Fizyka kwarku t w przyszłych zderzaczach e^+e^-

Aleksander Filip Żarnecki
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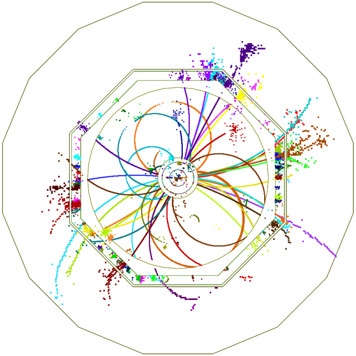
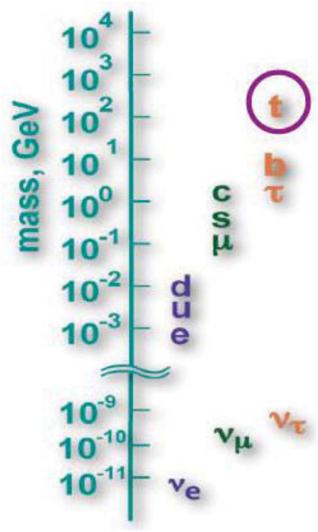


XLIII Zjazd Fizyków Polskich, Kielce 2015

Sesja równoległa: W poszukiwaniu fizyki poza Modelem Standardowym

Outline

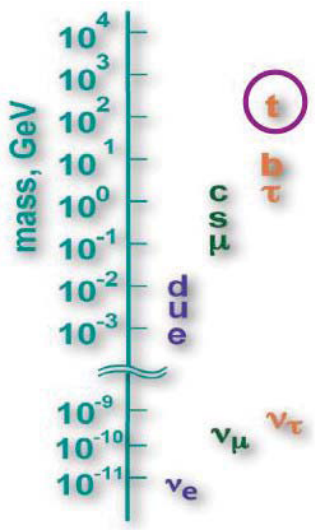
1. Motivation
2. Future Colliders and Experiments
3. Top measurements
   - Mass and width
   - Yukawa coupling
   - Electroweak couplings
   - Rare decays
4. Conclusions



Top quark

- the heaviest known elementary particle
- Yukawa coupling to Higgs boson $y_t \sim 1$
  $\Rightarrow$ key to understanding of EWSB

Motivation



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  $\Rightarrow$ test ground for QCD

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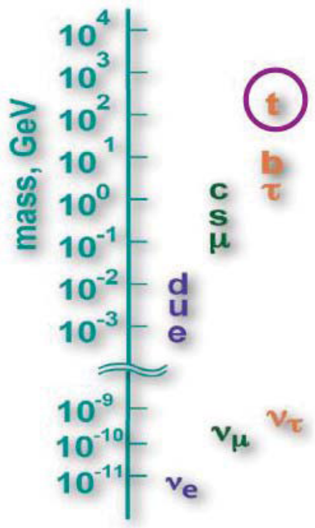

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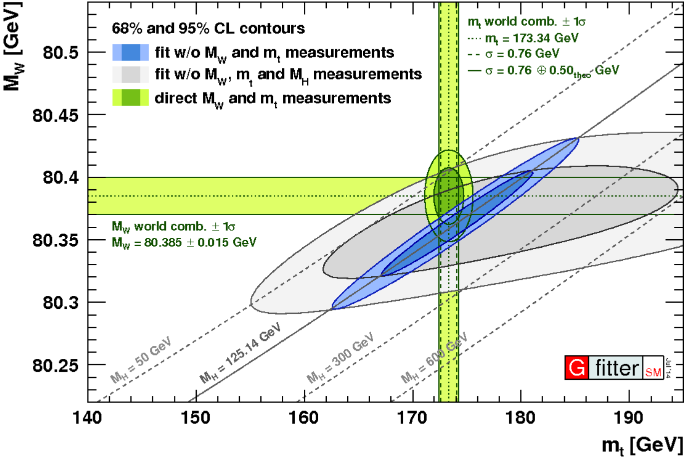
  $\Rightarrow$ key to understanding of EWSB
- decays before hadronizing:
  the only "naked" quark
  $\Rightarrow$ test ground for QCD
- large loop contributions to many precision measurements
- sensitive to many BSM scenarios
  $\Rightarrow$ a window to "new physics"

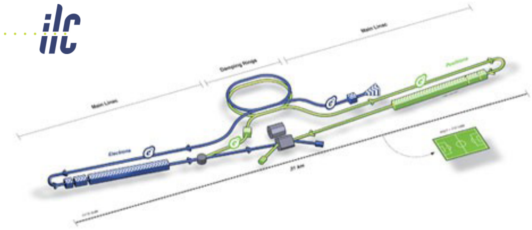
Motivation

Precise determination of the top properties crucial for Standard Model verification and indirect "new physics" searches



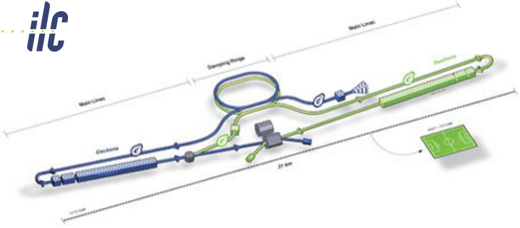
e.g. uncertainty on the SM stability conditions dominated by top mass

Linear Colliders



Technical Design (TDR) completed in 2013

- 500 GeV baseline
  1 TeV upgrade possible
- e^- and e^+ polarization



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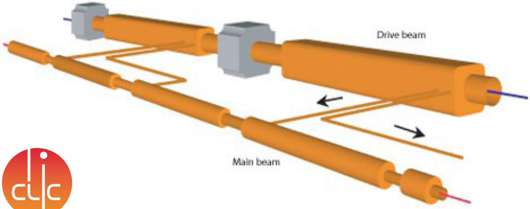
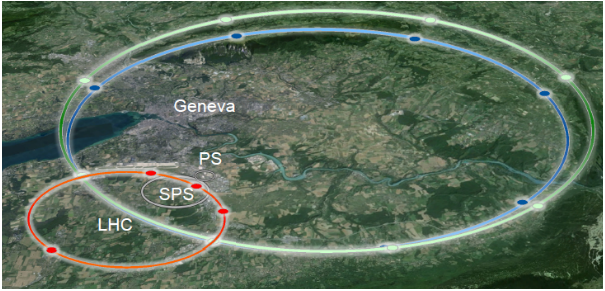


Conceptual design in 2012
Ongoing R&D towards TDR

- energy 380 GeV - 3 TeV
- e^- polarization

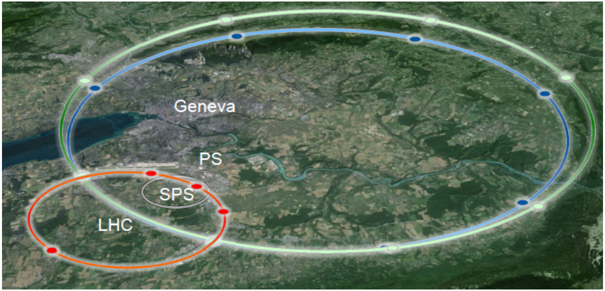
Circular Colliders



FCC-ee @ CERN

- 80-100 km ring
- focus on 250 GeV
  $\Rightarrow$ Higgs factory
- 350 GeV possible
- no polarization

Circular Colliders



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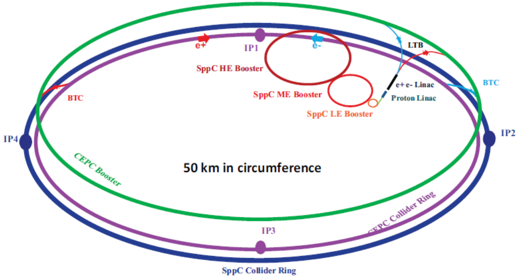


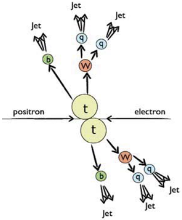
CEPC @ China

- 50 km ring
- up to 240 GeV
  $\Rightarrow$ Higgs factory

$t\bar{t}$ threshold not reachable

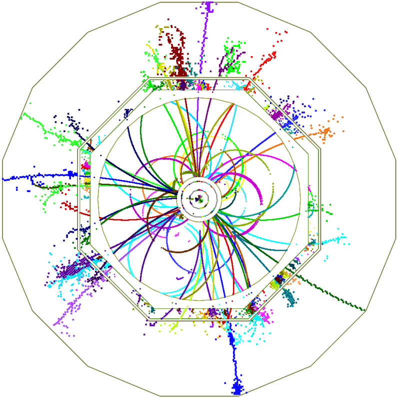
Detector Requirements

Jet reconstruction and jet energy measurement based on "Particle Flow" concept



High detector granularity
⇒ reconstruction of single particles

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



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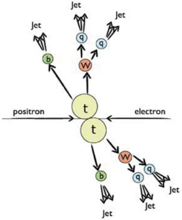

Jet reconstruction and jet energy measurement based on "Particle Flow" concept

High detector granularity
$\Rightarrow$ reconstruction of single particles

Excellent momentum measurement
$\Rightarrow$ best possible jet energy estimate

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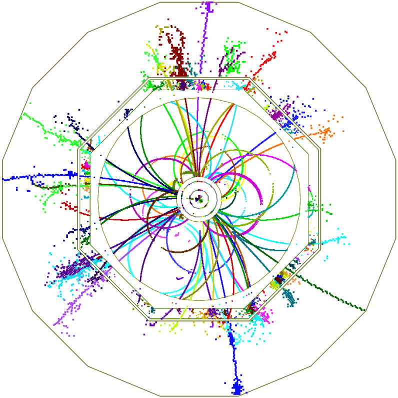

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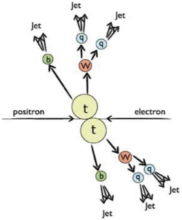

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Excellent momentum measurement
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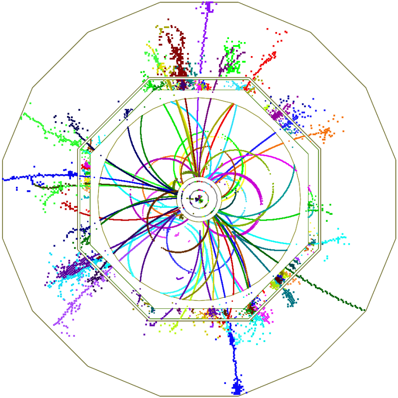
High precision vertex detector
$\Rightarrow$ very efficient flavour tagging

$e^+e^- \rightarrow t\bar{t} \rightarrow 6j$



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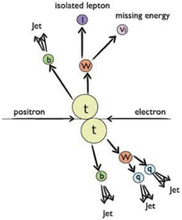
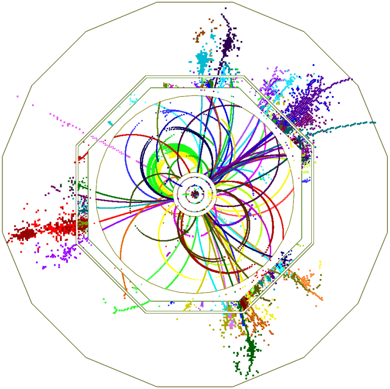


Jet reconstruction and jet energy measurement based on "Particle Flow" concept

$e^+e^- \rightarrow t\bar{t} \rightarrow 4j + l + \nu$



High detector granularity
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High precision vertex detector
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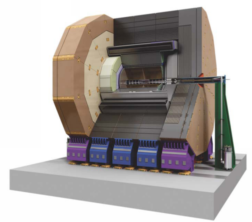
Hermecity
$\Rightarrow$ missing energy measurement

Detector Requirements

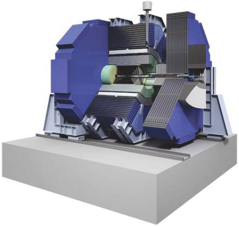
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Energy resolution: $\sigma_E/E = 3 - 4\%$
- Hermecity: $\Theta_{min} = 5$ mrad

Three detailed LC detector concepts:

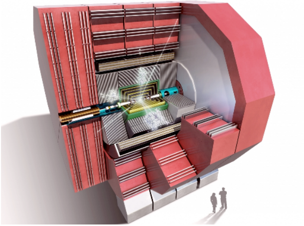
ILD



SiD



CLIC



H-20 scenario for ILC

Initial stage

- $\sqrt{s} = 500$ GeV with 500 fb^{-1} in 3.7 years
- $\sqrt{s} = 350$ GeV with 200 fb^{-1} in 1.3 years
- $\sqrt{s} = 250$ GeV with 500 fb^{-1} in 3.1 years

Running scenarios

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Additional 3'500 fb^{-1} at $\sqrt{s} = 500$ GeV and 1'500 fb^{-1} at $\sqrt{s} = 250$ GeV possible after luminosity upgrade (in about 11 years)

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CLIC runnning scenario

Three construction stages:

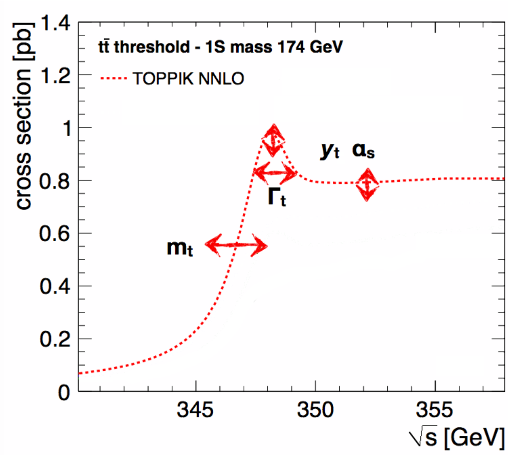
- $\sqrt{s} = 380$ GeV with 500 fb^{-1} - initial stage
  selected as an optimal choice for precision Higgs and top physics
- $\sqrt{s} = 1.4$ TeV with 1500 fb^{-1}
- $\sqrt{s} = 3$ TeV with 2000 fb^{-1}

Threshold scan

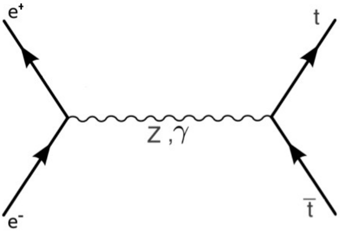
Top pair production cross section around threshold

Resonance-like structure corresponding to $t\bar{t}$ bound state

Very sensitive to top properties and model parameters:



- top quark mass m_t
- top quark width Γ_t



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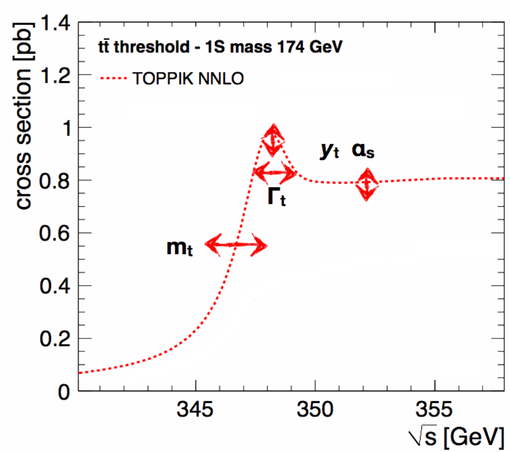

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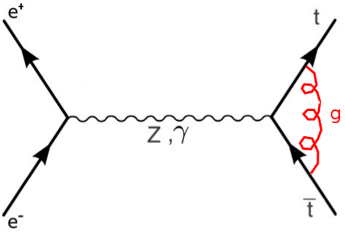

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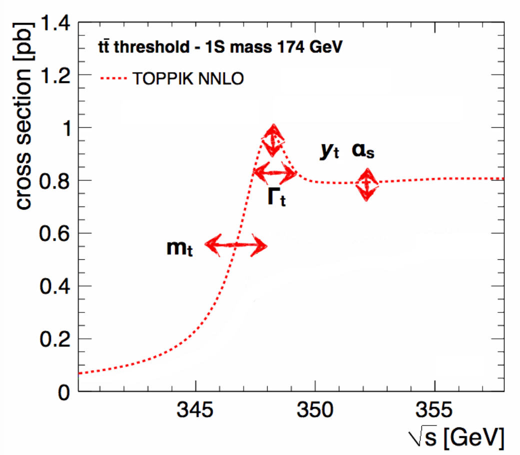
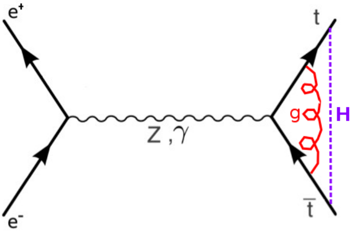


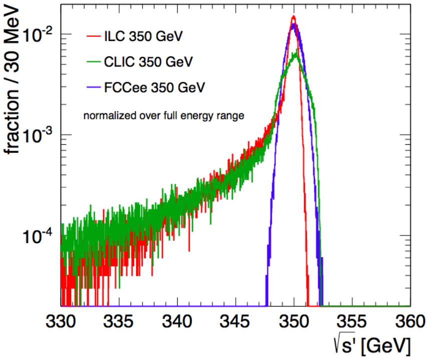
- top quark mass m_t
- top quark width Γ_t
- strong coupling α_s
- top Yukawa coupling y_t



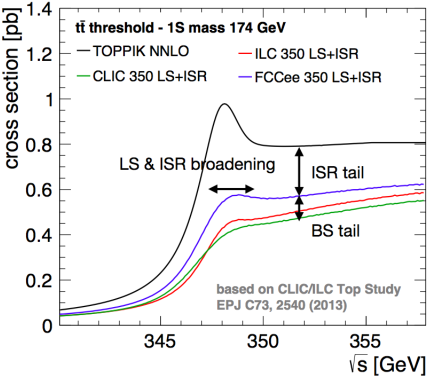
Threshold scan

Significant cross section smearing due to luminosity spectra and ISR

Luminosity spectra



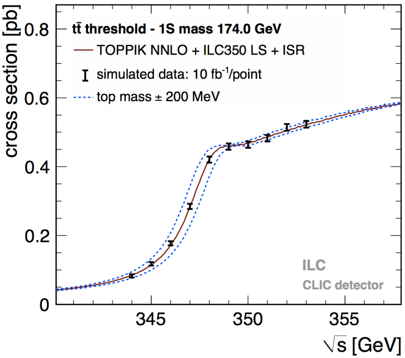
Measured cross section

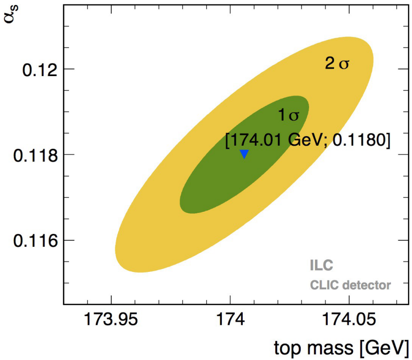


Threshold scan

Precision top mass measurement possible already with 100 fb^{-1}

- statistical uncertainty 10–30 MeV
- experimental systematics ∼30 MeV (dominated by beam energy)
- theoretical uncertainties: 20 MeV possible (currently ∼100 MeV)





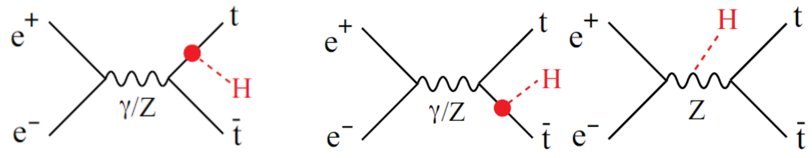
Yukawa coupling

Threshold scan

y_t can be extracted with statistical uncertainty $\sim$6% (100 fb^{-1}), if α_s constrained from other measurements. Model dependent!

Higher energies

Can be extracted from the measurement of $e^+e^- \rightarrow t\bar{t}H$ events



Model independent!

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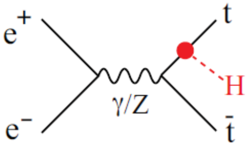
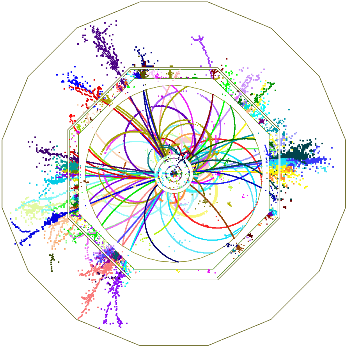


Very difficult measurement:

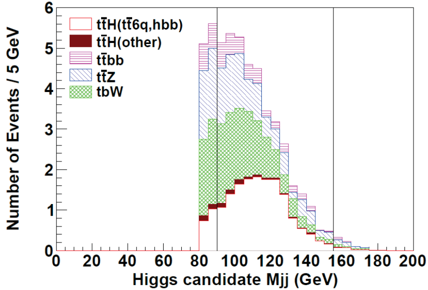
- low statistics
- large backgrounds
- require prefect detector performance (8 jets, 4 b-tags)



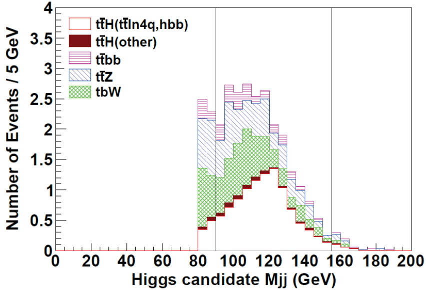
Yukawa coupling

Results of ILD simulation (500 fb^{-1} at 500 GeV)

$t\bar{t}H \to 8j$



$t\bar{t}H \to l\nu + 6j$



$\Rightarrow$ statistical uncertainty of about 17% expected (6% with 4'000 fb^{-1})

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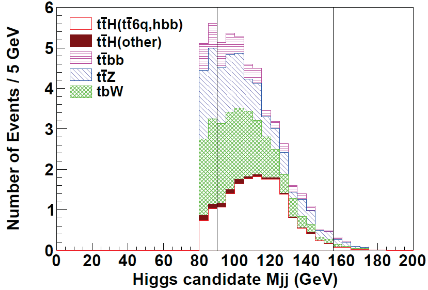

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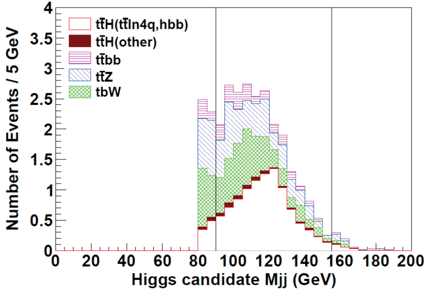


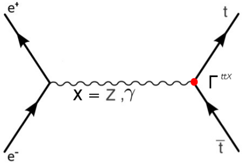
$\Rightarrow$ statistical uncertainty of about 17% expected (6% with 4'000 fb^{-1})

Significant improvement when going to higher energies:

- 7% with 500 fb^{-1} at 550 GeV (!)
- 4.3-4.5% with 1.5 ab^{-1} at 1 TeV (ILC) or 1.4 TeV (CLIC)

Pair production provides direct access to top electroweak couplings

Possible higher order corrections
⇒ sensitive to "new physics" contribution



General coupling form:

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

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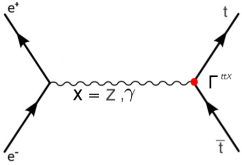

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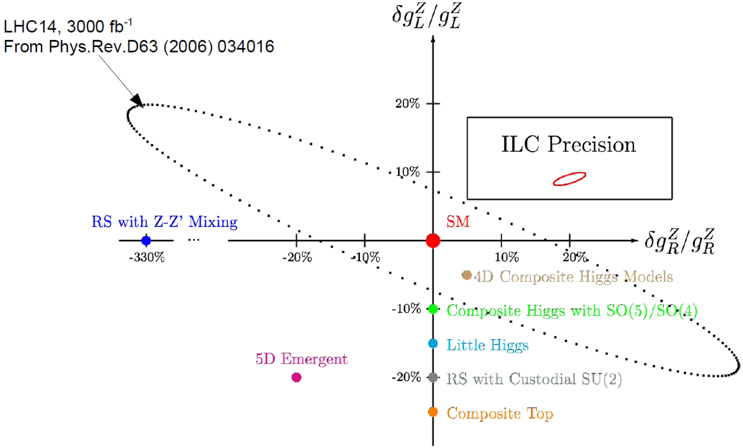
5 non-trivial form factors can be constrained through measurement of:

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

for two polarization combinations: $e_L^- e_R^+$ and $e_R^- e_L^+$

Electroweak couplings

Already the initial ILC running will allow for top coupling determination with 1-2% accuracy



Rare decays

In the Standard Model, FCNC top decays are strongly suppressed (GIM mechanism + CMK suppression):

$$
\begin{aligned}
BR(t \rightarrow c\,\gamma) &\sim 5 \cdot 10^{-14} \\
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Decay $t \rightarrow c\,H$ considered in the presented study:

- enhancement up to $10^{-5} - 10^{-2}$ possible
- test of Higgs boson couplings
- well constrained kinematics
- seems to be most difficult for LHC

Two Higgs Doublet Model (2HDM) type III used as a test scenario.

Event selection: $t\bar{t}$ final state

"Signal" top: $t \to cH$, followed by Higgs decay to $b\bar{b}$ $\Rightarrow$ 2 b tags
"Spectator" top: $t \to bW$ (dominant SM decay) $\Rightarrow$ 1 b tag

Considered final states (resulting from "spectator" $W^{\pm}$ decay channels):

- semileptonic: 4 jets (3 b-tags) + lepton + missing p_t
- fully hadronic: 6 jets (3 b-tags), no leptons, no missing p_t

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Background

Kinematic constraints allow for selection of high purity $t\bar{t}$ sample
Main background expected from:

- top decays followed by CKM suppressed $W^- \to b\bar{c}$
- miss-reconstruction of standard $t\bar{t}$ events

Signal selection

Compare two hypothesis:

- background hypothesis

$$\chi^2_{bg} = \left(\frac{M_{bl\nu} - m_t}{\sigma_{t,lep}}\right)^2 + \left(\frac{M_{l\nu} - m_W}{\sigma_{W,lep}}\right)^2 + \left(\frac{M_{bbq} - m_t}{\sigma_{t,had}}\right)^2 + \left(\frac{M_{bq} - m_W}{\sigma_{W,had}}\right)^2$$

- signal hypothesis

$$\chi^2_{sig} = \left(\frac{M_{bl\nu} - m_t}{\sigma_{t,lep}}\right)^2 + \left(\frac{M_{l\nu} - m_W}{\sigma_{W,lep}}\right)^2 + \left(\frac{M_{bbq} - m_t}{\sigma_{t,had}}\right)^2 + \left(\frac{M_{bb} - m_h}{\sigma_h}\right)^2$$

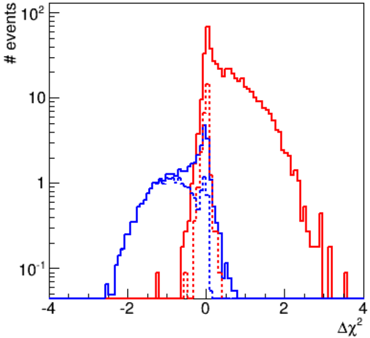
Independent search for best background and signal combinations

Signal selection

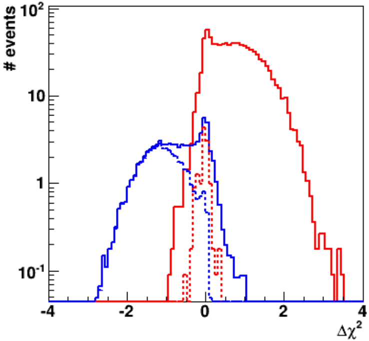
Difference of $\log_{10}\chi^2$ for two hypothesis, for signal and background events

Before (solid) and after (dashed) other selection cuts

Semi-leptonic events



Fully hadronic events

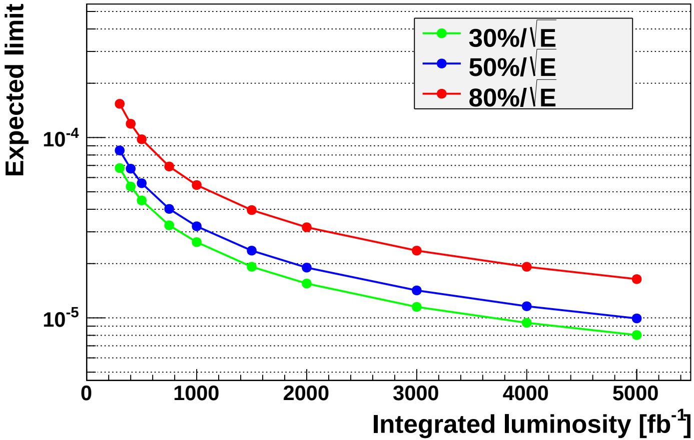


Jet energy resolution 50%, 70% *b*-tagging efficiency

Very efficient background rejection possible

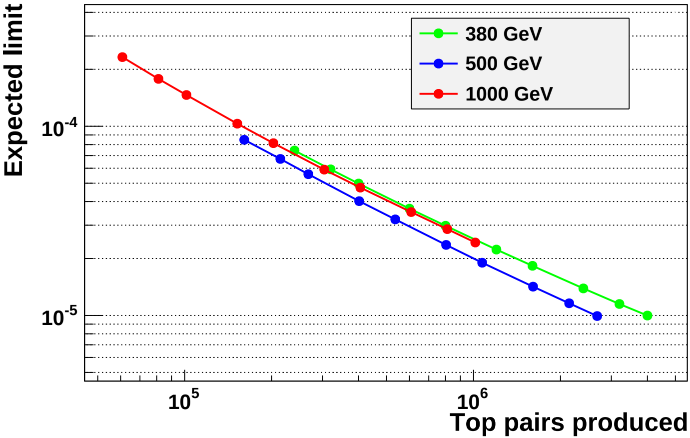
Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Collision energy 500 GeV, different jet energy resolutions



Expected limits on $BR(t \to ch) \times BR(h \to b\bar{b})$

Jet energy resolution 50%, different collision energies



Conclusions

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

Top threshold scan at the e^+e^- collider gives unique oportunities for precise mass, width and coupling determination

Direct measurement of Yukawa and electroweak couplings require running at higher beam energies

High background suppression capabilities will allow searches for FCNC top decays down to $BR \sim 10^{-5} - 10^{-4}$

Even in clean e^+e^- environment, top event reconstruction is very challenging. Stringent requirements are imposed on detector performance.

Selected presentations used as a source of plots or results:

- Philipp Roloff, *Measurement of the top Yukawa coupling CLIC*, Americas Workshop on Linear Colliders (AWLC14), Fermilab 2014
- Roman Pöschl, *ILC Physics Case*, XXI Cracow EPIPHANY Conference, Cracow 2015
- Frank Simon, *Threshold Scans at Linear Colliders*, Top physics at Lepton Colliders, Valencia 2015
- Roman Pöschl, *Top quark physics at Linear Colliders*, EPS-HEP 2015, Vienna 2015

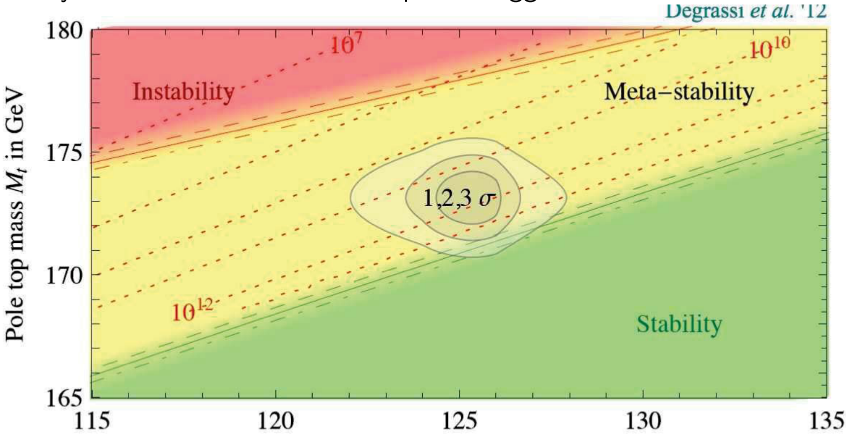
For more details on top FCNC decays see:

- A.F.Żarnecki, *Sensitivity to top FCNC decay $t \rightarrow ch$ at future e^+e^- colliders*, Top physics at Lepton Colliders, Valencia 2015

Thank you!

Standard Model stability

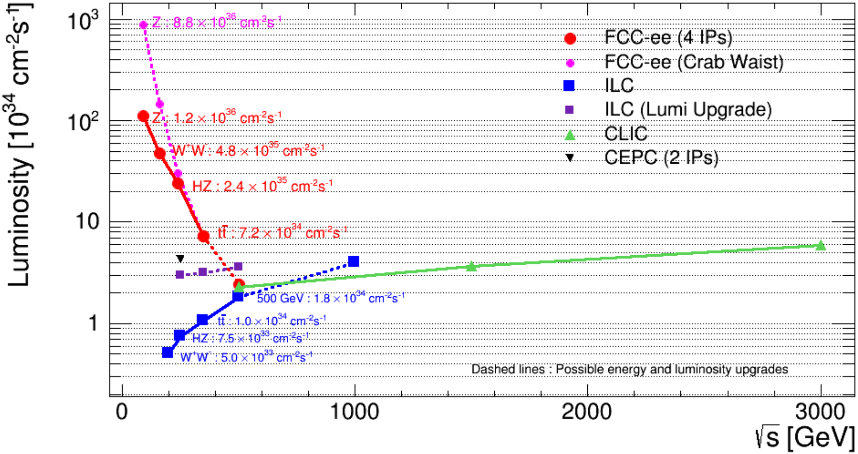
Stability criteria as a function of top and Higgs boson mass



Higgs mass in GeV

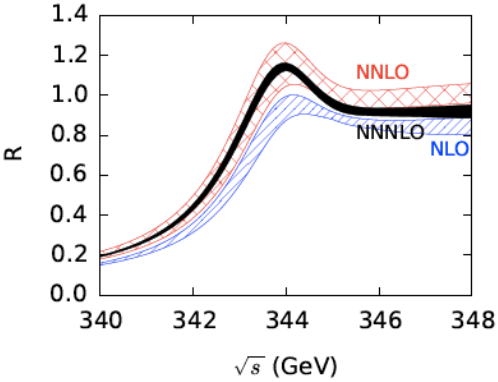
Future e^+e^- colliders

Expected luminosity of considered accelerators



Top threshold

Results of the NNNLO threshold cross section computations



arXiv:1506.06864[hep-ph]

Prospects for reducing theoretical uncertainty to 20 MeV

Rare decays

Expected maximal FCNC branching ratios for different models

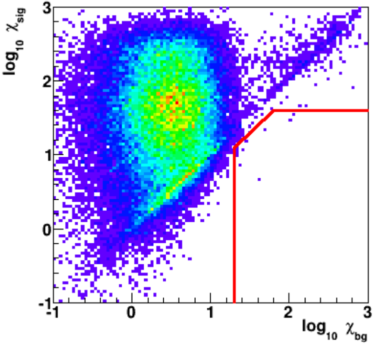
Model	BR($t \to c\ H$)	BR($t \to c\ \gamma$)	BR($t \to c\ g$)	BR($t \to c\ Z$)
SM	$3 \cdot 10^{-15}$	$5 \cdot 10^{-14}$	$5 \cdot 10^{-12}$	10^{-14}
2HDM	10^{-5} - 10^{-4}	10^{-9}	10^{-8}	10^{-10}
2HDM (FV)	10^{-3} - 10^{-2}	10^{-6} - 10^{-7}	10^{-4}	10^{-6}
MSSM	10^{-5} - 10^{-4}	10^{-8} - 10^{-6}	10^{-7} - 10^{-4}	10^{-8} - 10^{-6}
$\not{R}$ SUSY	10^{-9} - 10^{-6}	10^{-9} - 10^{-5}	10^{-5} - 10^{-3}	10^{-6} - 10^{-4}
Little Higgs	10^{-5}	$1.3 \cdot 10^{-7}$	$1.4 \cdot 10^{-2}$	$2.6 \cdot 10^{-5}$
Quark Singlet	$4.1 \cdot 10^{-5}$	$7.5 \cdot 10^{-9}$	$1.5 \cdot 10^{-7}$	$1.1 \cdot 10^{-4}$
Randal-Sundrum	10^{-4}	10^{-9}	10^{-10}	10^{-3}

Rare decays

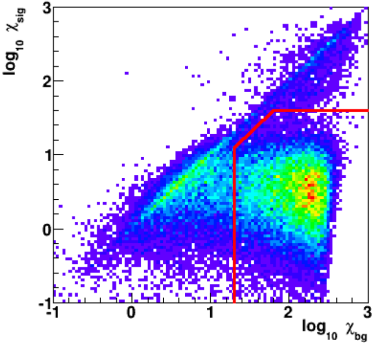
Selection of $t \to cH$ events - comparison of signal and bg. hypothesis

Correlation of $\log_{10} \chi^2$ for two hypothesis (possible cut indicated)

SM background



Signal events



80% *b*-tagging efficiency (scenario B)