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m_{top} perspectives at the future linear collider

LINEAR COLLIDER COLLABORATION

Mainz Institute for Theoretical Physics

Cluster of Excellence
Precision Physics, Fundamental Interactions and Structure of Matter

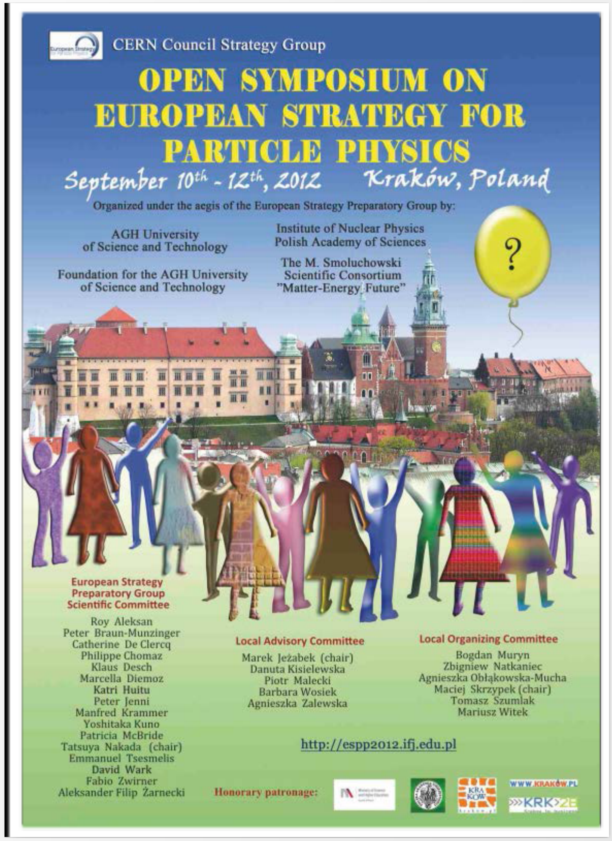
J. Fuster, IFIC-Valencia
(thanks to F. Simon for providing material)

High precision fundamental constants at the TeV scale
10-21 March 2014, Mainz, Germany

Outline

- General introduction to the e+e- future linear collider
- Experimental strategies to measure the top-quark mas in e+e-:
  - ✓ Threshold scan
  - ✓ Invariant mass reconstruction
  - ✓ Other observables sensitive to the top-quark mass
- Summary

Update of the European Particle Strategy



Proposed Update of the European Strategy for Particle Physics concerning LHC and HL-LHC:

- The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. **The LHC is in a unique position to pursue this programme. Europe's top priority should be the exploitation of the full potential of the LHC, including the high luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030**. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark gluon plasma.

The LHC and HL-LHC is highest priority for Europe HEP

Update of the European Particle Startegy

Proposed Update of the European Strategy for Particle Physics concerning ILC and CLIC activities:

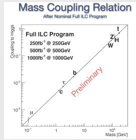
- To stay at the forefront of particle physics, Europe needs to be in a position to propose an ambitious post-LHC accelerator project at CERN by the time of the next Strategy update, when physics results from the LHC running at 14 TeV will be available. **CERN should undertake design studies for accelerator projects in a global context, with emphasis on proton-proton and electron positron high-energy frontier machines**. These design studies should be coupled to a vigorous accelerator R&D programme, including high-field magnets and high-gradient accelerating structures, in collaboration with national institutes, laboratories and universities worldwide

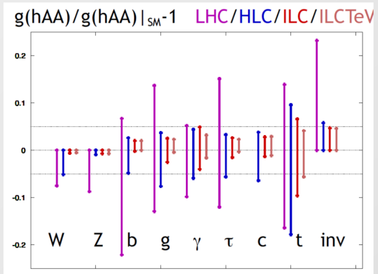
- There is a strong scientific case for an electron-positron collider, complementary to the LHC, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded. The Technical Design Report of the International Linear Collider (ILC) has been completed, with large European participation. **The initiative from the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate. Europe looks forward to a proposal from Japan to discuss a possible participation**

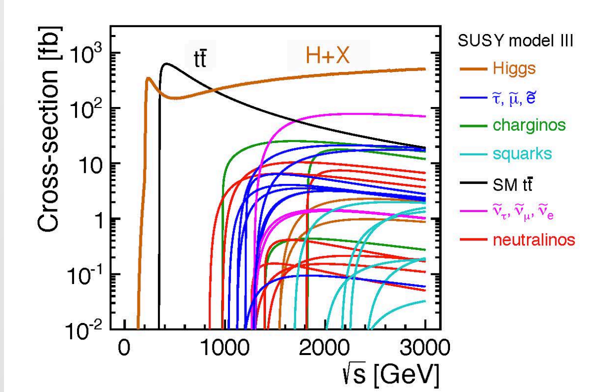
The LC community has received these recommendations very well and very positively

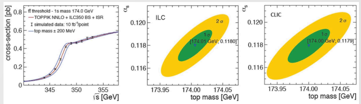
Physics at Linear Colliders from 250 GeV to 3000 GeV

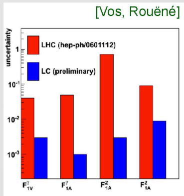
- **Physics case for the Linear Collider:**
  - Higgs physics (SM and non-SM)
  - Top
  - SUSY
  - Higgs strong interactions
  - New Z' sector
  - Contact interactions
  - Extra dimensions
  - ….
- **ILC and CLIC physics case is very similar,** (energy range, technical readiness are the issue)

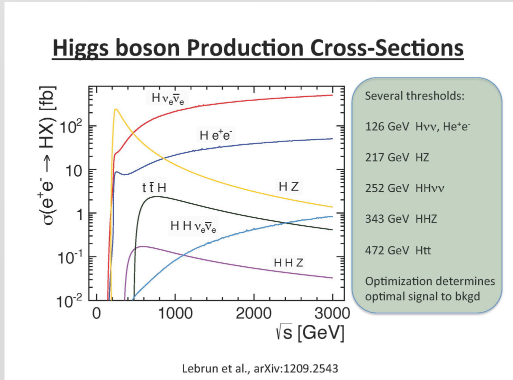








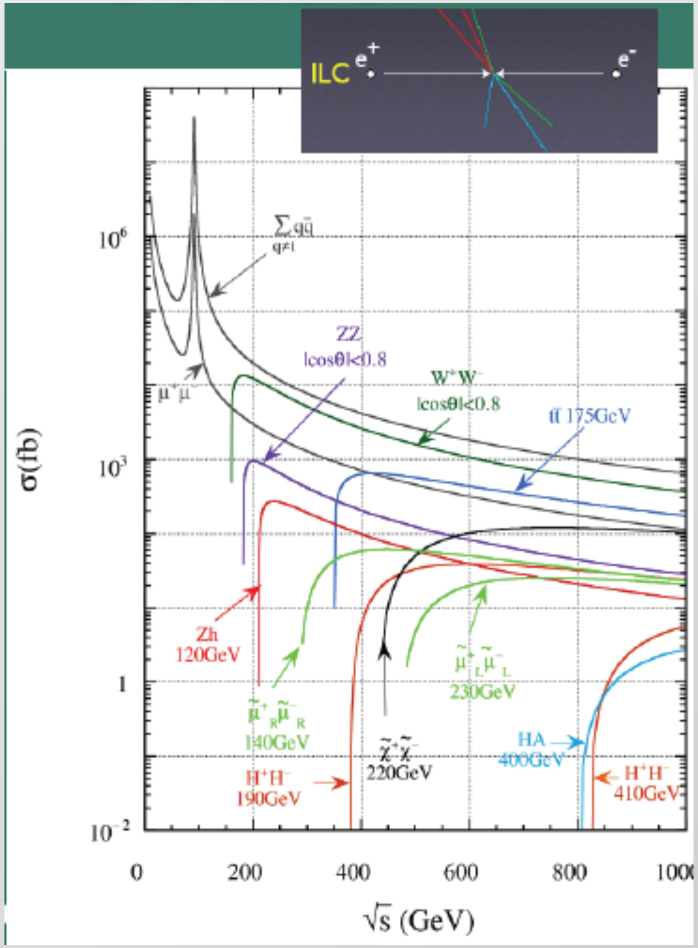




J. Brau et al.	The Physics Case for an e+e- Linear Collider, arXiv:1210.0202
L. Linssen et al **P. Lebrun et al**	CLIC CDR, arXiv:1202.5940,1209.2543
H. Baer et al.	ILC Technical Design Report, Volume 2, Physics at the International Linear Collider, 2013

Main characteristics of linear colliders

- Elementary interactions at known E_{cm}
- Democratic cross section (i.e., signal and background events of similar size)
- Inclusive trigger-free data
- Use of polarized electron beam (80%).
  Positron polarization being investigated (>30%)
- Calorimetry with Particle Flow Precision (introduced at LEP, developed at LC R&D, used already at LHC)
  $\sigma_E / E_{jet} \sim 3\%$ for E_{jet} > 100 GeV
- Excellent vertex reconstruction
- $R_{beanpipe}$ ~ 1 cm and σ_{hit}~3 μm, H-> cc
- Model independent measurements



EW-fits

G-fitter experimental inputs

- **Latest experimental inputs:**
  - Z-pole observables: from LEP / SLC
    [ADLO+SLD, Phys. Rept. 427, 257 (2006)]
  - M_W and Γ_W from LEP/Tevatron
    [arXiv:1204.0042]
  - m_{top} : average from Tevatron
    [arXiv:1207.1069]
  - m_c, m_b world averages (PDG)
    [PDG, J. Phys. G33,1 (2006)]
  - $\Delta\alpha_{had}^{(5)}(M_Z^2)$ including α_S dependency
    [Davier et al., EPJC 71, 1515 (2011)]
  - M_H from LHC
    [arXiv:1207.7214, arXiv:1207.7235]
- **7+2 free fit parameters:**
  - M_Z, M_H, $\alpha_S(M_Z^2)$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_t, $\overline{m}_c$, $\overline{m}_b$
  - 2 theory nuisance parameters
    - *δM_W (4 MeV), $\delta \sin^2\theta^l_{eff}$ (4.7×10^{-5})*

M_H [GeV]$^{(\circ)}$	125.7 ± 0.4	LHC
M_W [GeV]	80.385 ± 0.015	Tevatron
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLC
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	
A_c	0.670 ± 0.027	SLC
A_b	0.923 ± 0.020	
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	
R^0_c	0.1721 ± 0.0030	SLC
R^0_b	0.21629 ± 0.00066	
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.18 ± 0.94	Tevatron
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\triangle\nabla)}$	2757 ± 10	

M. Baak G fitter IVICFA 2013

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e+e- results still very relevant to test the consistency of the SM

Polarization is an important tool

- 7+2 free fit parameters:
  - M_Z, M_H, $\alpha_S(M_Z^2)$, $\Delta\alpha_{had}^{(5)}(M_Z^2)$, m_t, $\overline{m}_c$, $\overline{m}_b$
  - 2 theory nuisance parameters
    - δM_W (4 MeV), $\delta \sin^2\theta^l_{eff}$ (4.7×10^{-5})

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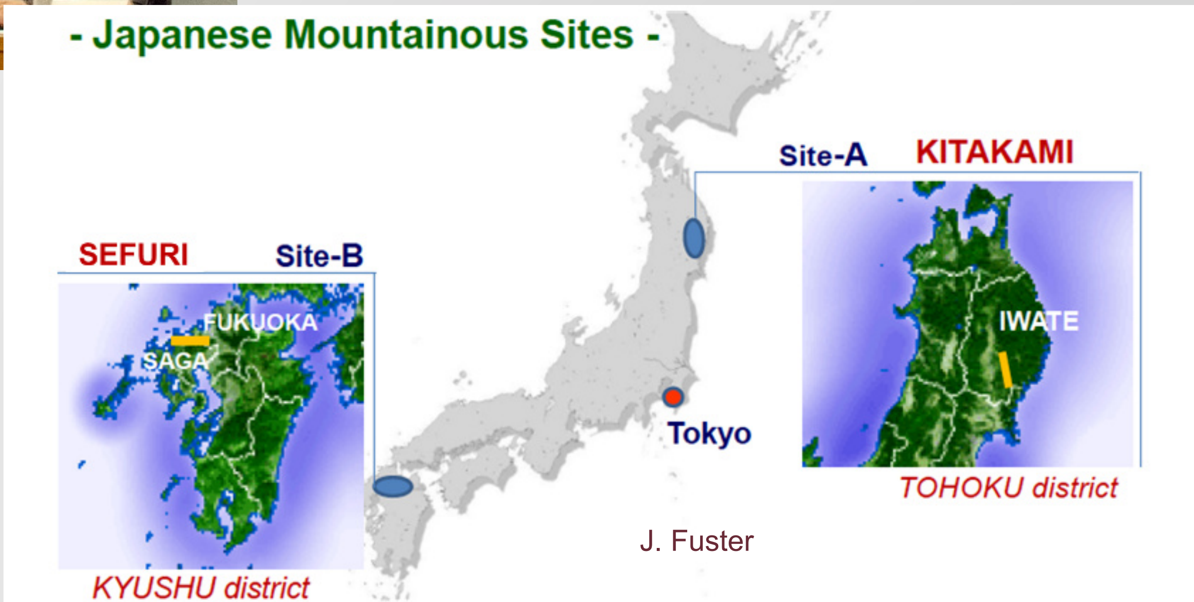
Japan – Preferred Site selection

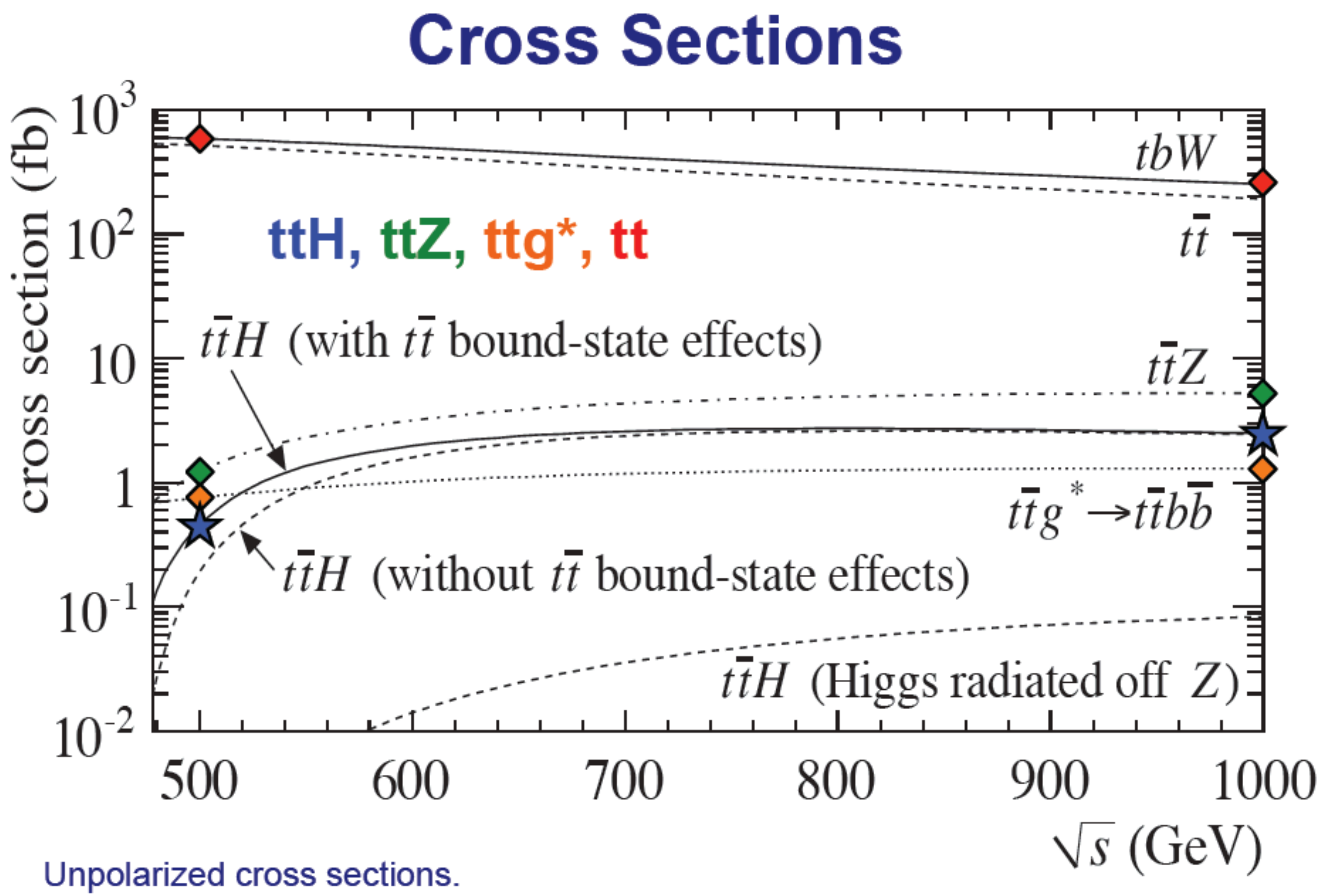
"Issues that could lead to particularly serious difficulties for the Sefuri site are that the route passes under or near a dam lake, and that the route passes under a city zone.

Also, the lengths of access tunnels are longer for the Sefuri site than for the Kitakami site leading to a large merit for the latter in terms of cost, schedule, and drainage"



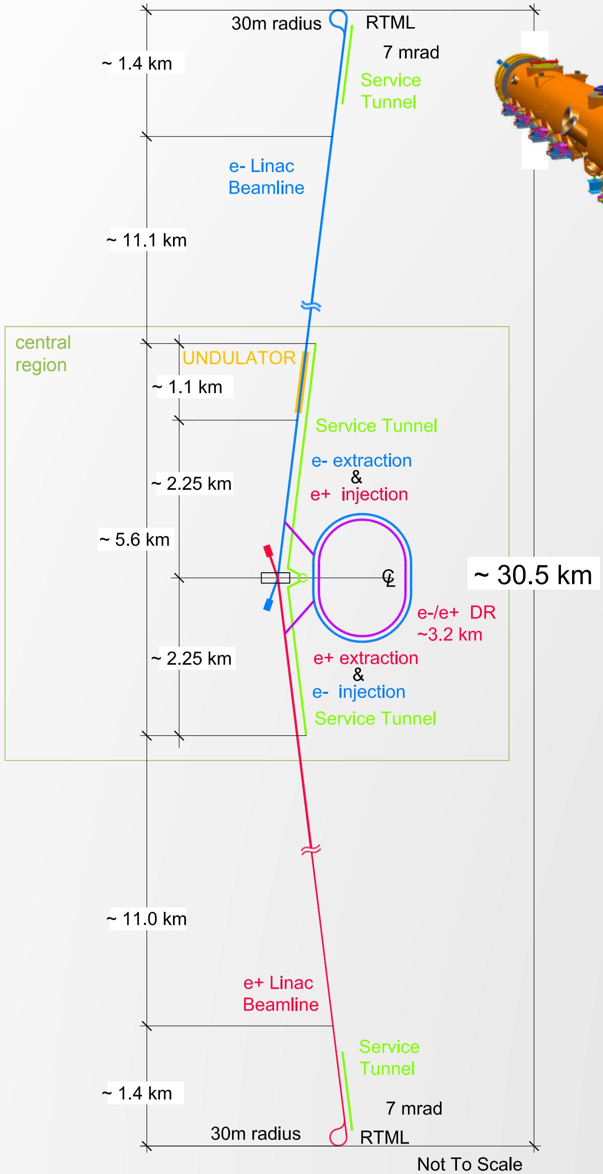
North side selected

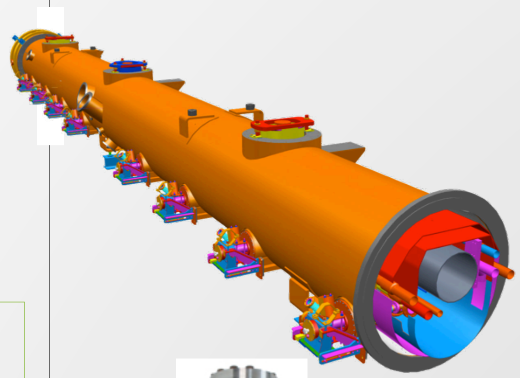
Cross sections



Unpolarized cross sections.
For ttH: m_H = 120 GeV

ILC in a glance



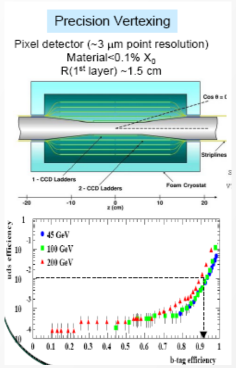


- 200-500 GeV E_{cm} e^+e^- collider
  L ~2×10^{34} $cm^{-2}s^{-1}$
  - upgrade: ~1 TeV
- SCRF Technology
  - 1.3GHz SCRF with 31.5 MV/m
  - 17,000 cavities
  - 1,700 cryomodules
  - 2×11 km linacs
- Developed as a truly global collaboration
  - **G**lobal **D**esign **E**ffort – **GDE**
  - ~130 institutes
  - http://www.linearcollider.org/ILC

Operating parameters at 500 GeV

Physics	Max. E_{cm}	500 GeV
	Luminosity	1.8×10^{34} cm^{-2}s^{-1}
	Polarisation (e-/e+)	80% / 30%
	δ_{BS}	4.5%
Beam (interaction point)	σ_x / σ_y	574 nm / 6 nm
	σ_z	300 μm
	$\gamma\varepsilon_x$ / $\gamma\varepsilon_y$	10 μm / 35 nm
	β_x / β_y	11 mm / 0.48 mm
	bunch charge	2×10^{10}
Beam (time structure)	Number of bunches / pulse	1312
	Bunch spacing	554 ns
	Pulse current	5.8 mA
	Beam pulse length	727 μs
	Pulse repetition rate	5 Hz
Accelerator (general)	Average beam power	10.5 MW (total)
	Total AC power	163 MW
	(linacs AC power	107 MW)

Challenges for ILC (0.25-1.0 TeV)/CLIC (0.5-3.0 TeV) detectors



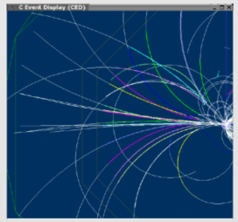
- Vertex, "flavour tag" (heavy quark and lepton identification)

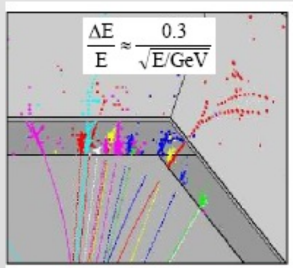
  ~1/5 $r_{beampipe}$, ~1/30 pixel size (ILC vs LHC),

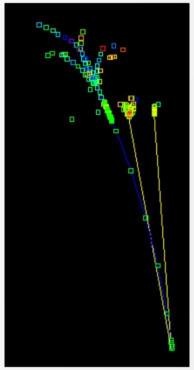
  vtx 1-2 cm (ILC), vtx 2-3 cm (CLIC)

  $$(h \to b\bar{b}, c\bar{c}, \tau^+\tau^-)$$

  $$\boxed{\sigma_{ip} = 5\mu m \oplus 10-15\mu m / p\sin^{3/2}\theta}$$





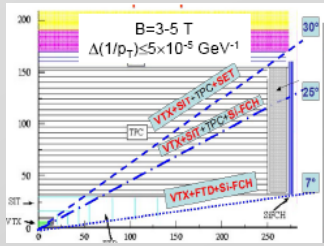


- Tracking, "recoil mass" $(e^+e^- \to Zh \to \ell^+\ell^- X)$

  ~1/6 material, ~1/7 resolution (ILC wrt LHC),

  B=4-5 T (CLIC and ILC)

  $$\boxed{\sigma(1/p) \le 2\times10^{-5}\,\mathrm{GeV}^{-1}}$$



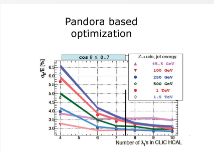
- Particle Flow, Jet Energy Rec. → Tracker+Calo.

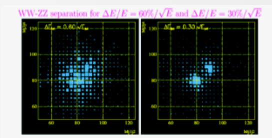
  Di-jet mass Resolution, Event Reconstruction, Hermiticity,

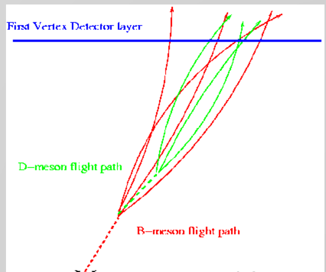
  Detector coverage down to very low angle

  CLIC vs ILC: Redesign Forward Region, HCAL 7,5 λ

  $$\boxed{\sigma_E / E = 3-4\%}$$



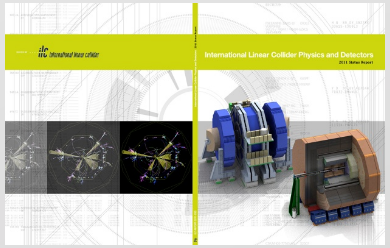
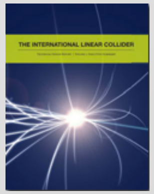
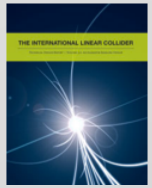


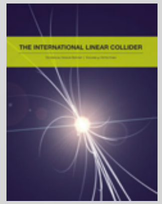


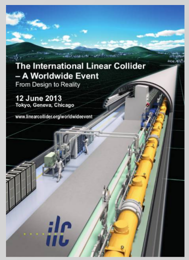
ILC Physics and Detector Roadmap

Aug. 2007	Detector Concept Report, Four detector concepts: LDC, GLD, SiD, 4th
Oct. 2007	ILCSC calls for LOIs and appoints Research Director (RD)
Jan. 2008	RD forms detector management
Mar. 2008	IDAG formed, Three LOIs groups identified
Mar. 2009	Three LOIs submitted (detector description, status of R&D, GEANT4 simulation, benchmark process, costs..)
Mar. 2009	IDAG began monitoring the progress
Aug. 2009	IDAG recommends validation of two (2) and ILCSC approves
Oct. 2009	Work plan of the validated groups
End 2011	Interim Report being produced http://www.linearcollider.org/about/Publications/interim-report
End 2012	Physics at the International Linear Collider (ILC TDR Vol. 2) Detailed Baseline Design Report (ILC TDR Vol. 4) http://www.linearcollider.org/ILC/Publications/Technical-Design-Report
June 12th 2013	Public TDR Launch event worldwide http://www.linearcollider.org/events/2013/ilc-tdr-world-wide-event



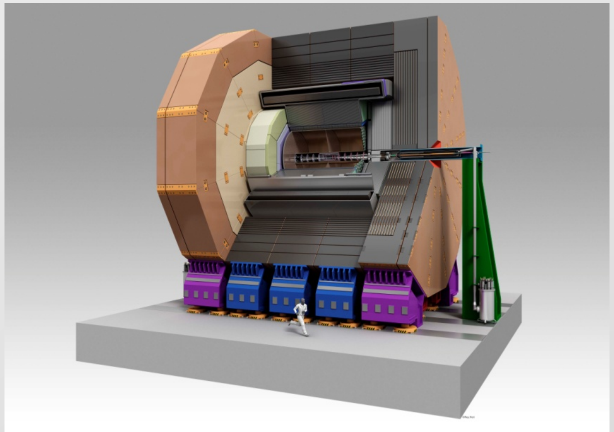




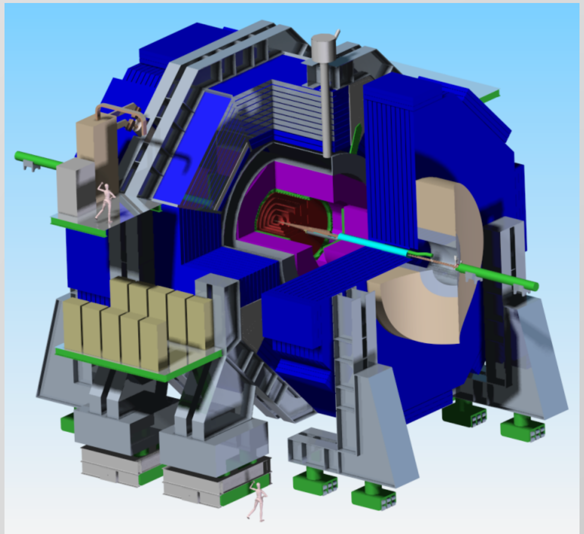



Validated ILC Detectors: SiD & ILD

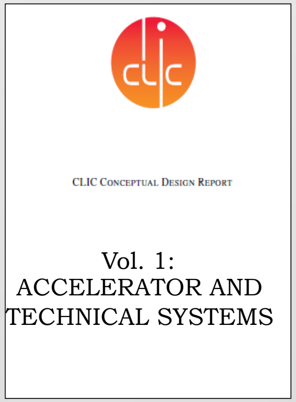
Both, ILD and SiD, are 4π detectors with complementary designs	
Common Systems	Thin pixel vertex detectors Si-W Electromagnetic Calorimeter
ILD	TPC tracking aided with silicon detectors
	Scintillator-Steel hadron calorimeter
	Excellent tracking and calorimetry performance for best possible event reconstruction
SiD	Silicon tracking
	Gaseous (RPC) digital hadron calorimeter
	Fast tracking and calorimeter for robustness

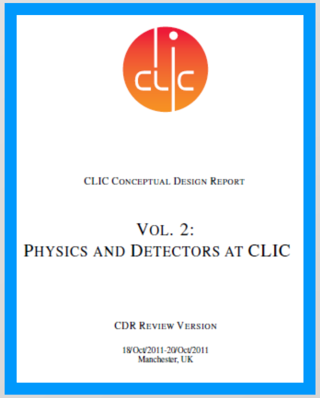


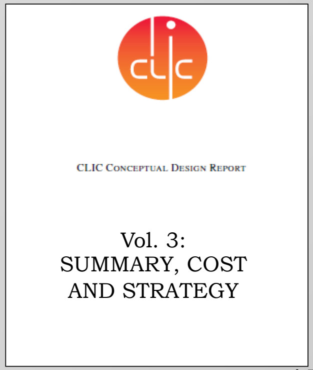


CLIC Physics and Detector Roadmap

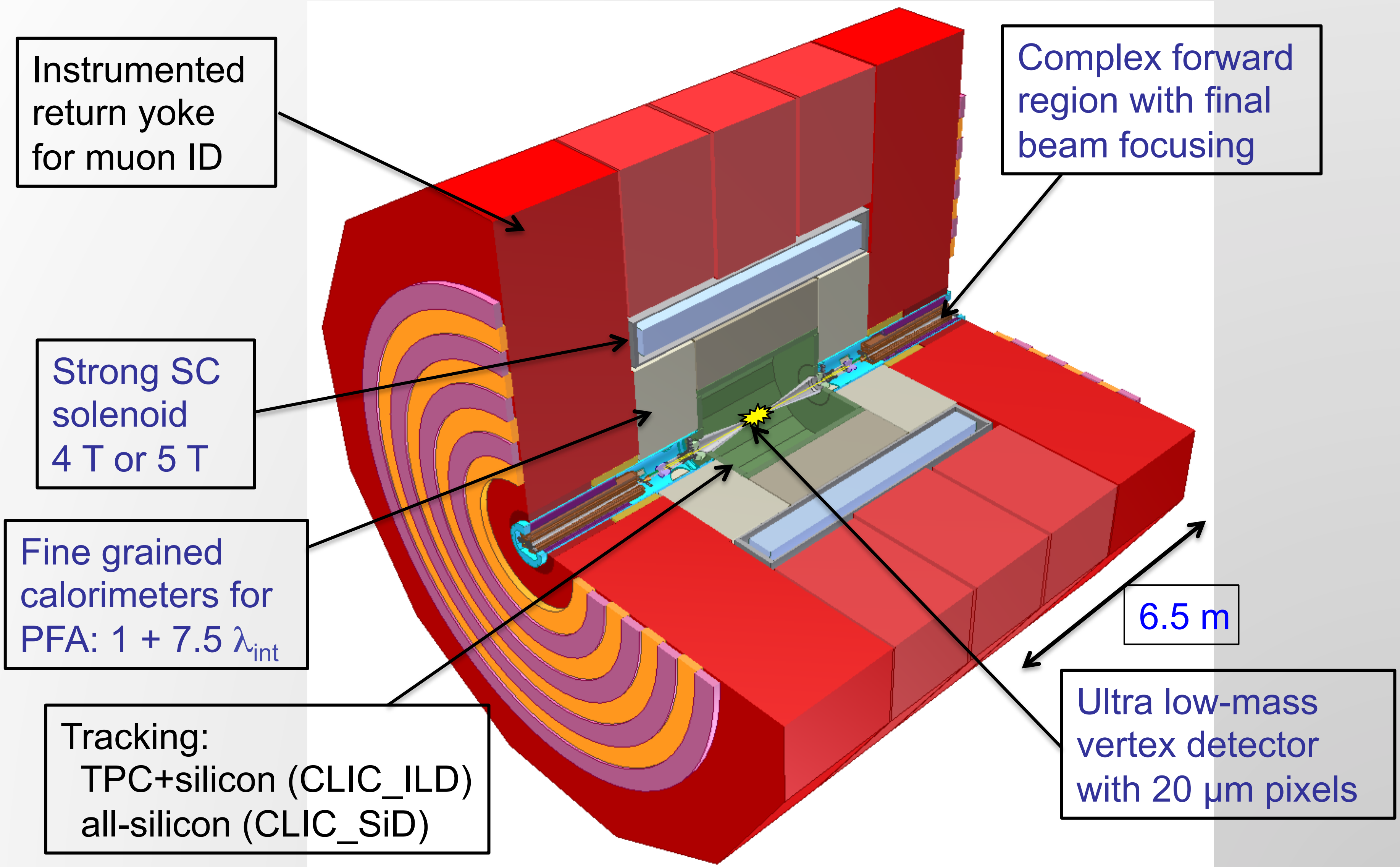
2004	"Physics at the CLIC multi-TeV linear collider" Report on physics potential
2008	First meetings between ILC and CLIC physics efforts Start" Linear Collider Detector (LCD) effort @ CERN Linear Collider Detector (LCD) @CERN group signs LOIs
Jun. 2009	IDAG meeting: Plan ILC-CLIC cooperation
End 2009	For CLIC CDR pursue ILD & SID concepts and use their software frameworks. Start work towards CDR
2009-210	CERN LCD joins detector R&D collaborations
Sep. 2011	Physics and detectors at CLIC CLIC Conceptual Design Report (CDR Vol. 2) External review procedure in October CDR to SPC in December (http://arxiv.org/pdf/1202.5940v1)
2012	Cooperation with ILC to complete DBD
Mid. 2012	CLIC study summary CLIC Conceptual Design Report (CDR Vol. 3) Work plan of post CDR phase (2012-2016) (http://arxiv.org/pdf/1209.2543v1)



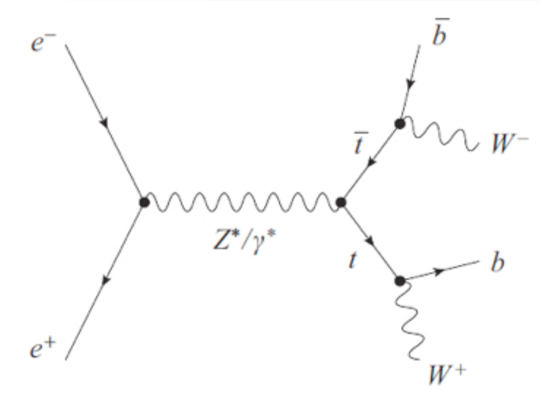




CLIC detector and physics study



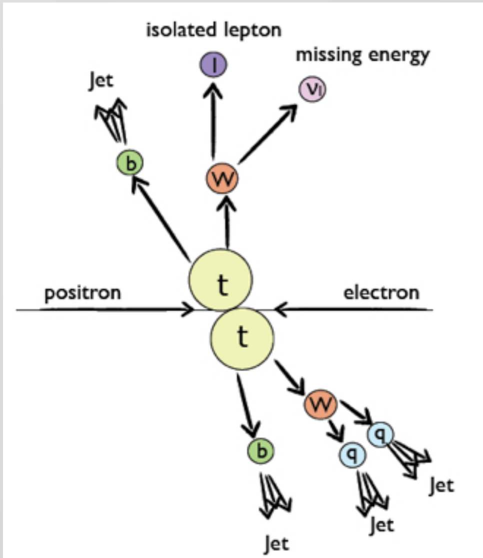
Top-quark mass determination at Linear colliders



- ✓ M. Martínez, R. Miquel, Eur. Phys. J. C27 49 (2003)
- ✓ K. Seidel, F. Simon, M. Tesař, S. Poss, Eur. Phys. J. C73 2530 (2013) (no polarization)
- ✓ T. Horiguchi, A. Isihikawa, T. Suehara, K. Fuji, Y. Sumino, Y. Kiyo, Y. Yamamoto (with polarization)

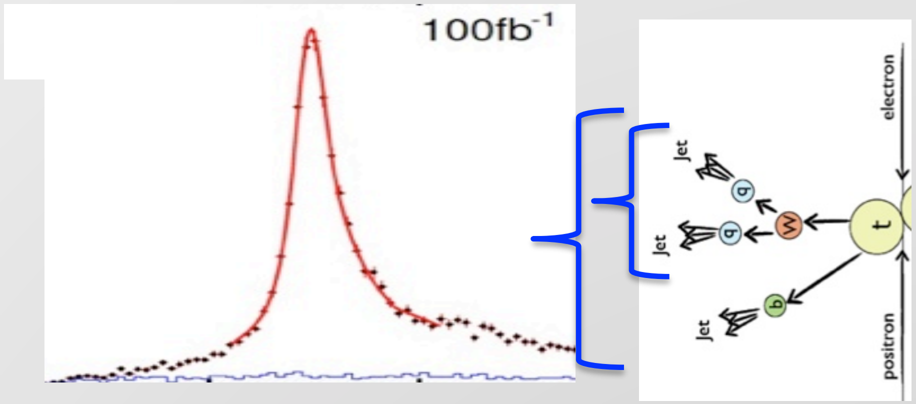
- Pair production in s-channel e^+e^- annihilation
- Cross-section ~ 500 fb (350 GeV - 500 GeV)
  - ✓ relevant backgrounds comparable in cross-section, up to a factor of ~ 10 higher

- Using key features of Linear Collider detectors:
  - ✓ Flavor tagging
  - ✓ Precise jet reconstruction with PFAs
  - ✓ Total energy measurement => Neutrino reconstruction
  - ✓ Possibility for kinematic fitting due to well-known overall energy

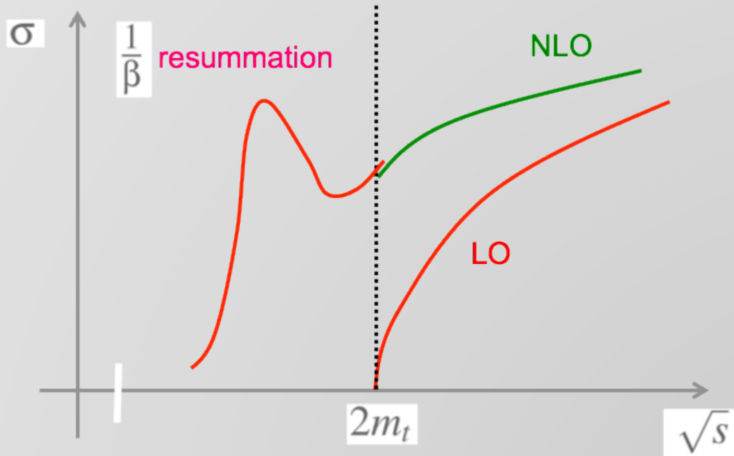


Top-quark mass determination at Linear colliders

- ✓ Invariant mass of decay products
  - ✧ can be performed at arbitrary energy above threshold: high integrated luminosity
  - ✧ Interpretation in the context of event generator: “PYTHIA mass”



- ✓ Threshold scan
  - ✧ theoretically well understood, can be calculated to higher orders
  - ✧ needs dedicated running of the accelerator (but is also in a sweet spot for Higgs physics)



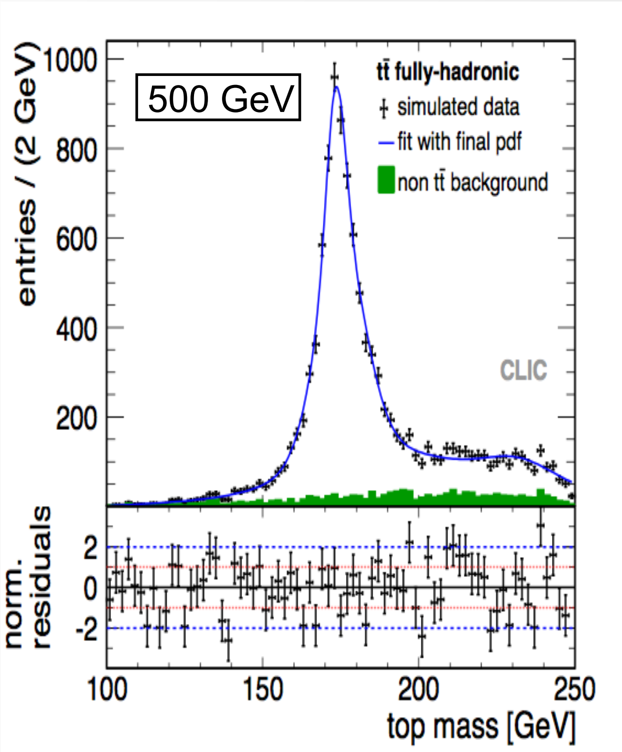
P. Uwer, LCForum 02/2012

- ✓ Other observables above threshold (event shapes, ISR/FSR, etc..). Can include the “good” features of the above methods.

Top-quark mass: invariant mass

K. Seidel, F. Simon, M. Tesař, S. Poss, Eur. Phys. J. C73 2530 (2013)

- Flavor-tagging to identify b-jets
- Kinematic fit imposing W mass, energy & momentum conservation
- Background rejection by kinematic fit & multivariate likelihood



✓ Very clean top identification with high (~35% - 50%) efficiency, using high-BR decays

✓ Full detector simulations including backgrounds, integrated lumi 100 fb^{-1}

channel	m_{top}	Δm_{top}	Γ_{top}	$\Delta\Gamma_{top}$
fully-hadronic	174.049	0.099	1.47	0.27
semi-leptonic	174.293	0.137	1.70	0.40
combined	174.133	0.080	1.55	0.22

Total experimental systematics (JES, m_t assumption in MC, ...) of order 100 MeV

Theoretical uncertainties larger! (>100 MeV)

Top-quark mass: threshold scan

- Theoretical situation very impressive (see talk by J. Piclum)

- NNLO [Hoang, Teubner; Melnikov, Yelkhovsky; Yakovlev; Beneke, Signer, Smirnov; Nagano, Ota, Sumino; Penin, Pivovarov]
- NNNLO
  - potential contributions [Beneke, Kiyo, Schuller; Kniehl, Penin, Smirnov, Steinhauser]
  - 3-loop static potential [Anzai, Kiyo, Sumino; Smirnov, Smirnov, Steinhauser]
  - ultrasoft corrections [Beneke, Kiyo, Penin]
  - 3-loop contribution to c_v [Marquard, JP, Seidel, Steinhauser]
- NNLL
  - vNRQCD [Hoang, Manohar, Stahlhofen, Stewart, Teubner]
  - pNRQCD [Pineda, Signer]
- electroweak corrections [Guth, Kühn; Eiras, Steinhauser; Kiyo, Seidel, Steinhauser]
- finite-width effects [Fadin, Khoze; Hoang, Reißer, Ruiz-Femenía; Beneke, Jantzen, Ruiz-Femenía; Penin, JP]
- most recent analysis: $\frac{\delta\sigma}{\sigma}\Big|_{\mathrm{NNLL}} = \pm 5\%$ [Hoang, Stahlhofen 2013]

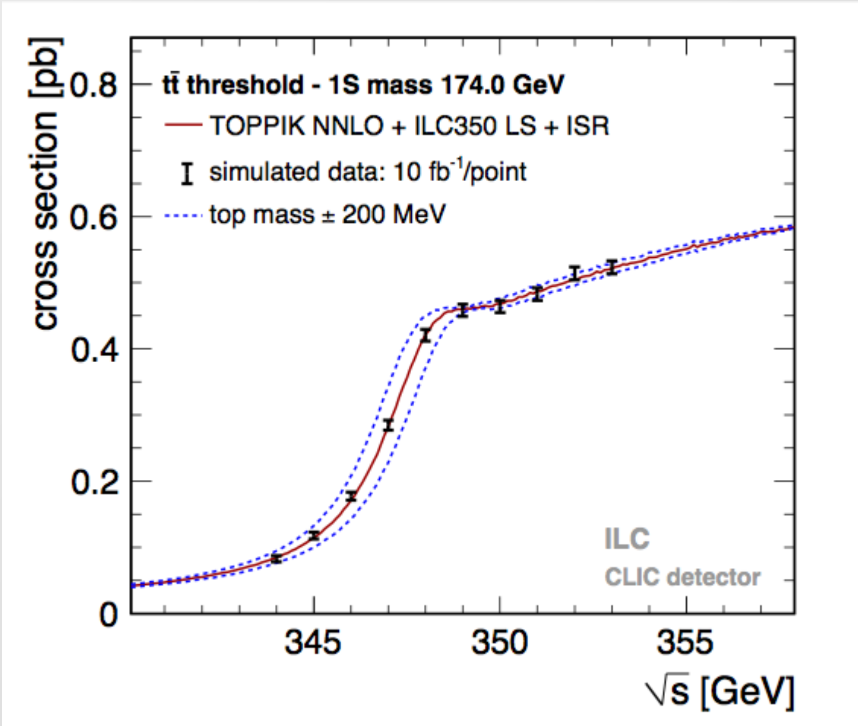
Top-quark mass: threshold scan

K. Seidel, F. Simon, M. Tesař, S. Poss, Eur. Phys. J. C73 2530 (2013)

- The cross-section near the pair production threshold provides high sensitivity to the top mass - and can be calculated to higher orders
  - ✓ Using theoretically well-defined mass definition, 1S particularly well suited

- Experimentally: A cross-section measurement, using similar event selection techniques as for the invariant mass

- Simulation studies: Reconstruction efficiency and background levels from full detector simulations, NNLO cross section from TOPPIK (Hoang, Teubner)

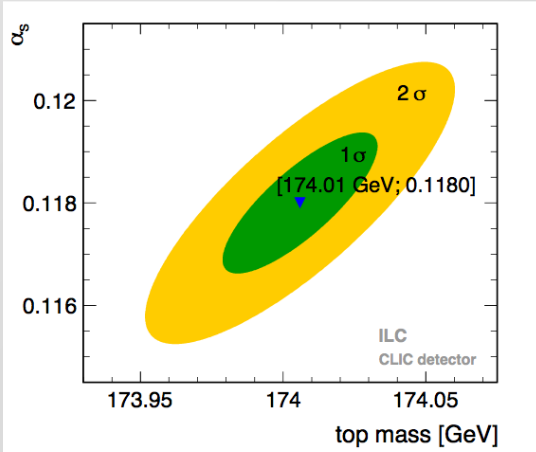


Top-quark mass: threshold scan

K. Seidel, F. Simon, M. Tesař, S. Poss, Eur. Phys. J. C73 2530 (2013)

- Correlation of M_t and α_s: Simultaneous determination
- Experimental systematics (beam energy, luminosity, luminosity spectrum, background & efficiency, …):
  - No dependence on location of scan energy
  - 5% uncertainty non-tt background, 18 MeV
  - 10^{-4} precision on beam energy (machine parameters and LEP experience), 30 MeV
  - 20% uncertainty on lumi-spectrum, 75 MeV
- Theoretical uncertainties in 1S mass scheme comparable to statistical errors, currently *O*(100 MeV) due to additional uncertainty when translating to $\overline{\text{MS}}$ mass

1S top mass and α_s combined 2D fit	
m_t stat. error	27 MeV
m_t theory syst. (1%/3%)	5 MeV / 9 MeV
α_s stat. error	0.0008
α_s theory syst. (1%/3%)	0.0007 / 0.0022



Total uncertainty ~100 MeV is in reach and can be further improved

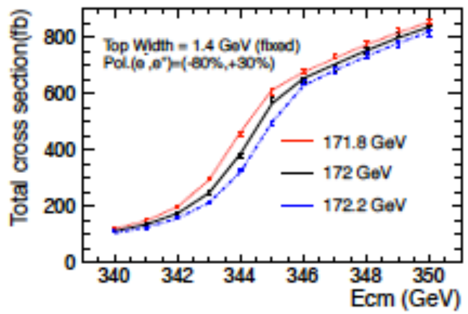
Top-quark mass: threshold scan

T. Horiguchi, A. Isihikawa, T. Suehara, K. Fuji, Y. Sumino, Y. Kiyo, Y. Yamamoto

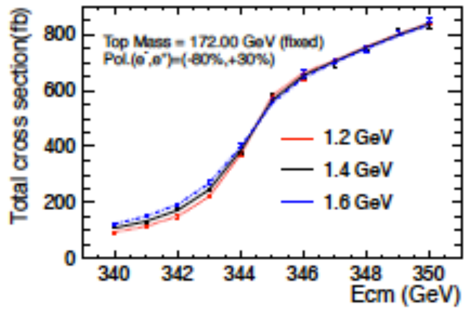
- Similar analysis as the one from K. Seidel et al. but including polarization, P(e+,e-)=(+-0.3,-+0.8)

	PS Mass (GeV)	Width (GeV)
"Left" (110 fb^{-1})	172.000 ± 0.020	1.399 ± 0.026
"Right" (110 fb^{-1})	172.000 ± 0.028	1.398 ± 0.038
"Left" + "Right" (220 fb^{-1})	172.000 ± 0.016	1.399 ± 0.021

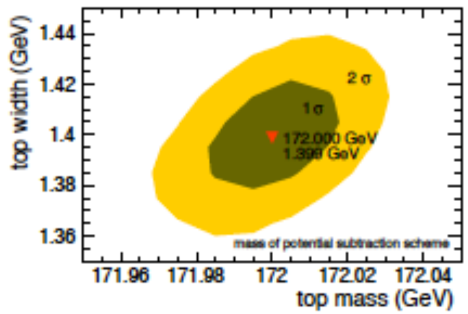
- Obtained PS mass and width with statistical errors assuming 10 fb^{-1} integrated luminosity and 11 energy points (340-350 GeV)



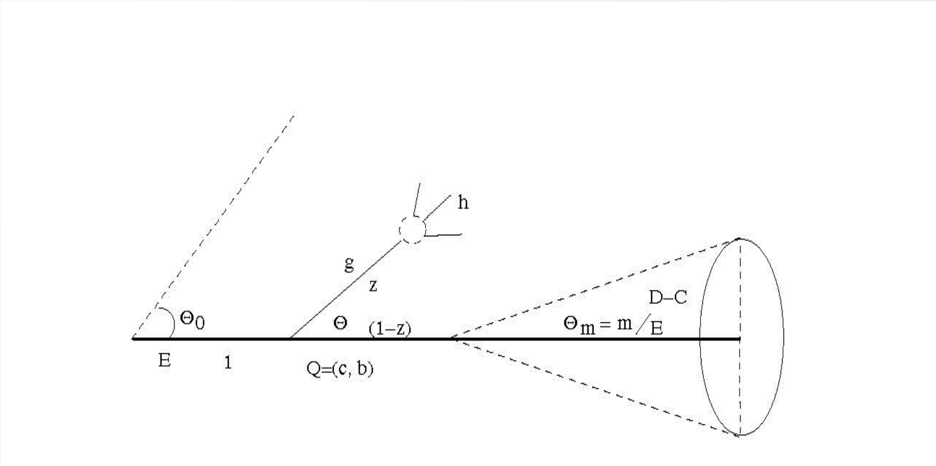
(a) Obtained cross section error at various top masses.



(b) Obtained cross section error at various top widths.



Top-quark mass: other observables possible ?



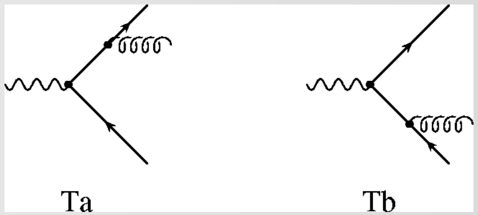
- Angular effects (dead cone)

$$\theta_{\min} \sim \frac{m_q}{E}$$

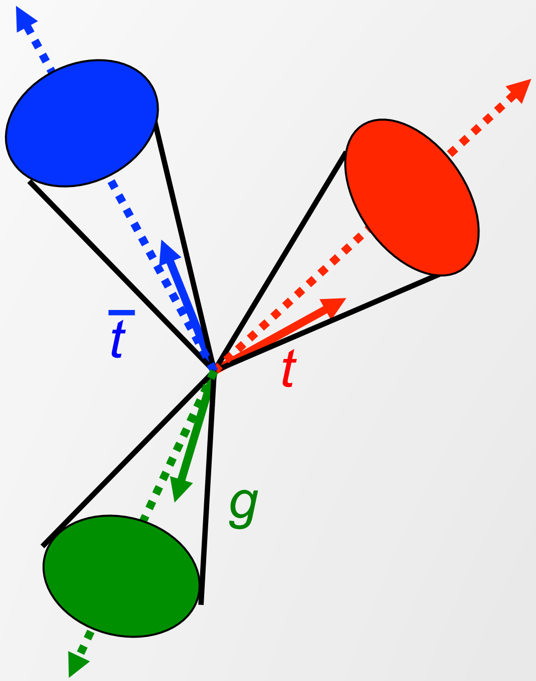
Yu L Dokshitzer, V A Khoze and S I 'Tkoyan

$$\frac{1}{\sigma_0}\frac{d^2\sigma}{dx_1 dx_2} = C_F\frac{\alpha_s}{2\pi}\left[\frac{x_1^2+x_2^2}{(1-x_1)(1-x_2)} - \frac{4m_q^2}{s}\left(\frac{1}{1-x_1}+\frac{1}{1-x_2}\right) - \frac{2m_q^2}{s}\left(\frac{1}{(1-x_1)^2}+\frac{1}{(1-x_2)^2}\right) - \frac{4m_q^4}{s^2}\left(\frac{1}{1-x_1}+\frac{1}{1-x_2}\right)^2\right]$$

Ioffe, e+e- interactions LO-analytical expressions. (calculations exist at NLO, NNLO, NLL, NNLL, etc..)



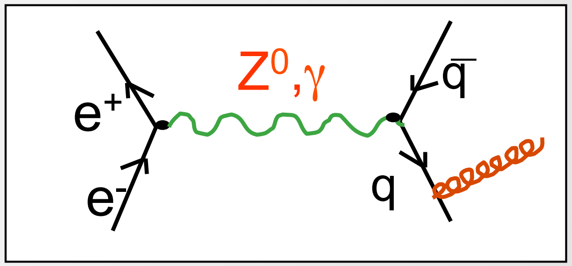
Top-quark mass: other observables possible ?



- Jet reconstruction algorithms introduce new scales which can increase the mass effects

$$s = E \bullet y \quad (y << 1)$$

- In general, gluon emission from quarks gets suppressed for heavier quarks

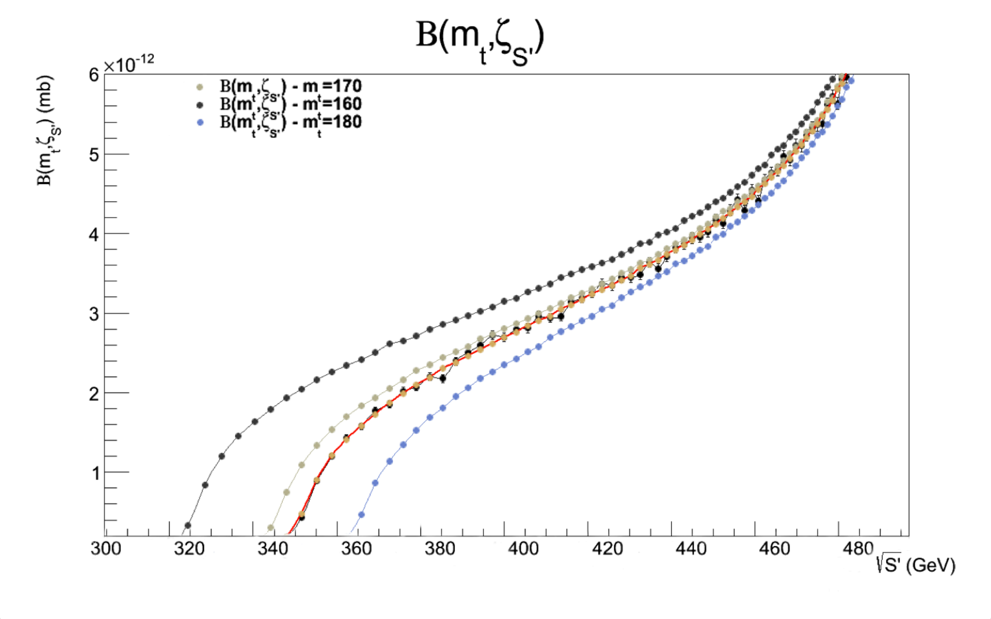


$$\frac{\sigma(QQG)}{\sigma(qqg)} \sim A(\alpha_s,\mu) + B(\alpha_s,\mu)\left(\frac{m_Q}{E}\right)^2 + \ldots$$

Top-quark mass: threshold scan above threshold !

M. Boronat, JF

Extracting the top-quark mas at 500 GeV in e+e- using tt+γ events



$$B(m_t, \zeta_{S'}) = \frac{d\sigma_{t\bar{t}+\gamma}}{d\zeta_{S'}}$$

$$\zeta_{S'} = \sqrt{S'}$$

$$S' = S(1 - \frac{2 \cdot E_\gamma}{\sqrt{S}})$$

Stage	L_a (fb^{-1})	$\Delta^+ m_t(MeV)$	$\Delta^- m_t(MeV)$
1			
2	500	147	142
3	1000	102	100
4	2600	64	63

A simple exercise using Pythia and experimental γ identification and resolution as given by ILD simulation

Summary and conclusions

- The Linear Collider study for physics and detector represents a tremendous effort of “many-many” people for “many–many” years (for more than 17 years).

- LHC and LC can complement extremely well and provide a physics programme for the next 20-30 years to continue exploring the mysteries of “symmetry breaking” in the Standard Model.

- In particular, the top-quark mass (m_t) as an extremely important parameter of the SM which needs to be determined experimentally with high precision. Together with M_W and M_H plays a major role for testing the validity of the SM and also for New Physics models.

- Major developments both in theoretical calculations and experimental studies are still being performed despite the lack of resources

- A future measurement of m_t at an e^+e^- Linear Collider with an accuracy better than 100 MeV is feasible including all uncertainties: statistics, theory and experimental systematics.