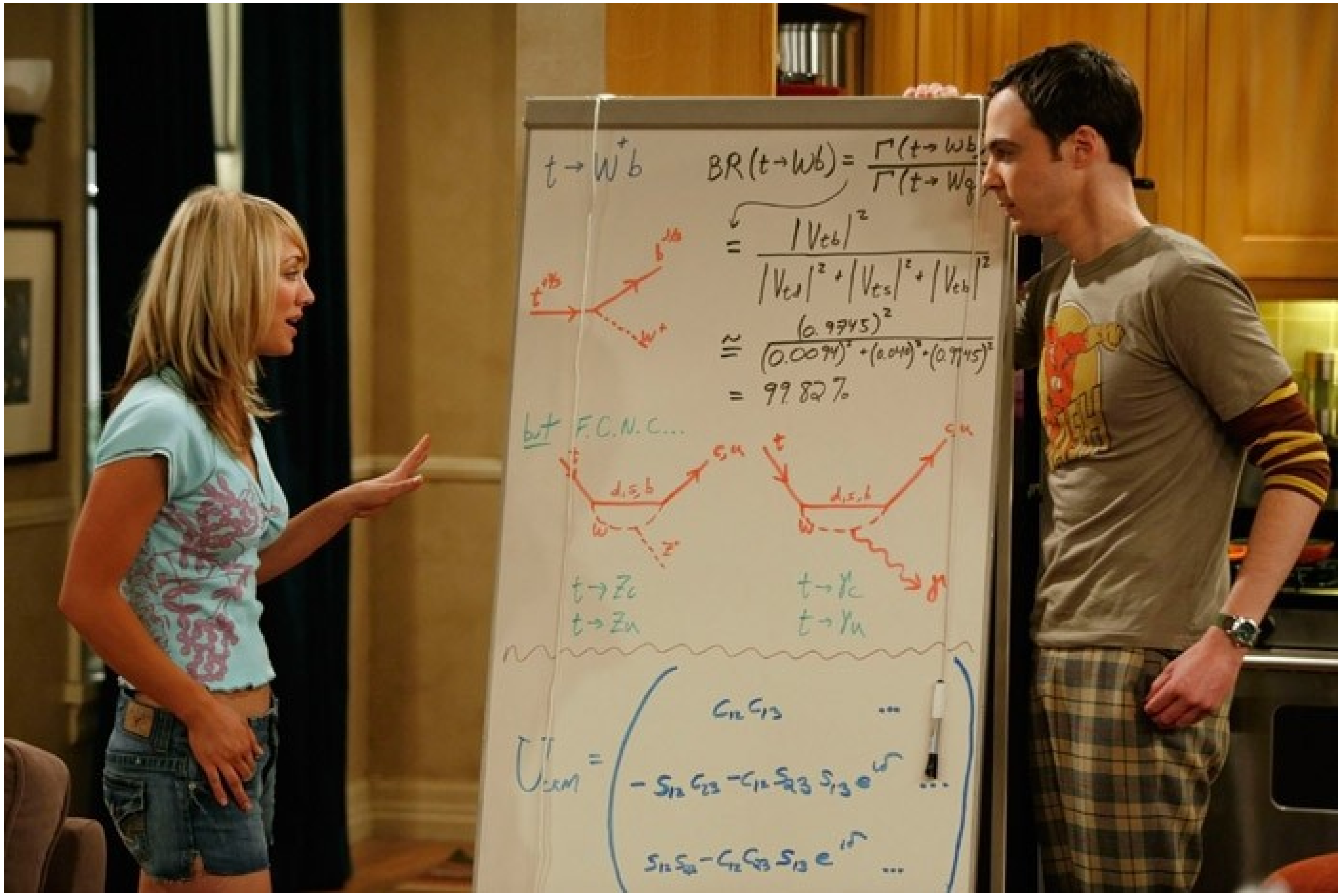
Top physics at CLIC

Marcel Vos

IFIC (UVEG/CSIC) Spain

on behalf of the CLICdp collaboration

At a bit over twenty…



… top continues to baffle the best minds on the planet

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 CLIC top physics program can answer:

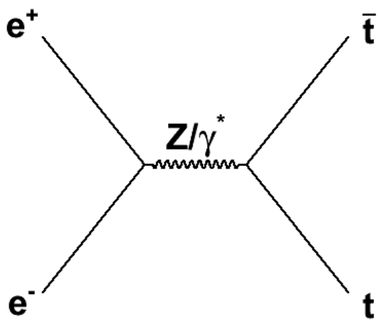
Is the SM internally consistent?
Top mass: a key parameter of the EW fit and extrapolation of EW vacuum to high scales.

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

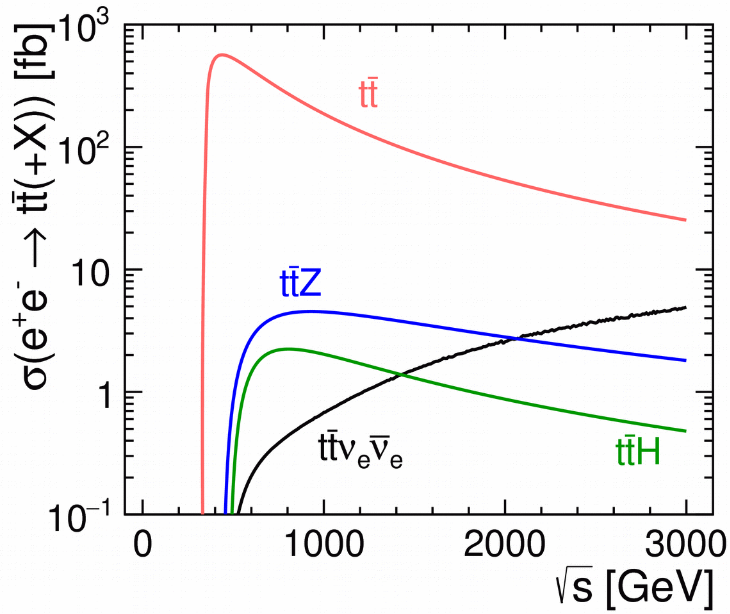
What's behind the hierarchy of fermion masses?
Top Yukawa: one of the key measurements in HEP

The next collider must be able to transform HEP. CLIC precision top physics 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 CLIC



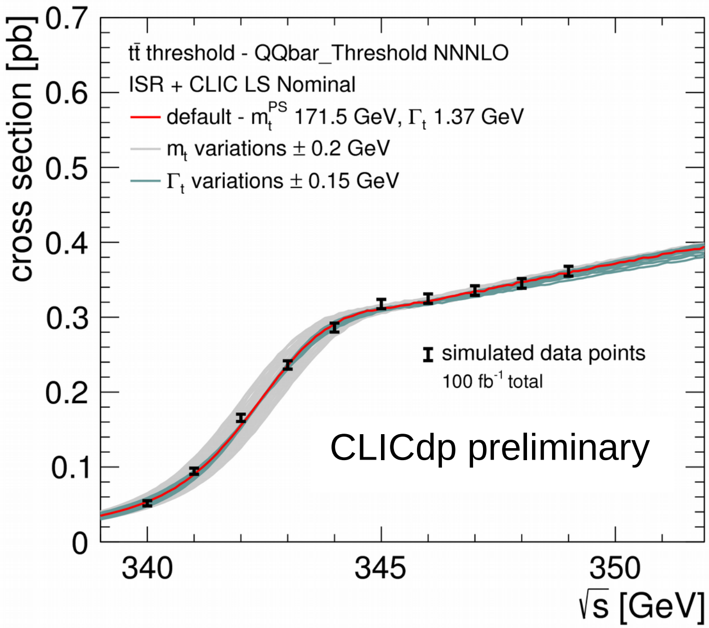
Pair production provides direct access to $Zt\bar{t}$, $\gamma t\bar{t}$ vertices



- 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

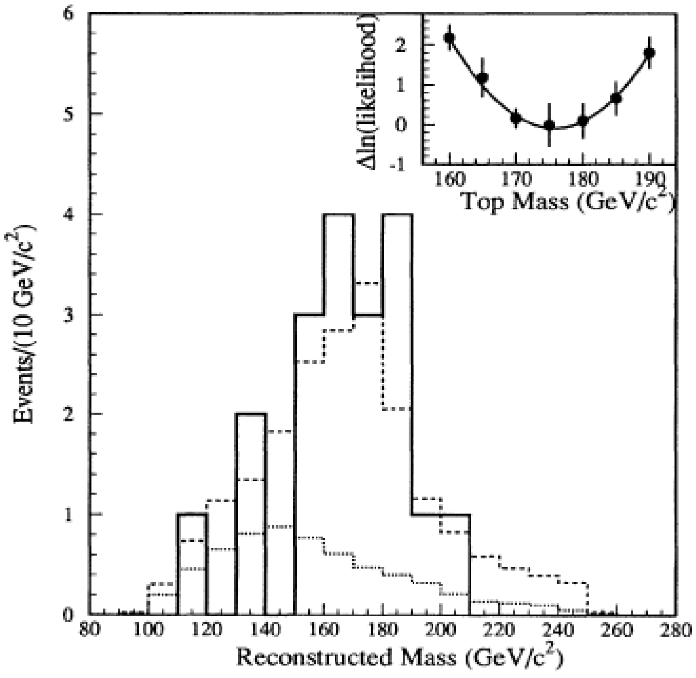
Calculability is a real asset of e^+e^- colliders. QCD corrections are tiny; rates can often be predicted with sub-% precision already today.

CLIC initial stage:
threshold scan



The top quark mass

The only quark whose mass can be determined directly

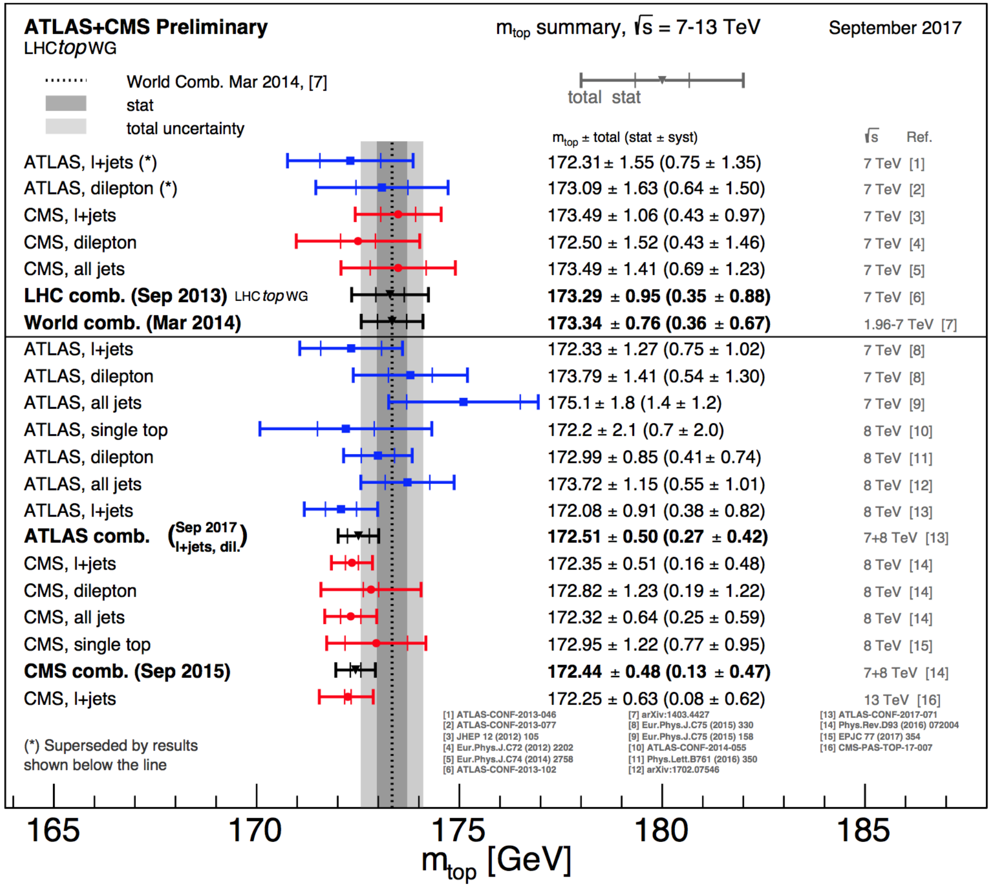


Reconstructed top quark mass distribution at the Tevatron

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

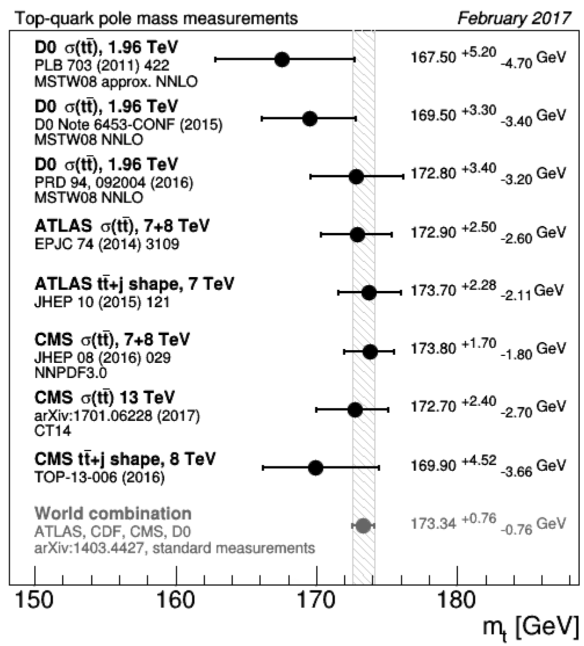
LHC + Tevatron today:

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)

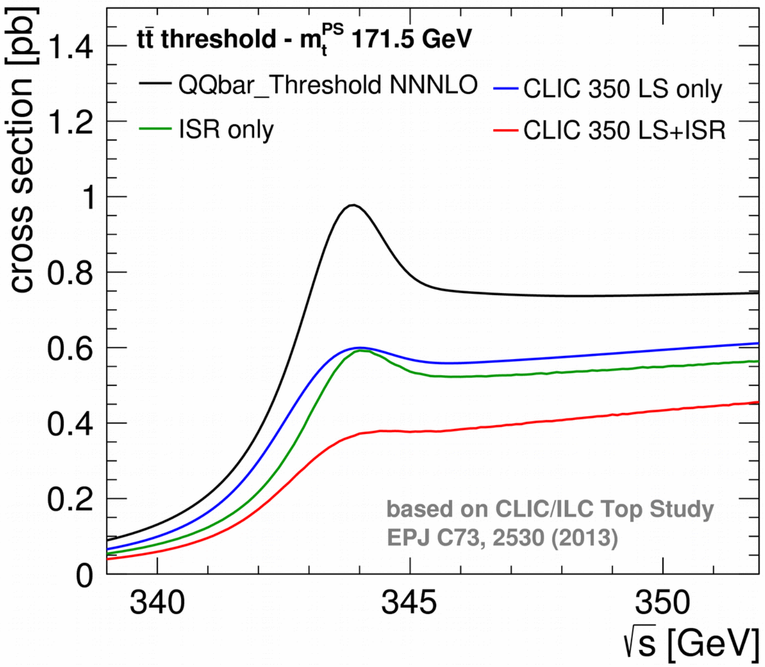


Threshold scan: theory

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

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



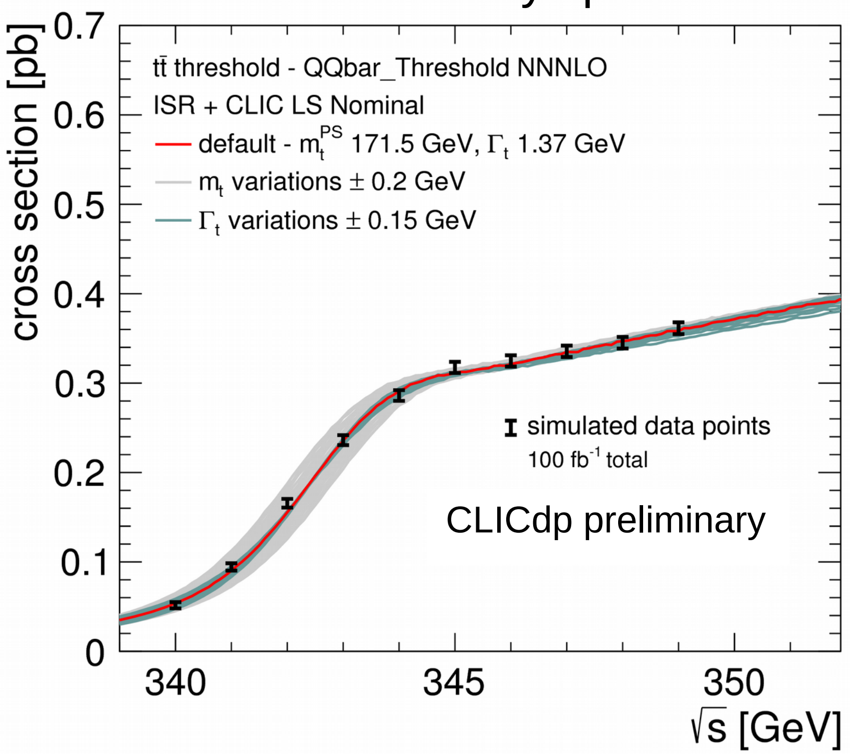
We can study this in detail thanks to tremendous work by theorists, right from the initial idea (Kuhn, 1981!) to today's sophisticated calculations (Beneke et al., Hoang et al., Marquard et al.)

Threshold scan: experiment

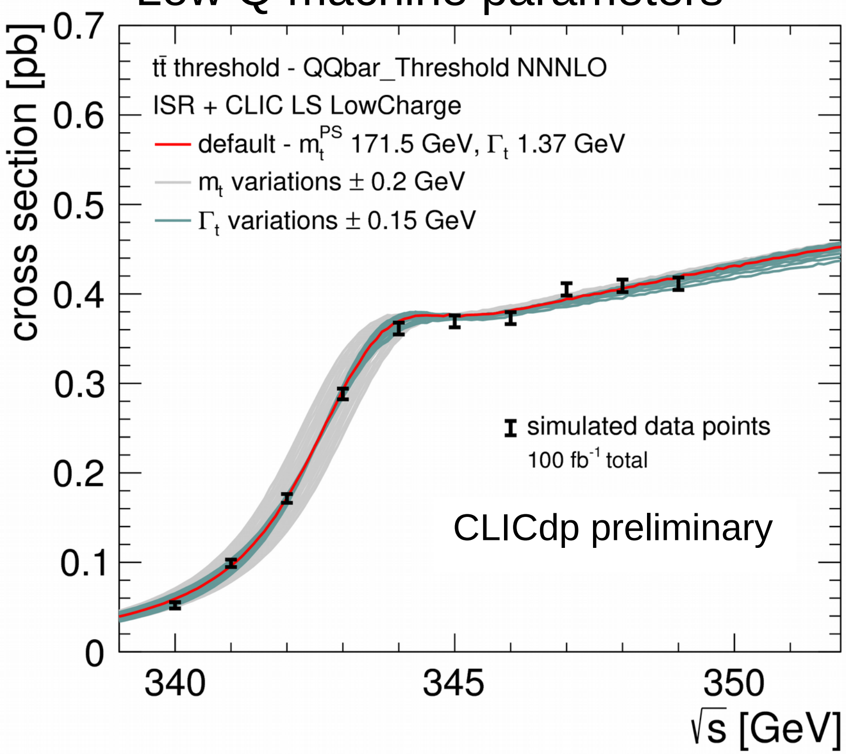
Detailed estimates of the precision in multi-parameter fits

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

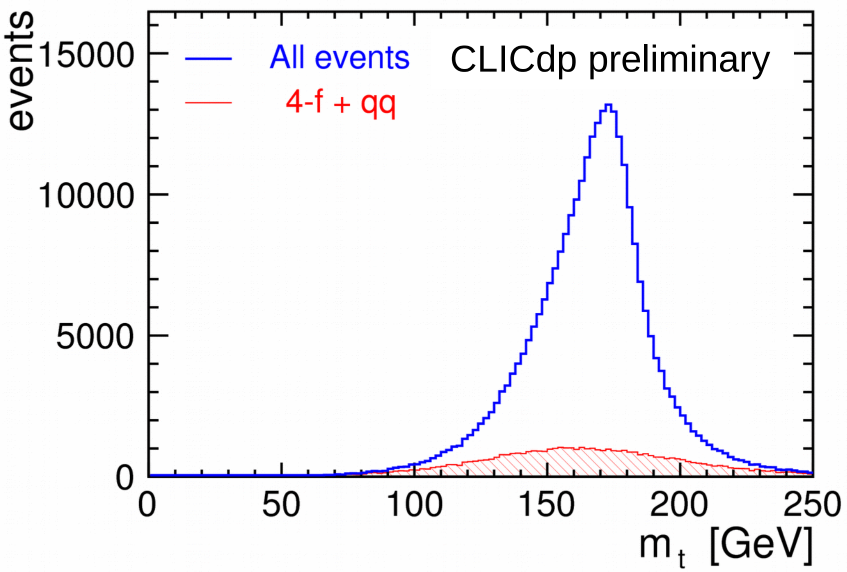
A very competitive top quark mass measurement:

Δm_t ~ 50 MeV *(= 3 x* 10^{-4}*, cf.* Δm_b *~1%)*

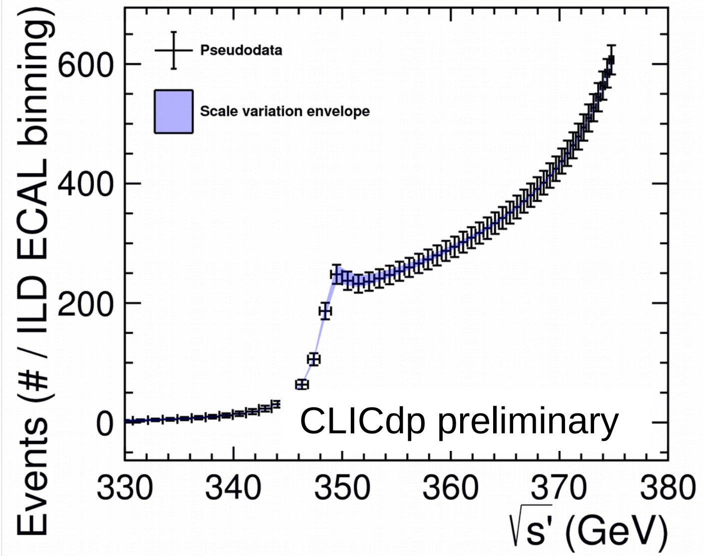
This is a real prospect, not a target! Build the machine and we perform the measurement.

Top quark mass: alternatives

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



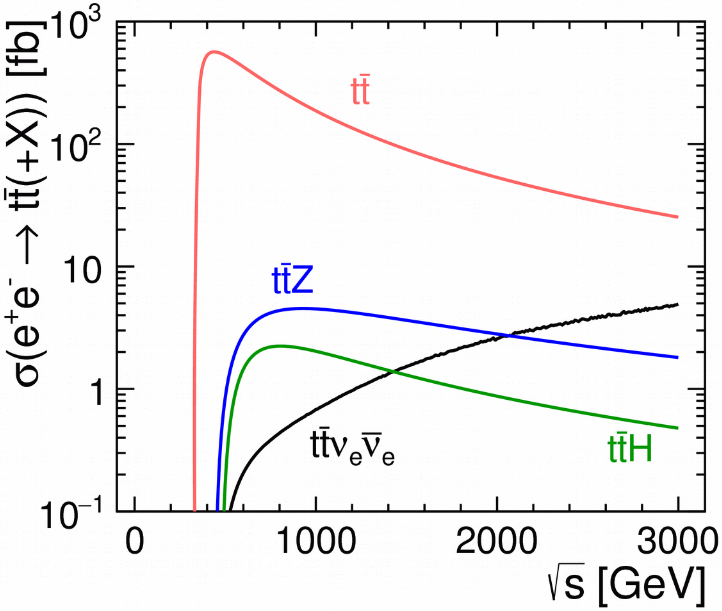
Radiative events: "return-to-threshold"
Access to the running of the mass



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)

CLIC initial stage:
precision at 380 GeV



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

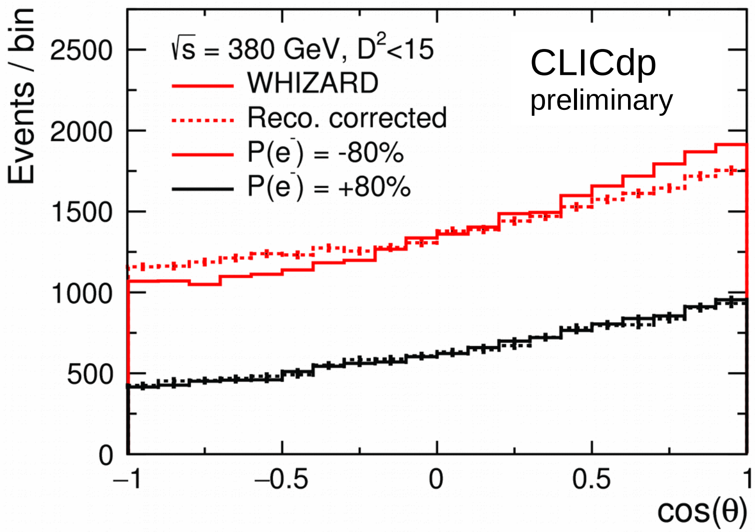
Easily isolated by requiring isolated lepton + b-tagging:

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

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:

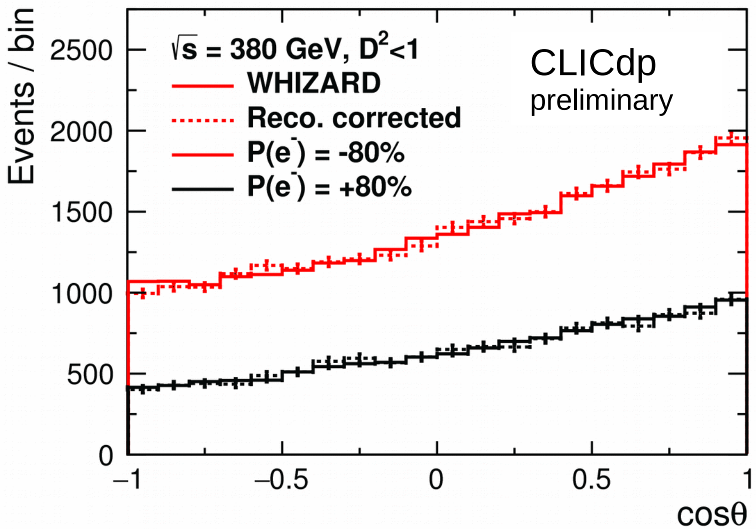
Efficiency ~ 70%

Purity > 80%

Top reconstruction is affected by ambiguity in W-b pairing

Migrations are mitigated by quality requirements

Purity increases further

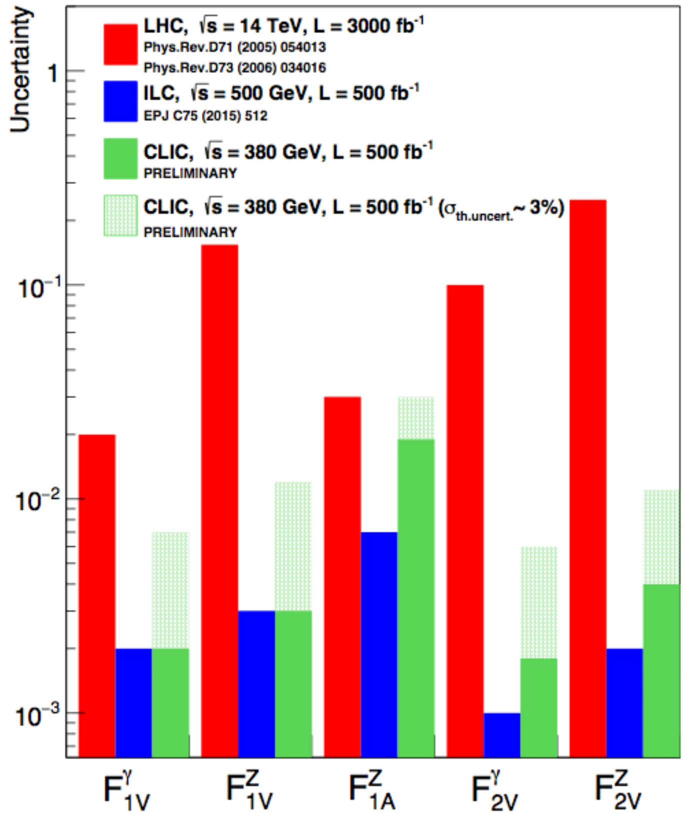


Techniques and analysis are likely to improve further

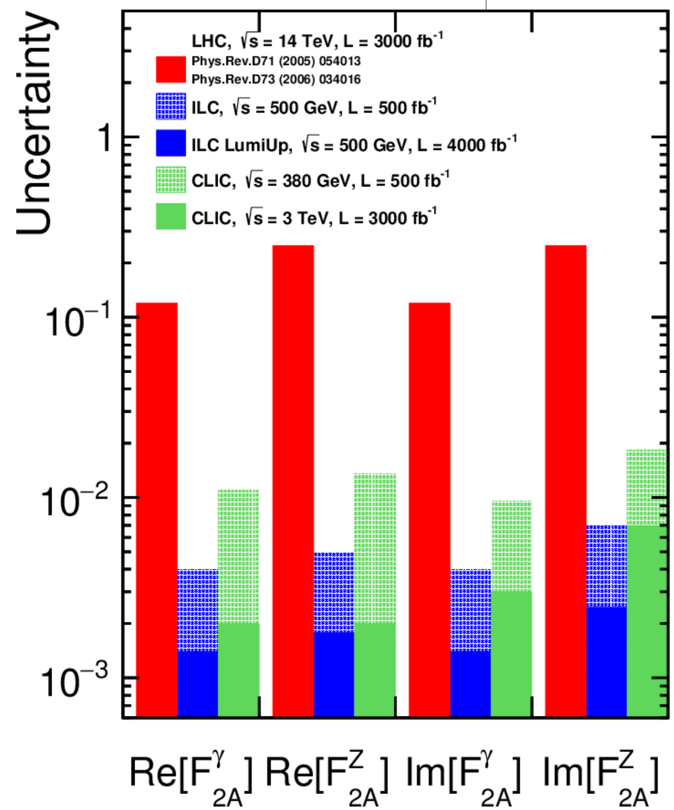
Top anomalous couplings

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

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



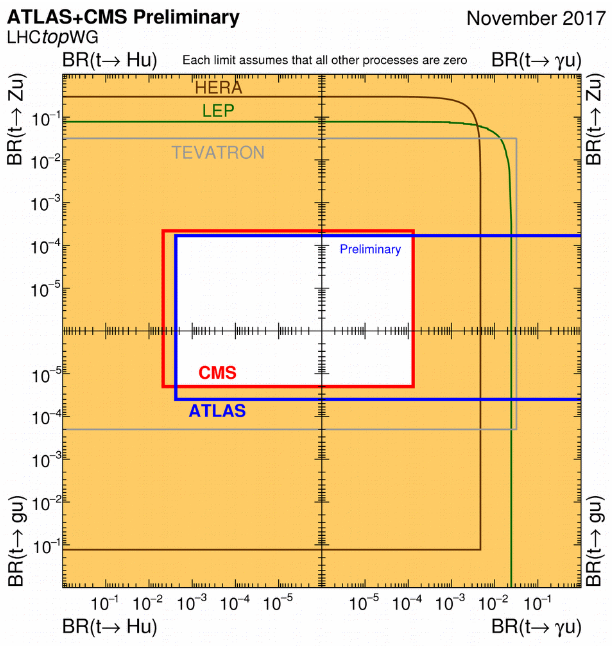
arXiv:1710.06737

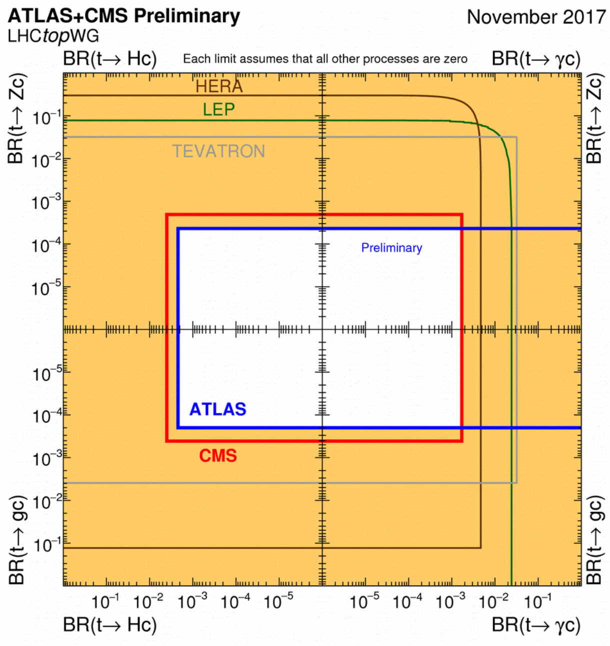


Measurements in pair production in early stage have excellent BSM sensitivity

Top FCNC decays

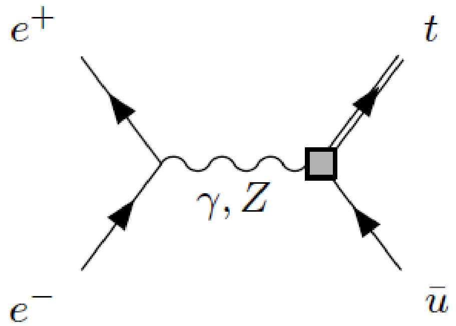
- Highly suppressed in the SM, possibly enhanced by New Physics
- LHC produces millions of tops → BR to improve to 10^{-4} – 10^{-5} level



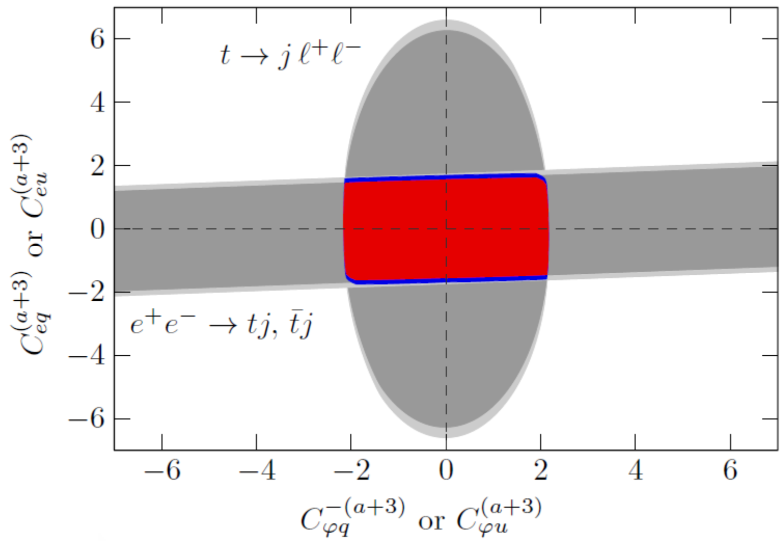


- What can a lepton collider do after the LHC is done?

Lepton colliders may provide complementary constraints



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



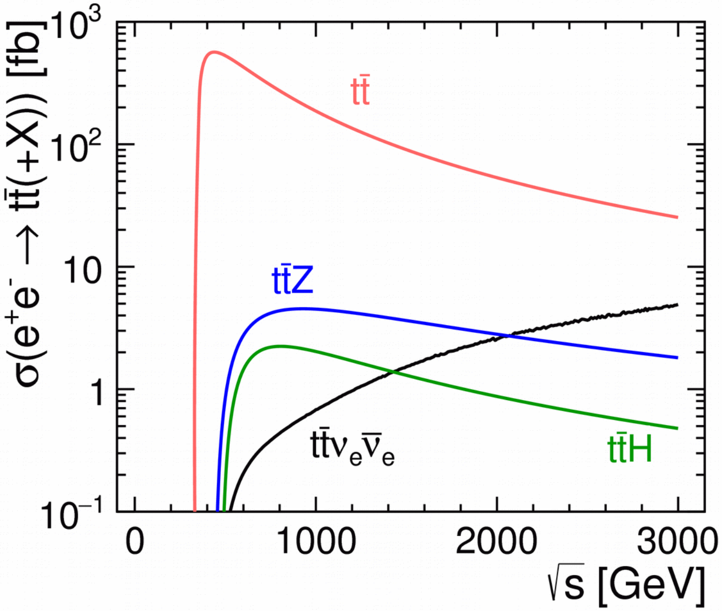
And can be competitive in some channels

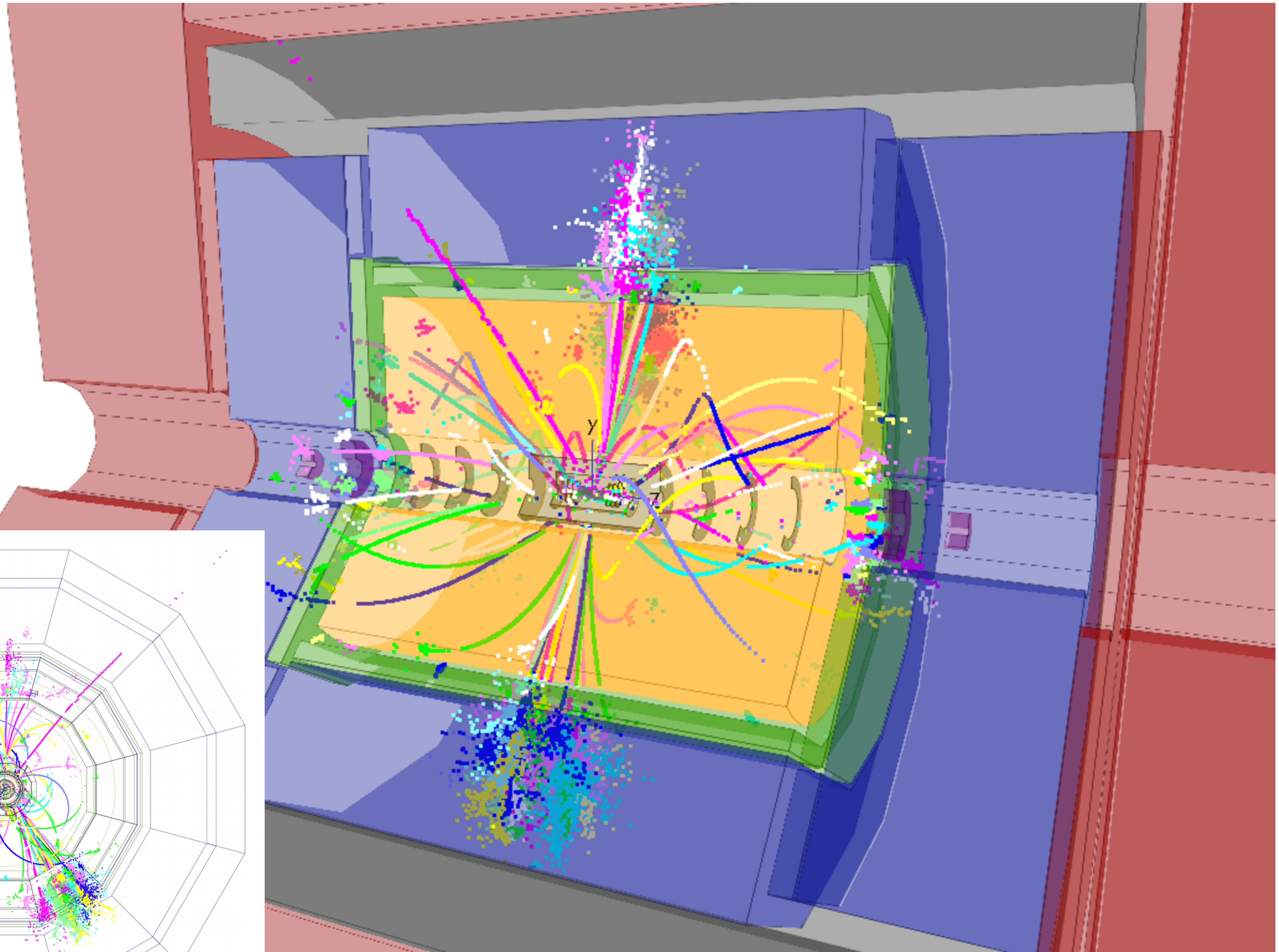
Focus on hardest cases: $t \rightarrow cH$, $t \rightarrow c\gamma$

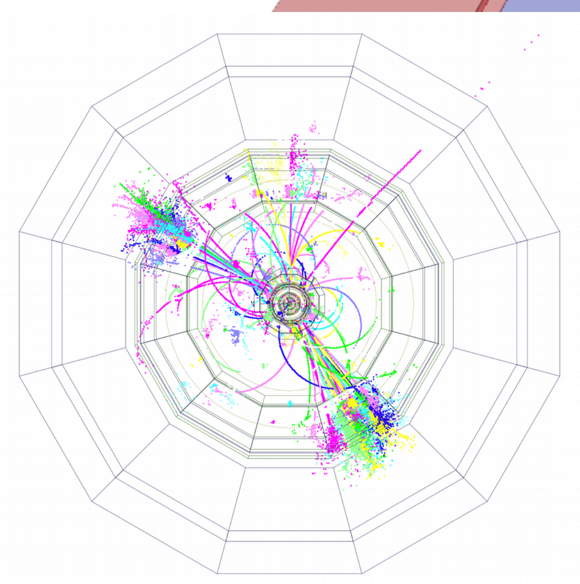
- BR ($t \rightarrow c\gamma$) < 4.7×10^{-5} at 95% C.L.
- BR ($t \rightarrow cH$) x BR ($H \rightarrow b\bar{b}$) < 1.2×10^{-4} at 95% C.L.

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

CLIC high energy:
$t\bar{t}$+X production & BSM sensitivity

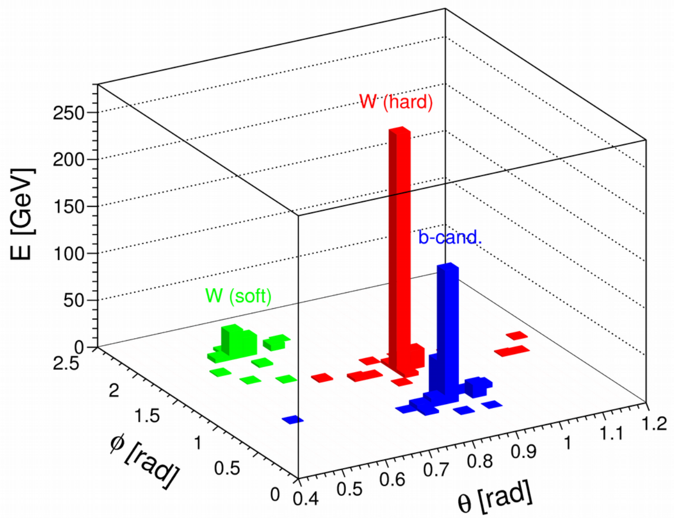


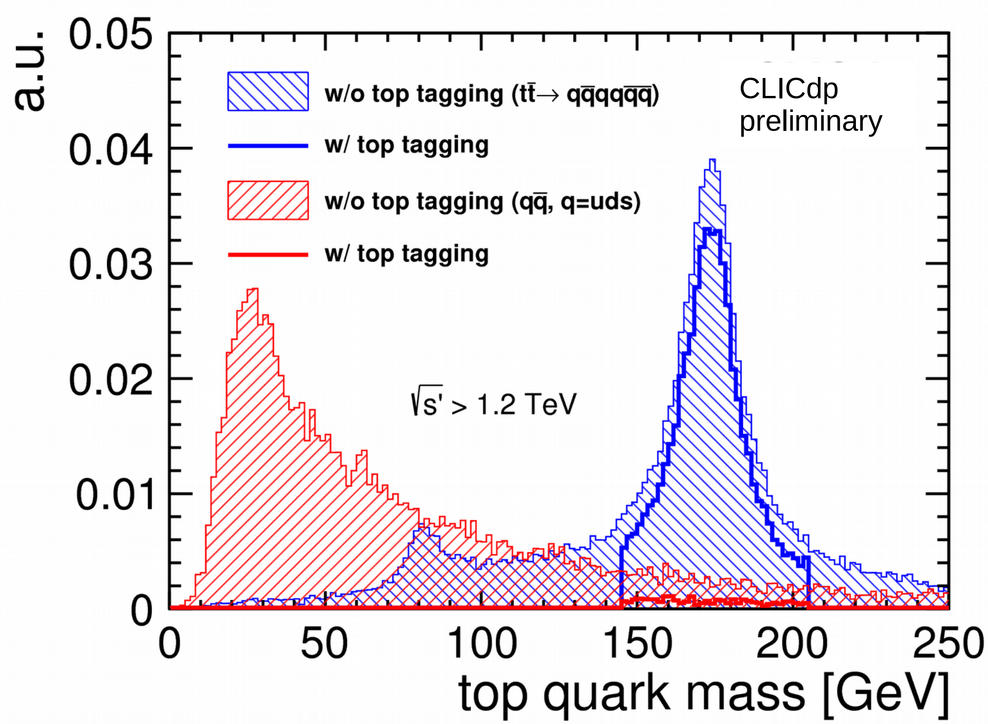




Selection and reconstruction

- 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

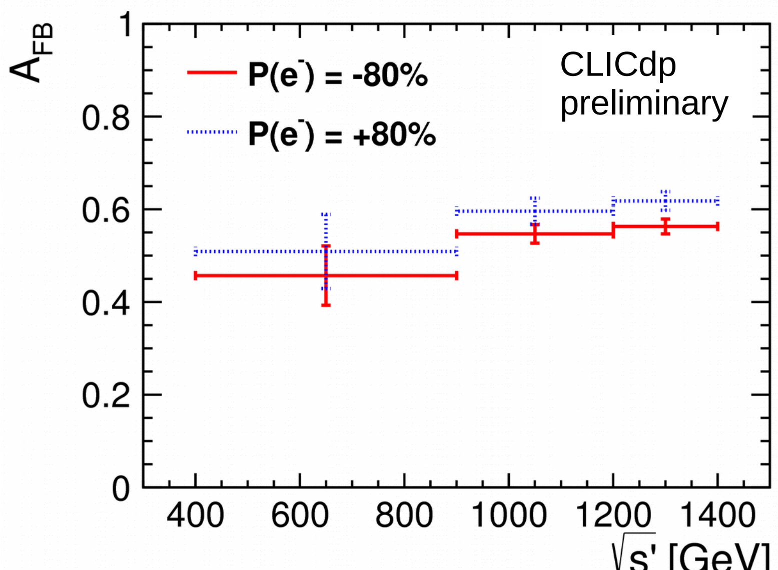
Main background due to single top → larger for left-handed e$^-$ beam

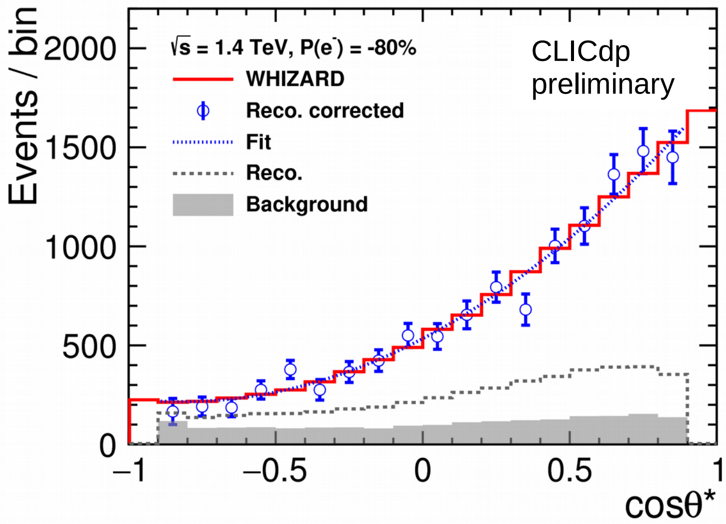
Selection and reconstruction

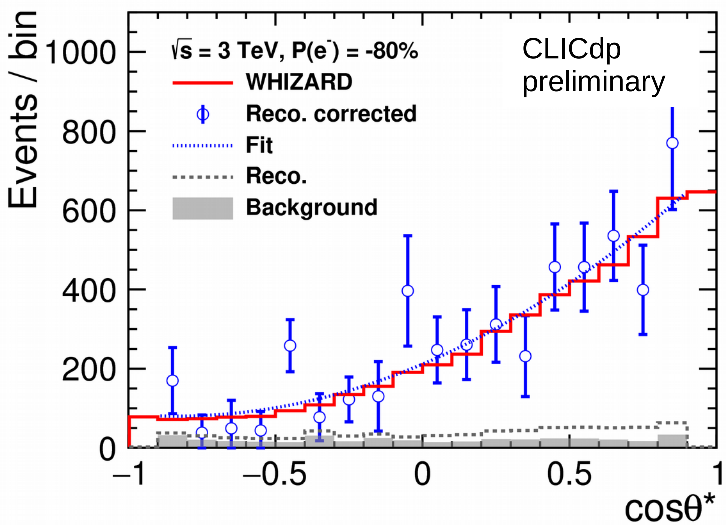
Performance at 1.4 TeV
Efficiency 19-23%
Purity 55-62%

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

Take advantage of the low-energy tail due to radiative events







improvement in progress

Effective field theory

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

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

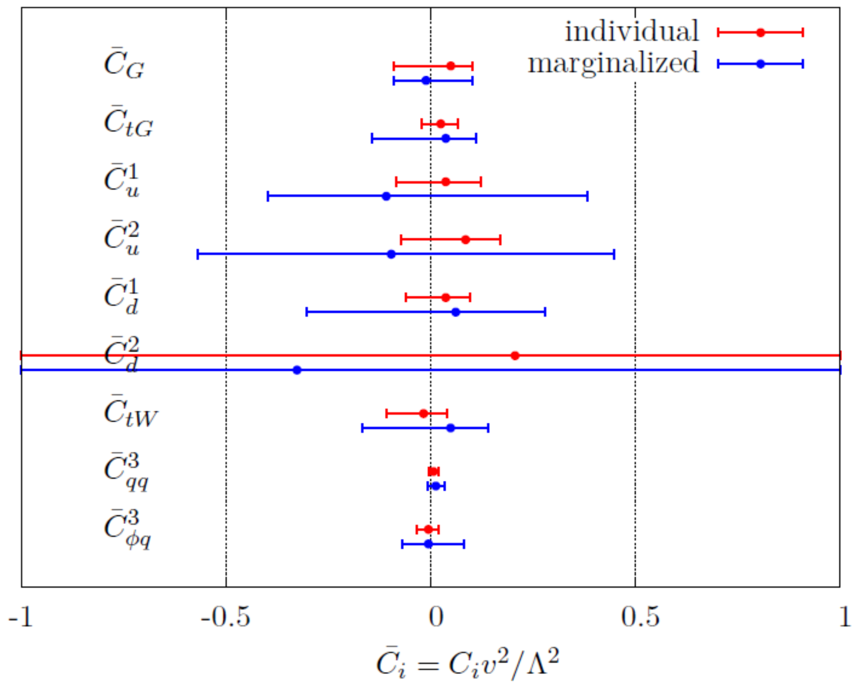
(represents any high-scale NP compatible with gauge invariance)

EFT is an excellent tool to quantify the potential of different measurements

EFT limits can be mapped on any concrete NP scenario

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

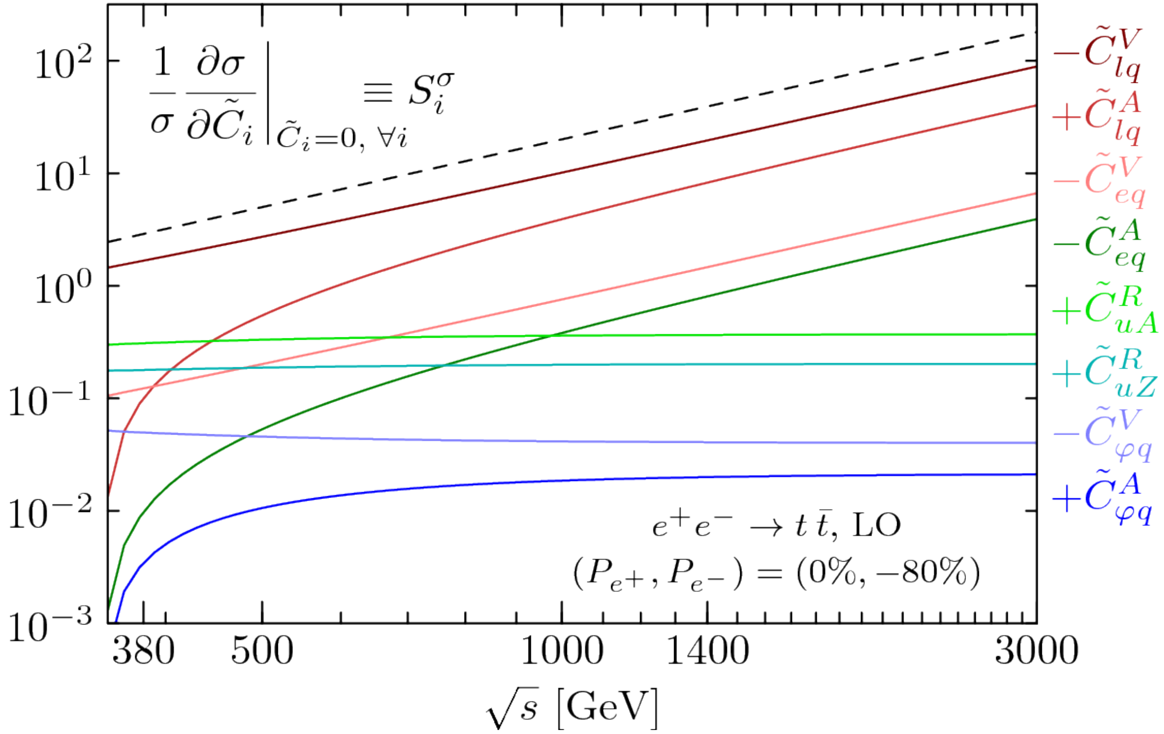
Top-philic scenario (arXiv:1802.07237): focus on operators that emerge from the direct BSM coupling to the top-quark fields q = $\{t_L, b_L\}$ and t = t_R.



See talk by Andrea Wulzer

CLIC complementarity

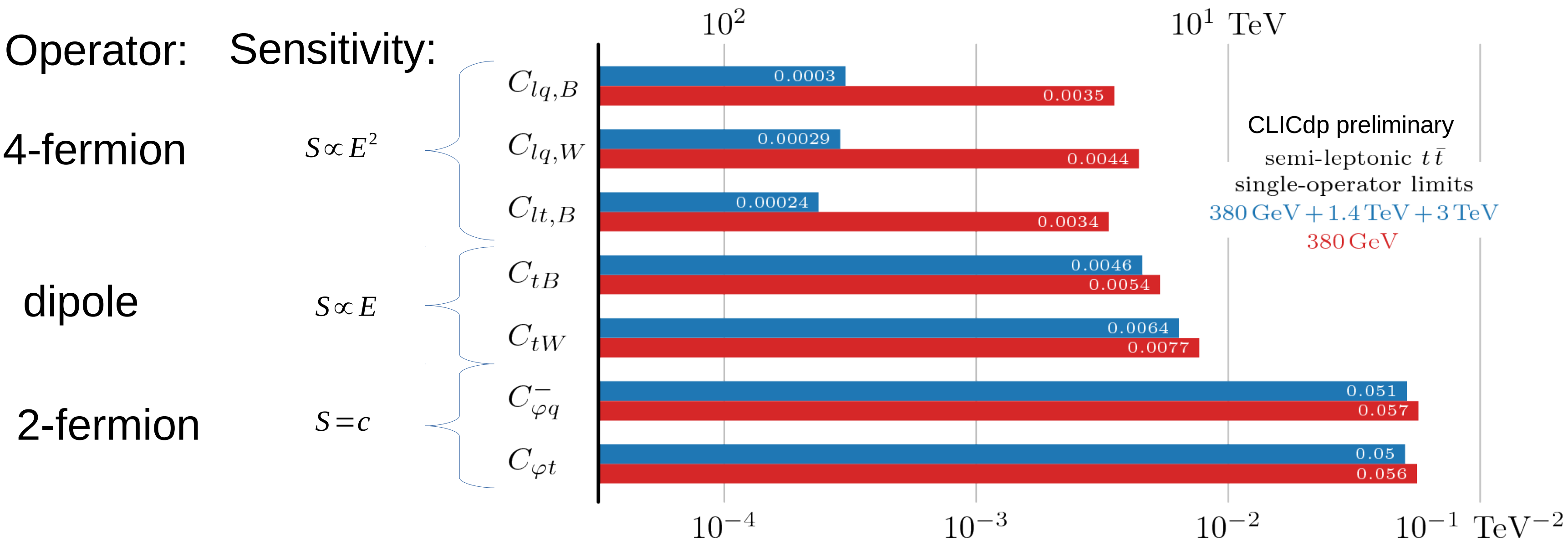
Low-energy operation:
    high-precision constraints on two-fermion operators
High-energy operation:
    quadratic increase in sensitivity to four-fermion operator coefficients



Durieux, Perelló, Vos, Zhang

EFT fit

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

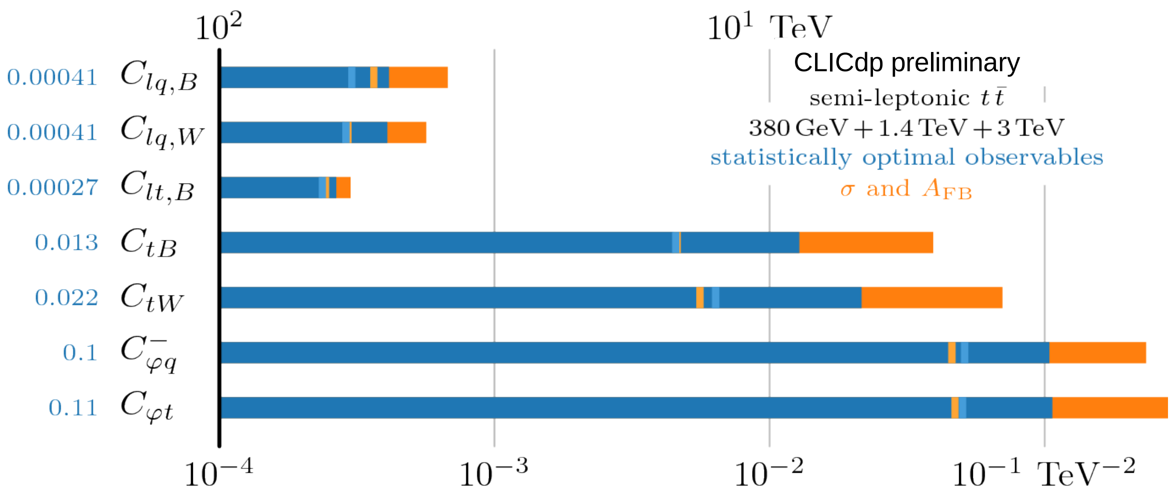


An excellent global fit of all relevant D6 operators requires at least two energy points and beam polarization

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}

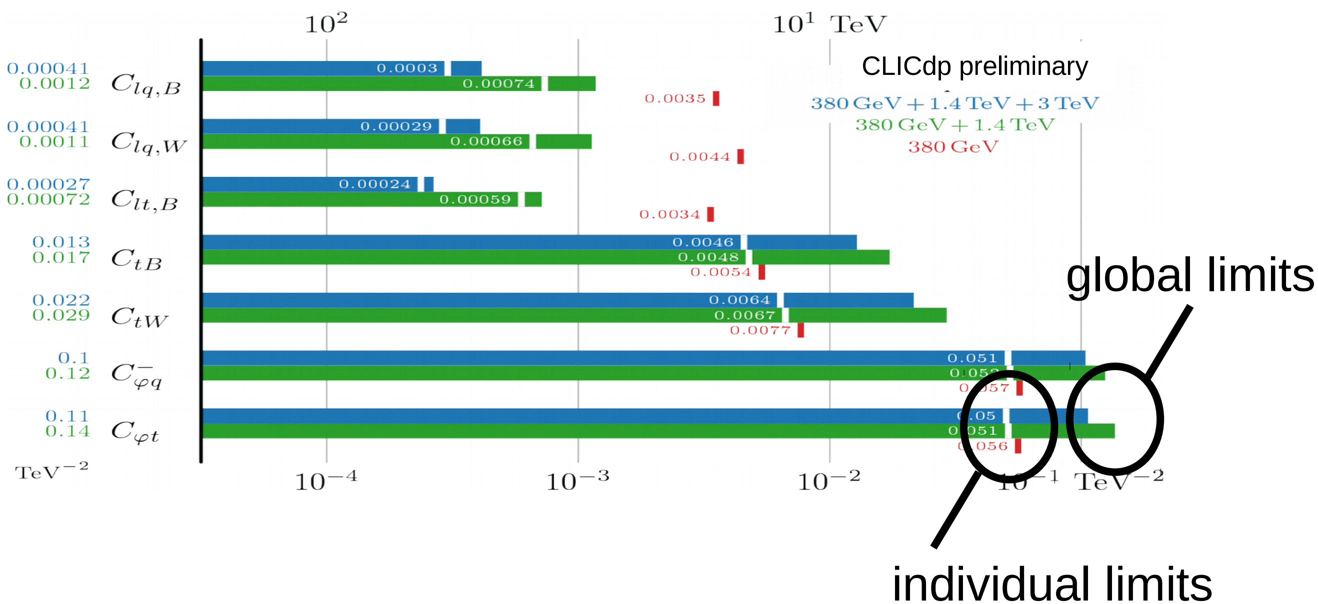
Global EFT fit

Global 7-parameter fit

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!

See talk by Andrea Wulzer

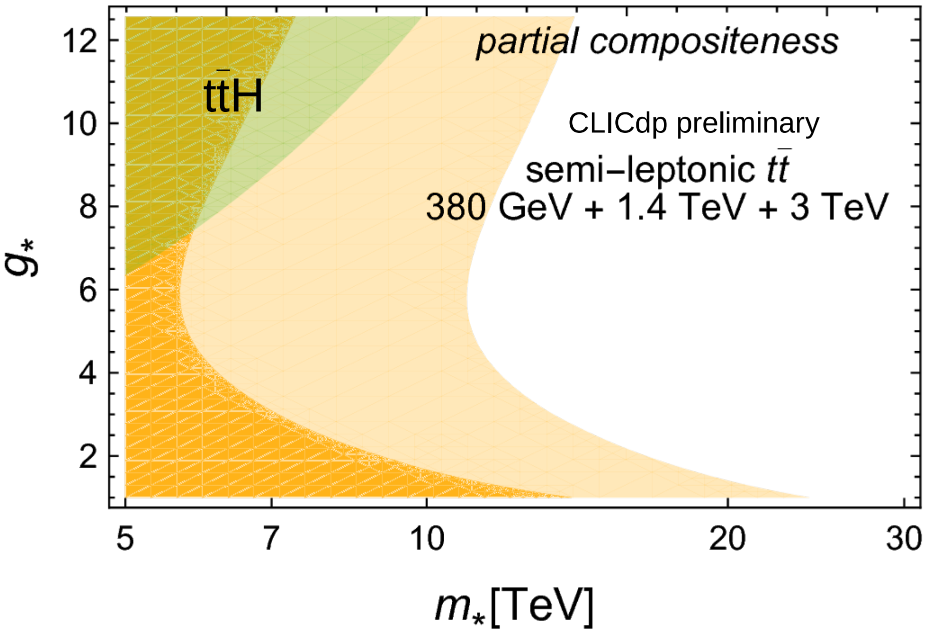
From EFT to concrete scenario

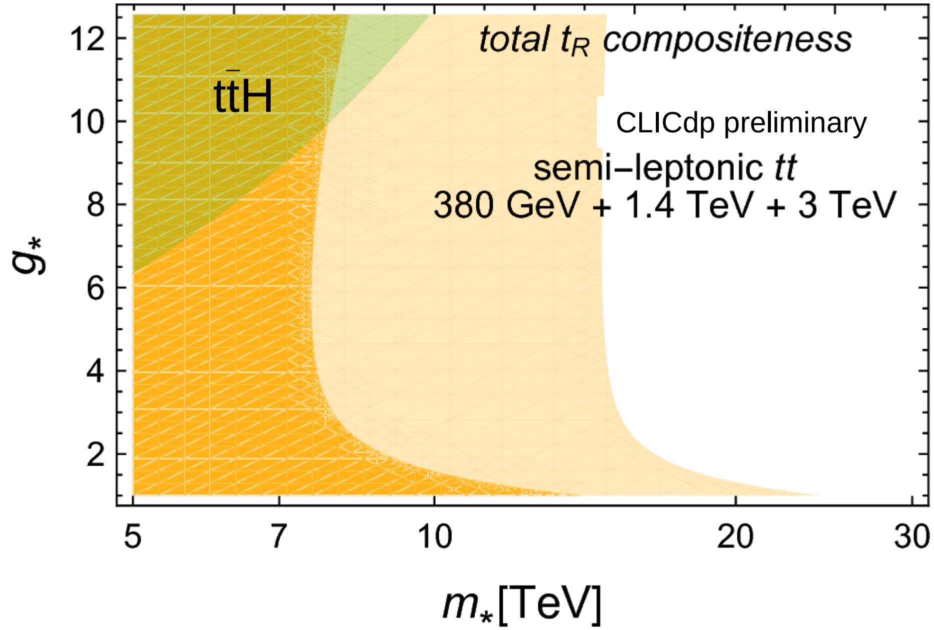
Re-express EFT constraints as limits on the canonical composite Higgs scenario, characterized by a coupling strength g_* and NP scale m_* (*Giudice 2007*)

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

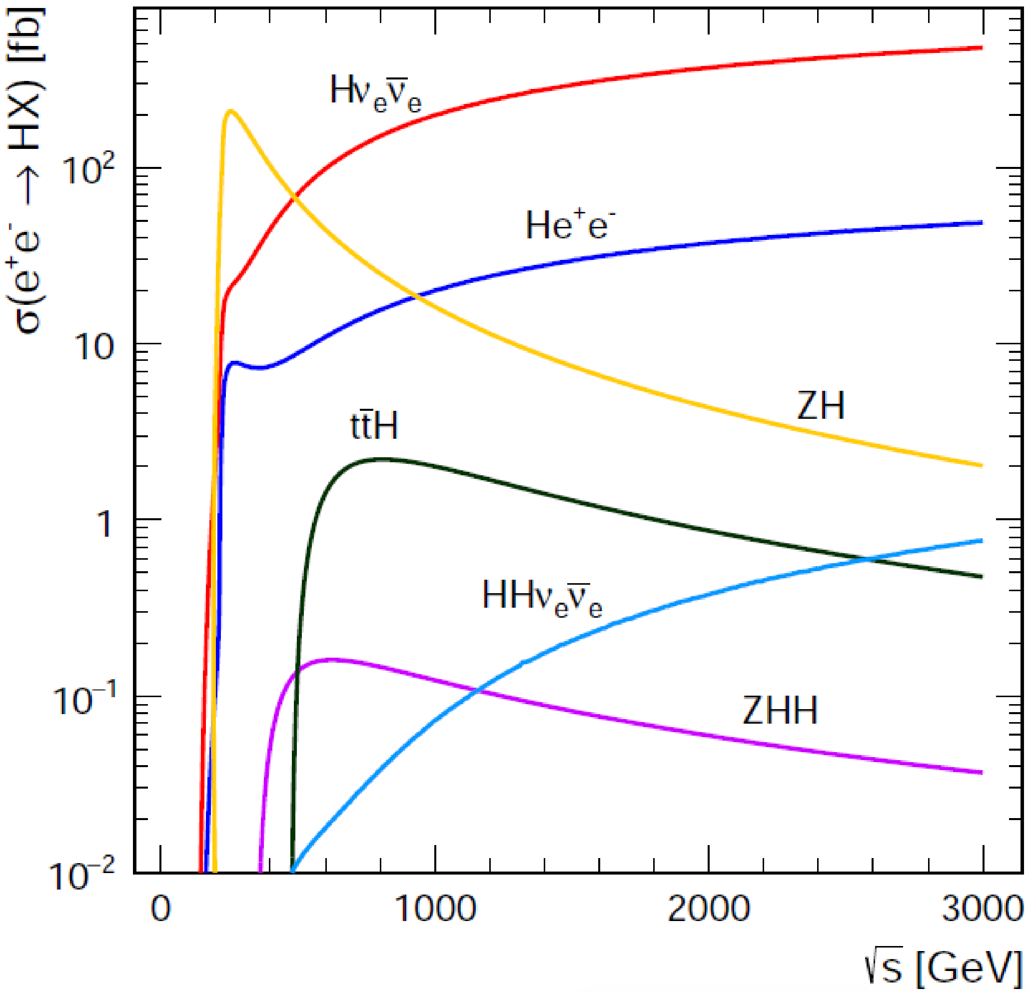
Benchmarks: partial (t_L and t_R composite) & total (t_R maximally composite)

Pessimistic 5σ discovery contours reach 5-10 TeV, in favourable cases >20 TeV





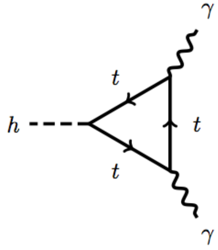
CLIC high energy:
$t\bar{t}$+H production

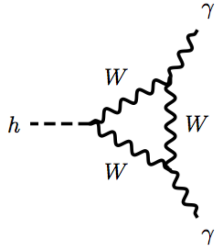


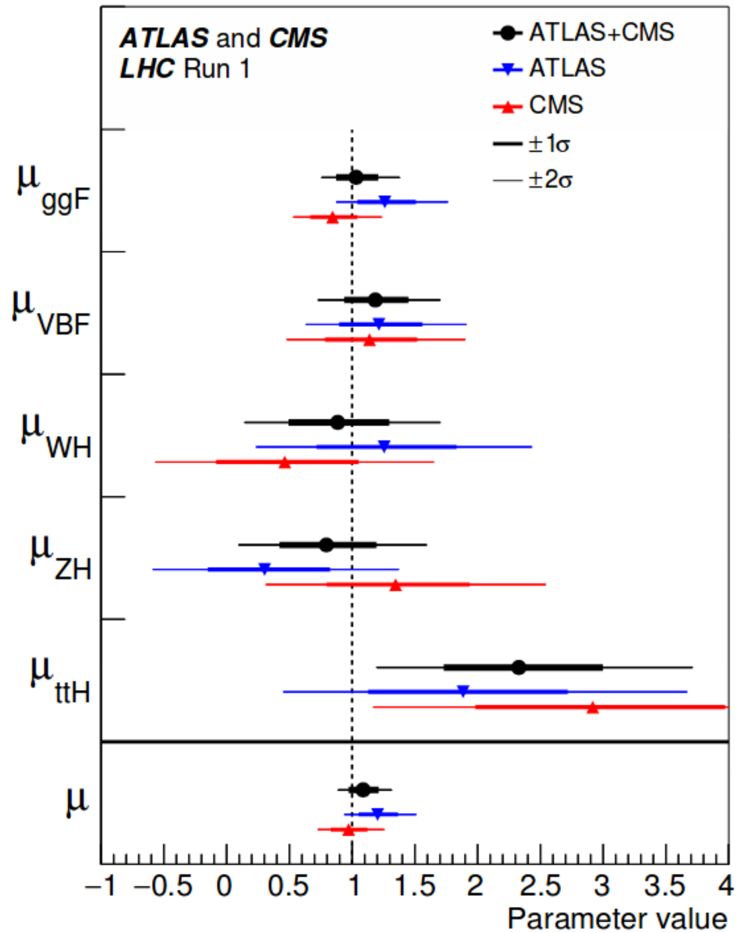
Top Yukawa coupling

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.

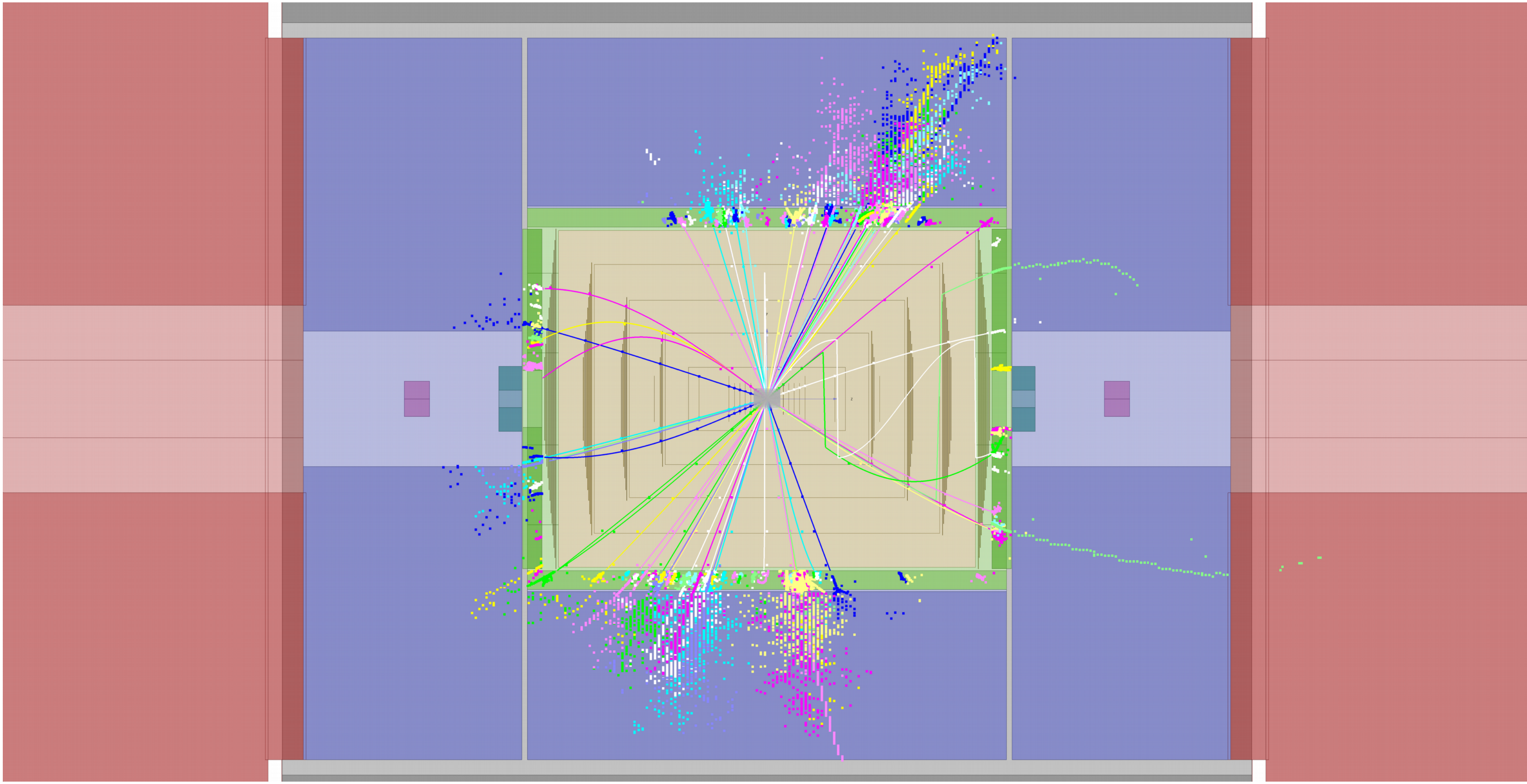
Run I result: $\mu_{ttH} = 2.3 \pm 0.7$

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 at CLIC



Top quark Yukawa coupling

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

Challenge: over 2 orders of magnitude background rejection

Jet pairing into W-boson, top and Higgs candidates based on simple χ^2

Boosted decision tree based on flavour tagging, events kinematics and candidate properties

Achieve over 50% signal efficiency
→ 7% stat. uncertainty on x-sec

Process	N	Selected as	
		fully-hadronic	semi-leptonic
$e^+e^- \rightarrow t\bar{t}H$, 6 jet, $H \rightarrow b\bar{b}$	647	367	38
$e^+e^- \rightarrow t\bar{t}H$, 4 jet, $H \rightarrow b\bar{b}$	623	1	270
$e^+e^- \rightarrow t\bar{t}H$, 2 jet, $H \rightarrow b\bar{b}$	150	2	22
$e^+e^- \rightarrow t\bar{t}H$, 6 jet, $H \not\rightarrow b\bar{b}$	473	54	11
$e^+e^- \rightarrow t\bar{t}H$, 4 jet, $H \not\rightarrow b\bar{b}$	455	8	22
$e^+e^- \rightarrow t\bar{t}H$, 2 jet, $H \not\rightarrow b\bar{b}$	110	0	1
$e^+e^- \rightarrow t\bar{t}b\bar{b}$, 6 jet	824	326	26
$e^+e^- \rightarrow t\bar{t}b\bar{b}$, 4 jet	794	57	226
$e^+e^- \rightarrow t\bar{t}b\bar{b}$, 2 jet	191	2	18
$e^+e^- \rightarrow t\bar{t}Z$, 6 jet	2,843	345	34
$e^+e^- \rightarrow t\bar{t}Z$, 4 jet	2,738	59	217
$e^+e^- \rightarrow t\bar{t}Z$, 2 jet	659	1	16
$e^+e^- \rightarrow t\bar{t}$	203,700	498	742

CLIC Yukawa coupling measurement: 3.8% with 1.5 ab^{-1} at 1.4 TeV

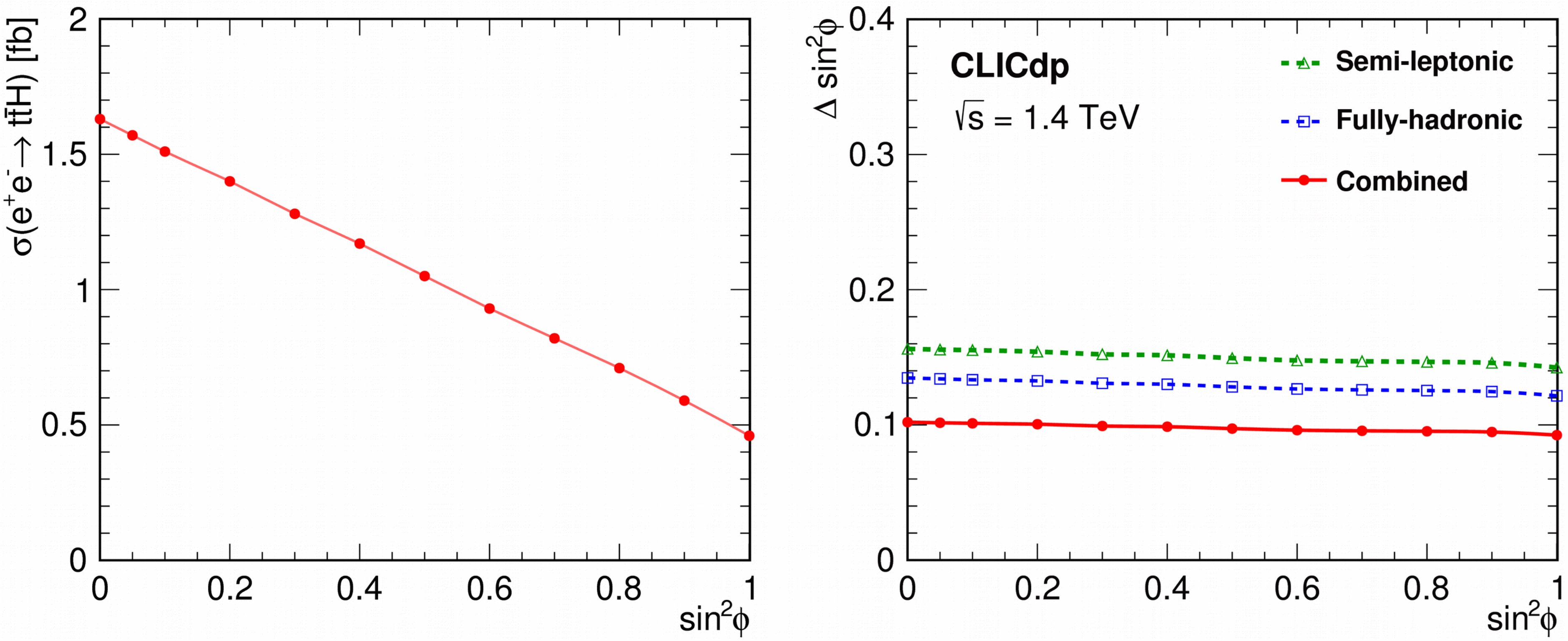
Improved wrt previous results (arXiv:1608.07538 and Higgs paper) thanks to better flavour tagging

$t\bar{t}H$ and CP properties

Parametrize CP mixing in $t\bar{t}H$ coupling as: $-i\, g_{ttH}\,(\cos\phi + i \sin\phi)$

Extraction from cross section yields $\Delta \sin^2\phi \sim 0.1$

Better result from beam polarization and differential analysis coming soon



Summary

The CLIC top physics program complements the LHC + HL-LHC in important ways.

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

- top mass measurement: **$\Delta m_t \sim 50$ MeV**
- constraints on top quark EW couplings, **improved by order of magnitude**
- the determination of the **top Yukawa coupling to 3.8%**