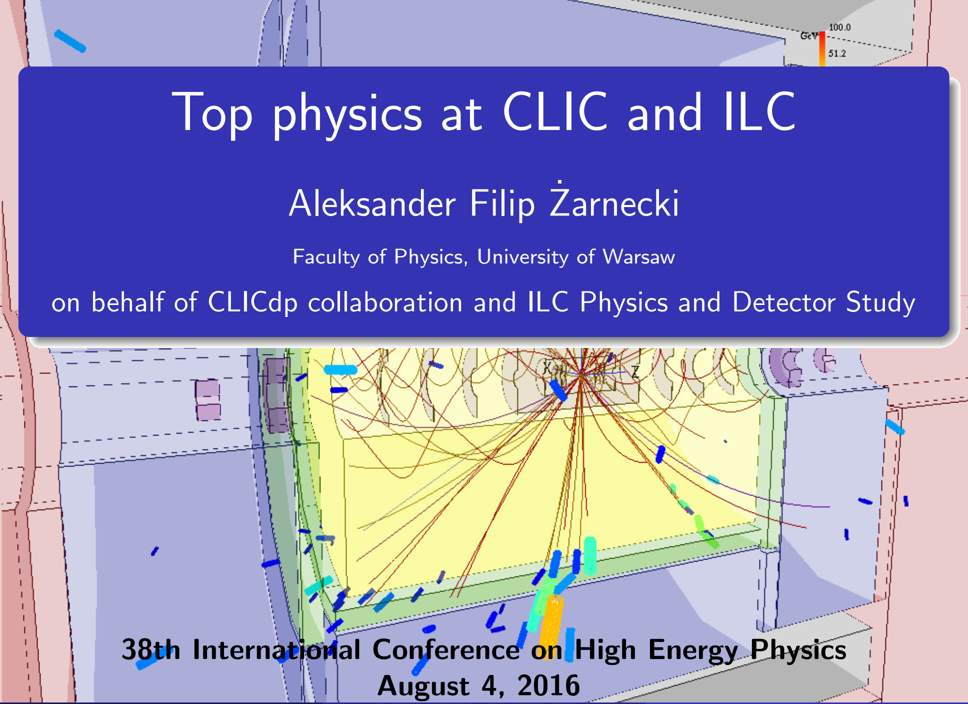


Top physics at CLIC and ILC

Aleksander Filip Żarnecki

Faculty of Physics, University of Warsaw

on behalf of CLICdp collaboration and ILC Physics and Detector Study

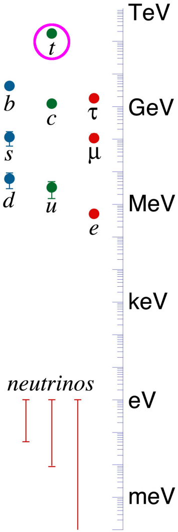
38th International Conference on High Energy Physics

August 4, 2016

Outline

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

Motivation

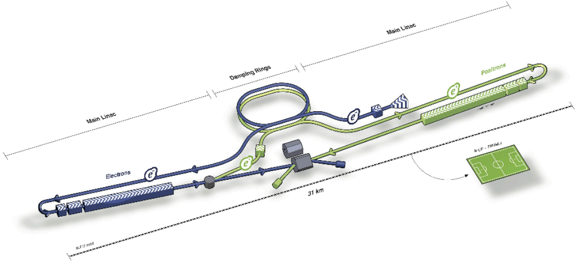


Credit: Hitoshi Murayama

Top quark

- the heaviest known elementary particle
- Yukawa coupling to Higgs boson $y_t \sim 1$
  $\Rightarrow$ 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"

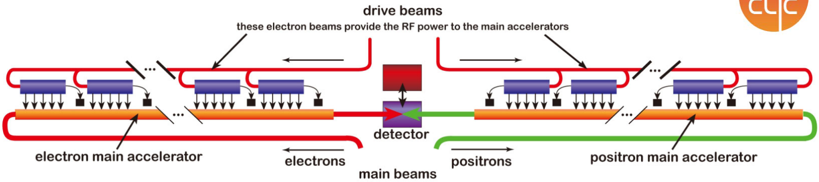
International Linear Collider



Technical Design (TDR) completed 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%)

Compact LInear Collider



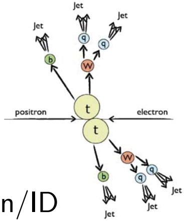
Conceptual Design (CDR) presented in 2012 CERN-2012-007

- high gradient, two-beam acceleration scheme
- staged implementation plan with c.m.s energy from 380 GeV to 3 TeV
- footprint of 11 to 50 km
- e^{-} polarisation, e^{+} polarisation as possible upgrade
- ongoing R&D and large-scale system tests

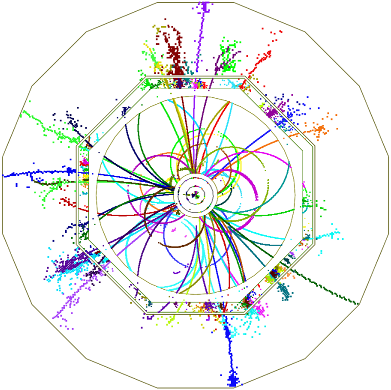
Detector Requirements

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

Single particle reconstruction/ID
$\Rightarrow$ high calorimeter granularity



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



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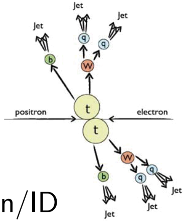

Single particle reconstruction/ID
$\Rightarrow$ high calorimeter granularity

Best possible jet energy estimate
$\Rightarrow$ precise momentum measurement

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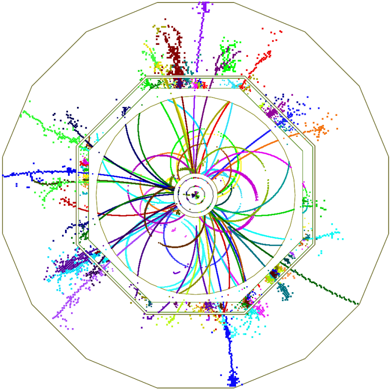

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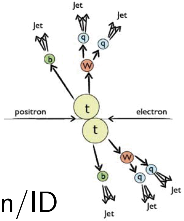
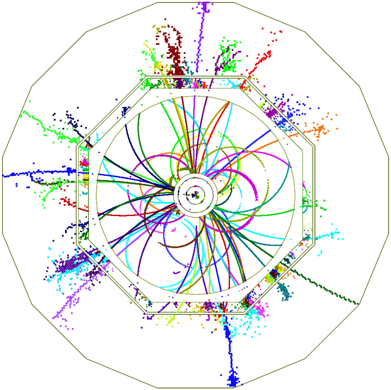


Single particle reconstruction/ID
$\Rightarrow$ high calorimeter granularity

Best possible jet energy estimate
$\Rightarrow$ precise momentum measurement

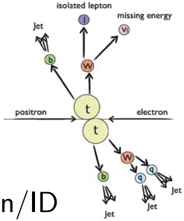
Very efficient flavour tagging
$\Rightarrow$ high precision vertex detector

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



Detector Requirements

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



Single particle reconstruction/ID
⇒ high calorimeter granularity

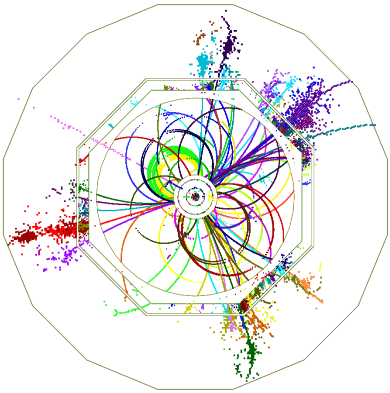
Best possible jet energy estimate
⇒ precise momentum measurement

Very efficient flavour tagging
⇒ high precision vertex detector

Missing energy measurement
⇒ hermecity

Benchmark reaction

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



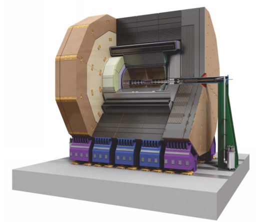
Experiments

Detector Requirements

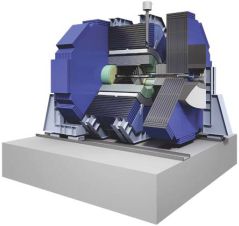
- Track momentum resolution: $\sigma_{1/p} < 5 \cdot 10^{-5}\ \mathrm{GeV}^{-1}$
- Impact parameter resolution: $\sigma_d < 5\mu m \oplus 10\mu m\ \frac{1\ \mathrm{GeV}}{p\ \sin^{3/2}\Theta}$
- Jet energy resolution: $\sigma_E/E = 3 - 4\%$ (highest jet energies)
- Hermecity: $\Theta_{min} = 5$ mrad

Three detailed LC detector concepts:

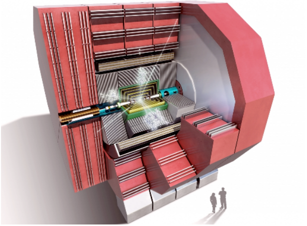
ILD



SiD



CLIC



Running scenarios

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

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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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)

CLIC running scenario

Three construction stages (each 5 to 7 years of running)

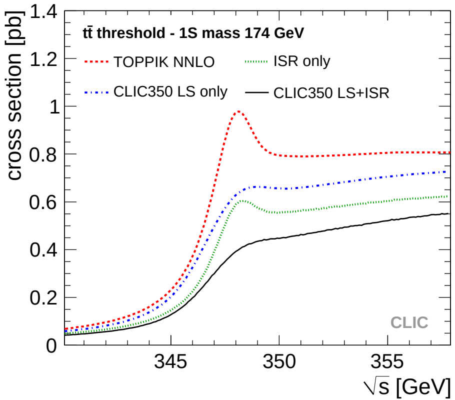
- $\sqrt{s} = 380$ GeV with 500 fb^{-1} + 100 fb^{-1} at $t\bar{t}$ threshold
  selected as an optimal choice for precision Higgs and top physics
- $\sqrt{s} = 1.5$ TeV with 1500 fb^{-1}
- $\sqrt{s} = 3$ TeV with 3000 fb^{-1}

Threshold scan

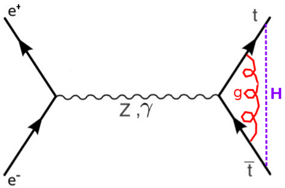
Top pair production cross section around threshold:

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
- strong coupling α_s
- top Yukawa coupling y_t

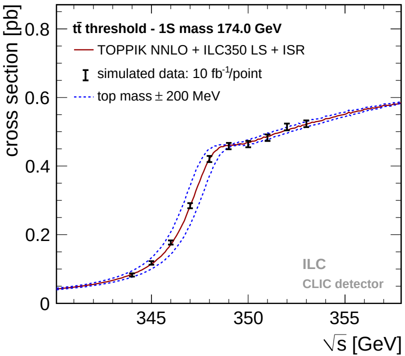


Significant cross section smearing due to luminosity spectra and ISR

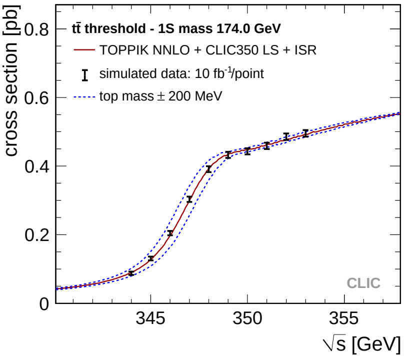
Threshold scan

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

ILC

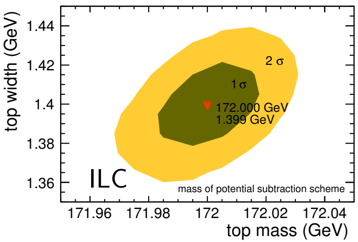


CLIC

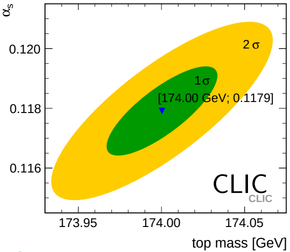


Energy scan: 10 cross section measurements, 10 fb^{-1} each

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



T.Horiguchi et al., arXiv:1310.0563



K.Seidel et al., Eur. Phys. J. C73 (2013) 2530

- statistical uncertainty 15–20 MeV
- current theoretical uncertainties ∼40 MeV F.Simon ID:953 (poster)

  \+ parametric α_s uncertainty ∼30 MeV (for today's WA)
- other uncertainties (backgrounds, spectra, etc.) on 10–20 MeV level

⇒ total uncertainty on the top mass ∼50 MeV feasible

- top width can be extracted to 40 MeV A.Ishikawa @ TopLC'2015

Top mass

Threshold scan

Main advantage: well defined from theoretical point of view
Total uncertainty on the top mass ∼50 MeV

Direct reconstruction

K.Seidel et al., Eur. Phys. J. C73 (2013) 2530

Possible for all energies above the threshold (continuum)
High statistical precision: 80 MeV estimated for 100 fb^{-1} at 500 GeV
Suffers from significant theoretical uncertainties when converting to particular mass scheme (as in LHC).

Radiative events

P. Gomis @ ECFA LC Workshop 2016

At higher energies, we are still sensitive to $t\bar{t}$ threshold in radiative events.
Threshold in ISR distribution ⇒ statistical precision ∼100 MeV feasible

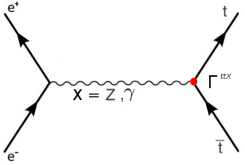
Other considered methods

- *b*-jet energy distribution ("one prong") R.Franceschini @ TopLC'2016
- event shape analysis (Thrust distribution) A.Hoang @ TopLC'2016

Electroweak couplings

Pair production provides direct access to top electroweak couplings

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



General coupling form:

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

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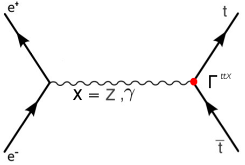

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Form factors can be constrained through measurement of:

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

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

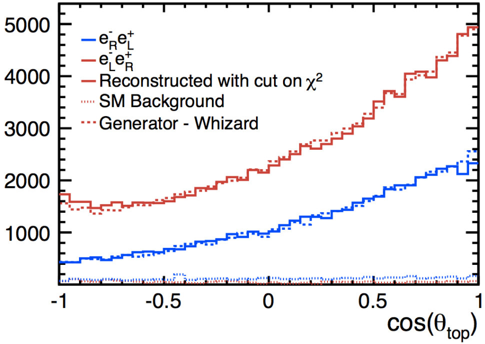
Electroweak couplings

$500\ fb^{-1}$ @ $500\ GeV$

The cross section can be measured to 0.5%

For semi-leptonic events slope of the helicity angle distribution measured to $\sim$4%

Polar Angle Spectrum requires tighter selection cuts to reach 2% precision



Detailed simulation of the ILD detector
M.S. Amjad, et al., Eur.Phys.J. C75 (2015) 512

Electroweak couplings

$500\ fb^{-1}$ @ 500 GeV

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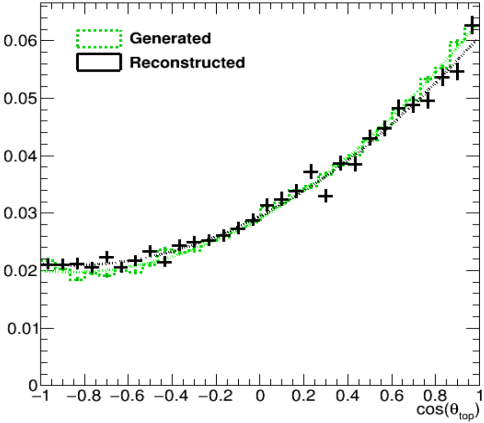
For semi-leptonic events slope of the helicity angle distribution measured to ∼4%

Polar Angle Spectrum requires tighter selection cuts to reach 2% precision

Analysis can still be improved by b-jet charge reconstruction



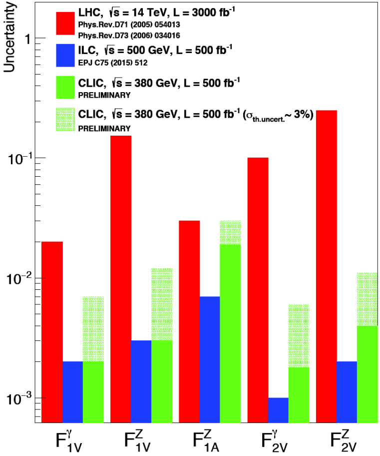
ongoing study for ILD, S.Bilokin @ TopLC'2016

With improved particle ID one could also consider using hadronic decays

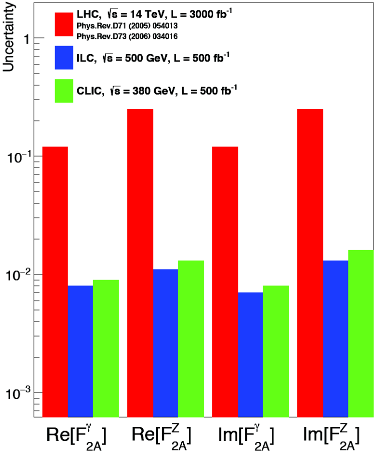
Electroweak couplings

Expected coupling precision at LHC, ILC (500 GeV) and CLIC (380 GeV)
initial stage

CP conserving couplings

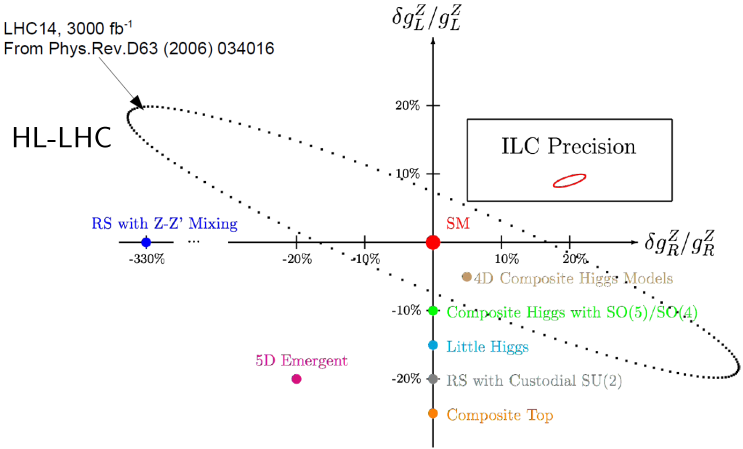


CP violating couplings



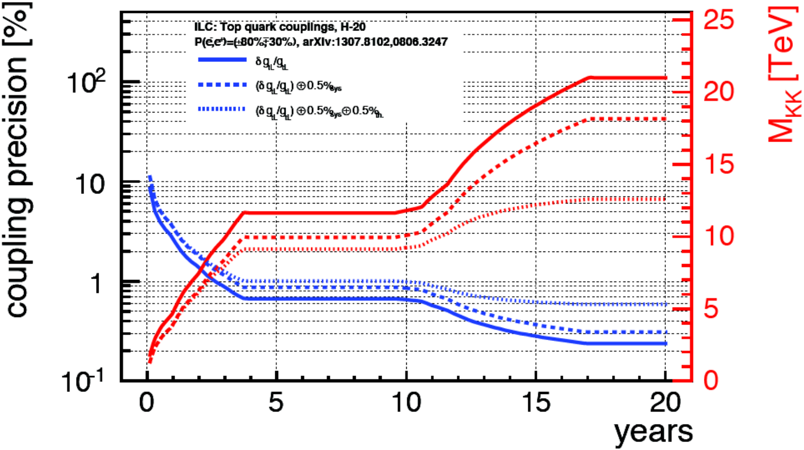
IFIC-LAL Collaboration, M.Perello @ ECFA LC'2016

Already with 500 fb^{-1} top coupling determinated to $\sim$1% at ILC



⇒ significant constraints on different SM extensions

Already with 500 fb^{-1} top coupling determinated to $\sim$1% at ILC



$\Rightarrow$ to profit from ILC luminosity upgrade we need to control theoretical and experimental uncertainties to per mille level

Yukawa coupling

Threshold scan

A.Ishikawa @ TopLC'2015

Pair production at threshold: 9% Higgs exchange contribution

$\Rightarrow$ y_t can be extracted with statistical uncertainty $\sim$6% (100 fb^{-1}),

assuming α_s can be constrained from other measurements

theoretical uncertainties $\sim$20%, need to be reduced

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A.Ishikawa @ TopLC'2015

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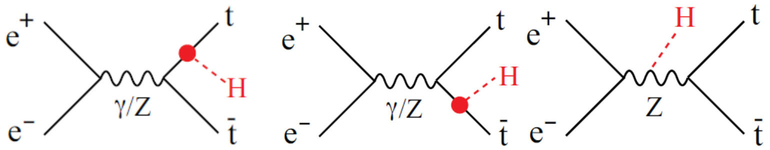
Higher energies (above 500 GeV)

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



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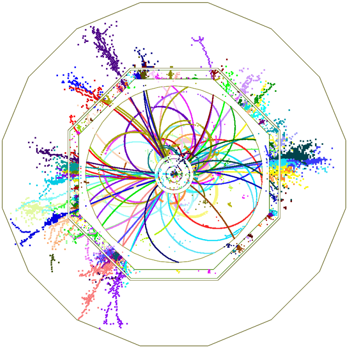
Can be extracted from the measurement of $e^+e^- \rightarrow t\bar{t}H$ events

Difficult measurement:

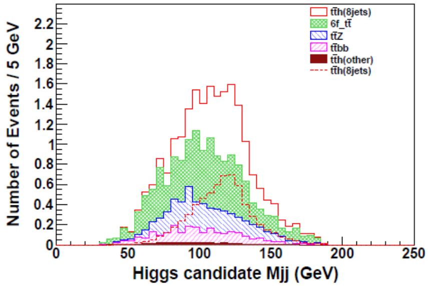
- very low statistics
- large backgrounds
- requires perfect detector performance (8 jets, 4 b-tags)



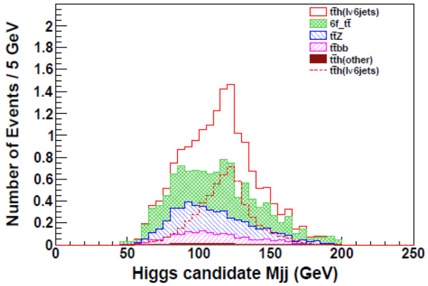
ILD simulation, $2\times 500\ \mathrm{fb}^{-1}$ at 500 GeV

Y.Sudo @ TopLC'2016

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



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



$\Rightarrow$ statistical uncertainty of about 11% (6.4% with 4'000 fb^{-1})

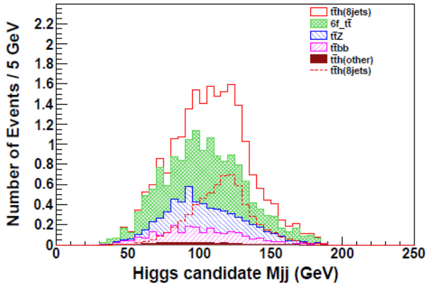
Yukawa coupling

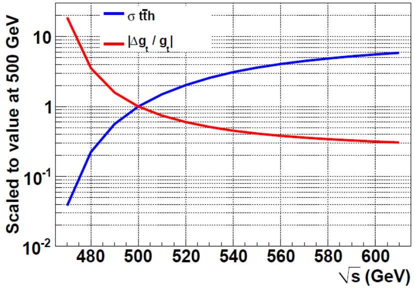
ILD simulation, 2×500 fb^{-1} at 500 GeV

Y.Sudo @ TopLC'2016

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

Precision vs energy





$\Rightarrow$ statistical uncertainty of about 11% (6.4% with 4'000 fb^{-1})

Significant improvement when going to higher energies:

- 4% at 520 GeV and 3% at 540 GeV, with 4'000 fb^{-1}
- 4-5% at 1 TeV (ILC) or 1.4 TeV (**CLIC**), with 1'500 fb^{-1}

T.Price et al., Eur.Phys.J. C75 (2015) 309

Rare decays

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

$BR(t \to c\,\gamma) \sim 5 \cdot\ 10^{-14}, \quad BR(t \to c\,Z) \sim 1 \cdot 10^{-14}, \quad BR(t \to c\,H) \sim 3 \cdot 10^{-15}$

Significant enhancement possible in many "new physics" scenarios

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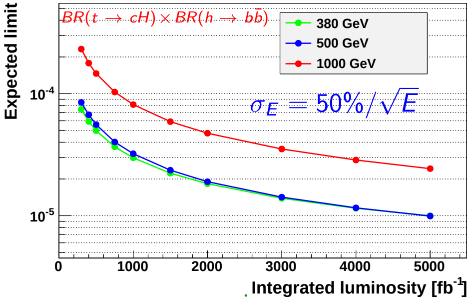
Significant enhancement possible in many "new physics" scenarios

Decay $t \to c\,H$ most interesting

- enhancement up to 10^{-5}–10^{-2}
- test of Higgs boson couplings
- well constrained kinematics
- seems most difficult for LHC
  Run II: $BR < 0.46\%$
  HL-LHC: $BR < 2 \cdot 10^{-4}$

Parton level simulation results, 2HDM(III)



A.F.Żarnecki @ TopLC'2015

Full simulation study ongoing.

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

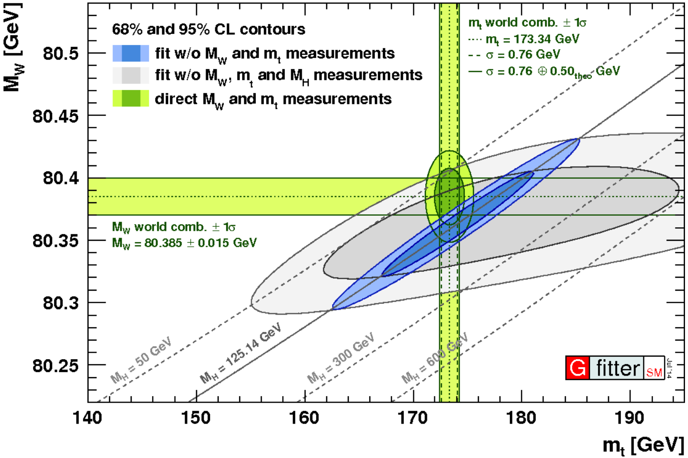
High precision and background suppression capabilities allow per mile level measurements and searches for rare processes.

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

Thank you!

Motivation

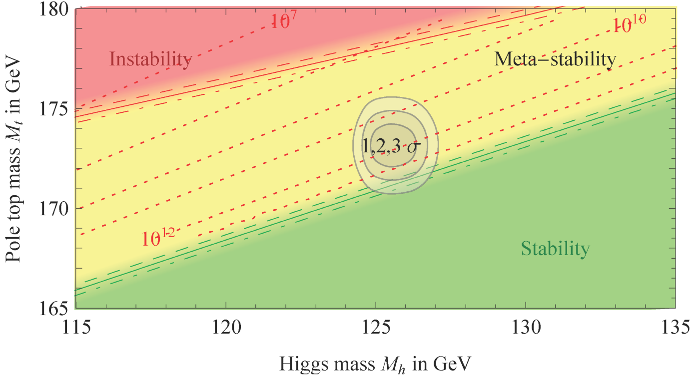
Precise determination of the top mass and other properties crucial for Standard Model verification and indirect "new physics" searches



Motivation

Top mass is a key to understanding of the SM stability

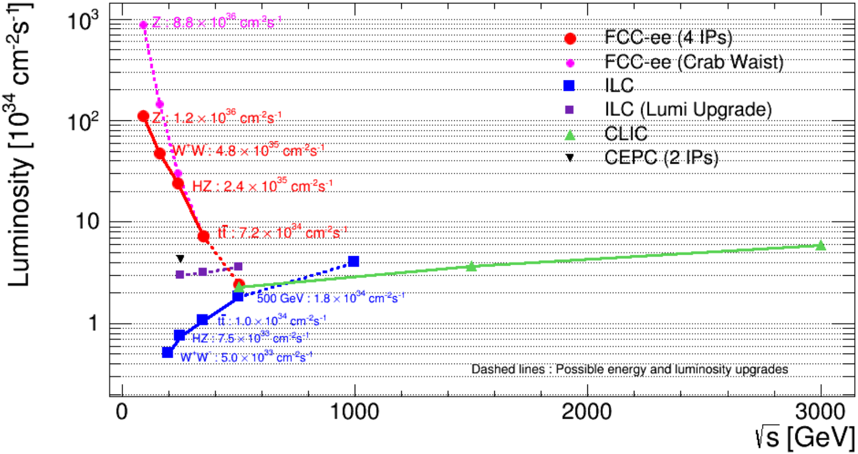
G.Degrassi et al., JHEP 1208 (2012) 098



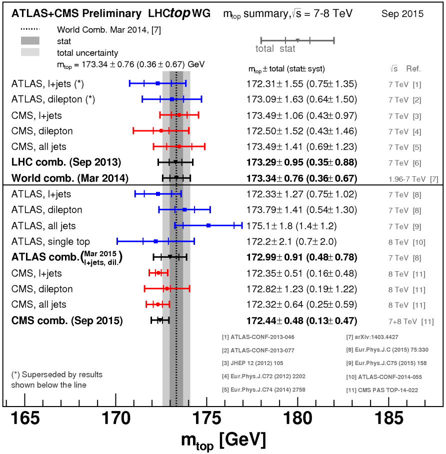
uncertainty on the stability conditions dominated by top mass

Future e^+e^- colliders

Expected luminosity of considered accelerators



Top mass

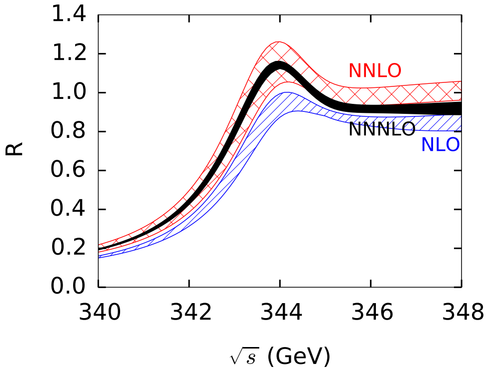


LHC mass measurements
dominated by systematics

The mass extracted from data-MC comparison
⇒ theoretical uncertainties
when converting to particular mass scheme

Top mass

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



LHC mass measurements
dominated by systematics

The mass extracted from data-MC comparison
⇒ theoretical uncertainties
when converting to particular mass scheme

Threshold for

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

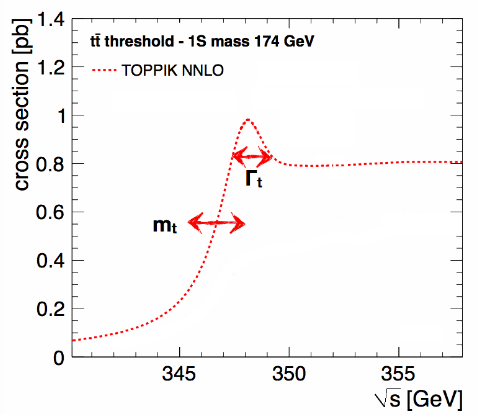
⇒ much better understood

theoretical error below 50 MeV feasible

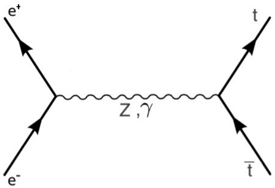
Top pair production cross section around threshold:

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

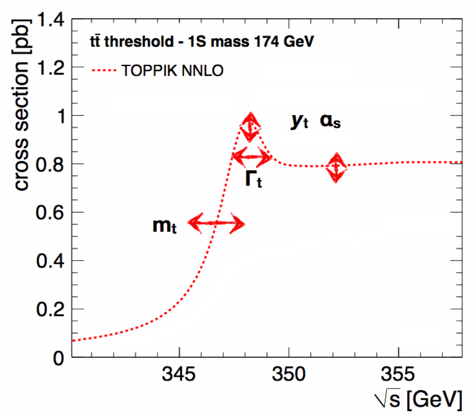


Threshold scan

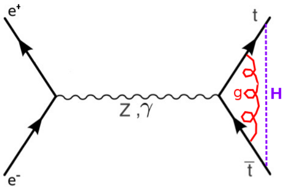
Top pair production cross section around threshold:

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
- strong coupling α_s
- top Yukawa coupling y_t

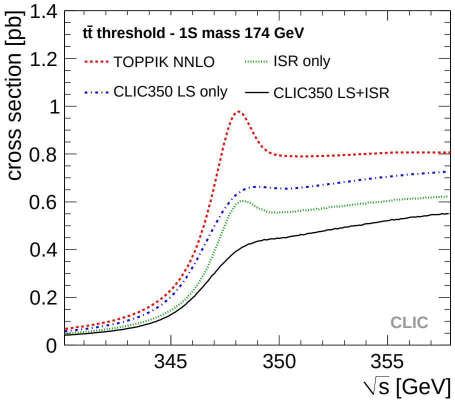


Threshold scan

Top pair production cross section around 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
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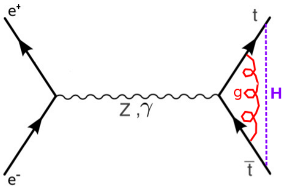


Significant cross section smearing due to luminosity spectra and ISR

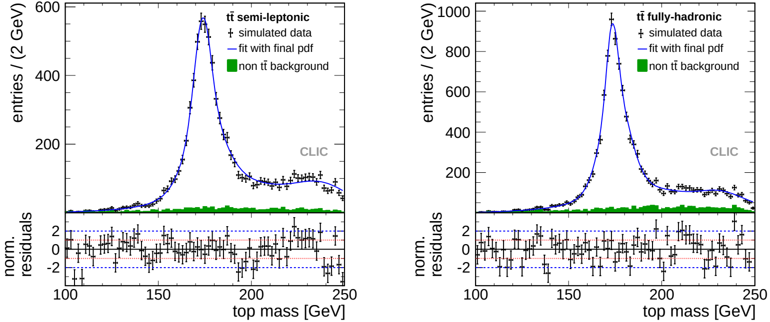
Continuum

Mass measurement above the threshold is still interesting

- help to understand the "different" masses better
- try to see the running of the top quark mass

For CLIC running at 500 GeV

K.Seidel et al., Eur. Phys. J. C73 (2013) 2530

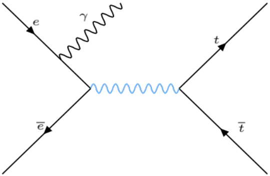


⇒ statistical precision of 80 MeV expected already with 100 fb^{-1}

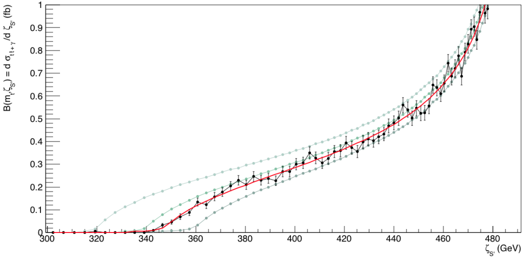
Radiative events

At higher energies, we are still sensitive to $t\bar{t}$ threshold in radiative events. We can determine threshold position by reconstructing

$$s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$



P. Gomis @ ECFA LC Workshop 2016



⇒ statistical precision of 100 MeV feasible   full simulation study ongoing