Status of a next-generation electron-positron collider: ILC and CLIC

Philip Burrows

John Adams Institute, Oxford University

Outline

- Introduction
- The Higgs boson + the Large Hadron Collider
- An e+e- collider Higgs factory
- International Linear Collider (ILC)
- Compact Linear Collider (CLIC)
- Project implementation and timeline

Large Hadron Collider (LHC)

Largest,

highest-energy

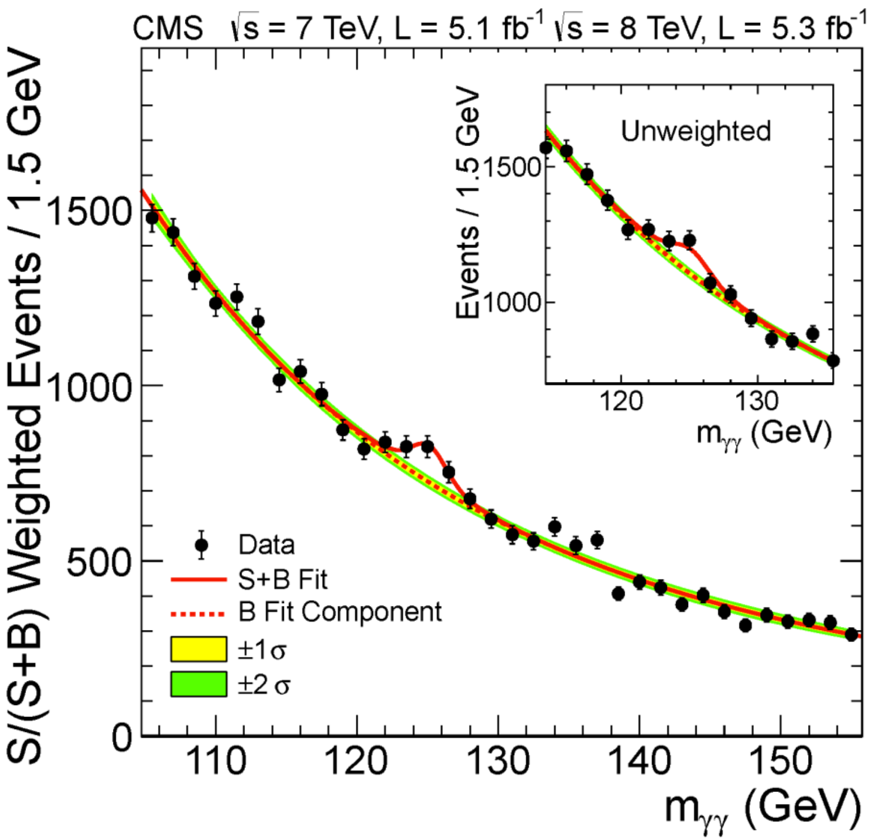
particle

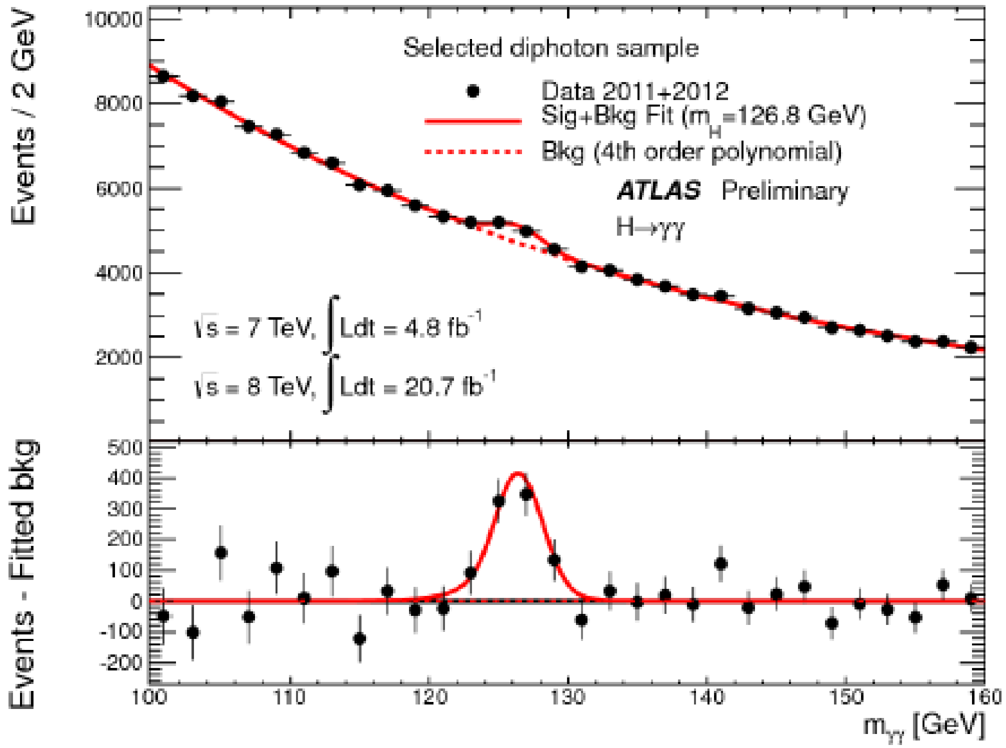
collider

CERN,

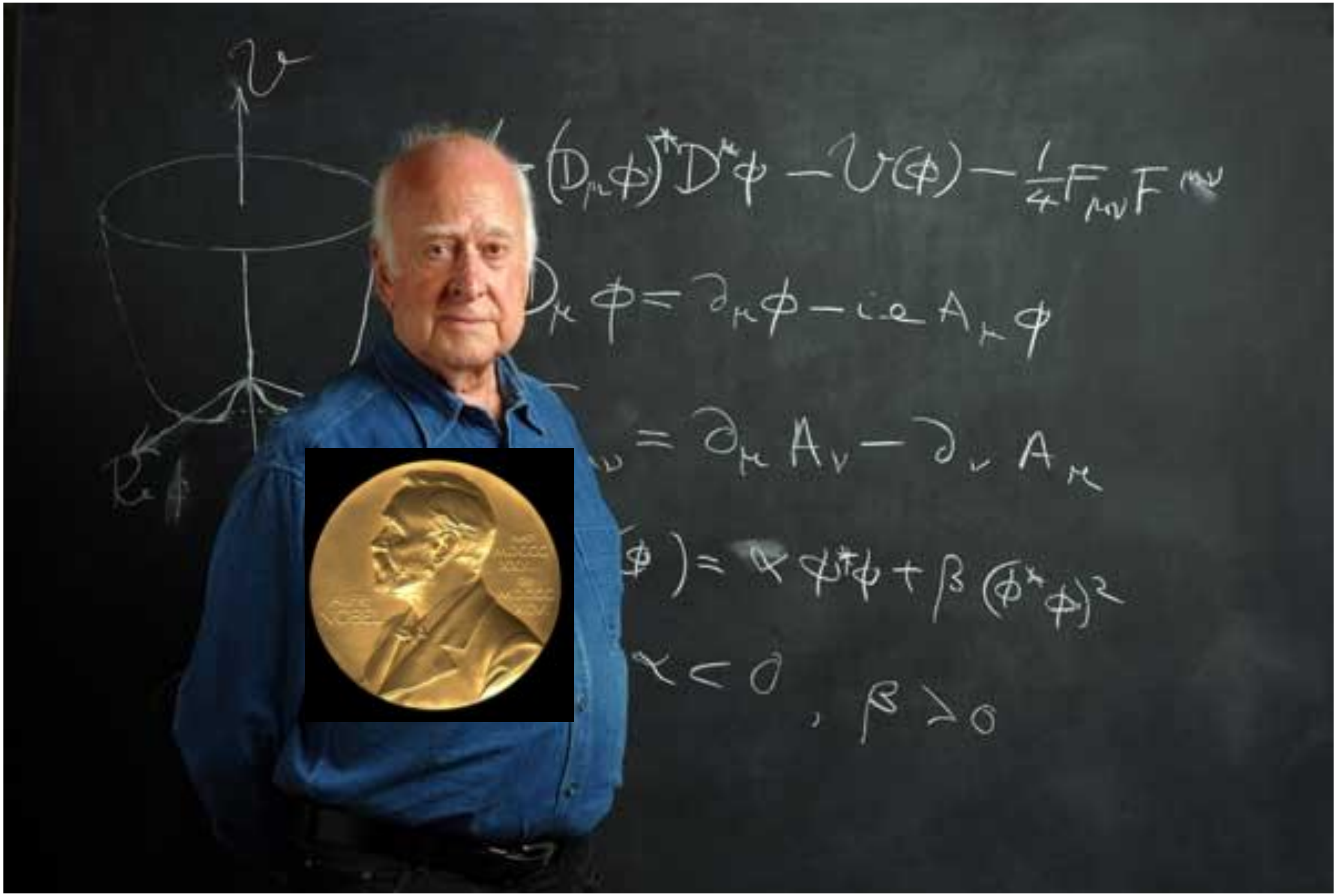
Geneva

The 2012 discovery





It’s officially a Higgs Boson!

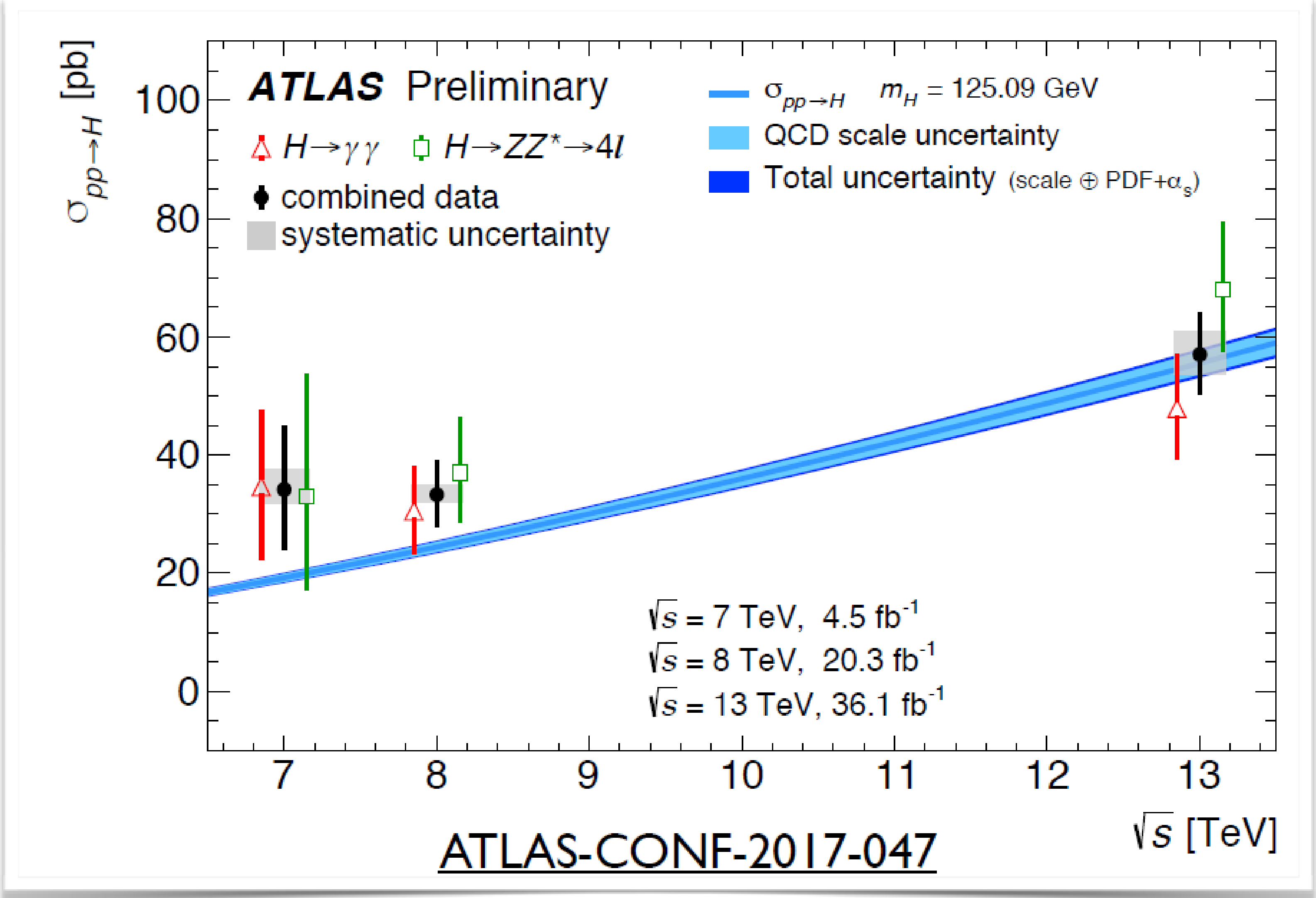


Finger-printing the Higgs boson

Determine its ‘profile’:

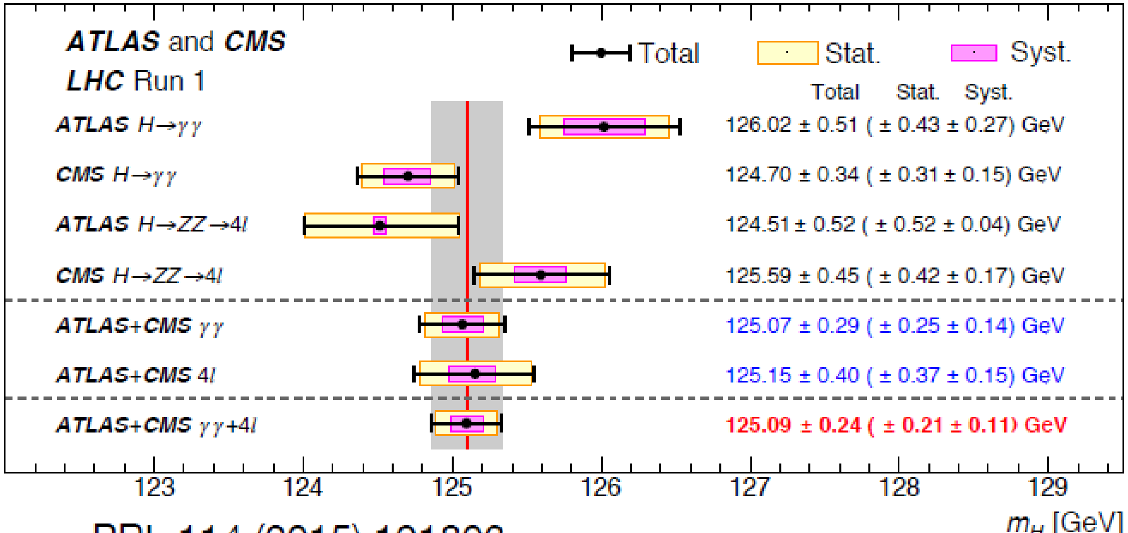
- **Mass**
- **Width**
- **Spin**
- **CP nature**
- **Coupling to fermions**
- **Coupling to gauge bosons**
- **Yukawa coupling to top quark**
- **Self coupling → Higgs potential**

Higgs production cross section



Heather Gray

Higgs mass/width



PRL 114 (2015) 191803

- Lower bound on total width from decay measurements
- Direct experimental measurements probe 3 orders of magnitude larger than SM width (Γ=4 MeV)
- Indirect constraint* on the width via measurement of ratio of off-peak to on-peak cross-section
  - CMS: Γ < 13 MeV
  - ATLAS: Γ < 22 MeV

Run-2
CMS: 125.26 ± 0.21 GeV
ATLAS: 124.98 ± 0.28 GeV

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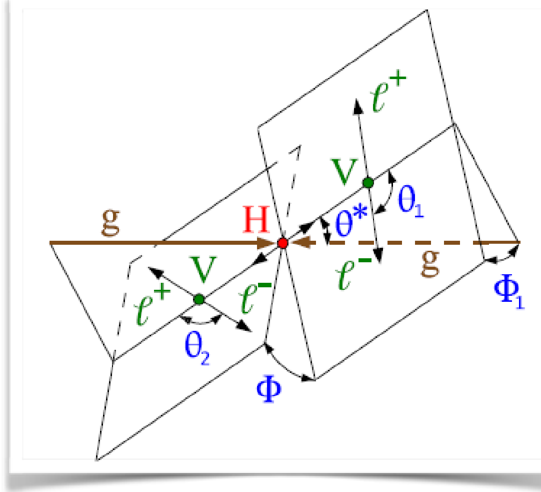
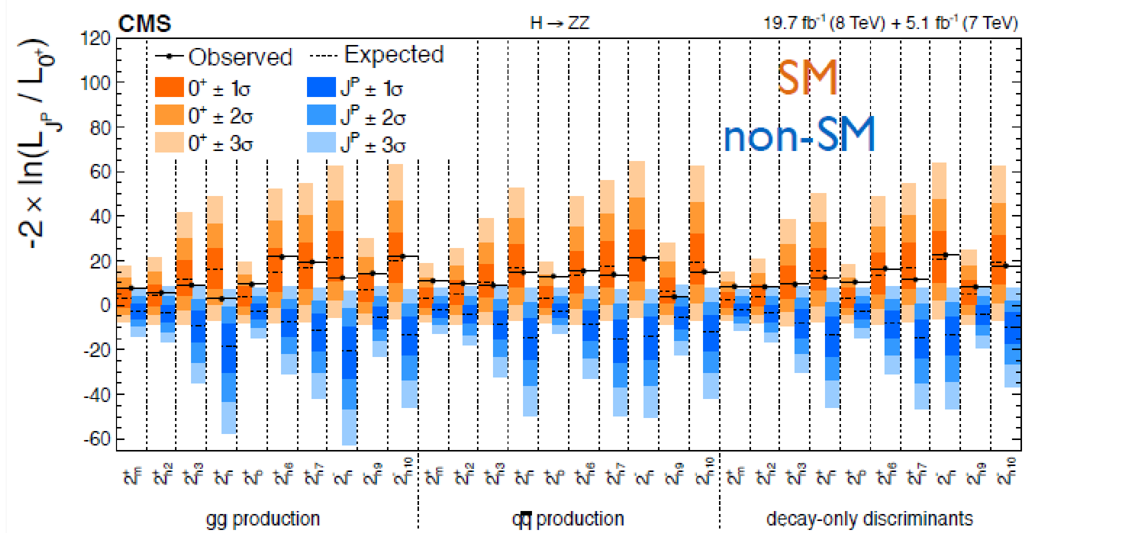
Higgs spin/parity

- SM predicts $J^{PC} = 0^{++}$
- Angular distributions sensitive to JP
- Wide range of alternative quantum numbers excluded at >99% CL
- All observations consistent with expectations for the SM Higgs boson

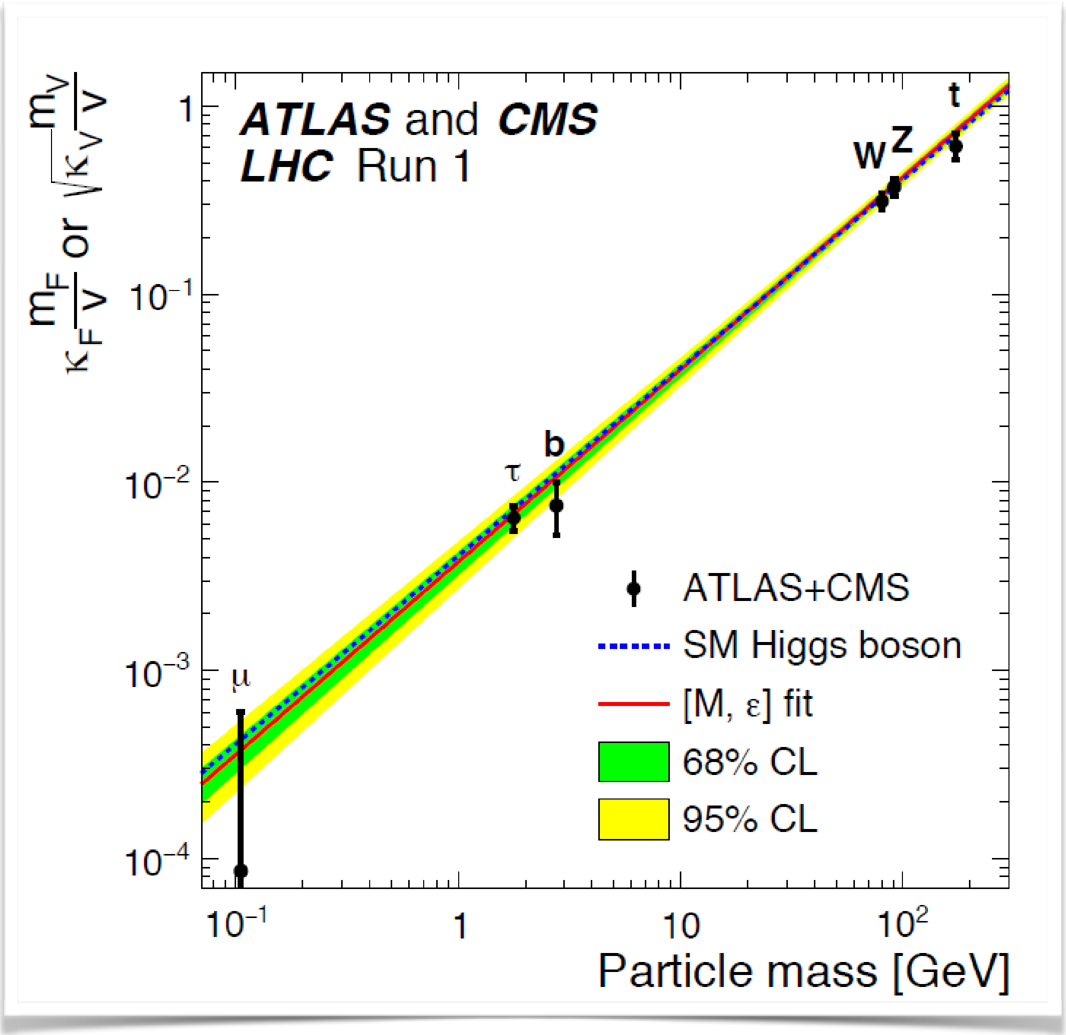




PRD 92 (2015) 012004

Tests of alternative J^P hypotheses in ZZ

Higgs couplings



JHEP08 (2016) 045

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Finger-printing the Higgs boson

Is it:

the Higgs Boson of the Standard Model?

another type of Higgs boson?

something that looks like a Higgs boson but is actually more complicated?

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→ Measurements of the Higgs couplings to the different species of quarks, leptons and gauge bosons are the key to answering these questions

Non-Standard Higgs couplings

Snowmass Higgs working group:

Decoupling limit:

If all new particles (except Higgs) are at a (high) high mass scale M

deviations from SM predictions

are of order m_H^2 / M^2

Non-Standard Higgs couplings

For M = 1 TeV, deviations of couplings from SM:

Model	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

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Deviations in the range 1% → 10%

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Deviations in the range 1% → 10%

→ measurements must be significantly more precise to resolve such deviations

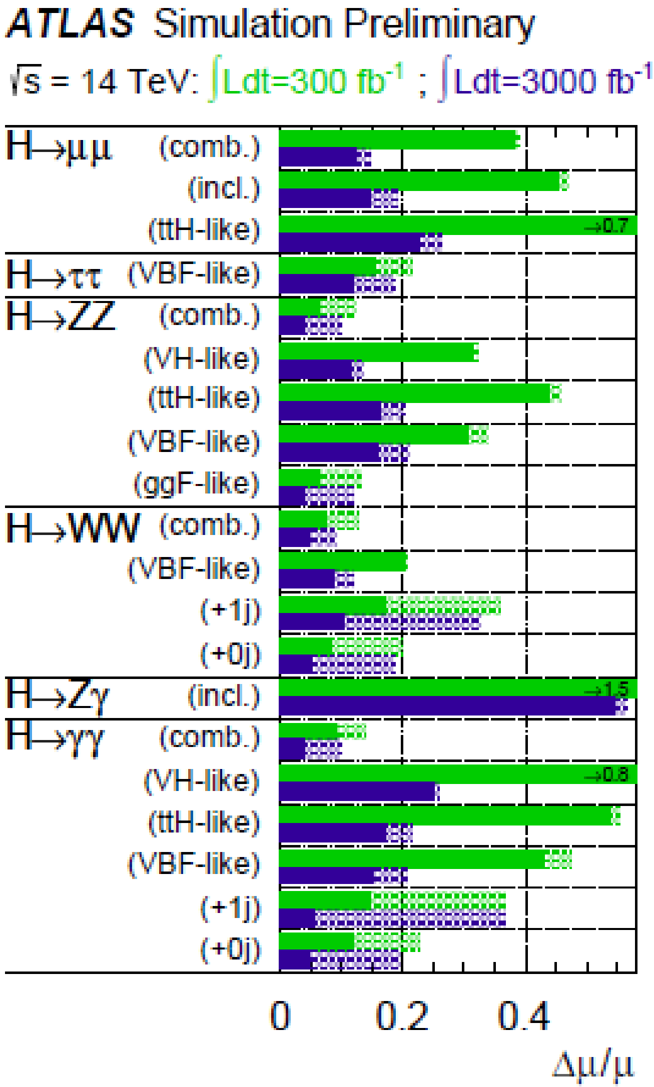
LHC projections

LHC projections

Currently, typically LHC projected precisions on Higgs coupling measurements assume that:

- **Standard Model is correct**
- **No non-Standard decay modes (total width = SM)**
- **Charm and top couplings deviate from SM by same factor**

ATLAS projections

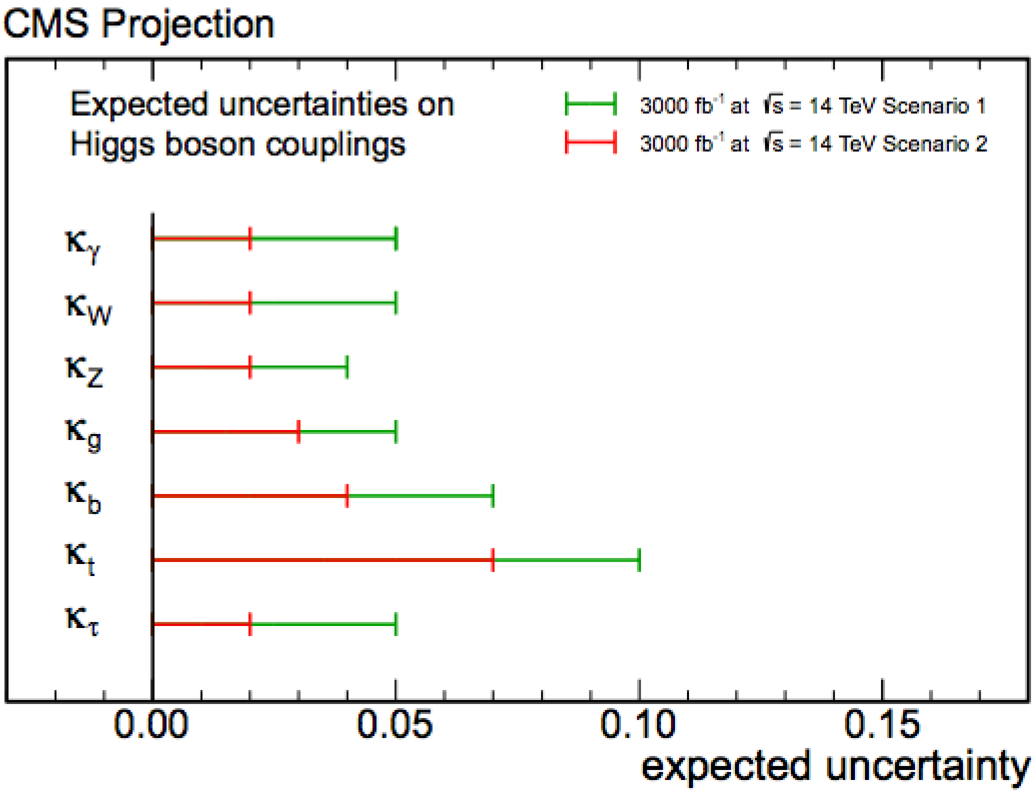


ATL PHYS PUB 2013 014

Luca Fiorini, LHCC Dec 2013

CMS projections

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	$\kappa_{\mu\mu}$	BR_{SM}
300	[5, 7]	[4, 6]	[4, 6]	[6, 8]	[10, 13]	[14, 15]	[6, 8]	[41, 41]	[23, 23]	[14, 18]
3000	[2, 5]	[2, 5]	[2, 4]	[3, 5]	[4, 7]	[7, 10]	[2, 5]	[10, 12]	[8, 8]	[7, 11]



CMS-NOTE-2013-002

Yurii Maravin, LHCC Dec 2013

LHC projections

Currently, typically LHC projected precisions on Higgs coupling measurements assume that:

- **Standard Model is correct**
- **No non-Standard decay modes (total width = SM)**
- **Charm and top couplings deviate from SM by same factor**

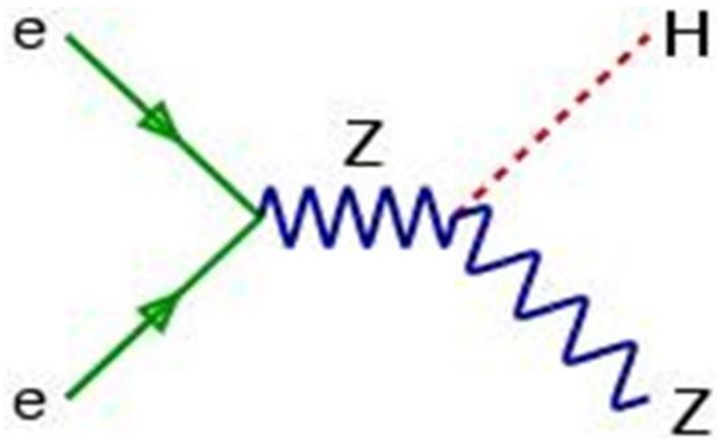
Such assumptions are not necessary for Higgs coupling measurements at e+e- Higgs Factory …

e+e- Higgs factory

e+e- annihilations:

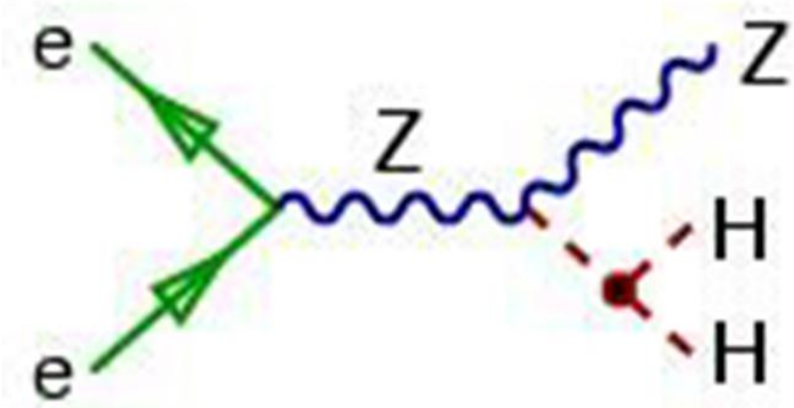
E > 91 + 125 = 216 GeV

E ~ 250 GeV



E > 91 + 250 = 341 GeV

E ~ 500 GeV



e+e- colliders

- **Produce annihilations of point-like particles under controlled conditions:**

e+e- colliders

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well defined centre of mass energy: 2E

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p = 0, M = 2E

e+e- colliders

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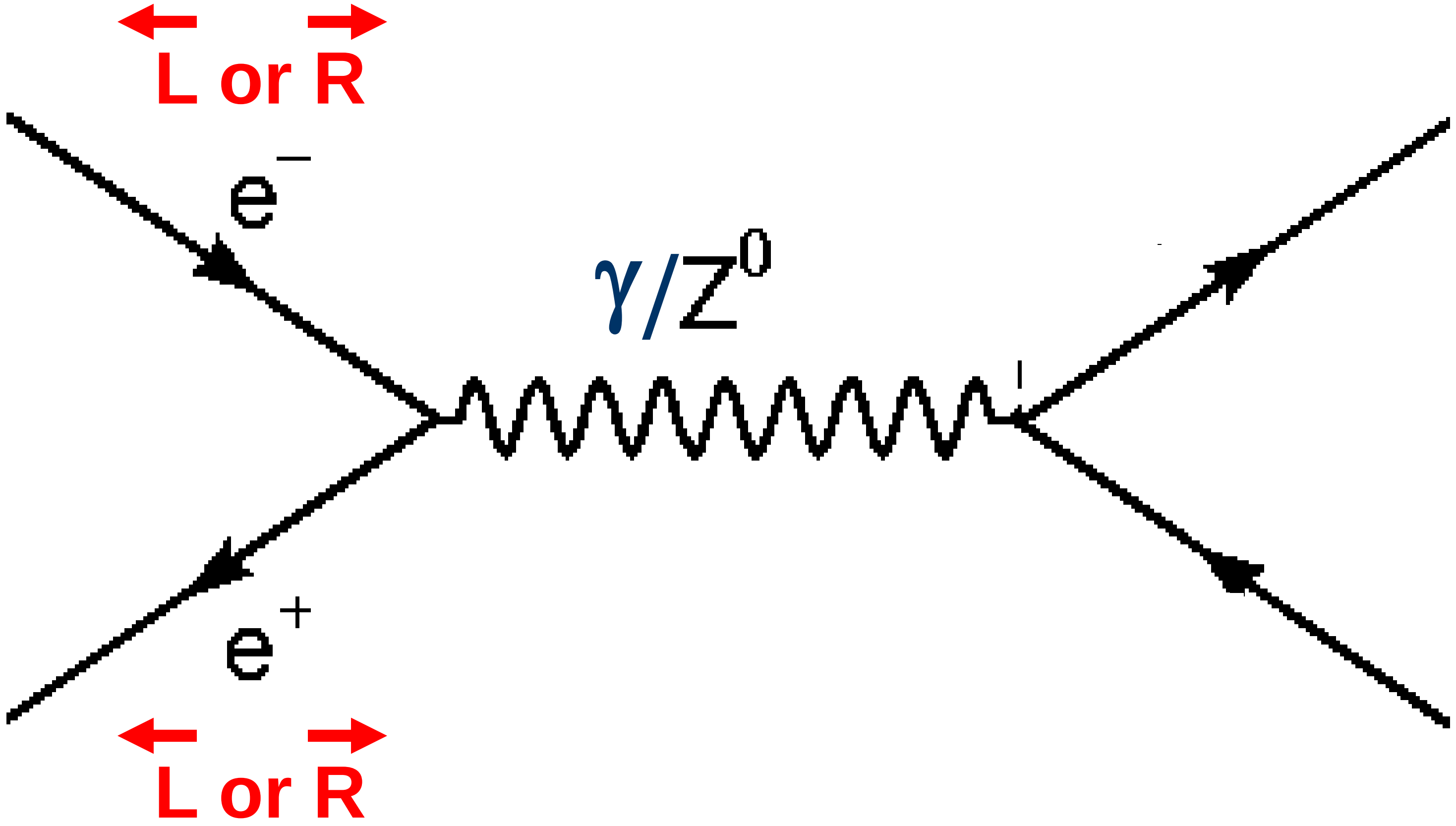
polarised beam(s)

e+e- annihilations



e+e- colliders

- **Produce annihilations of point-like particles under controlled conditions:**

well defined centre of mass energy: 2E

complete control of event kinematics:

p = 0, M = 2E

polarised beam(s)

clean experimental environment

European particle physics strategy 2013

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.

European particle physics strategy 2013

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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.

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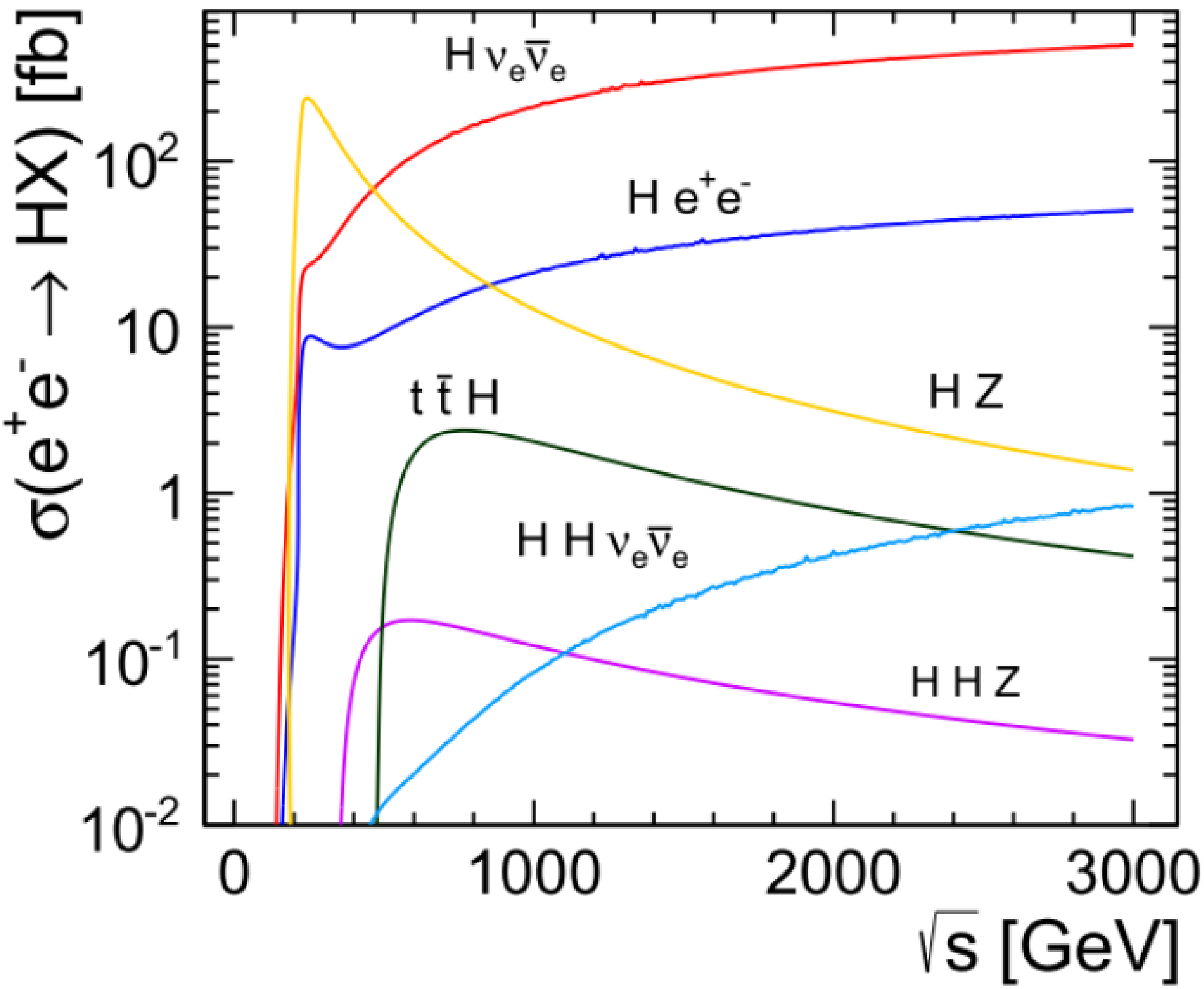
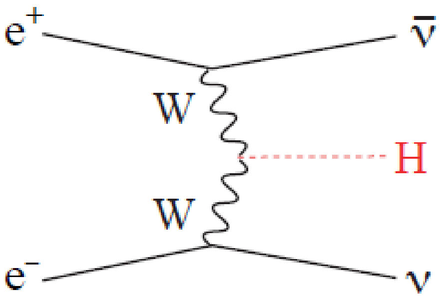
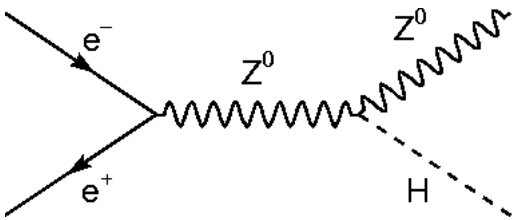
Europe looks forward to a proposal from Japan to discuss a possible participation.

e+e- Higgs Factory







Possible Higgs Factory Roadmap

250 GeV:

- **Mass, Spin, CP nature**
- **Absolute measurement of HZZ**
- **BRs Higgs → qq, ll, VV**

350-380 GeV:

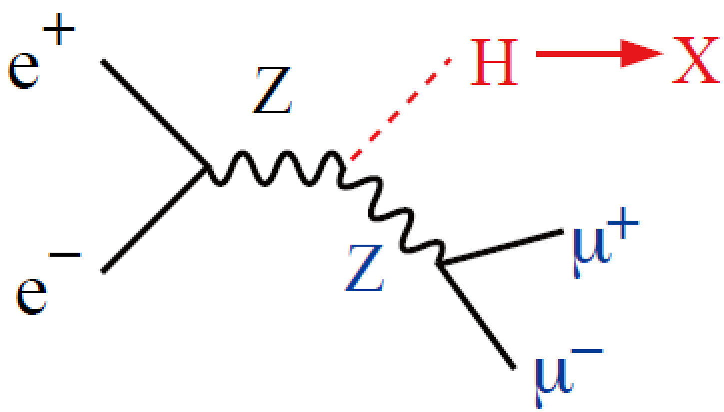
- **Absolute HWW measurements**
- **Top threshold: mass, width, anomalous couplings …**

500 GeV:

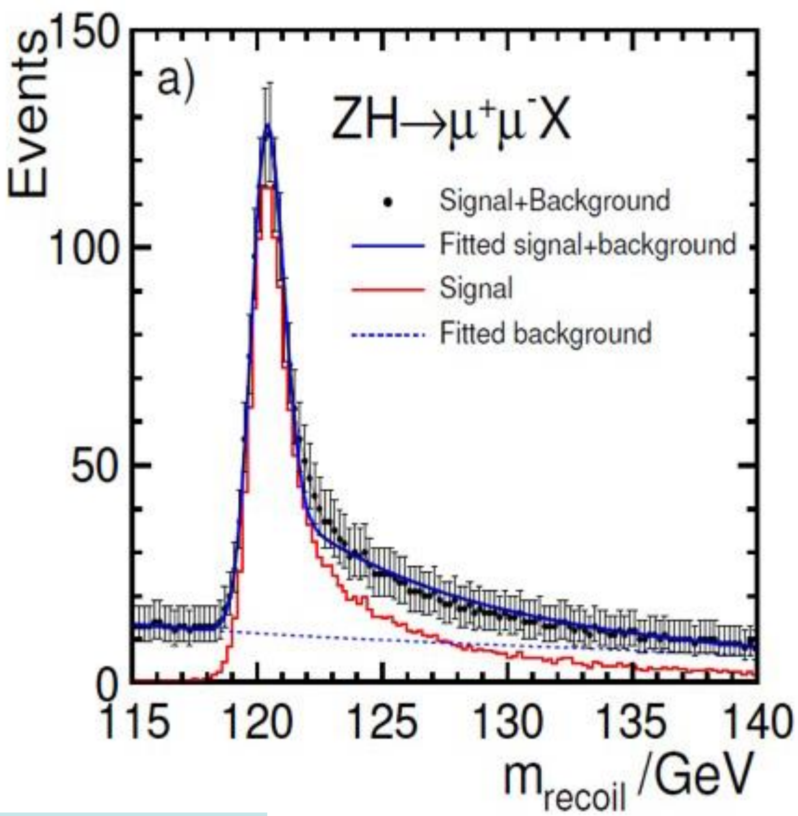
- **Higgs self coupling**
- **Top Yukawa coupling**

→ 1000 GeV: as motivated by physics

Higgs mass measurement



$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$



Recoil mass:
- independent of Higgs decay

Discovery mode for 'H' decay to weakly-interacting particles

$$250\,\mathrm{fb}^{-1} @ 250\,\mathrm{GeV}$$

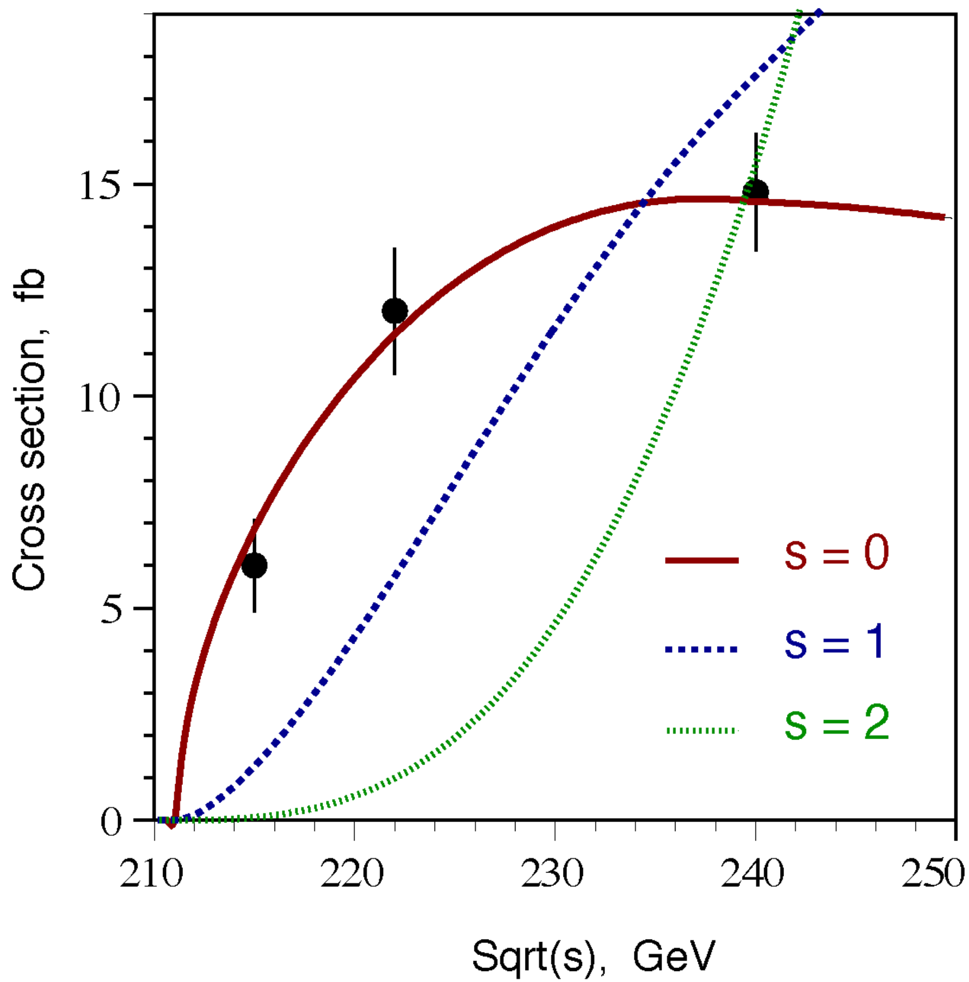
$$\Delta\sigma_H/\sigma_H = 2.5\%$$

$$\Delta m_H = 30\,\mathrm{MeV}$$

(Fujii)

Higgs spin determination

Rise of cross-section near threshold



(TESLA TDR)

Total Width and Coupling Extraction

One of the major advantages of the LC

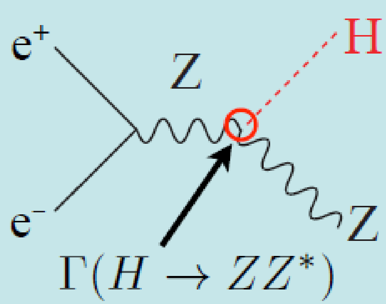
To extract couplings from BRs, we need the total width:

$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

To determine the total width, we need at least one partial width and corresponding BR:

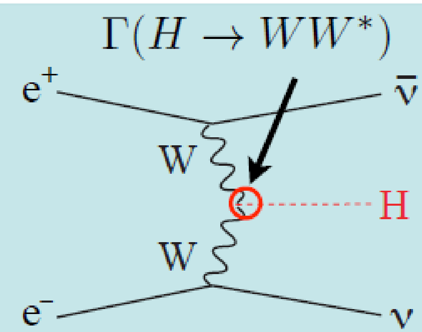
$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

In principle, we can use the A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

BR=O(1%): precision limited by low stat. for H->ZZ* events



$BR(H \to WW^*)$

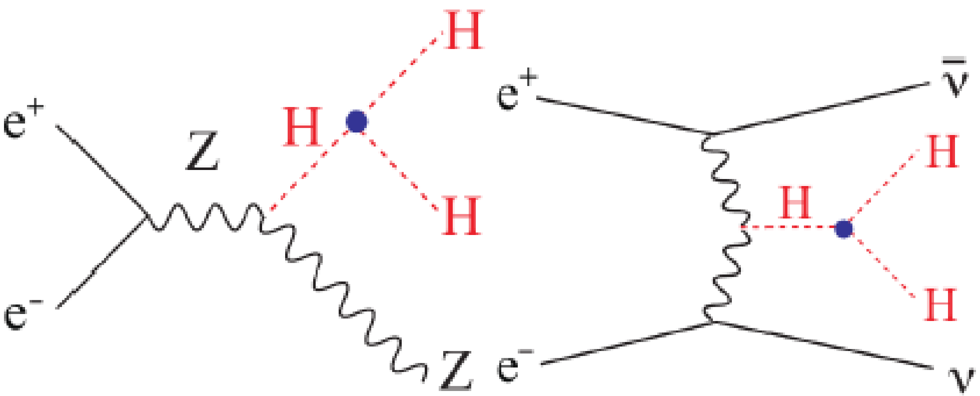
More advantageous but not easy at low E

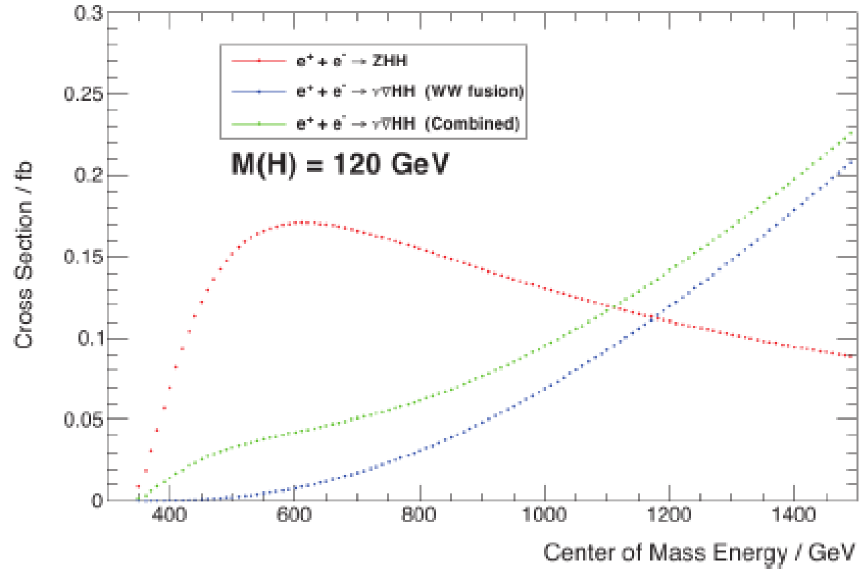
$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$

$\Delta\Gamma_H/\Gamma_H \simeq 10\%$

Jenny List's talk

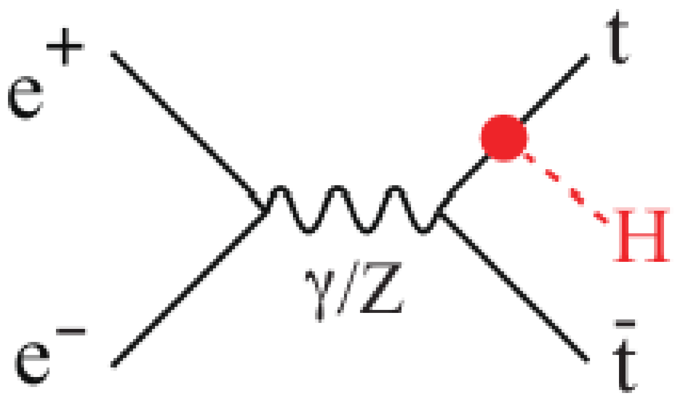
Higgs self-coupling determination

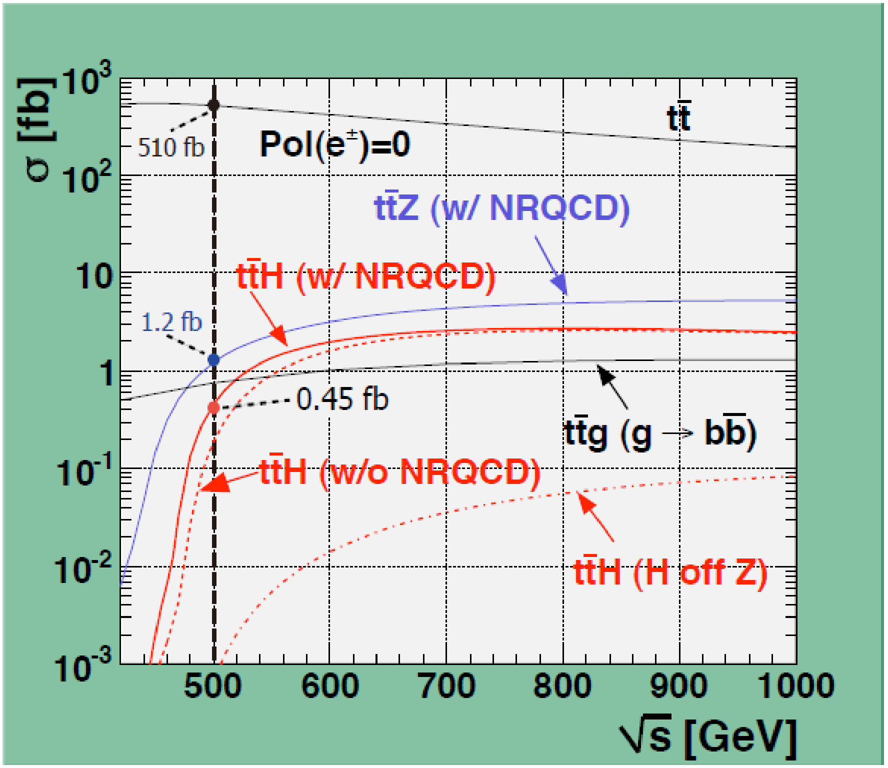




$\sqrt{s}$ (GeV) L (fb^{-1})	500 500	500 1600	500+1000 500+1000	500+1000 1600+2500
$\Delta\lambda/\lambda$	83%	46%	21%	13%

Higgs top-coupling determination





$$1\,\mathrm{ab}^{-1}@500\,\mathrm{GeV}$$

$$\Delta g_Y(t)/g_Y(t) = 10\,\%$$

(Price, Roloff)

ILC roadmap

Baseline:	**250 fb^{-1}**	**@ 250 GeV**	**3 years**
	500 fb^{-1}	**@ 500 GeV**	**3 years**
	1000 fb^{-1}	**@ 1000 GeV**	**3 years**

ILC roadmap

Baseline:	**250 fb^{-1}**	**@ 250 GeV**	**3 years**
	500 fb^{-1}	**@ 500 GeV**	**3 years**
	1000 fb^{-1}	**@ 1000 GeV**	**3 years**

Followed by luminosity upgrade:

'HL-ILC':	**+900 fb^{-1}**	**@ 250 GeV**	**+3 years**
	+1100 fb^{-1}	**@ 500 GeV**	**+3 years**
	+1500 fb^{-1}	**@ 1000 GeV**	**+3 years**

ILC baseline precisions

$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	250 fb^{-1} at 250 GeV (-0.8,+0.3)		500 fb^{-1} at 500 GeV (-0.8,+0.3)				1 ab^{-1} at 1 TeV (-0.8,+0.2)		
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$	Zhh	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}hh$
$\Delta\sigma/\sigma$	2.6%	-	3.0	-		42.7%			26.3%
BR(invis.)	$<$ 0.9 %	-	-	-	-				
mode	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \to b\bar{b}$	1.2%	10.5%	1.8%	0.7%	28%		0.5%	6.0%	
$h \to c\bar{c}$	8.3%	-	13%	6.2%			3.1%		
$h \to gg$	7.0%	-	11%	4.1%			2.3%		
$h \to WW^*$	6.4%	-	9.2%	2.4%			1.6%		
$h \to \tau^+\tau^-$	4.2%	-	5.4%	9.0%			3.1%		
$h \to ZZ^*$	19%	-	25%	8.2%			4.1%		
$h \to \gamma\gamma$	34%	-	34%	23%			8.5%		
$h \to \mu^+\mu^-$	100%	-	-	-			31%		

Model-independent couplings extraction

33 input measurements

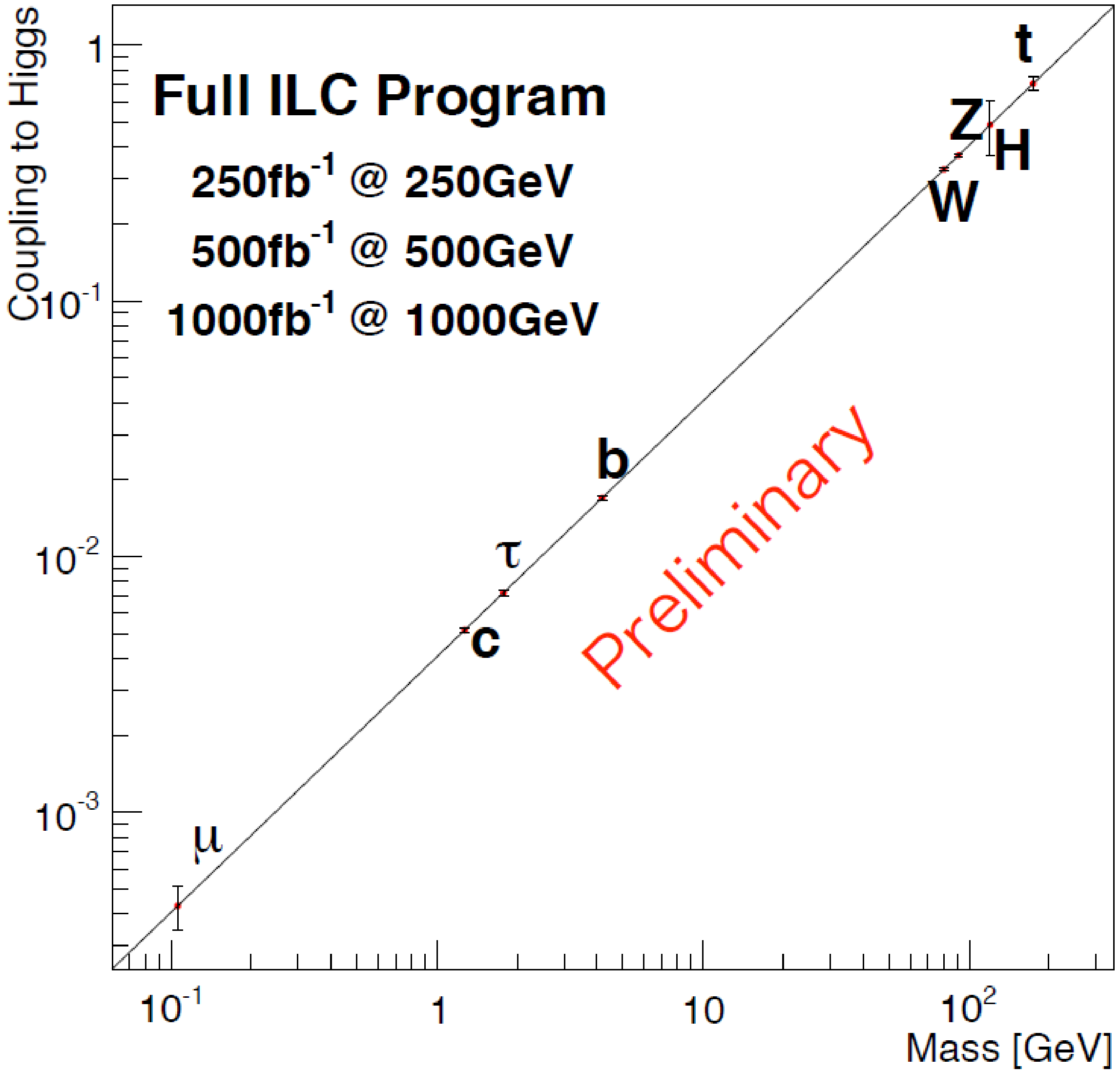
11-parameter fit

$$\chi^2 = \sum_{i=1}^{i=33} \left(\frac{Y_i - Y_i'}{\Delta Y_i}\right)^2 ,$$

$$Y_i' = F_i \cdot \frac{g^2_{HZZ} g^2_{Hb\bar{b}}}{\Gamma_0}, \text{ or } Y_i' = F_i \cdot \frac{g^2_{HWW} g^2_{Hb\bar{b}}}{\Gamma_0}, \text{ or } Y_i' = F_i \cdot \frac{g^2_{Htt} g^2_{Hb\bar{b}}}{\Gamma_0}$$

$$F_i = S_i G_i \quad \text{where } S_i = \left(\frac{\sigma_{ZH}}{g_Z^2}\right), \ \left(\frac{\sigma_{\nu\bar{\nu}H}}{g_W^2}\right), \text{ or } \left(\frac{\sigma_{t\bar{t}H}}{g_t^2}\right), \text{ and } G_i = \left(\frac{\Gamma_i}{g_i^2}\right).$$

Higgs coupling map



(Fujii)

ILC baseline + HL-ILC precisions

$\sqrt{s}$ and $\mathcal{L}$ (P_{e^-}, P_{e^+})	1150 fb^{-1} at 250 GeV (-0.8,+0.3)		1600 fb^{-1} at 500 GeV (-0.8,+0.3)				2.5 ab^{-1} at 1 TeV (-0.8,+0.2)		
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	$t\bar{t}h$	Zhh	$\nu\bar{\nu}h$	$t\bar{t}h$	$\nu\bar{\nu}hh$
$\Delta\sigma/\sigma$	1.2%	-	1.7	-		23.7%			16.7%
BR(invis.)	$<$ 0.4 %	-	-	-			-		
mode	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \to b\bar{b}$	0.6%	4.9%	1.0%	0.4%	16%		0.3%	3.8%	
$h \to c\bar{c}$	3.9%	-	7.2%	3.5%			2.0%		
$h \to gg$	3.3%	-	6.0%	2.3%			1.4%		
$h \to WW^*$	3.0%	-	5.1%	1.3%			1.0%		
$h \to \tau^+\tau^-$	2.0%	-	3.0%	5.0%			2.0%		
$h \to ZZ^*$	8.8%	-	14%	4.6%			2.6%		
$h \to \gamma\gamma$	16%	-	19%	13%			5.4%		
$h \to \mu^+\mu^-$	46.6%	-	-	-			20%		

Model-independent couplings

	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	18 %	8.4 %	4.0 %	2.4 %
gg	6.4 %	2.3 %	1.6 %	0.9 %
WW	4.8 %	1.1 %	1.1 %	0.6 %
ZZ	1.3 %	1.0 %	1.0 %	0.5 %
$t\bar{t}$	–	14 %	3.1 %	1.9 %
$b\bar{b}$	5.3 %	1.6 %	1.3 %	0.7 %
$\tau^+\tau^-$	5.7 %	2.3 %	1.6 %	0.9 %
$c\bar{c}$	6.8 %	2.8 %	1.8 %	1.0 %
$\mu^+\mu^-$	91%	91%	16 %	10 %
$\Gamma_T(h)$	12 %	4.9 %	4.5 %	2.3 %
hhh	–	83 %	21 %	13 %
BR(invis.)	$<$ 0.9 %	$<$ 0.9 %	$<$ 0.9 %	$<$ 0.4 %

Model-dependent couplings extraction

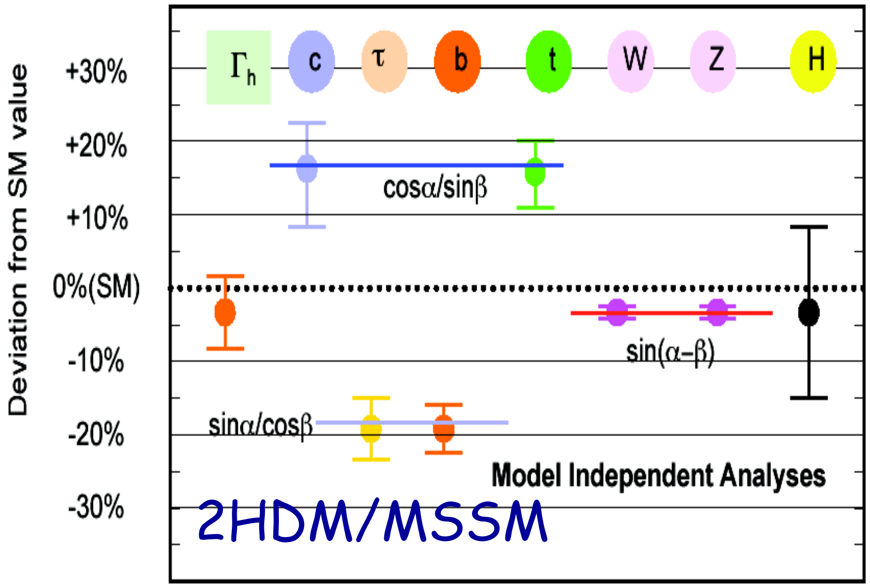
7 Parameter HXSWG Benchmark *

Mode	LHC 300 fb^{-1}	LHC 3000 fb^{-1}	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)			250+500+1000	250+500+1000
L (fb^{-1})			250+500+1000	1150+1600+2500
$\gamma\gamma$	$(5-7)\%$	$(2-5)\%$	3.8 %	2.3 %
gg	$(6-8)\%$	$(3-5)\%$	1.1 %	0.7 %
WW	$(4-5)\%$	$(2-3)\%$	0.3 %	0.2 %
ZZ	$(4-5)\%$	$(2-3)\%$	0.5 %	0.3 %
$t\bar{t}$	$(14-15)\%$	$(7-10)\%$	1.3 %	0.9 %
$b\bar{b}$	$(10-13)\%$	$(4-7)\%$	0.6 %	0.4 %
$\tau^+\tau^-$	$(6-8)\%$	$(2-5)\%$	1.3 %	0.7 %

~10 x LHC sensitivity

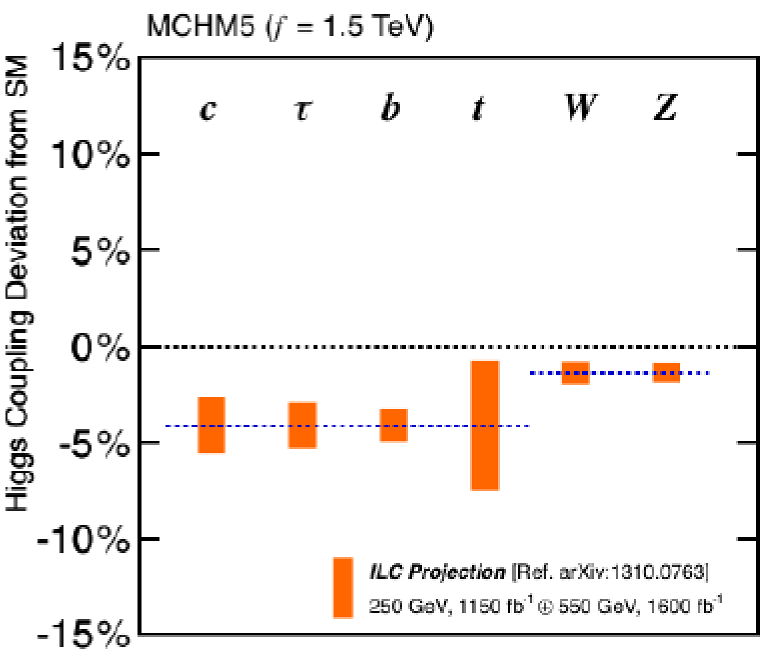
* Assume $\kappa_c = \kappa_t$ & $\Gamma_{tot} = \sum_{\text{SM decays } i} \Gamma_i^{SM} \kappa_i^2$

Specific beyond-SM examples



Zivkovic et al

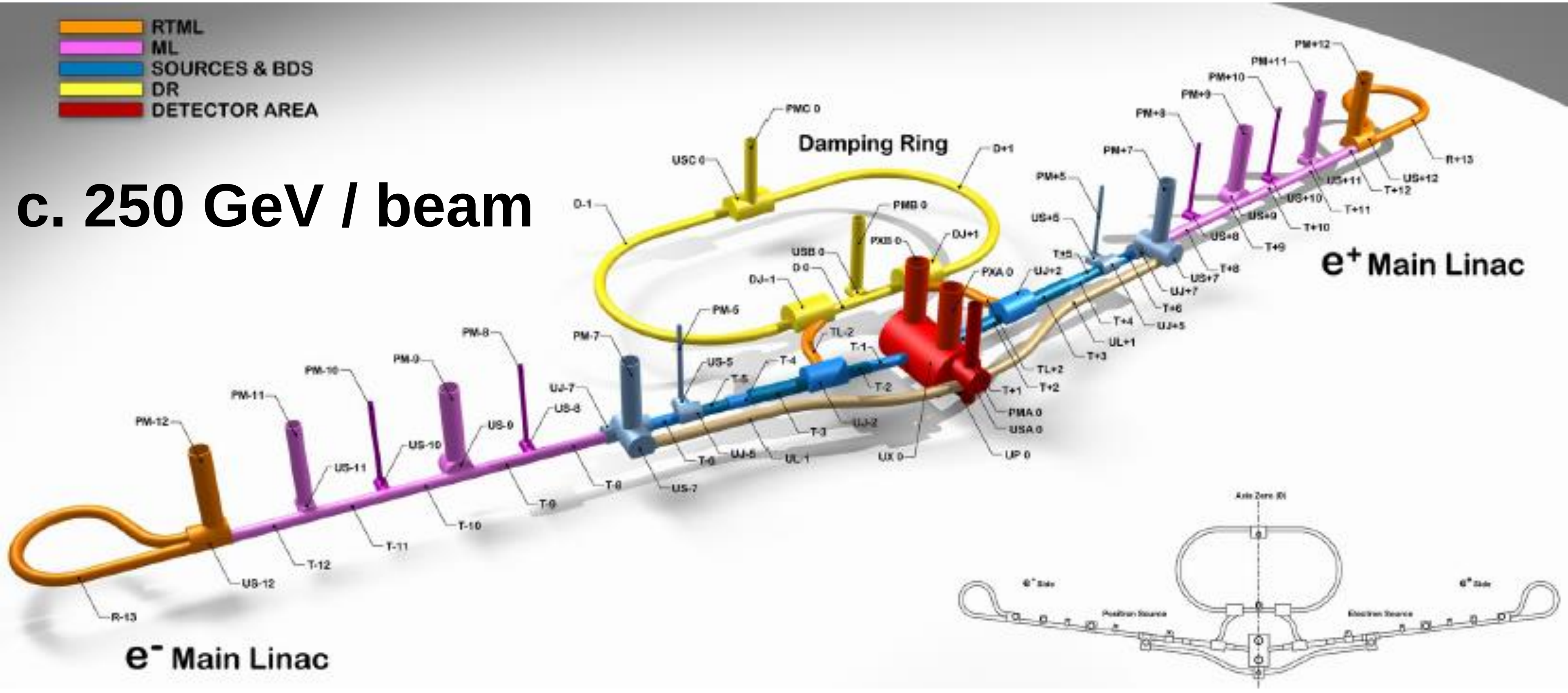
Composite Higgs
(MCHM5)



Simulated ILC measurements

The linear collider projects

International Linear Collider (ILC)



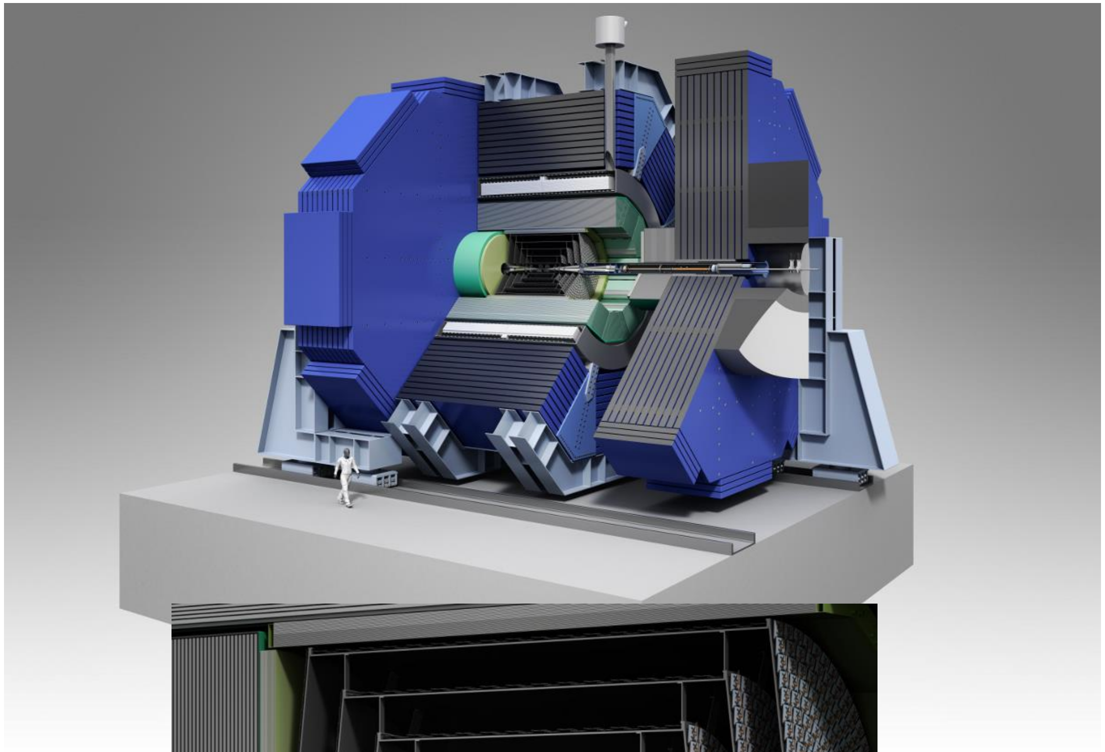
c. 250 GeV / beam

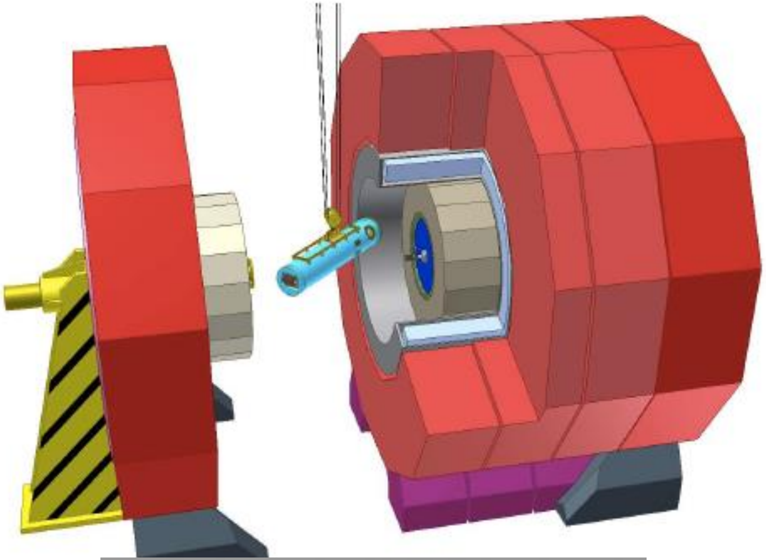
31 km

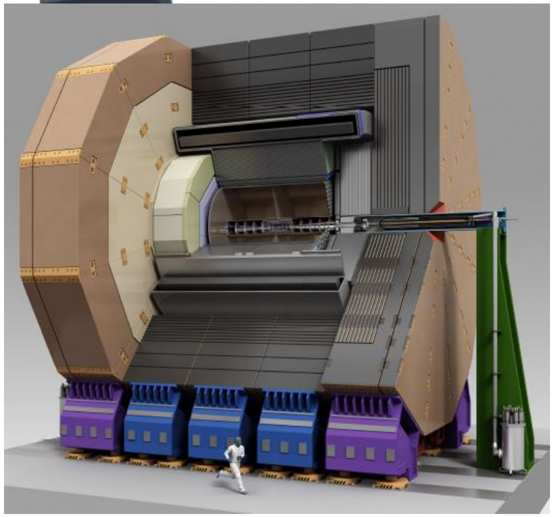
Beam parameters

	ILC (500)	
Electrons/bunch	0.75	10**10
Bunches/train	2820	
Train repetition rate	5	Hz
Bunch separation	308	ns
Train length	868	us
Horizontal IP beam size	655	nm
Vertical IP beam size	6	nm
Longitudinal IP beam size	300	um
Luminosity	2	10**34

ILC Detectors







ILC project status

- 2005-12 ILC run by Global Design Effort (Barish)
- C. 500 accelerator scientists worldwide involved
- A Reference Design Report (RDR) was completed in 2007

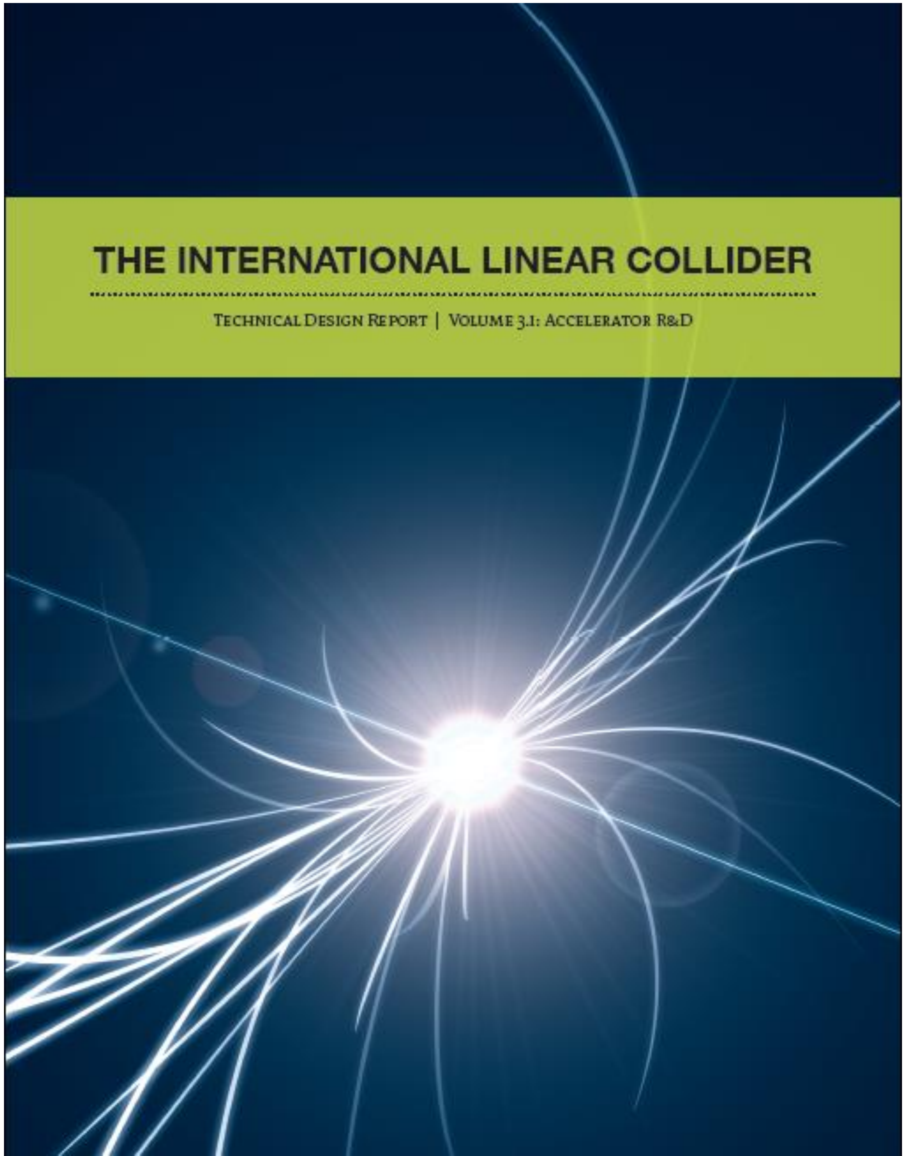
  including a first cost estimate
- 2008-12 engineering design phase

  major focus on risk minimisation + cost reduction
- Technical Design Report released end 2012

  revised cost estimate + project implementation plan
- Lyn Evans assumed project leadership 2013

  Japan preparing implementation of ILC at Kitakami

ILC Technical Design Report



John Adams Institute leadership

Part I:

ILC R&D IN THE TECHNICAL DESIGN PHASE

Part II:

THE ILC BASELINE DESIGN

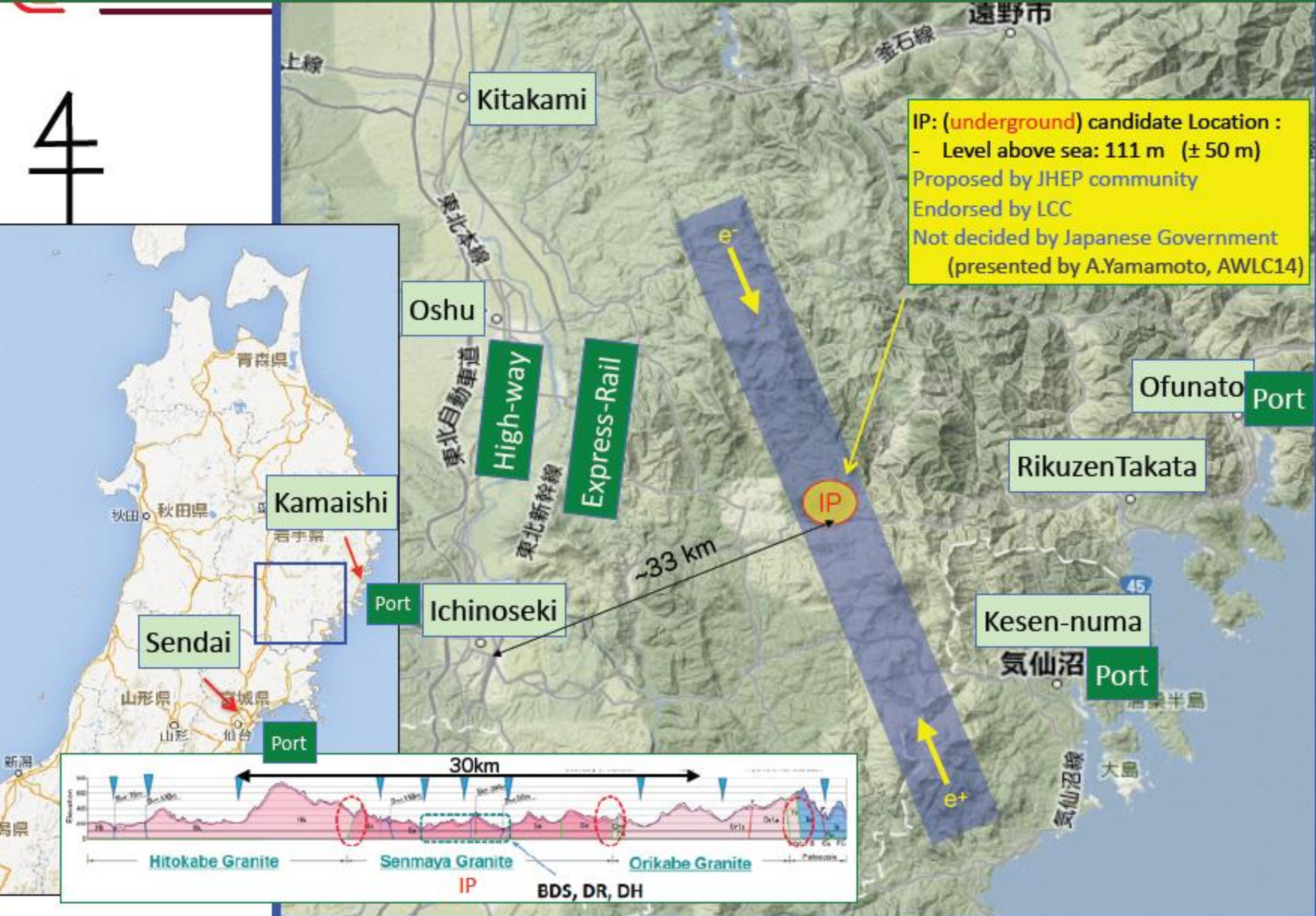
Editors:

Phil Burrows, John Carwardine, Eckhard Elsen,
Brian Foster, Mike Harrison, Hitoshi Hayano,
Nan Phinney, Marc Ross, Nobu Toge,
Nick Walker, Akira Yamamoto, Kaoru Yokoya

Technical Editors:

Maura Barone, Benno List

ILC Candidate Location: Kitakami Area

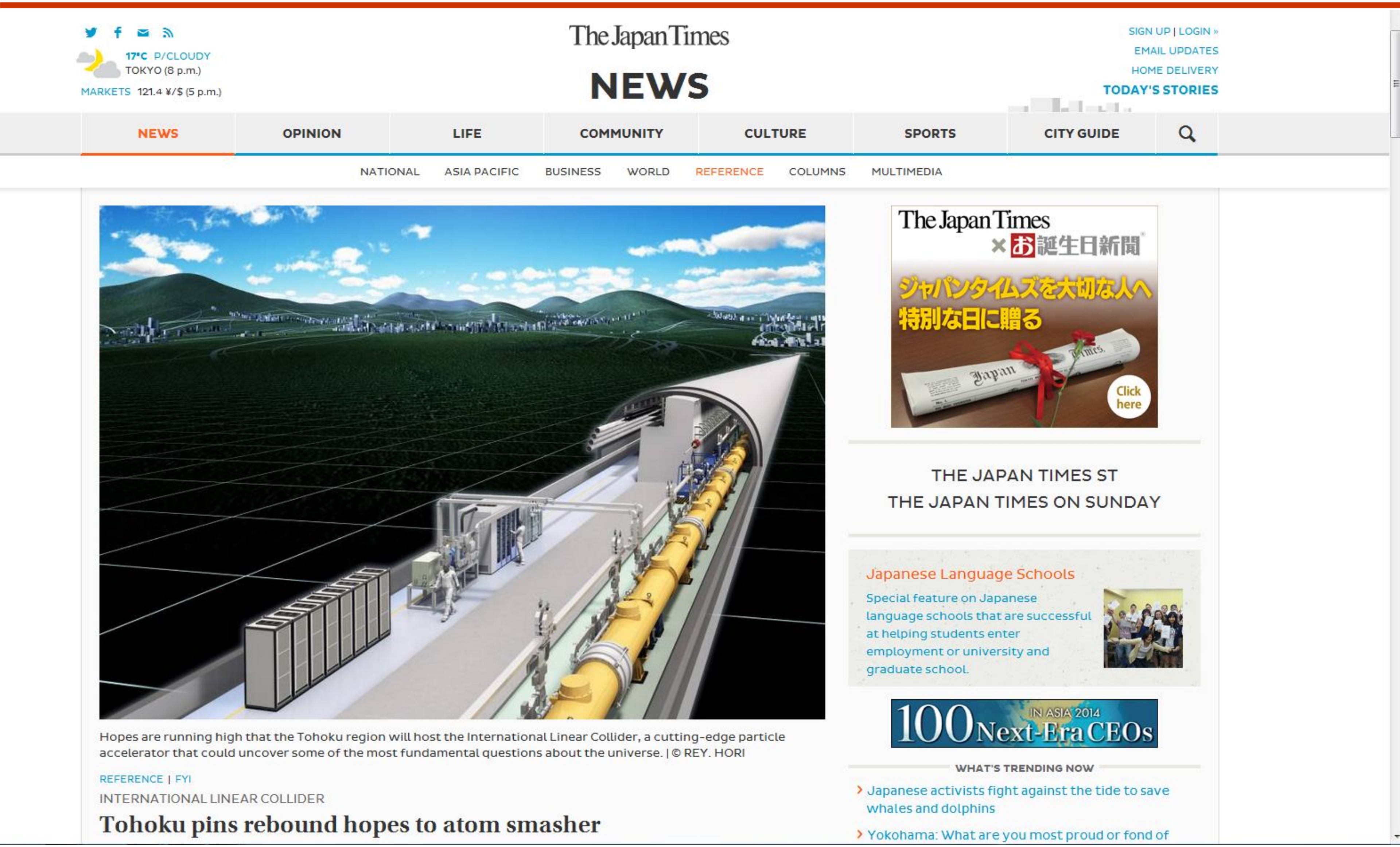


Kitakami Site

Kitakami Site: Interaction Point

Kitakami Site: Interaction Point

National news



17°C P/CLOUDY
TOKYO (8 p.m.)
MARKETS 121.4 ¥/$ (5 p.m.)

The Japan Times

NEWS

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Hopes are running high that the Tohoku region will host the International Linear Collider, a cutting-edge particle accelerator that could uncover some of the most fundamental questions about the universe. | © REY. HORI

REFERENCE | FYI

INTERNATIONAL LINEAR COLLIDER

Tohoku pins rebound hopes to atom smasher

The Japan Times ×お誕生日新聞
ジャパンタイムズを大切な人へ
特別な日に贈る
Click here

THE JAPAN TIMES ST
THE JAPAN TIMES ON SUNDAY

Japanese Language Schools
Special feature on Japanese language schools that are successful at helping students enter employment or university and graduate school.

100 Next-Era CEOs IN ASIA 2014

WHAT'S TRENDING NOW
- Japanese activists fight against the tide to save whales and dolphins
- Yokohama: What are you most proud or fond of

Regional enthusiasm

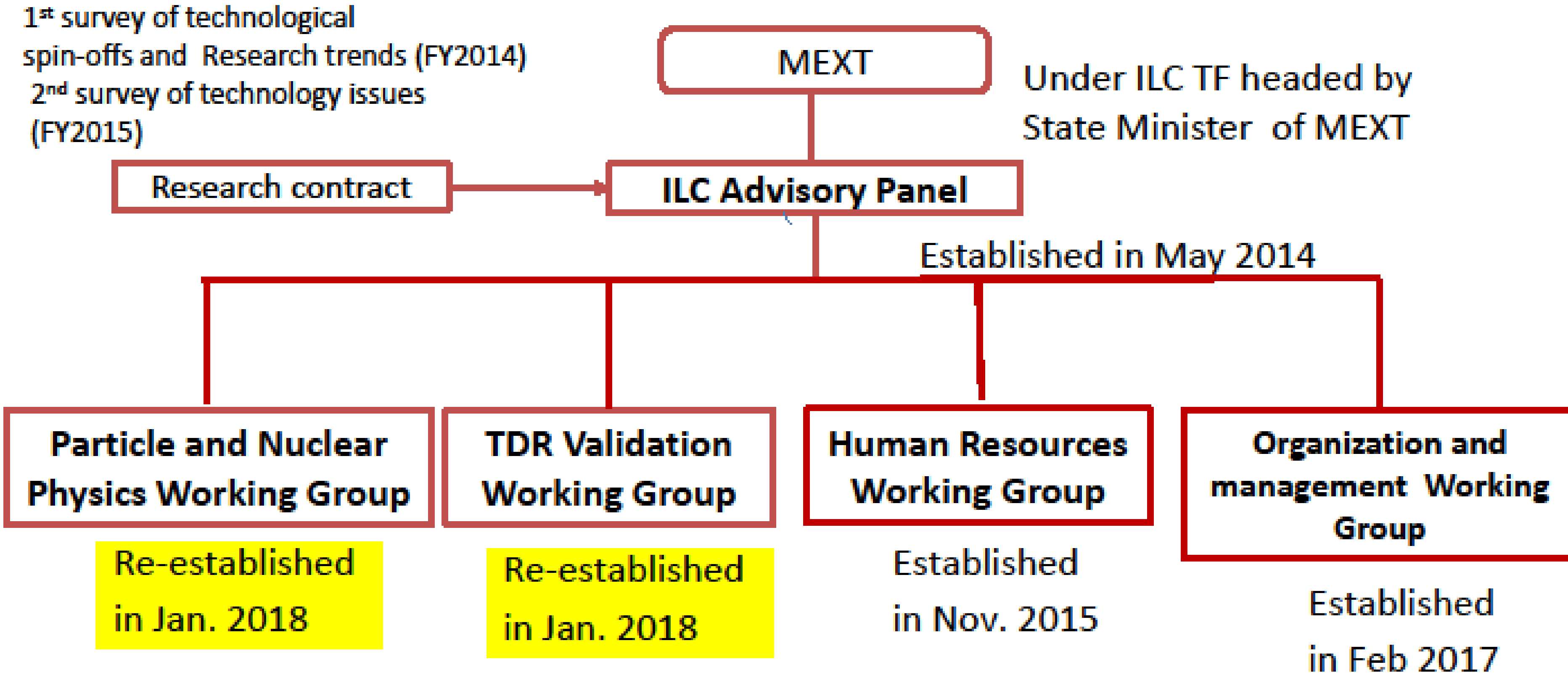
Local enthusiasm

Kitakami Site: road to port

ILC in Japan?

meeting of Lyn Evans and Prime Minister Abe, March 27, 2013

ILC Advisory Panel in MEXT



- Special Committee investigates critical issues required to judge hosting ILC.
- ILC Advisory Panel's Summary (Aug 2015)
- "Report on measures to secure and develop human resources for the ILC" (July 2016)
- A WG to investigate organizational and management issues was recently set up (Feb 2017).
- Particle and Nuclear Physics Working Group and TDR Validation Working group are re-established to evaluate ILC250GeV.
- First working group will be held on middle of January, 2018.

US-Japan cost reduction R&D

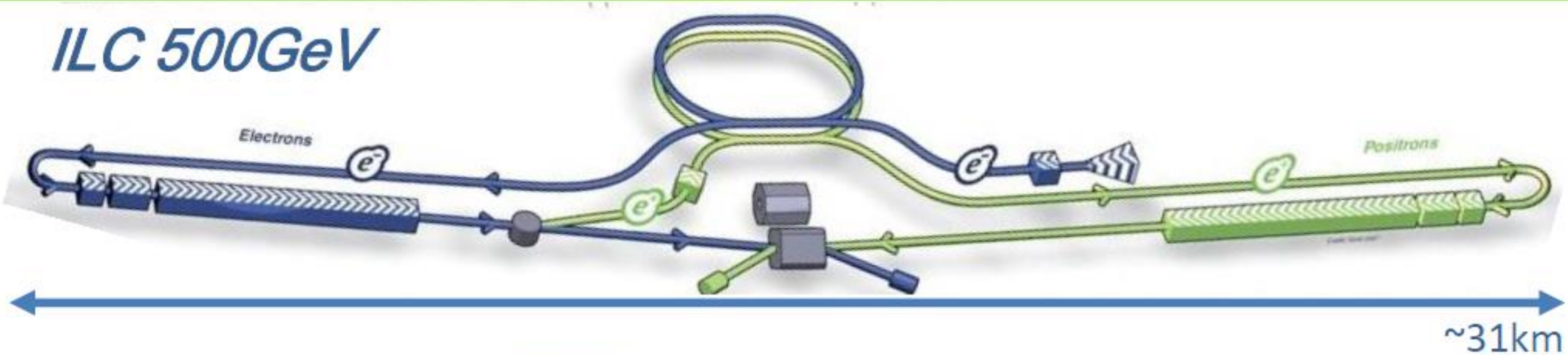
Cost reduction by technological innovation

Innovation of Nb (superconducting) material process: decrease in material cost

Innovative surface process for high efficiency cavity (N-infusion): decrease in number of cavities

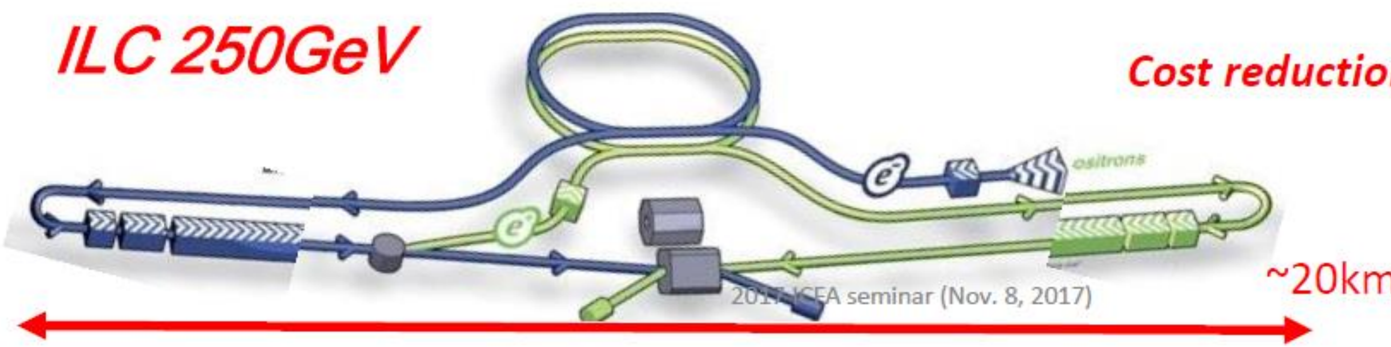
Staging

ILC 500GeV



ILC 250GeV

Cost reduction by compact ILC



2017 ICFA seminar (Nov. 8, 2017)

Michizono

DESY-17-155
KEK Preprint 2017-31
LAL 17-059
SLAC–PUB–17161
October 2017

Physics Case for the 250 GeV Stage of the International Linear Collider

LCC Physics Working Group

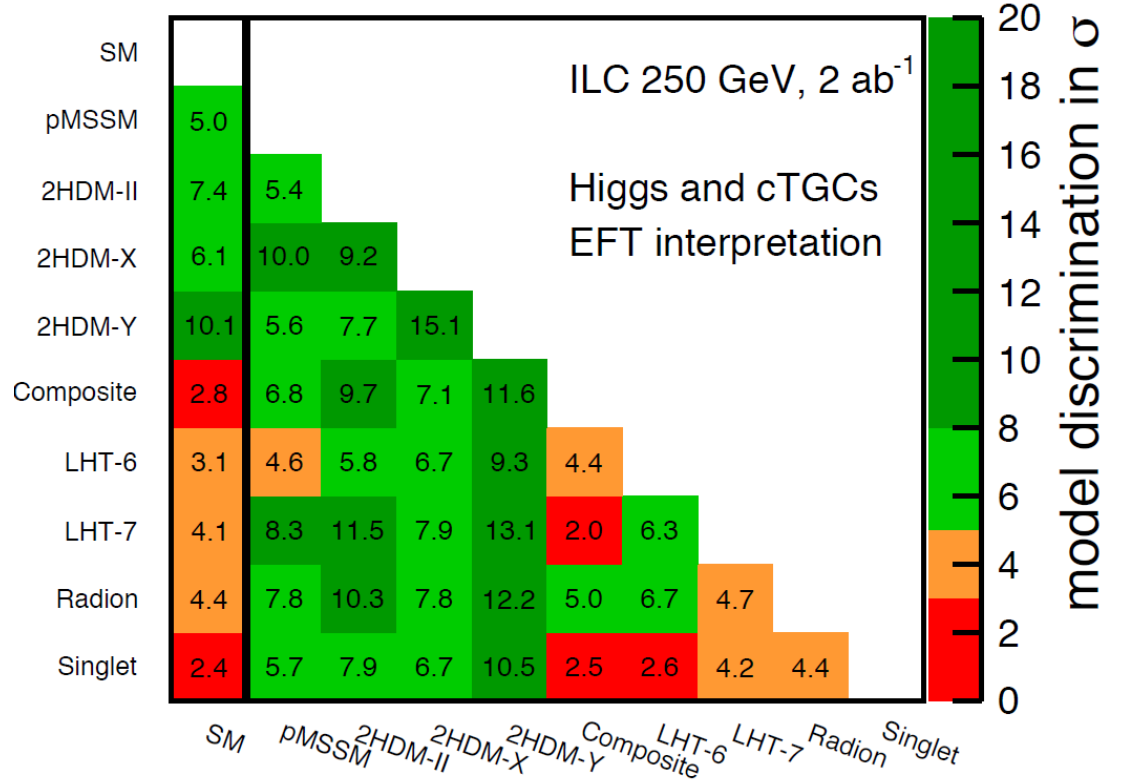
Keisuke Fujii[1], Christophe Grojean[2,3], Michael E. Peskin[4] (Conveners); Tim Barklow[4], Yuanning Gao[5], Shinya Kanemura[6], Hyungdo Kim[7], Jenny List[2], Mihoko Nojiri[1,8], Maxim Perelstein[9], Roman Pöschl[10], Jürgen Reuter[2], Frank Simon[11], Tomohiko Tanabe[12], James D. Wells[13], Jaehoon Yu[14]; Mikael Berggren[2], Moritz Habermehl[2], Sunghoon Jung[7], Robert Karl[2], Tomohisa Ogawa[1], Junping Tian[12]; James Brau[15], Hitoshi Murayama[8,16,17] (ex officio)

ABSTRACT

The International Linear Collider is now proposed with a staged machine design, with the first stage at 250 GeV with a luminosity goal of 2 ab^{-1}. In this paper, we review the physics expectations for this machine. These include precision measurements of Higgs boson couplings, searches for exotic Higgs decays, other searches for particles that decay with zero or small visible energy, and measurements of e^+e^- annihilation to W^+W^- and 2-fermion states with improved sensitivity. A summary table gives projections for the achievable levels of precision based on the latest full simulation studies.

1. PMSSM model with b squarks at 3.4 TeV.
2. Type II 2-Higgs-doublet model with H at 600 GeV
3. Type X 2-Higgs-doublet model with H at 450 GeV
4. Type Y 2-Higgs-doublet model with H at 600 GeV
5. MCHM5 Composite Higgs model, with f = 1.2 TeV
6. Little Higgs model w. T-parity, f = 0.8 TeV
7. Little Higgs model w. T-parity, f = 1 TeV, extension for light quark Yukawa couplings
8. Higgs-radion mixing model, radion at 500 GeV
9. Higgs-singlet mixing model, singlet at 2.8 TeV

results: ILC 250 GeV 2 ab-1



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.0									
2HDM-II	7.4	5.4								
2HDM-X	6.1	10.0	9.2							
2HDM-Y	10.1	5.6	7.7	15.1						
Composite	2.8	6.8	9.7	7.1	11.6					
LHT-6	3.1	4.6	5.8	6.7	9.3	4.4				
LHT-7	4.1	8.3	11.5	7.9	13.1	2.0	6.3			
Radion	4.4	7.8	10.3	7.8	12.2	5.0	6.7	4.7		
Singlet	2.4	5.7	7.9	6.7	10.5	2.5	2.6	4.2	4.4	

ICFA STATEMENT ON THE ILC OPERATING AT 250 GEV AS A HIGGS BOSON FACTORY

The discovery of a Higgs boson in 2012 at the Large Hadron Collider (LHC) at CERN is one of the most significant recent breakthroughs in science and marks a major step forward in fundamental physics. Precision studies of the Higgs boson will further deepen our understanding of the most fundamental laws of matter and its interactions.

The International Linear Collider (ILC) operating at 250 GeV center-of-mass energy will provide excellent science from precision studies of the Higgs boson. Therefore, ICFA considers the ILC a key science project complementary to the LHC and its upgrade.

ICFA welcomes the efforts by the Linear Collider Collaboration on cost reductions for the ILC, which indicate that up to 40% cost reduction relative to the 2013 Technical Design Report (500 GeV ILC) is possible for a 250 GeV collider.

ICFA emphasises the extendibility of the ILC to higher energies and notes that there is large discovery potential with important additional measurements accessible at energies beyond 250 GeV.

ICFA thus supports the conclusions of the Linear Collider Board (LCB) in their report presented at this meeting and very strongly encourages Japan to realize the ILC in a timely fashion as a Higgs boson factory with a center-of-mass energy of 250 GeV as an international project[1] , led by Japanese initiative.

1 In the LCB report the European XFEL and FAIR are mentioned as recent examples for international projects.

Ottawa, November 2017

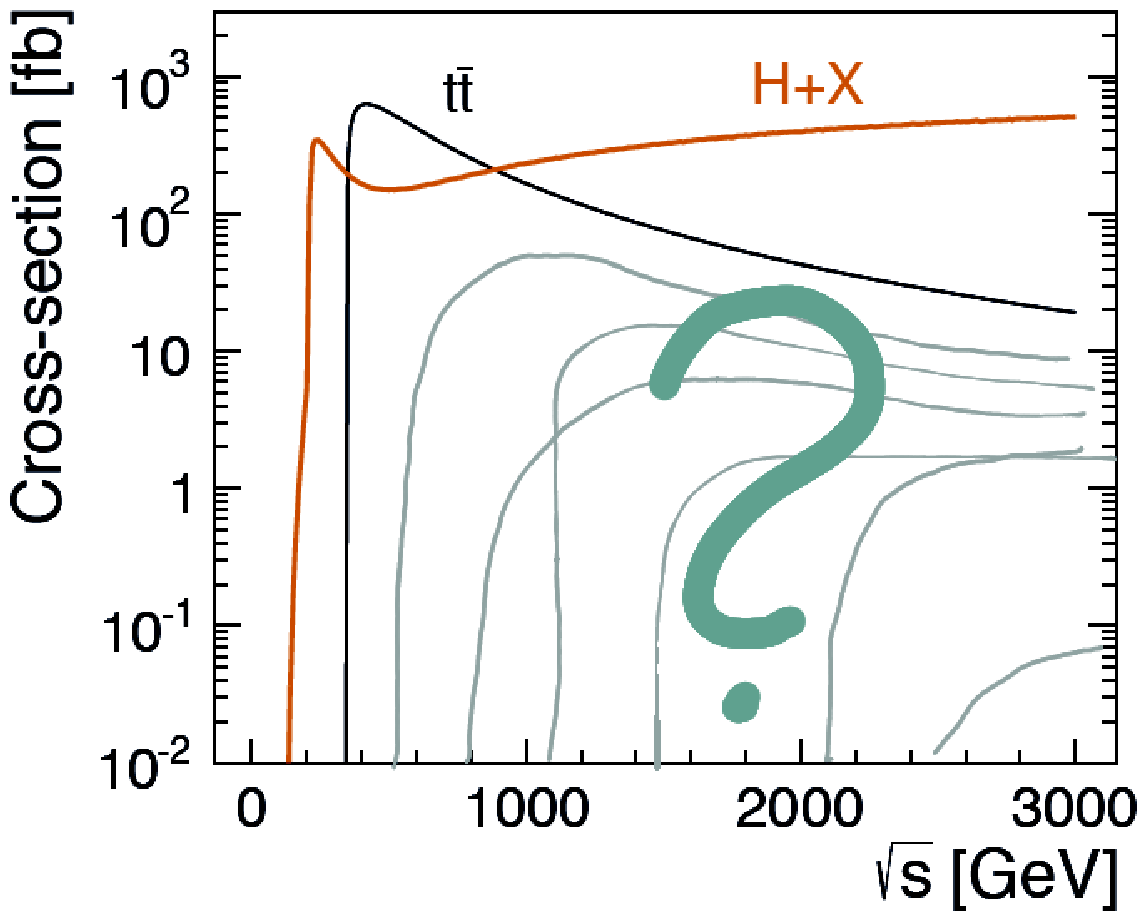
CLIC Collaborations

31 Countries – over 70 Institutes

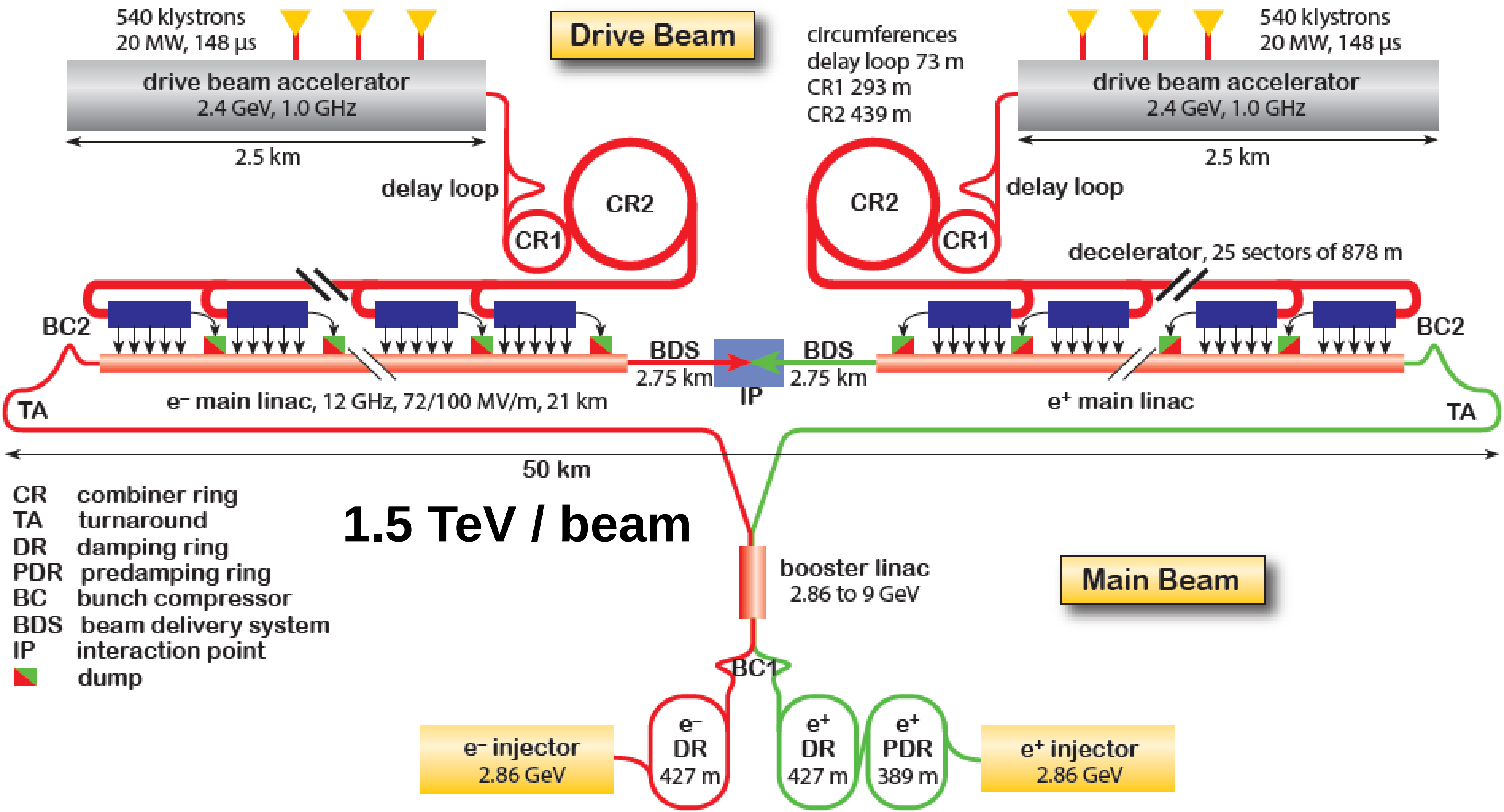
CLIC physics context

Energy-frontier capability for electron-positron collisions,

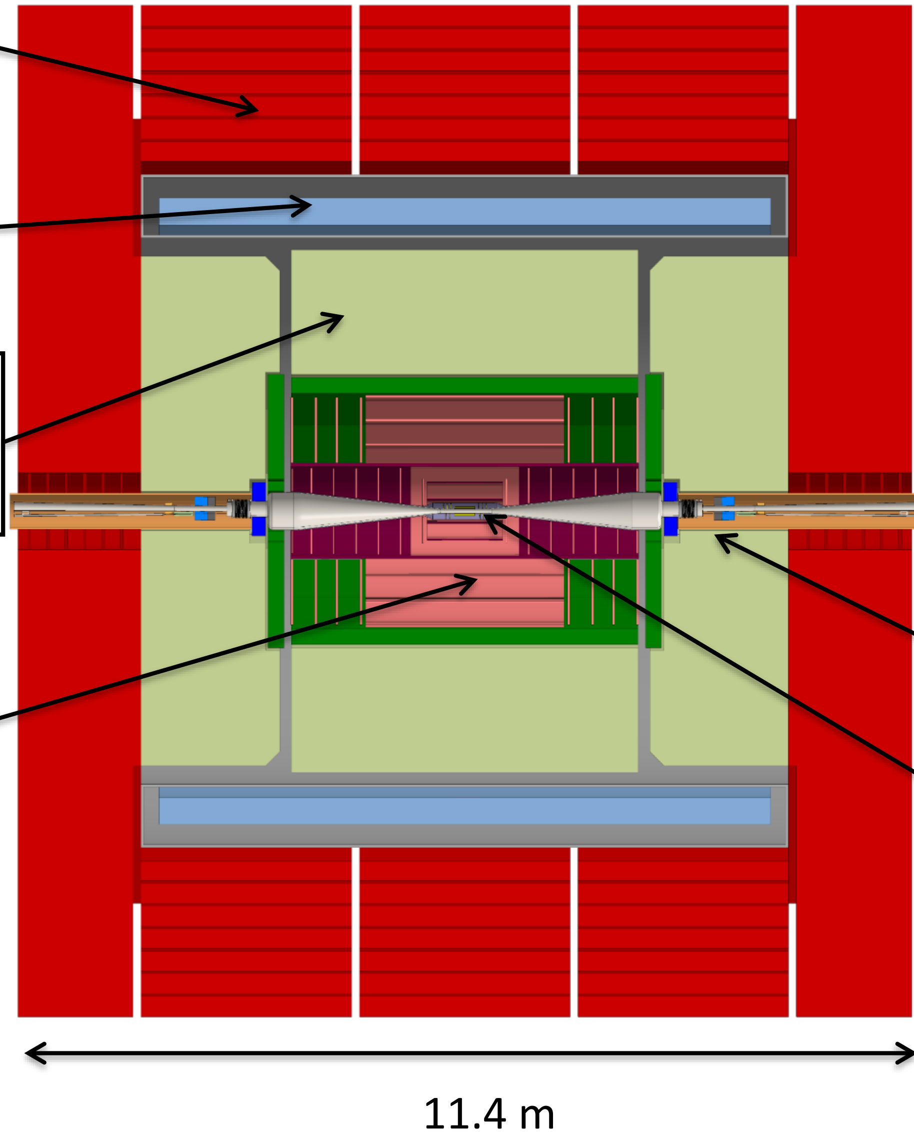
for precision exploration of potential new physics that may emerge from LHC

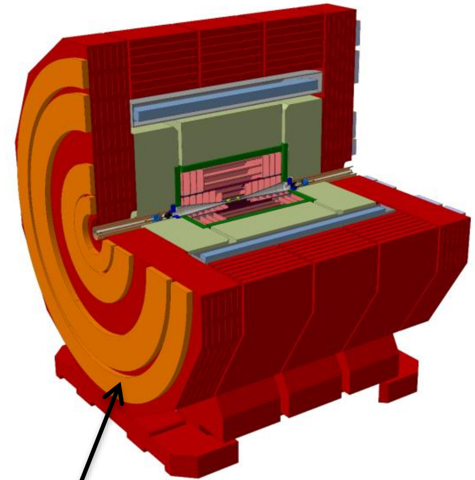


CLIC layout (3 TeV)



CLIC detector model





return yoke (Fe) with muon-ID detectors

superconducting solenoid, 4 Tesla

fine grained (PFA) calorimetry, 1 + 7.5 Λ_i, Si-W ECAL, Sc-FE HCAL

silicon tracker, (large pixels / short strips)

end-coils for field shaping

forward region with compact forward calorimeters

ultra low-mass vertex detector, ~25 µm pixels

Note: final beam focusing is outside the detector

Project staging

Optimize machine design w.r.t. cost and power for a staged approach to reach multi-TeV scales:

~ 380 GeV (optimised for Higgs + top physics)
~ 1500 GeV
~ 3000 GeV

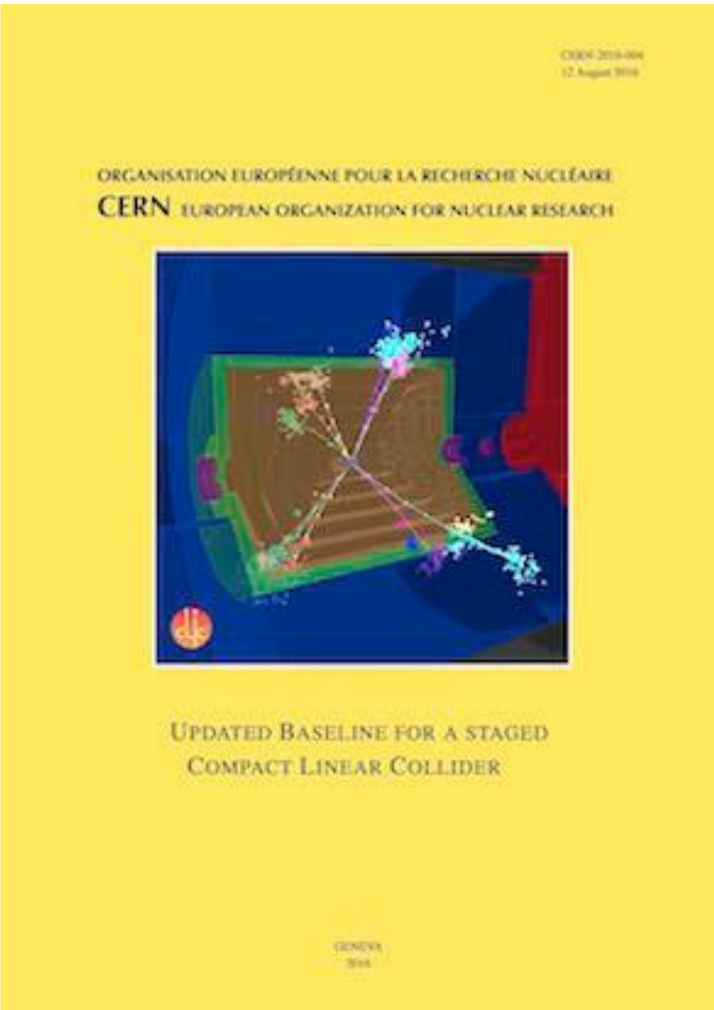
Adapting appropriately to LHC + other physics findings

Possibility for first physics no later than 2035

Project Plan to include accelerator, detector, physics

LINEAR COLLIDER COLLABORATION

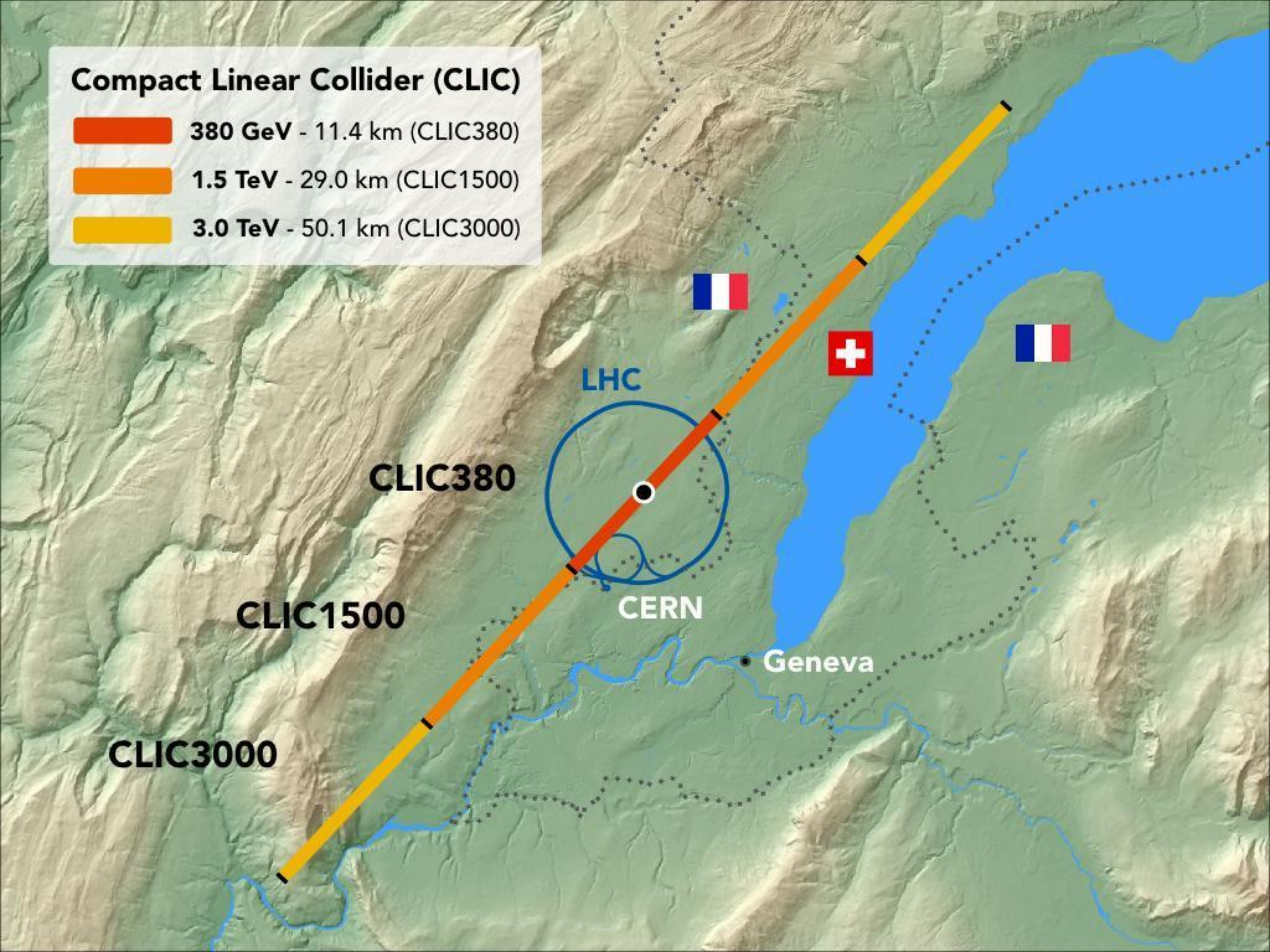
Updated baseline



The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear e^+e^- collider under development. For an optimal exploitation of its physics potential, CLIC is foreseen to be built and operated in a staged approach with three centre-of-mass energy stages ranging from a few hundred GeV up to 3 TeV. The first stage will focus on precision Standard Model physics, in particular Higgs and top measurements. Subsequent stages will focus on measurements of rare Higgs processes, as wells as searches for new physics processes and precision measurements of new states, e.g. states previously discovered at LHC or at CLIC itself. In the 2012 CLIC Conceptual Design Report, a fully optimised 3 TeV collider was presented, while the proposed lower energy stages were not studied to the same level of detail. This report presents an updated baseline staging scenario for CLIC. The scenario is the result of a comprehensive study addressing the performance, cost and power of the CLIC accelerator complex as a function of centre-of-mass energy and it targets optimal physics output based on the current physics landscape. The optimised staging scenario foresees three main centre-of-mass energy stages at 380 GeV, 1.5 TeV and 3 TeV for a full CLIC programme spanning 22 years. For the first stage, an alternative to the CLIC drive beam scheme is presented in which the main linac power is produced using X-band klystrons.

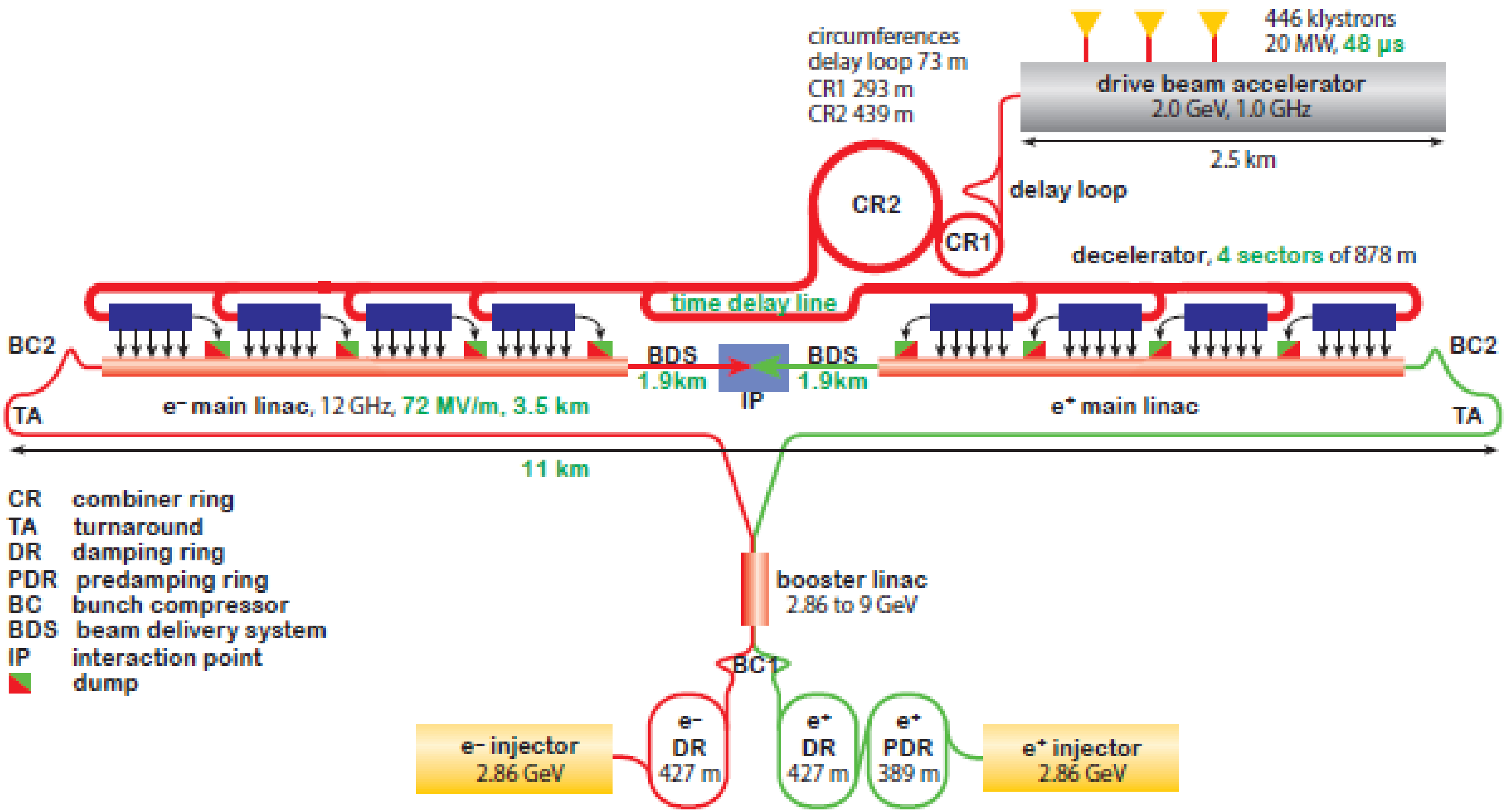
CERN-2016-004

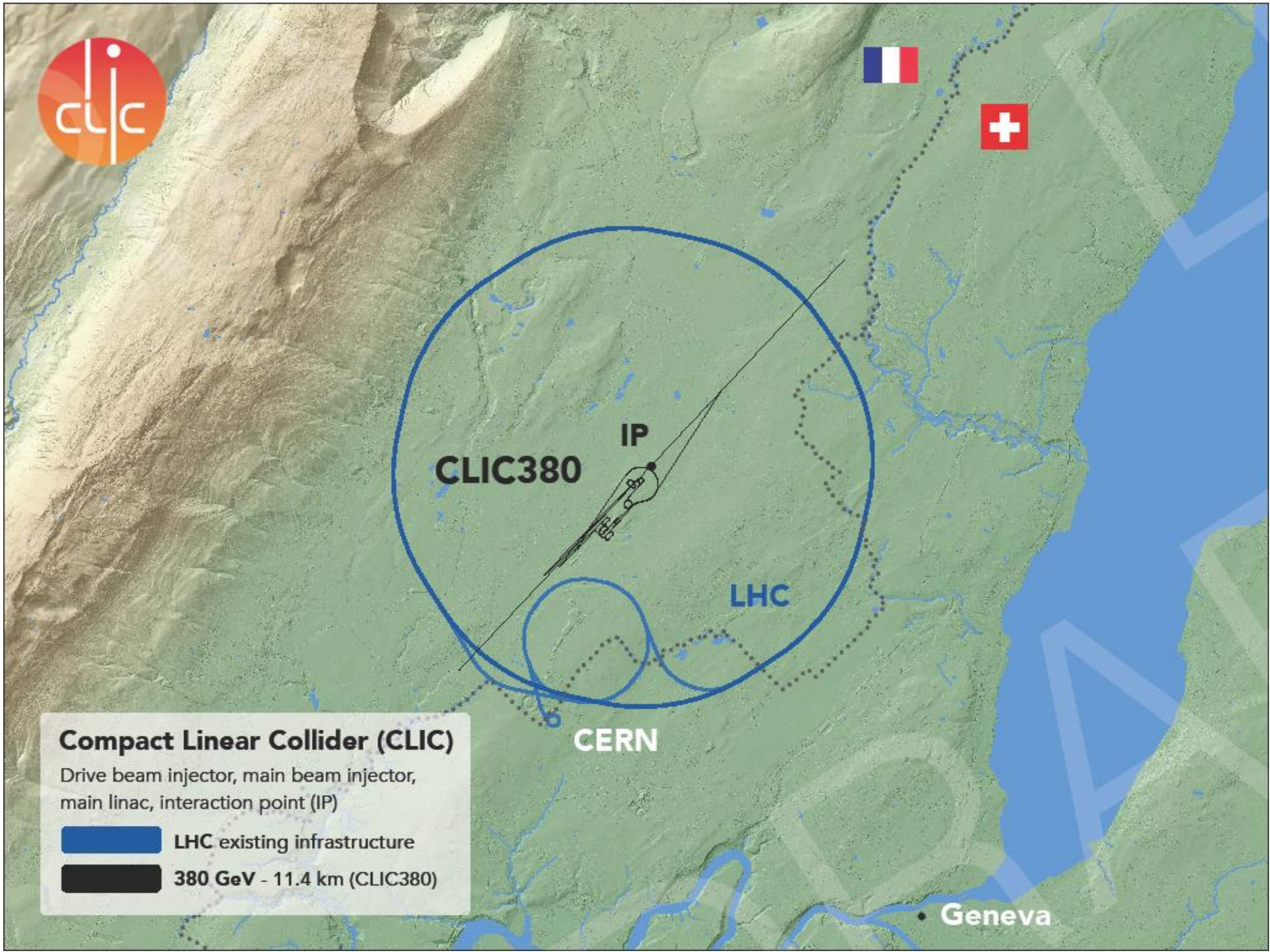
arXiv:1608.07537



Compact Linear Collider (CLIC)
380 GeV - 11.4 km (CLIC380)
1.5 TeV - 29.0 km (CLIC1500)
3.0 TeV - 50.1 km (CLIC3000)
LHC
CLIC380
CLIC1500
CLIC3000
CERN
Geneva

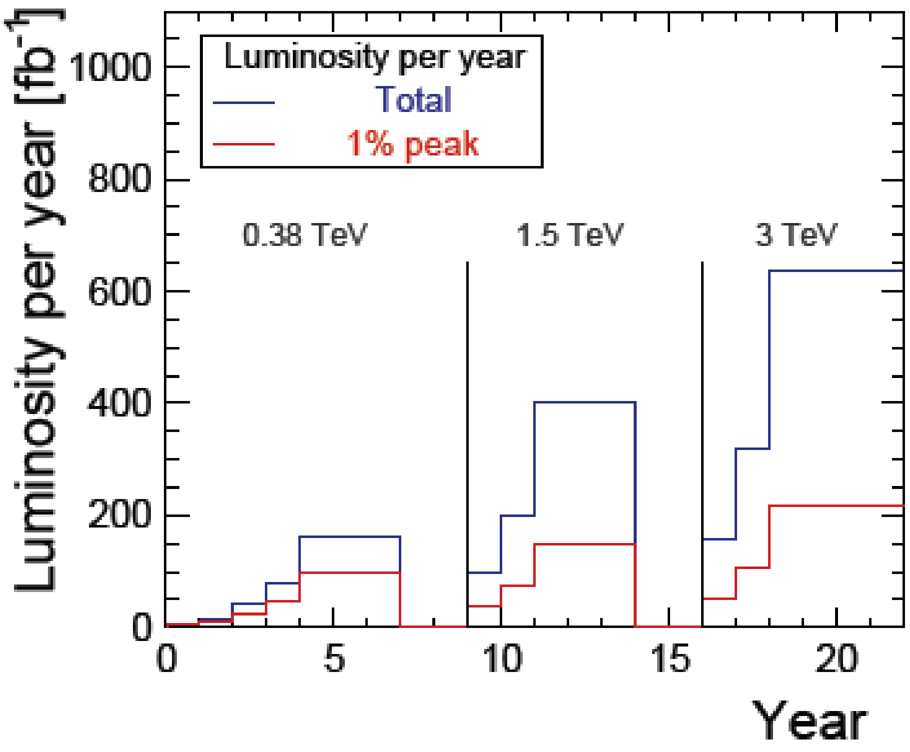
CLIC layout 380 GeV




CLIC380
IP
LHC
CERN
Geneva
Compact Linear Collider (CLIC)
Drive beam injector, main beam injector, main linac, interaction point (IP)
LHC existing infrastructure
380 GeV - 11.4 km (CLIC380)

LINEAR COLLIDER COLLABORATION

CLIC staged run model



Stage	$\sqrt{s}$ (GeV)	$\mathscr{L}_{\text{int}}$ (fb^{-1})
1	380	500
	350	100
2	1500	1500
3	3000	3000

LINEAR COLLIDER COLLABORATION

Key technical challenges

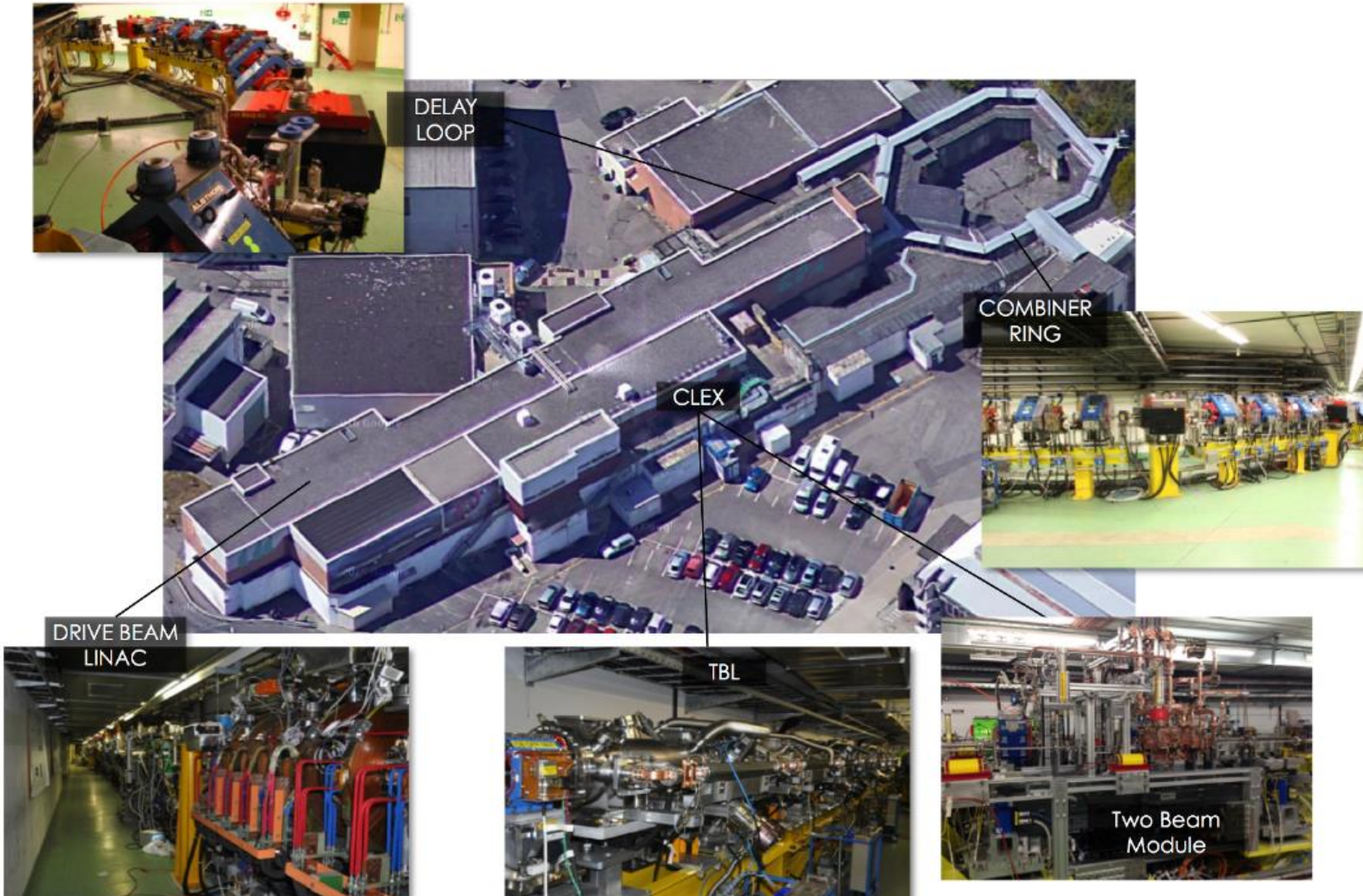
- High-current drive beam bunched at 12 GHz

- Power transfer + main-beam acceleration

- 100 MV/m gradient in main-beam cavities

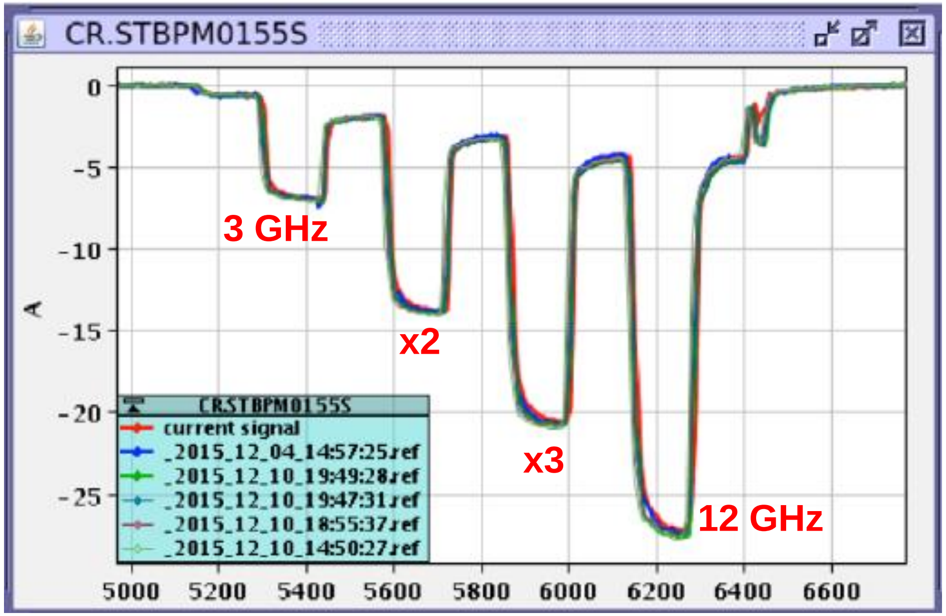
- Produce, transport + collide low-emittance beams
- System integration, engineering, cost, power …

CLIC Test Facility (CTF3)



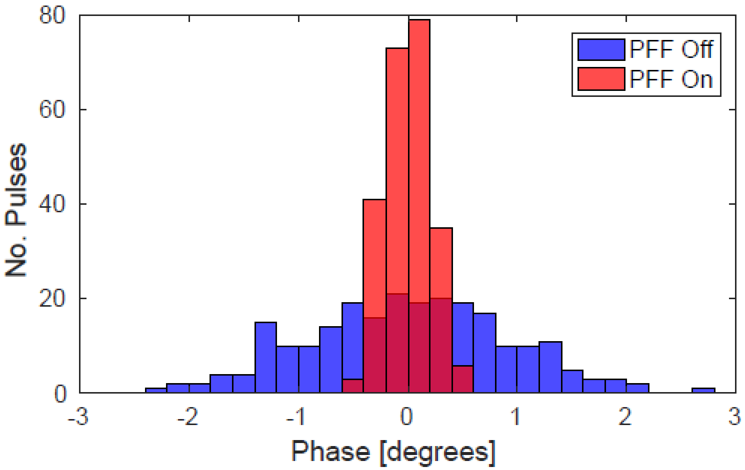
Status

- **Produced high-current drive beam bunched at 12 GHz**



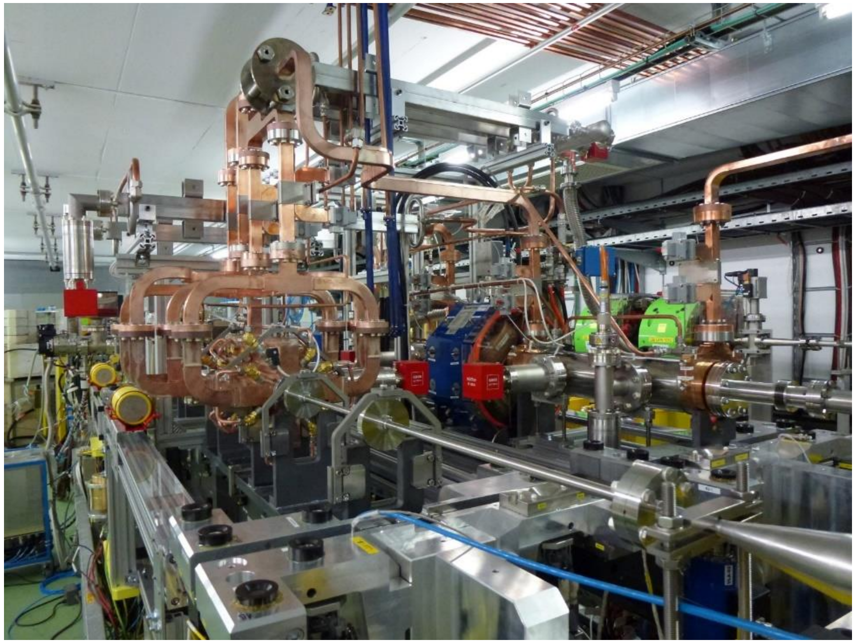
28A

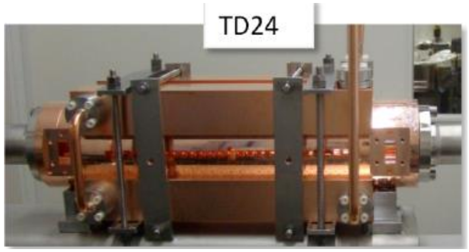
Arrival time stabilised to 50 fs



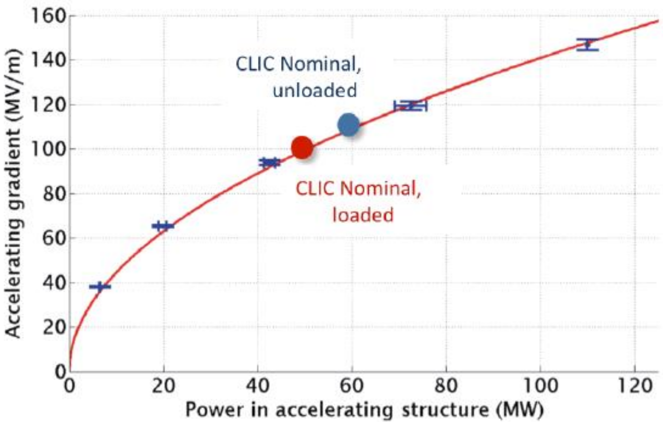
Status

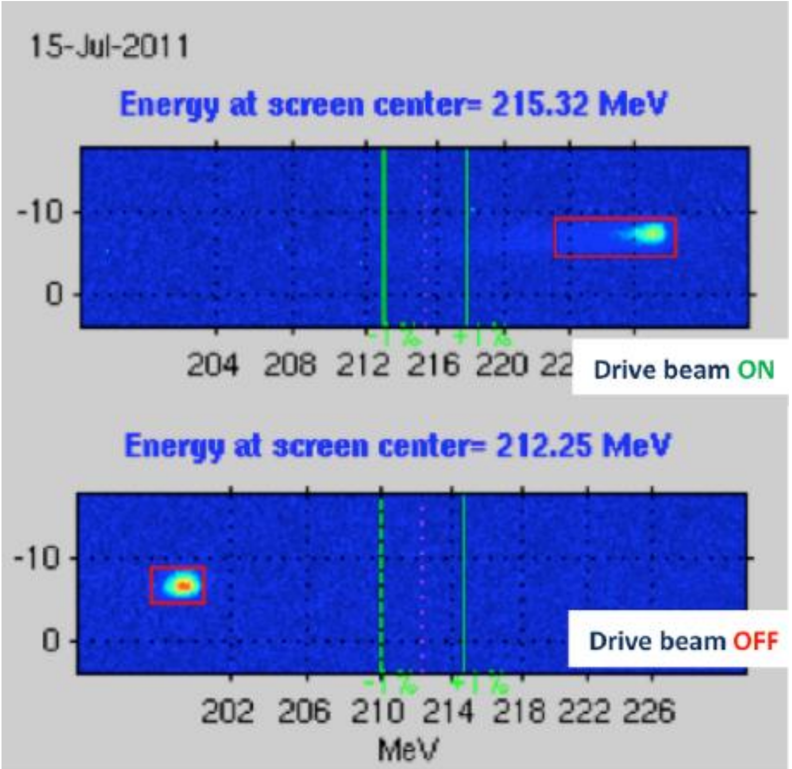
- **Demonstrated two-beam acceleration**





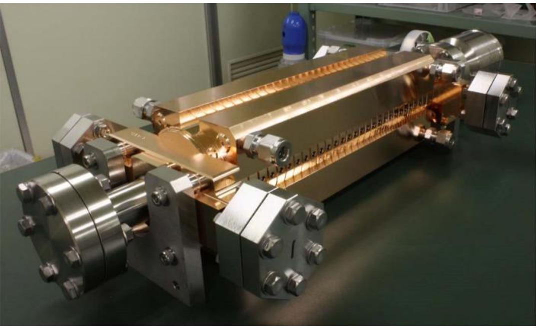
31 MeV = 145 MV/m

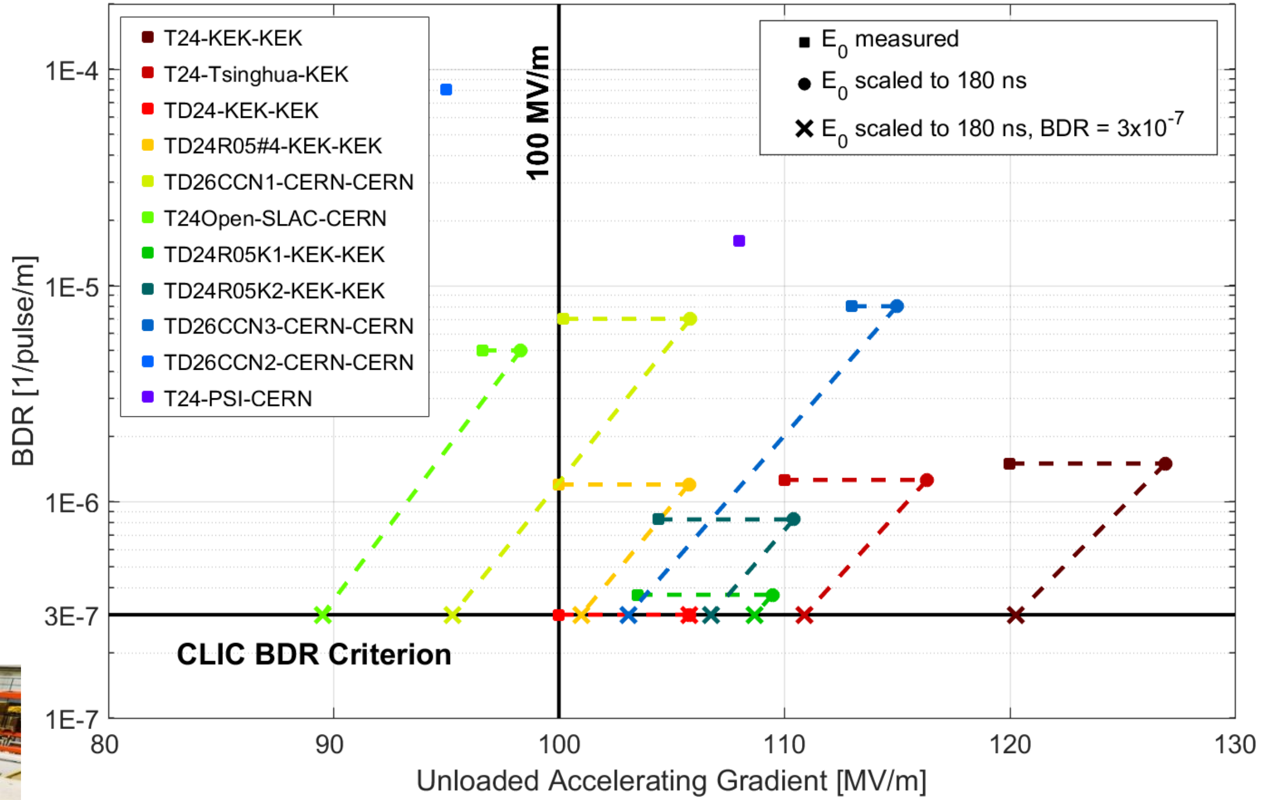


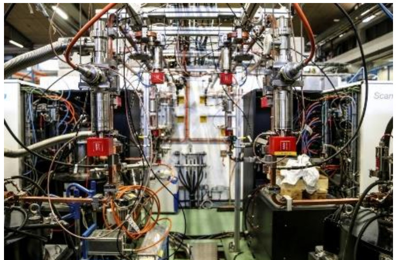


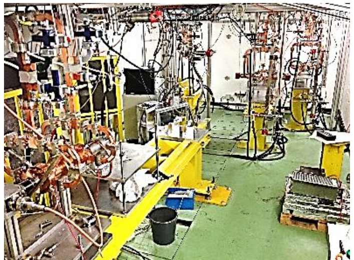
Status

- **Achieved 100 MV/m gradient in main-beam RF cavities**









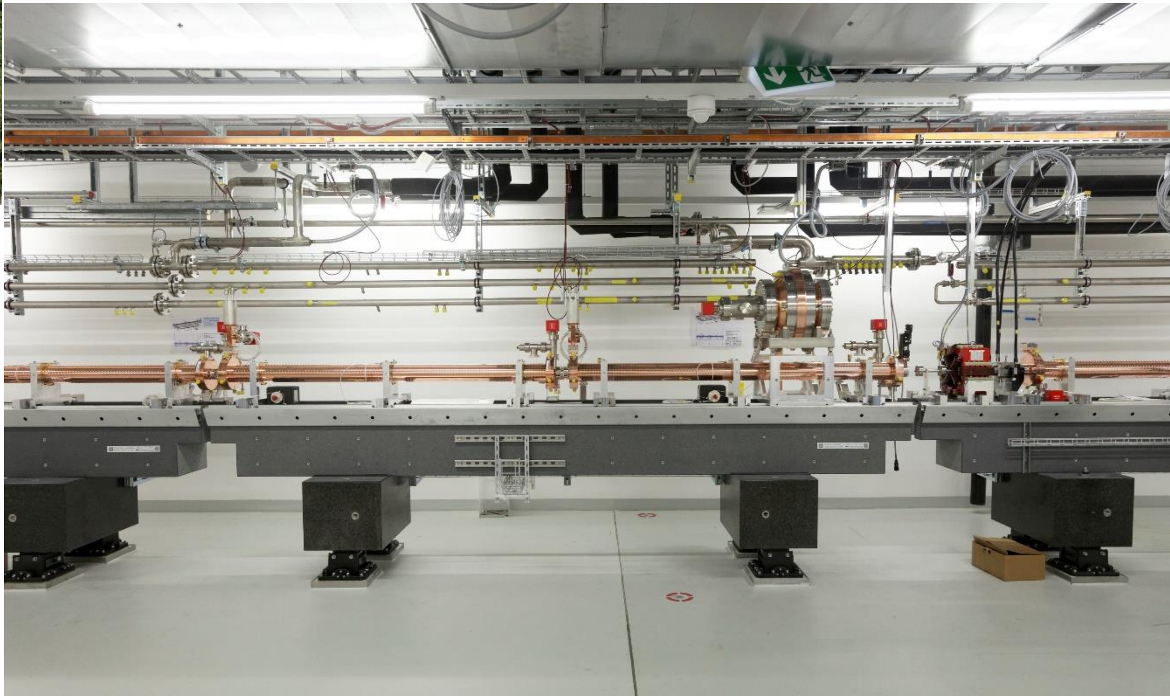
Key technical challenges

- **High-current drive beam bunched at 12 GHz** ✔
- **Power transfer + main-beam acceleration** ✔
- **100 MV/m gradient in main-beam cavities** ✔

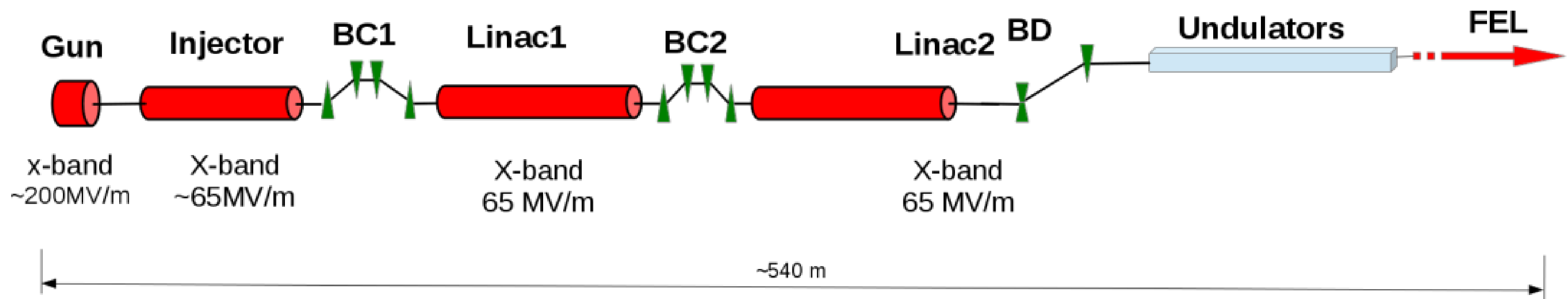
→ Industrialisation of 12 GHz RF/structure technologies
→ Application to medium- and large-scale systems

SwissFEL

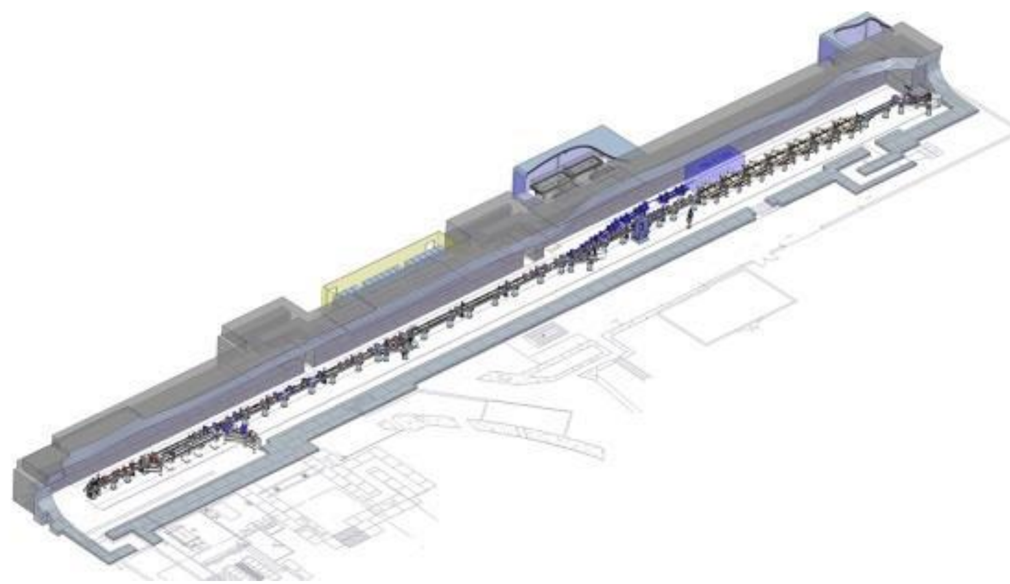
- 104 x 2m-long C-band structures
  (beam → 6 GeV @ 100 Hz)
- Similar um-level tolerances
- Length ~ 800 CLIC structures



CompactLight – EU H2020 design study for a compact XFEL based on X-band structures



1 (Coordinator)	Elettra - Sincrotrone Trieste S.C.p.A.	Italy
2	CERN - European Organization for Nuclear Research	International
3	STFC - Daresbury Laboratory	UK
4	SINAP, Chinese Academy of Sciences	China
5	Institute of Accelerating Systems and Applications	Greece
6	Uppsala Universitet	Sweden
7	The University of Melbourne	Australia
8	Australian Nuclear Science and Tecnology Organisation	Australia
9	Ankara University Institute of Accelerator Technologies	Turkey
10	Lancaster University	UK
11	VDL Enabling Technology Group Eindhoven BV	Netherlands
12	Technische Universiteit Eindhoven	Netherlands
13	Istituto Nazionale di Fisica Nucleare	Italy
14	Kyma S.r.l.	Italy
15	University of Rome "La Sapienza"	Italy
16	Italian National agency for new technologies, Energy and sustainable economic development, ENEA	Italy
17	Consorcio para la Construccion Equipamiento y Explotacion del Laboratorio de Luz Sincrotron	Spain
18	Centre National de la Recherche Scientifique, CNRS	France
19	Karlsruher Institut für Technologie	Germany
20	Paul Scherrer Institut PSI	Switzerland
21	Agencia Estatal Consejo Superior de Investigaciones Científicias	Spain
22	University of Helsinki - Helsinki Institute of Physics	Finland
23	Pulsar Physics	Netherlands
24	VU University Amsterdam	Netherlands
Third Parties	**Third party's organisation name**	**Country**
	Universitetet i Oslo - University of Oslo	Norway
	Advanced Research Center for Nanolithography (ARC UvA/VU)	Netherlands



Approved by EC!
Project start 1/1/18

CLIC project preparation

- Preparing CLIC Project Plan + supporting documents for input to European Strategy Update (ESU)
- Staged approach, starting at 380 GeV with costs and power not excessive compared with LHC
- Upgrade path in stages over 20-30 year horizon → 3 TeV
- Update costings, for both baseline *and a klystron-based* 380 GeV first stage
- Maintain flexibility and align with LHC physics outcomes
- Next step > 2020 is a ~5-year project preparation phase: critical parameters, detailed site layout, value engineering, risk mitigation … → plans to be presented to ESU

CLIC roadmap

2013 - 2019 Development Phase
Development of a Project Plan for a staged CLIC implementation in line with LHC results; technical developments with industry, performance studies for accelerator parts and systems, detector technology demonstrators

2020 - 2025 Preparation Phase
Finalisation of implementation parameters, preparation for industrial procurement, Drive Beam Facility and other system verifications, Technical Proposal of the experiment, site authorisation

2026 - 2034 Construction Phase
Construction of the first CLIC accelerator stage compatible with implementation of further stages; construction of the experiment; hardware commissioning

2019 - 2020 Decisions
Update of the European Strategy for Particle Physics; decision towards a next CERN project at the energy frontier (e.g. CLIC, FCC)

2025 Construction Start
Ready for construction; start of excavations

2035 First Beams
Getting ready for data taking by the time the LHC programme reaches completion

LINEAR COLLIDER COLLABORATION

CLIC workshop 2018

CLIC Workshop 2018

22-26 January 2018
CERN
Europe/Zurich timezone

- Overview
- Timetable
- Speaker List
- Registration

The **CLIC workshop 2018** covers Accelerator as well as the Detector and Physics studies, with their present activities and programme. Special focus of the workshop will go to the preparations for the European Strategy Update, for which the CLIC documentation is due by the end of 2018

For the **Accelerator studies**, the workshop spans over 5 days: **22nd-26th of January.**

For **CLICdp**, the workshop is scheduled from **Tuesday afternoon 23rd to lunchtime on Friday 26th.**

Programme

PPAP recommendation

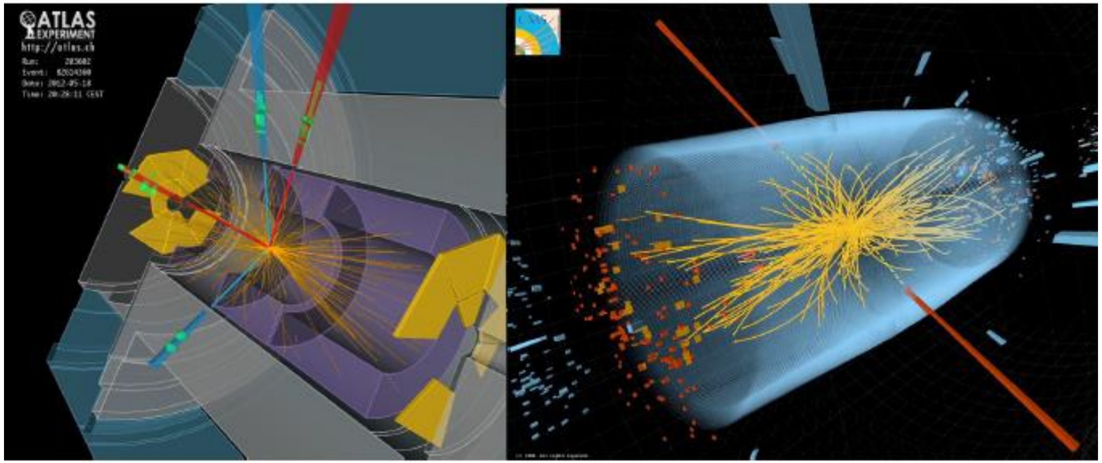
The UK Particle Physics Roadmap

Particle Physics Advisory Panel:

P. N. Burrows, C. Da Via, E. W. N. Glover, P.R. Newman, J. Rademacker,

C. Shepherd-Themistocleous, W.J. Spence, M. A. Thomson and M. Wing

7/11/12



'It is essential that the UK engages with the Higgs Factory initiative and positions itself to play a leading role should the facility go ahead.'

Extra material follows

‘Higgs factory’

- e+e- collider:
  - linear collider
  - storage ring

- photon-photon collider:
  - usually considered as add-on to linear collider

- muon collider:
  - usually considered as a next step beyond a future neutrino factory

Snowmass executive summary 2013

Compelling science motivates continuing this program with experiments at lepton colliders. Experiments at such colliders can reach sub-percent precision in Higgs boson properties in a unique, model-independent way, enabling discovery of percent-level deviations from the Standard Model predicted in many theories.

Snowmass executive summary 2013

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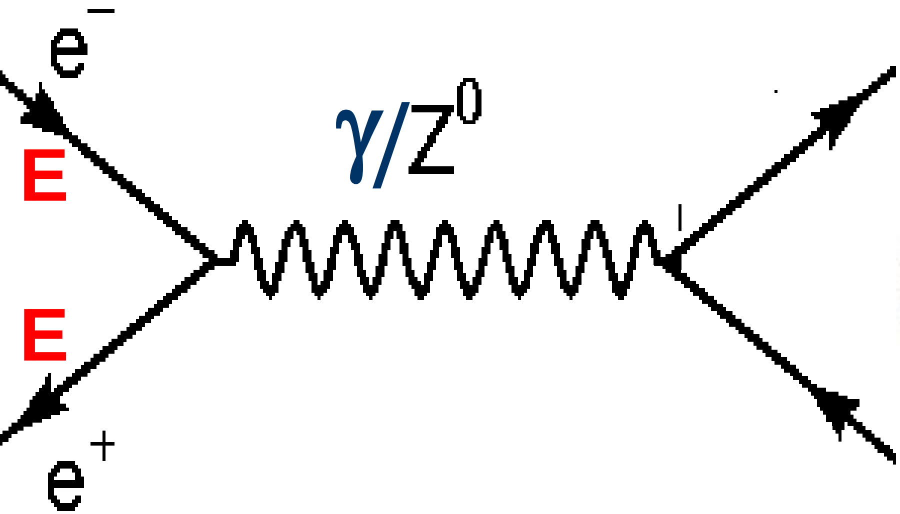
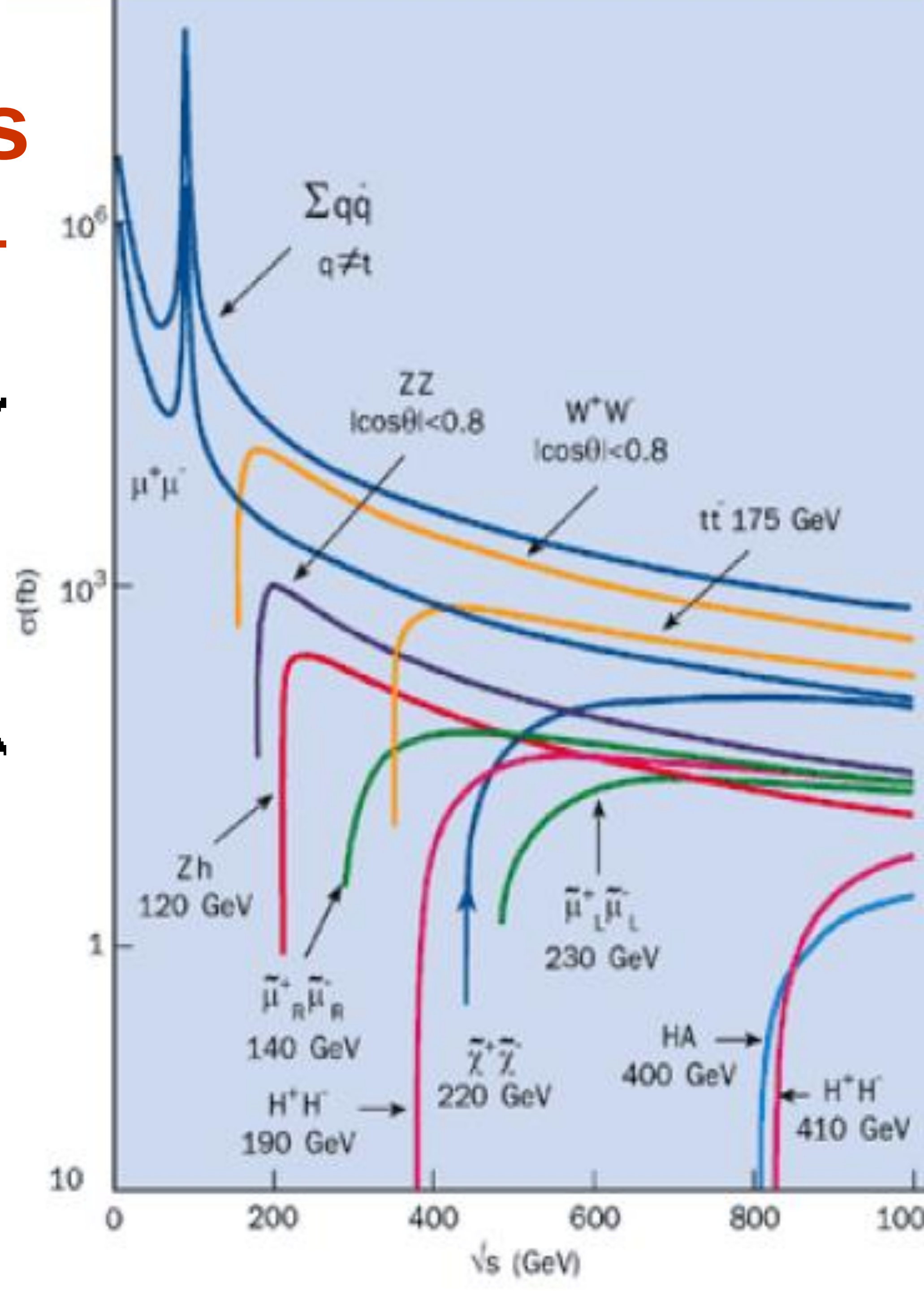
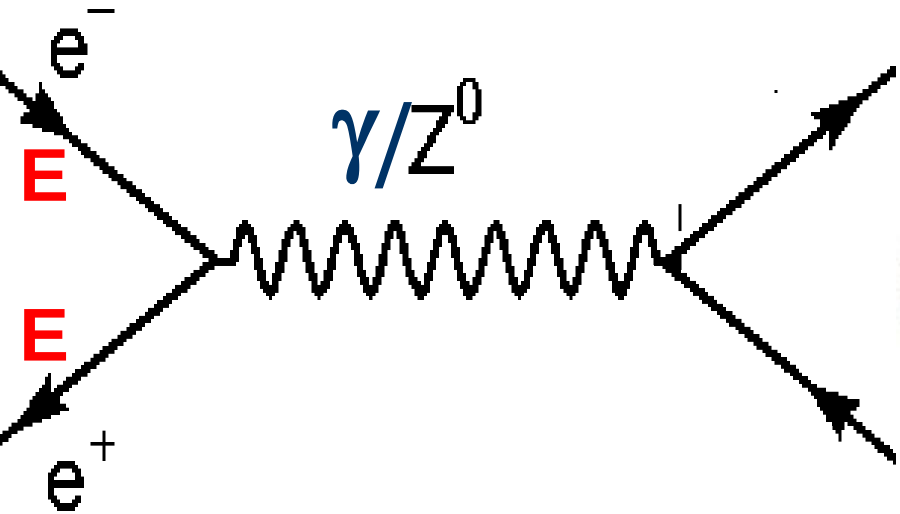
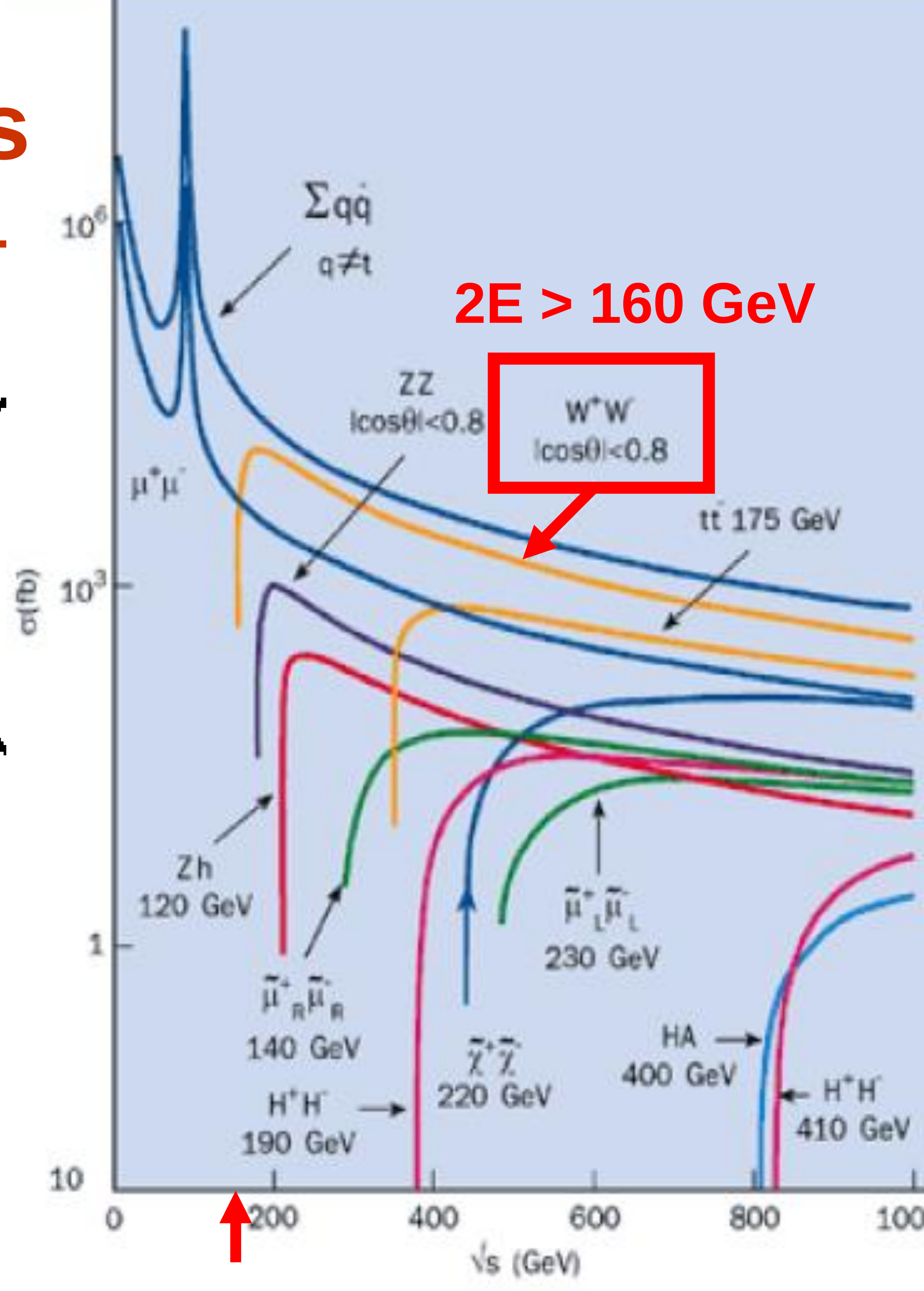
e+e- annihilations



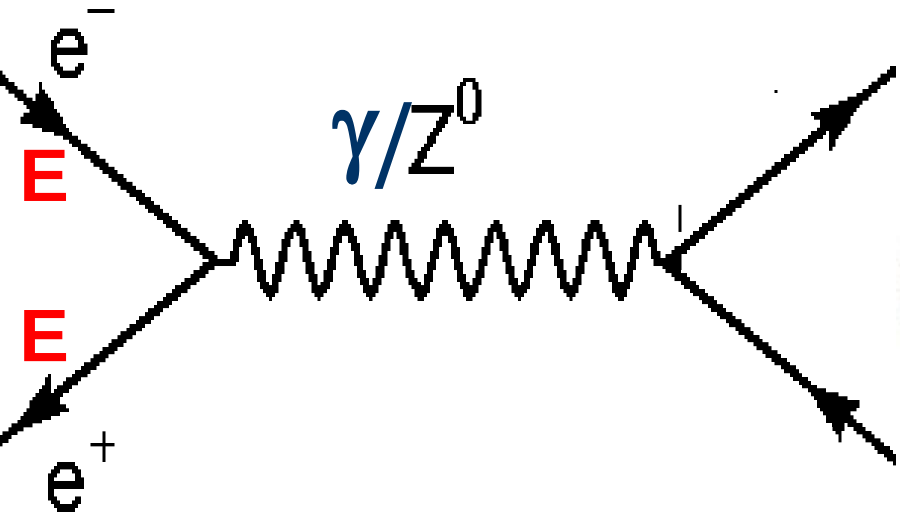


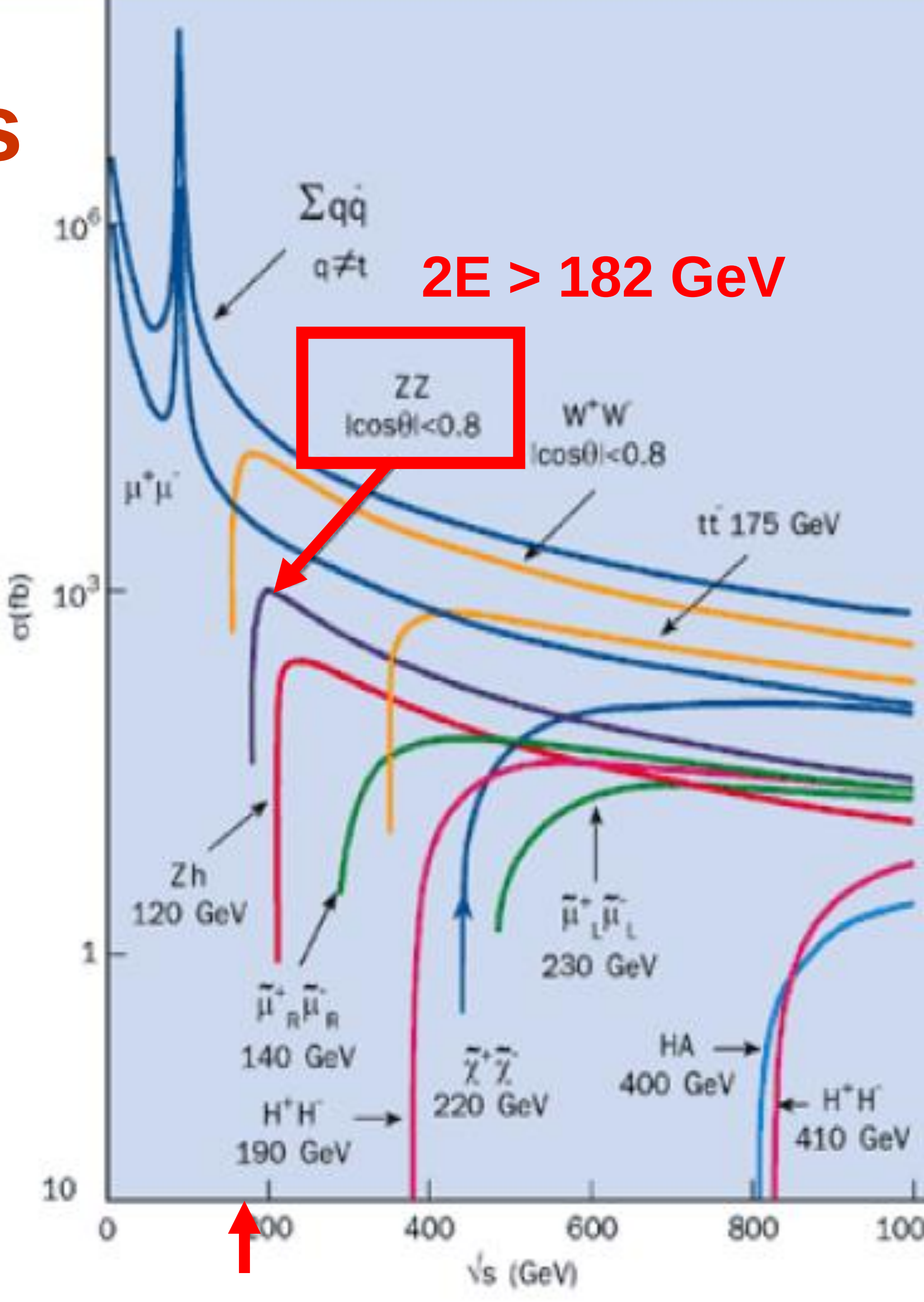
e+e- annihilations





e+e- annihilations





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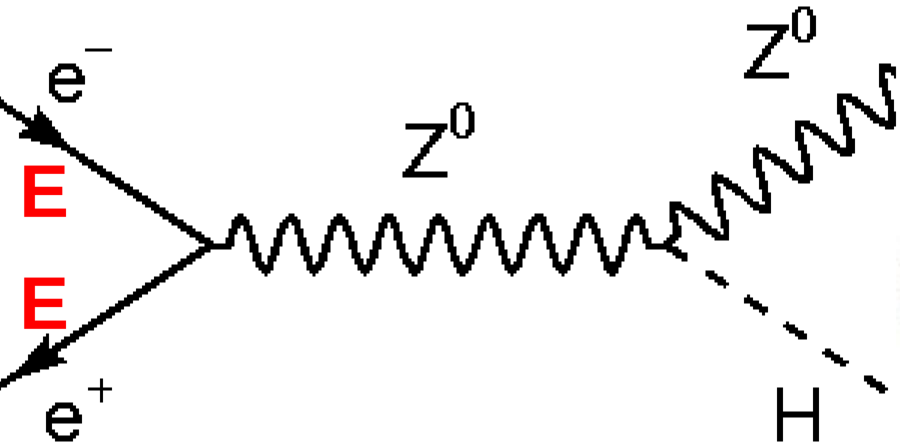
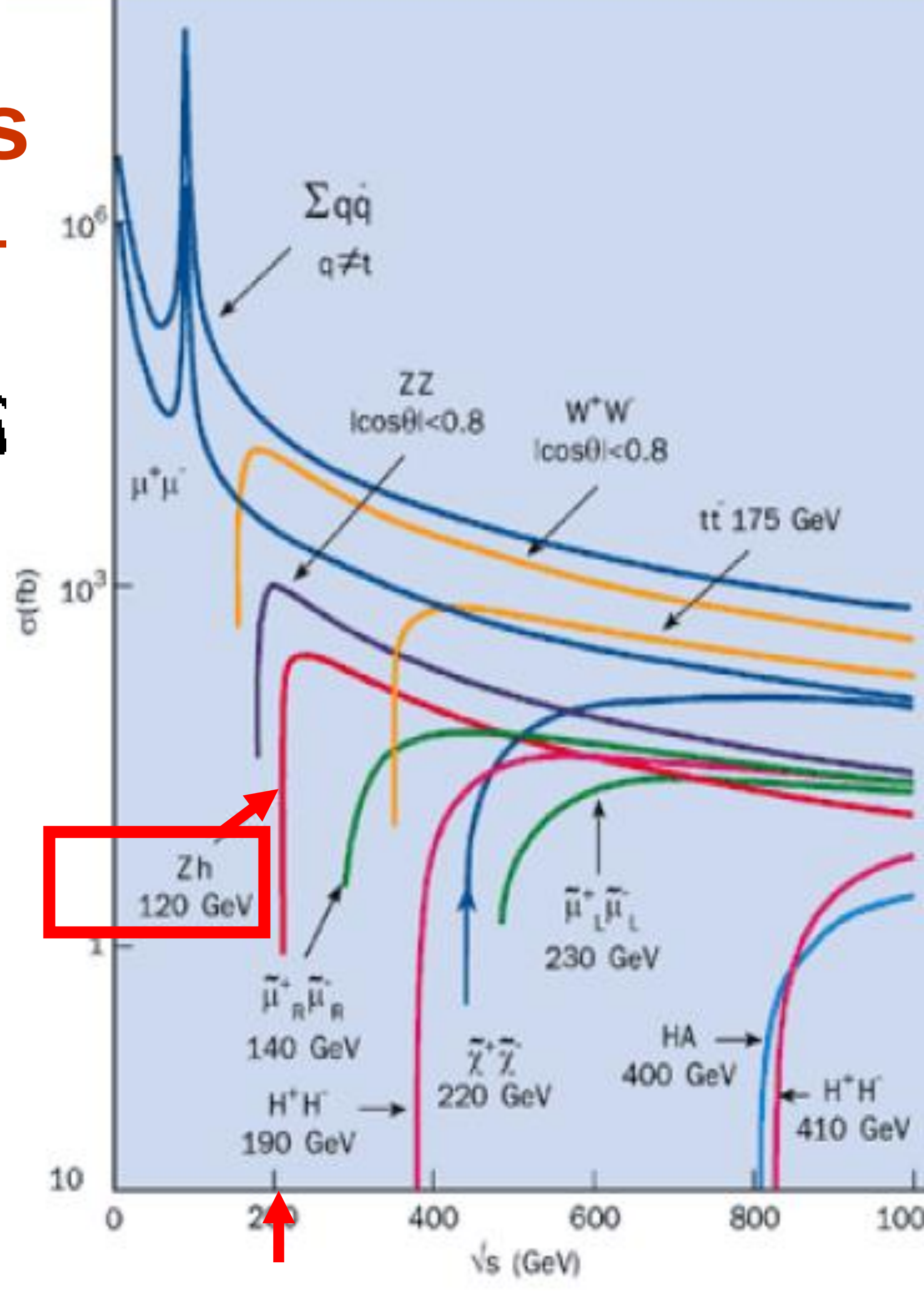
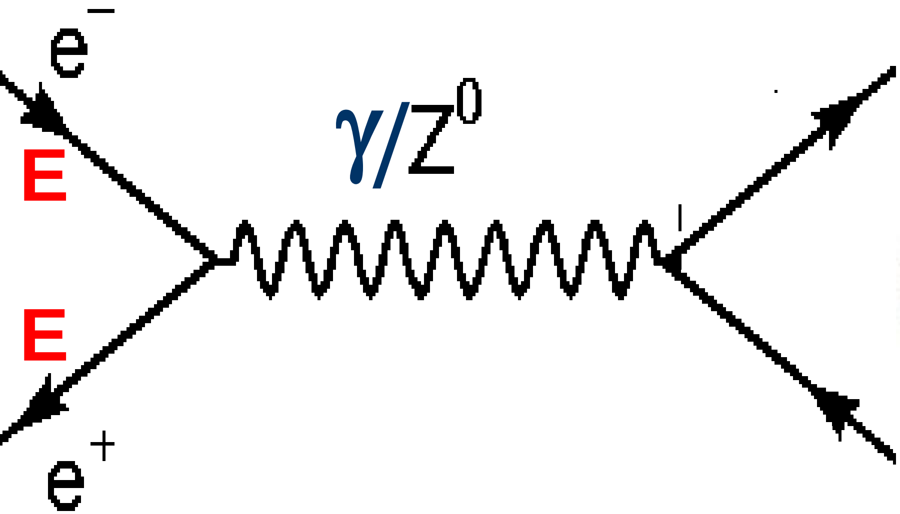
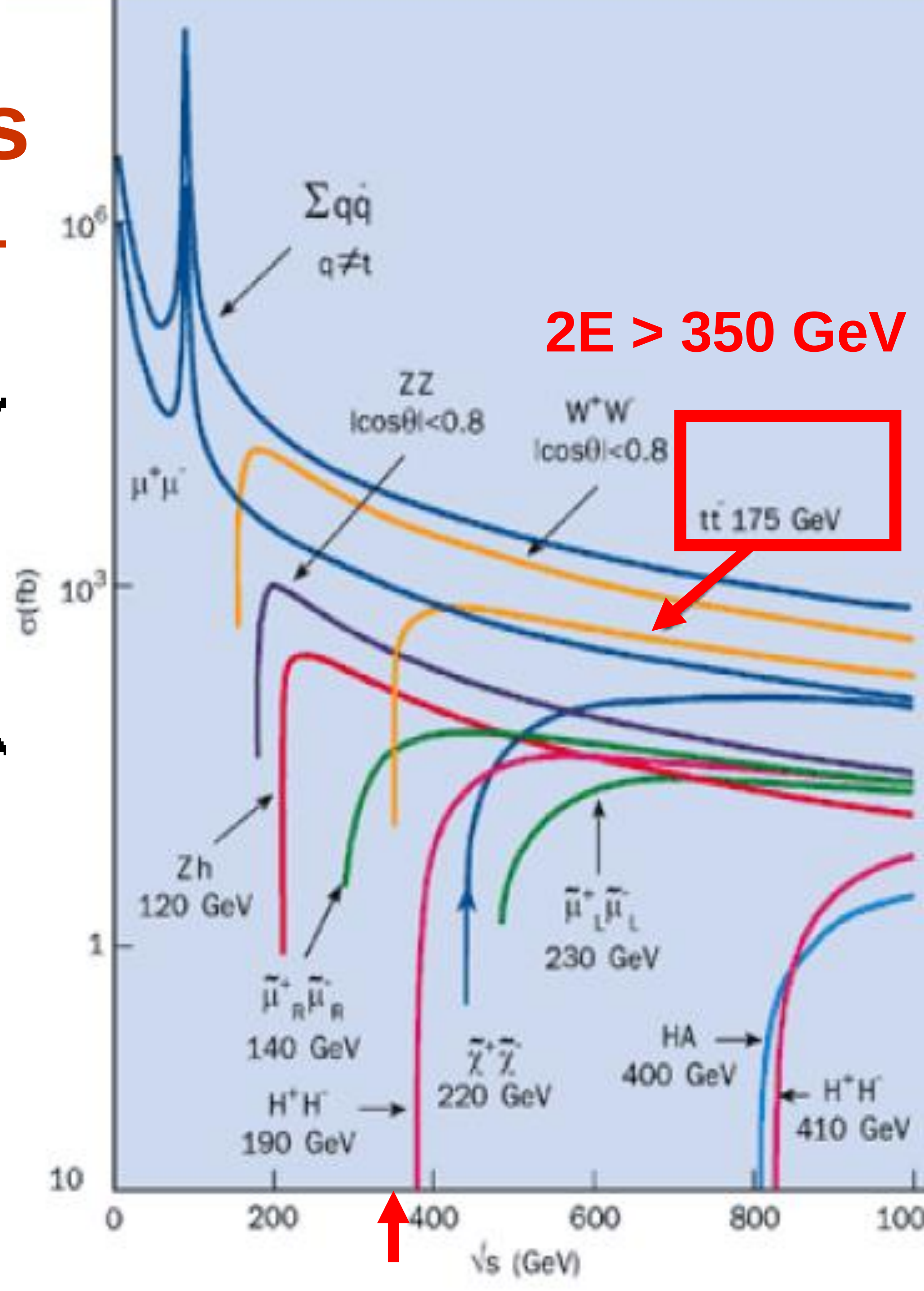


2E > 216 GeV



e+e- annihilations





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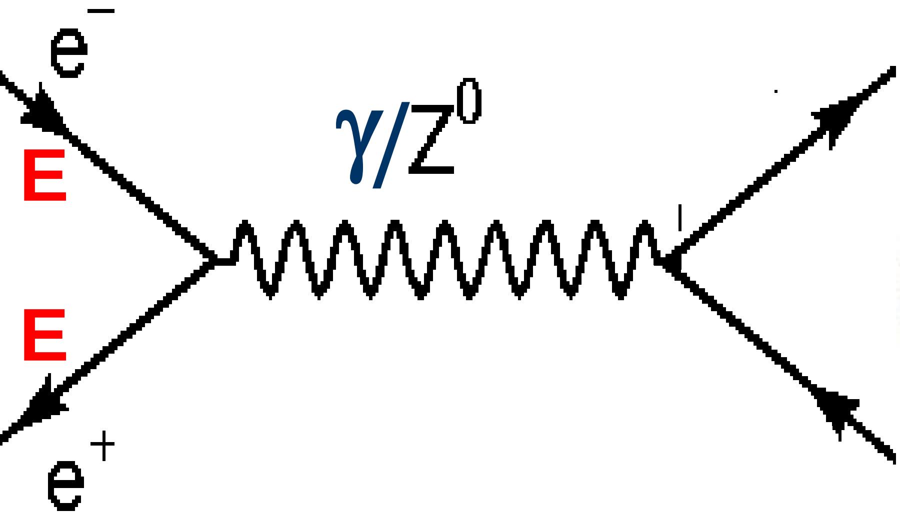
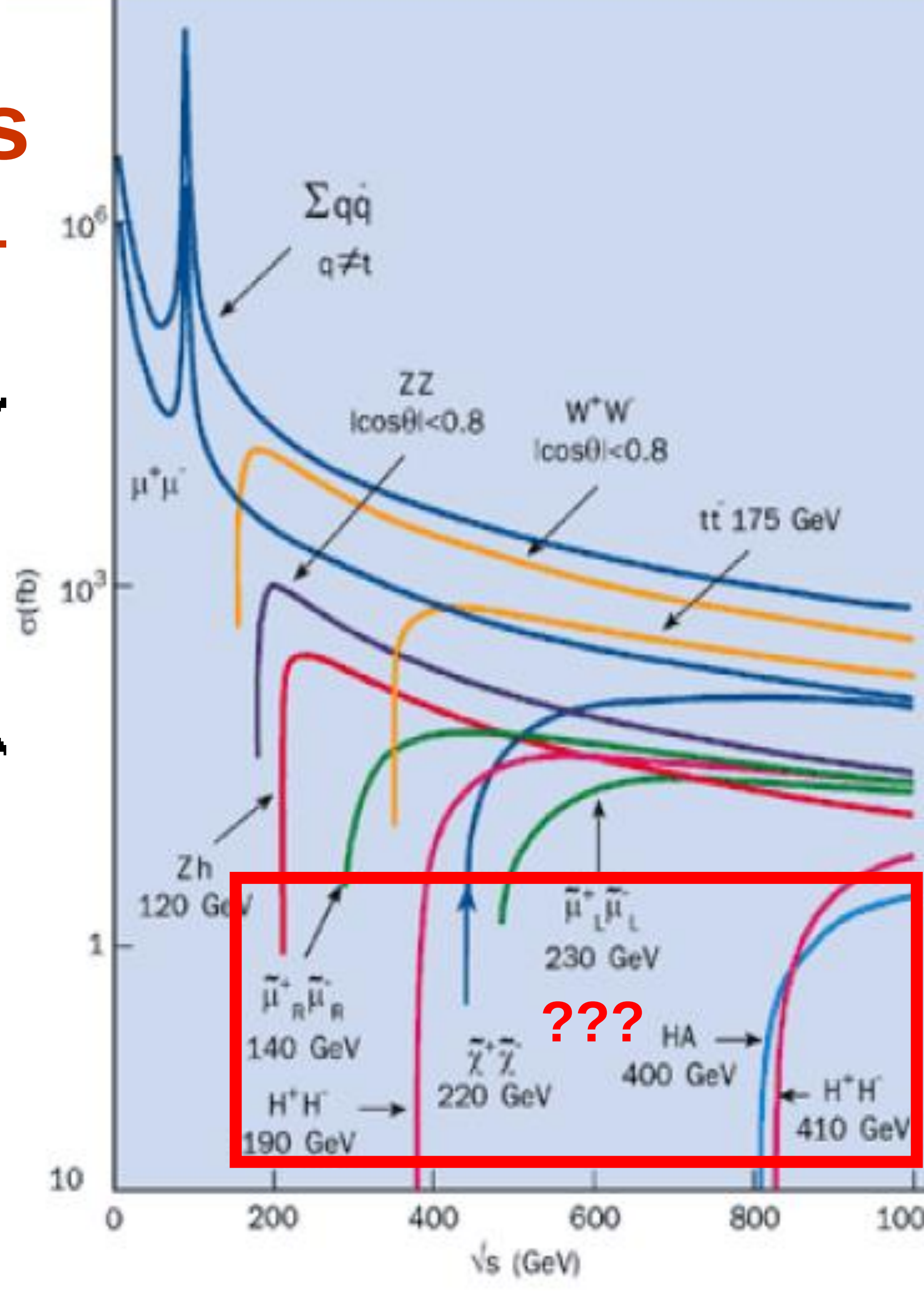
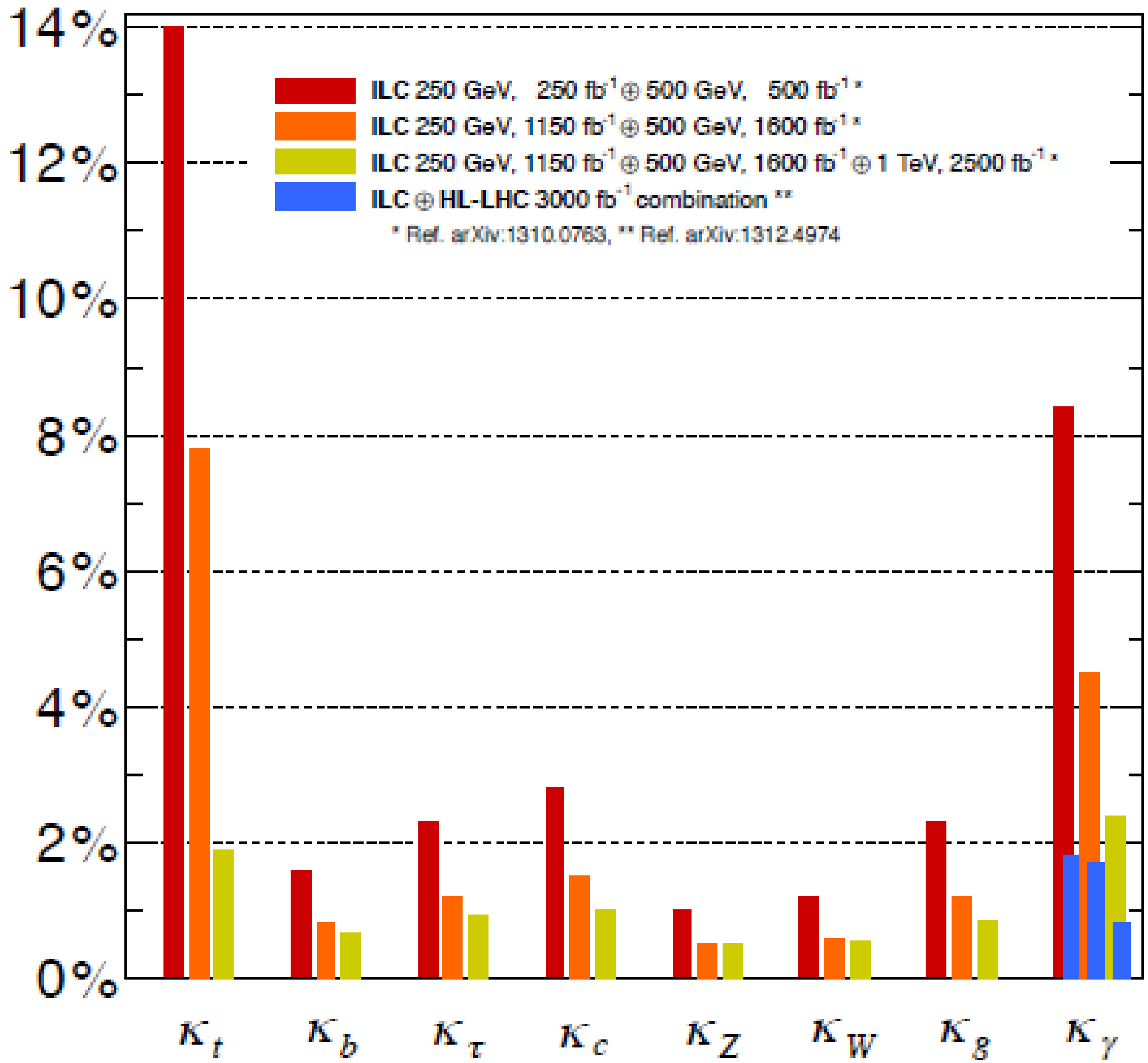




Model-independent couplings



KEK-ILC Action Plan

KEK-DG Yamauchi set up a WG to develop a KEK-ILC action plan in May, 2015.

The KEK-ILC Action Plan was released in January 2016. It contains technical preparation tasks and a human resource development plan for the pre-preparation phase (current efforts) and the main-preparation phase (after "green sign" from MEXT). It focuses mainly on a development plan for KEK.

"Producing a EAP (European Action Plan) for the ILC in timely manner is very important."

"After having established a discussion group with DOE, discussions with Europe are likely to become the next important topic for MEXT."

Extracted from slides of Y.Okada, KEK – EJADE meeting 6.9.16

On the European side it was suggested to use the EJADE H2020 MC project to prepare the EAP – the effort was started October 2016

E-JADE

Europe-Japan Accelerator Development Exchange Programme

Programme 2015-2018:

- Three main technical WPs
- Supports extended stays of European Researchers in Japan
- Recently adapted to include detector and physics studies for ILC (new partners)

Technical WPs: WP1: LHC with upgrades/FFC/ SuperKEKb, WP2: ATF2, WP3: ILC/CLIC

Partners: CERN (coord), DESY, CEA, CNRS, CSIC, RHUL, OXF with Uni. Tokyo and KEK -> WG for EAP

New partners: VINCA, AGH-Cracow, Tel Aviv University, Liverpool University, Université de Strasbourg, Université Paris-Sud, Tohoku University and Kyushu University.

Authors of EAP:
For EJADE institutes:
CERN: S.Stapnes, CEA: O.Napoli, DESY: N.Walker/H.Weise/B.List, CNRS: P.Bambade/A.Jeremi, UK: P.Burrows, CSIC: A.Faust-Golfe

EJADE WP3 and centrally: T.Schoerner-Sadenius, M. Stanitzki
TDR: B.Foster

European X-FEL at DESY

ILC Project Phases

2017–2018: Pre-preparation phase

The on-going activities with relevance to the ILC in Europe are reviewed.

2019–2022: Preparation phase

This period needs to be initiated by a positive statement from the Japanese government about hosting the ILC, followed by a European strategy update that ranks European participation in the ILC as a high-priority item. The preparation phase focuses on preparation for construction and agreement on the definition of deliverables and their allocation to regions.

2023 and beyond: Construction phase

The construction phase will start after the ILC laboratory has been established and inter-governmental agreements are in place. At the current stage, only the existing capabilities of the European groups relevant for this phase can be described.

Linear Colliders for electrons + positrons

Stanford

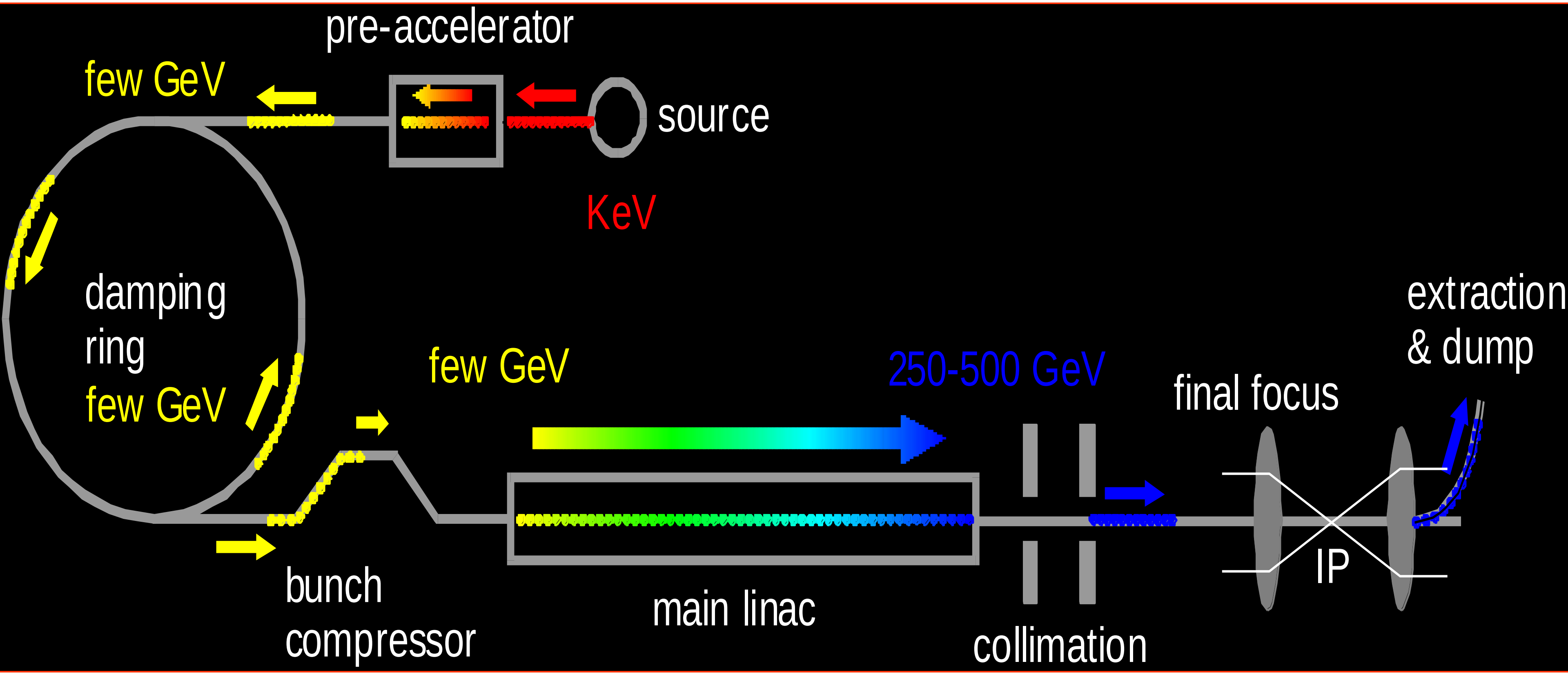
Linear

Accelerator

Center

(California)

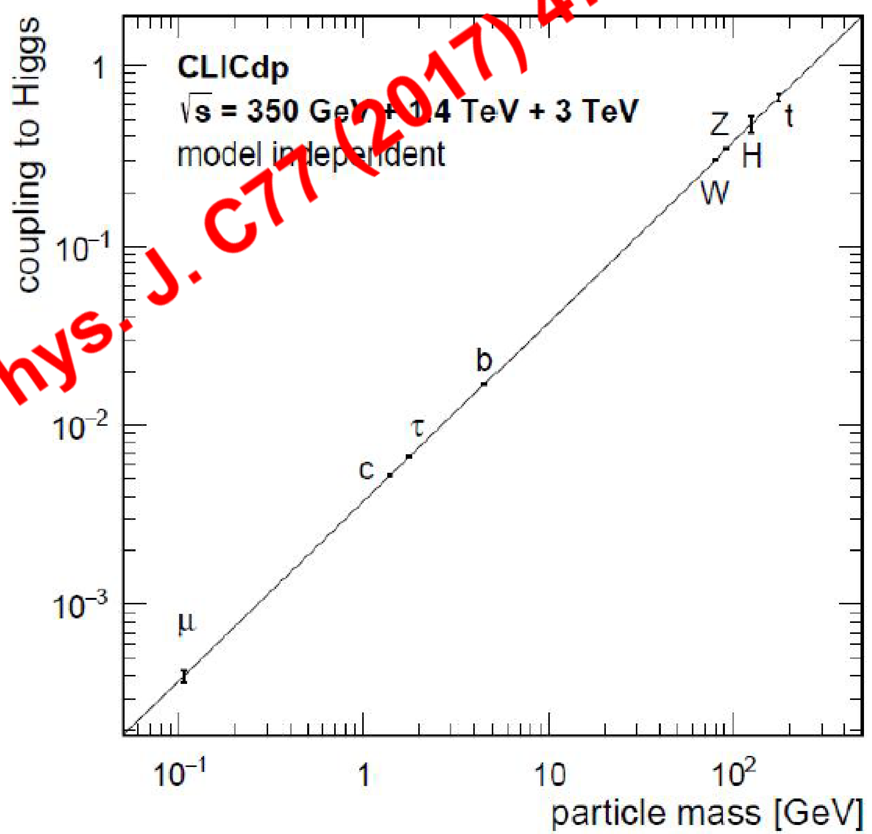
Designing a Linear Collider



LINEAR COLLIDER COLLABORATION

CLIC Higgs coupling capabilities

Parameter	Relative precision		
	350 GeV 500 fb^{-1}	+ 1.4 TeV + 1.5 ab^{-1}	+ 3 TeV + 2 ab^{-1}
g_{HZZ}	0.8 %	0.8 %	0.8 %
g_{HWW}	1.4 %	0.9 %	0.9 %
g_{Hbb}	3.0 %	1.0 %	0.9 %
g_{Hcc}	6.2 %	2.3 %	1.9 %
$g_{H\tau\tau}$	4.3 %	1.7 %	1.4 %
$g_{H\mu\mu}$	–	14.1 %	7.8 %
g_{Htt}	–	4.2 %	4.2 %
$g^{\dagger}_{Hgg}$	3.7 %	1.8 %	1.4 %
$g^{\dagger}_{H\gamma\gamma}$	–	5.7 %	3.2 %
$g^{\dagger}_{HZ\gamma}$	–	15.6 %	9.1 %
Γ_H	6.7 %	3.7 %	3.5 %

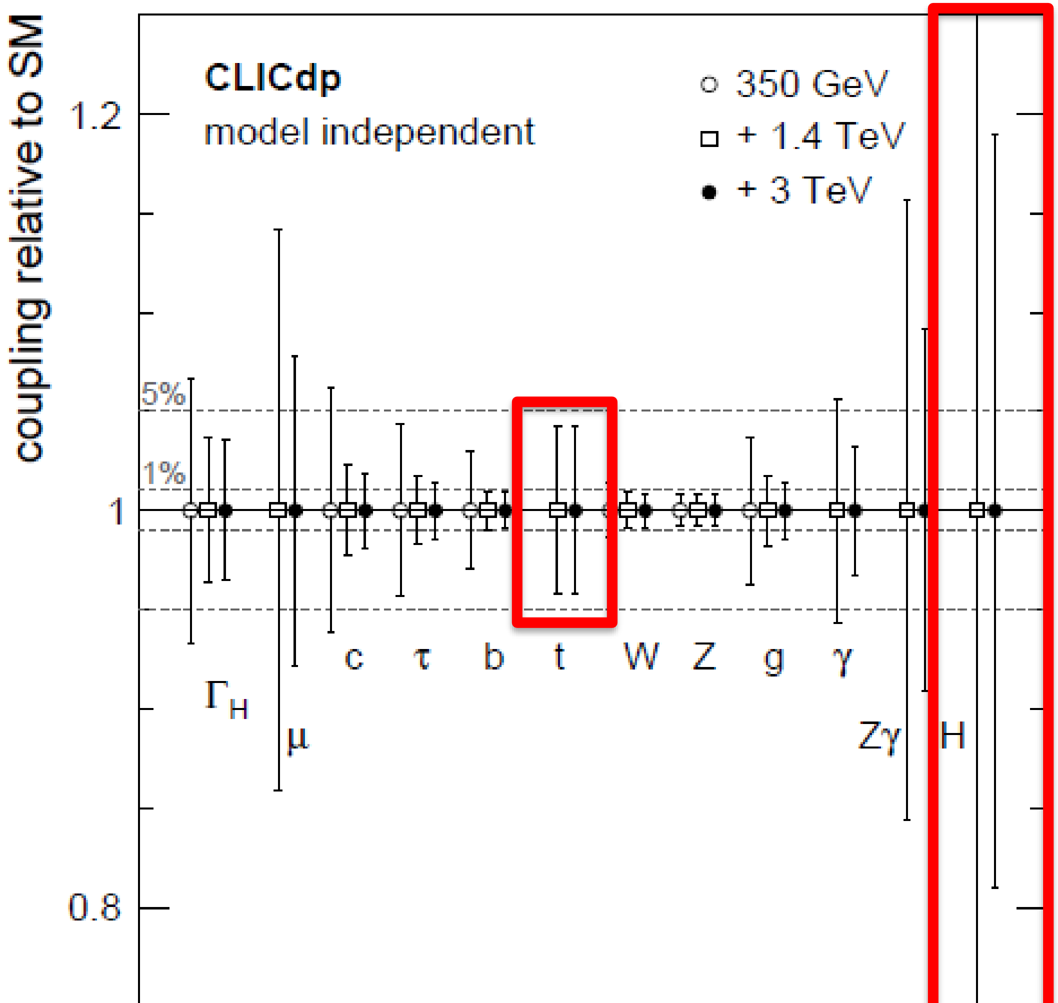


LINEAR COLLIDER COLLABORATION

CLIC Higgs-top + self couplings

Higgs couplings to heavy particles benefit from higher c.m. energies:

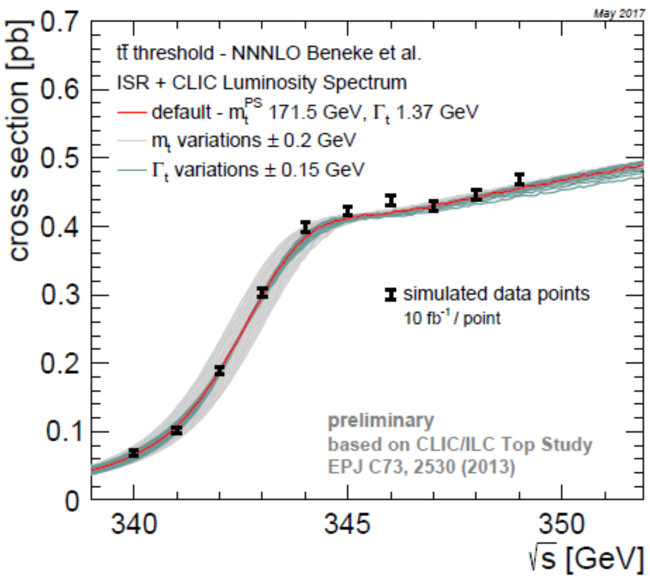
ttH ~ 4%
HH ~ 20%



LINEAR COLLIDER COLLABORATION

CLIC top physics: examples

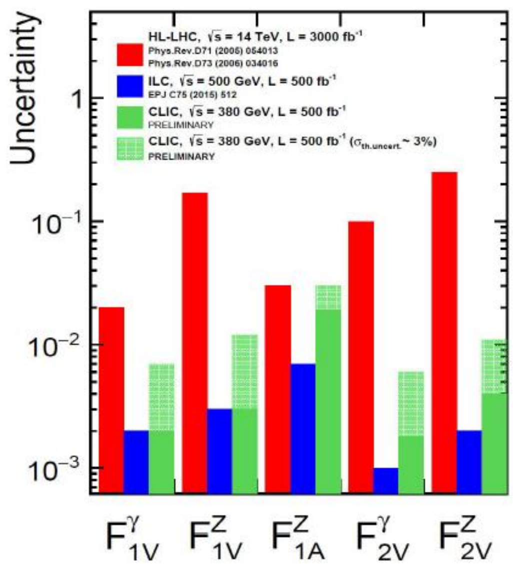
Threshold scan



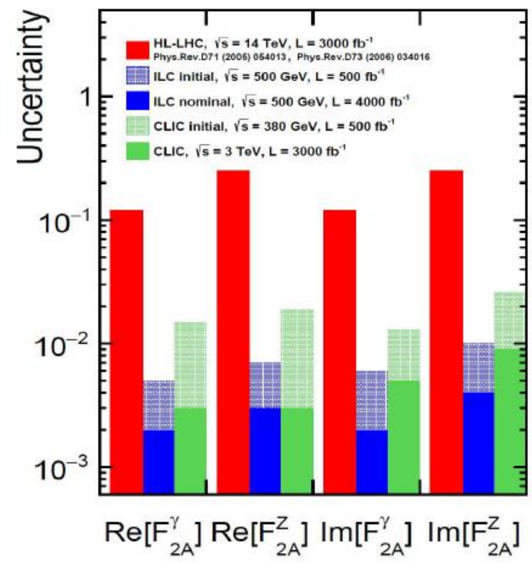
Anomalous couplings

$$\Gamma^{t\bar{t}X}(k^2,q,\bar{q}) = ie\left\{\gamma_\mu\left(F^X_{1V}(k^2)+\gamma_5F^X_{1A}(k^2)\right)-\frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(iF^X_{2V}(k^2)+\gamma_5F^X_{2A}(k^2)\right)\right\}$$

vector axial tensor CPV



arXiv:1608.07537



arXiv:1710.06737

Omnibus CLIC top paper in preparation, for ~ end 2017

Also CLIC BSM Physics study group