Top physics at the next e^+e^- collider

CEPC workshop

Rome, 24-26 May 2018

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Acknowledgements: source of material

This talk is a personal view and does not necessarily reflect the position of projects I'm involved in (LCC, ILC, ILD, CLIC)

Most of the material is based on studies in the framework of ILD or CLICdp, and would not have been possible without a large effort of many people to design detectors, develop MC tools, etc.

This talk is somewhat biased towards the top physics paper that is being prepared by CLIC, and several supporting documents.

A useful forum for discussion is the annual LC top workshop. This year's workshop: Sendai (Japan) 4-6 June.

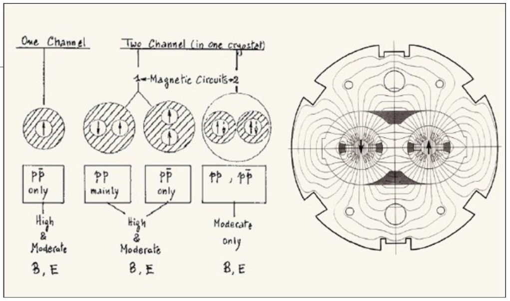
A review: top physics at high-energy lepton colliders, arXiv:1604.08122

A brief history of top quark physics

Particle physics was so easy back then!

1972: a 5M$ collider starts operation on a SLAC parking lot
1973: The top quark is born as a hypothetical particle
1974: Two colliders in one country discover the same particle

1984: First LHC workshop



1994: SSC canceled
1995: top quark discovery at FNAL

2010: start of the LHC (top turns 25)

2020: decide next energy-frontier facility?

2035: start of operation of collider XXX

ILC operating scenario

ILC-NOTE-2015-068
DESY 15-102
IHEP-AC-2015-002
KEK Preprint 2015-17
SLAC-PUB-16309
June 25, 2015

ILC Operating Scenarios

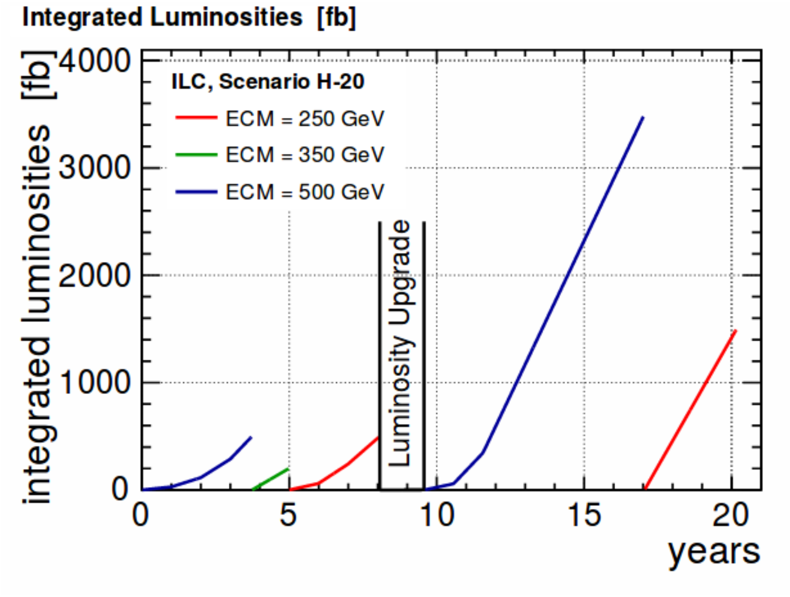
ILC Parameters Joint Working Group

T. Barklow, J. Brau, K. Fujii, J. Gao, J. List, N. Walker, K. Yokoya

Abstract

The ILC Technical Design Report documents the design for the construction of a linear collider which can be operated at energies up to 500 GeV. This report summarizes the outcome of a study of possible running scenarios, including a realistic estimate of the real time accumulation of integrated luminosity based on ramp-up and upgrade processes. The evolution of the physics outcomes is emphasized, including running initially at 500 GeV, then at 350 GeV and 250 GeV. The running scenarios have been chosen to optimize the Higgs precision measurements and top physics while searching for evidence for signals beyond the standard model, including dark matter. In addition to the certain precision physics on the Higgs and top that is the main focus of this study, there are scientific motivations that indicate the possibility for discoveries of new particles in the upcoming operations of the LHC or the early operation of the ILC. Follow-up studies of such discoveries could alter the plan for the centre-of-mass collision energy of the ILC and expand the scientific impact of the ILC physics program. It is envisioned that a decision on a possible energy upgrade would be taken near the end of the twenty year period considered in this report.

Scenarios to accumulate:
2 ab^{-1} at 250 GeV
4 ab^{-1} at 500 GeV
200 fb^{-1} at top threshold



CLIC operating scenario

CLIC technology has the unique capability to reach a center-of-mass energy of 1.5-3 TeV

The staging scheme envisages:

- 500 fb^{-1} at 380 GeV (initial stage)
- 100 fb^{-1} at 350 GeV (threshold scan)

Top, Higgs indirect BSM

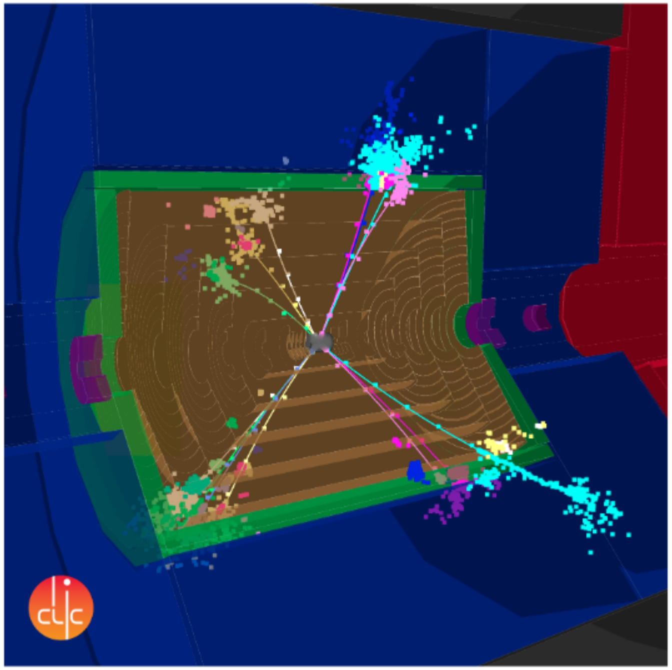
- 1.5 ab^{-1} at 1.5 TeV
- 3 ab^{-1} at 3 TeV

$t\bar{t}H$, HH, direct BSM

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE

CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

arXiv:1608.07537v3 [physics.acc-ph] 27 Mar 2017



UPDATED BASELINE FOR A STAGED COMPACT LINEAR COLLIDER

The top quark

The heaviest fermion and the heaviest elementary particle

Tightly linked to the Higgs ($y_t \sim 1$) and EW symmetry breaking

The top quark (from an experimentalist's point of view)

Top escaped scrutiny at lepton colliders so far

An accessible quark: top/anti-top, polarization

Questions that the e^+e^- top physics program can answer:

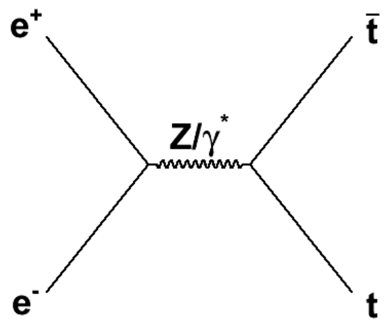
Is the SM internally consistent?
Top mass: a key parameter of the EW fit and extrapolation of EW vacuum to high scales.

Are there extra dimensions/are Higgs and top composite?
Top quark couplings to γ/Z: exquisite sensitivity to broad BSM family

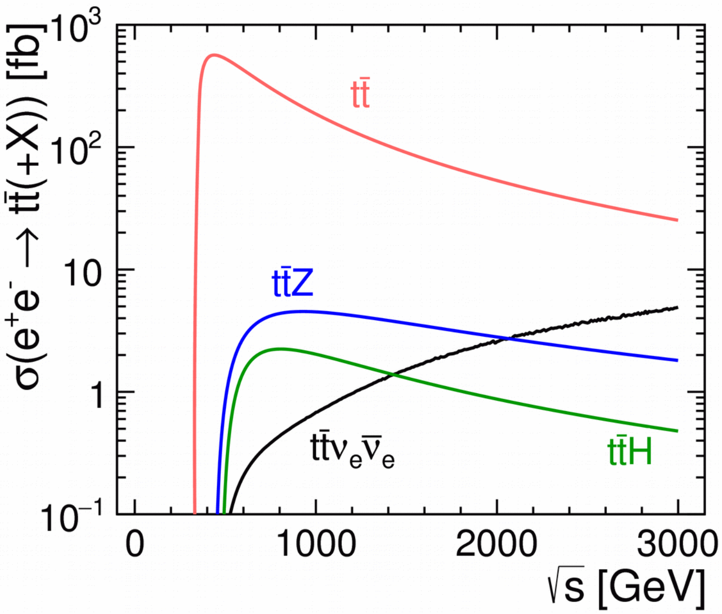
What's behind the hierarchy of fermion masses?
Top Yukawa: one of the key measurements in HEP

The next collider must be able to transform HEP. Precision top physics at an e^+e^- collider has this potential. SM results answer an important question. One 5σ deviation may guide us to what lies beyond the SM.

Top quark production at e^+e^- colliders



Pair production provides direct access to $Zt\bar{t}$, $\gamma t\bar{t}$ vertices



- Sizeable pair production cross section right above threshold: 700 fb
- At higher-energy 1/s decline for s-channel processes
- Associated production processes accessible above 550 GeV
- Vector-boson-fusion production and single top increasingly important

Calculability is a real asset of e^+e^- colliders. QCD corrections are tiny; rates can often be predicted with sub-% precision already today.

Selection and reconstruction

Nearly all results based on full simulation, including realistic detector response, ISR + LS, machine background, reconstruction algorithms

Top quark pair production is the dominant source of 6-fermion events

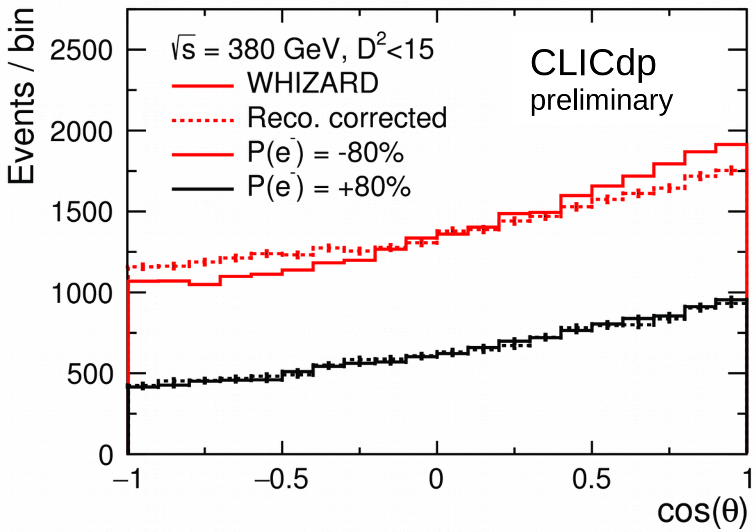
Easily isolated by requiring isolated lepton + b-tagging:

Efficiency ~ 70%
Purity > 80%

Top reconstruction is affected by ambiguity in W-b pairing

Migrations are mitigated by quality requirements

Purity increases further



More sophisticated techniques and analysis are likely to do better than this

Selection and reconstruction

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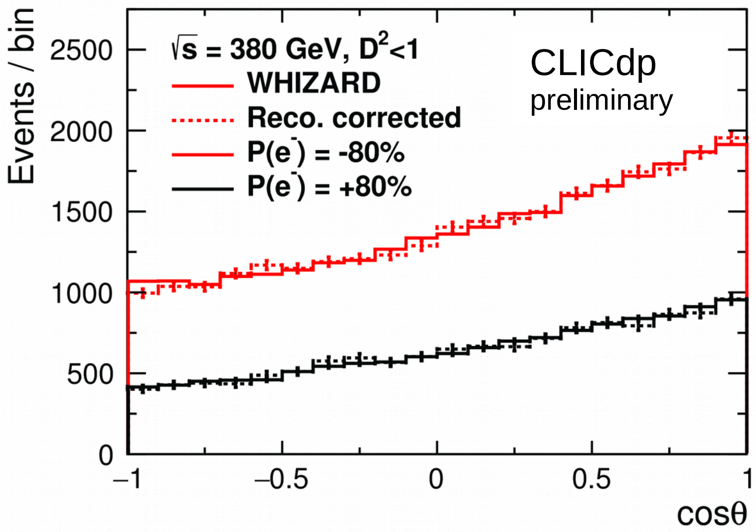
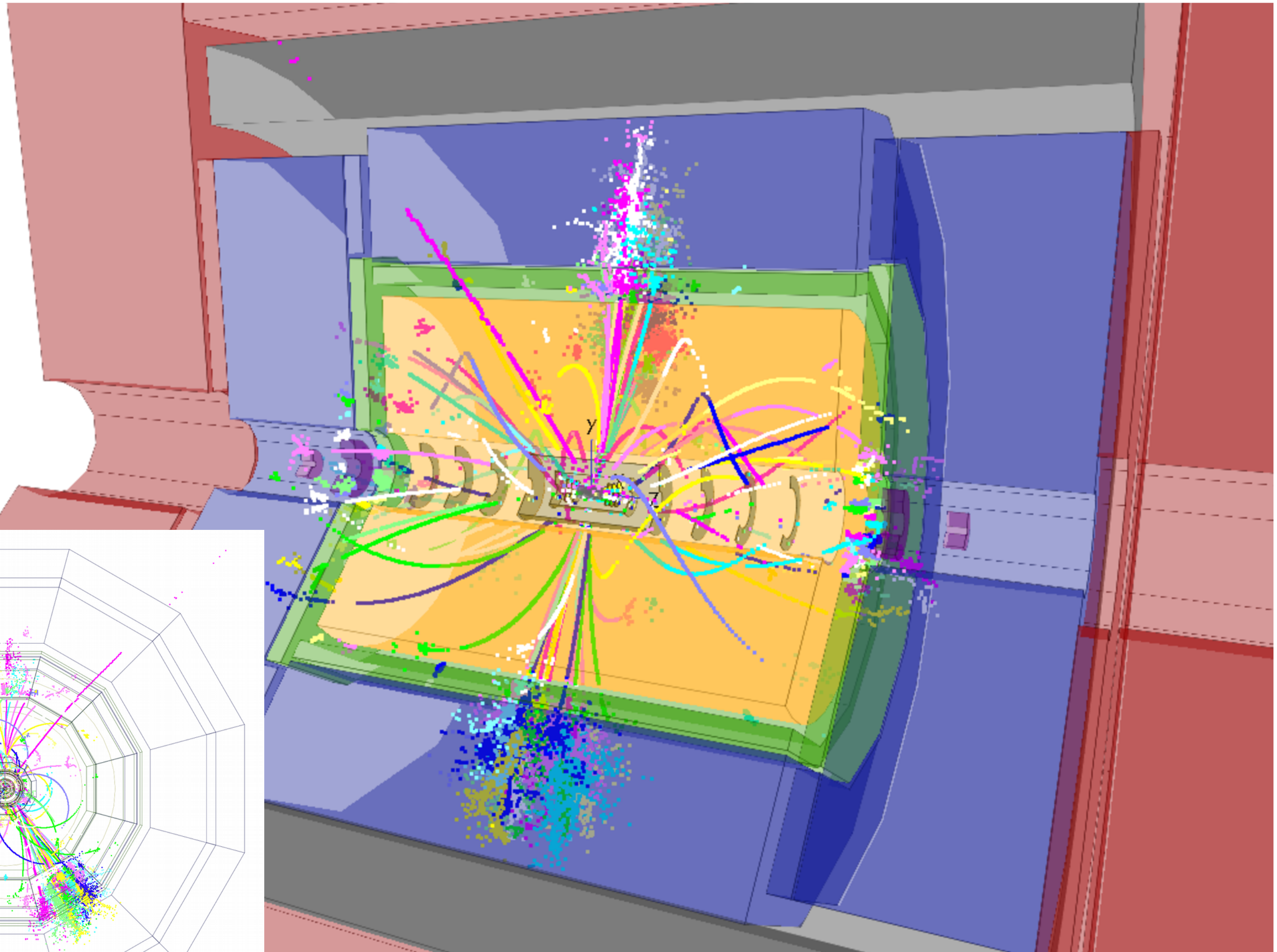
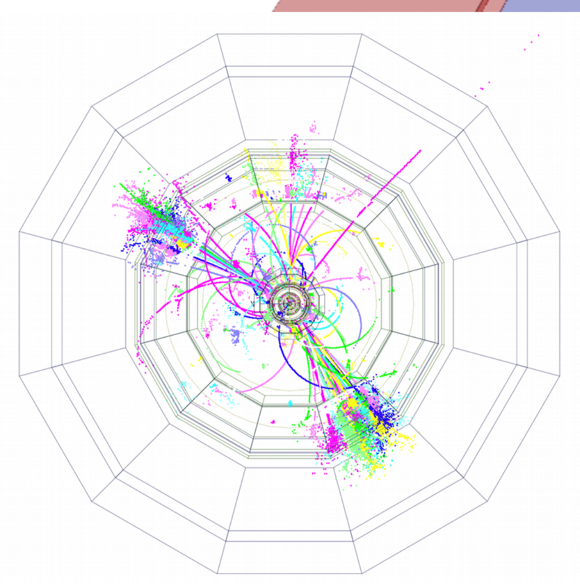


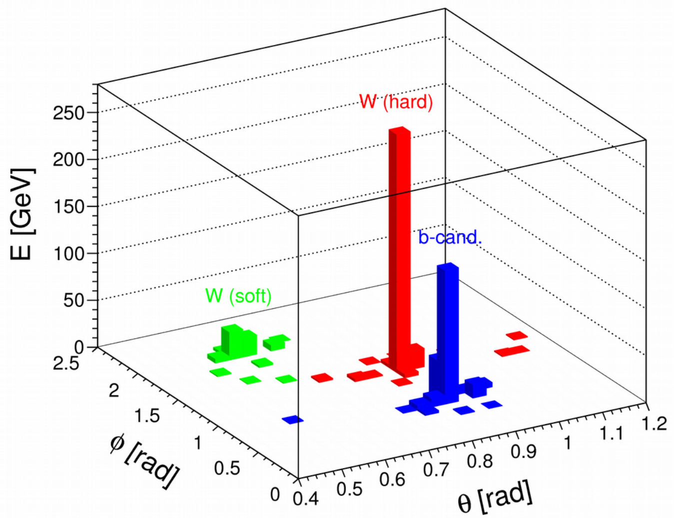
Techniques and analysis are likely to improve further

Boosted top quark production: √s > 1 TeV

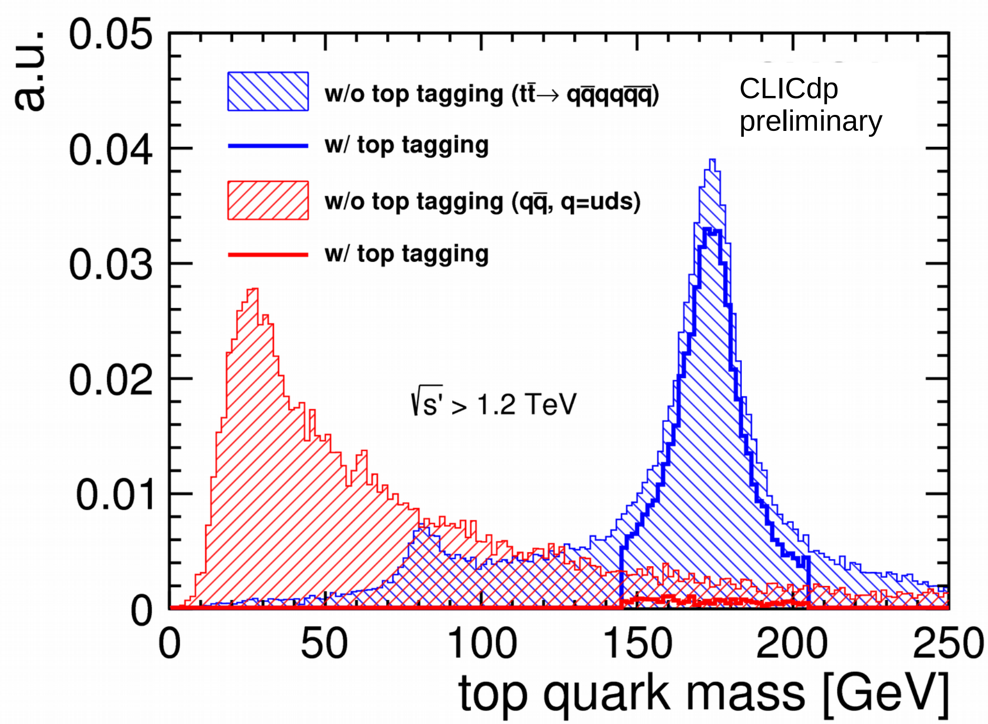




Selection and reconstruction at high energy



- High energy is a different ball game
- Capture hadronic top in a single large-R jet
  (VLC, arXiv:1607.05039)
- Tag events using jet substructure analysis
  (Hopkins tagger, arXiv:0806.0848)
- Final selection based on multi-variate analysis



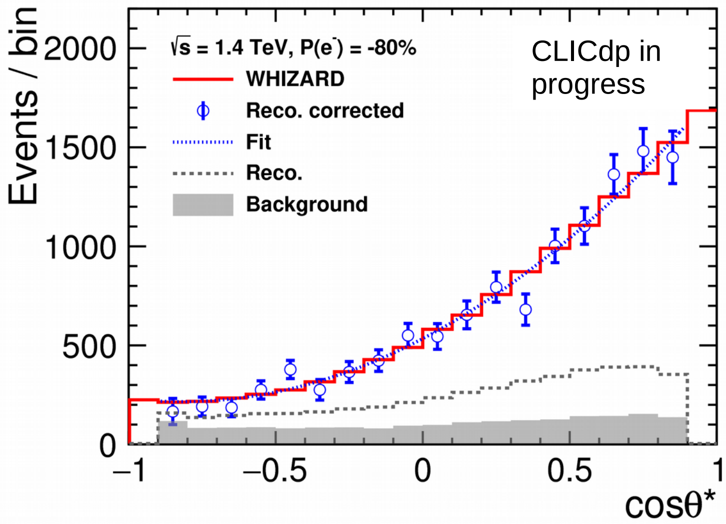
Two analyses at 1.4 TeV yield comparable results for √s’ > 1.2 TeV

Main background due to single top
→ larger for left-handed e^- beam

Selection and reconstruction at high energy

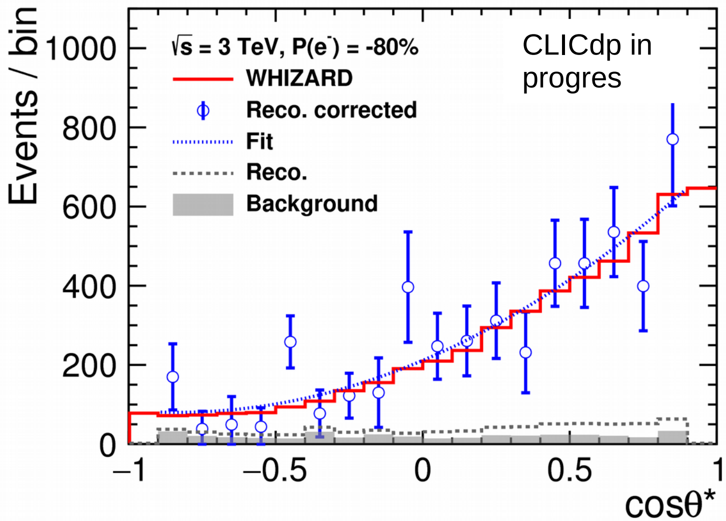
Performance at 1.4 TeV
Efficiency 19-23%
Purity 55-62%

Performance at 3 TeV
Efficiency 10-15%
Purity 30-50%



Performance at 1.4 TeV
Efficiency ~40%
Purity 55-62%

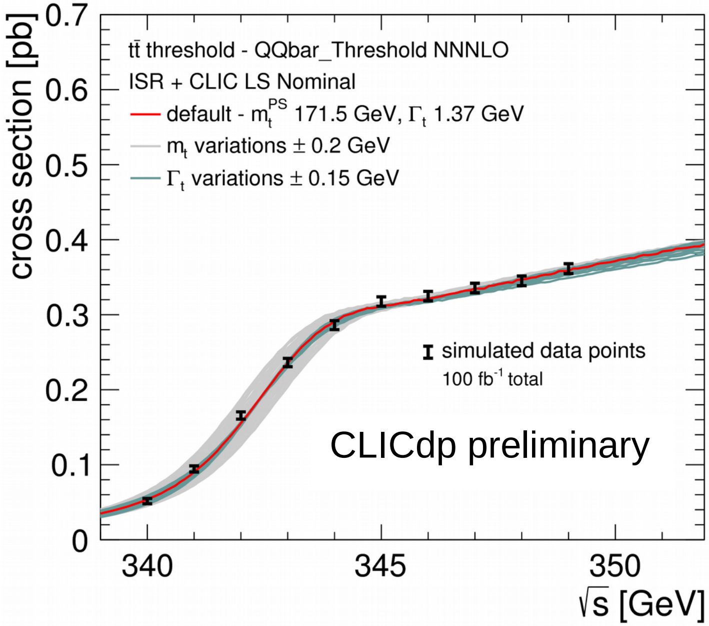
Performance at 3 TeV
Efficiency ~30%
Purity 30-50%



Main background is single top production (part of $e^+e^- \rightarrow W^+bW^-\bar{b}$)

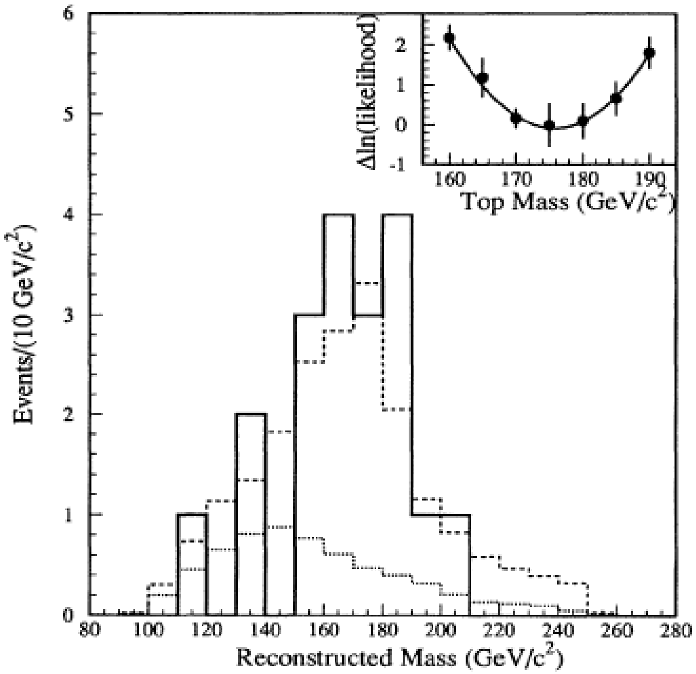
improvement in progress

Top threshold scan



The top quark mass

The only quark whose mass can be determined directly

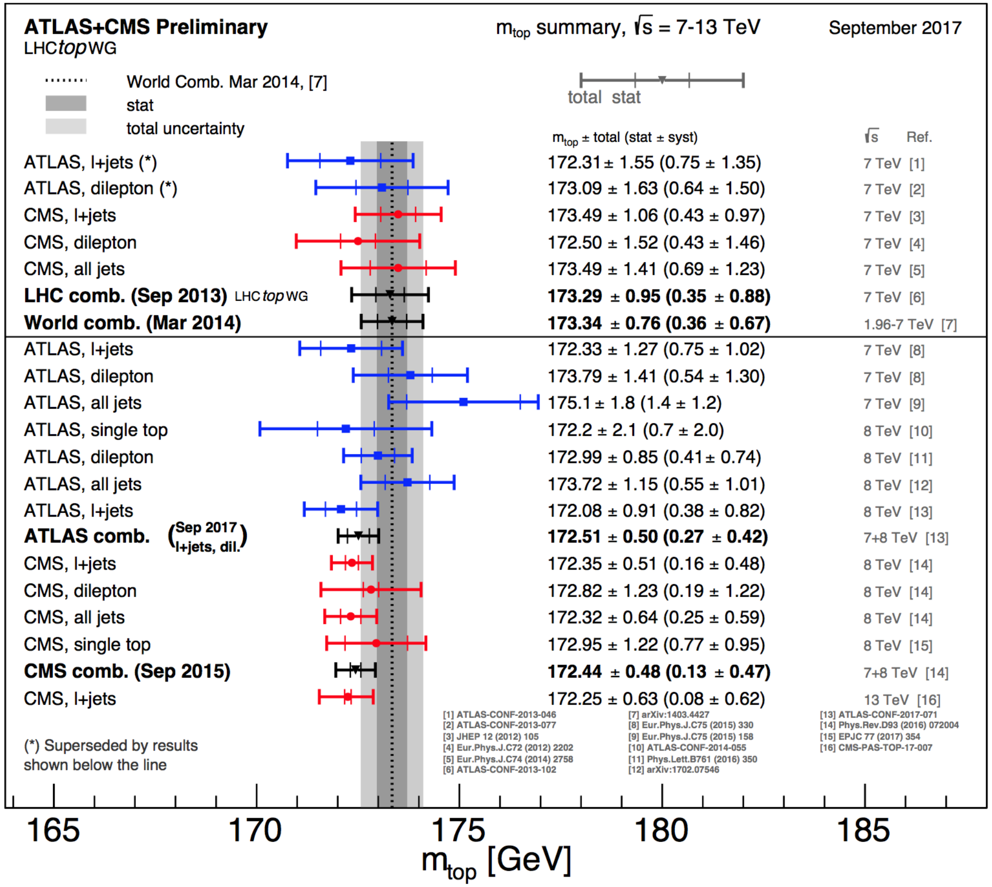


Reconstructed top quark mass distribution at the Tevatron

The top quark mass

LHC + Tevatron direct:
$m_t = 173.3 \pm 0.7$ GeV
(arXiv:1403.4427)

LHC 3 ab^{-1} prospects:
$\Delta m_t = \pm 0.2$ (exp.) $\pm$? GeV
(CMS-DP-2016-064)



Interpretation of direct mass and value of ? hotly debated (arXiv:1608.01318,arXiv:1310.0799)

FCChh: “We avoid here a discussion of the determination of the top mass at 100 TeV: any progress relative to what will be known at the end of the LHC will depend on theoretical progress that is hard to anticipate now […]” arXiv:1607.01831

The top quark pole mass

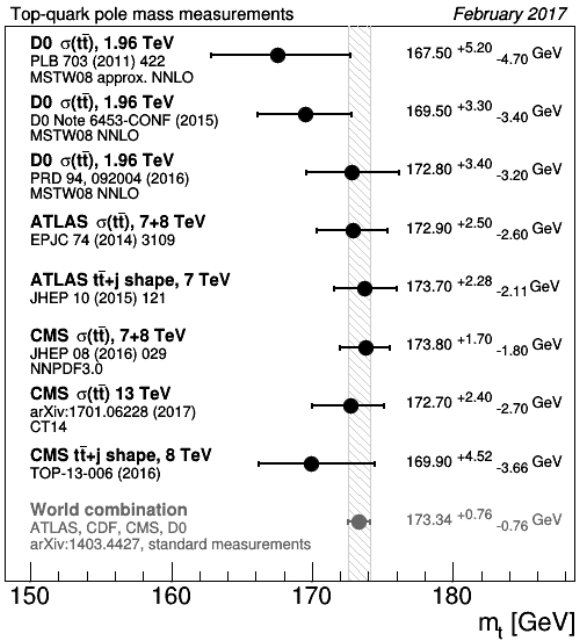
LHC + Tevatron today:

Pole mass $m_t = 173.8 \pm 1.8$ GeV (CMS, NNPDF3, x-sec)

LHC 3 ab^{-1} prospects:

Pole mass $\Delta m_t = \pm 1.2$ GeV

(CMS-DP-2016-064)

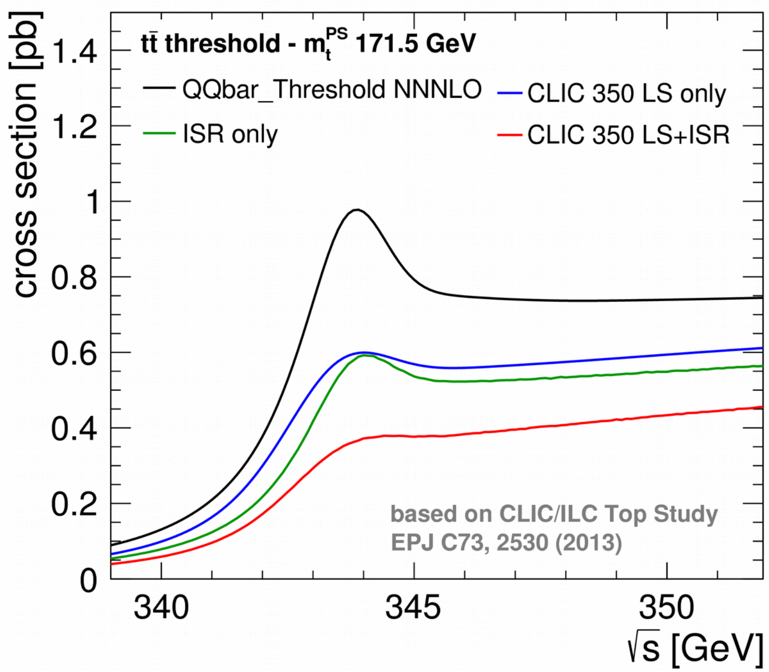


Threshold scan: theory

At the $t\bar{t}$ production threshold the cross section is strongly enhanced as a quasi-bound-state forms

The line shape is affected by ISR and beam energy spread, and is sensitive to the mass & width, α_s and the top Yukawa coupling

ILC and CLIC include a scan of the c.o.m. energy through the threshold region in the initial stage (100-200 fb^{-1}, less than 1 year)



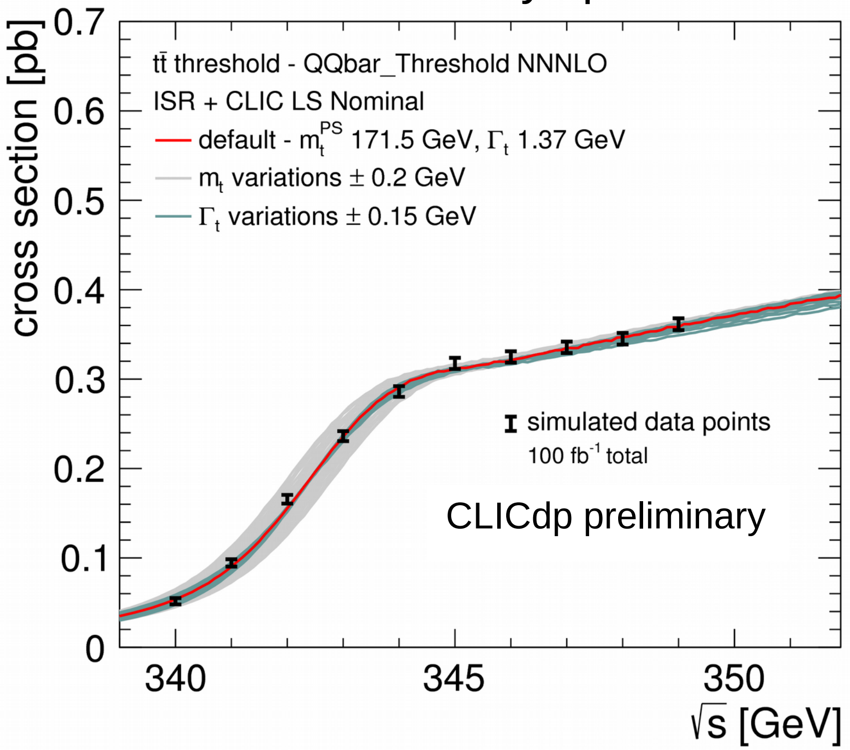
We can study this in detail thanks to tremendous work by theorists, right from the initial idea (Kuhn, 1981!) to today's sophisticated calculations (Beneke et al., Hoang et al., Marquard et al.)

Threshold scan: experiment

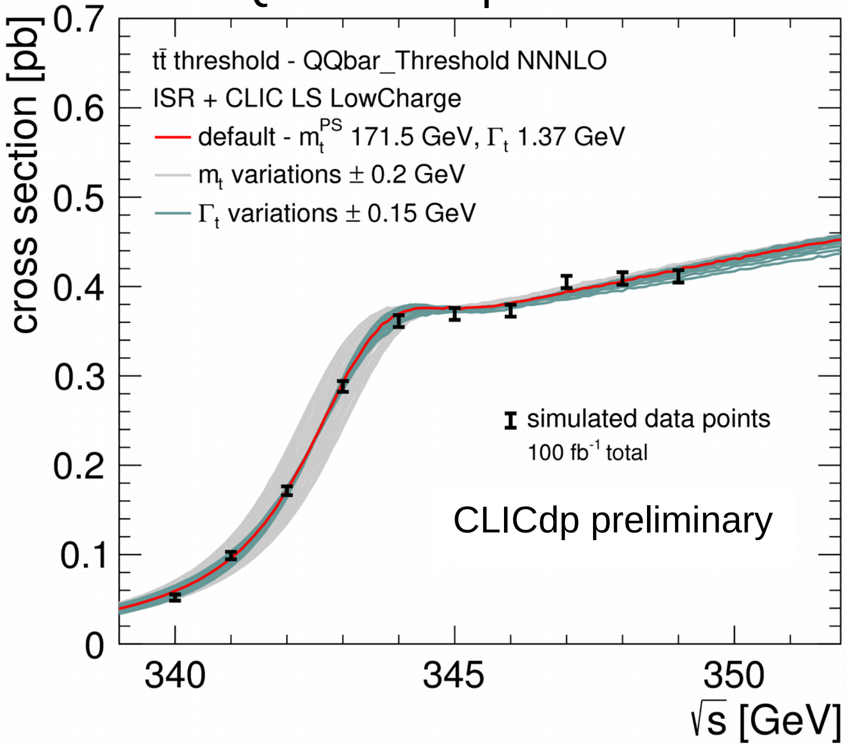
Detailed estimates of the precision in multi-parameter fits

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

Nominal luminosity spectrum



Low Q machine parameters



The machine parameters can be tuned (at a cost in instantaneous luminosity) to minimize the impact of the luminosity spectrum on the threshold shape Higher precision - per unit luminosity – in the mass extraction + potential gain in the width measurement. The details of the scan can be further optimized.

Threshold scan: potential

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

Statistical uncertainty:	~20 MeV	*100 fb^{-1}*
Scale uncertainty:	~40 MeV	*N^{3}LO 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

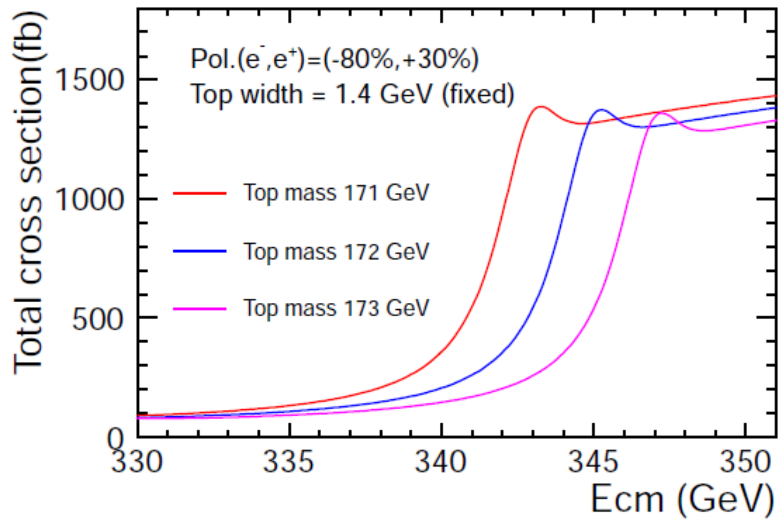
Marquard et al., PRL114, arXiv:1502.01030

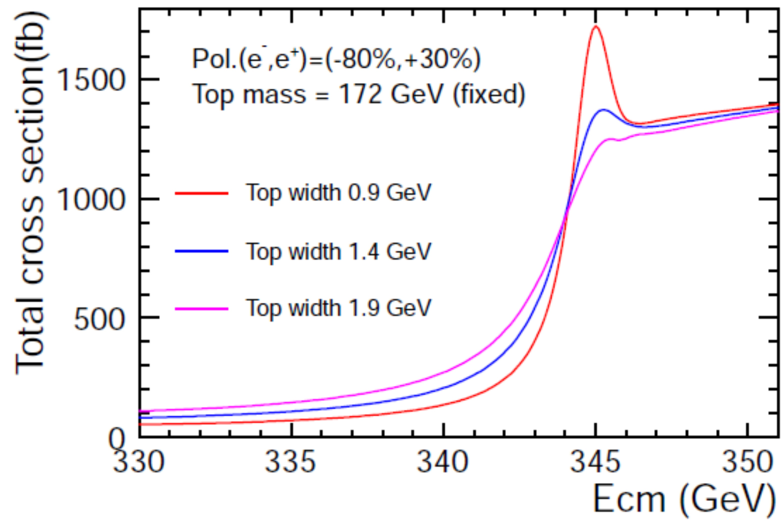
A very competitive top quark mass measurement:

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

This is a real prospect, based on technology available today, not a target!

Top quark Yukawa coupling at threshold?

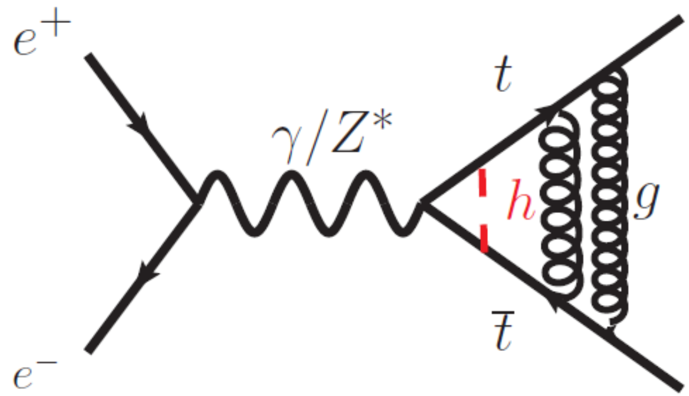




Horiguchi et al., arXiv:1310.0563

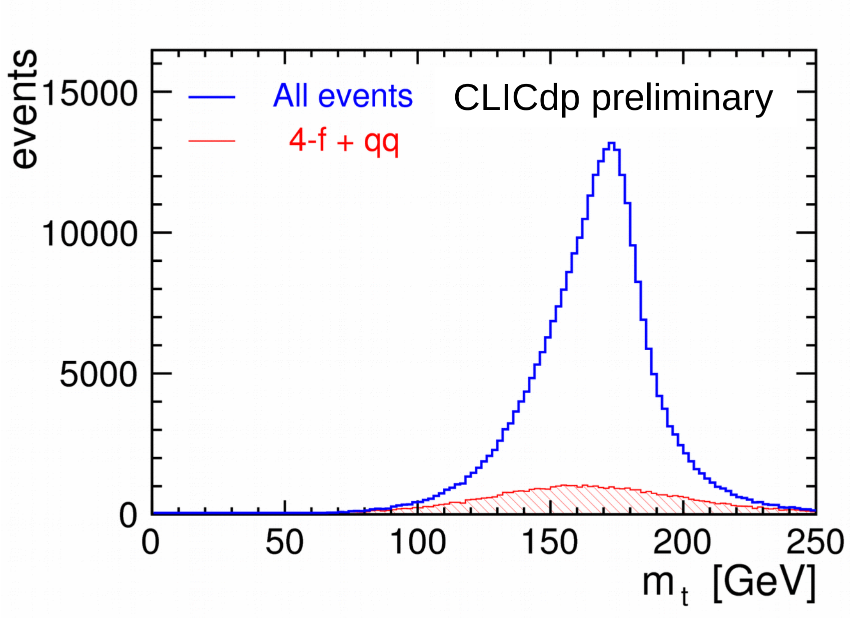
Threshold shape depends on the top quark mass and top quark width, and on the strong coupling constant and Yukawa coupling

4% (stat.) ⊕ 20% (theo.)

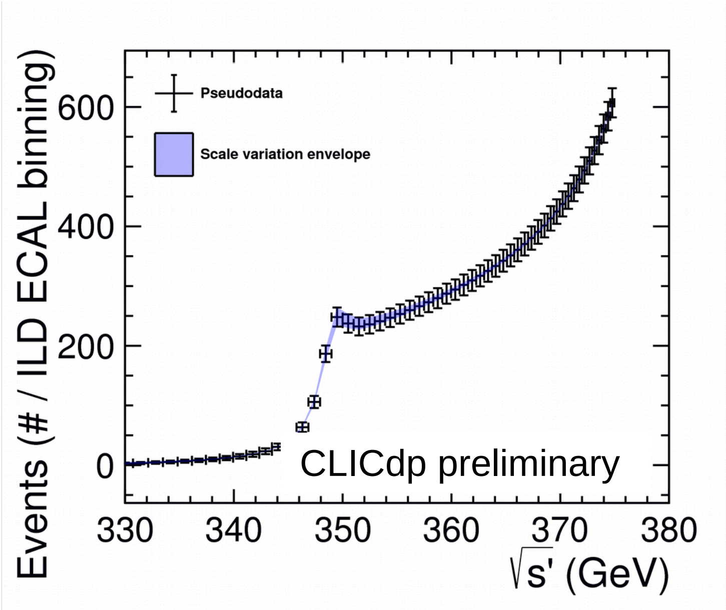


Top quark mass: alternatives

LHC style "direct reconstruction"
Understand MC mass post-hoc



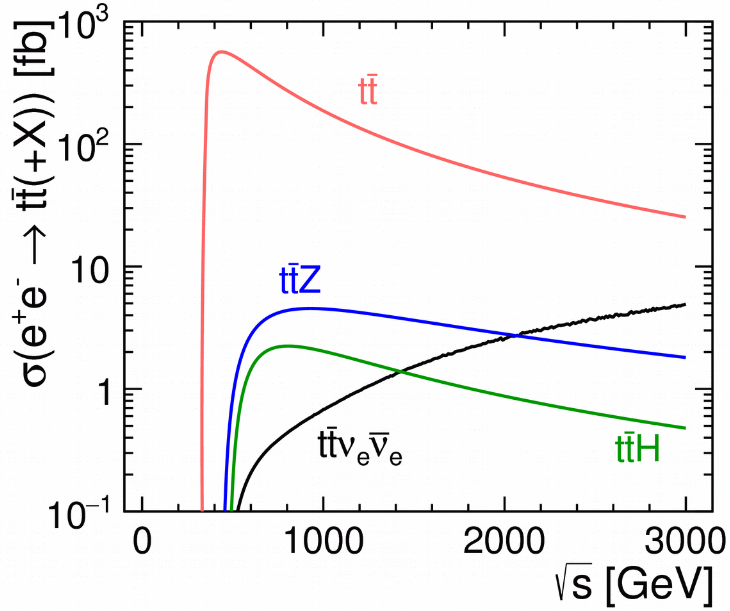
Radiative events: "return-to-threshold"
Access to the running of the mass



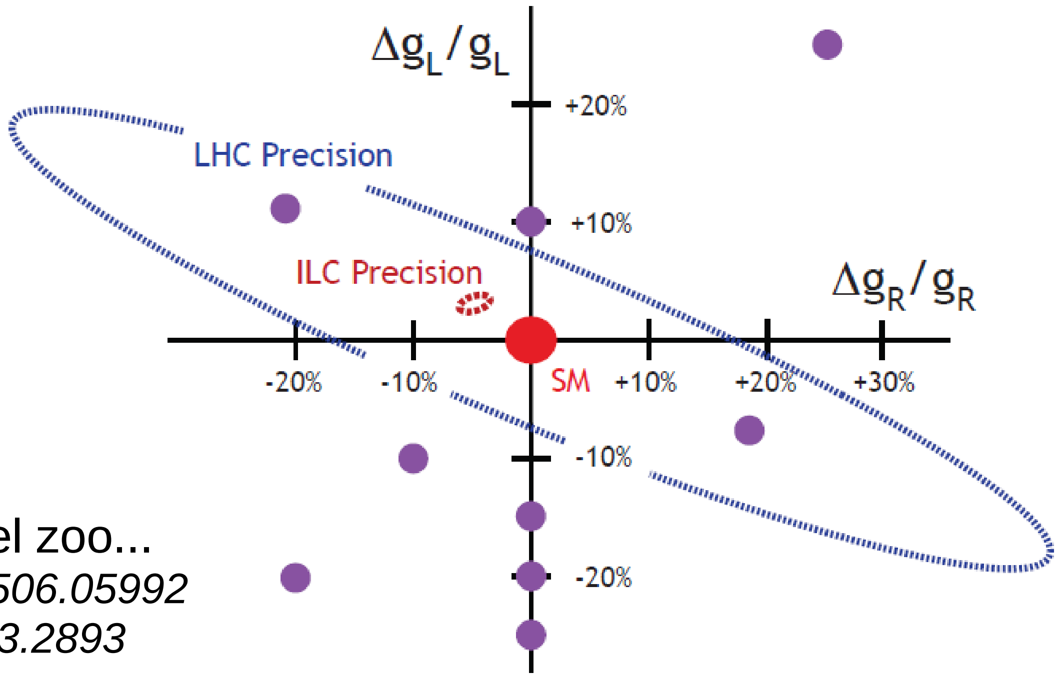
There are (at least) two further ways to determine the top quark mass with ~100 MeV statistical precision using the 380 GeV data

Potential of the high-energy run remains to be explored (see hep-ph/0703207)

Precision measurements of top EW couplings



BSM motiviation: strongly interacting high-scale physics predicts large deviations in $t\bar{t}Z$ coupling

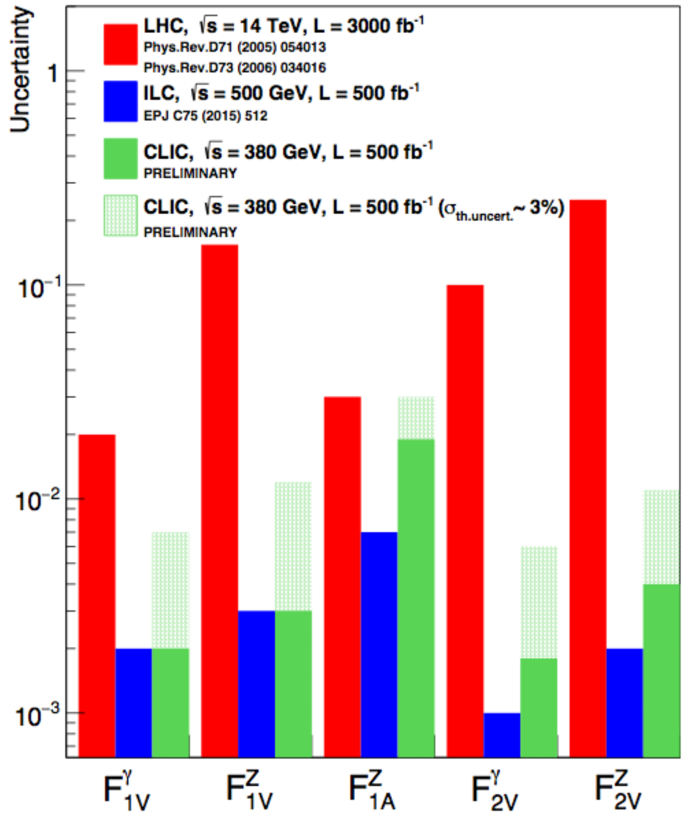


Scatter plot of the model zoo...
ILC Physics case, arXiv:1506.05992
Richard/Wulzer, arXiv:1403.2893

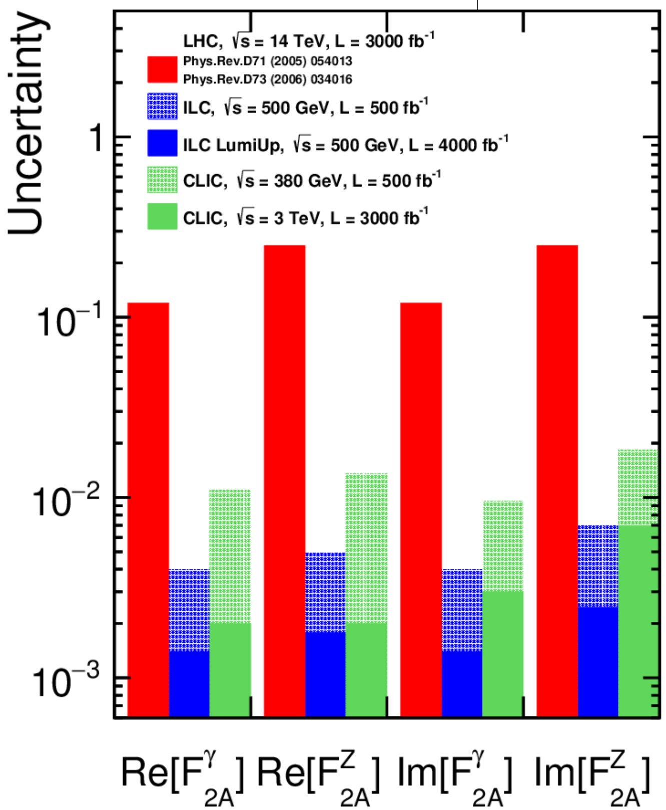
Top anomalous couplings

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

CLIC staging, CERN-2016-004
based on arXiv:1505.06020



arXiv:1710.06737



For FCCee perspective, see
P. Janot, arXiv:1503.01325

Measurements in pair production in early stage have excellent BSM sensitivity

Effective field theory

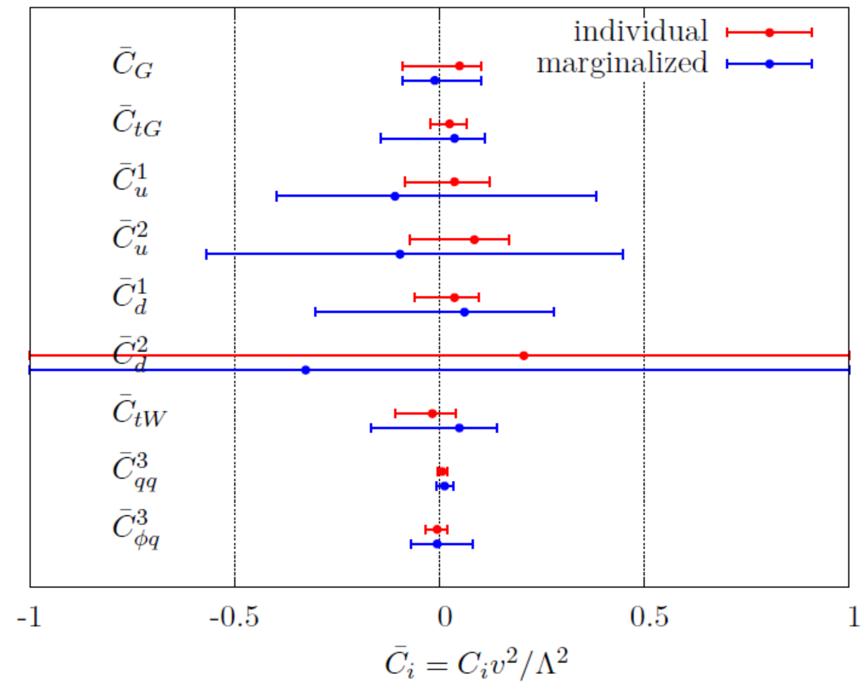
Extend SM Lagrangian with D6 operators. Effect suppressed by new physics scale Λ

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

(represents any high-scale NP compatible with gauge invariance)

9-parameter fit to Tevatron + LHC top data yields first, weak constraints
arXiv:1506.08845, arXiv:1512.03360

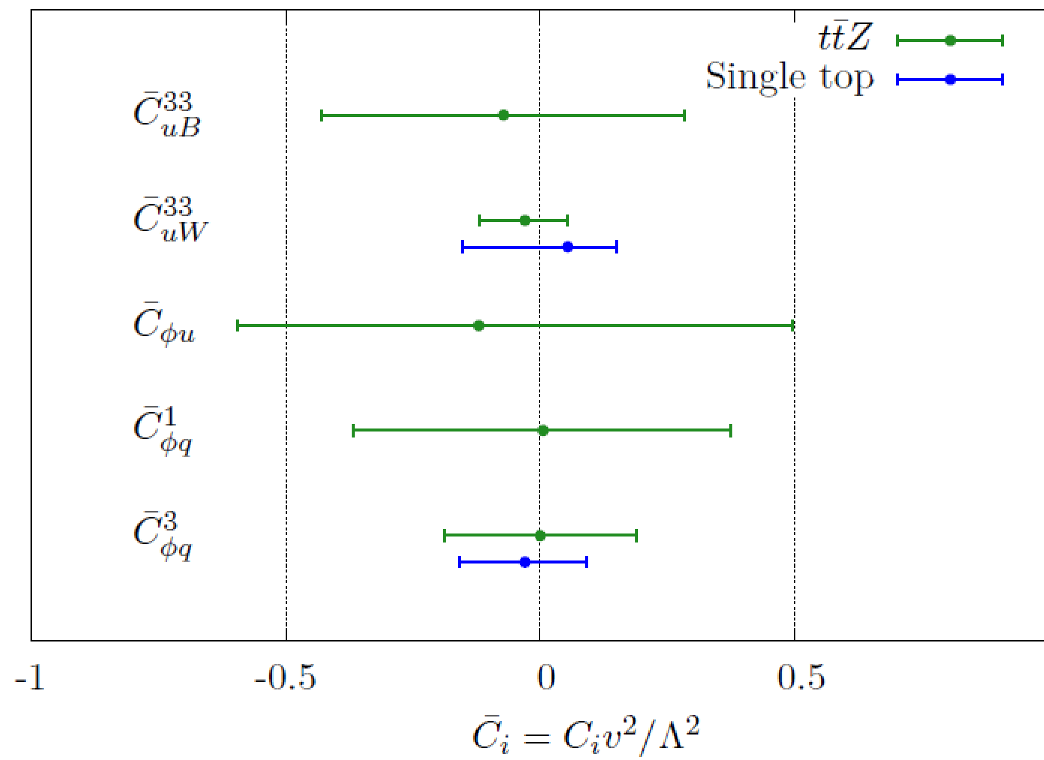
Top-philic scenario (arXiv:1802.07237): focus on operators that emerge from the direct BSM coupling to the top-quark fields q = $\{t_L, b_L\}$ and t = t_R.



Top EW couplings at LHC

Top EW couplings are accessible in several ways at hadron colliders:
- *single top production, associated ttZ/ttγ/ttW production, top decay*
- *$f\bar{f} \rightarrow Z/\gamma \rightarrow t\bar{t}$ swamped at the LHC (but dominant channel at lepton colliders)*

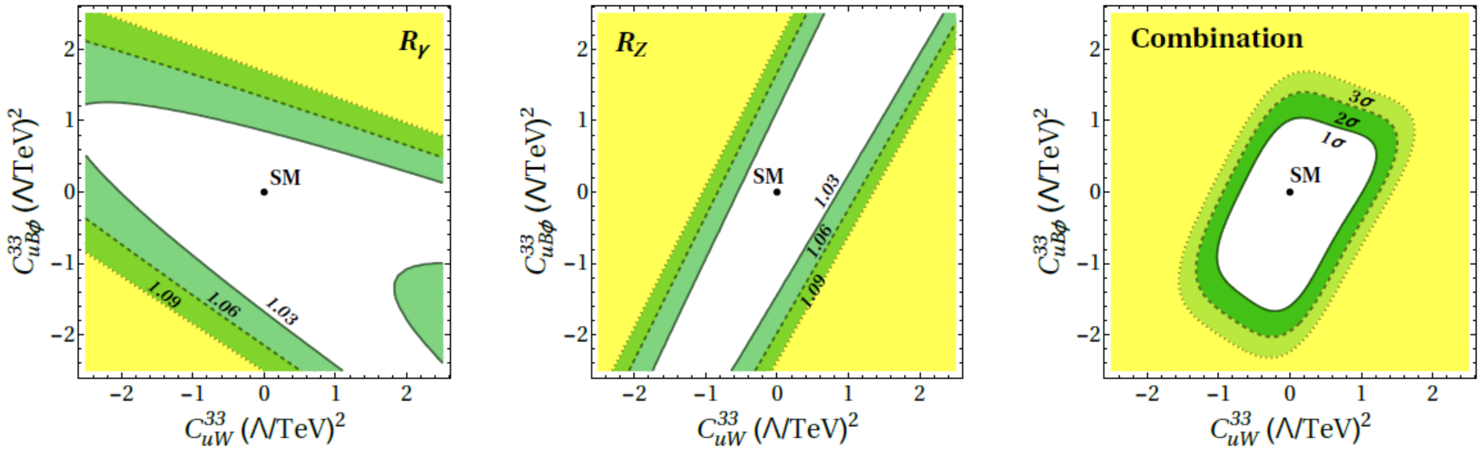
Simultaneous fit to Tevatron and LHC yields first (rather poor) constraints
arXiv:1506.08845, arXiv:1512.03360



Associated production at 100 TeV

Analyses of still "rare" processes to profit most from increase in rate.

Cross-section at $\sqrt{s}$ = *100 TeV*	$t\bar{t}$	$t\bar{t}t\bar{t}$	$t\bar{t}W^{\pm}$	$t\bar{t}Z^0$	$t\bar{t}WW$	$t\bar{t}W^{\pm}Z$	$t\bar{t}ZZ$
σ(pb)	$3.2 \cdot 10^4$	4.9	16.8	56.3	1.1	0.17	0.16



Expect rapid improvement at LHC, HL-LHC, FCC

Rontsch & Schulze, arXiv:1501.05939
Schulze & Soreq, arXiv:1603.08911

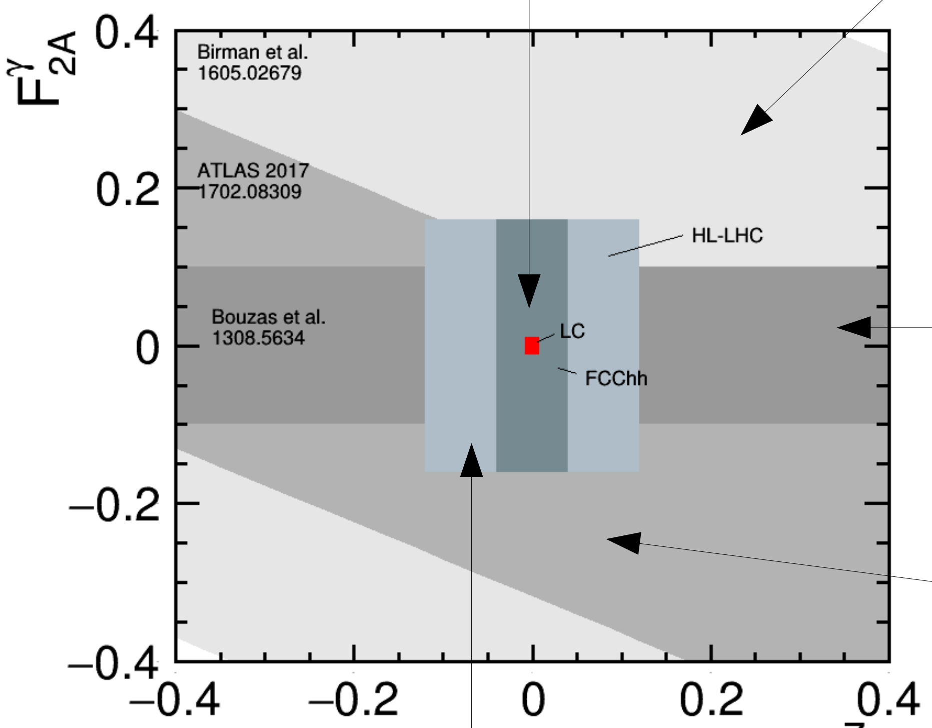
arXiv:1607.01831

	$C_{1,V}$	$C_{1,A}$	$C_{2,V}$	$C_{2,A}$
SM value	0.24	-0.60	< 0.001	$\ll 0.001$
13 TeV, 3 ab^{-1}	$[-0.4, +0.5]$	$[-0.5, -0.7]$	$[-0.08, +0.08]$	$[-0.08, +0.08]$
100 TeV, 10 ab^{-1}	$[+0.2, +0.28]$	$[-0.63, -0.57]$	$[-0.02, +0.02]$	$[-0.02, +0.02]$

Many directions to approach the same problem

$e^+e^- \rightarrow t\bar{t}$

Top decay $t \rightarrow Wb$



ep collider
single top + photo-prod

Single top production

F^{Z}_{2A} **= f(Im(C_{tW}), Im(C_{tB}))**

Associated production: $pp \rightarrow t\bar{t}Z$

Current and future constraints from different processes and colliders on CP violating electric dipole moments of the top quark

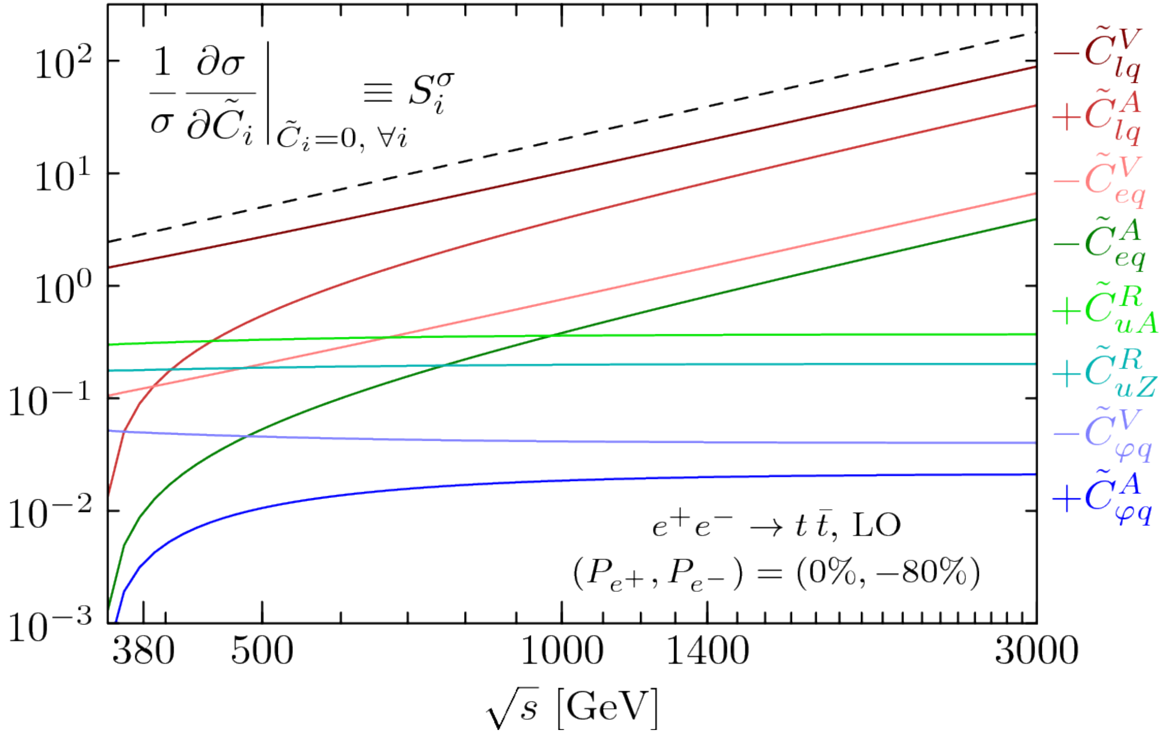
The impact of center-of-mass energy

Low-energy operation:

high-precision constraints on two-fermion operators

High-energy operation:

quadratic increase in sensitivity to four-fermion operator coefficients

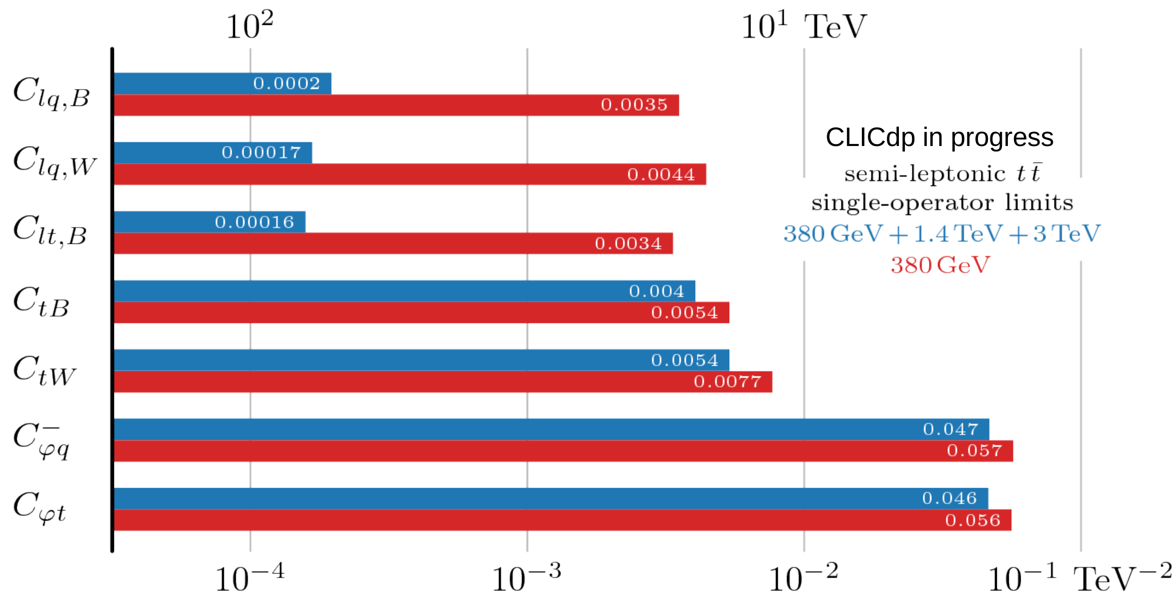


Durieux, Perelló, Vos, Zhang

EFT fit

High-energy runs are crucial to constrain the four-fermion operators

Operator:	Sensitivity:
4-fermion	$S \propto E^2$
dipole	$S \propto E$
2-fermion	$S = c$

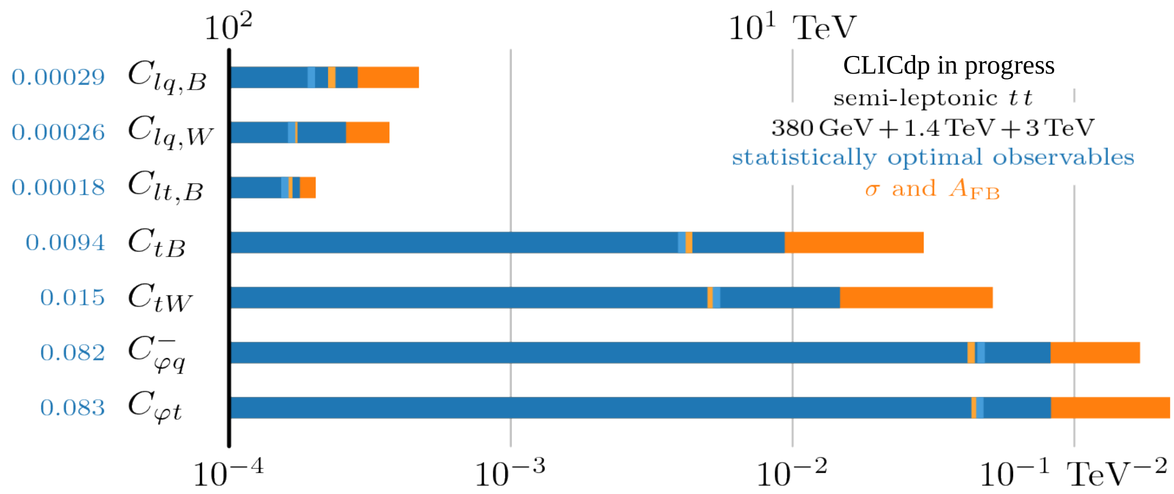


An excellent global fit of all relevant D6 operators requires at least two energy points and beam polarization

Global EFT fit

Global 7-parameter fit

two observables ⊗ three c-o-m energies ⊗ two polarizations = robust limits



Optimal observables are designed to constrain all directions in parameter space
→ improve limits by a factor 1.1-3.2 wrt classical cross-section and A_{FB}

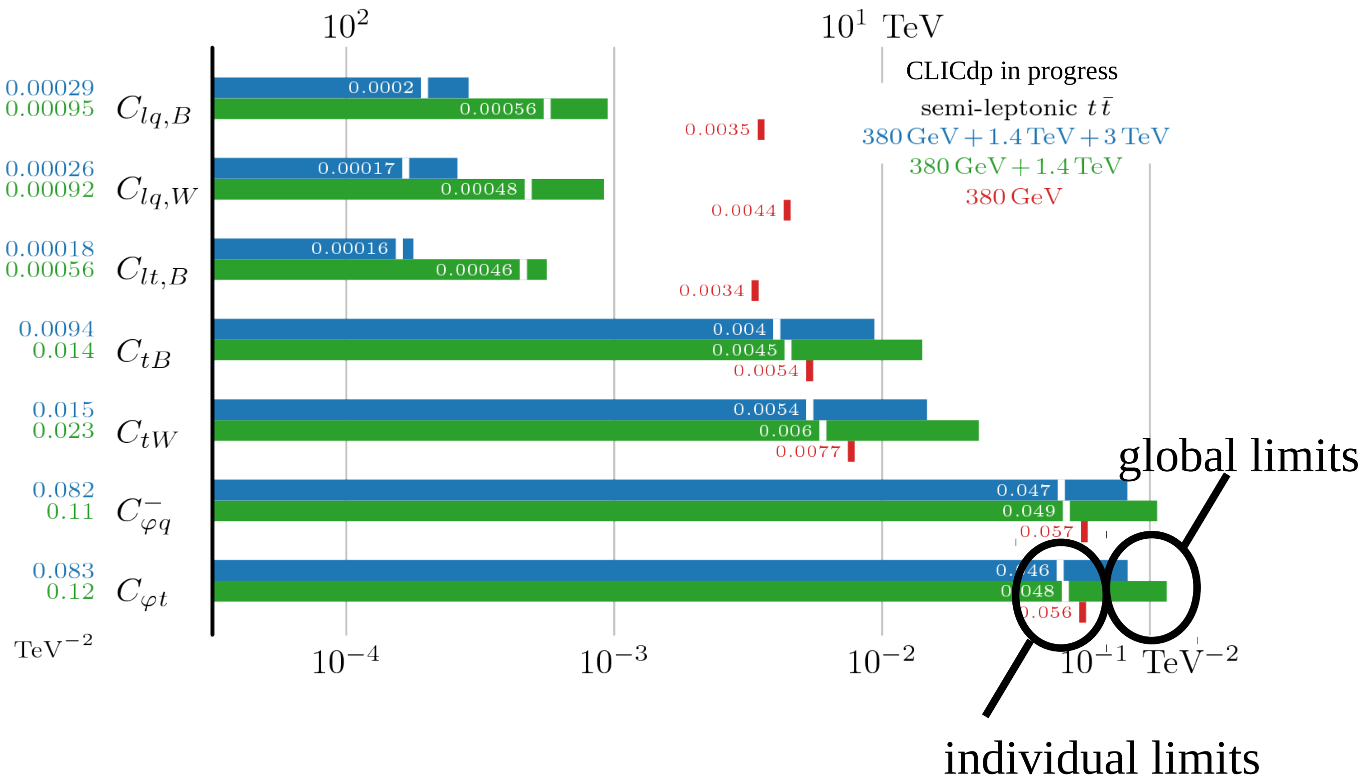
Global EFT fit

Global 7-parameter fit – top-philic scenario

380GeV+1.4TeV+3TeV
(indiv. + global limits)

380GeV+1.4TeV
(indiv. + global limits)

380 GeV
(individual limits only)



CLIC top physics program provides tight constraints on all 7 coefficients

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

Excellent limits on 4-fermion and dipole moment operators!

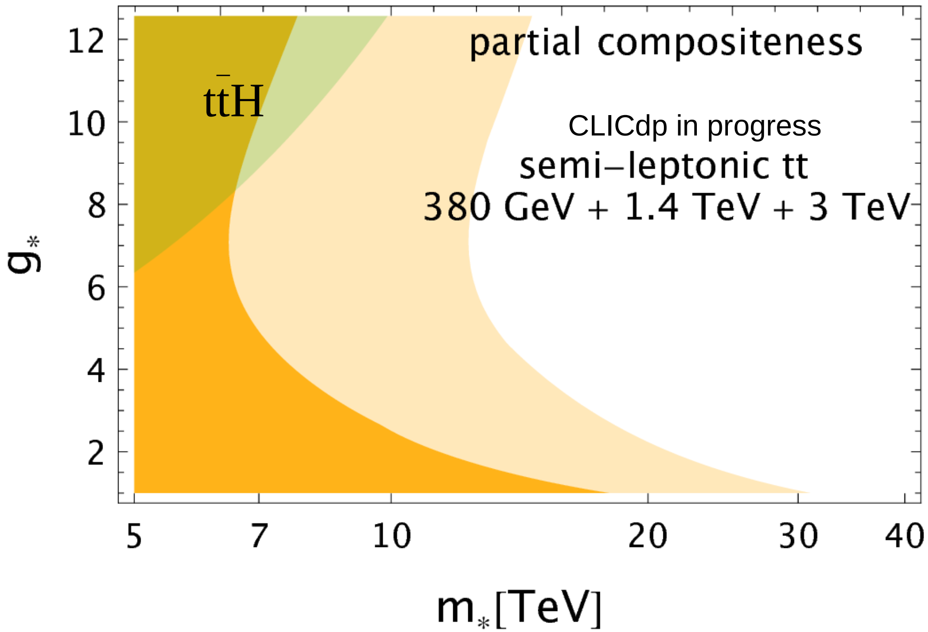
From EFT to concrete scenario

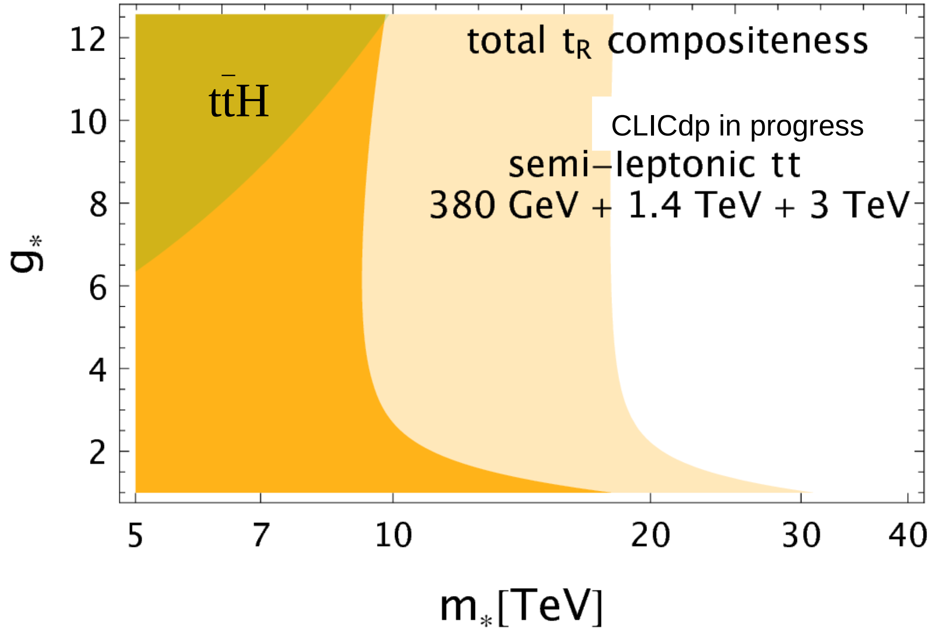
Re-express EFT constraints as limits on the canonical composite Higgs scenario, characterized by a coupling strength g_* and NP scale m_* (*Giudice 2007*)

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

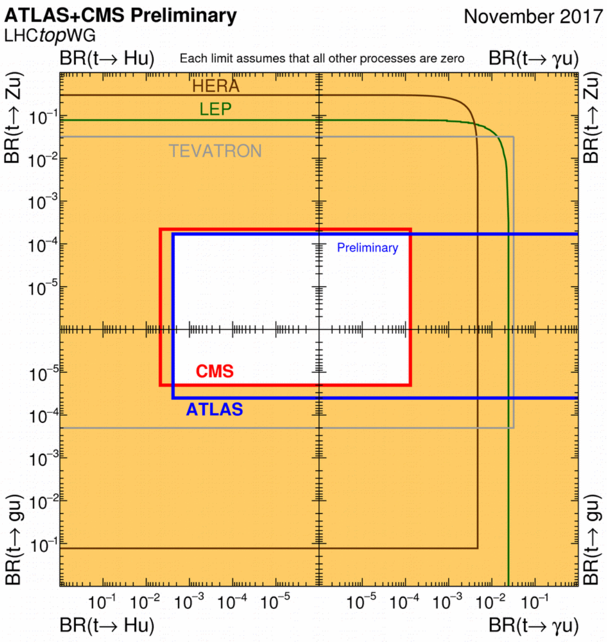
Benchmarks: partial (t_L and t_R composite) & total (t_R maximally composite)

Pessimistic 5σ discovery contours reach 7-15 TeV, in favourable cases > 20 TeV



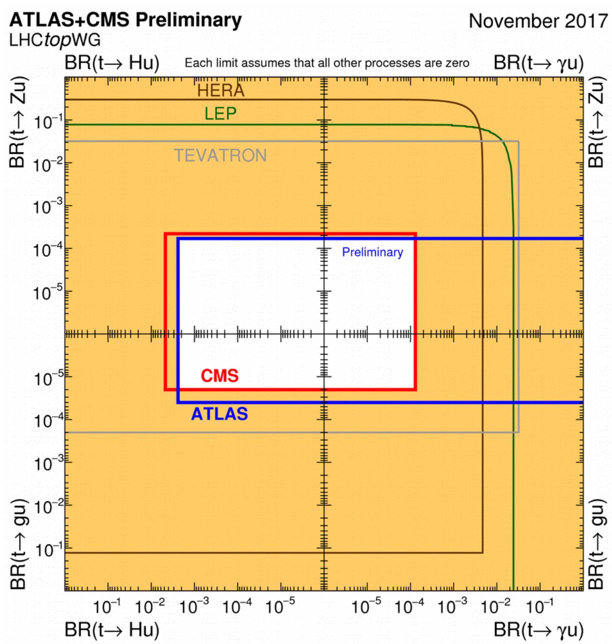


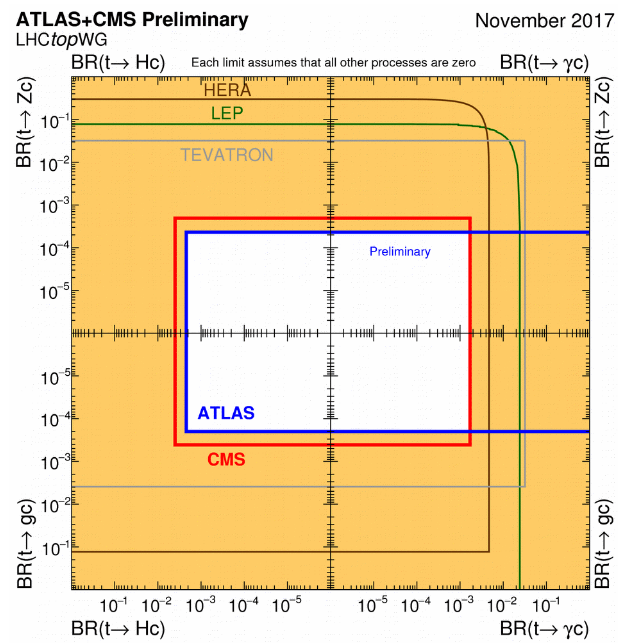
FCNC top interactions



Top FCNC decays

- Highly suppressed in the SM, possibly enhanced by New Physics
- LHC produces millions of tops → BR to improve to 10^{-4} – 10^{-5} level

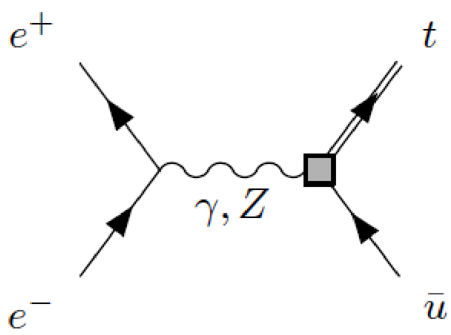




- What can a lepton collider do after the LHC is done?

Top FCNC interactions at CLIC

Lepton colliders may provide complementary constraints



$e^+e^- \rightarrow tj$ limits from LEP2 in arXiv:1412.7166

Integrated luminosity	Branching ratio	240 GeV	350 GeV	500 GeV
300 fb^{-1}	$Br(t \to q\gamma)$	1.23×10^{-4}	3.43×10^{-5}	2.45×10^{-5}
	$Br(t \to qZ)$ $(\sigma_{\mu\nu})$	1.50×10^{-4}	4.97×10^{-5}	3.94×10^{-5}
	$Br(t \to qZ)$ (γ_μ)	3.06×10^{-4}	1.83×10^{-4}	2.67×10^{-4}
3 ab^{-1}	$Br(t \to q\gamma)$	3.70×10^{-5}	9.86×10^{-6}	6.76×10^{-6}
	$Br(t \to qZ)$ $(\sigma_{\mu\nu})$	4.50×10^{-5}	1.41×10^{-5}	1.09×10^{-5}
	$Br(t \to qZ)$ (γ_μ)	9.25×10^{-5}	5.27×10^{-5}	7.49×10^{-4}
10 ab^{-1}	$Br(t \to q\gamma)$	2.01×10^{-5}	5.25×10^{-6}	3.59×10^{-6}
	$Br(t \to qZ)$ $(\sigma_{\mu\nu})$	2.44×10^{-5}	7.60×10^{-6}	5.85×10^{-6}
	$Br(t \to qZ)$ (γ_μ)	5.02×10^{-5}	2.83×10^{-5}	4.00×10^{-5}

H. Khanpour et al., Single top quark production as a probe of anomalous tqγ and tqZ couplings at the FCC-ee , arXiv:1408.2090 .

And can be competitive in some decay channels

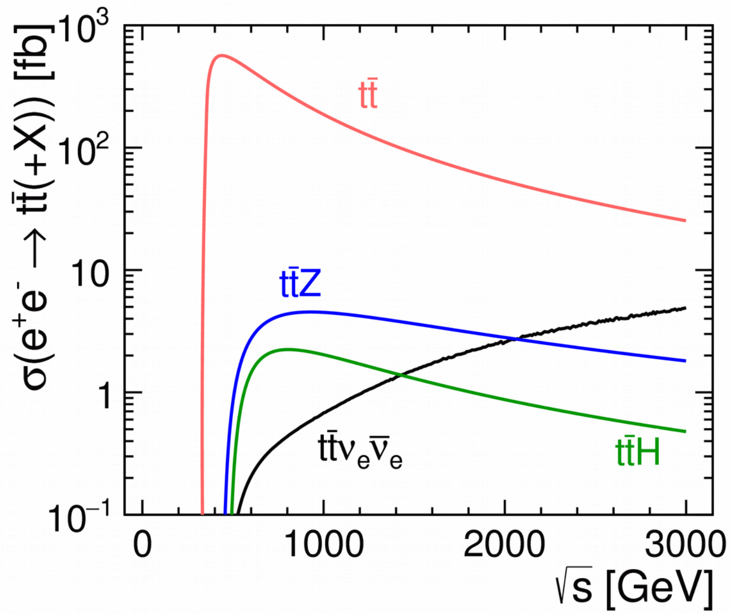
CLIC380 study, with focus on hardest cases: $t \rightarrow cH$, $t \rightarrow c\gamma$

- BR ($t \rightarrow c\gamma$) < 4.7×10^{-5} at 95% C.L.
- BR ($t \rightarrow cH$) x BR ($H \rightarrow b\bar{b}$) < 1.2×10^{-4} at 95% C.L.

LC assets – excellent charm tagging and possibility to exploit $b\bar{b}$ final state – make up for smaller production rates and yield competitive limits

0.5(5) – 3 TeV:

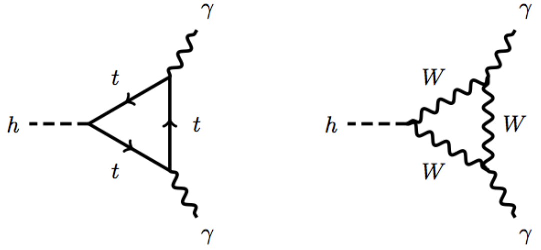
$t\bar{t}$+H production



Top Yukawa coupling

At the LHC the top quark Yukawa coupling is inferred from the observed gg → H and H → γγ rates.

Run I result: $k_t = 1.43 \pm 0.23$



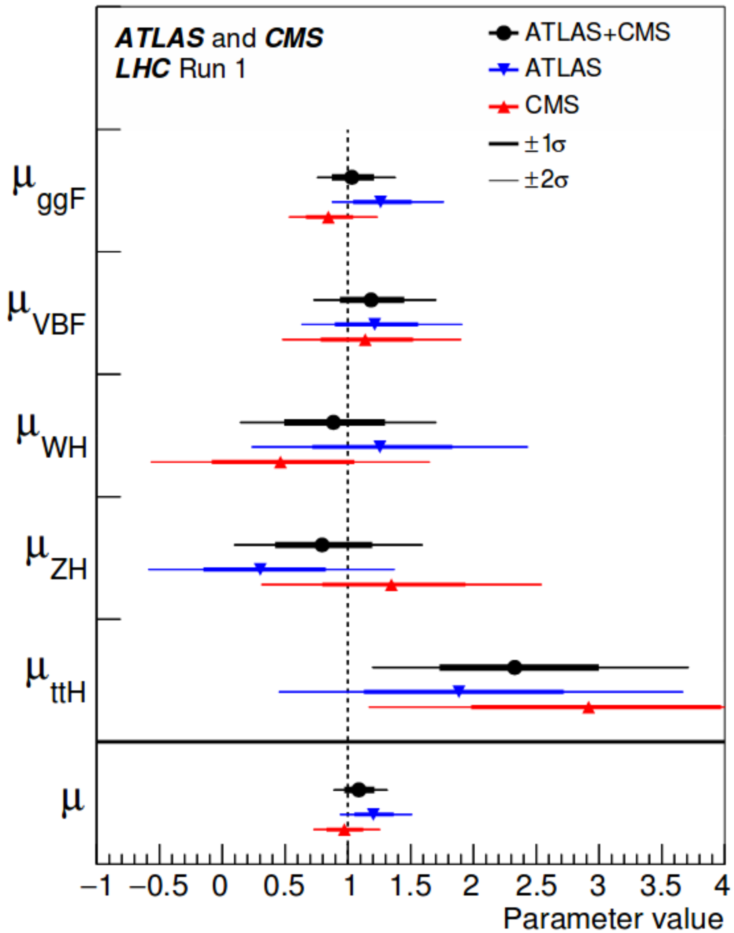
The top Yukawa coupling can be measured directly in associated ttH production.

Run I result: $\mu_{ttH} = 2.3 \pm 0.7$

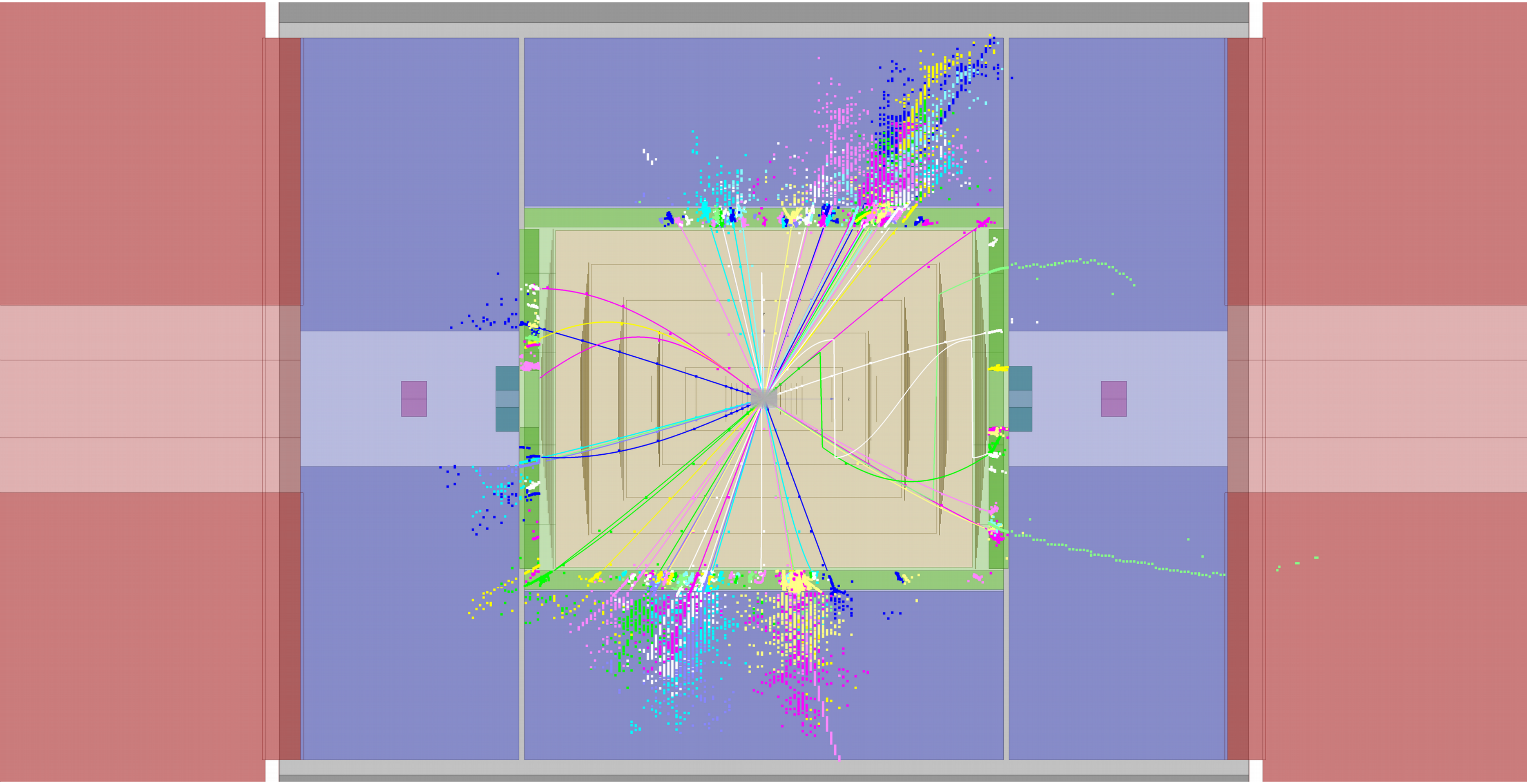
Prospects for full LHC programme:

K_u → 14-15% (300/fb)

K_u → 7-10% (3/ab) *Snowmass Higgs report*

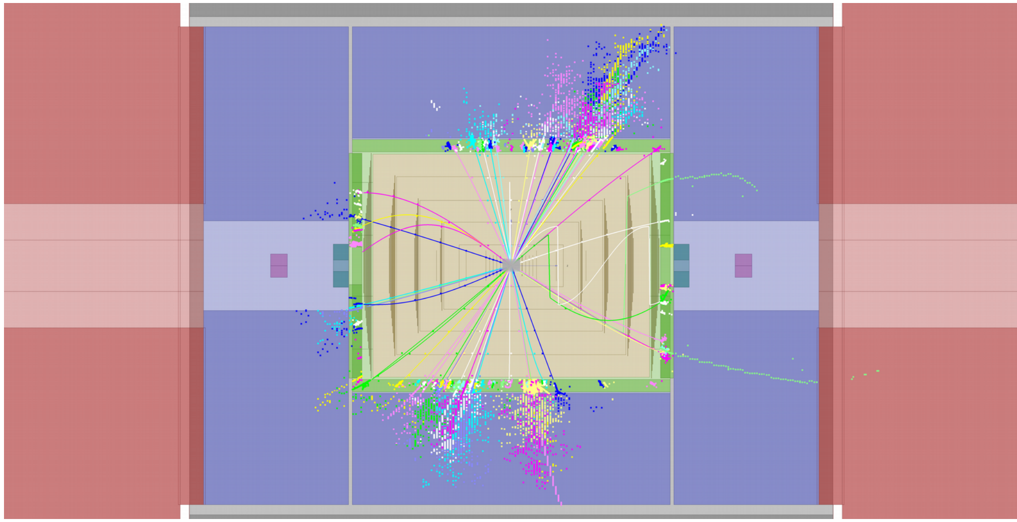


$t\bar{t}H$ production



Complex multi-jet events: $t\bar{t}H$, $H \rightarrow b\bar{b}$
0 leptons $\rightarrow$ 8 jets, 1 lepton $\rightarrow$ 6 jets

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:1608.07538*

FCChh target: 1% precision *arXiv:1507.08169*

Summary

The LC top physics program complements hadron colliders in important ways.

The precision of several key measurements exceeds the HL-LHC significantly:

- top mass measurement: **Δm_t ~ 50 MeV**

- FCNC interactions: **competitive for $t \rightarrow c\gamma$, $t \rightarrow ch$**

- top quark EW couplings: **improved by order of magnitude**

- the determination of the **top Yukawa coupling to 3-4%**

With this precision, these measurements have the potential answer important questions,

hopefully offering guidance towards a more complete theory