Measurement of the top quark mass and couplings at Linear Colliders

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On behalf of the ILC Physics and Detector Study and CLICdp

INSTITUTO DE FÍSICA CORPUSCULAR

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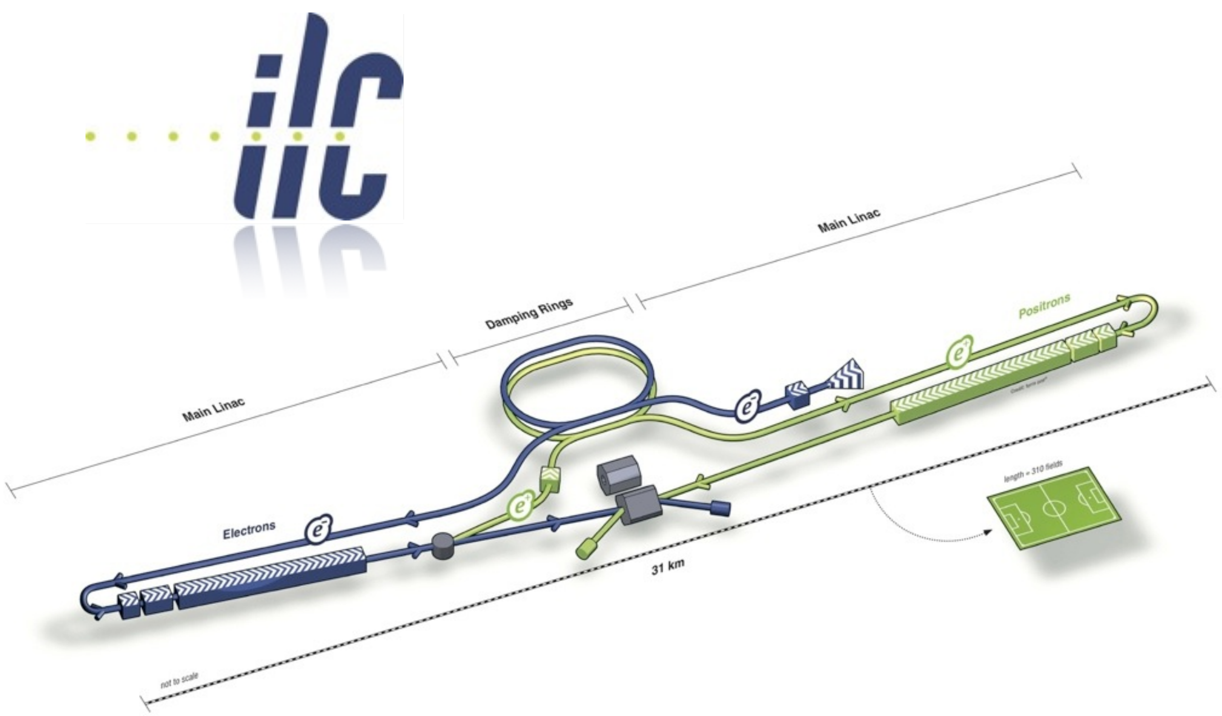
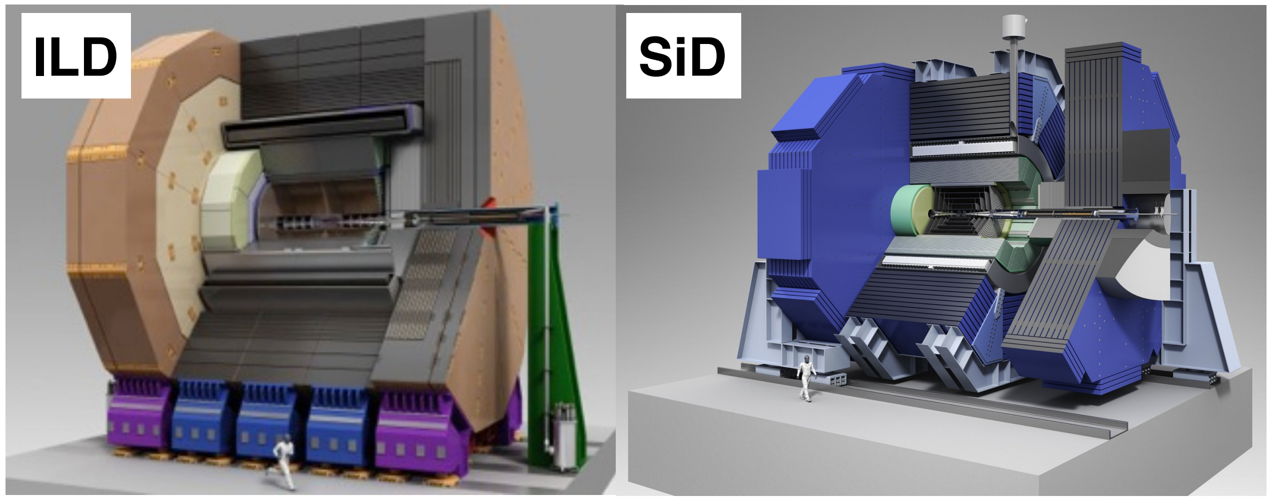
International Linear Collider (ILC)





ILD and **SiD detectors** are optimised for:
Particle Flow Algorithm (PFLOW)

Electron positron collisions

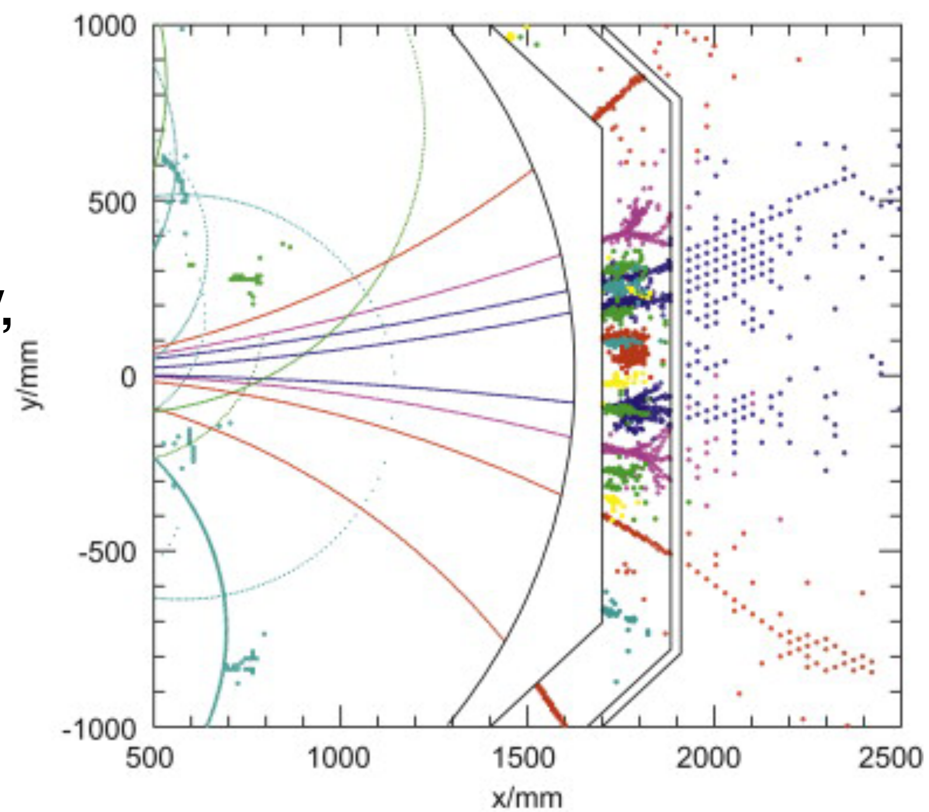
Superconducting acceleration technology

$\mathbf{E_{cms}}$ tuneable between **200 GeV** and **500GeV,** posible upgrade to **1TeV**

Integrated $\mathcal{L}$ **= 500 fb^{-1}** (2 years of running)

Beams are polarised:
P(e^{-}) ≈ ± 80% , P(e^{+}) ≈ ± 30%

About **31 km** site length



The **energy of charged hadrons** will be measured by the **tracking detectors**

The **energy of photons** will be measured by the **electromagnetic calorimeter**

The **hadronic calorimeter** is then used only to measure the **energy of neutral hadrons**

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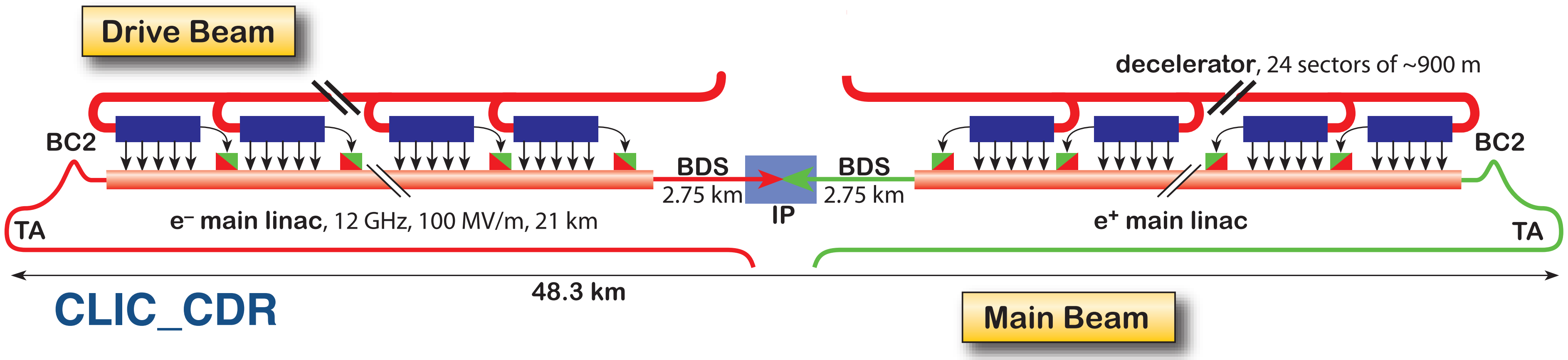
Compact Linear Collider (CLIC)



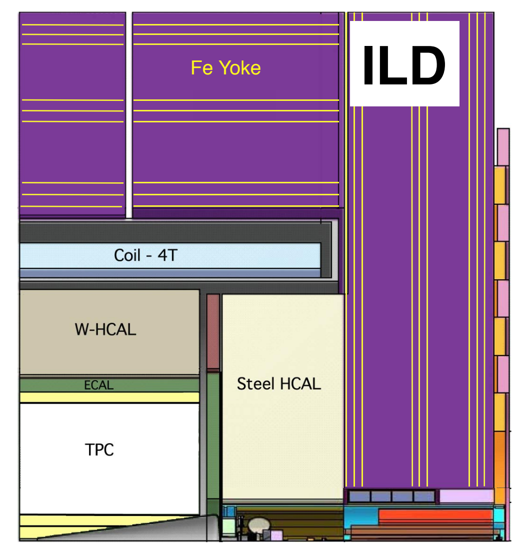
Electron-positron collider in the **multi-TeV** energy range

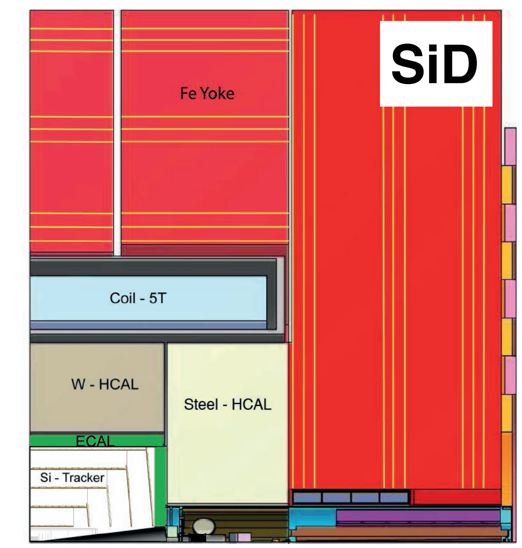
About **48 km** site length

The c.o.m. energy: **$\sqrt{s}$ = 3 TeV** (default design)
500 GeV - 1.5 TeV

Luminosity: **$\mathcal{L}$ = 2x10^{34} cm^{-2}s^{-1}**

Intense R&D in the CLIC collaboration to fully develop two-beam acceleration at high gradients





A **CLIC_ILD** and **CLIC_SiD** detector concepts have been developed from the ILD and SiD detector concepts for ILC

Modifications motivated by the **more challenging experimental conditions** at CLIC and by the **higher collision energy**

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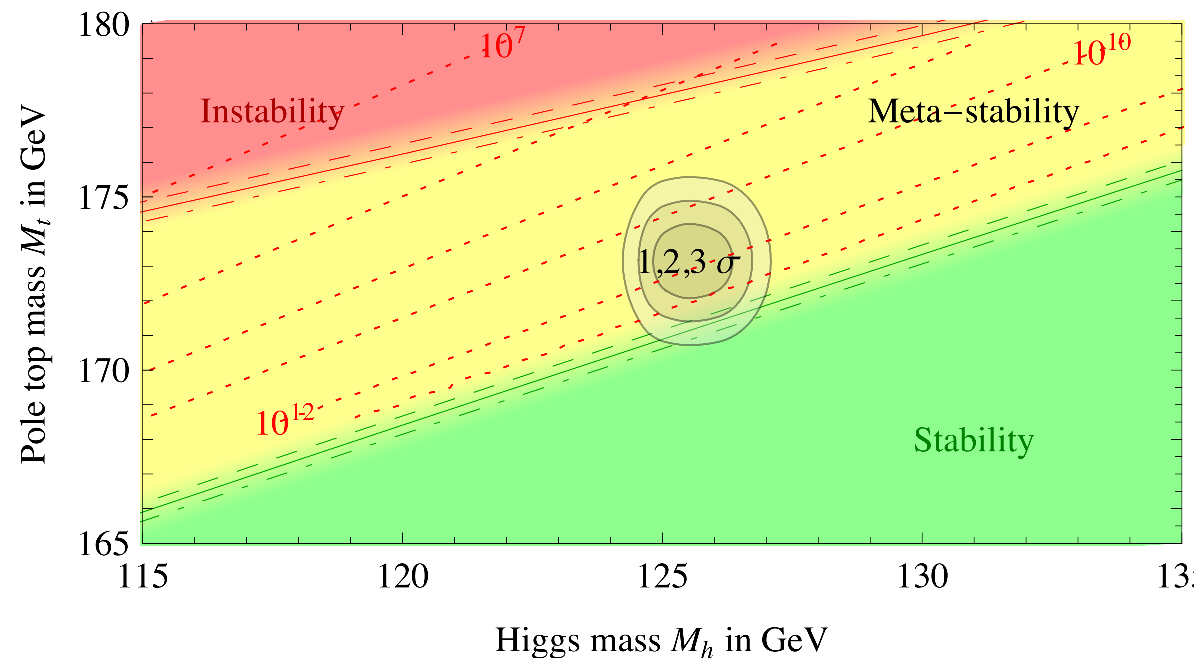
Motivation

arXiv:1205.6497



Top quark mass

- A small change in M_h and M_t can **drastically modify** the conclusions regarding **vacuum stability**
- M_t **must be characterised well**

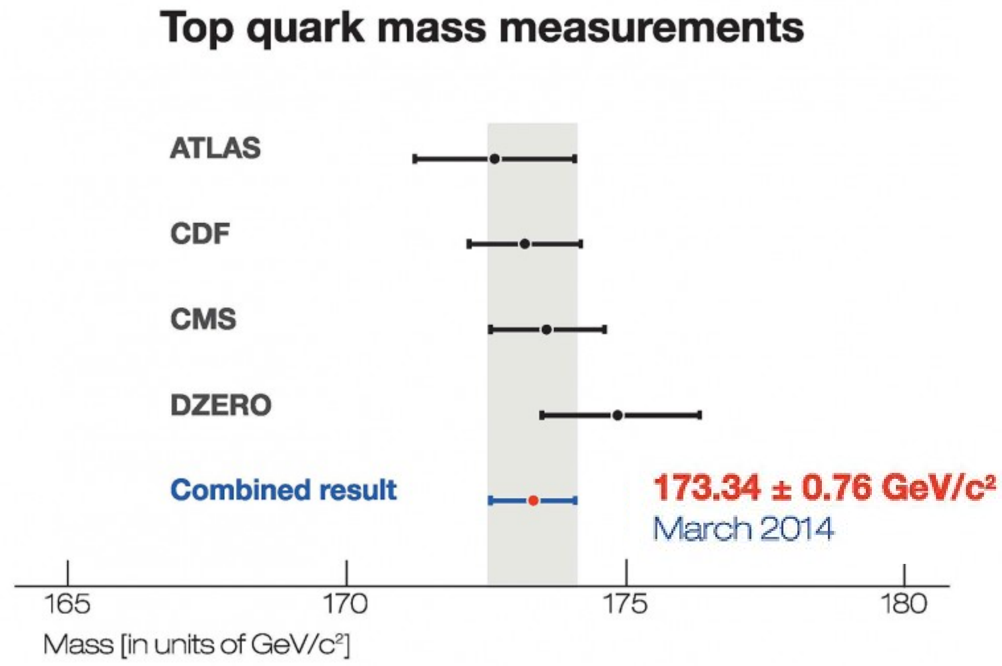
Top quark electroweak couplings

- **Learn about BSM** physics from the deviations observed on Higgs and top EW couplings.
- LHC cannot achieve enough accuracy in the measurement of the coupling deviations -> **ILC accuracies** are needed to access to **fully significant deviations** **arXiv:1403.2893**

Precision in the measurement of the top quark mass

- **Hadron colliders** achieve precisions in the measurement of the top mass of **~ 0.76 GeV**

Historical result, first ever LHC/Tevatron Combination [arXiv:1403.4427]



- At **linear colliders** there are **two techniques** to determine the mass of the top quark

1. Direct reconstruction of top from its decay products (above threshold)

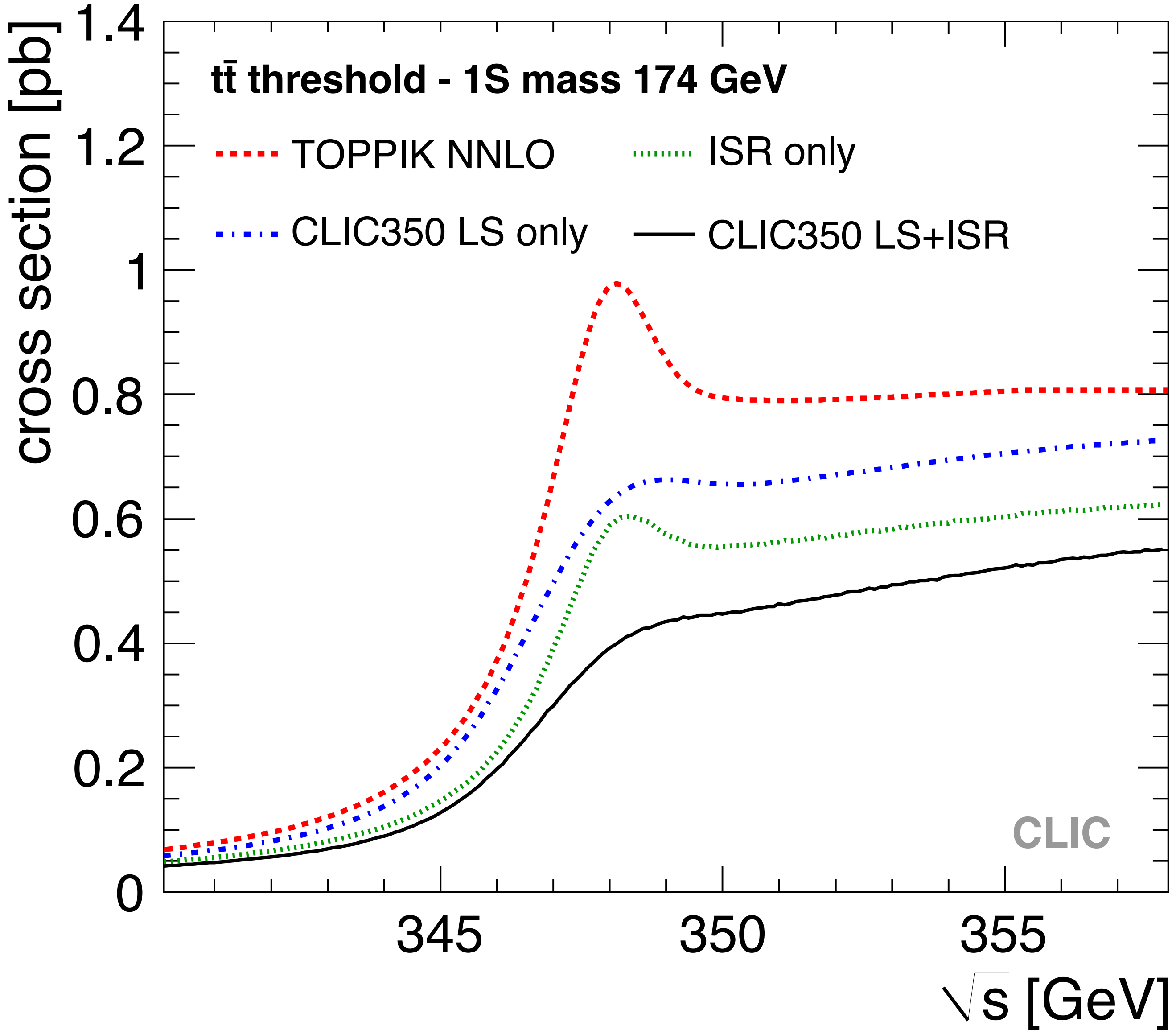
Experimentally well-defined but the generated mass is **not well-defined theoretically** and non-perturbative corrections could be substantial

2. A scan of the top pair production threshold

High degree of precision using a **theoretically** well-defined top mass (**1*S* mass**, can be transformed into other mass schemes). Precise top mass measurement with **well-controlled theory uncertainties**

See details about the **1*S* mass scheme**: arXiv:hep-ph/9904468v2

The $t\bar{t}$ threshold



- Top mass input **174 GeV** in the **1S mass scheme** and α_s **= 0.118**
- **NNLO calculations** provided by the code *TOPPIK*
- Corrections for **ISR** and **luminosity spectrum**
- These corrections result in a **smearing of the cross section** peak at threshold

- The **smearing** is due to the **statistical efficiency**, reduced by the luminosity spectra. Not affected by systematics.

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Event generation, detector simulation and reconstruction

$e^+e^- \rightarrow t\bar{t}$ **production at threshold CLIC@352 GeV**

m_t **= 174.0 GeV**

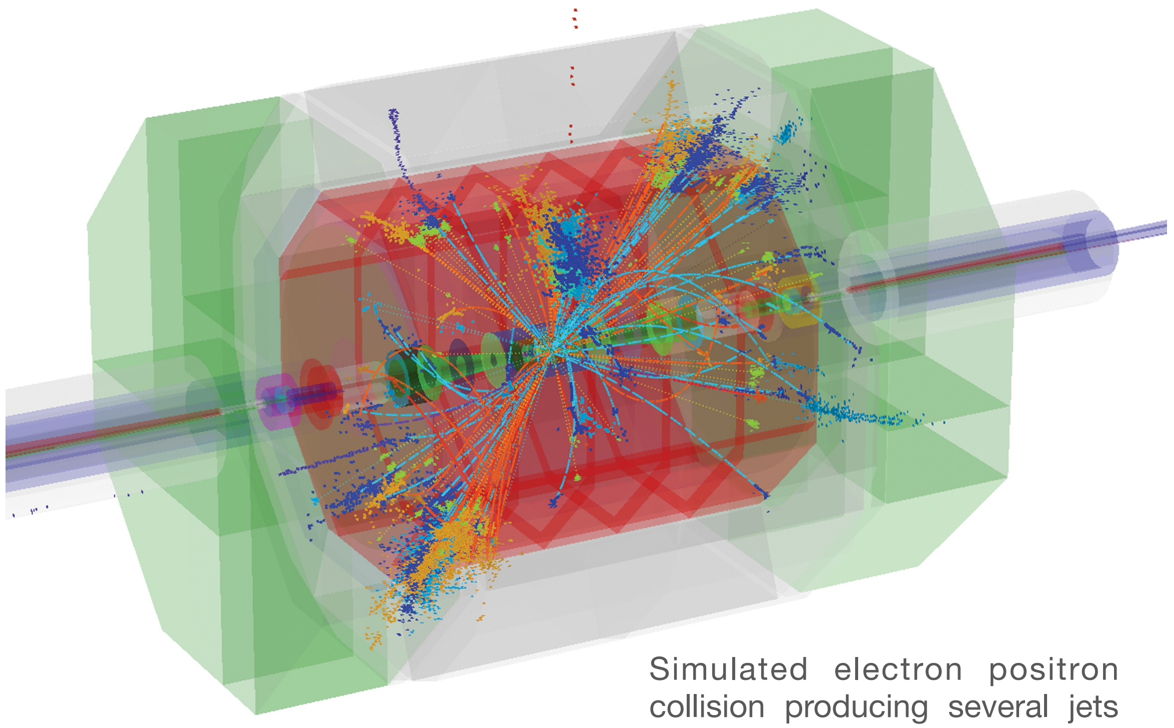
Γ_t **= 1.37 GeV**

1. Generated events (signal + background)

Pythia: $e^+e^- \rightarrow t\bar{t}, WW, ZZ$

WHIZARD: $e^+e^- \rightarrow q\bar{q}, q\bar{q}e^+e^-, q\bar{q}e\nu$

+ beam backgrounds are included



Simulated electron positron collision producing several jets in the ILD-like detector at CLIC

2. Simulation of the detector

Full simulation with high level of realism

3. Reconstruction

Standard algorithms

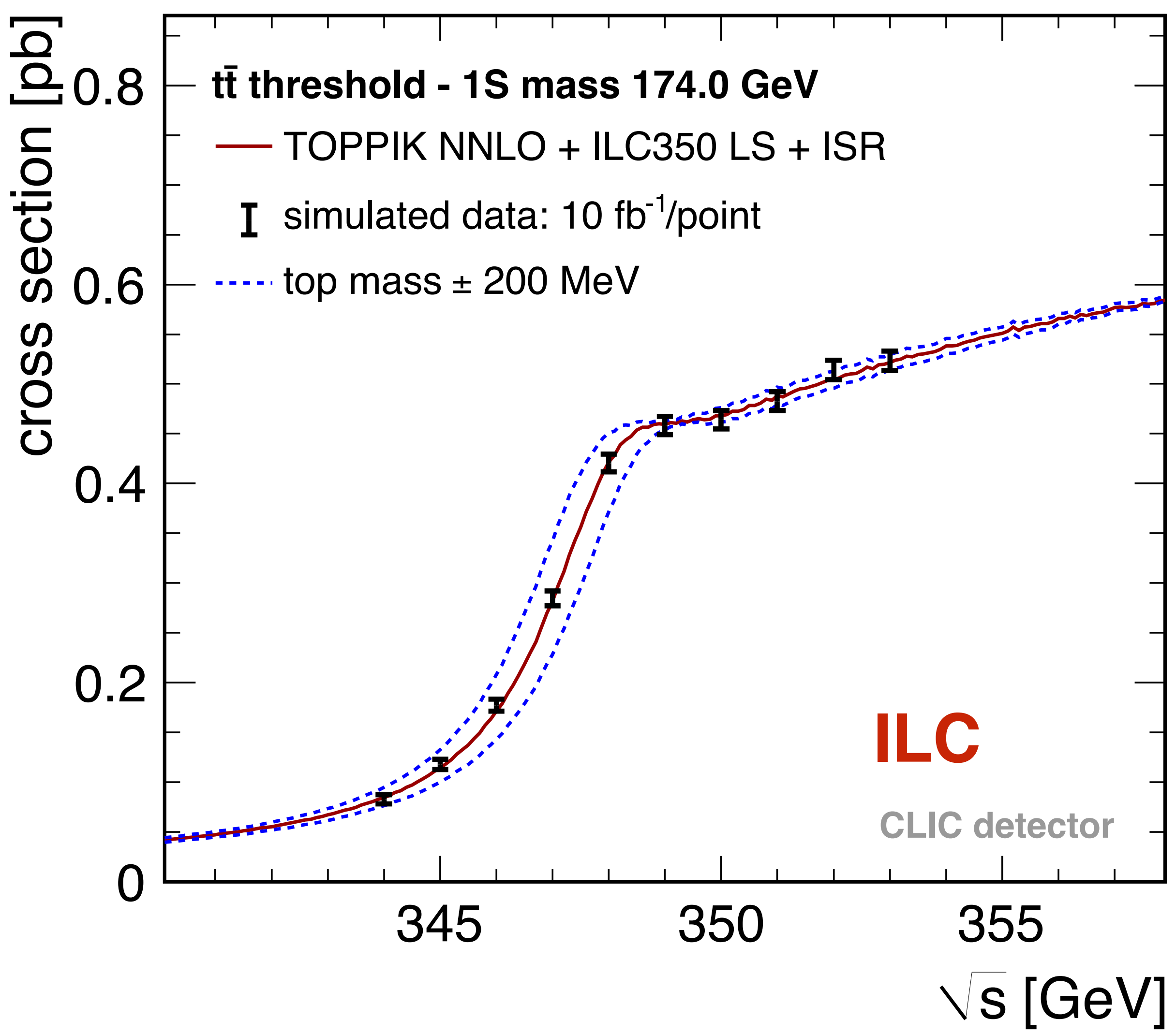
Kinematic fitting: Grouping W-bosons and b-jets into top quarks

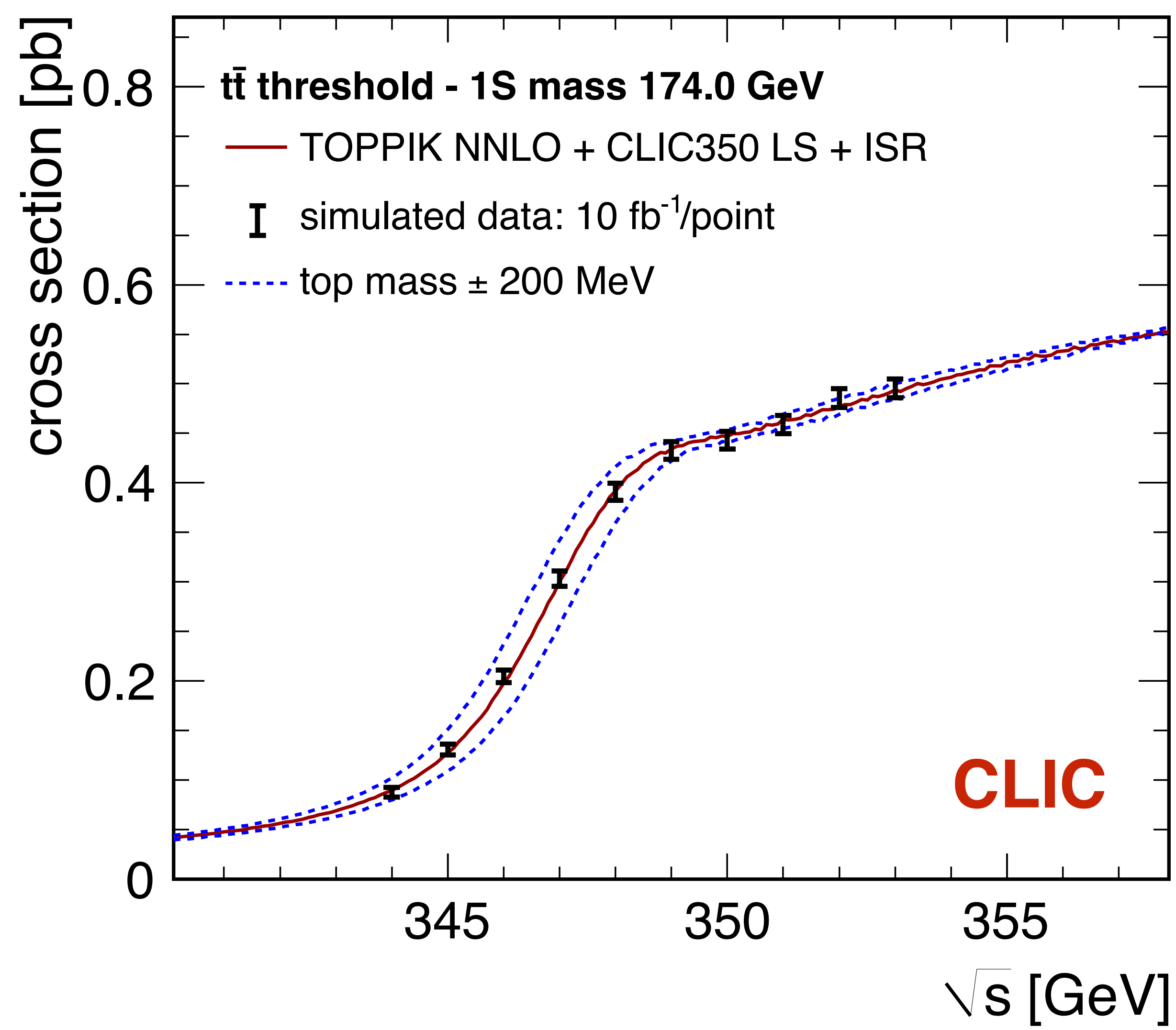
Katja Seidel, Frank Simon, Michal Tesar, Stephane Poss
Eur. Phys. J. C73 (2013) 2530

Top mass measurement in a threshold scan

- The **cross-section depends on** the **top mass**, so measuring the cross-section the top mass can be extracted (Also the α_s, Yukawa coupling, top width…)
- Inclusion of **higher-order QCD contributions** are needed for a correct description of the cross section
- Determination of **event selection efficiency** and **background contamination**
- Threshold scan with **10 energy points** spaced by 1 GeV **from 344 GeV to 353 GeV** with an integrated **luminosity of 10 fb^{-1}**

Threshold scans at ILC and CLIC





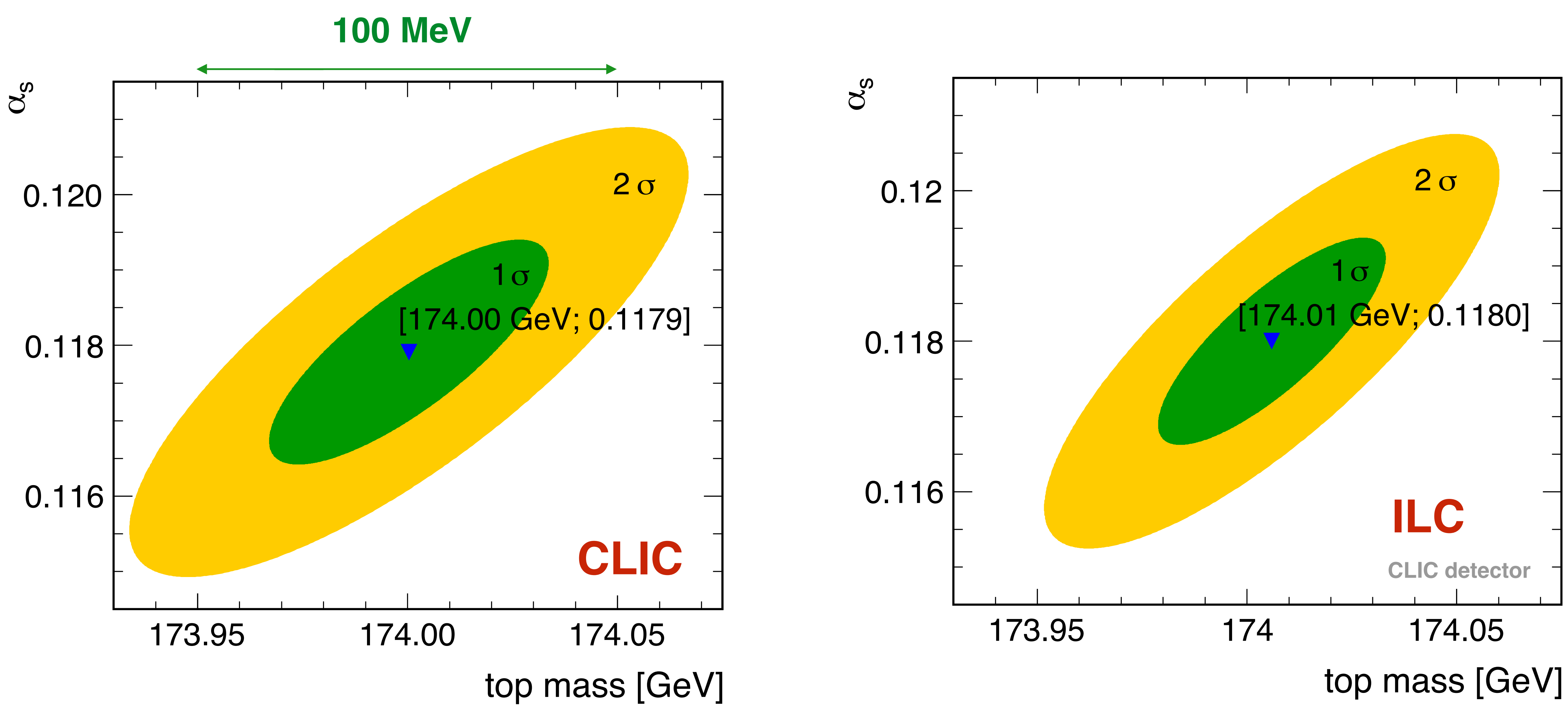
The cross section for ILC rises faster due to the luminosity peak is narrower

But it does not result in a significant difference of the precision of the top quark mass measurement

Measurement of the top mass and α_s at CLIC and ILC

- **Statistical uncertainty of top mass around 30 MeV** (CLIC ~ 20% larger than ILC due to different luminosity spectrum)

- In addition: **Experimental** and **theoretical systematics**, and uncertainties from the **conversion to the $\overline{\text{MS}}$** mass scheme. **Total uncertainty below 100 MeV** within reach.



Top quark electroweak couplings at the ILC

- **The process $e^+e^- \rightarrow t\bar{t}$ involves only $t\bar{t}Z_o$ and $t\bar{t}\gamma$ primary vertices**
- A way to describe the current at the $t\bar{t}X$ vertex:
- See details in: arxiv.org/abs/hep-ph/0601112

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

where:

V = Vector coupling

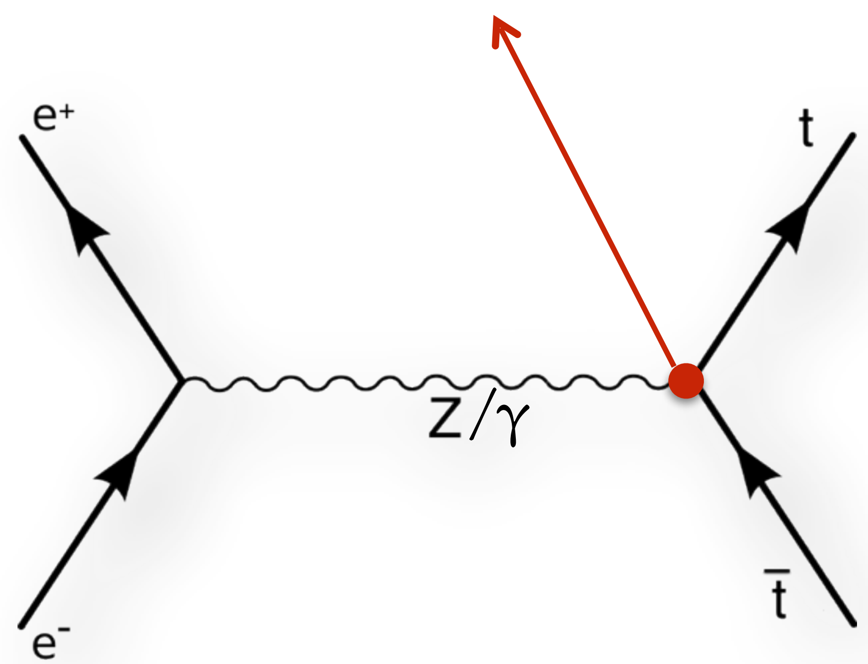
A = Axial coupling

X = Z,γ

$F_{1V}^\gamma \quad F_{1A}^\gamma \quad F_{2V}^\gamma$

$F_{1V}^Z \quad F_{1A}^Z \quad F_{2V}^Z$

Non CP violating top quark couplings



$e^+e^- \rightarrow t\bar{t}$ **semi-leptonic channel at ILC@500 GeV**

M.S. Amjad, M. Boronat, et al
http://www-flc.desy.de/lcnotes/
LC-REP-2013-007

1. Generated events (signal)

WHIZARD: Generate 6 fermions final state $e^+e^- \rightarrow q\bar{q}b\bar{b}l\nu$

Pythia: Parton shower and hadronisation

+ WbWb and beam backgrounds added

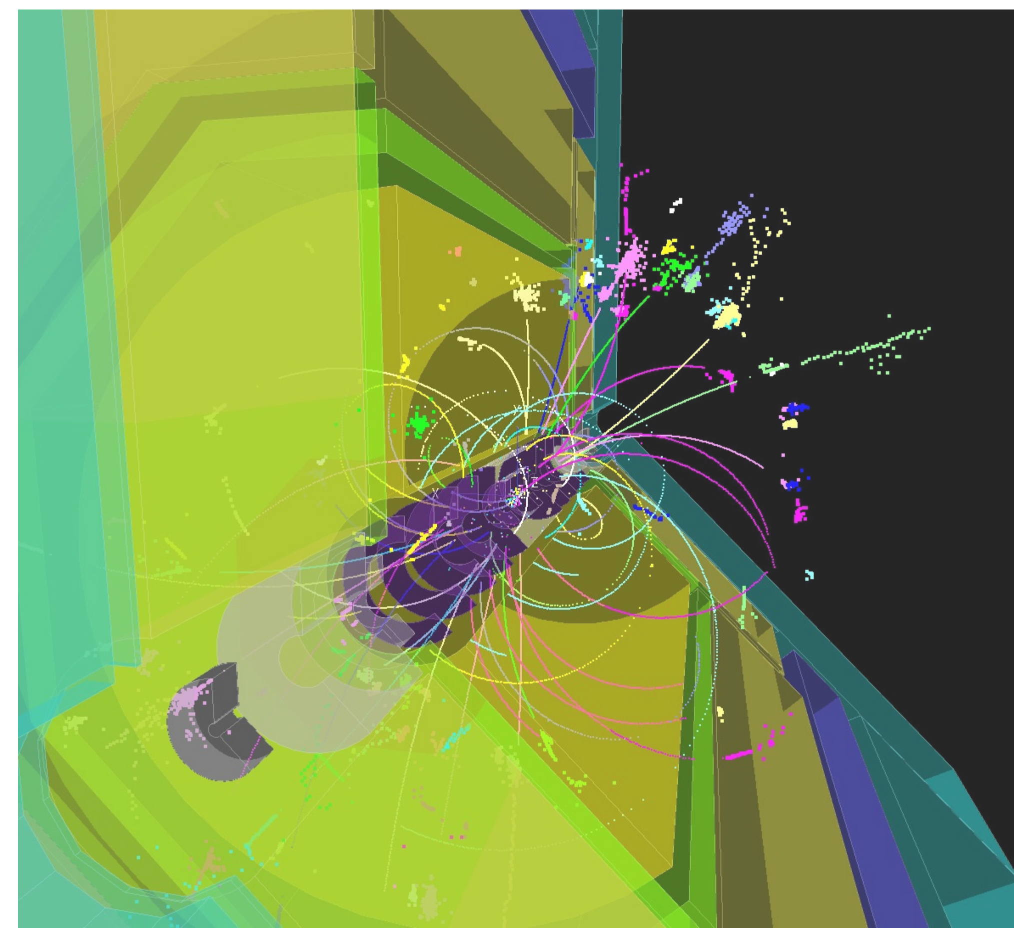
Beams are polarised

(2 samples)

1. $e^-_L\ e^+_R$ P(e$^-$) ≈ -80% , P(e$^+$) ≈ +30%
2. $e^-_R\ e^+_L$ P(e$^-$) ≈ +80% , P(e$^+$) ≈ -30%

2. Simulation of the detector

Full realistic simulation of the ILD detector concept



Three-dimensional image of a 500-GeV $t\bar{t}$ event simulated in the ILD detector

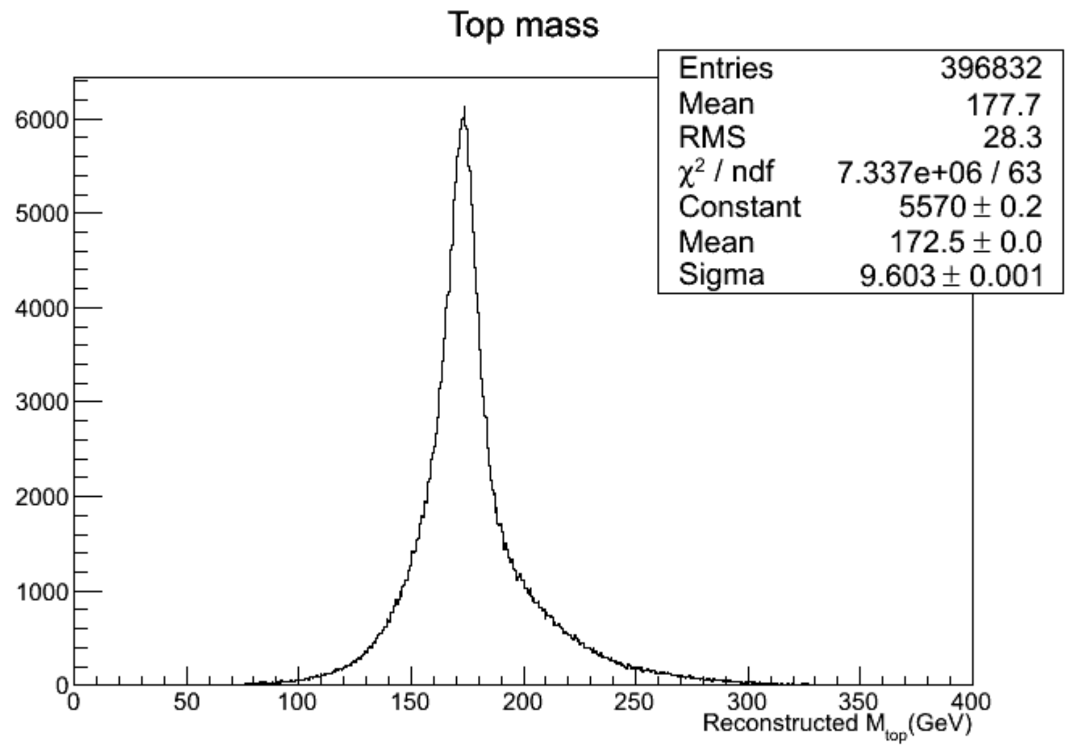
Event generation, detector simulation and reconstruction

3. Reconstruction

Standard algorithms for event selection

Signal reconstruction: **combination of *b*** quark jet and ***W*** boson that minimises the following equation

$$d^2 = \left(\frac{m_{cand.} - m_t}{\sigma_{m_t}}\right)^2 + \left(\frac{E_{cand.} - E_{beam}}{\sigma_{E_{cand.}}}\right)^2 + \left(\frac{p_b^* - 68}{\sigma_{p_b^*}}\right)^2 + \left(\frac{cos\theta_{bW} - 0.23}{\sigma_{cos\theta_{bW}}}\right)^2$$



Efficiency of selection

51.9% for P,P' = -1,+1 (Left-handed electrons)

55.0% for P,P' = +1, -1 (Right-handed electrons)

Observables

Total cross section (σ)

The Forward-Backward Asymmetry (A_{FB}^{top})

The slope of the distribution of the helicity angle (λ_t)

Standard model values

Observables	$e^-_L e^+_R$	$e^-_R e^+_L$
σ(fb)	1564	724
A_{FB}	0.38	0.47
$F_R = (1+ \lambda_t)/2$	0.25	0.76

But actually there are **6 independent observables** = 3 observables x 2 polarisations

So we can obtain the following **CP conserving 6 couplings of the top to Z and γ**

$$\left.\begin{matrix} \sigma(+) & A_{FB}(+) & \lambda_{hel}(+) & (+ = e^-_R) \\ \sigma(-) & A_{FB}(-) & \lambda_{hel}(-) & (- = e^-_L) \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F^{\gamma}_{1V} & F^{\gamma}_{1A} & F^{\gamma}_{2V} \\ F^{Z}_{1V} & F^{Z}_{1A} & F^{Z}_{2V} \end{matrix}\right\}$$

* ***$F_{1A}\gamma$ = 0*** *because of the gauge invariance*

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Measurement of observables

The cross section

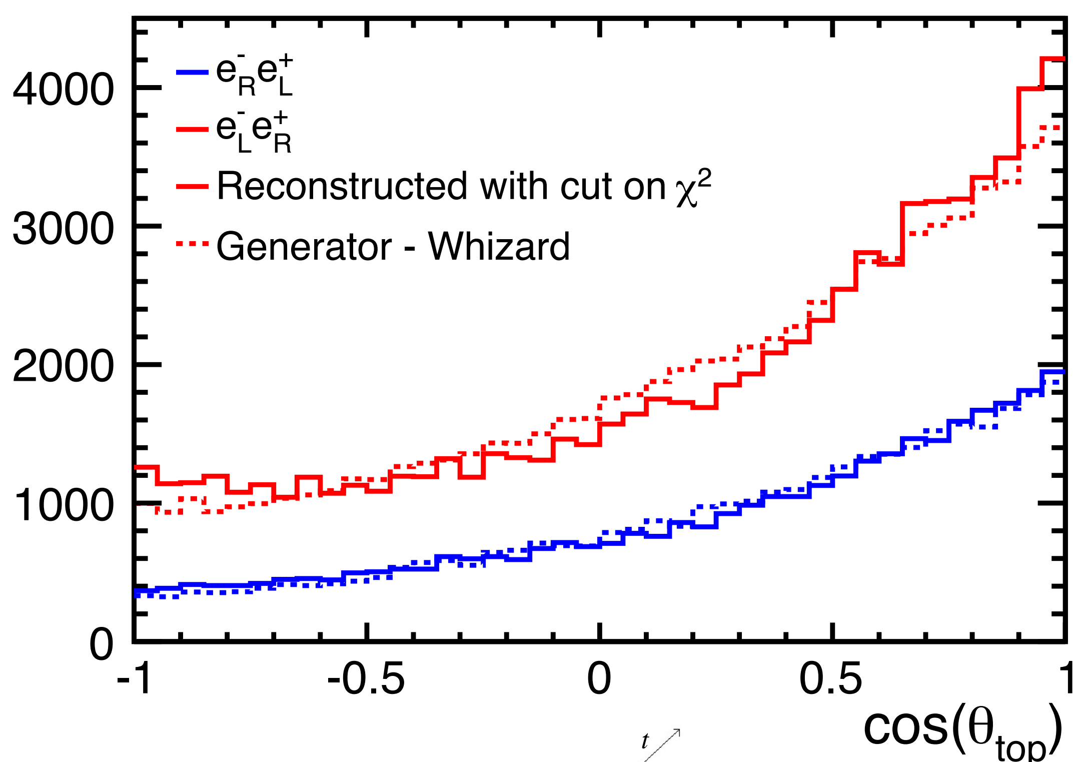
The cross section can be measured to

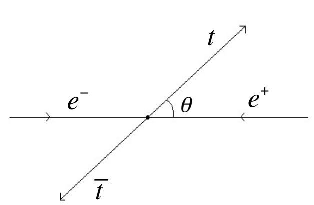
0.5% (stat. + lumi)

The Forward-Backward Asymmetry

$$A^t_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

2% (stat. + syst.)

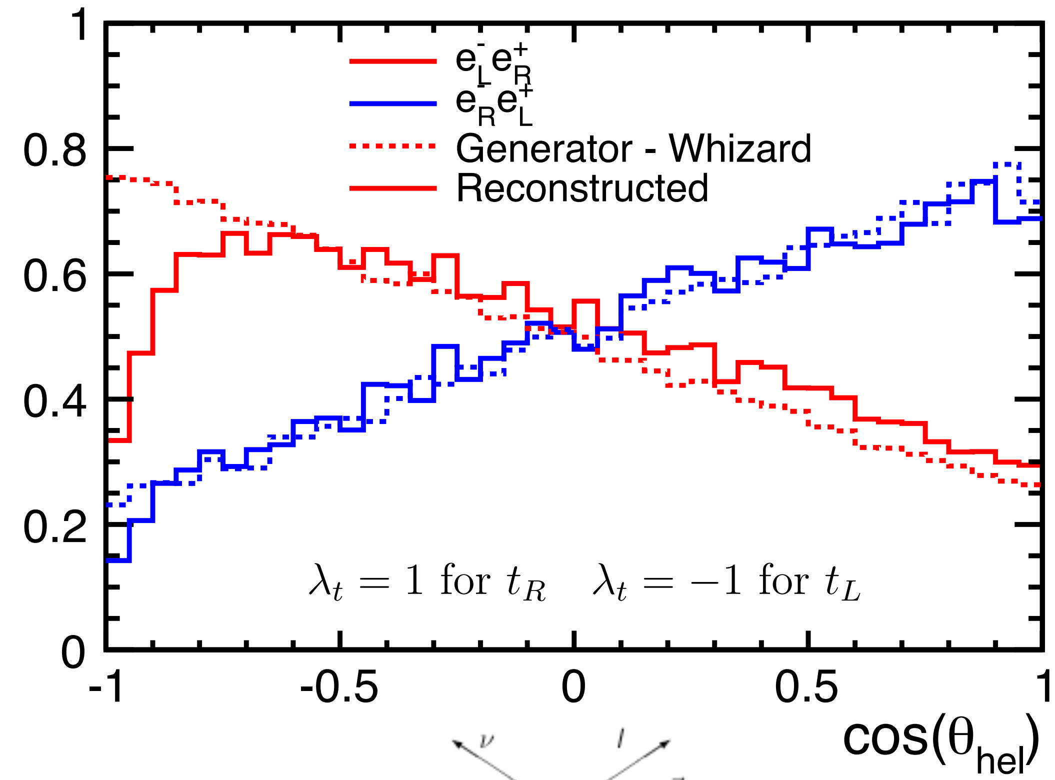


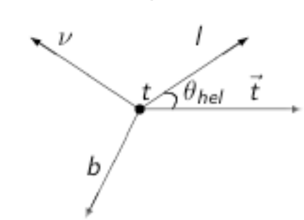


The helicity angle

$$\frac{1}{\Gamma}\frac{d\Gamma}{dcos\theta_{hel}} = \frac{1 + \lambda_t \cos\theta_{hel}}{2} = \frac{1}{2} + (2F_R - 1)\frac{\cos\theta_{hel}}{2}$$

~4% (stat. + syst.)





Sensitivities for the electroweak couplings

[1] arXiv:hep-ph/0601112

500/fb at **500 GeV** yields 1-2 orders of magnitude better sensitivity than the **LHC** (**300/fb at 14 TeV**)

Coupling	SM value	LHC [1] $\mathcal{L} = 300\ \text{fb}^{-1}$	e^+e^- [*ILC DBD*] $\mathcal{L} = 500\ \text{fb}^{-1}$ $\mathcal{P}, \mathcal{P}' = \pm 0.8, \mp 0.3$
$\Delta \widetilde{F}_{1V}^{\gamma}$	0.66	$^{+0.043}_{-0.041}$	$^{+0.002}_{-0.002}$
$\Delta \widetilde{F}_{1V}^{Z}$	0.23	$^{+0.240}_{-0.620}$	$^{+0.003}_{-0.003}$
$\Delta \widetilde{F}_{1A}^{Z}$	-0.59	$^{+0.052}_{-0.060}$	$^{+0.005}_{-0.005}$
$\Delta \widetilde{F}_{2V}^{\gamma}$	0.015	$^{+0.038}_{-0.035}$	$^{+0.003}_{-0.003}$
$\Delta \widetilde{F}_{2V}^{Z}$	0.018	$^{+0.270}_{-0.190}$	$^{+0.006}_{-0.006}$

LHC studies (Snowmass 2005)

Present study denoted as ILC DBD

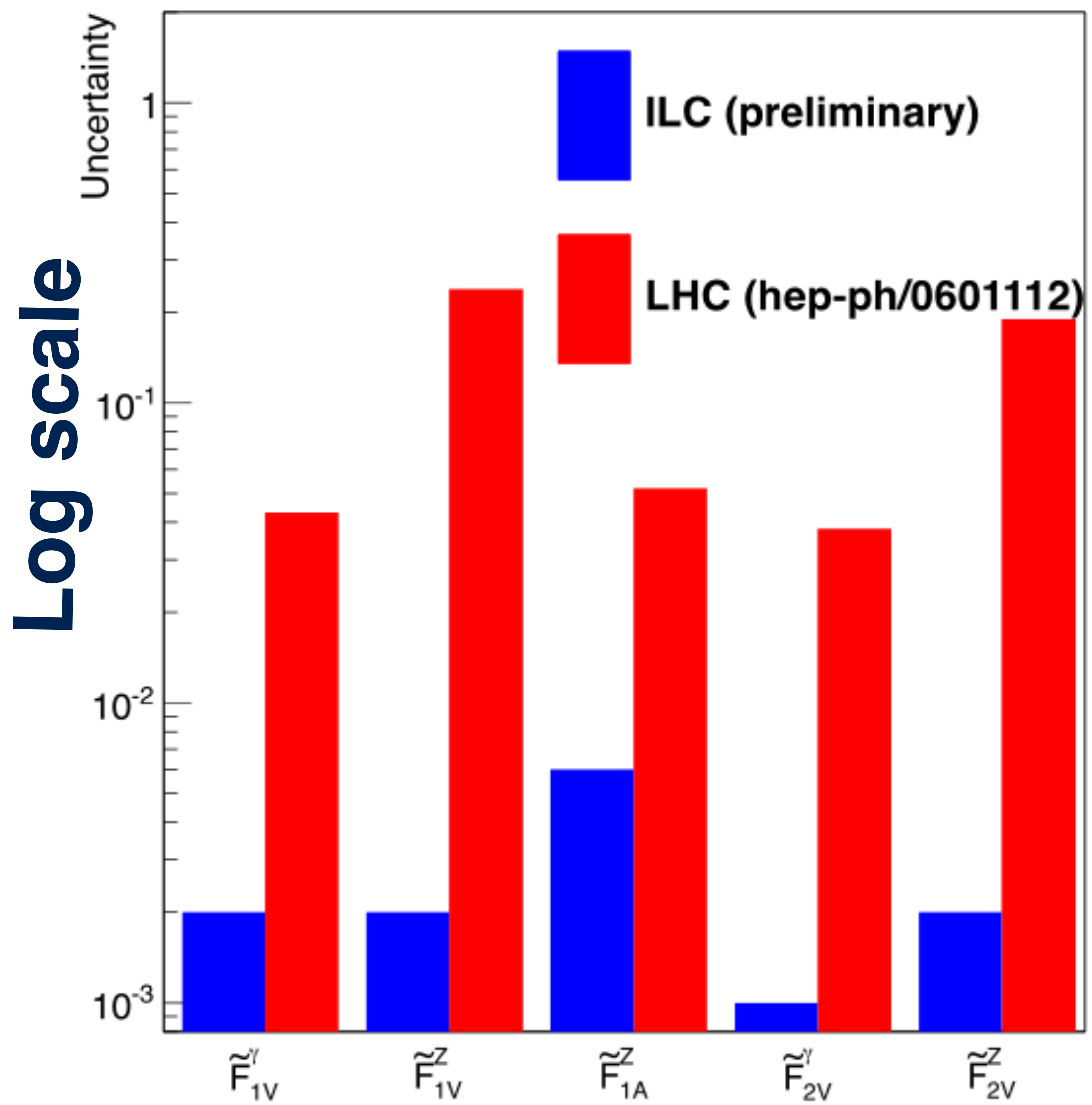
Summary

Top mass at threshold

Statistical uncertainty of top mass around 30 MeV
(CLIC ~ 20% larger than ILC due to different luminosity spectrum).

Total uncertainty below 100 MeV in reach, expected to be dominated by theory systematics.

Top electroweak couplings



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Conclusions

- In a **threshold scan**, the **top mass** can be determined in a **theoretically well defined** way, using 1*S* mass scheme

- These studies confirm the expectation that a **linear e^+e^- collider** will be capable of measuring the mass of the top quark with **30 MeV error**

- **Polarisation** allows to **double the number of observables**

- **It is a powerful tool for analysis** because it also allows **full separation** between **axial and vectorial couplings** and between $t\bar{t}Z$ **and** $t\bar{t}\gamma$ **vertices**

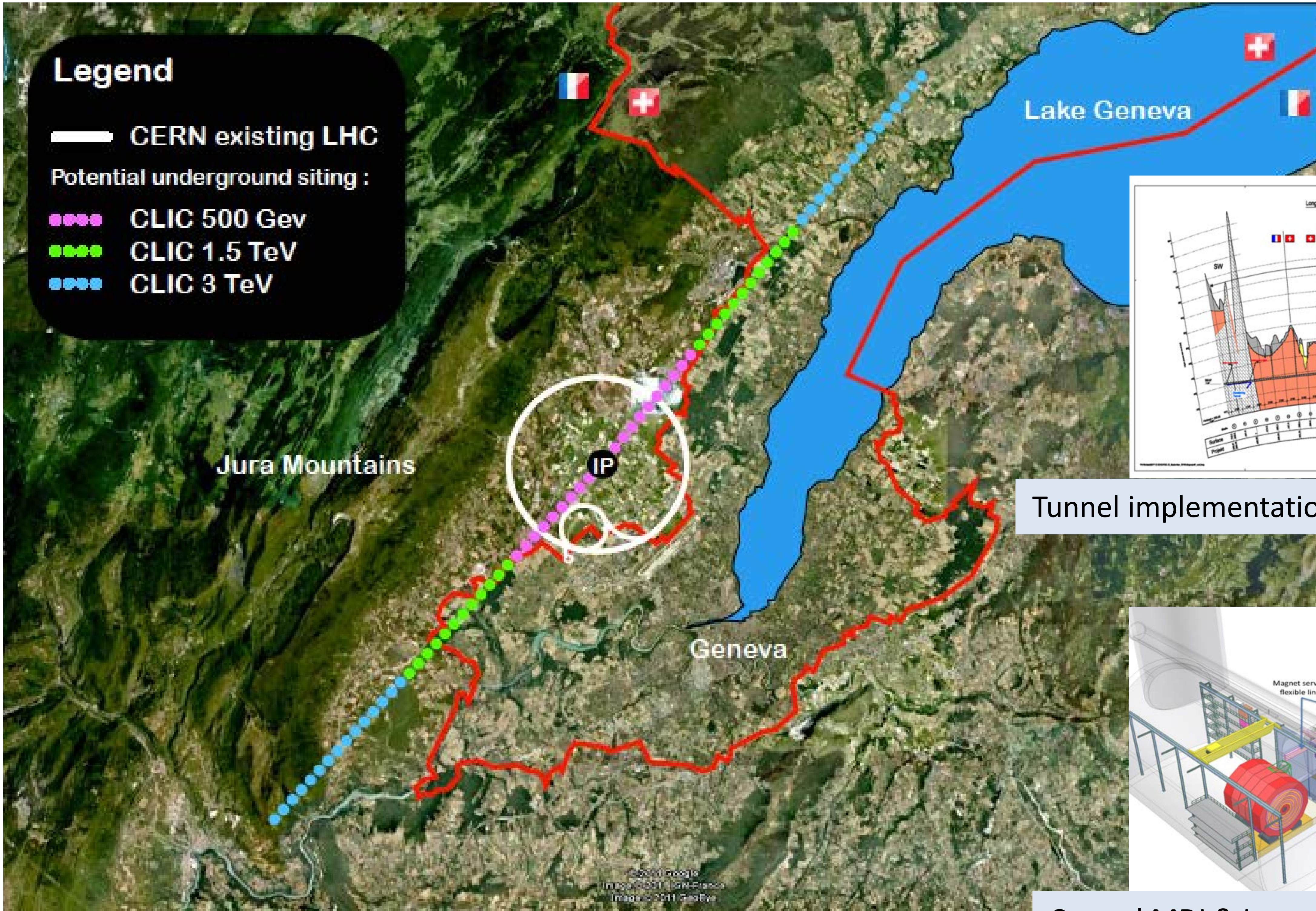
- In LC with polarised beams we can measure with **accuracies** one or two orders of magnitude **better than LHC**

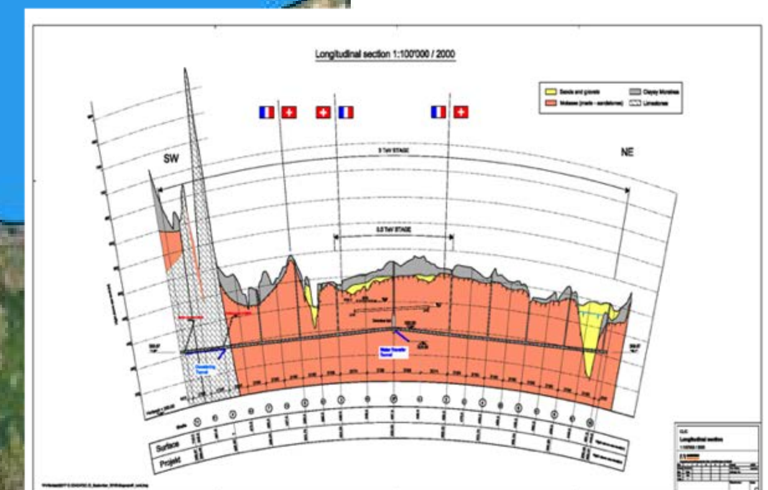
THANK YOUR FOR YOUR ATTENTION

BACKUP SLIDES

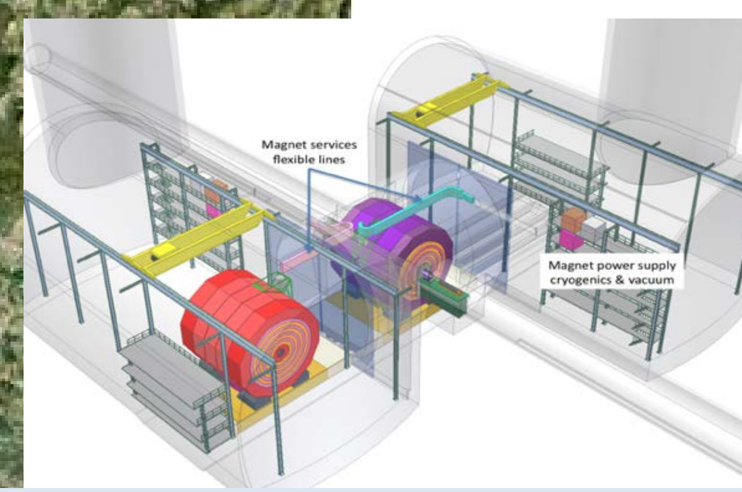
CLIC@CERN

Slide by Steinar Stapnes, CERN



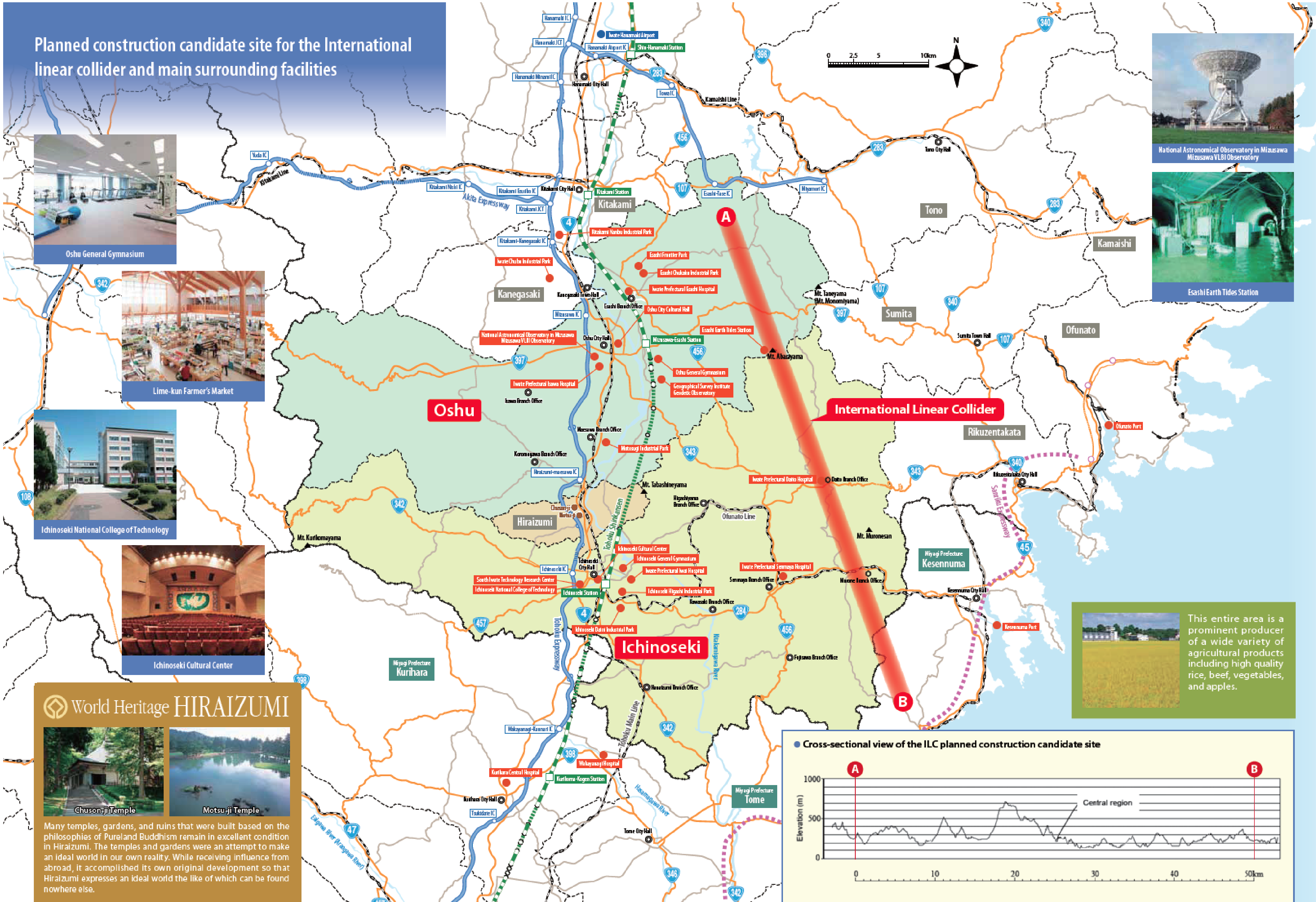


Tunnel implementations (laser straight)



Central MDI & Interaction Region

ILC@Japan

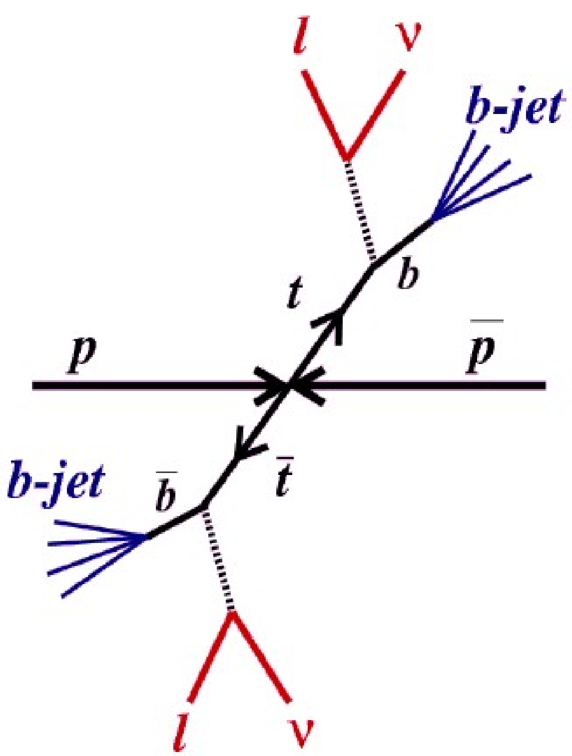


http://www.city.oshu.iwate.jp/htm/ilc/archives/rayofhopee.pdf

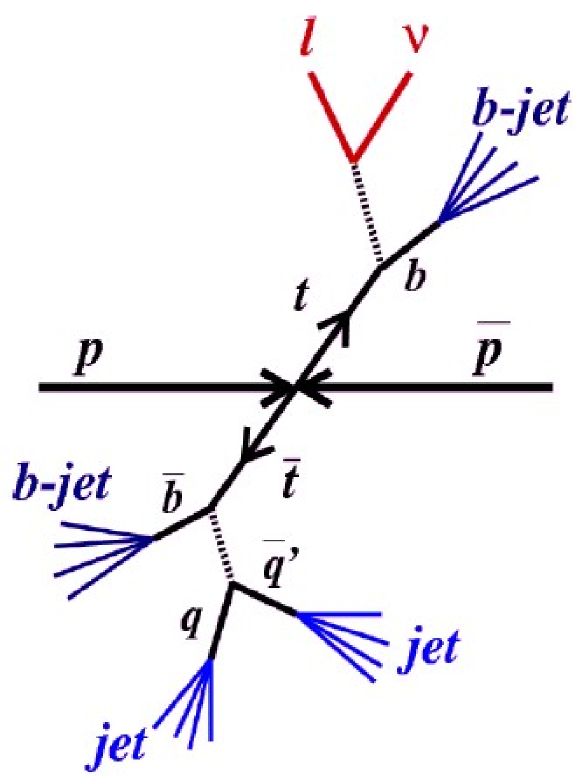
tt decay modes

$e^+e^- \rightarrow t\bar{t}$ gives three different final states:

Fully leptonic (10.3%)
2jets + 2 leptons + 2 neutrinos



Semi-leptonic (43.5%)
4 jets + lepton + neutrino



Fully hadronic (46.2%)
6 jets at final state