Search for non-Standard Model interactions of the top quark at the ILC

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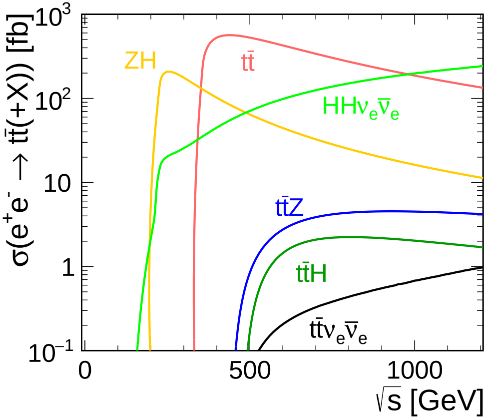
on behalf of the ILC International Development Team Physics and Detector Working Group

The European Physical Society Conference on High Energy Physics (EPS-HEP'2023)

T07: Top and Electroweak Physics

Outline

Top at Higgs factory



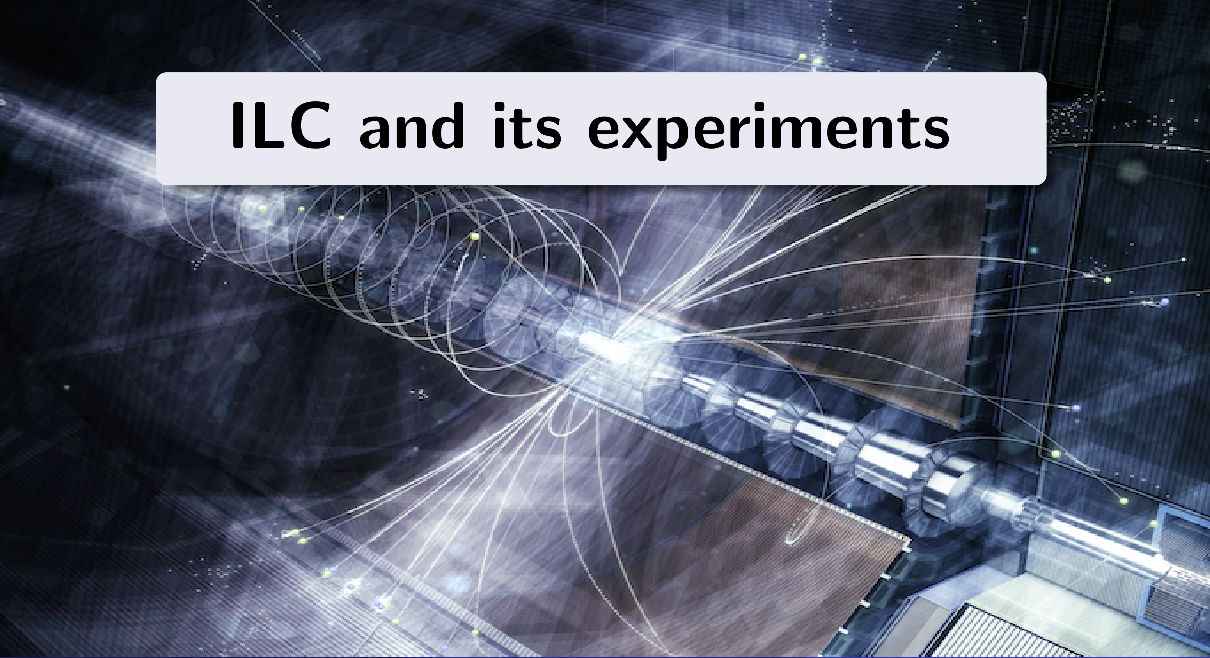
e^+e^- colliders are not only Higgs factories, but also top quark factories.

As the heaviest known particle, the top quark provides a unique probe of the SM.

Precise measurements of top-quark production give us also unique sensitivity to new physics

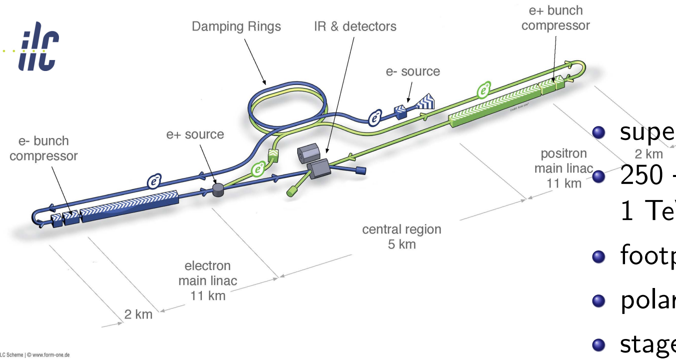
Top-quark observables give complementary constraints to those coming from light quark measurements

ILC and its experiments



International Linear Collider

Technical Design (TDR) presented in 2013 arXiv:1306.6328



- superconducting accelerating cavities
- 250 – 500 GeV c.m.s. energy (baseline), 1 TeV upgrade possible
- footprint 31 km
- polarisation for both e^- and e^+ (80%/30%)
- staged construction, arXiv:1903.01629 starting as 250 GeV Higgs factory

ILC running scenario

The unique feature of the ILC is the possibility of having both electron and positron beams polarised! This is crucial for many precision measurements as well as BSM searches.

Four independent measurements instead of one:

- increase accuracy of precision measurements
- more input to global fits and analyses
- remove ambiguity in many BSM studies
- reduce sensitivity to systematic effects

Integrated luminosity planned with different polarisation settings [fb^{-1}]

H-20	$\text{sgn}(P(e^-), P(e^+))$				Total
$\sqrt{s}$	$(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	
250 GeV	900	900	100	100	2000
350 GeV	135	45	10	10	200
500 GeV	1600	1600	400	400	4000

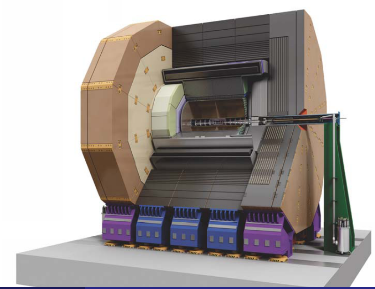
arXiv:1903.01629

Detector requirements

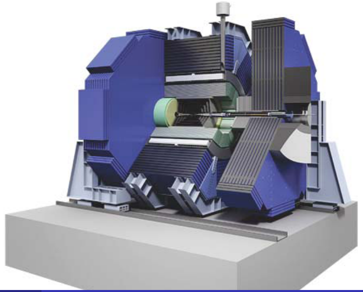
- Track momentum resolution: $\sigma_{1/p_t} = 2 \cdot 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \cdot 10^{-3}/(p_t\ \sin^{1/2}\Theta)$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\,\mu m\ \mathrm{GeV}/(p\ \sin^{3/2}\Theta)$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (for highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Two detailed ILC **detector concepts**

ILD



SiD



Particle Flow reconstruction

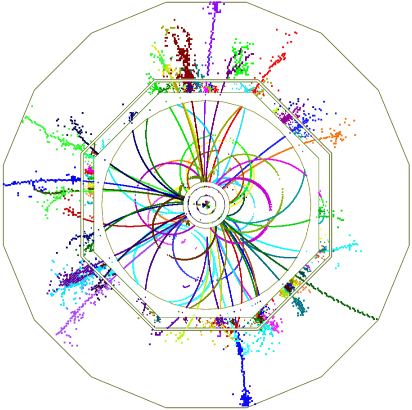
Large volume tracking
High calorimeter granularity
$\Rightarrow$ single particle reconstruction
$\Rightarrow$ extended particle identification capabilities

Precise momentum measurement
$\Rightarrow$ best energy estimate for charged particles
$\Rightarrow$ dominates jet energy resolution

High precision vertex detector
$\Rightarrow$ very efficient flavour tagging

Instrumentation down to smallest angles
$\Rightarrow$ hermecity, missing energy tagging

Example event
$e^+e^- \to t\bar{t} \to 6j$



Threshold scan

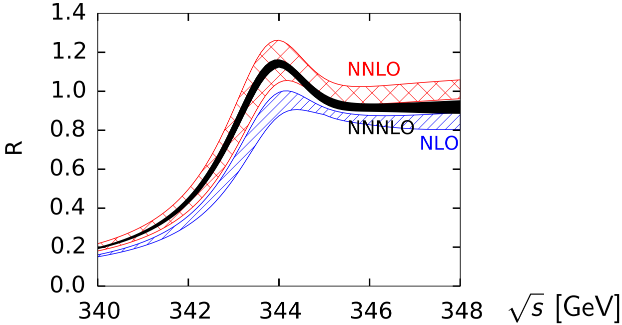
Theoretical uncertainties

Top quark mass measurement @ LHC dominated by systematics

Threshold study should allow for much higher precision, $\mathcal{O}(10 \text{ MeV})$

Total cross section calculations at NNNLO available

M.Beneke et al., Phys. Rev. Lett. 115, 192001 (2015)

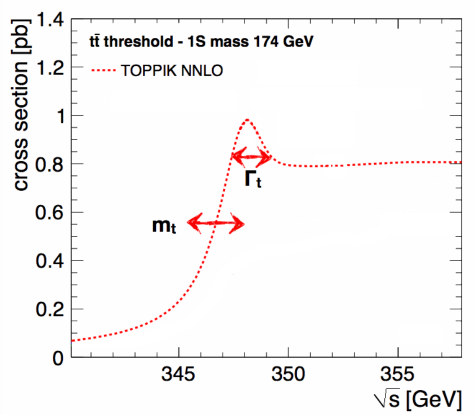


Threshold scan

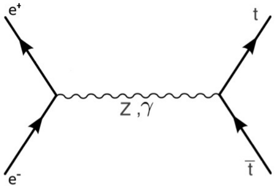
Top pair production cross section around the threshold:

resonance-like structure corresponding to narrow $t\bar{t}$ bound state.

Very sensitive to top properties and model parameters:



- top quark mass m_t
- top quark width Γ_t



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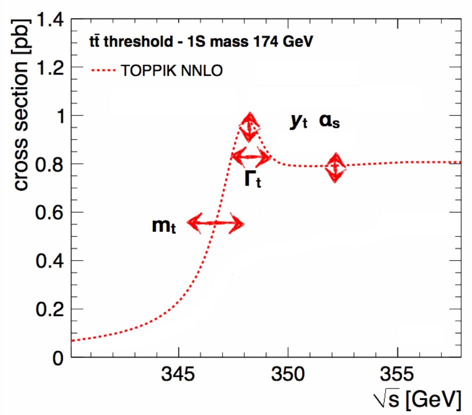
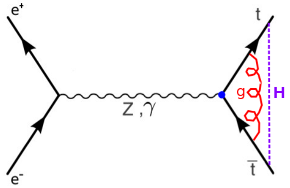


- top quark mass m_t
- top quark width Γ_t
- top Yukawa coupling y_t

- strong coupling α_s
- top EW couplings



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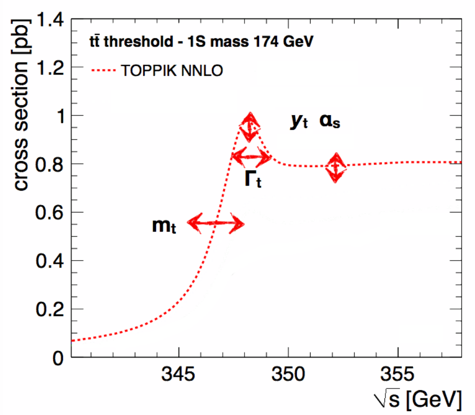

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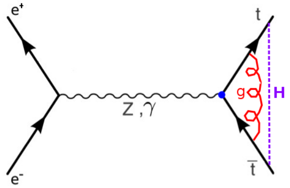


- strong coupling α_s
- top EW couplings

Mass is the only "free" top parameter in the SM

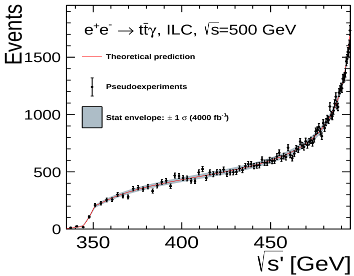
width and Yukawa coupling are not independent

Threshold scan

Measurement scenarios

Top quark pair-production at the threshold can be studied in two regimes

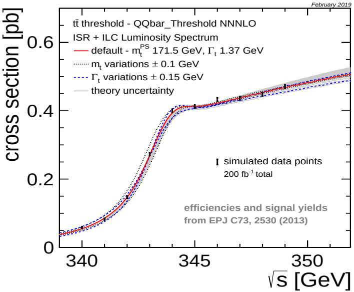
In radiative processes at 500 GeV



arXiv:1912.01275

$\sim$110 MeV statistical precision on m_t

Dedicated threshold scan



arXiv:1903.01629

Baseline scenario: 10×20 fb^{-1}

$\Rightarrow$ $\sim$20 MeV statistical precision

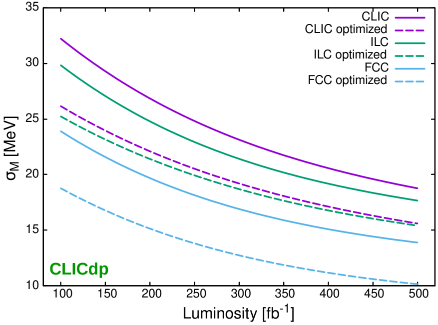
Optimizing the measurements

see backup sliders for some more details

Uncertainty in the extracted top quark mass can be further reduced by

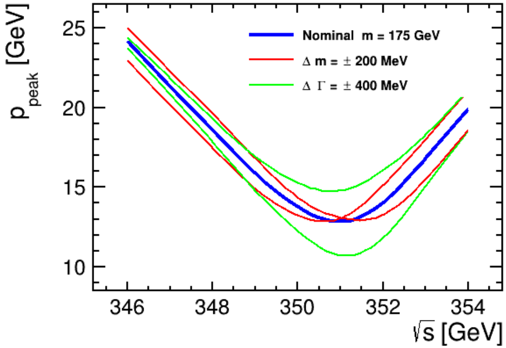
optimizing the scan sequence

Top quark mass uncertainty (stat.+exp.)



arXiv:2103.00522

and taking differential distributions into account



Adapted from: arXiv:hep-ph/0207315

still to be studied in more detail

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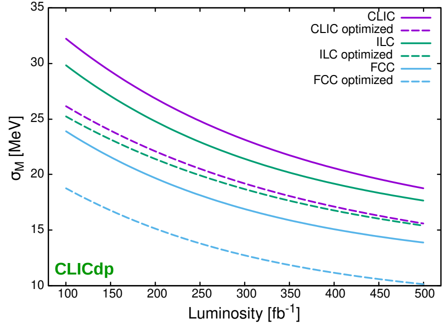
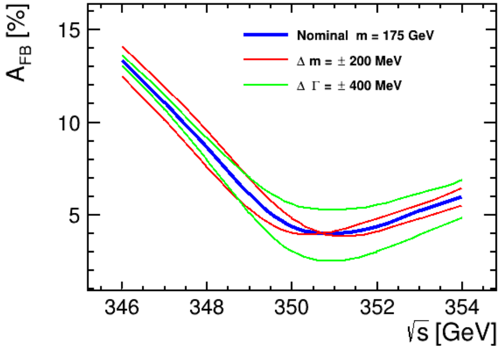


arXiv:2103.00522



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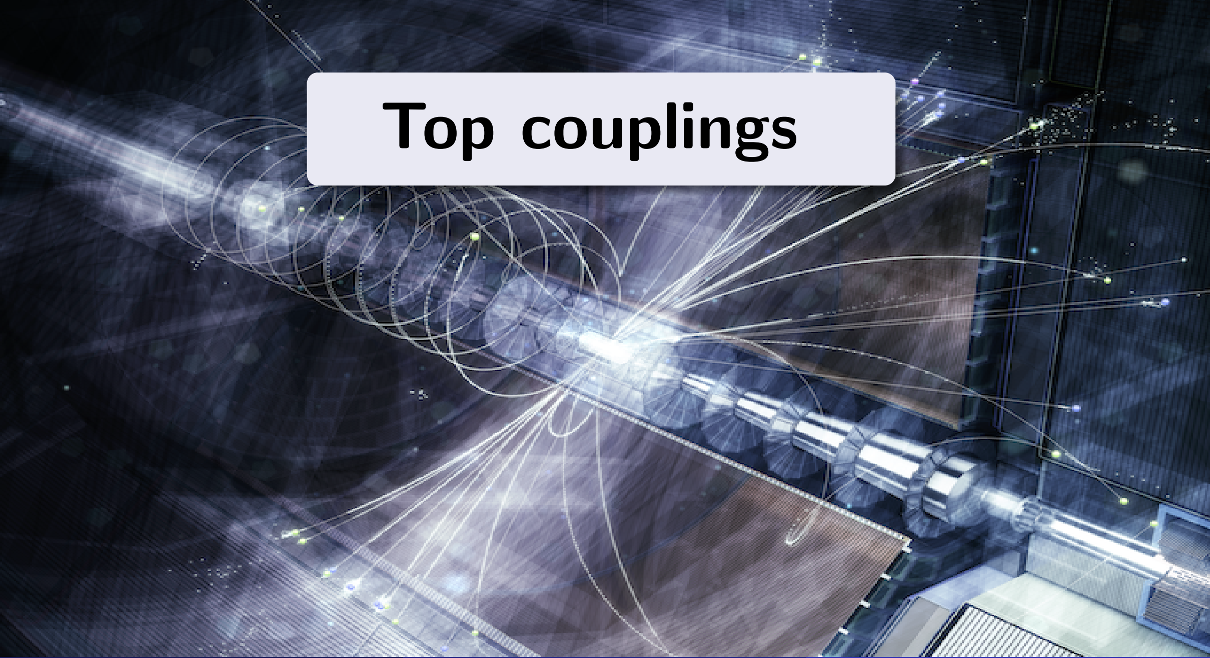
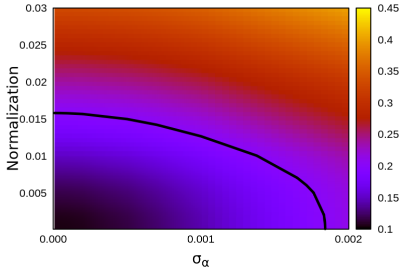


Top couplings

Top Yukawa coupling

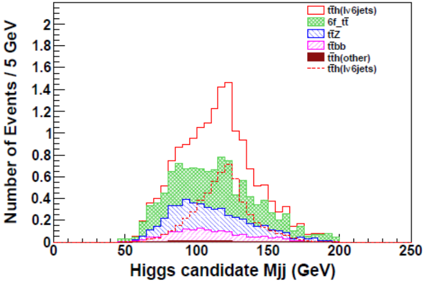
Higgs loop contribution at the threshold:



Statistical uncertainty of about 4%, but highly sensitive to systematics

Current theory uncertainties ∼20%

Direct measurement in $e^+e^- \to t\bar{t}H$



Measurement to 6.4% at 500 GeV (4 ab^{-1}).

Top Yukawa coupling

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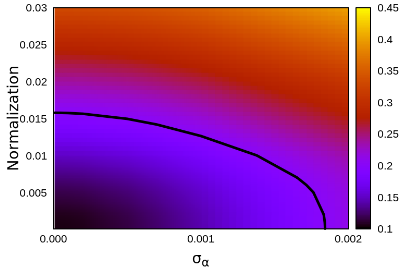

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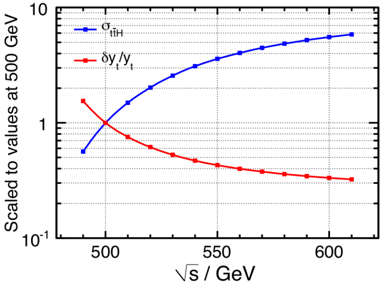
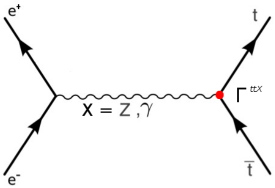


Measurement to 2.8% at 550 GeV (4 ab^{-1}). Improve to 1% with of 8 ab^{-1} at 1 TeV.

arXiv:2203.07622

Top EW couplings

Measurement of top quark pair production above the threshold provides direct access to top electroweak couplings



High precision ⇒ sensitivity to "new physics" contribution
entering via higher order corrections

BSM effects can be constrained through measurements of:

- total cross-section
- forward-backward asymmetry
- helicity angle distribution in top decays

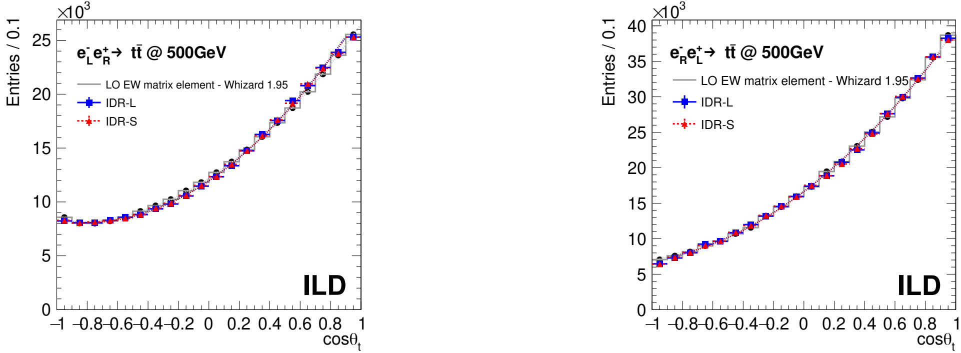
with additional constraints obtained by:

- combining measurements for different electron and positron beam polarizations
- measurements at different $\sqrt{s}$

Top EW couplings

ILD-PHYS-PUB-2019-007

Charge of the top quark can be determined by combining b quark charge information with the charge of isolated lepton (in leptonic W decays). Polar angle distribution for t quark:



All helicity amplitudes can be extracted when using polarised beams

Top EW couplings

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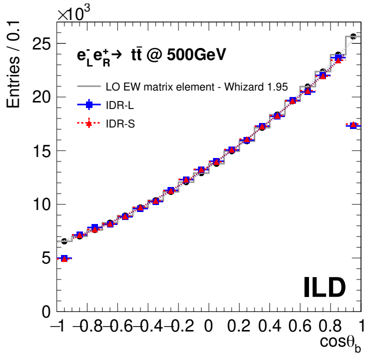
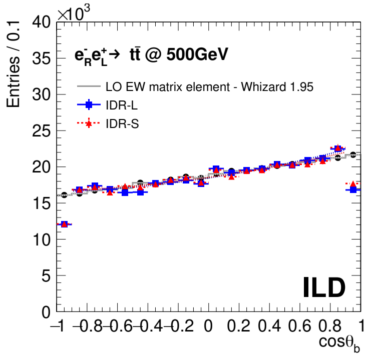


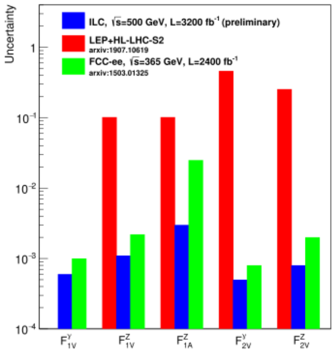


Impact of the *t* quark polarization clearly visible

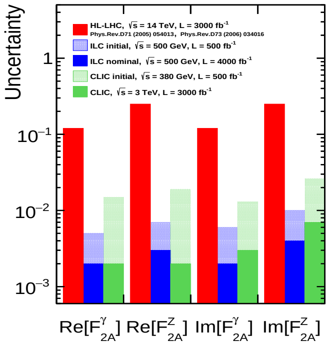
Top EW couplings

Precisions on the electromagnetic t quark form factors expected after ILC500 compared with those expected after the full HL-LHC running and an estimation for FCC-ee after 5000 fb^{-1}

CP-conserving form factors



CP-violating form factors



using optimal observables arXiv:1710.06737

BSM constraints

BSM constraints

Indirect constrains

Result from analysis of precision measurements involving top quark.

Global analysis can also include other precision measurements:
Higgs boson couplings, Z and $W^{\pm}$ properties, production of other SM fermions.

Direct constraints

From direct search for BSM processes in

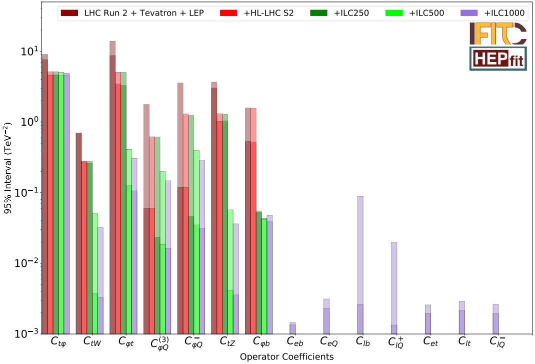
- top quark production and
- top quark decays

SMEFT analysis

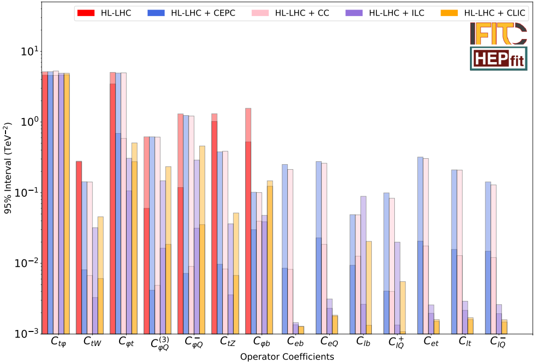
Global fit to $b\bar{b}$ and $t\bar{t}$ precision measurements in the SMEFT framework arXiv:2205.02140

Comparison of LHC constraints with those from ILC and other colliders.

LHC Run2, HL-LHC and ILC stages



HL-LHC and different HF concepts



Exotic production

Loop corrections from new particles coupling to the top quark would modify the pair-production threshold shape (indirect detection/constraints).

Light exotic particles could also be produced in association with the top-quark pair:

$$e^+e^- \rightarrow t\,\bar{t}\,\phi$$
$$\phi \rightarrow q\bar{q},\ l\bar{l},\ \ldots$$

Limits from LHC exist, but for not for small masses $\Rightarrow$ still to be studied for ILC

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We should also look for single top quark production:

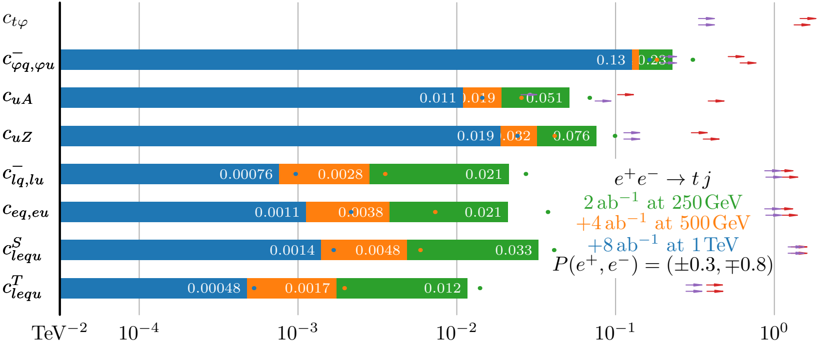
$$e^+e^- \rightarrow t\,\bar{q}\ /\ q\,\bar{t} \qquad q = u, c$$

FCNC - Flavour Changing Neutral Currents: absent in the SM
observation of any such events would be a direct evidence for the BSM physics!

Exotic production

Expected bounds on the FCNC EFT operators contributing to single top production

arXiv:2203.07622



Sensitivity to $\mathcal{O}$(10 TeV) scales already at 250 GeV ILC...

Exotic decays

For FCNC decays of the top quark to the SM final states:

$$t \rightarrow H\,q \quad \text{or} \quad Z\,q \qquad q = u, c$$

excellent limits expected from HL-LHC, hard to improve at Higgs factories.

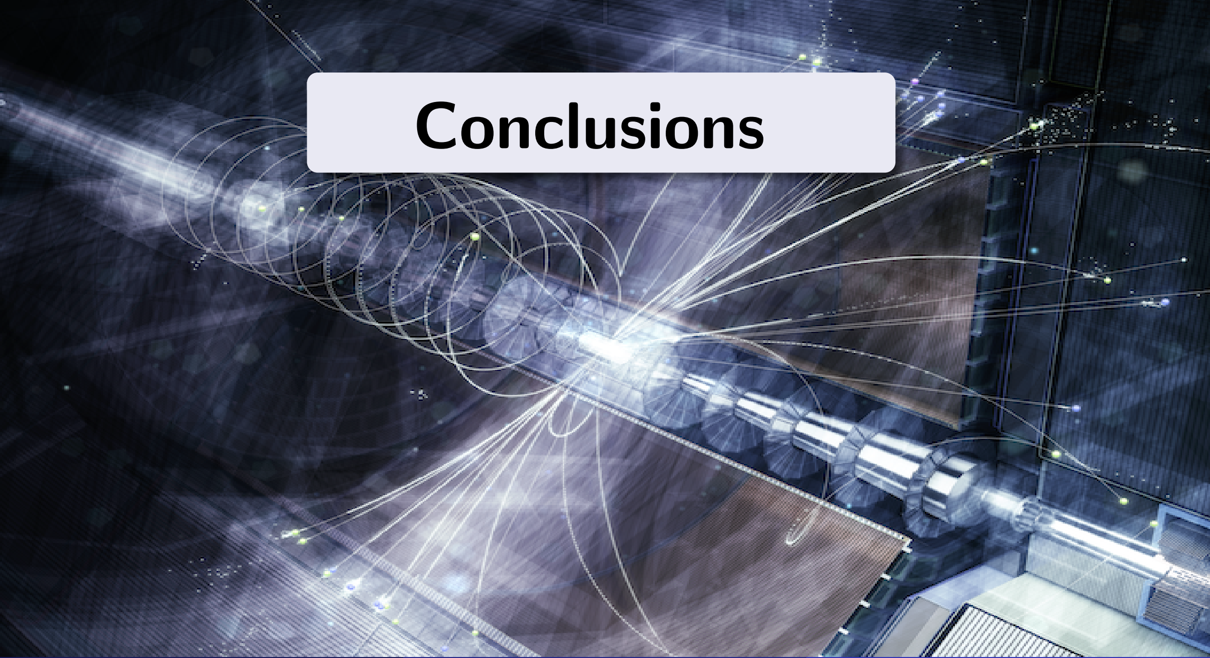
However, exotic FCNC decay channels much more difficult at the LHC:

$$t \rightarrow q + \text{invisible} \qquad q = u, c$$

$$\text{or} \quad t \rightarrow q\,\phi$$

$$\phi \rightarrow q\bar{q},\ l\bar{l},\ \ldots$$

⇒ still to be studied in details for ILC



Conclusions

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Precise determination of top parameters is crucial for validation of the Standard Model (or any alternative BSM theory)

With high luminosity, increasing with energy, ILC will be not only Higgs but also top factory.

Clean environment, high measurement precision and beam polarization allow per mile level coupling measurements.

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BSM scales of $\mathcal{O}(10\ \text{TeV})$ indirectly accessible already at 250 GeV ILC

Wide prospects for direct searches of exotic top production and decays!

New studies planned for ILC, as an input to the ECFA studies towards an e^+e^- Higgs factory

$\Rightarrow$ you are welcome to join!

Two relevant "focus topics" defined in ECFA study:
Top threshold (TTthres), Exotic top decays (EXtt).

Thank you!

Links

General

- ILC International Development Team https://linearcollider.org/
- ILC IDT Working Group 3 (Physics and Detectors) https://linearcollider.org/team/wg3/
  also including many links to subgroups, indico sites etc.
- ILC Newsline http://newsline.linearcollider.org/
- SiD detector concept for ILC http://silicondetector.org
- ILD detector concept for ILC https://www.ilcild.org/
  https://confluence.desy.de/display/ILD/ILD

Software tools

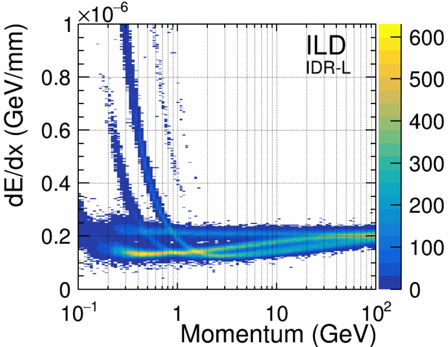
- WHIZARD repository https://whizard.hepforge.org/
- ILC beam spectra files for WHIZARD https://whizard.hepforge.org/circe_files/ILC/
- DELPHES repository https://github.com/delphes/delphes
- DELPHES wiki https://cp3.irmp.ucl.ac.be/projects/delphes
- ILCgen model documentation https://github.com/iLCSoft/ILCDelphes
- LCIO package at github https://github.com/iLCSoft/LCIO
- Delphes2LCIO documentation https://github.com/iLCSoft/LCIO/tree/master/examples/cpp/delphes2lcio

Particle identification capabilities

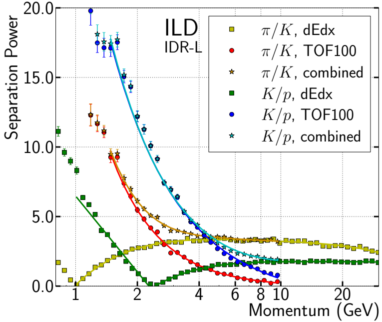
arXiv:2003.01116

Combining high precision of ionization loss measurement and Time of Flight information

dE/dx as a function of particle momentum for e, μ, π, K and p in the ILD TPC

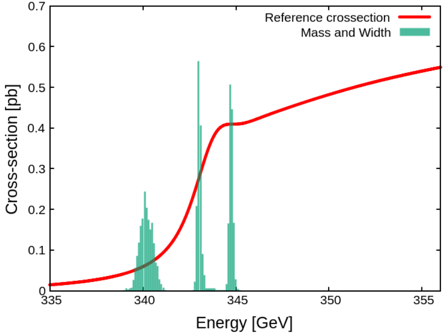


Separation power for dE/dx in the TPC combined with ToF measurement in ECAL



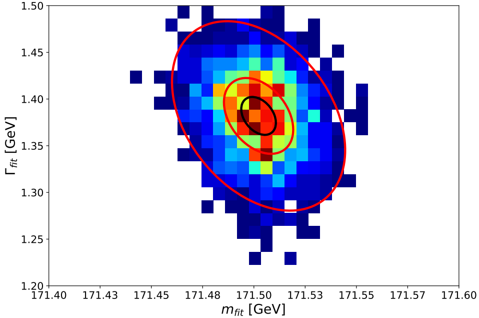
Optimizing the threshold measurement

Optimized scan points
$\Rightarrow$ up to 25% reduced mass uncertainty



Scenarios selected with genetic algorithm arXiv:2103.00522

Threshold fit including top quark momentum distribution $\Rightarrow$ ∼15% reduced mass uncertainty



K.Nowak M.Sc. thesis 2020

ECFA studies towards an e^+e^- Higgs/EW/top factory

The ECFA study, within its three working groups, is intended to:

- bring together communities & activities
- explore synergies between projects
- address the challenges

A set of "focus topics" have been defined in the Physics Potential working group (WG1) to point to concrete examples of work still to be done. These topics should help to bring people together (across projects) and to attract more people (e.g. LHC) into the e^+e^- community.

Two focus topics relevant for this talks

Top threshold (TTthres)
Exotic top decays (EXtt)