Future e+e- Linear Colliders

Philip Burrows

John Adams Institute, Oxford University

Outline

- Introduction
- The Large Hadron Collider + the Higgs boson
- A Higgs + top-quark factory
- The International Linear Collider (ILC)
- The Compact Linear Collider (CLIC)
- Project implementation and timelines
- The future

Large Hadron Collider (LHC)

Largest,

highest-energy

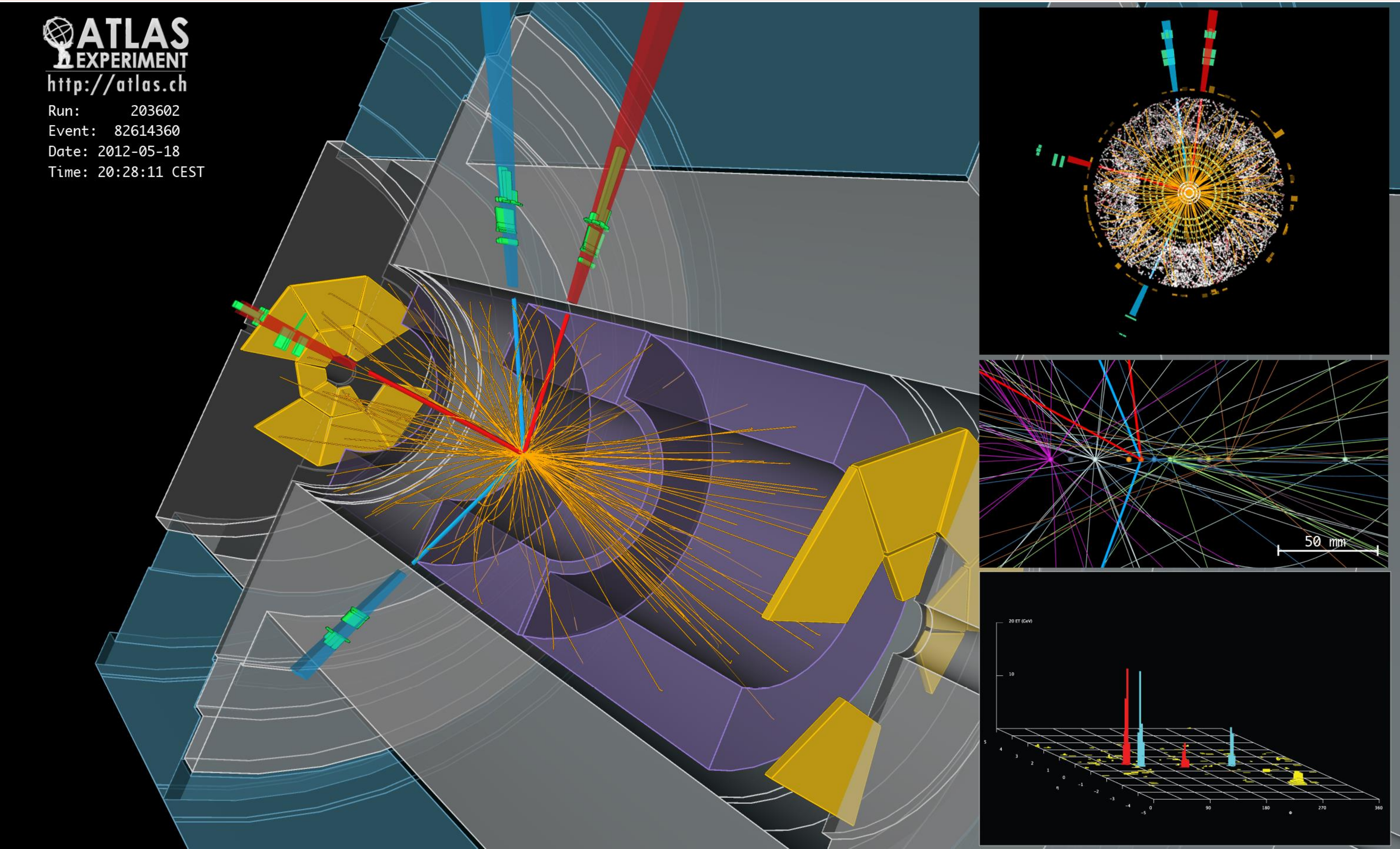
particle

collider

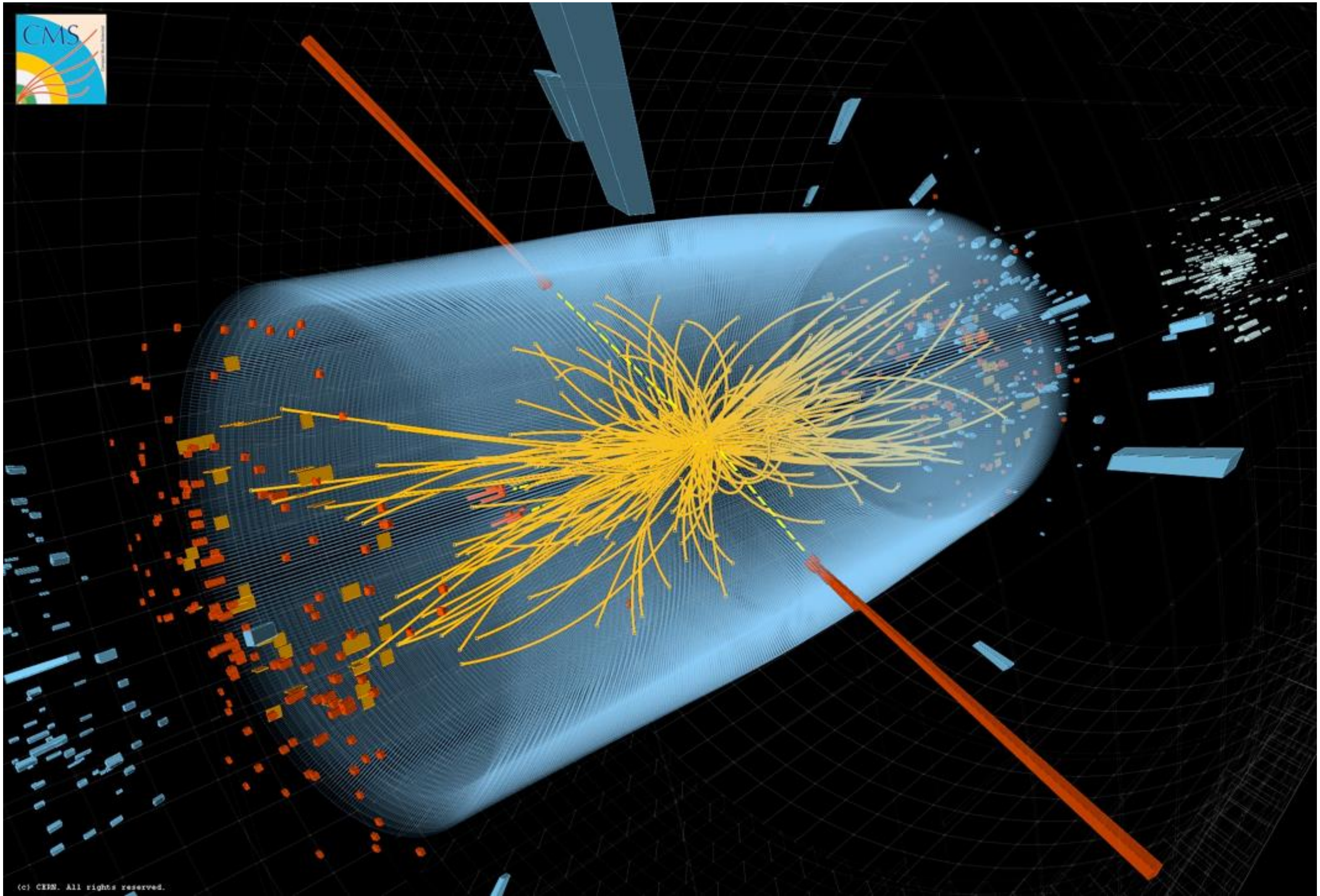
CERN,

Geneva

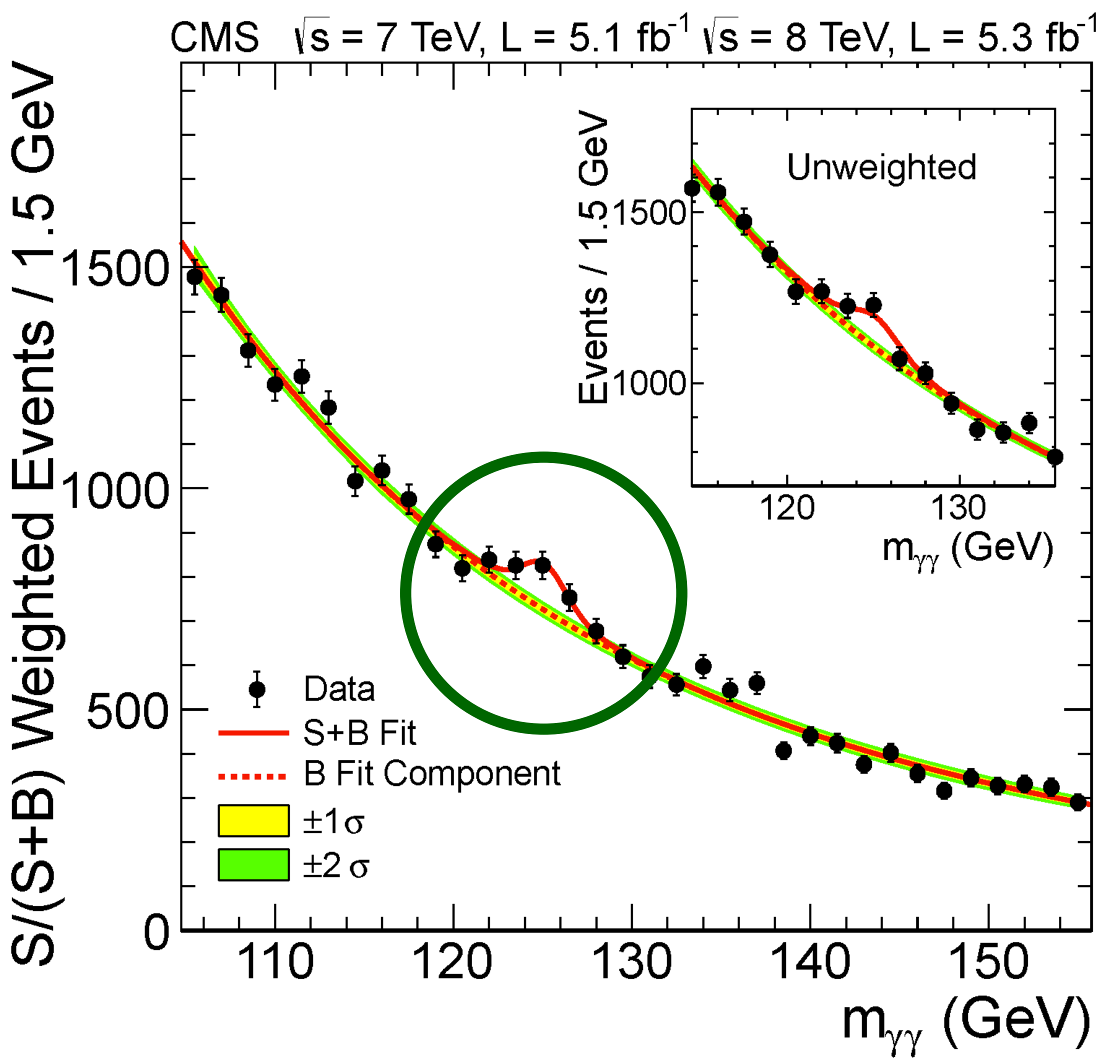
A Higgs boson?



A Higgs boson?



The 2012 discovery



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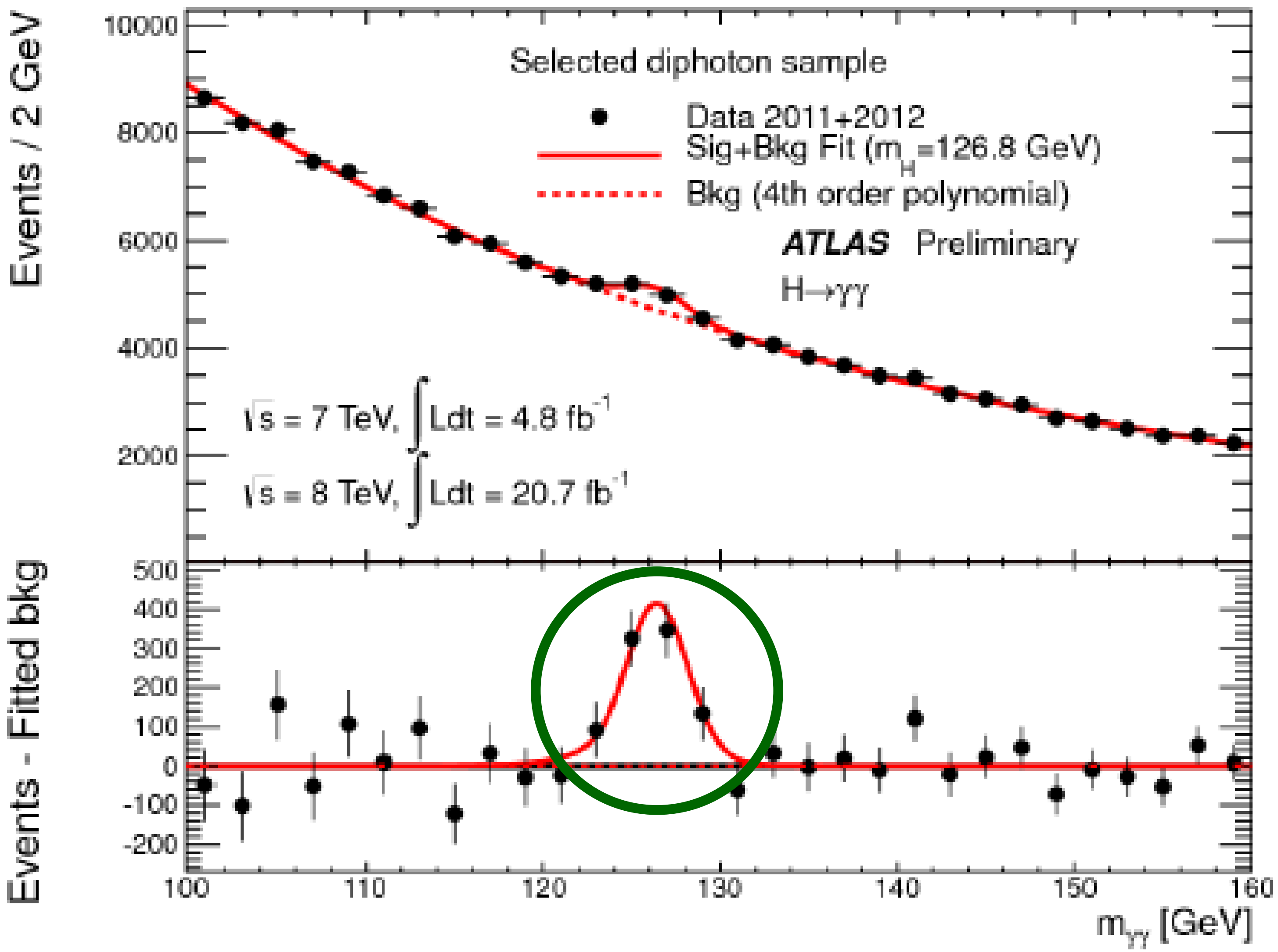
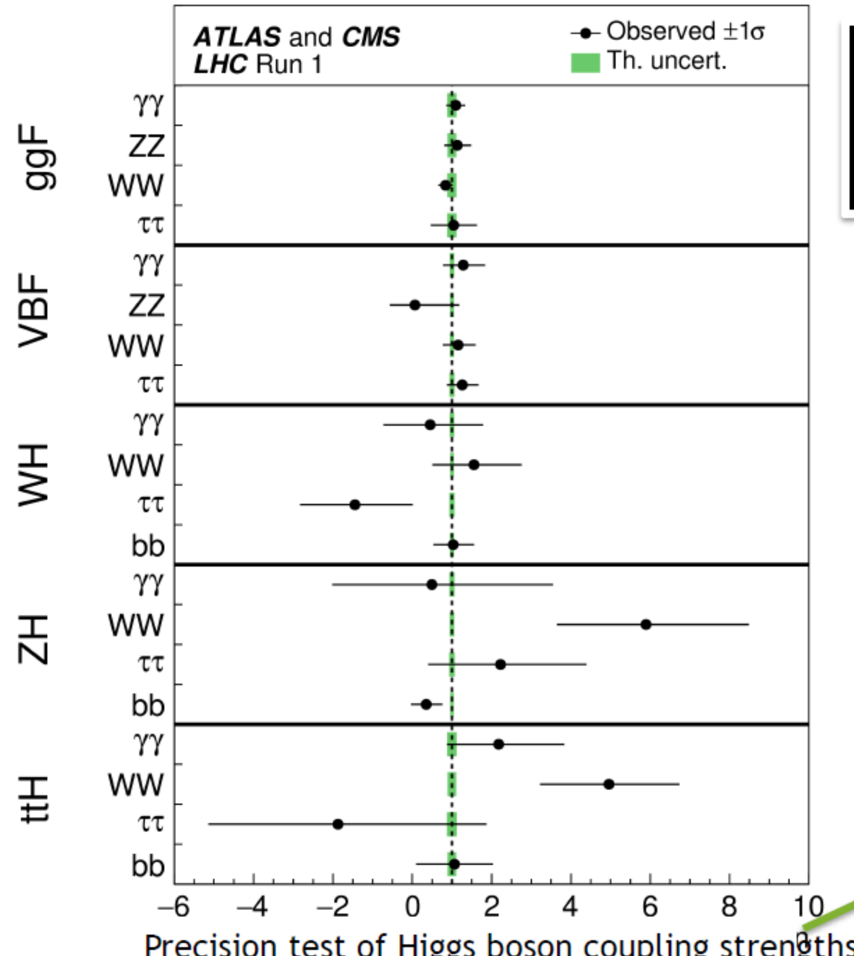


LHC combined Run 1 results



CMS and ATLAS combined 7 and 8 TeV results Run 1 legacy papers:

Mass: Phys. Rev. Lett. 114, 191803

Rates and couplings: arXiv:1606.02266

Coupling strengths

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

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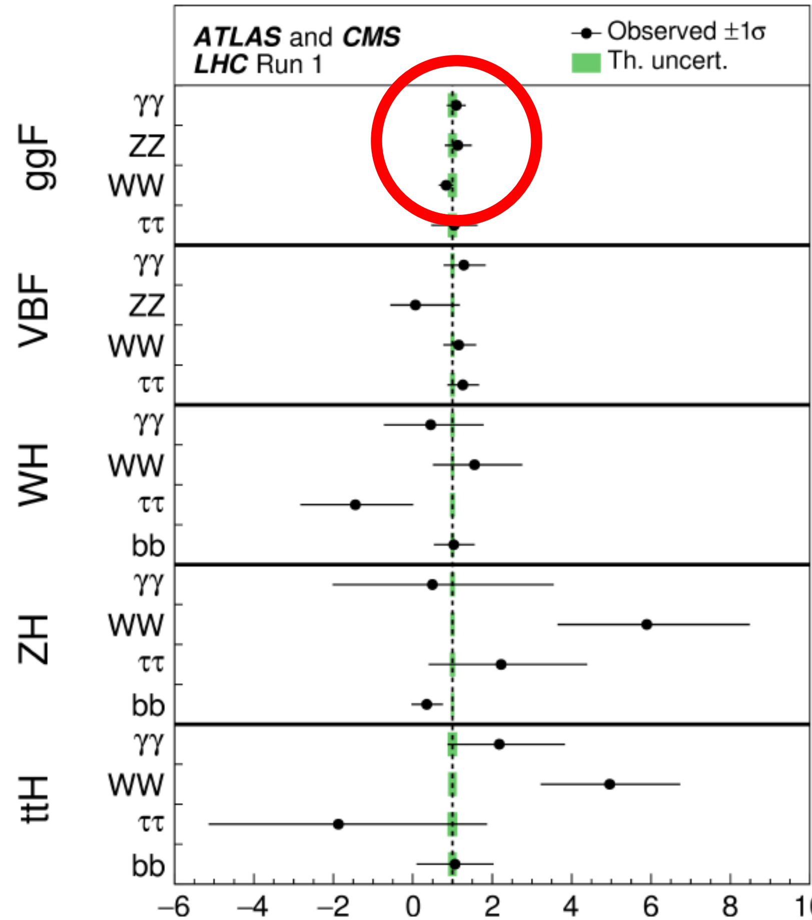

Precision test of Higgs boson coupling strengths

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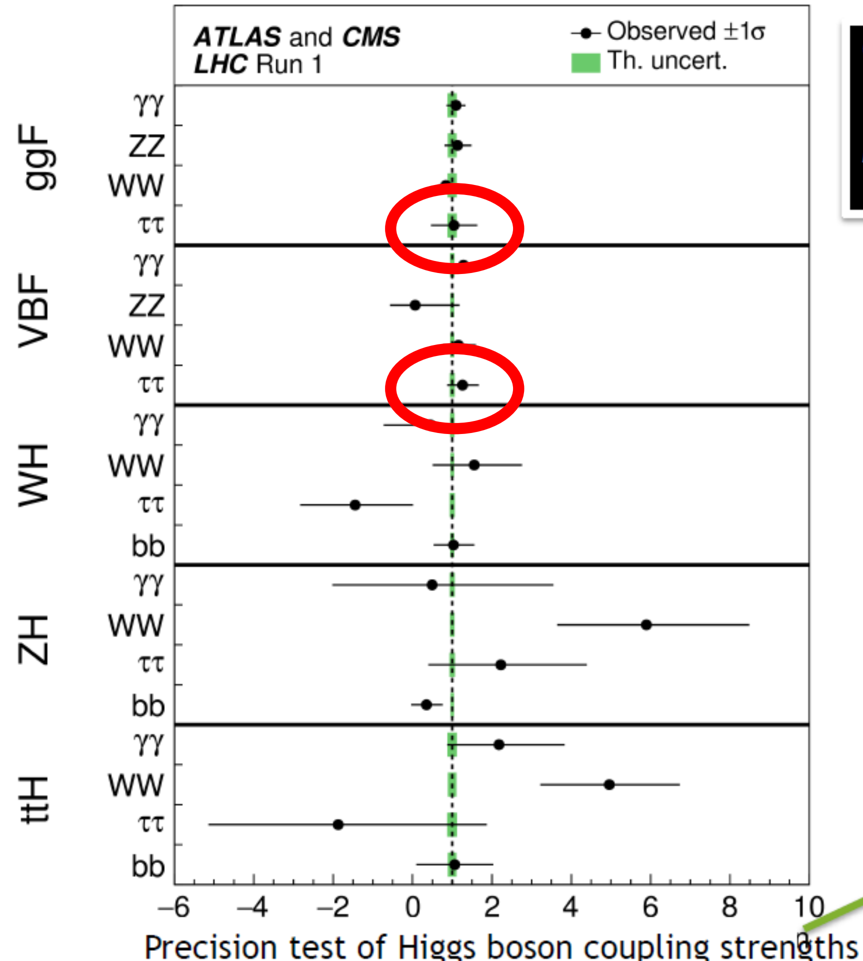

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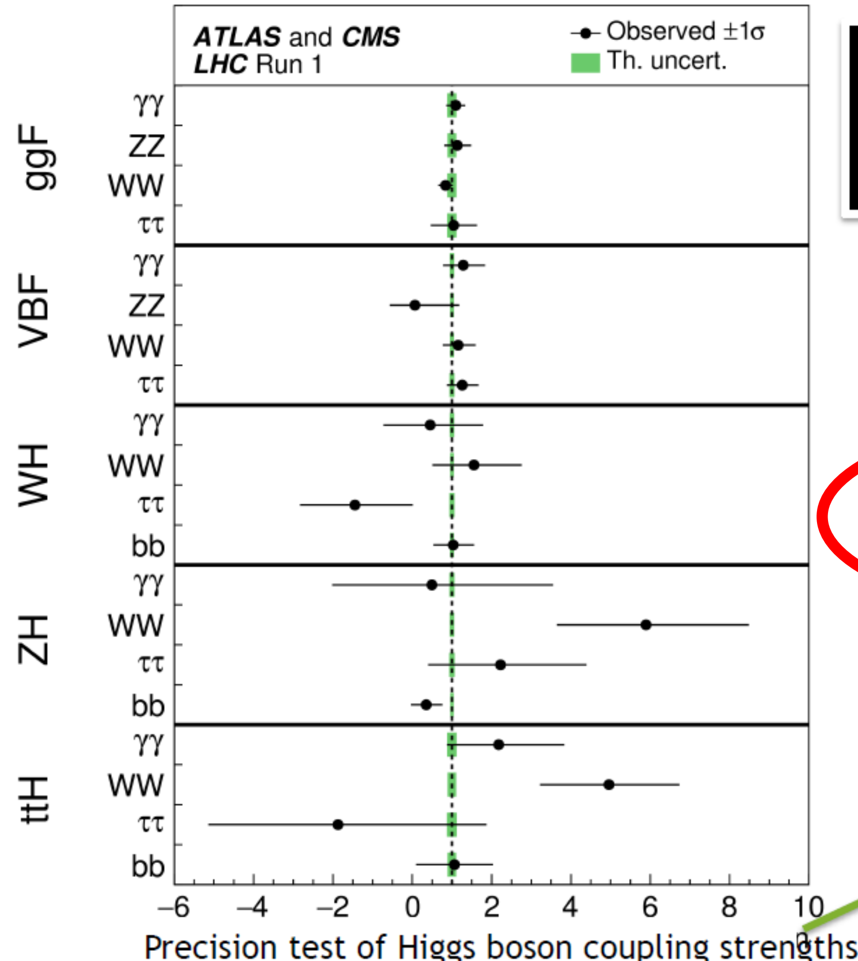

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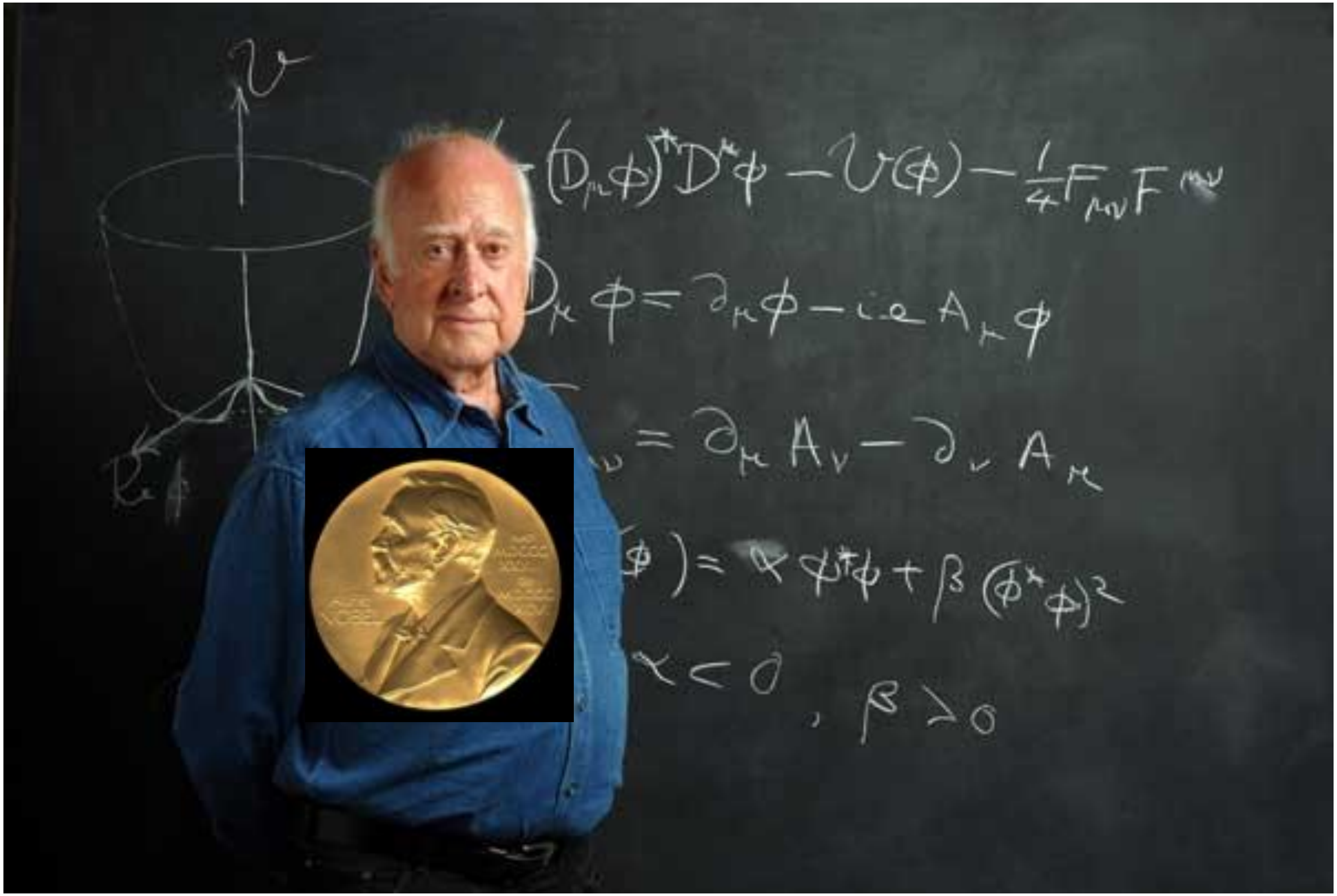
- Mass has been measured to 0.2% precision
  m_H=125.09±0.24 GeV
- Angular distributions consistent with spin 0 and even parity
- All couplings are consistent with SM within 2.5σ

Coupling strengths

$$\mu = \frac{\sigma}{\sigma_{SM}}$$

It’s officially a Higgs Boson!



Finger-printing the Higgs boson

Determine its 'profile':

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

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

→ 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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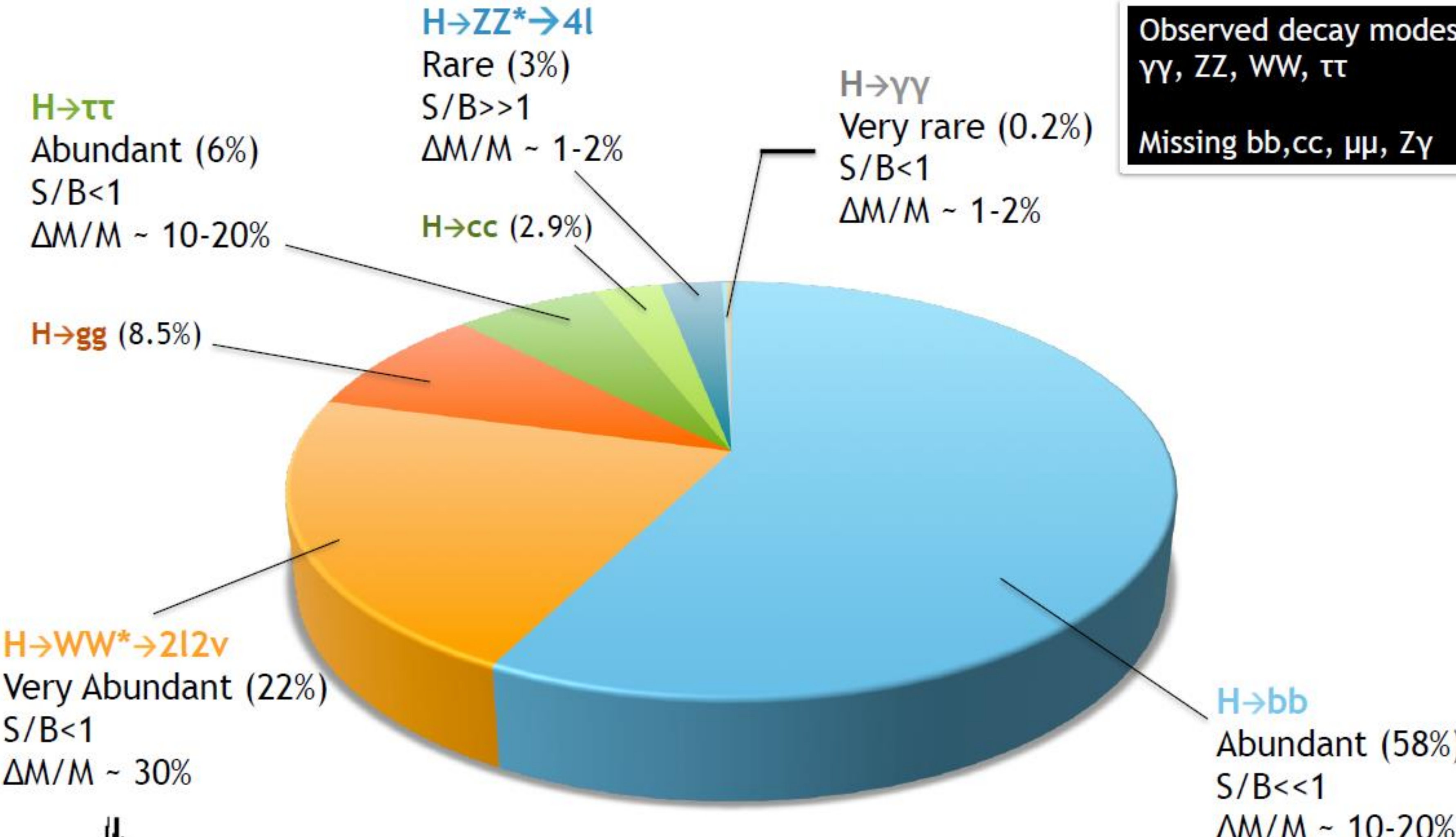
Deviations in the range 1% → 10%

→ measurements must be significantly more precise to resolve such deviations

LHC projections on Higgs couplings

Higgs Boson Decays at 125 GeV



Observed decay modes:
γγ, ZZ, WW, ττ

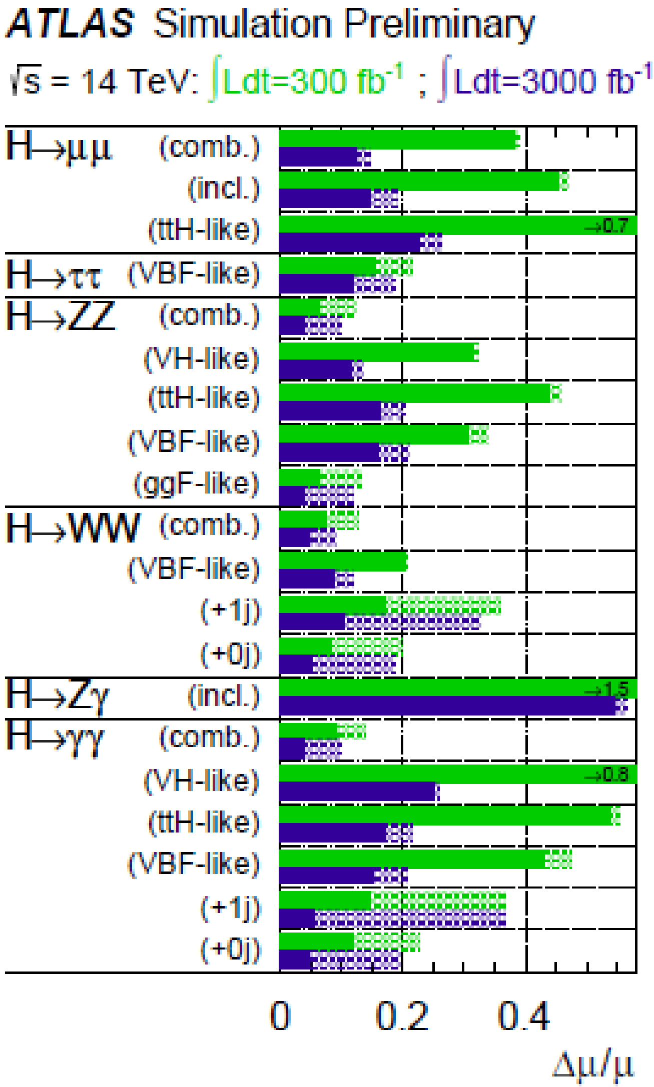
Missing bb, cc, μμ, Zγ

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**

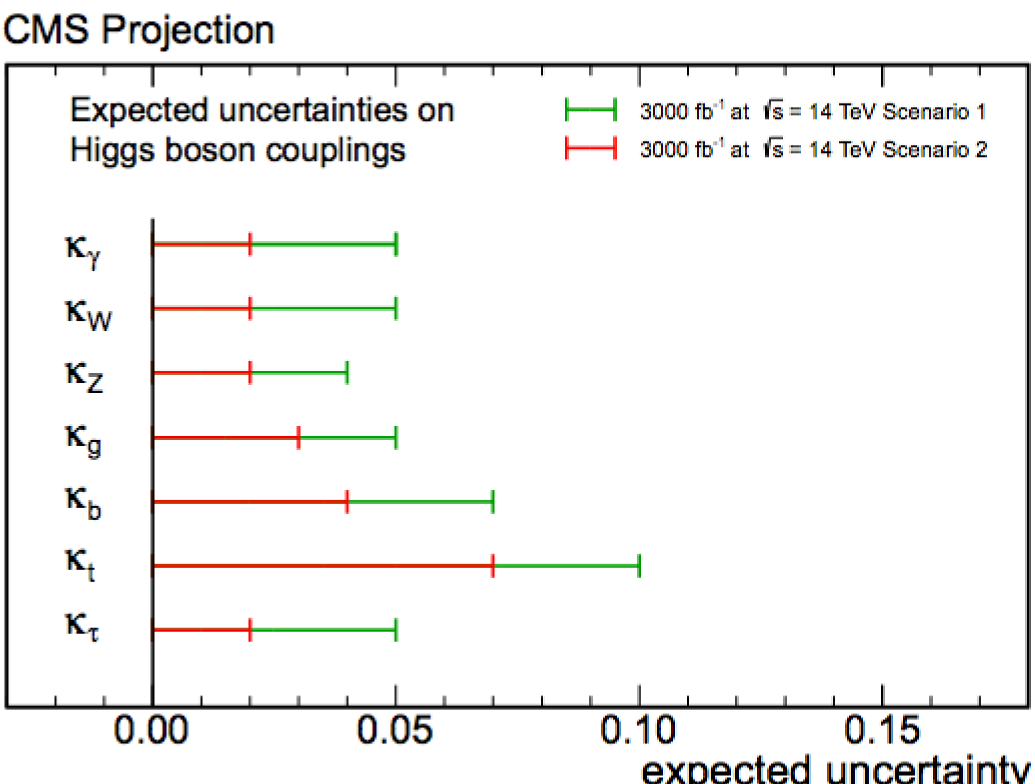
ATLAS projections



ATL PHYS PUB 2013 014

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

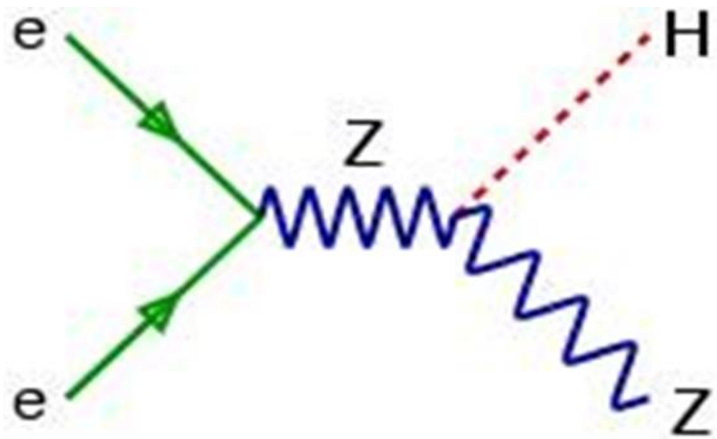
Currently, typically LHC projected precisions on Higgs coupling measurements assume that:

- **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 …

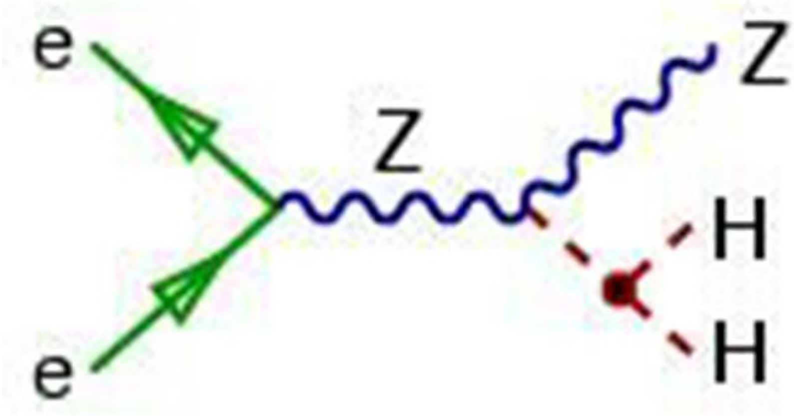
e+e- Higgs factory

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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complete control of event kinematics:

p = 0, M = 2E

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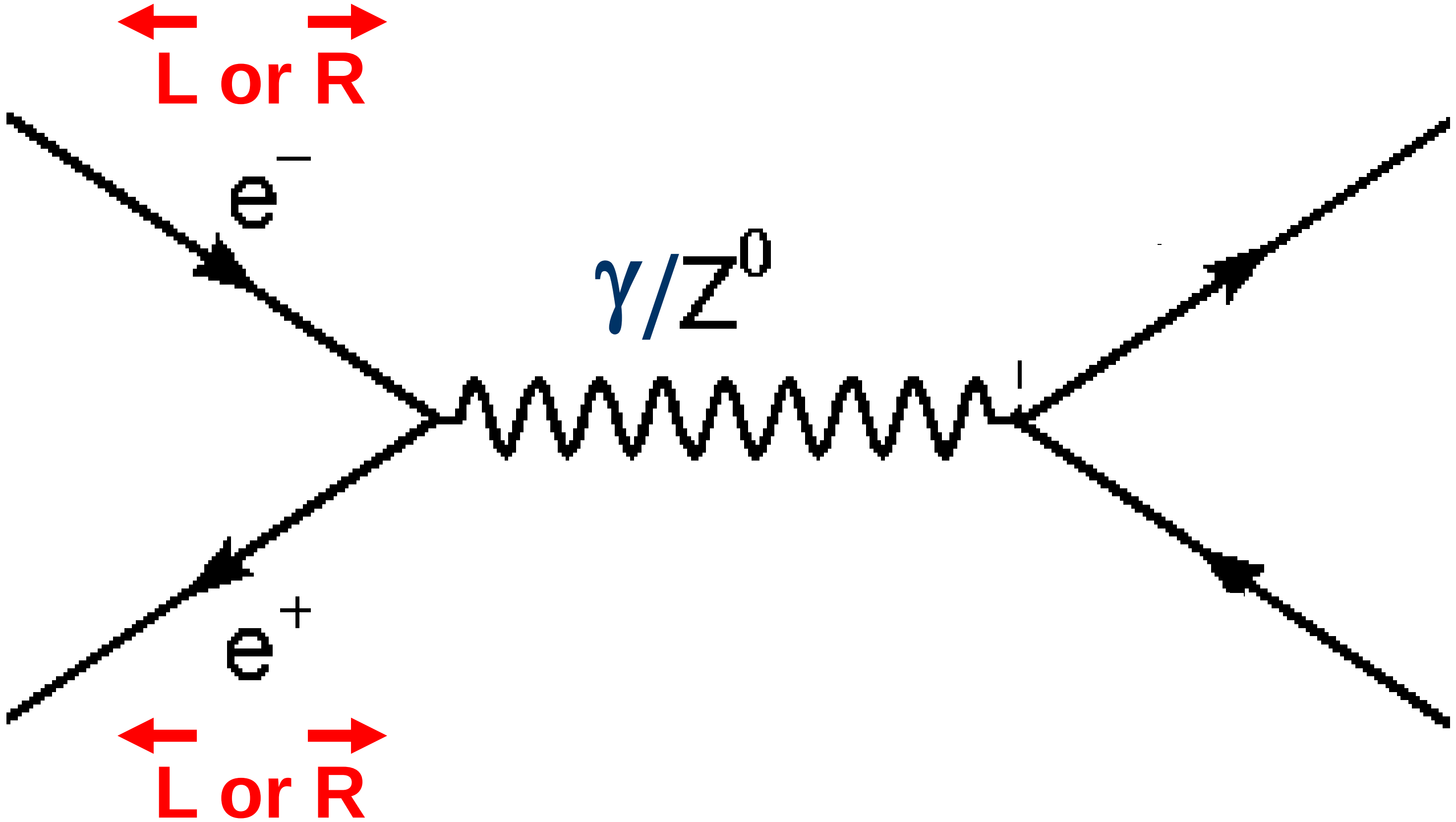
polarised beam(s)

e+e- annihilations



e+e- colliders

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

  well defined centre of mass energy: 2E

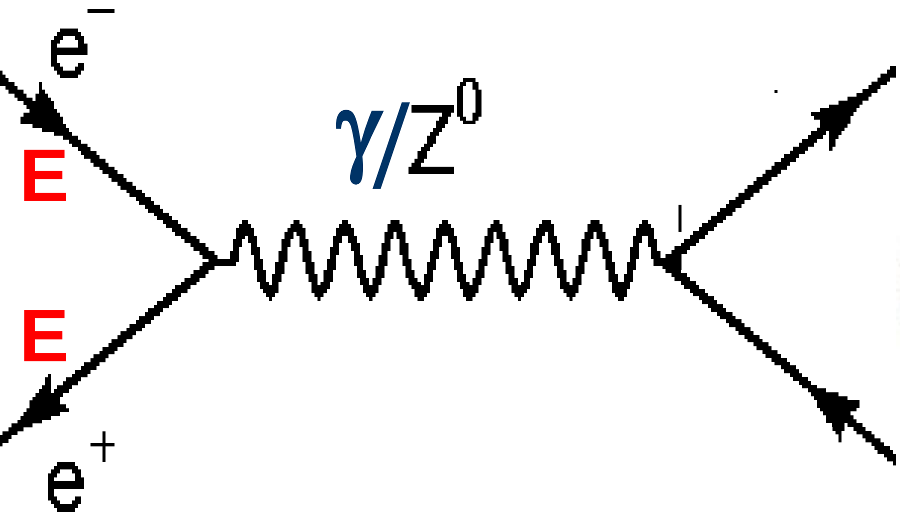
  complete control of event kinematics:

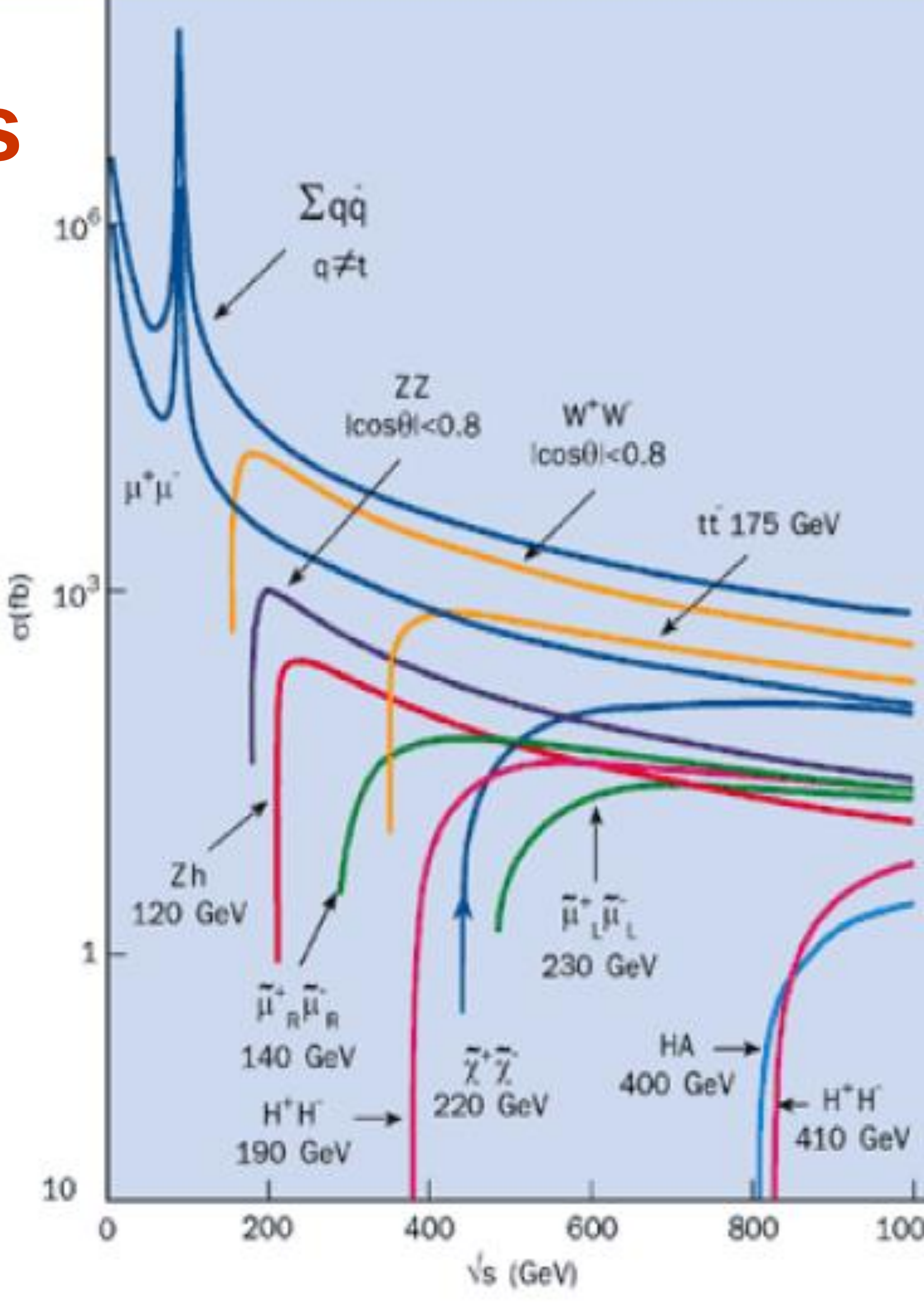
  p = 0, M = 2E

  polarised beam(s)

  clean experimental environment

e+e- annihilations





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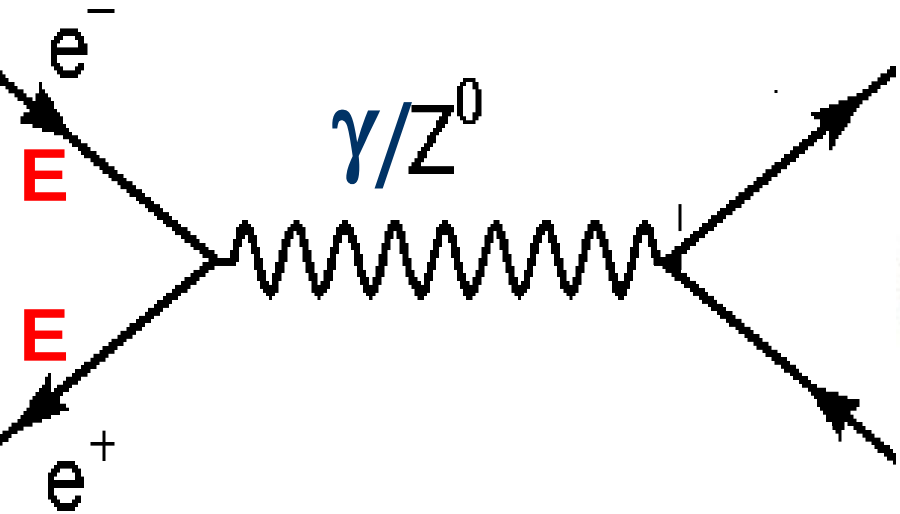

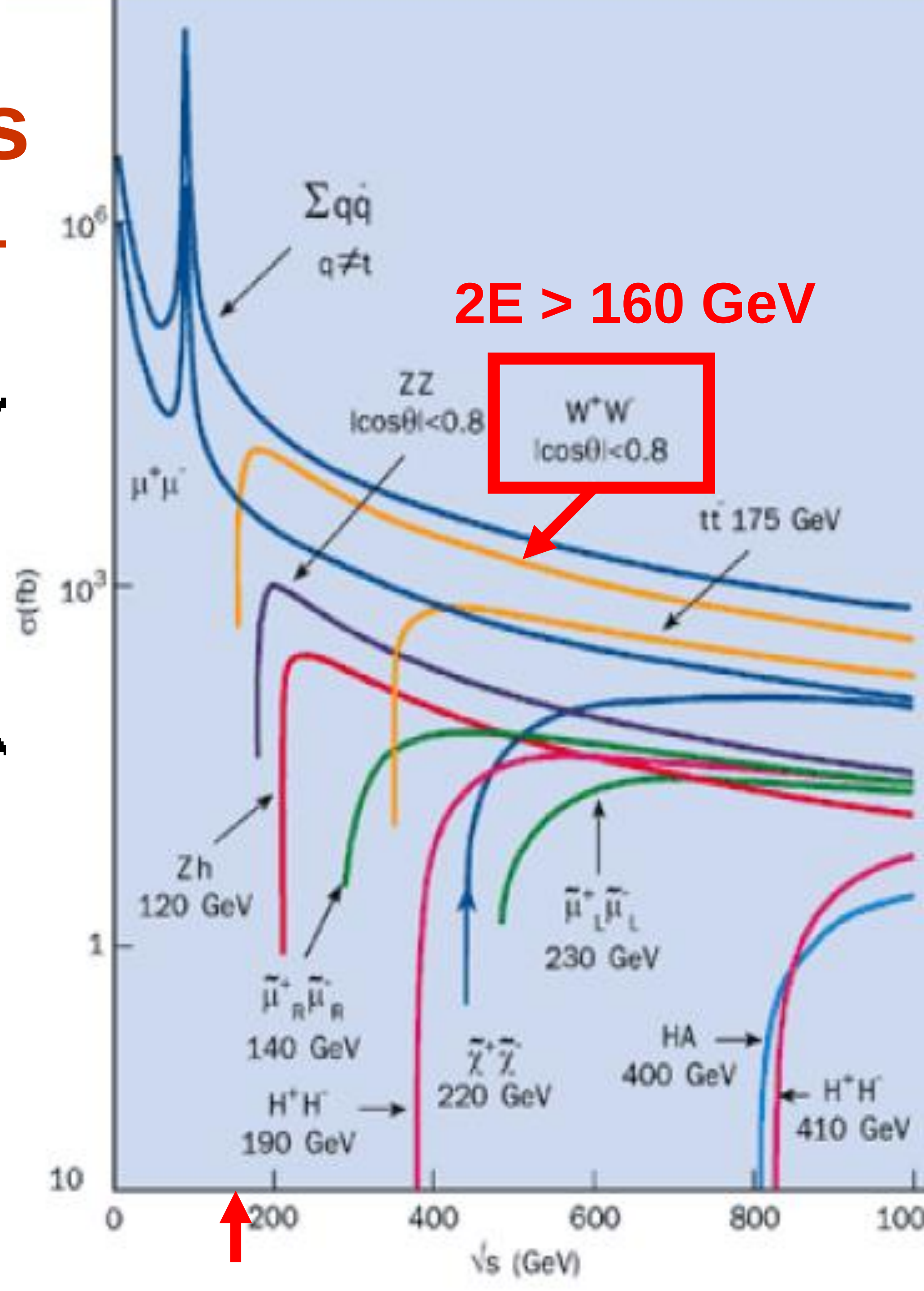

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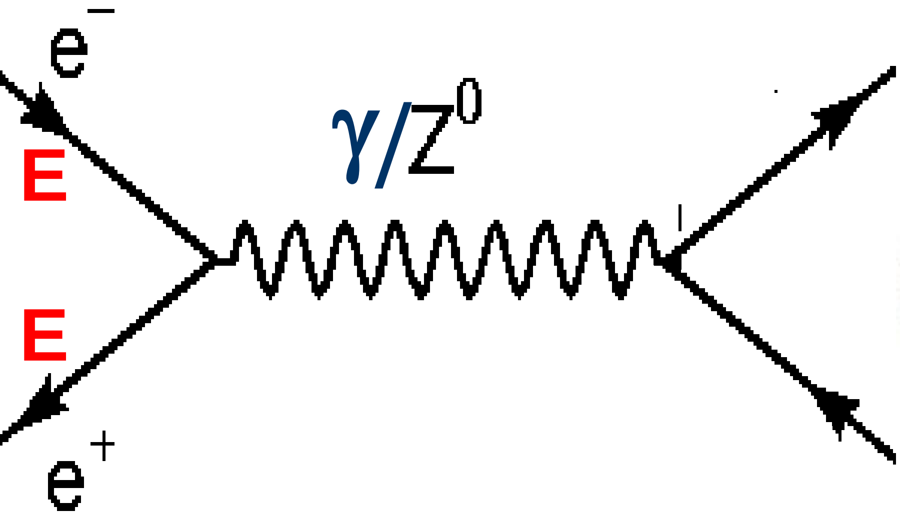

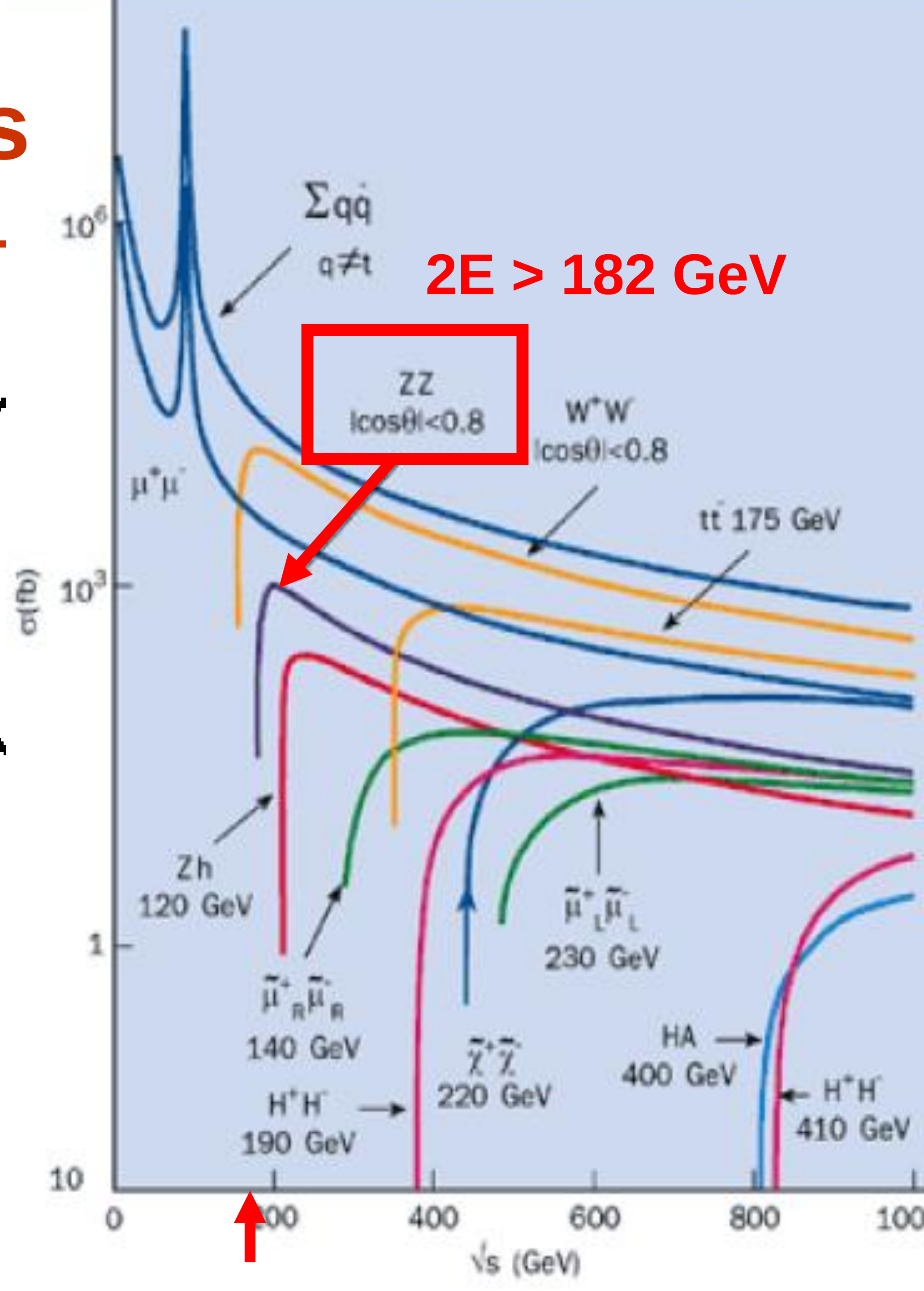

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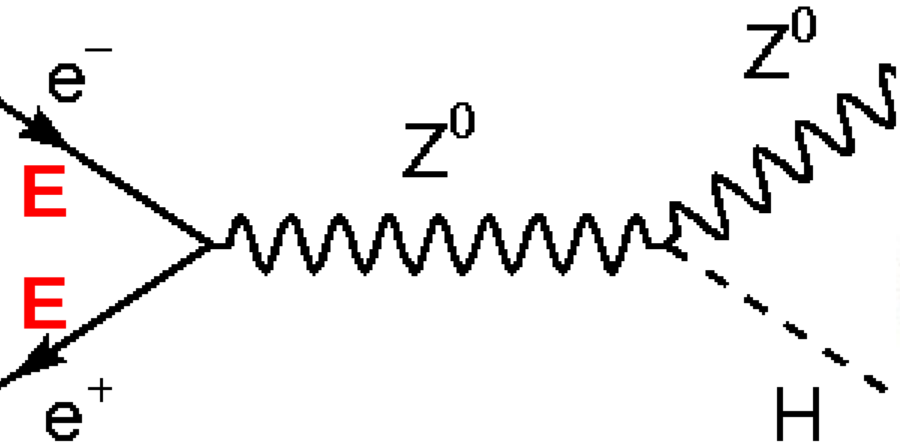
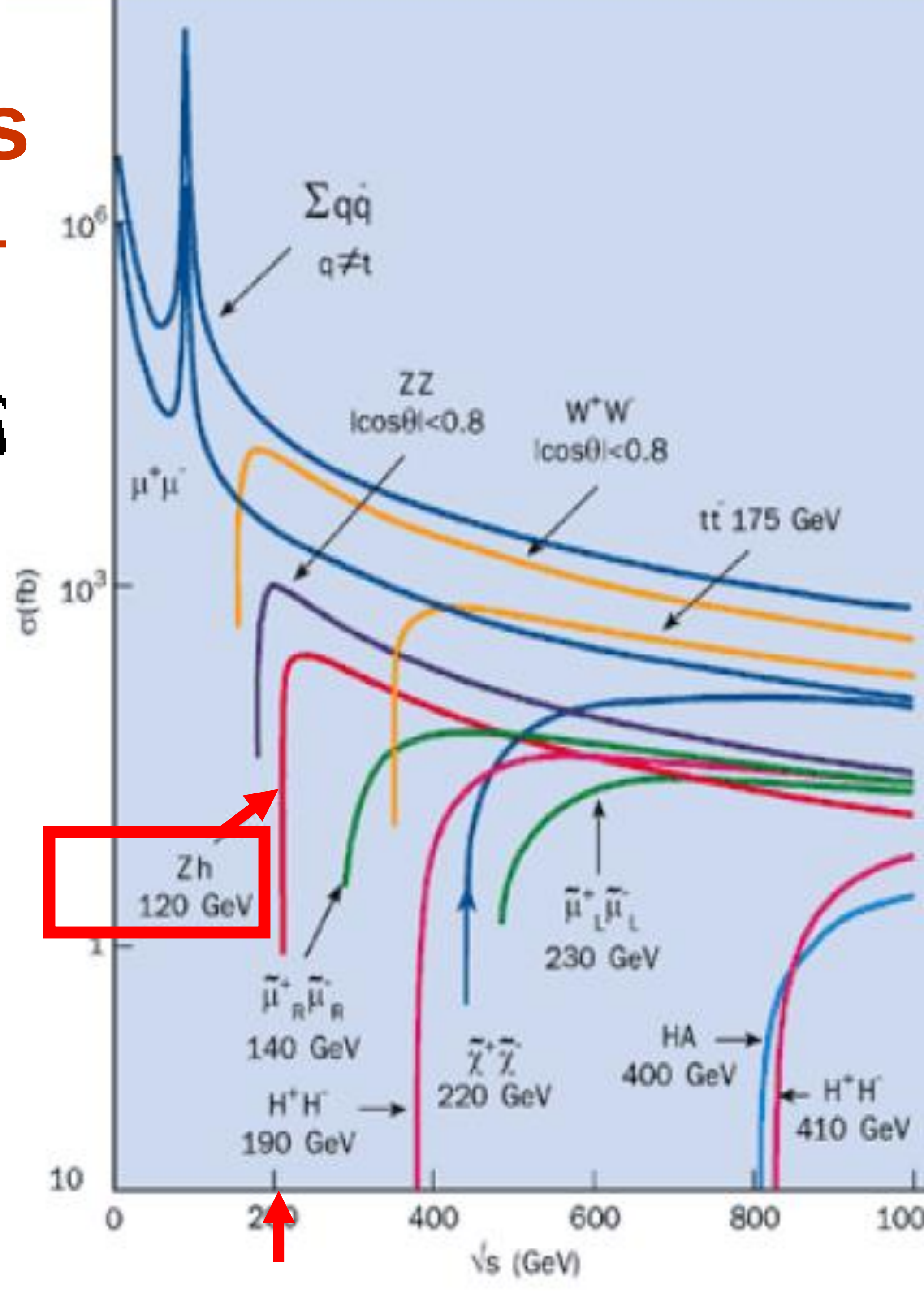


2E > 216 GeV



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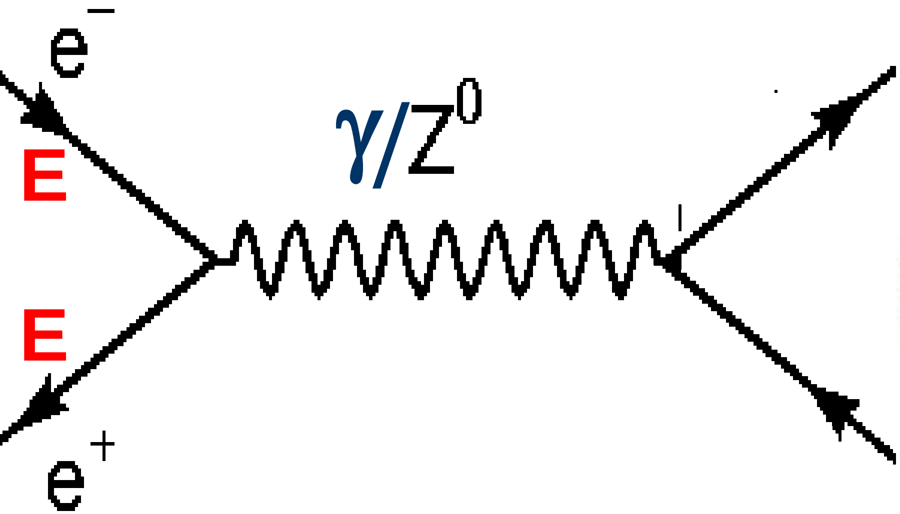

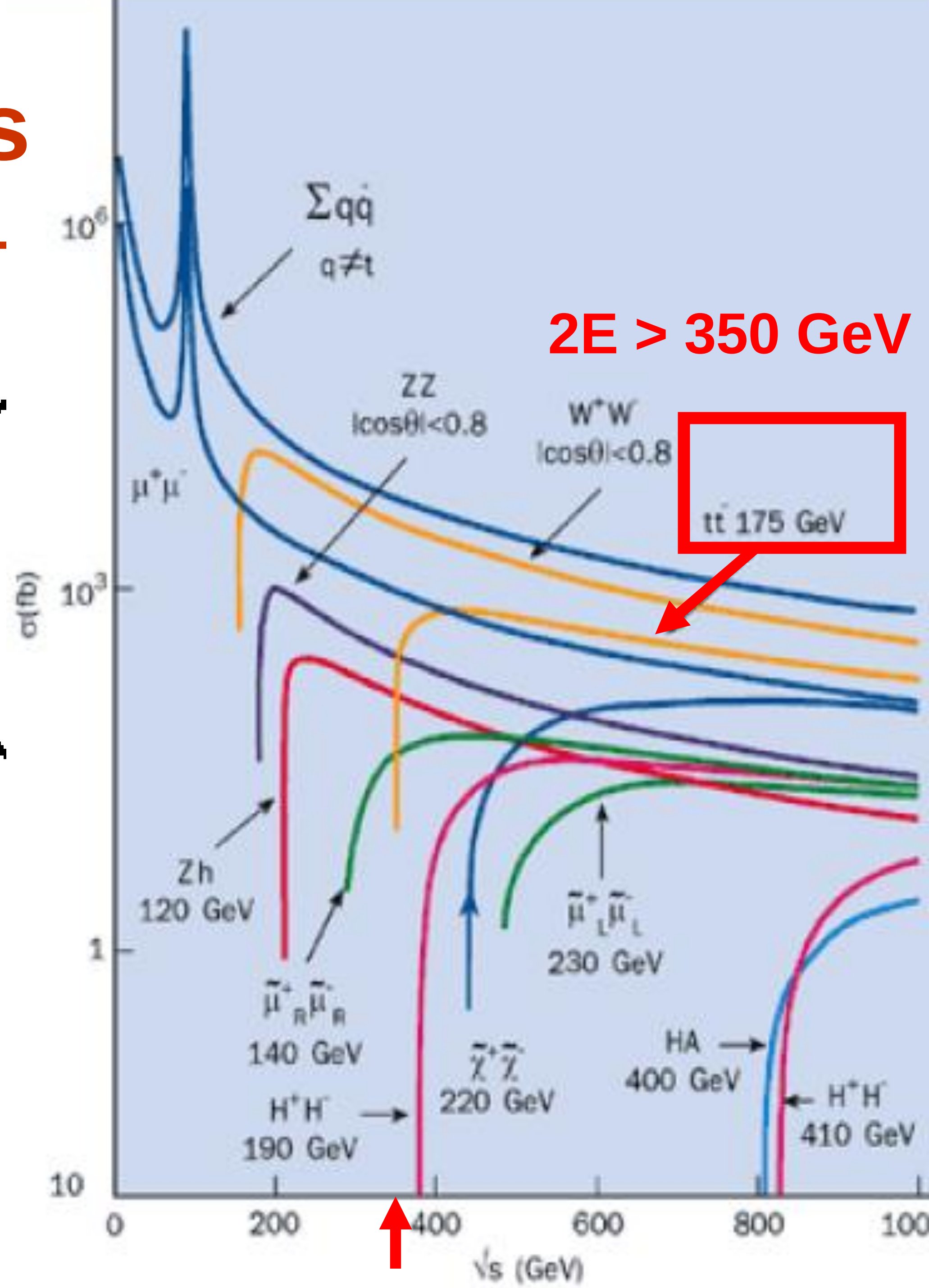

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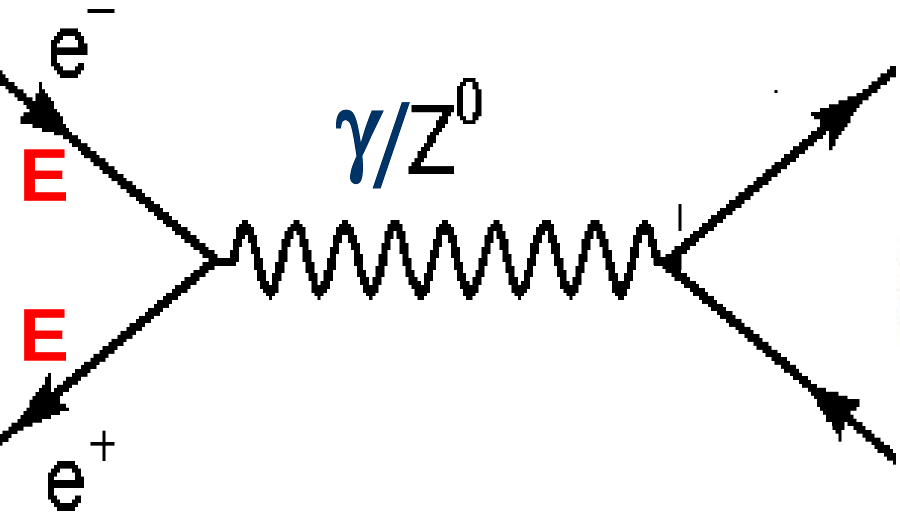

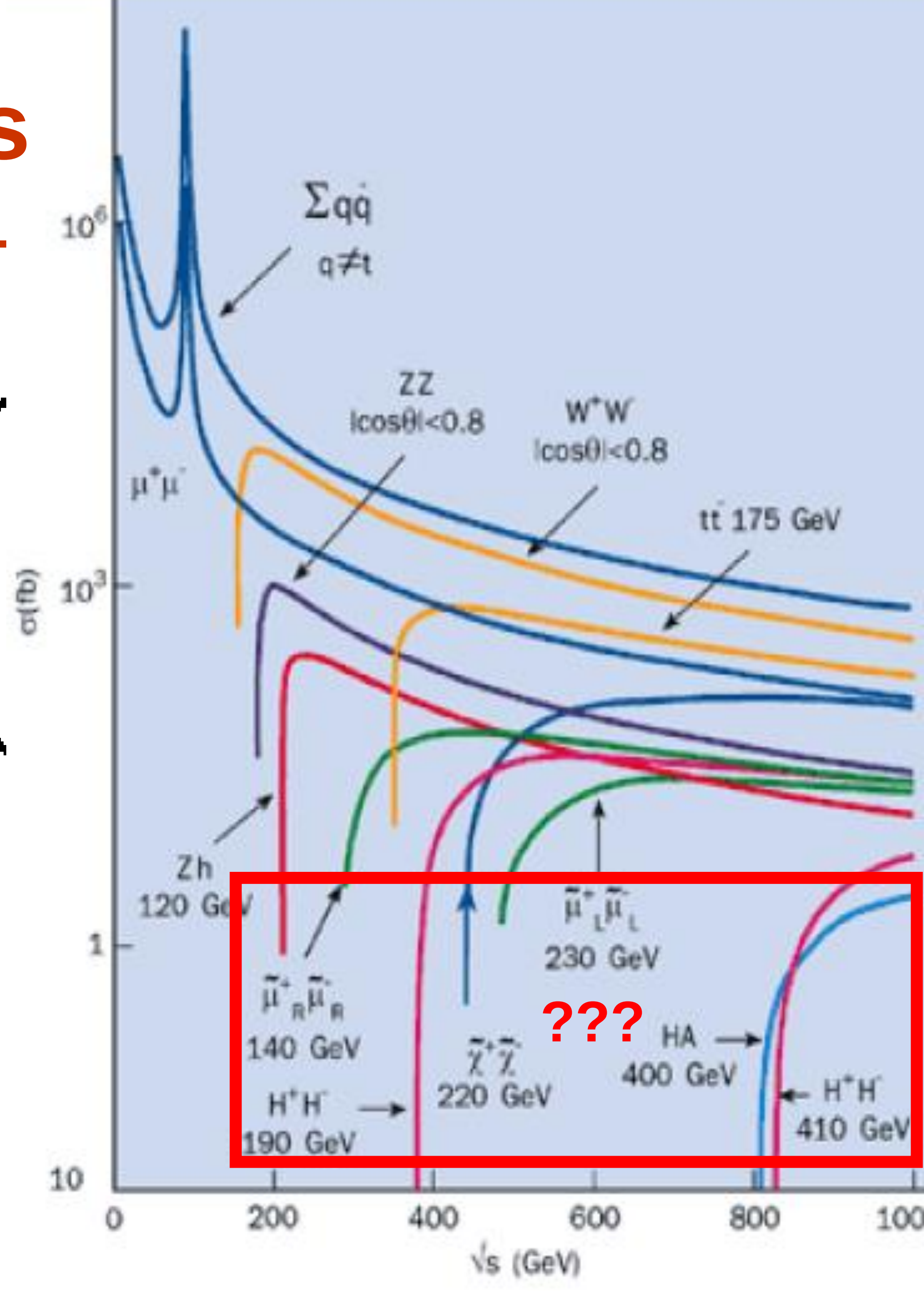

European particle physics strategy 2013

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

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.

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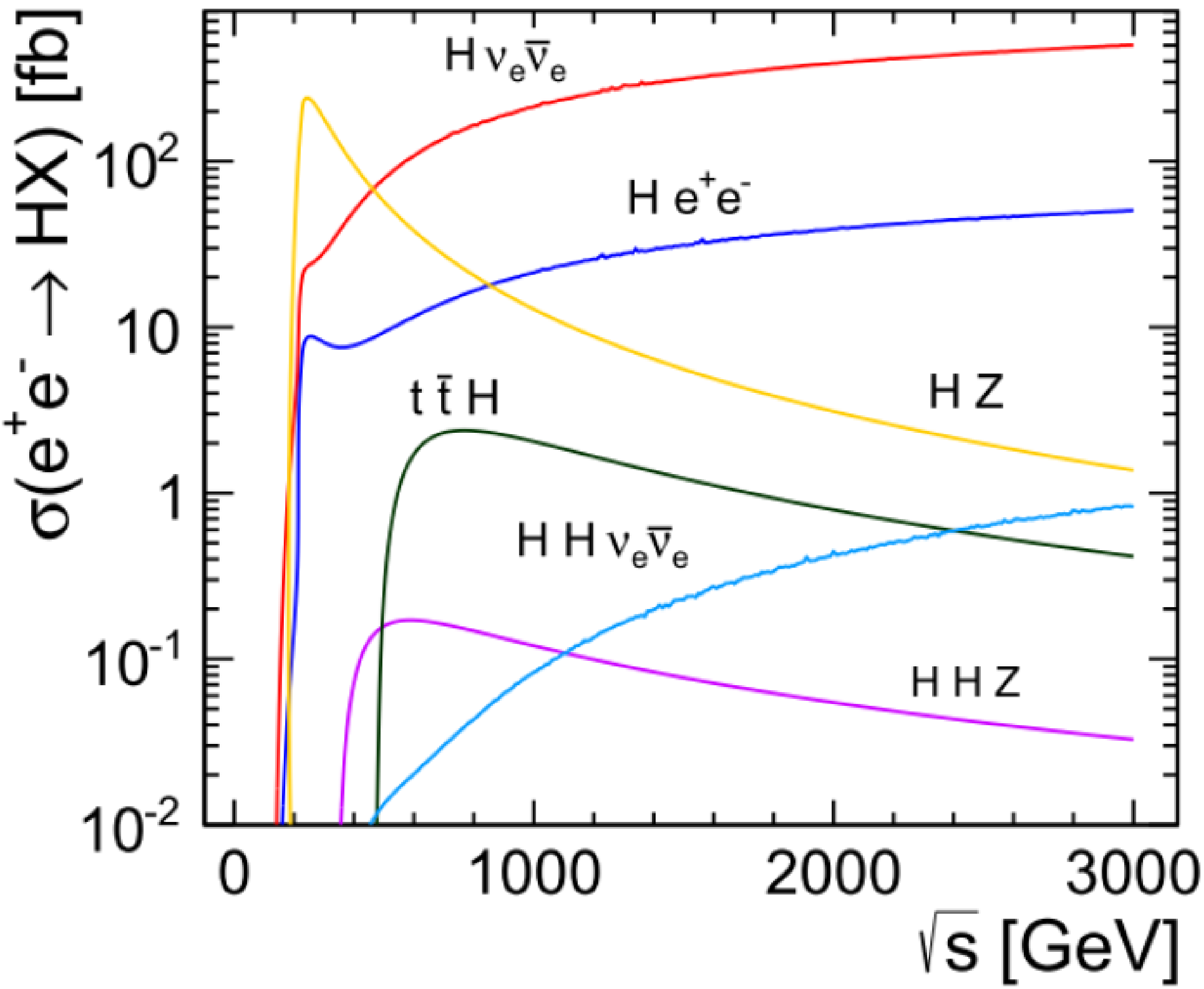
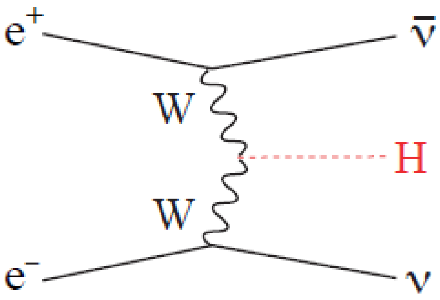
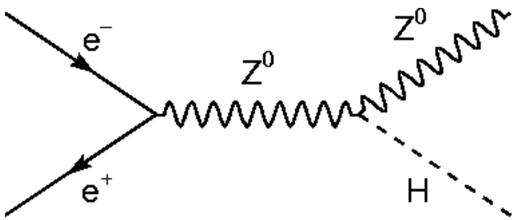
e+e- Higgs Factory







ILC Higgs Factory possible roadmap

250 GeV:

- Mass, Spin, CP nature
- Absolute meas. of HZZ
- BRs Higgs → qq, ll, VV

350 GeV:

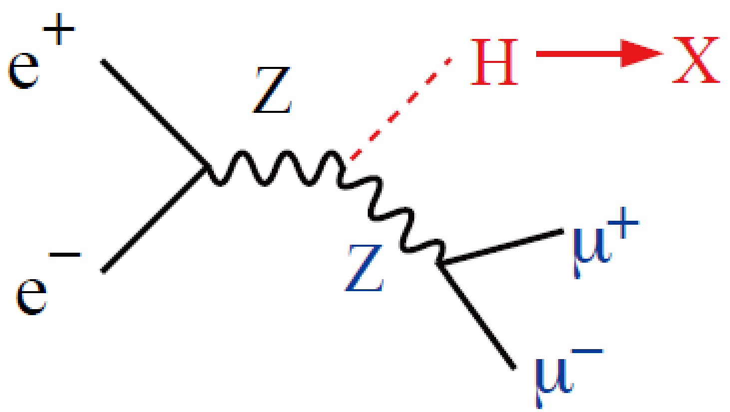
- Top threshold: mass, width, anomalous couplings …
- (more stats on Higgs BRs)

500-600 GeV:

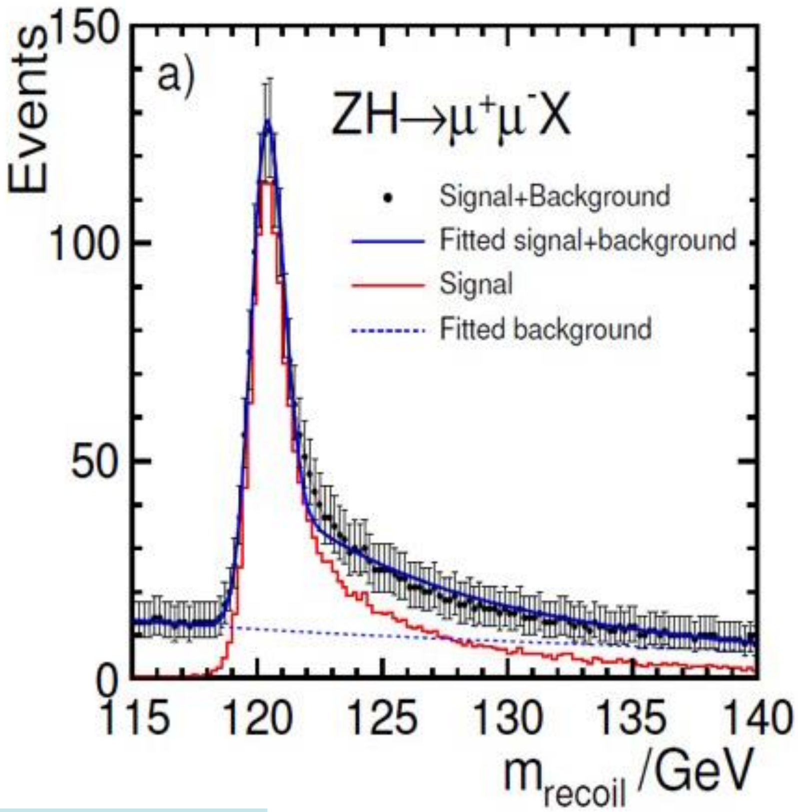
- HWW coupling → total width → absolute couplings
- Higgs self coupling
- Top Yukawa coupling

→ 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

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

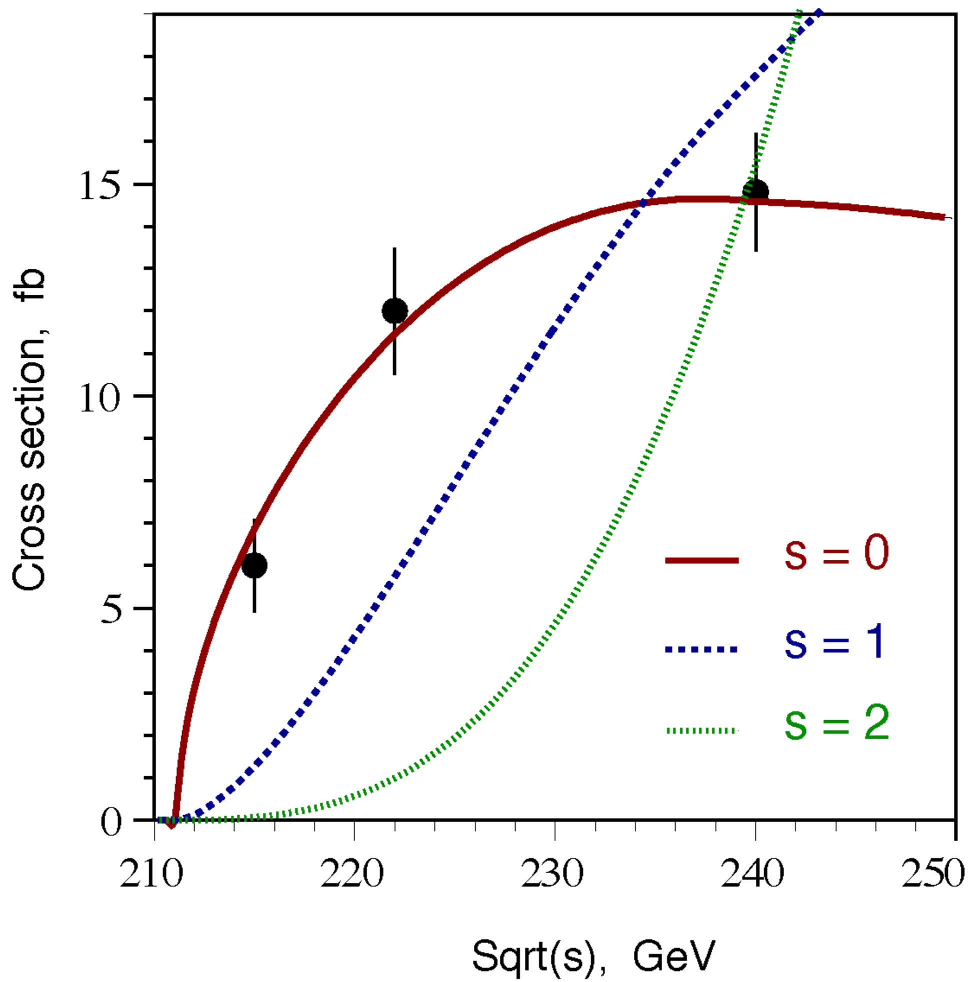
$$\Delta\sigma_H/\sigma_H = 2.5\%$$

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

(Fujii)

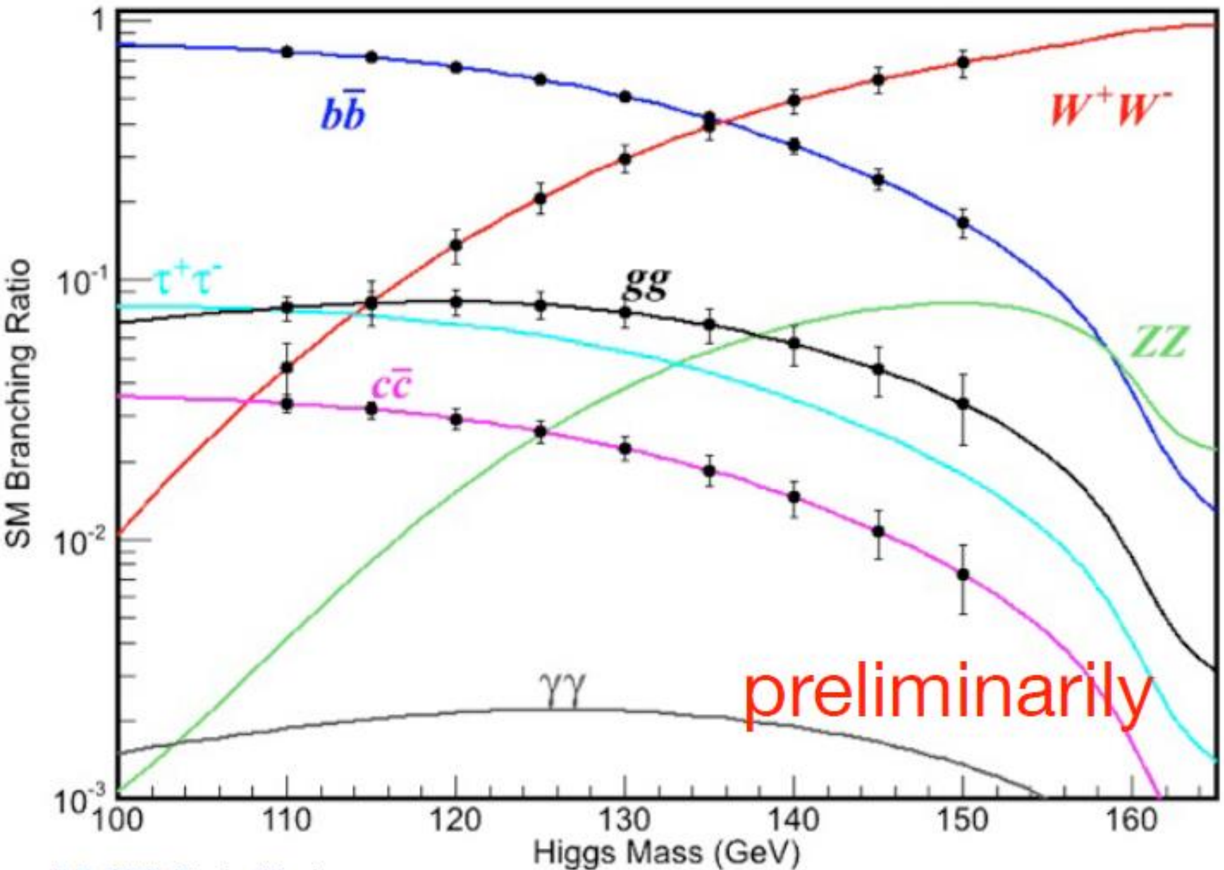
Higgs spin determination

Rise of cross-section near threshold



(TESLA TDR)

Higgs branching ratios determination (1)



ILD DBD Study (Ono)

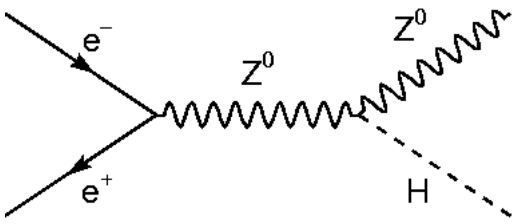
(ILC TDR)

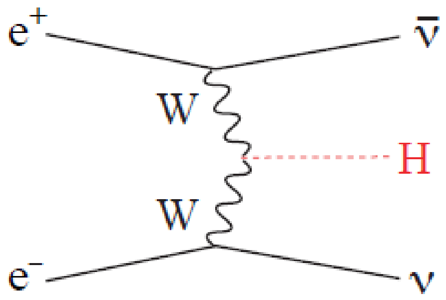
$$250\ \mathrm{fb}^{-1} @ 250\ \mathrm{GeV}$$
$$m_H = 120\ \mathrm{GeV}$$

	@ 250 GeV
process	ZH
luminosity · fb	250
cross section	2.5%
	σ·Br
H-->bb	1.0%
H-->cc	6.9%
H-->gg	8.5%
H-->WW*	8.2%
H-->ττ	4-6%
H-->ZZ*	28%
H-->γγ	23-30%

Higgs branching ratios determination (2)

measurements (independent)	precision
$X_1 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b})$ @ 250 GeV	1.0%
$X_2 = \sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c})$ @ 250 GeV	6.9%
$X_3 = \sigma_{ZH} \cdot \mathrm{Br}(H \to gg)$ @ 250 GeV	8.5%
$X_4 = \sigma_{ZH} \cdot \mathrm{Br}(H \to WW^*)$ @ 250 GeV	8.2%
$X_5 = \sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b})$ @ 500 GeV	1.6%
$X_6 = \sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c})$ @ 500 GeV	11%
$X_7 = \sigma_{ZH} \cdot \mathrm{Br}(H \to gg)$ @ 500 GeV	13%
$X_8 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to b\bar{b})$ @ 500 GeV	0.60%
$X_9 = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to c\bar{c})$ @ 500 GeV	4.0%
$X_{10} = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to gg)$ @ 500 GeV	4.9%
$X_{11} = \sigma_{\nu\bar{\nu}H} \cdot \mathrm{Br}(H \to WW^*)$ @ 500 GeV	3.0%
$X_{12} = \sigma_{ZH}$	2.5%





(Fujii / ILC TDR)

Total Width and Coupling Extraction

One of the major advantages of the LC

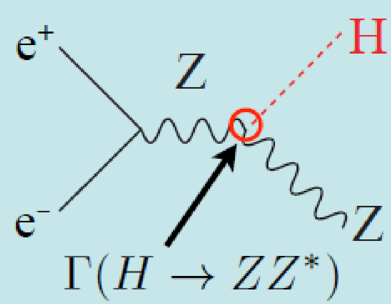
To extract couplings from BRs, we need the total width:

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

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

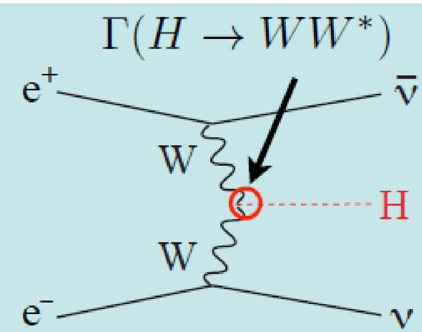
$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

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



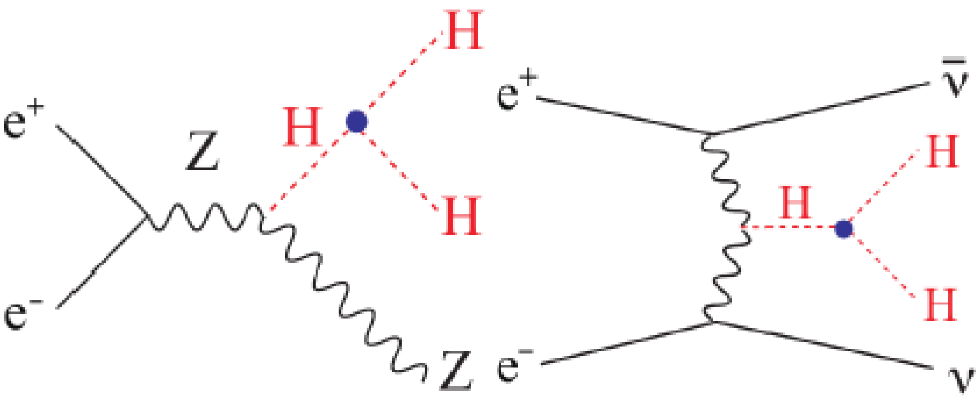
$BR(H \to WW^*)$

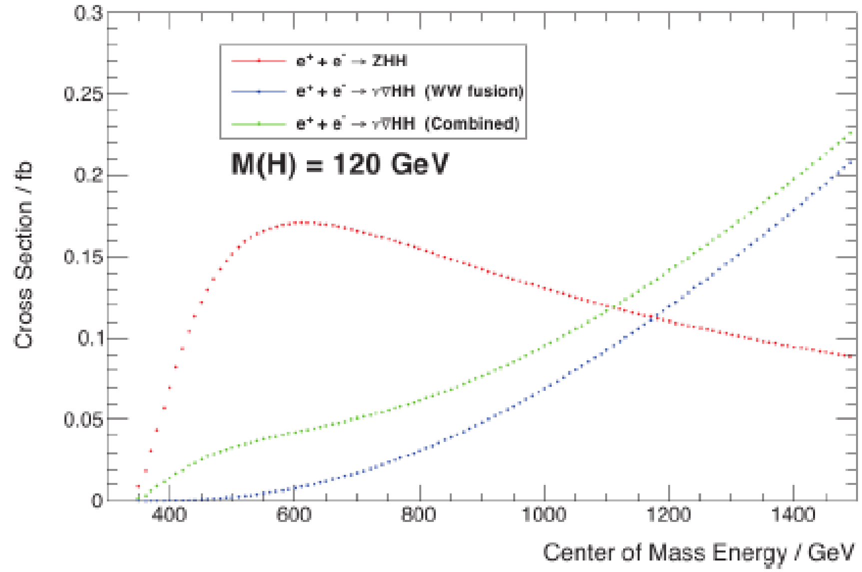
More advantageous but not easy at low E

$250\ \mathrm{fb}^{-1}$@$250\ \mathrm{GeV}$
$\Delta\Gamma_H/\Gamma_H \simeq 10\%$

Jenny List's talk

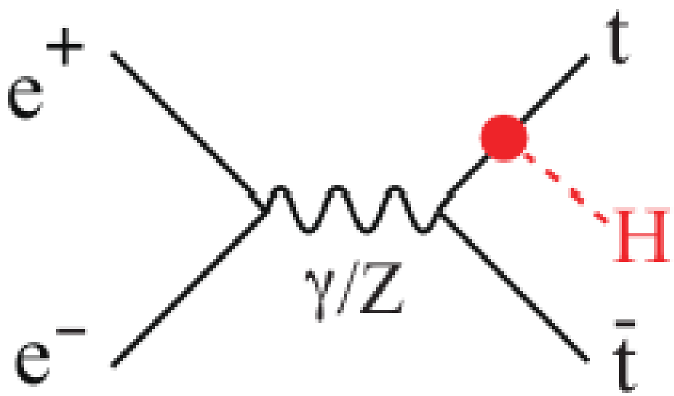
Higgs self-coupling determination

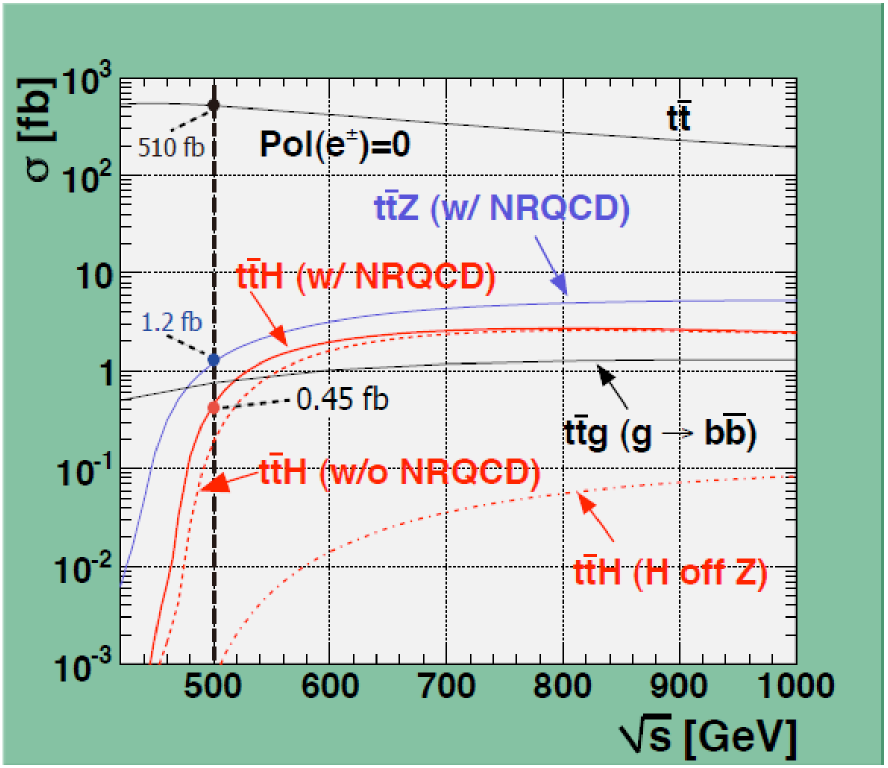




$\sqrt{s}$ (GeV) L (fb^{-1})	500 500	500 1600	500+1000 500+1000	500+1000 1600+2500
$\Delta\lambda/\lambda$	83%	46%	21%	13%

Higgs top-coupling determination





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

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

(Price, Roloff)

ILC roadmap Snowmass study

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

ILC roadmap Snowmass study

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

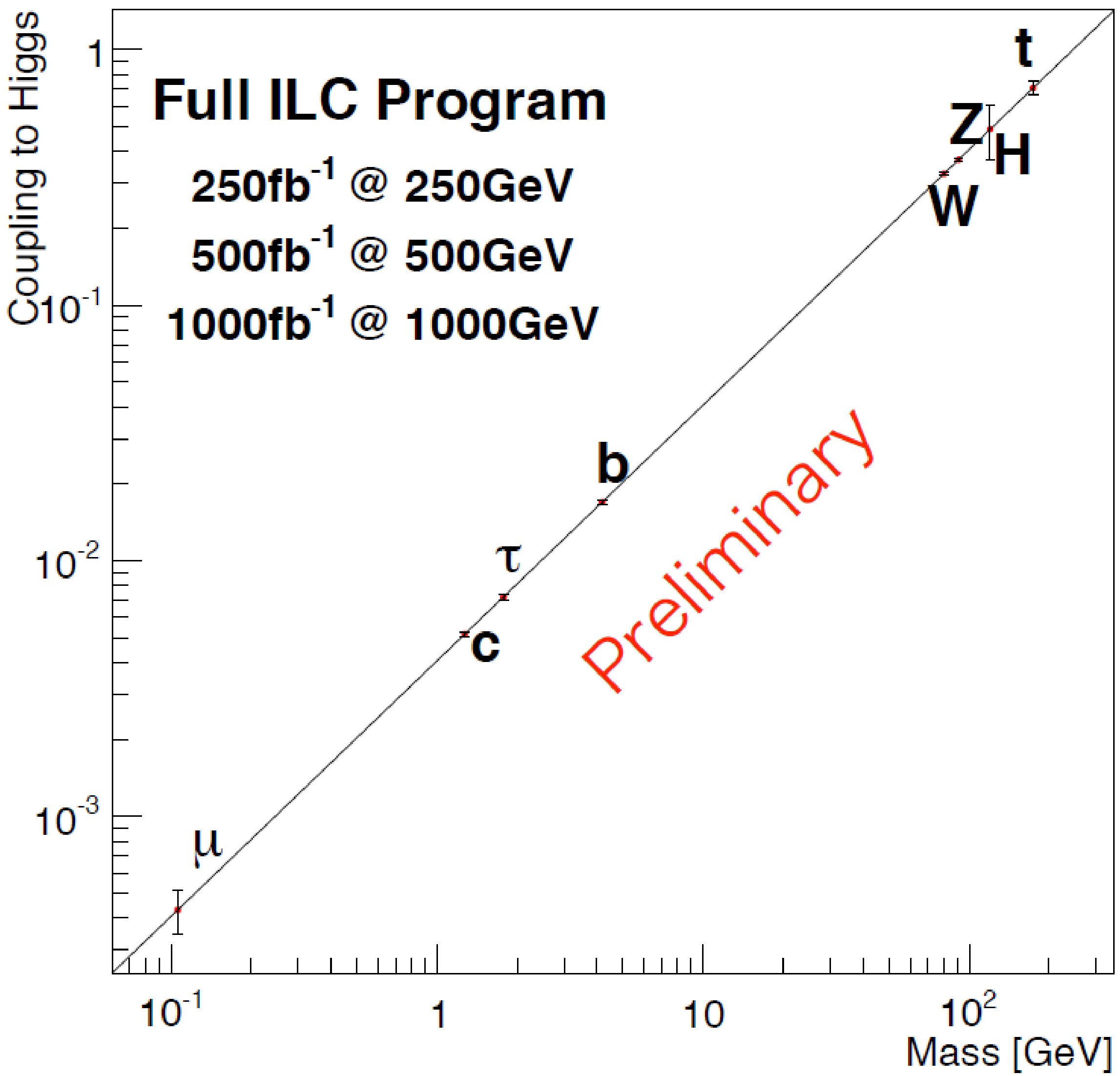
Followed by luminosity upgrade:

'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%		

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 extraction

33 input measurements

11-parameter fit

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

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

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

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

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	$\sim -2\%$	$\sim -2\%$	$\sim +1\%$

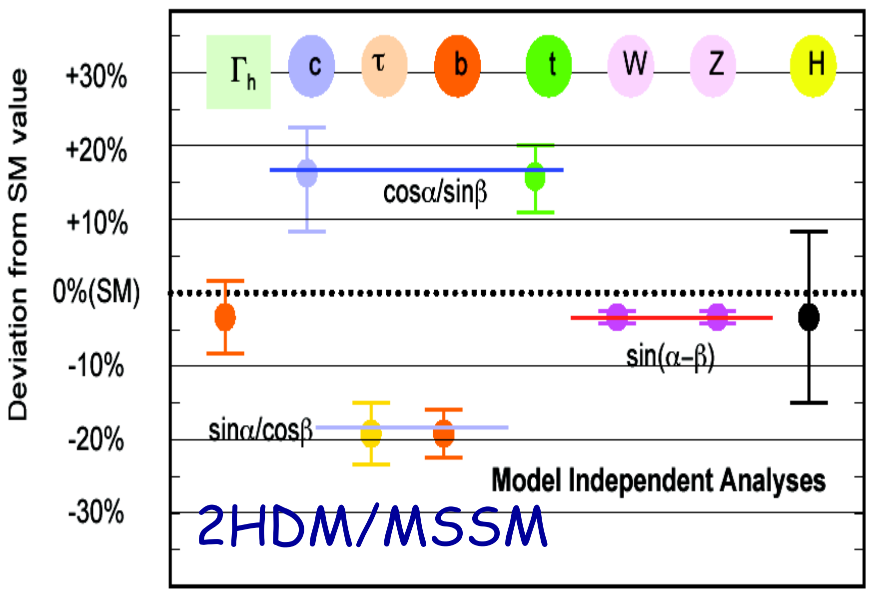
Deviations in the range 1% → 10%

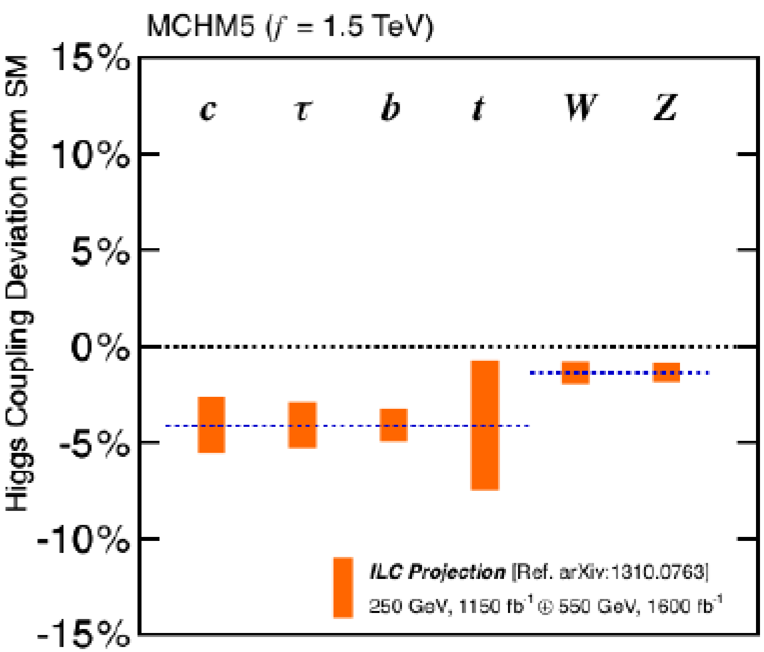
→ measurements must be significantly more precise to resolve such deviations

Specific beyond-SM examples

Composite Higgs

(MCHM5)





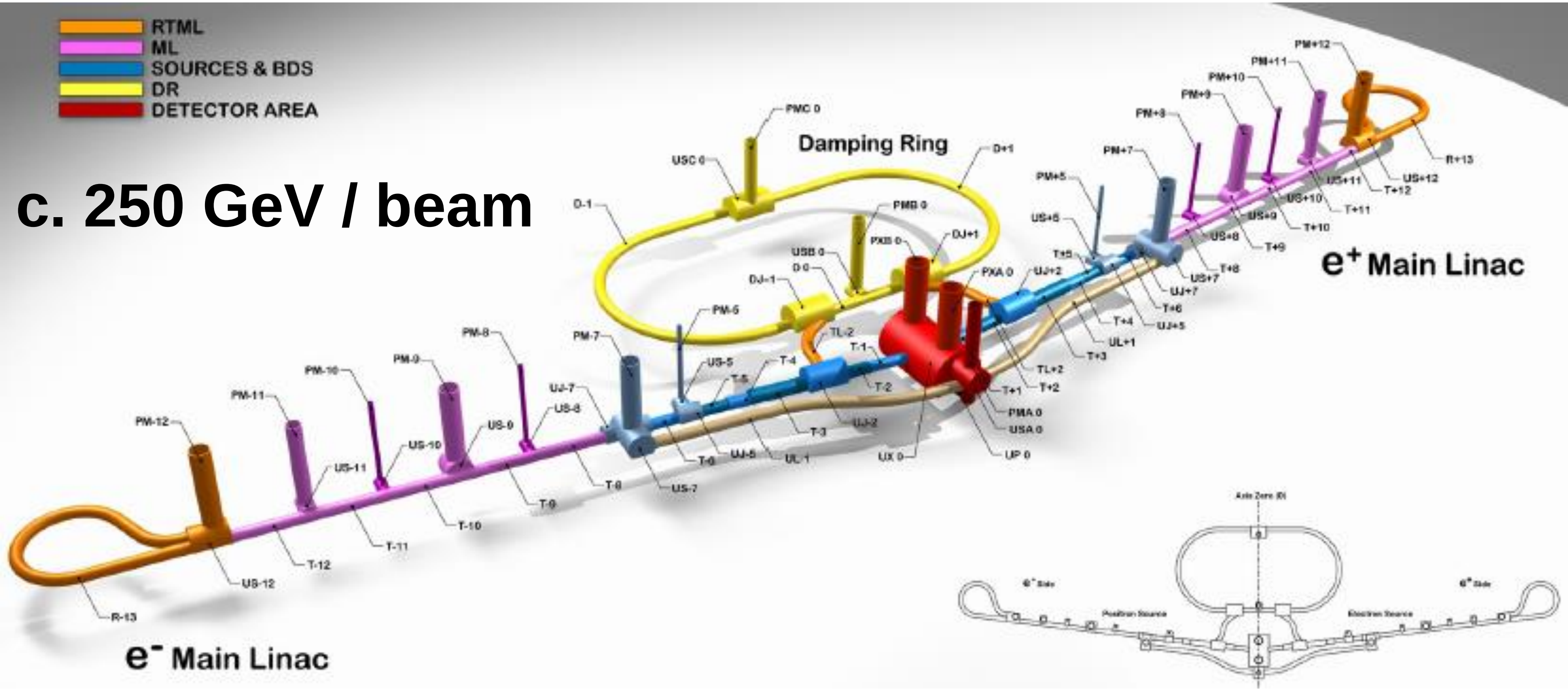
Zivkovic et al

Simulated ILC measurements

The accelerators

International Linear Collider (ILC)

c. 250 GeV / beam



31 km

Beam parameters

	ILC (500 GeV)	
Electrons/bunch	2	10**10
Bunches/train	1312	
Train repetition rate	5	Hz
Bunch separation	554	ns
Train length	730	us
Horizontal IP beam size	474	nm
Vertical IP beam size	6	nm
Longitudinal IP beam size	300	um
Luminosity	1.8	10**34

SCRF Linac Technology

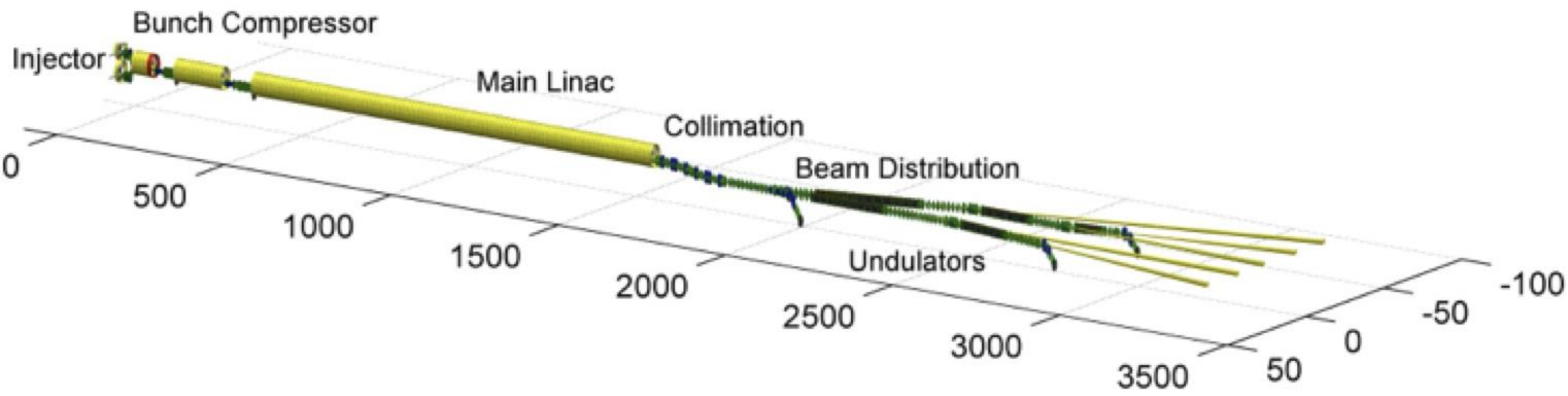
- **solid niobium**
- **standing wave**
- **9 cells**
- **operated at 2K (Lqd. He)**
- **35 MV/m**
- **$Q_0 \geq 10^{10}$**

1.3 GHz Nb 9-cell Cavities	16,024
Cryomodules	1,855
SC quadrupole package	673
10 MW MB Klystrons & modulators	436 / 471*

* site dependent

Approximately 20 years of R&D Worldwide → Mature technology

European XFEL @ DESY

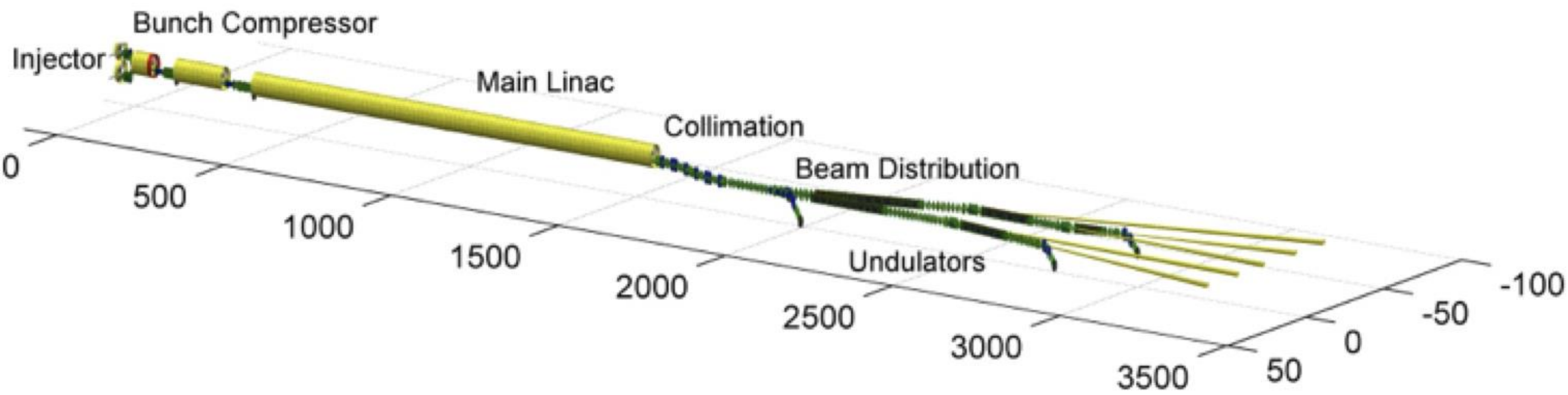


Largest deployment of SCRF technology

- **100 cryomodules**
- **800 cavities**
- **17.5 GeV**

The ultimate 'integrated systems test' for ILC. Commissioning with beam begins 2016

European XFEL @ DESY



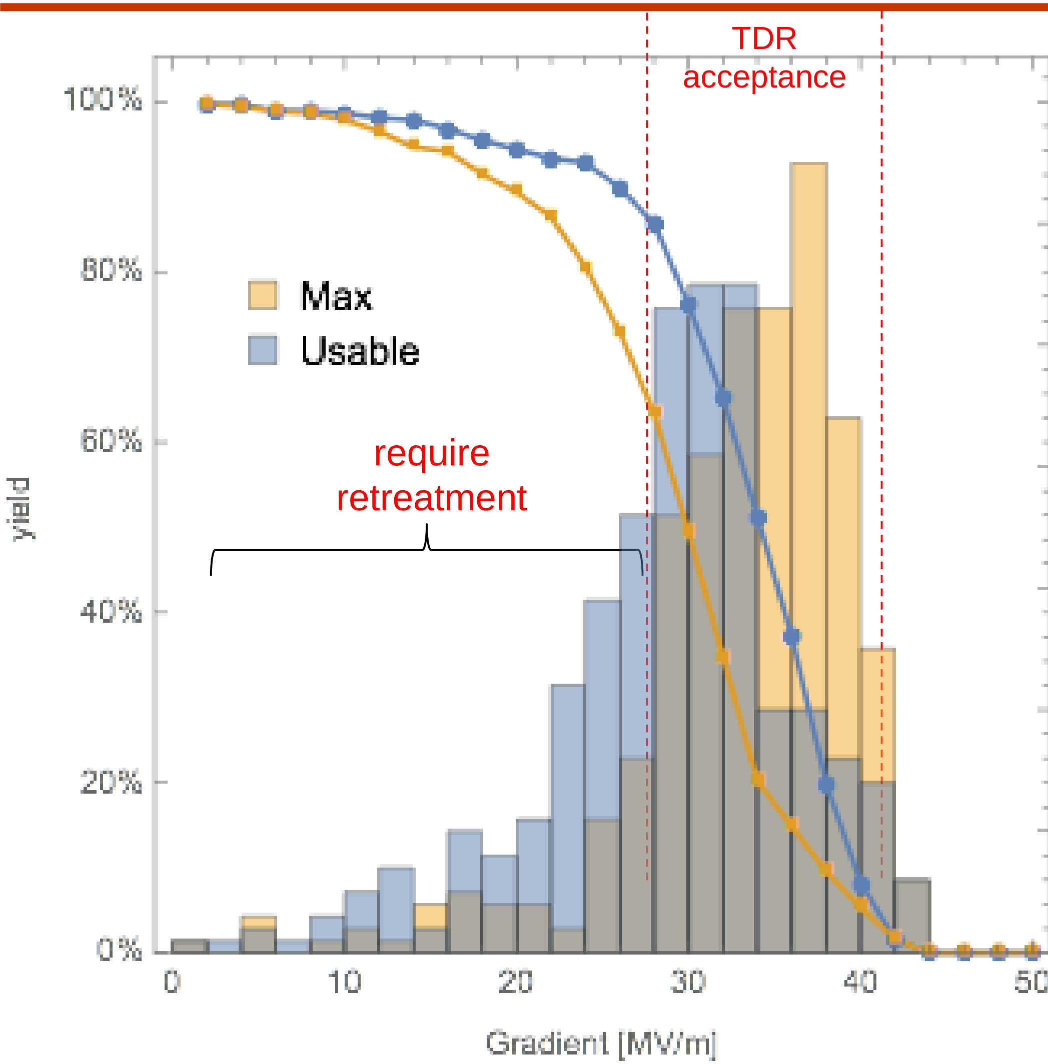
Similar technology for LCLS2 at SLAC


Largest deployment of SCRF technology

- **100 cryomodules**
- **800 cavities**
- **17.5 GeV**

The ultimate 'integrated systems test' for ILC. Commissioning with beam begins 2016

Industrial production - XFEL



quench limit

Maximum
Usable

Field emission
Limit (XFEL spec.)

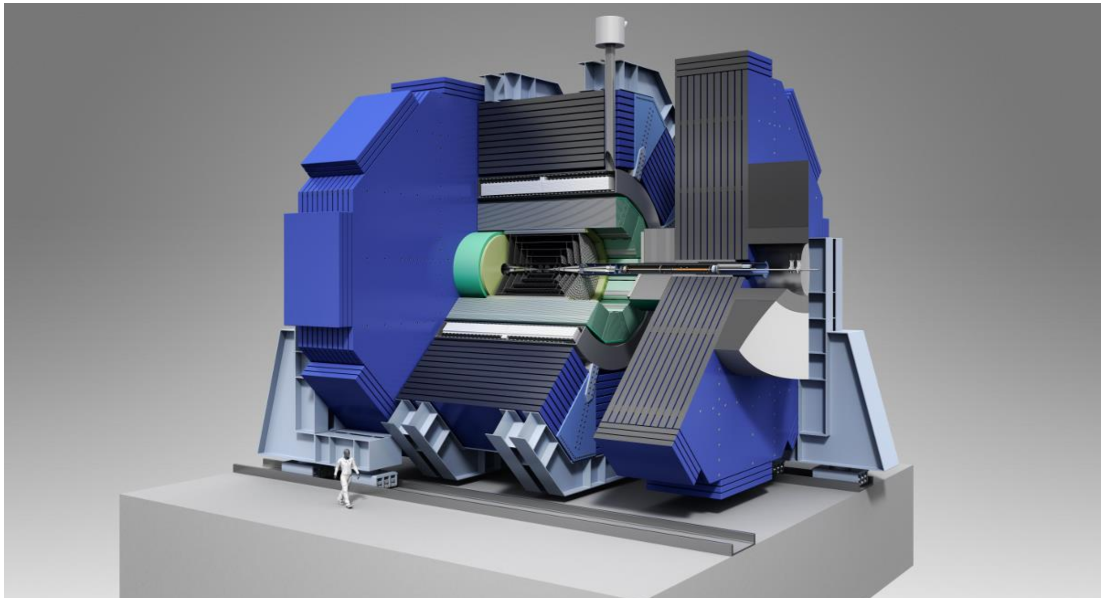
	Max	Usable
Number of tests	377	377
⟨G⟩ (MV/m)	33.	29.
G_{RMS} (MV/m)	6.6	7.4
Yield @ 28 MV/m	86%	63%
Yield @ 35 MV/m	44%	18%

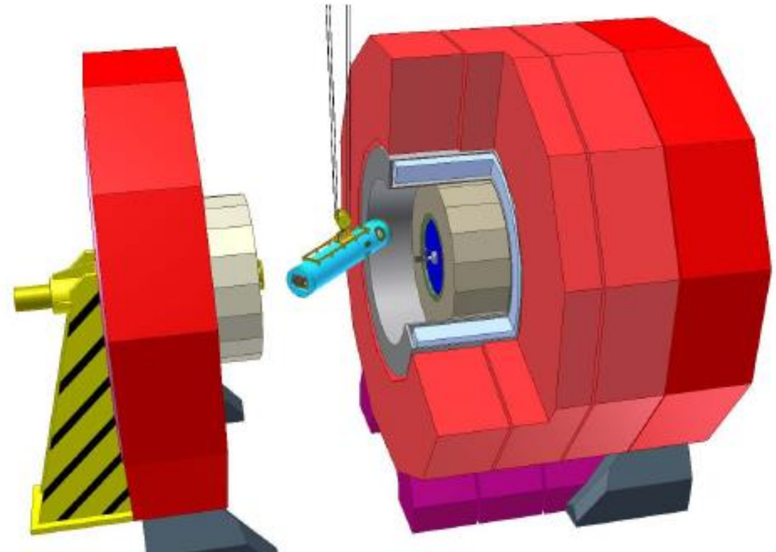
status:01.06.2016

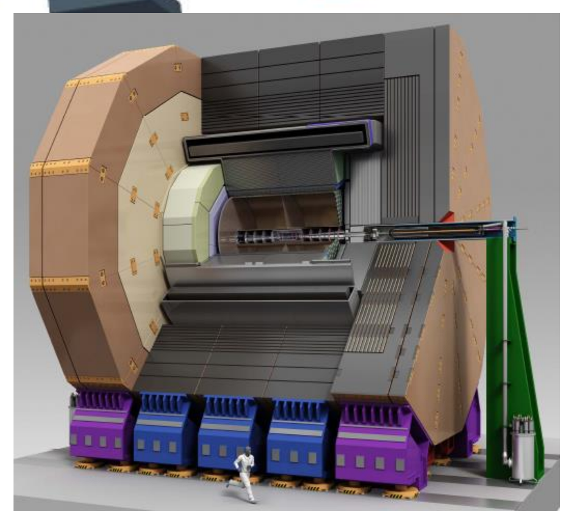
(Thanks to Nick Walker)

One vendor following ILC baseline recipe

ILC Detectors







ILC project status

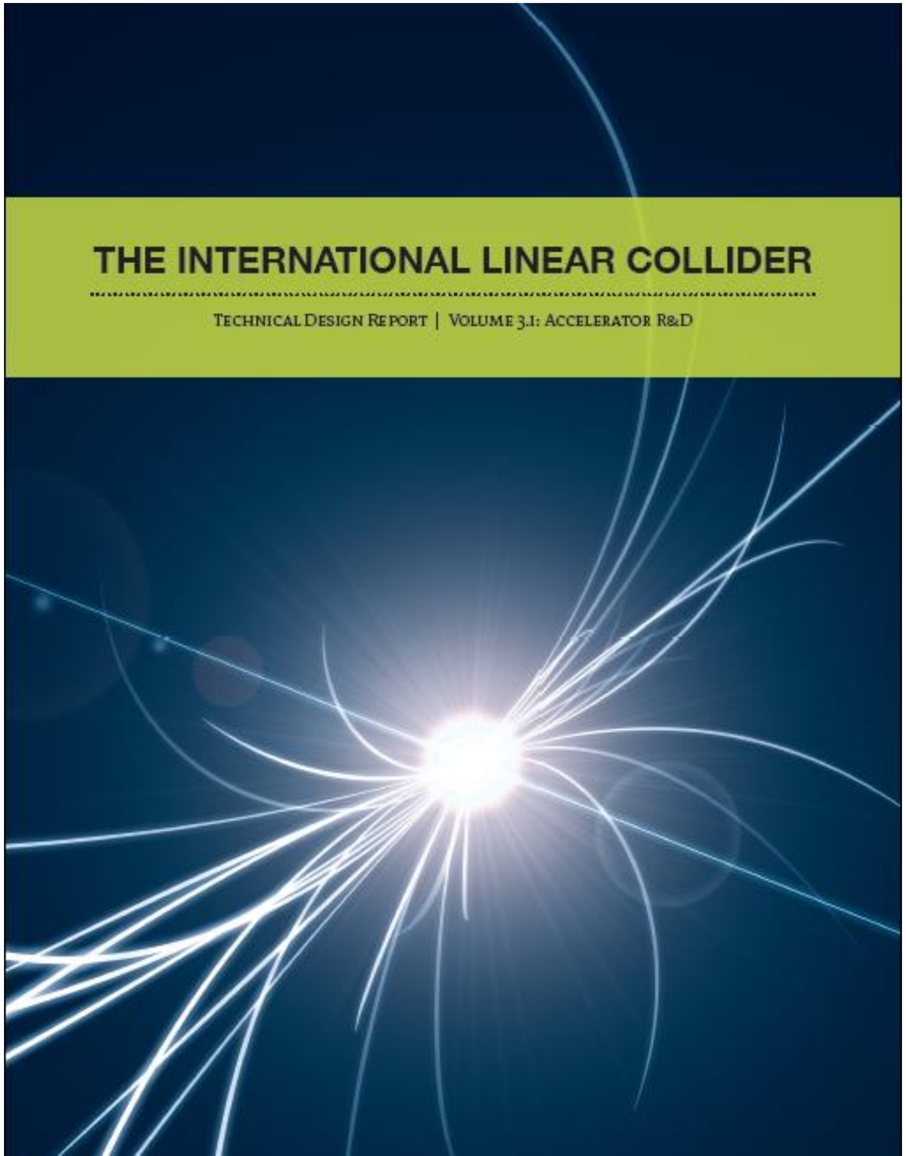
- 2005-12 ILC run by Global Design Effort (Barish)
- C. 500 accelerator scientists worldwide involved
- A Reference Design Report (RDR) was completed in 2007

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

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

  revised cost estimate + project implementation plan

ILC Technical Design Report



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

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

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

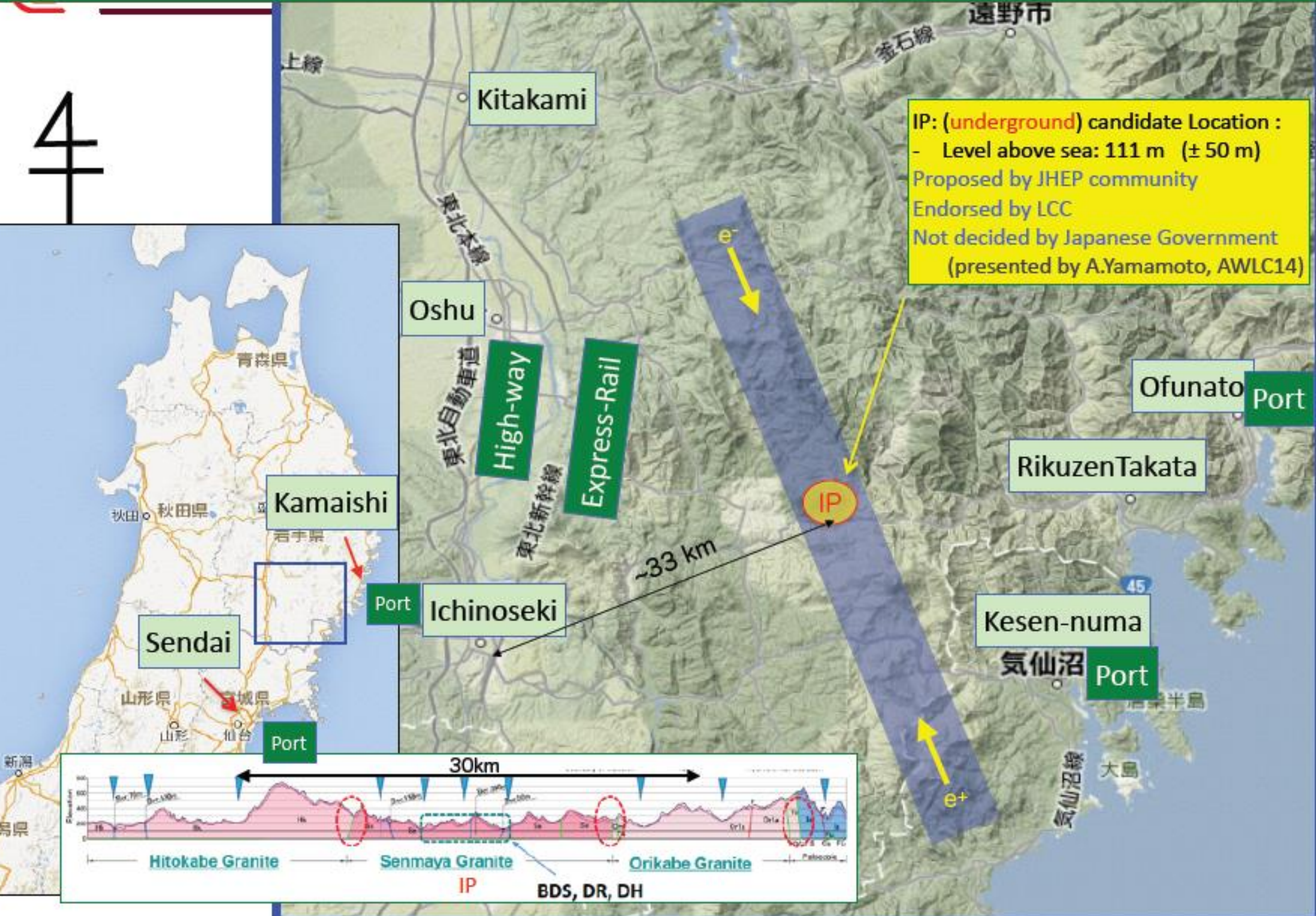
  Japan preparing implementation of ILC at Kitakami

Yamauchi

ILC Plan in Japan

- Japanese HEP community proposes to host ILC based on the “staging scenario” to the Japanese Government.
  - ILC starts as a 250GeV Higgs factory, and will evolve to a 500GeV machine.
  - Technical extendability to 1TeV is to be preserved.

ILC Candidate Location: Kitakami Area



Kitakami Site

Kitakami Site: Interaction Point

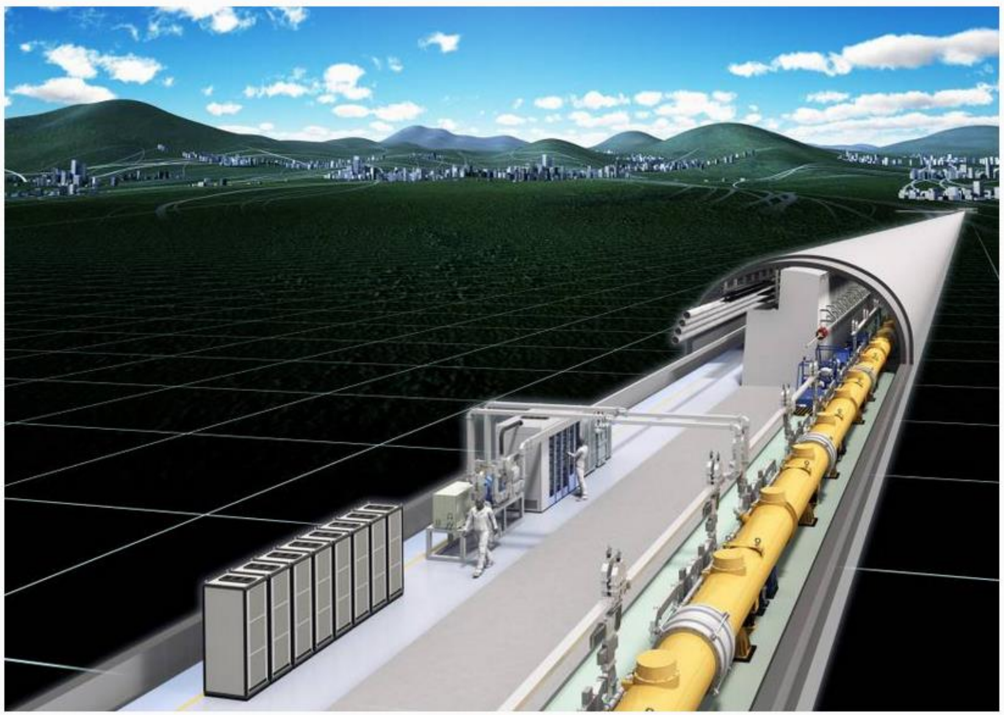
Kitakami Site: Interaction Point

National news

The Japan Times

NEWS

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



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

WHAT'S TRENDING NOW

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

Local enthusiasm

Local enthusiasm

Kitakami Site: road to port

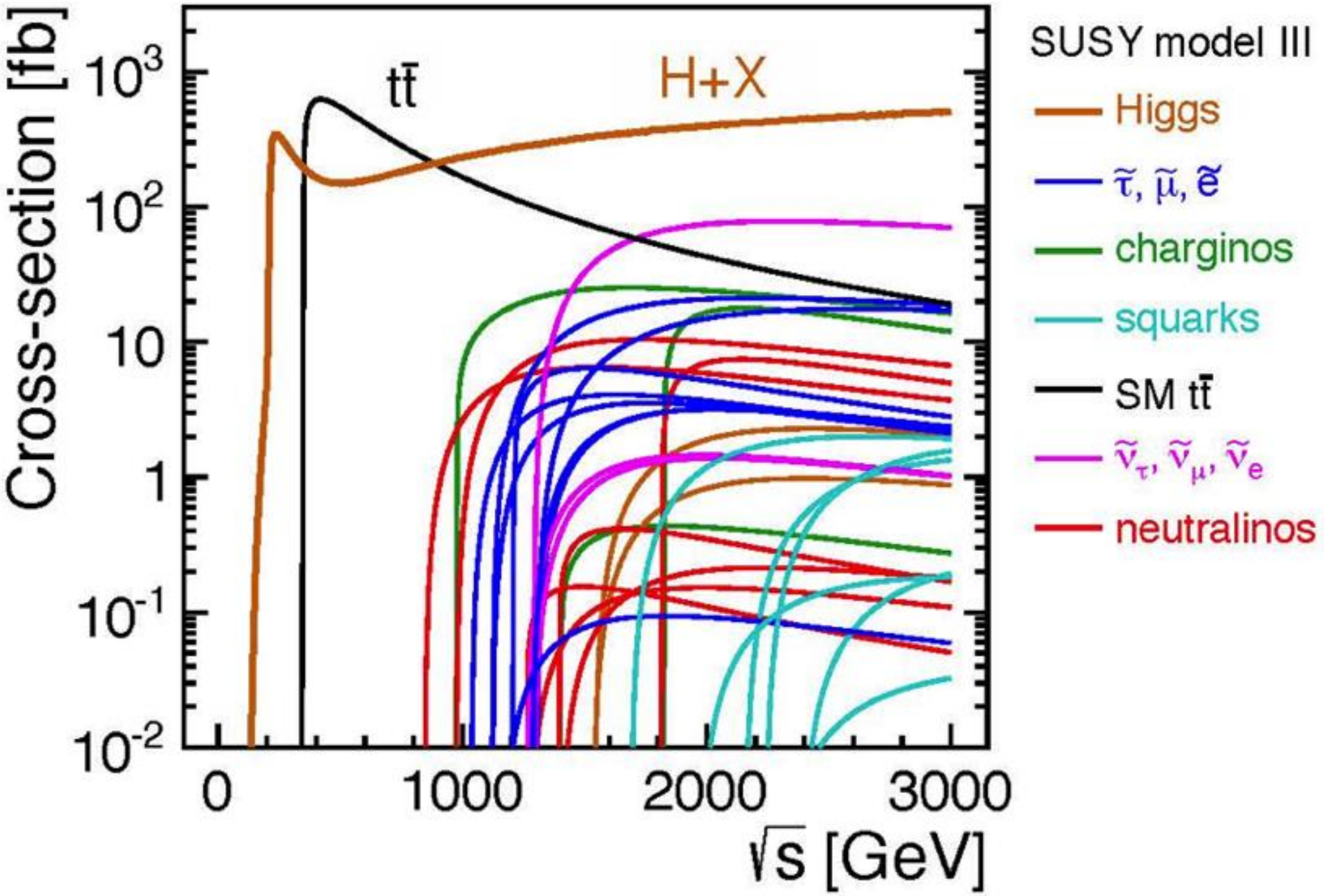
High-level politics

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

CLIC physics context

Energy-frontier capability for electron-positron collisions,

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



CLIC physics context

Energy-frontier capability for electron-positron collisions,

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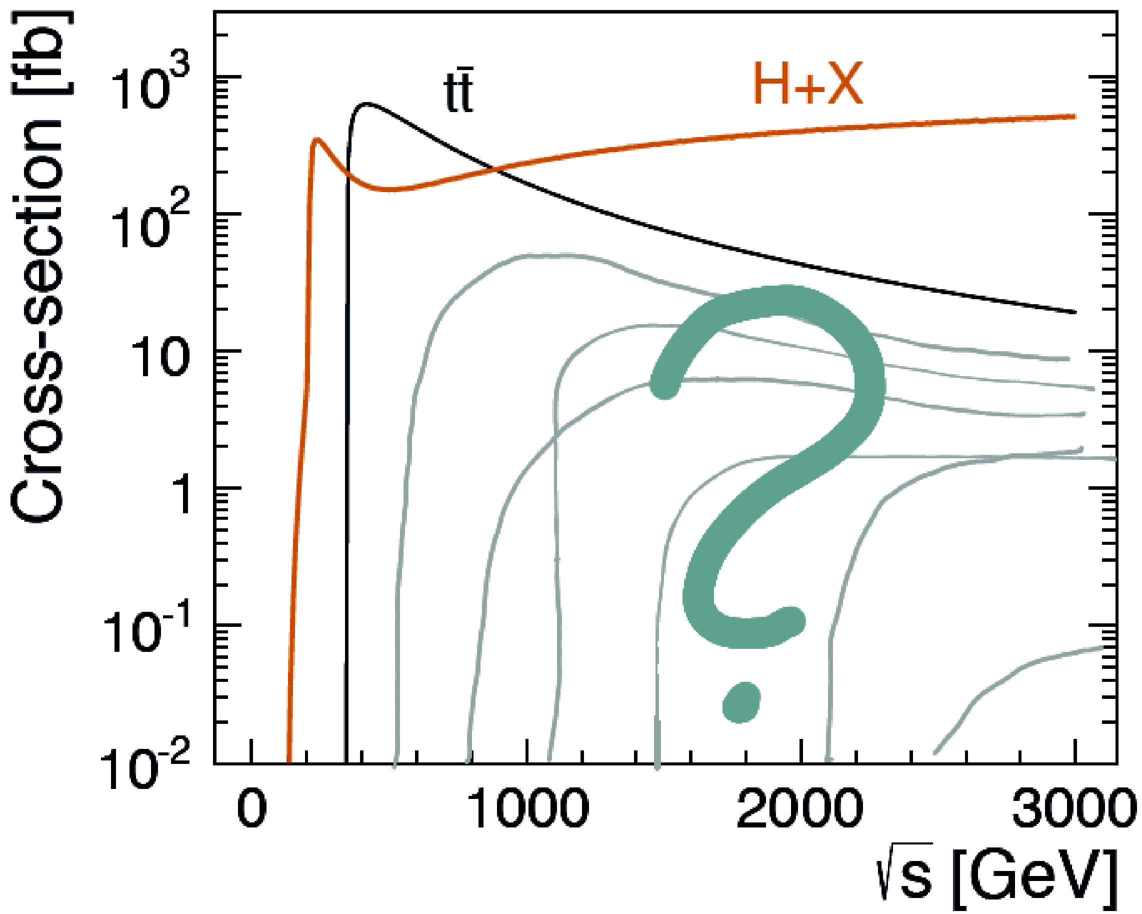
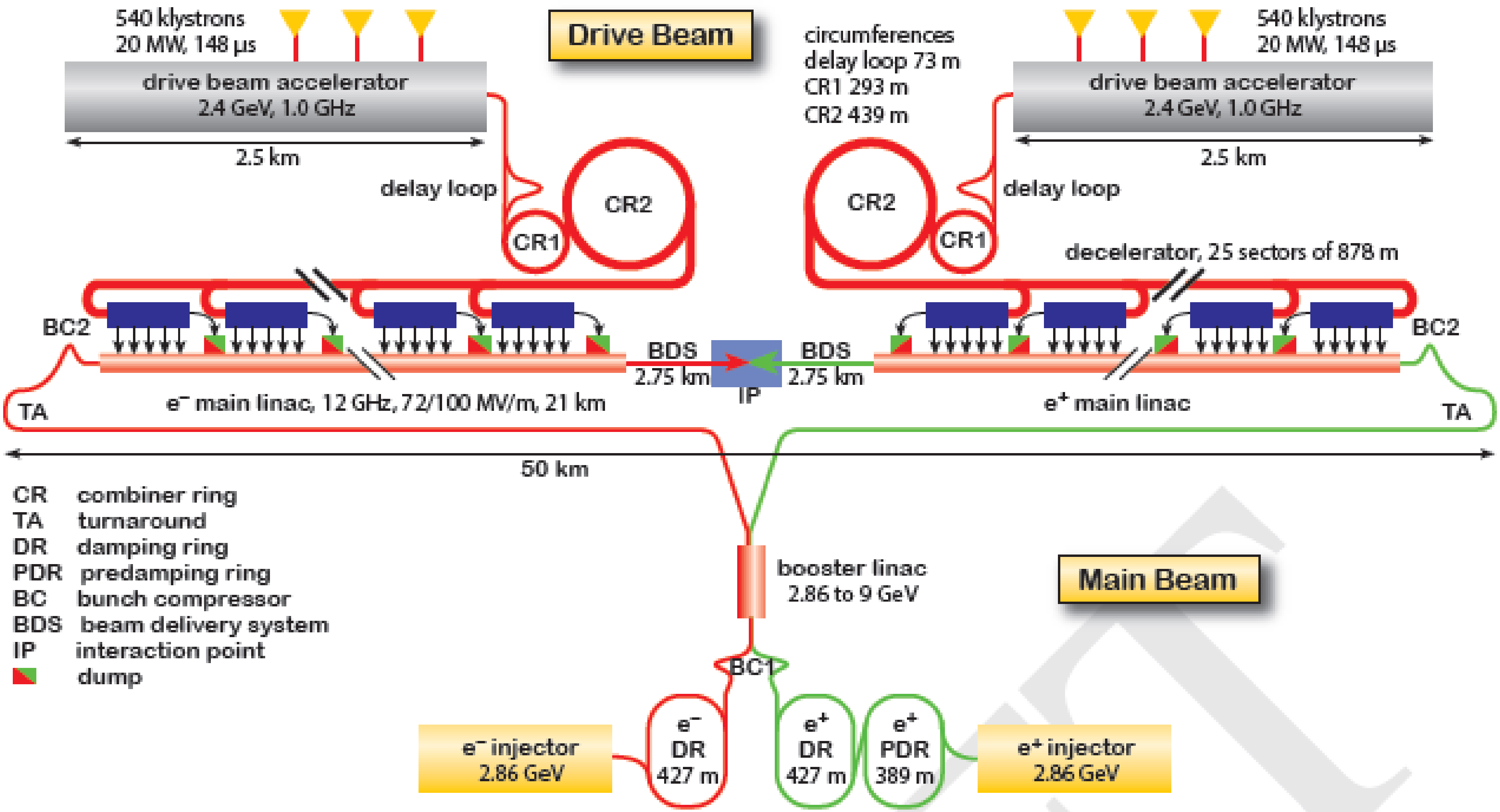


New CLIC layout 3 TeV



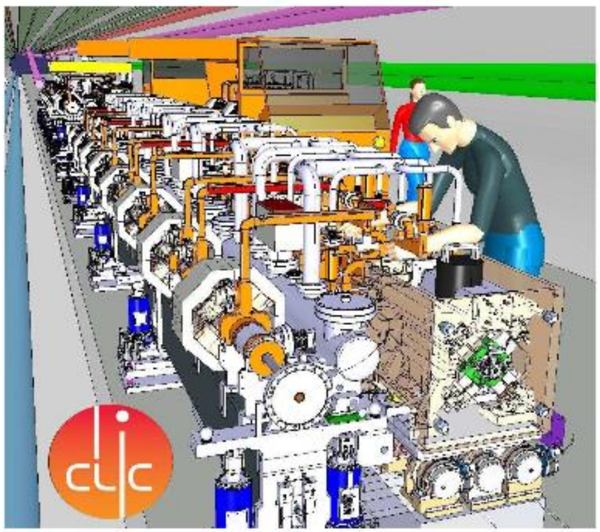
CLIC Collaborations

31 Countries – over 70 Institutes

CDR (2012)

SLAC-R-985
KEK Report 2012-
PSI-12-01
JAI-2012-001
CERN-2012-007
12 October 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



A MULTI-TEV LINEAR COLLIDER
BASED ON CLIC TECHNOLOGY

CLIC CONCEPTUAL DESIGN REPORT

GENEVA
2012

ANL-HEP-TR-12-01
CERN–2012–003
DESY 12-008
KEK Report 2011-7
14 February 2012

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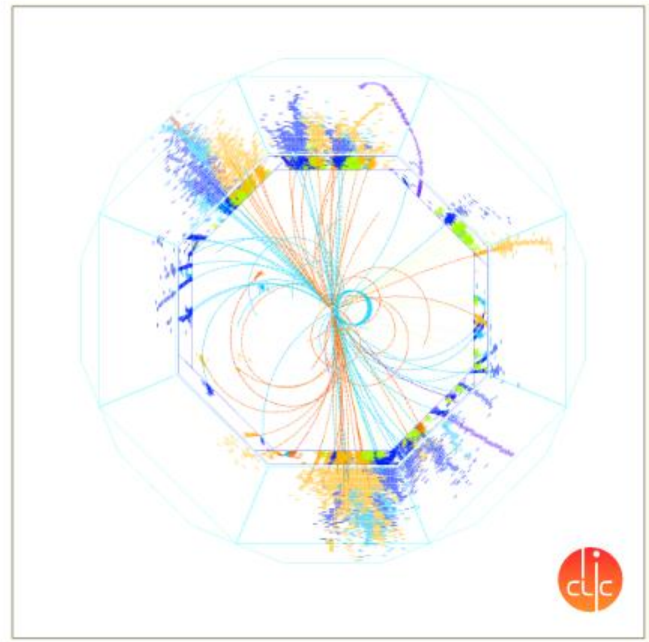
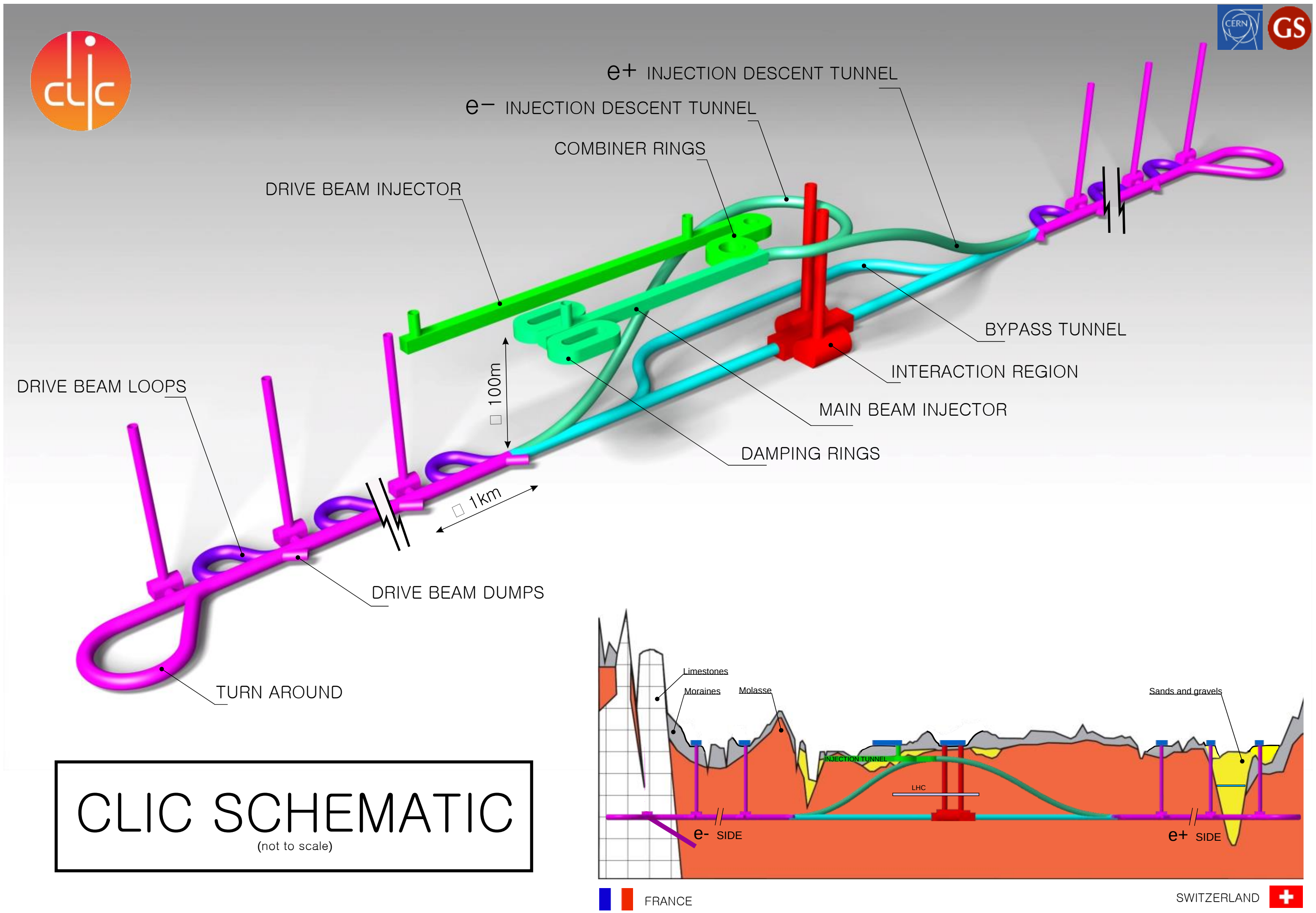


PHYSICS AND DETECTORS AT CLIC

CLIC CONCEPTUAL DESIGN REPORT

LINEAR COLLIDER COLLABORATION

CDR tunnel layout

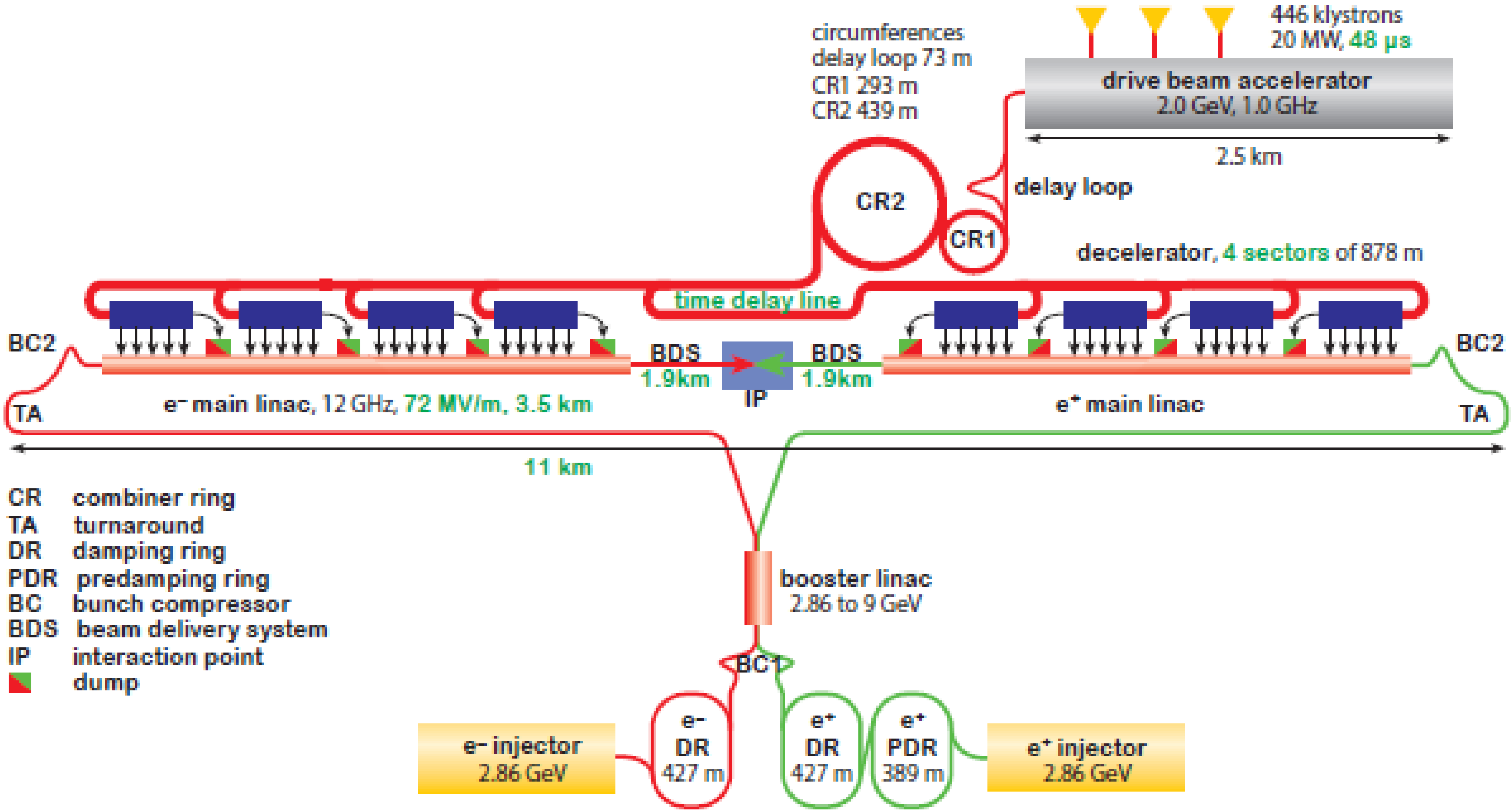


Rebaselining: first stage energy ~ 380 GeV

Parameter	Unit	380 GeV	3 TeV
Centre-of-mass energy	TeV	0.38	3
Total luminosity	$10^{34}cm^{-2}s^{-1}$	1.5	5.9
Luminosity above 99% of √s	$10^{34}cm^{-2}s^{-1}$	0.9	2.0
Repetition frequency	Hz	50	50
Number of bunches per train		352	312
Bunch separation	ns	0.5	0.5
Acceleration gradient	MV/m	72	100
Site length	km	11	50

LINEAR COLLIDER COLLABORATION

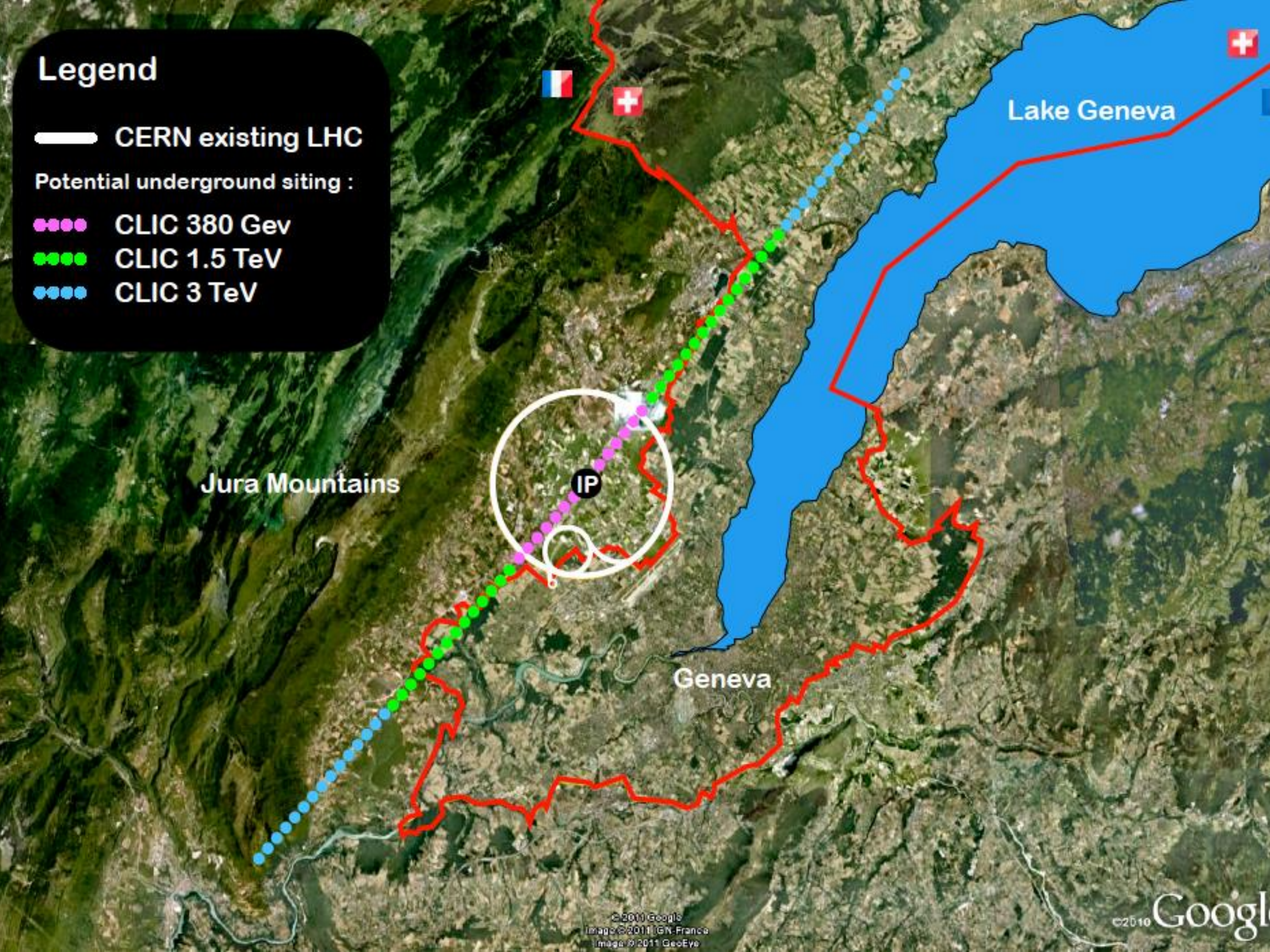
New CLIC layout 380 GeV



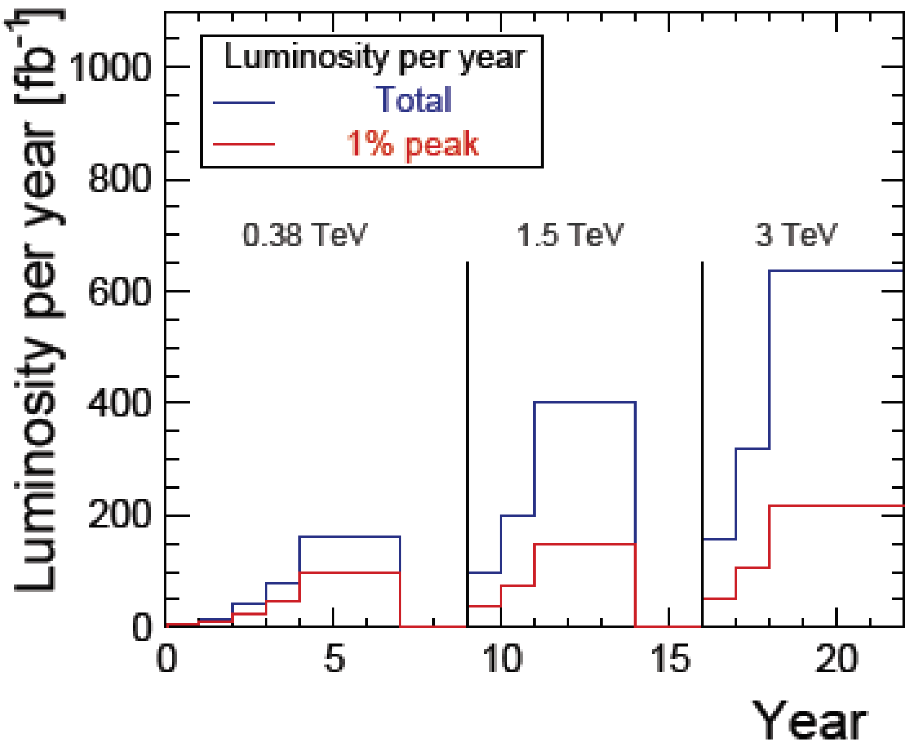
Current rebaselined parameters

Table 8: Parameters for the CLIC energy stages. The power consumptions for the 1.5 and 3 TeV stages are from the CDR; depending on the details of the upgrade they can change at the percent level.

Parameter	Symbol	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	$\sqrt{s}$	GeV	380	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		352	312	312
Bunch separation	Δt	ns	0.5	0.5	0.5
Pulse length	τ_{pulse}	ns	244	244	244
Accelerating gradient	G	MV/m	72	72/100	72/100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.5	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.9	1.4	2
Main tunnel length		km	11.4	29.0	50.1
Charge per bunch	N	10^9	5.2	3.7	3.7
Bunch length	σ_z	μm	70	44	44
IP beam size	σ_x/σ_y	nm	149/2.9	~ 60/1.5	~ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	950/30	—	—
Estimated power consumption	P_{wall}	MW	252	364	589


Legend
CERN existing LHC
Potential underground siting :
CLIC 380 Gev
CLIC 1.5 TeV
CLIC 3 TeV
Lake Geneva
Jura Mountains
IP
Geneva
©2011 Google
Image ©2011 IGN-France
Image ©2011 GeoEye
©2010 Google

Current CLIC run model



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

Rebaselining document

CERN–2016–XXX
XX XXXX 2016

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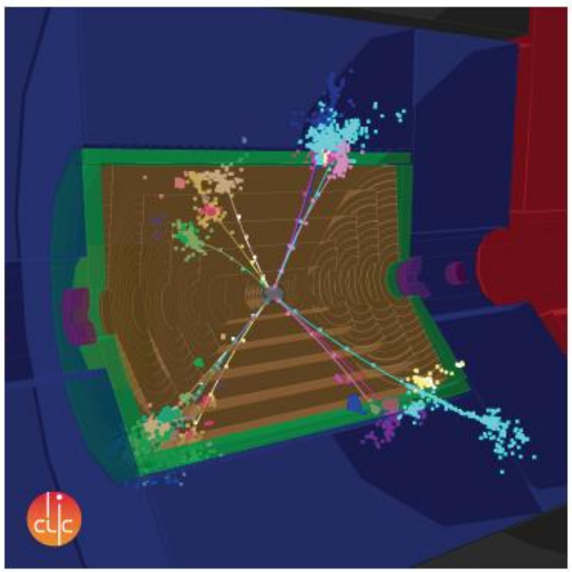


UPDATED BASELINE FOR A STAGED
COMPACT LINEAR COLLIDER

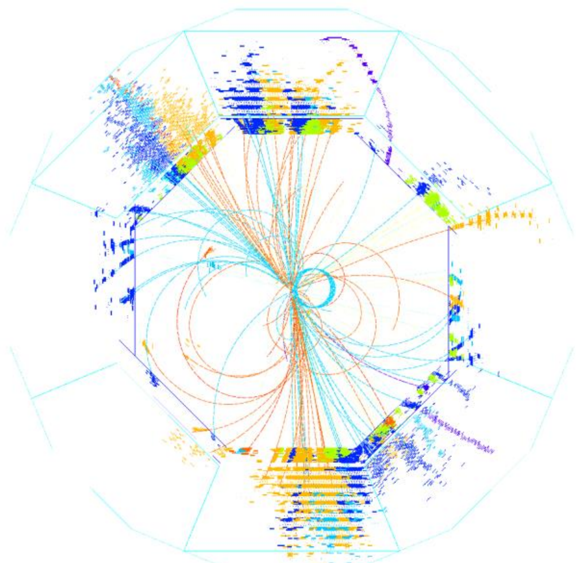
The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear e^+e^- collider under development. For an optimal exploitation of its physics potential, CLIC is foreseen to be built and operated in a staged approach with three centre-of-mass energy stages ranging from a few hundred GeV up to 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.

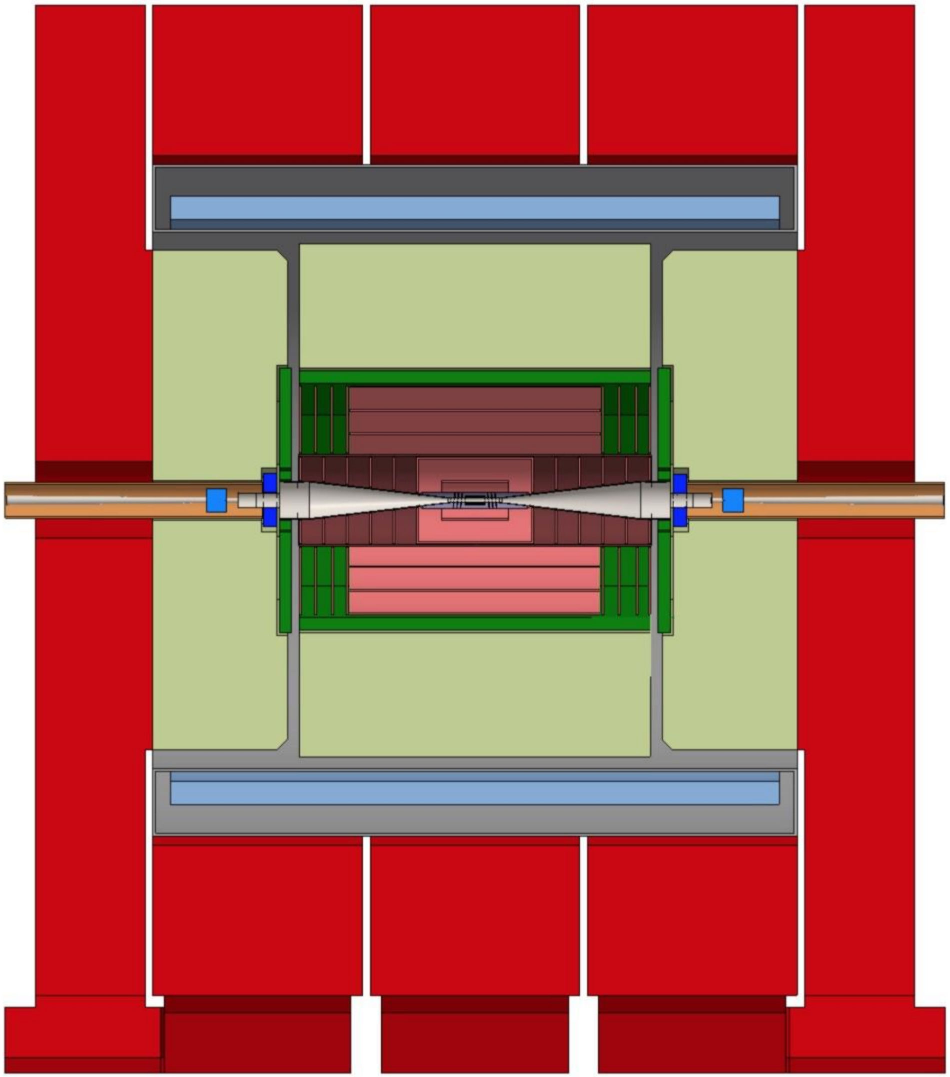
‘yellow report’ in preparation

CLIC detector concept

ILC concepts adapted to a single detector for CLIC:

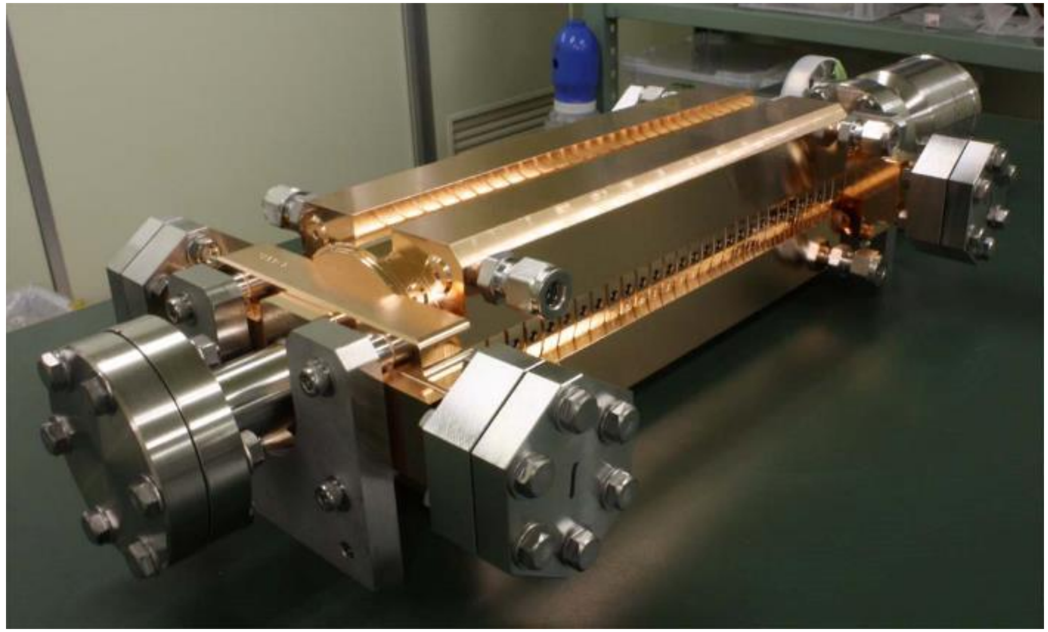
- **Highly-granular, deep calorimeter**
- **4T solenoid**
- **Low-mass Si tracking system**
- **Precision vertexing close to IP**
- **10ns time-stamping**





CLIC accelerating structure

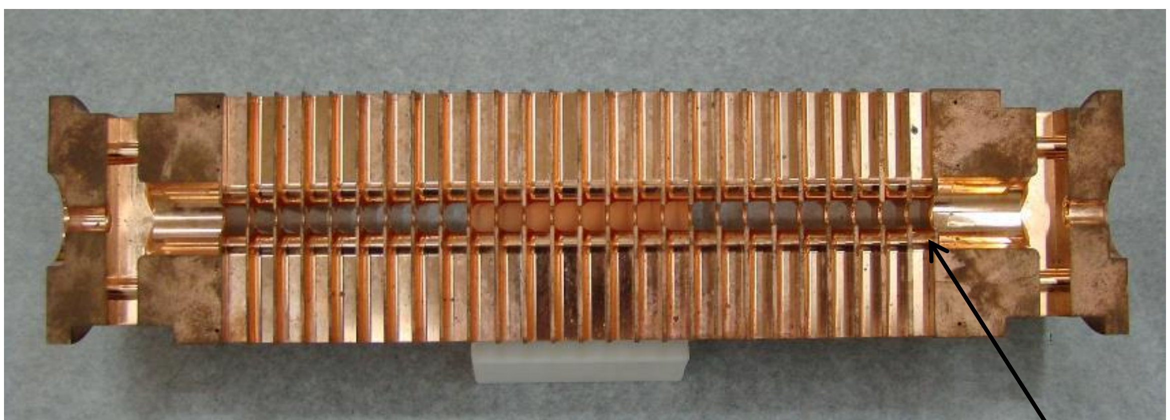
Outside



11.994 GHz X-band
100 MV/m
Input power ≈50 MW
Pulse length ≈200 ns
Repetition rate 50 Hz

HOM damping waveguide

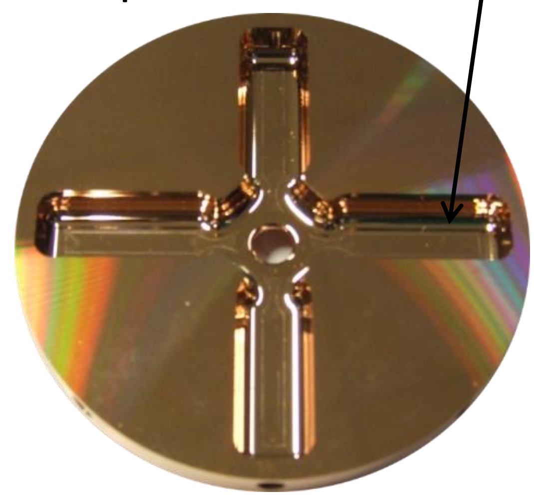
Inside



25 cm

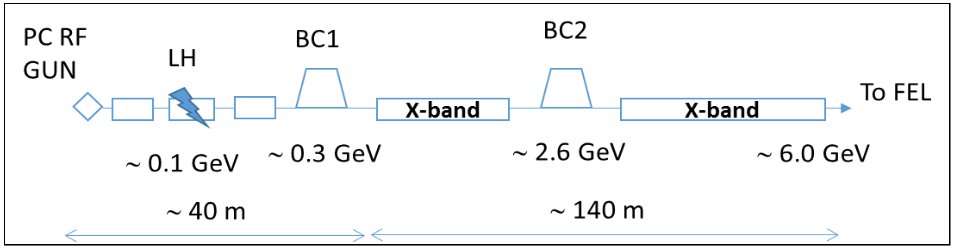
6 mm diameter beam aperture

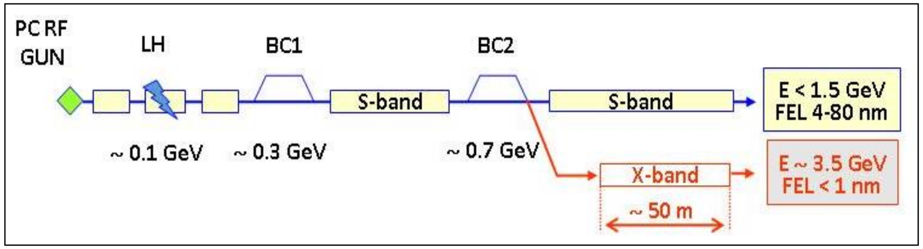
Micron–precision disk




drive beam
main beam
Recently installed 2-beam acceleration module in CTF3
(according to latest CLIC design)

Possible X-band FELs





- X-band technology appears interesting for compact, relatively low cost FELs – new or extensions
  - Logical step after S-band and C-band
  - Example similar to SwissFEL: E=6 GeV, Ne=0.25 nC, σ_z=8μm
- Use of X-band in other projects will support industrialisation
  - They will be klystron-based, additional synergy with klystron-based first energy stage
- Collaborating on use of X-band in FELs
  - Australian Light Source, Turkish Accelerator Centre, Elettra, SINAP, Cockcroft Institute, TU Athens, U. Oslo, Uppsala University, CERN
- Share common work between partners
  - Cost model and optimisation
  - Beam dynamics, e.g. beam-based alignment
  - Accelerator systems, e.g. alignment, instrumentation…
- Define common standard solutions
  - Common RF component design, -> industry standard
  - High repetition rate klystrons (200->400 Hz now into test-stands)

Important collaboration for X-band technology

LINEAR COLLIDER COLLABORATION

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

The Future?

The Future

- **YOU are the future!**
- **There is a powerful physics case for an e+e- linear collider to explore the known Higgs and top-quark sectors … and search for new physics, directly and indirectly, at the energy frontier**
- **ILC technology is mature, industrialised, and the project is ready for a construction start – awaiting a decision by Japanese Government**
- **CLIC is promising technology to provide direct reach for new physics up to multi-TeV energy scales**
- **Energy-staged CLIC design to be presented to European PP Strategy update in 2019/20**
- **We hope that future results from 13 TeV LHC will guide us …**