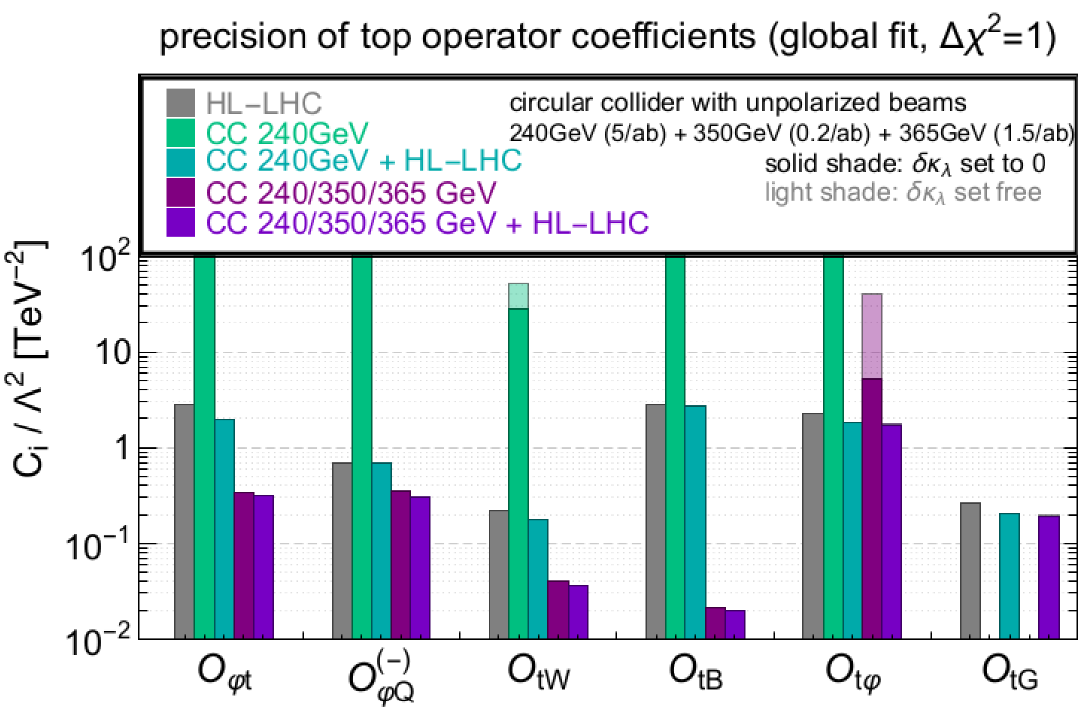
Top Yukawa coupling: global analyis at lepton colliders

Global limits on top operators from 250 GeV measurements
Vryonidou & Zhang, arXiv:1804.09766, Durieux et al., arXiv:1809.03520

Indirect sensitivity is not robust in global analyis!
- global limits >> individual limits

Including $t\bar{t}$ data helps!
> 350 GeV

Ultimately, direct $t\bar{t}H$ production is crucial!
> 550 GeV



Repeat in ILC environment with realistic HL-LHC constraints

Planning for success: a possible discovery scenario

Assuming the top quark Yukawa coupling differs from SM expectation O(15%)

2020s: LHC programme sees persistent deviation from SM

2037: HL-LHC programme ends with 3σ effect

~204?: ILC250 programme sees > 5σ effect in H$\rightarrow$ gg and H$\rightarrow$ $\gamma\gamma$

~20??: ILC380 discards top EW couplings as source of deviations

~20??: ILC550 sees 5σ effect in $t\bar{t}$H production

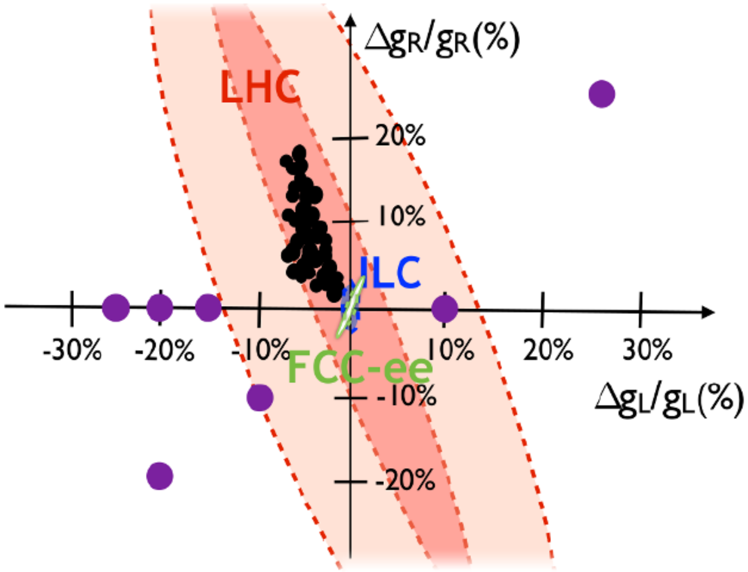
Proposed Texas statement (Lyn Evans): "Based on the findings of the precision Higgs study, the collision energy of the ILC can be upgraded to the optimal energy with reasonable cost."

EW couplings of the top quark

First precision constraints on top (right-handed) coupling

Large BSM family predicts sizeable deviations from SM prediction

- 5D models by several authors
  Richard, arXiv:1403.2893
- 4D Composite Higgs Model
  Barducci, de Curtis, Moretti, Pruna, JHEP 08 (2015)



Top quark EW couplings

Proposal for a (weak) no-loose argument

A challenge for the theorists present

A measurement of top EW couplings to sub-% precision provides an answer to the question: are Composite Higgs/ RS models realized at their natural scale?

Top EW couplings: LHC status

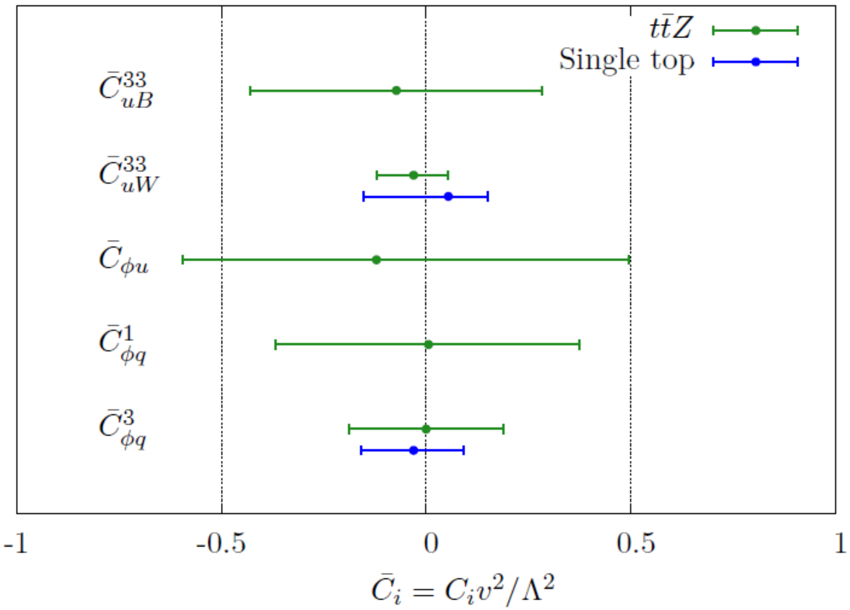
Neutral current: ttZ, ttγ associated production (tZ, tγ)
→ processes "discovered", cross section measurements 10-20%

Charged current: single top production, top decay observables
→ precision top physics at the LHC

Fit to Tevatron and LHC data
arXiv:1506.08845, arXiv:1512.03360

2015: first attempt to fit all top data

Weak limits on the edge of EFT validity
Truly global analysis not yet feasible



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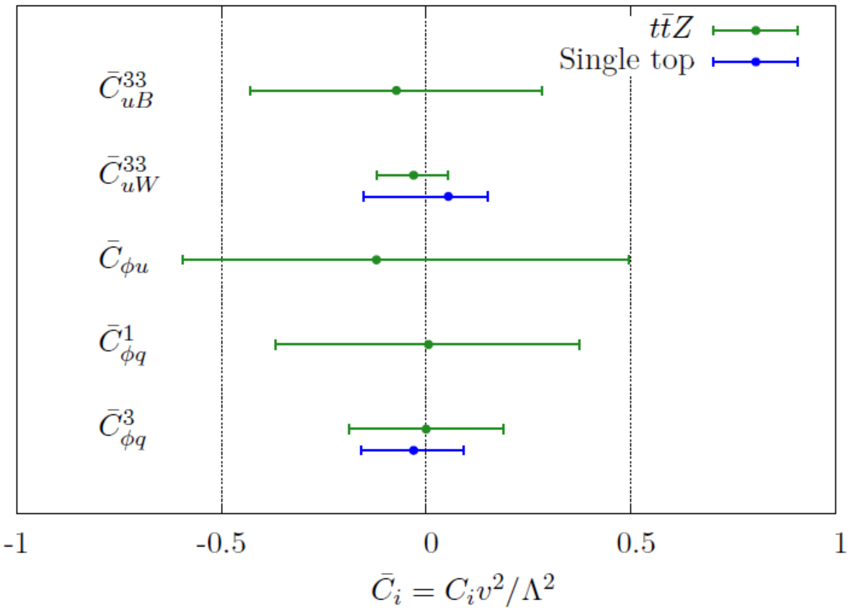
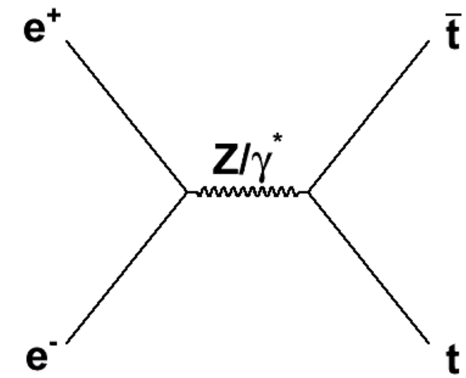


Prospects:
BSM sensitivity rougly independent of √s
Gain at HL-LHC, HE-LHC, FCChh/SPPC must come from control of systematics

Rontsch & Schulze, arXiv:1501.05939
Schulze & Soreq, arXiv:1603.08911
FCChh SM study, arXiv:1607.01831

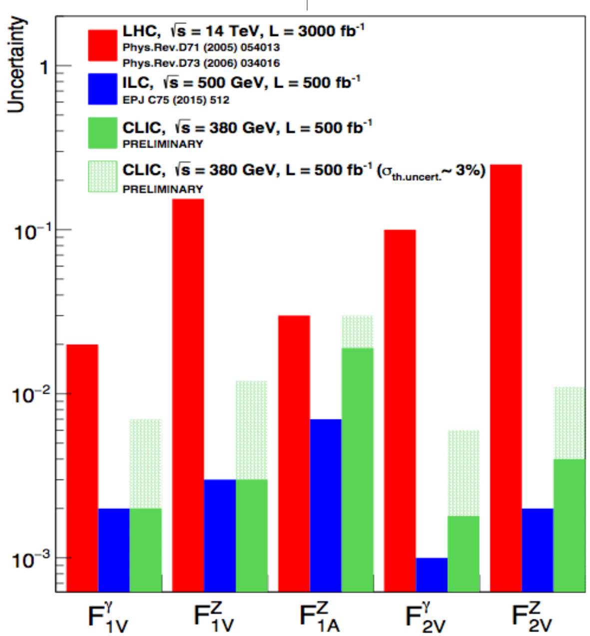
Top EW couplings at lepton colliders

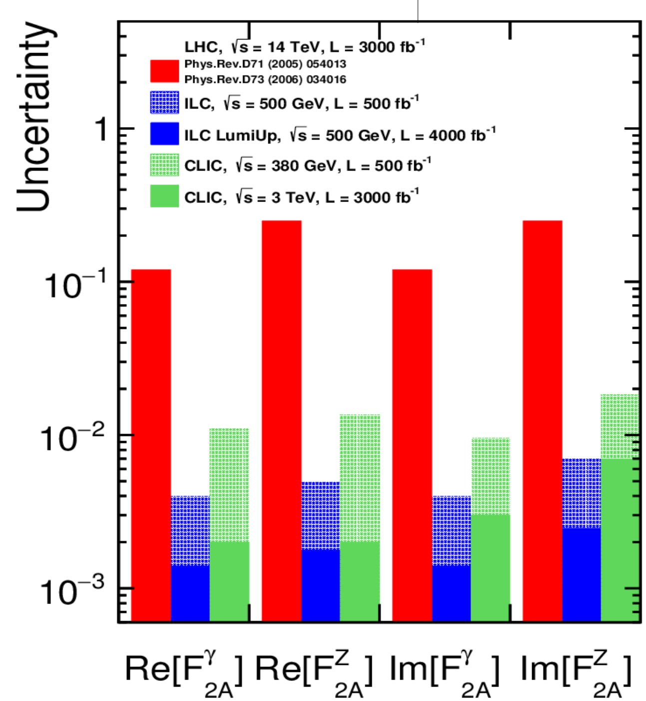


The best laboratory to test $\gamma t\bar{t}$ and $Z t\bar{t}$ vertices

FCC-ee, arXiv:1503.01325, 1509.09056
ILC di-lepton, arXiv:1503.04247

$$\Gamma_{\mu}^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(F_{1V}^X(k^2) + \gamma_5 F_{1A}^X(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF_{2V}^X(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\}$$





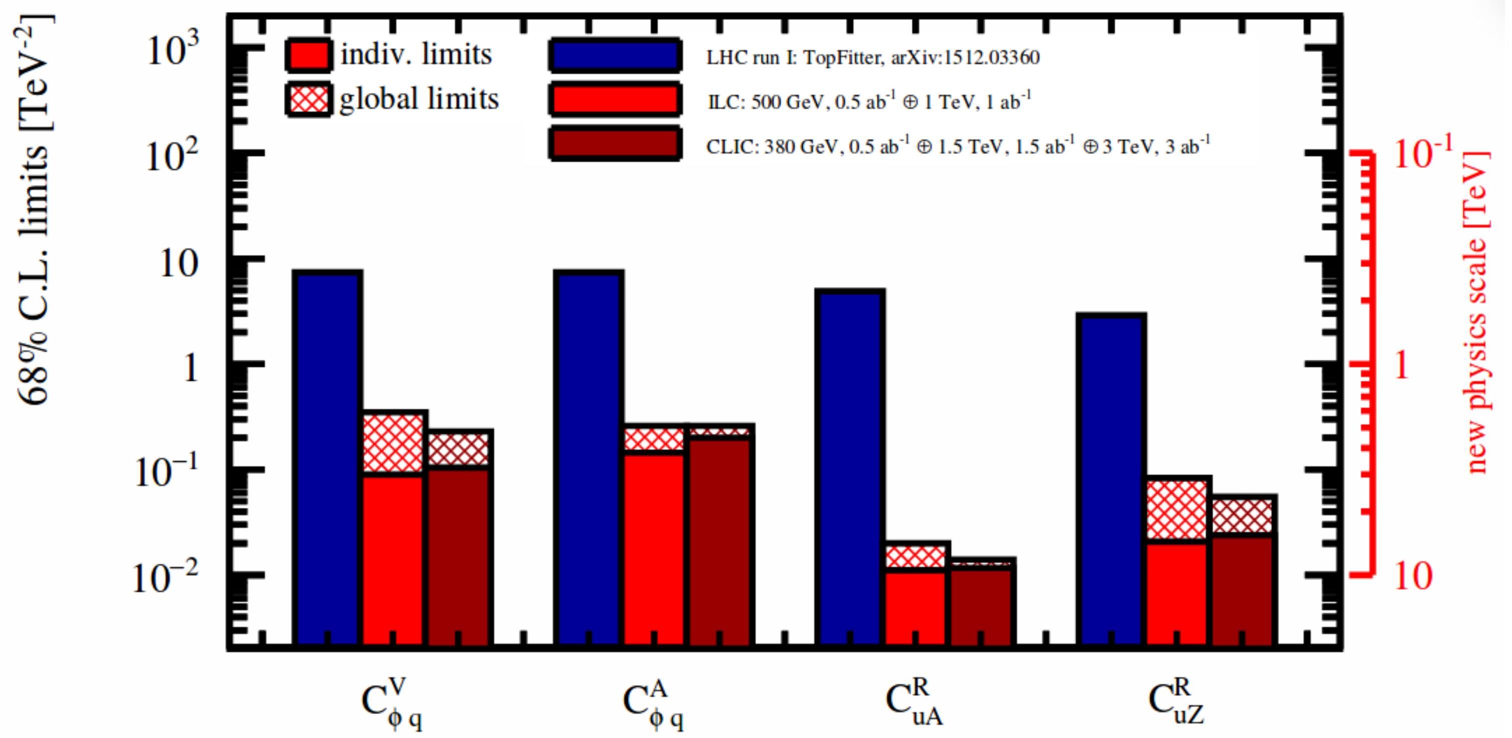
Prospects for HL-LHC/ILC500/CLIC380

arXiv:1307.8102, arXiv:1505.0620

Top EFT fit at the LC

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLICdp top paper, arXiv:1807.02441



Two-fermion operator limits exceed HL-LHC prospects by a large factor

Constraints on 4-fermion and dipole moment operators probe very high scale
- TeV LC competitive with qq → tt at the LHC and possibly FCChh

Global EFT fit

Durieux, Perello, Zhang, Vos, arXiv:1807.02121

CLIC top paper, arXiv:1807.02441

Circular Collider 350+365

Sensitivity to four-fermion operators increases strongly with energy

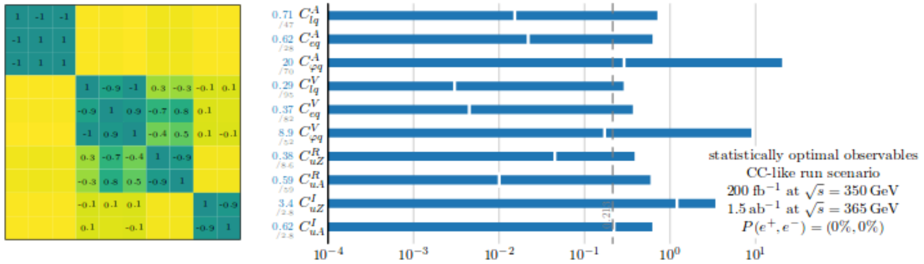


Figure 23. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables in a circular collider (CC-)like benchmark run scenario.

ILC500+ ILC1000

Ultimate precision in global EFT fit requires a collider with two energy stages and polarization

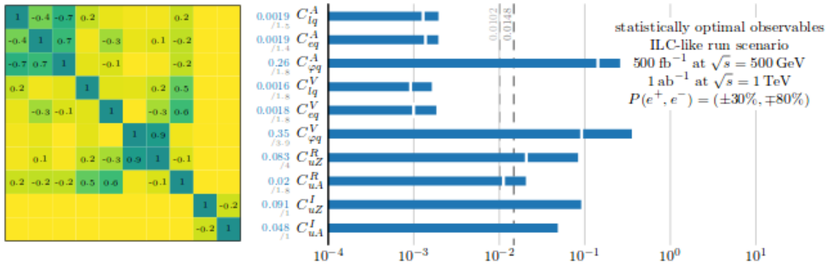


Figure 24. Global one-sigma constraints and correlation matrix deriving from the measurements of statistically optimal observables, in an ILC-like benchmark run scenario.

CLIC380+ CLIC1500+ CLIC3000

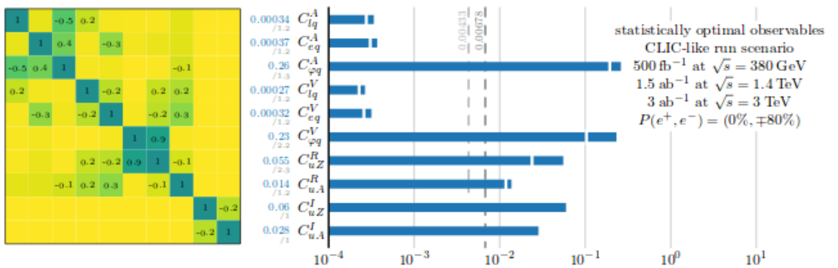


Figure 25. Global one-sigma constraints and correlation matrix arising from the measurement of statistically optimal observables in a CLIC-like benchmark run scenario.

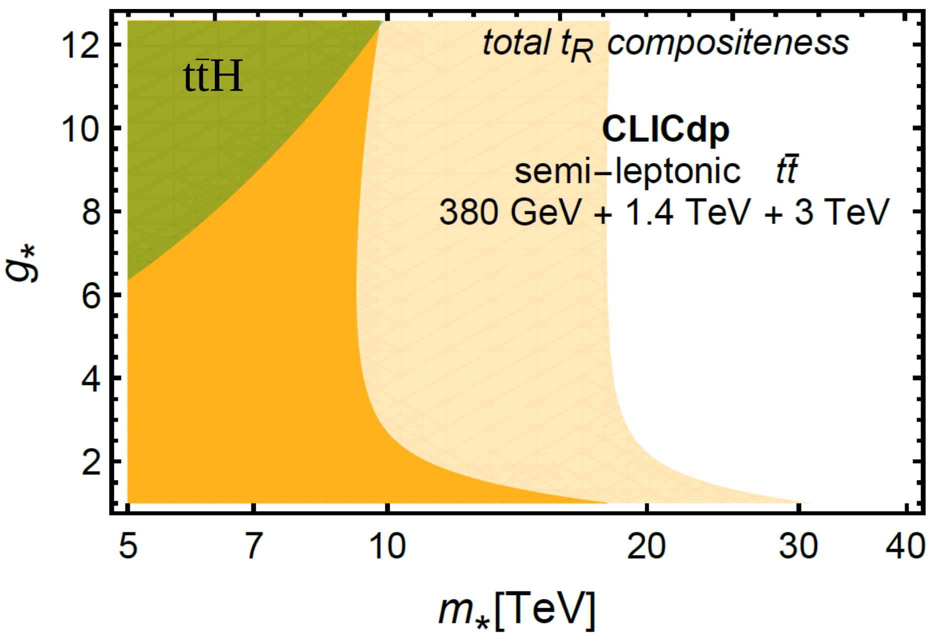
Durieux, Matsedonskiy, arXiv:1807.10273
CLIC top paper, arXiv:1807.02441

From EFT to concrete scenario

Re-express EFT constraints as limits on the canonical composite Higgs scenario, characterized by a coupling strength g_* and NP scale m_* (*Giudice 2007*)

The top quark is naturally composite in this framework (*Pomarol 2008*), the only viable option to generate the top Yukawa coupling (*Ratazzi 2008*)

Benchmarks: partial (t_L and t_R composite) & total (t_R maximally composite)
Pessimistic 5σ discovery contours reach 7-15 TeV, in favourable cases > 20 TeV



Sensitivity to new physics at 10-30 TeV!

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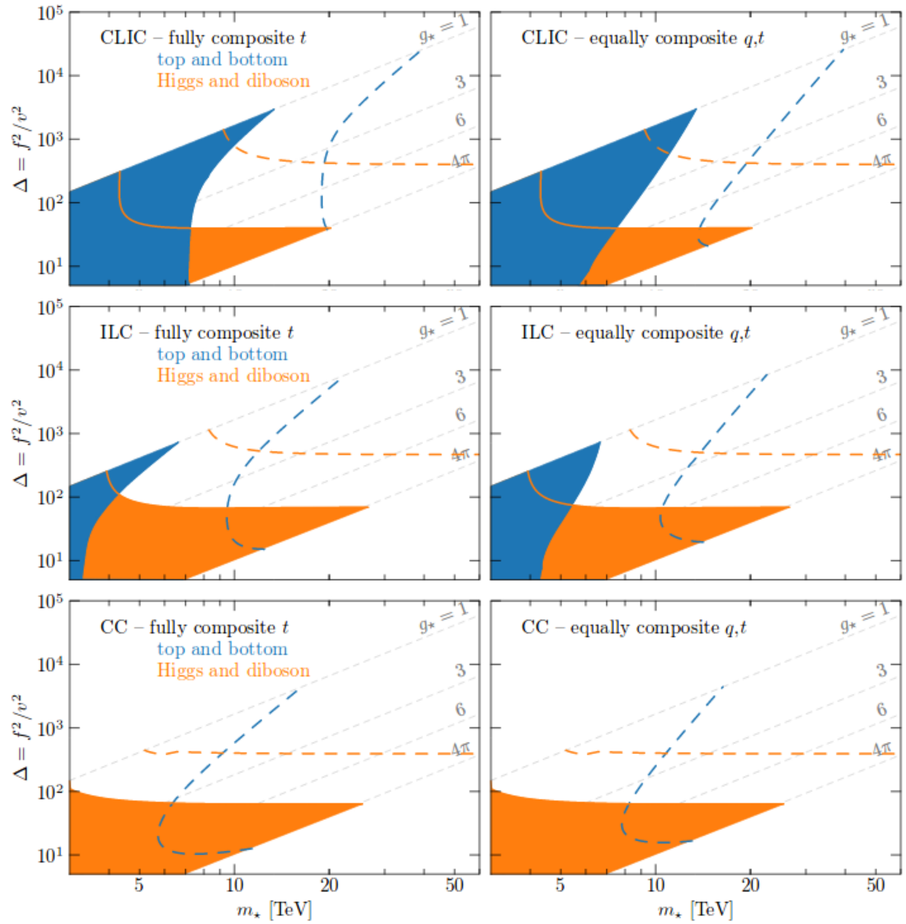
Durieux, Matsedonskiy, arXiv:1807.10273

Complementarity with Higgs physics



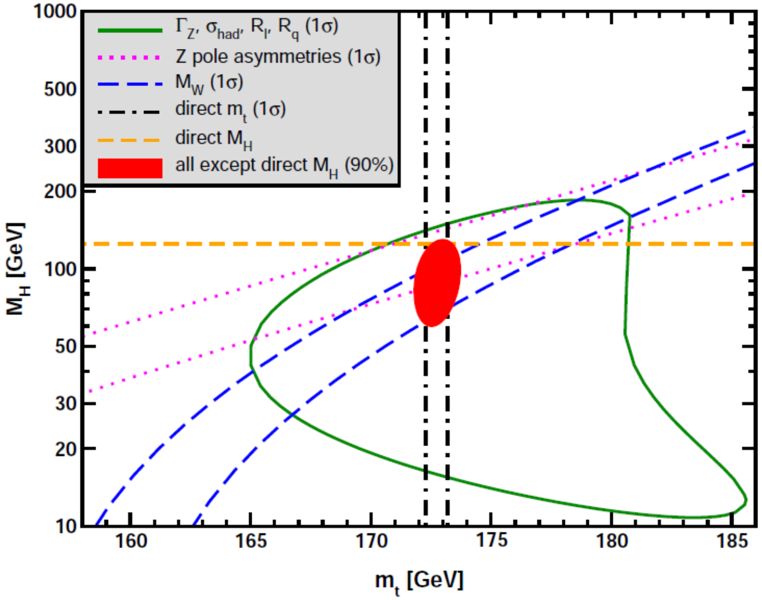
Measurements in top and Higgs/di-boson sector yield complementary constraints

Coverage of model parameter space up to >10 TeV

"Our results show that one can probe a significant fraction of the natural CH parameter space through the top portal, especially at TeV centre-of-mass energies"

Top mass

One of the most important SM parameters
Precise top mass measurement allows to verify internal consistency of the theory



PDG2018

EW fit

Indirect determination of the W mass:

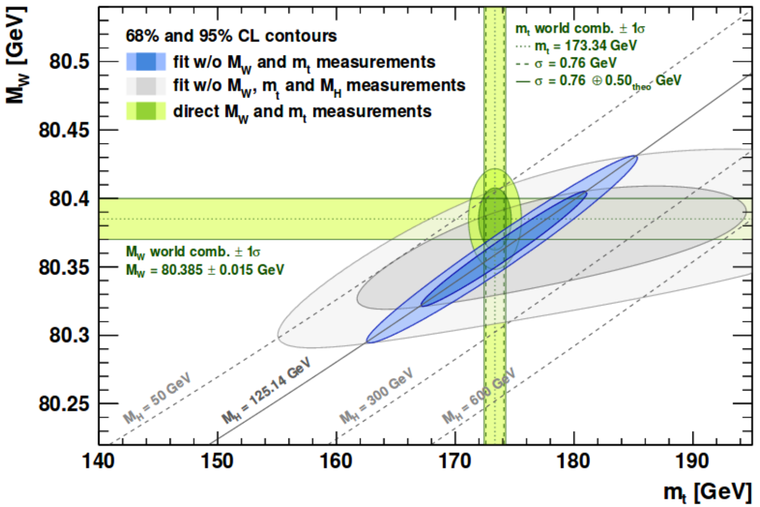
$$\begin{aligned} m_W = \quad & 80.3584 \quad \pm 0.0055_{m_{top}} \pm 0.0025_{m_Z} \pm 0.0018_{\alpha_{QED}} \\ & \quad \pm 0.0020_{\alpha_S} \pm 0.0001_{m_H} \pm 0.0040_{theory} \text{ GeV} \\ = \quad & 80.358 \quad \pm 0.008_{total} \text{ GeV}, \end{aligned}$$

Todays direct measurement:

$$m_W = 80.379 \pm 0.012 \text{ GeV}$$

Snowmass EW, arXiv:1310.6708
TLEP physics case, arXiv:1308.6176

Direct W mass measurement will improve ($\pm$ 0.002 GeV)
To match this precision with the indirect determination, m_t (and theory) must be made more precise



arXiv:1407.3792

Progress at the LHC: top quark mass revisited

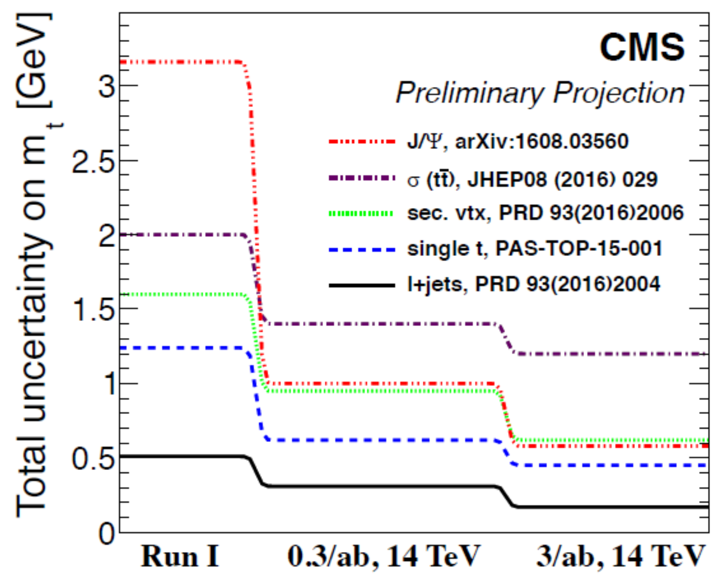
Direct mass measurement can reach 200-300 MeV precision (CMS)

Interpretation and theory uncertainty is hotly debated.

Calibrate MC mass parameter: *Hoang et al., PRL117*
Parton shower analytics: *Hoang et al., arXiv:1807.06617*
Improve MC precision: *Nason et al., arXiv:1607.04538, arXiv:1801.03944*
Renormalon ambiguity: *Beneke et al., arXiv:1605.03609*

*Status quo: quote "**direct mass**" measurements without theory uncertainty and distinguish from proper "**pole mass**" extraction*

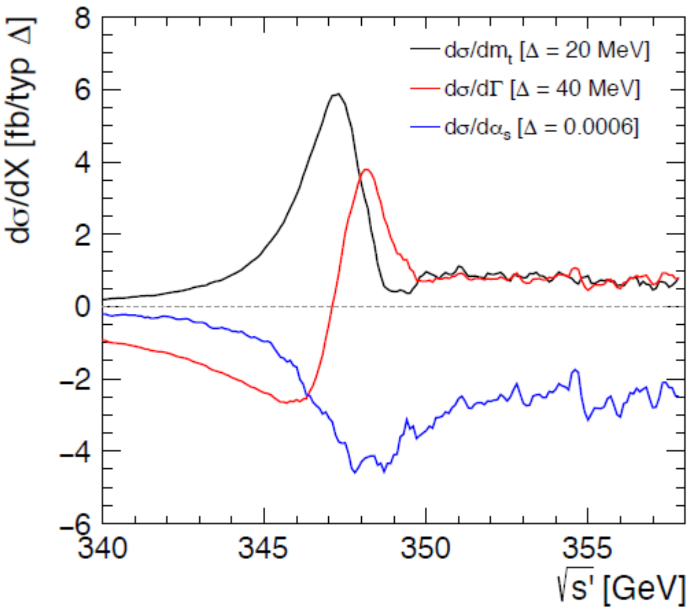
Progress beyond 500 MeV requires significant experimental and theory work
arXiv:1310.0799

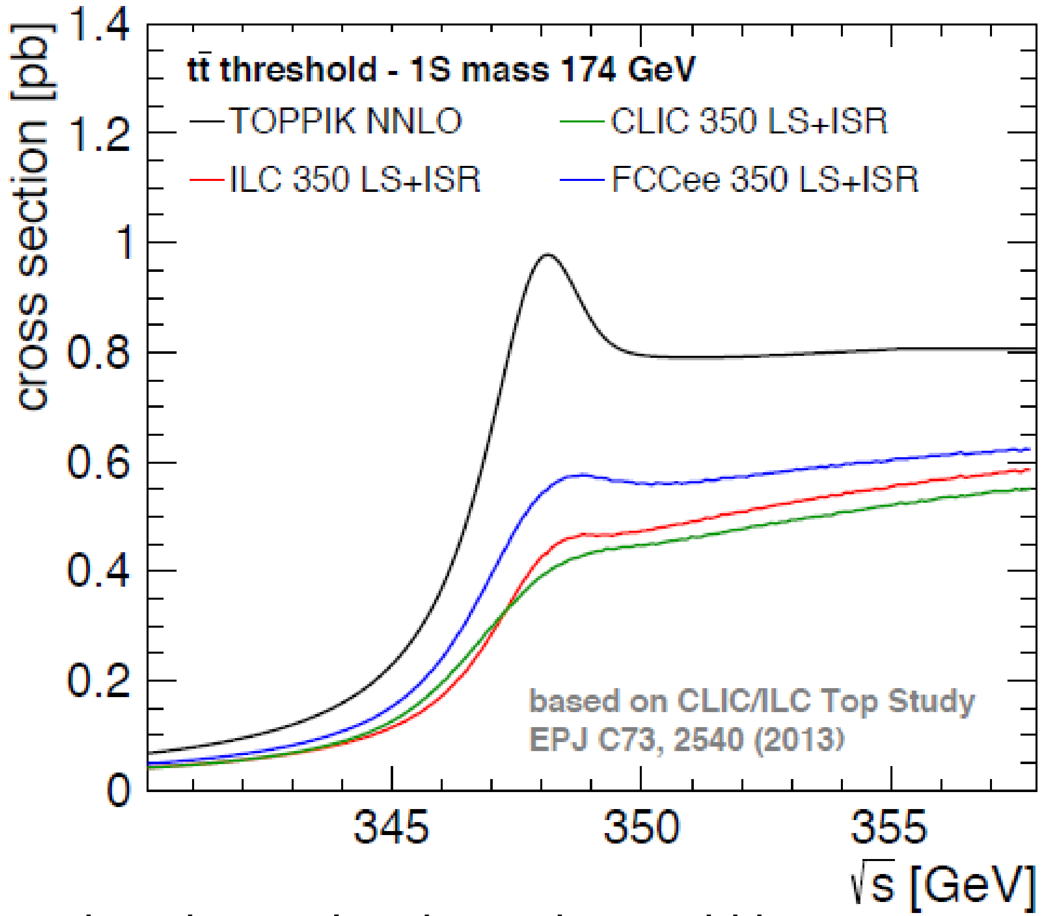


Top quark mass from e^+e^- threshold scan

Threshold shape reveals the top quark mass

Kuhn, Acta Phys.Polon. B12 (1981)





Line shape also depends on width,
Normalization sensitive to α_s and y_t

Detailed estimates of the precision in multi-parameter fits

Martinez, Miquel, EPJ C27, 49 (2003), Horiguchi et al., arXiv:1310.0563, Seidel, Simon, Tesar, Poss, EPJ C73 (2013)

Top quark mass from e+e- threshold scan

A multi-parameter fit can extract the PS mass with excellent precision

Statistical uncertainty:	~20 MeV	*100 fb^{-1}*
Scale uncertainty:	~40 MeV	*N^3LO QCD, arXiv:1506.06864*
Parametric uncertainty:	~30 MeV	*α_s world average, arXiv:1604.08122*
Experimental systematics:	25-50 MeV	*including LS, arXiv:1309.0372*

This threshold mass can be converted to the $\overline{\mathrm{MS}}$ scheme with ~10 MeV precision

Marquard et al., PRL114, arXiv:1502.01030

A very competitive top quark mass measurement:

$\Delta m_t \sim 50$ MeV ($= 3 \times 10^{-4}$, cf. $\Delta \mathbf{m}_b$ **~1%)**

(nearly) independently of machine design and parameters.

Note: this is a prospect, not a target!

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A few answers to concrete questions

Is there top physics below threshold?

Yes!

Search for $e^+e^- \rightarrow$ tc production at 250 GeV

→ competitive limits on FCNC vertices tZq and tγq

→ ILC and CLIC studies so far have focused on top decay

Indirect sensitivity to top quark EW and Yukawa couplings

→ very interesting single-parameter sensitivity

→ no robust result in proper global EFT fit

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Answers to concrete questions

How does the top quark affect the overall programme?

In many important ways!

The EW fit requires a balanced precision of all parameters

→ the top quark mass must be measured to few 100 MeV precision

The Higgs coupling fit is affected by top operators at loop level

→ PRELIMINARY results on interplay HL-LHC-LC are appearing

High energy operation, with $t\bar{t}$, $t\bar{t}H$ and TeV runs, is ultimately needed to completely exploit the LC potential and balance the overall programme

The future (of top physics) is bright

Linear colliders offer a very exciting top physics programme

→ *a precise view on key parts of the SM, with exquisite BSM sensitivity!*

Precise measurements at a Higgs factory are sensitive to the top

→ *competitive results already at 250 GeV* Up-to-date LC studies urgently needed

High-energy operation is what linear colliders do best

→ *a LC operated above 350 GeV delivers first-class top physics*

Recommended reading: CLIC top paper, *arXiv:1807.02441*

A summary in simple terms

1973: The top quark is conceived

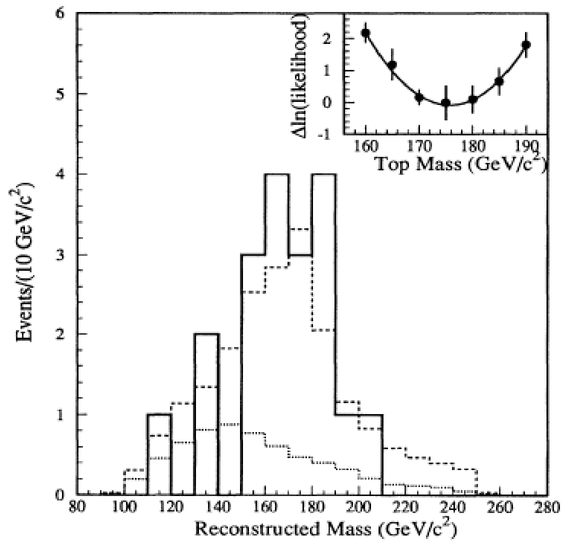
Kobayashi and Maskawa postulate the third generation

Particle physics was so easy back then!

1972 A 5M$ collider on the SLAC parking lot

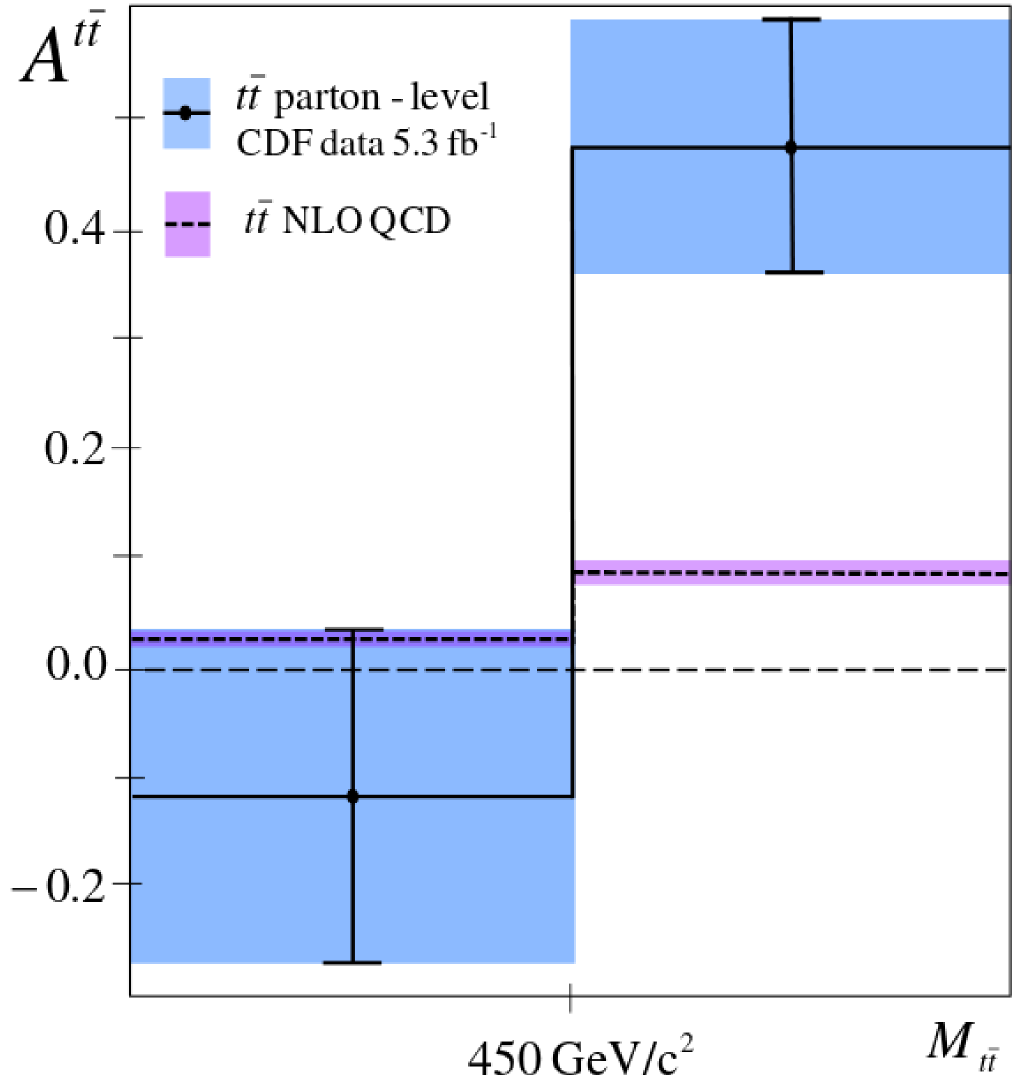
1974 Two colliders in one country discover the same particle

1995: The top quark is born



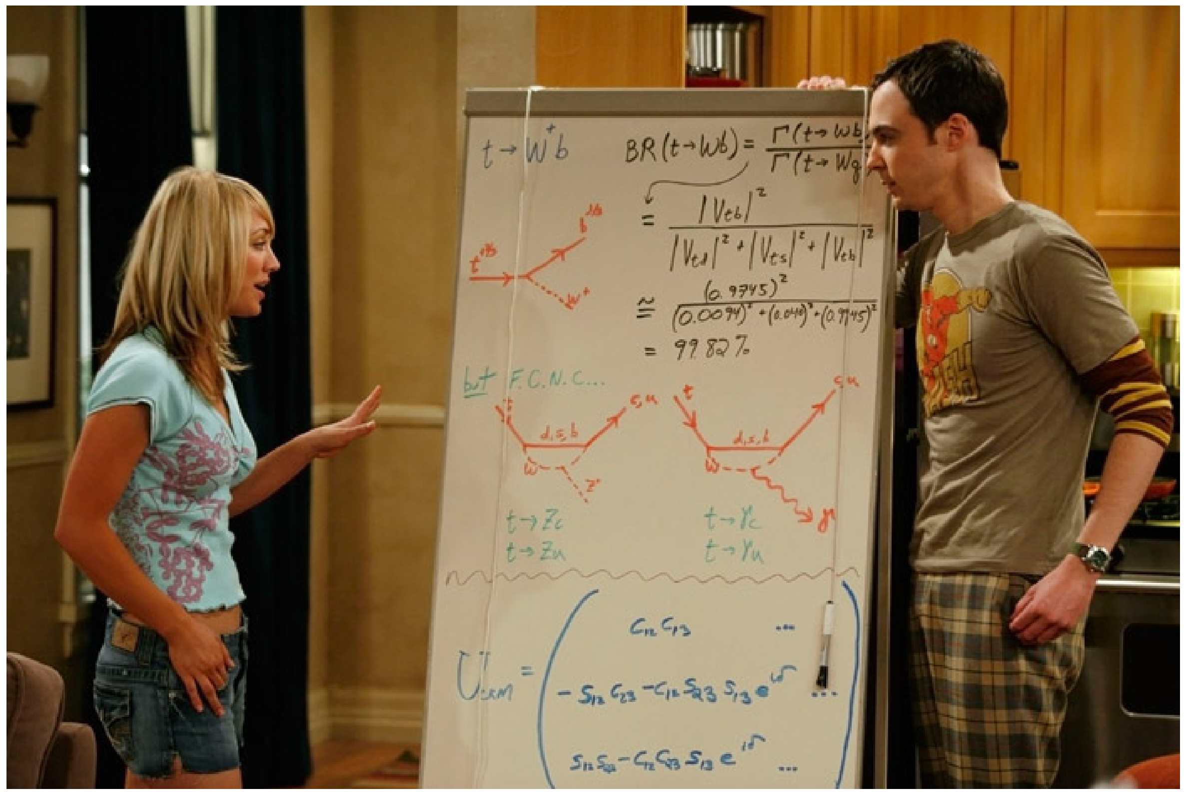
CDF and D0 collaborations, Observation of the top quark
PRL 75 (1995) 2632-2637, 2626-2631

2011: top turns 16 puberty (sigh)



2015: The top quark turns 20

2015: Life is great at 20!



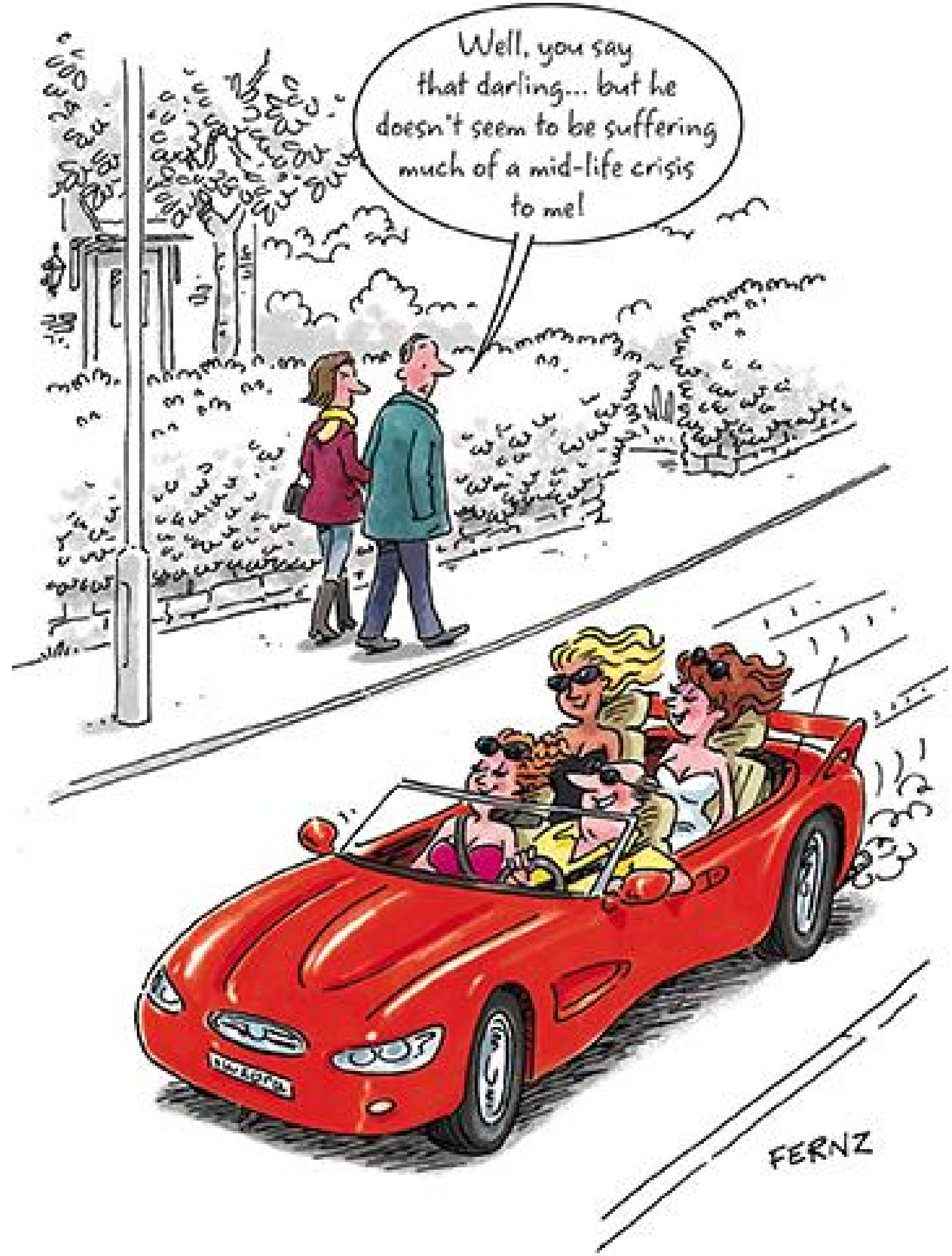
2016: top (finally) grows up...
Another day at the top factory

2018: top meets Higgs

2037: top turns 42

The factory closes: looking for a new job

Mid-life crisis?



2037: or happily ever after?

2037: or happily ever after?