Future high energy colliders

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- LHC, today and prospects(25→300→3000 fb^{-1})
- Physics motivation for Higgs factories (e+e-(LC,ring), $\gamma\gamma$, μ+μ-)
- Linear colliders: ILC, CLIC
- Circular colliders:
  - FCC-ee,FCC-hh - CERN
  - CEPC, SppC - China
  - Muon colliders (briefly)
- Conclusion

Here:
FCC (ee, hh) – Future Circular Collider
CEPC – Circular Electron Positron Collider
SppC – Super proton proton Collider

In July 2012 two detectors ATLAS and CMS working at LHC have discovered the particle with the mass M~125 GeV with properties very similar to the predicted Higgs boson

and (still) nothing else … What to do?

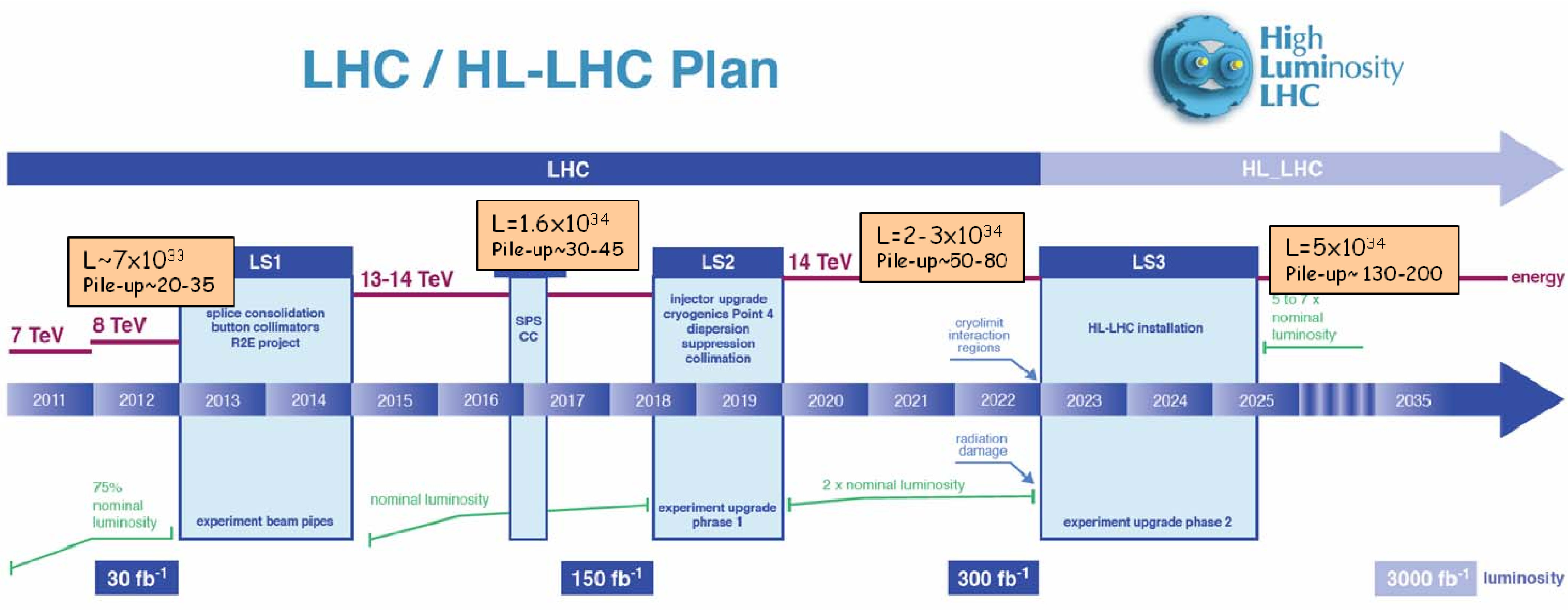
The LHC is a Higgs Factory !
1M Higgs already produced – more than any other Higgs factory projects.

15 Higgs bosons/minute – and more to come (gain factor 3 going to 13 TeV)

For nominal LHC	300 fb-1	20 M Higgs bosons
HL-LHC	3000 fb-1	200 M

LHC plans

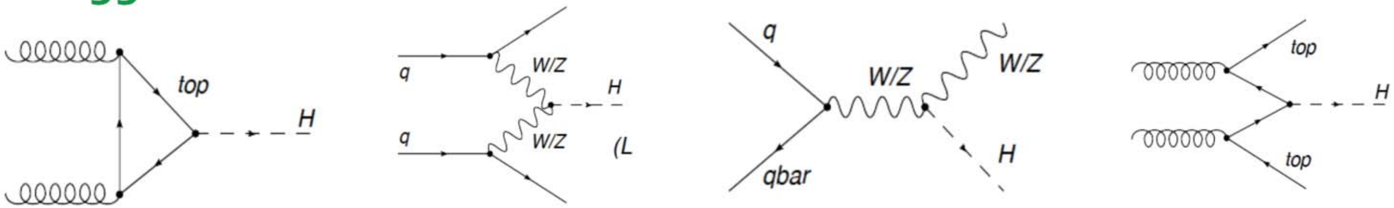
L.Rossi



Situation in 2022 and with lum. upgrade (2035)

The approved LHC programme will be completed

- With 300 fb^{-1} @ 13 TeV, CMS and ATLAS will measure five production modes
  - $gg \to H$ VBF WH, ZH ttH



  - ... and six decay modes : $\gamma\gamma$, ZZ, WW, $\tau\tau$, bb, $\mu\mu$

Approved LHC 300 fb^{-1} at 14 TeV:

- Higgs mass at 100 MeV
- Disentangle Spin 0 vs Spin 2 and main CP component in ZZ*
- Coupling rel. precision/Exper.
  - Z, W, b, τ 10-15%
  - t, μ 3-2 σ observation
  - $\gamma\gamma$ and gg 5-11%

HL-LHC 3000 fb^{-1} at 14 TeV:

Higgs mass at 50 MeV

More precise studies of Higgs CP sector

Couplings rel. precision/Exper.

- Z, W, b, τ, t, μ 2-10%
- $\gamma\gamma$ and gg 2-5%
- H→HH >3 σ observation (2 Exper.)

LHC can't measure Br(cc, invisible) and Γ_{tot}.

Precision needed after LHC

- **New physics affects the Higgs couplings**
  - **SUSY** $\frac{g_{hbb}}{g_{h_{\mathrm{SM}}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\mathrm{SM}}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$ **, for tanβ = 5**
  - **Composite Higgs** $\frac{g_{hff}}{g_{h_{\mathrm{SM}}ff}} \simeq \frac{g_{hVV}}{g_{h_{\mathrm{SM}}VV}} \simeq 1 - 3\% \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$
  - **Top partners** $\frac{g_{hgg}}{g_{h_{\mathrm{SM}}gg}} \simeq 1 + 2.9\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2, \quad \frac{g_{h\gamma\gamma}}{g_{h_{\mathrm{SM}}\gamma\gamma}} \simeq 1 - 0.8\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$
  - **Other models may give up to 5% deviations with respect to the Standard Model**

For observation (and some study) of new physics beyond standard Higgs one need precision better than 1%!

Colliders for precision Higgs study

e+e- linear colldiders

e+e- circular colliders

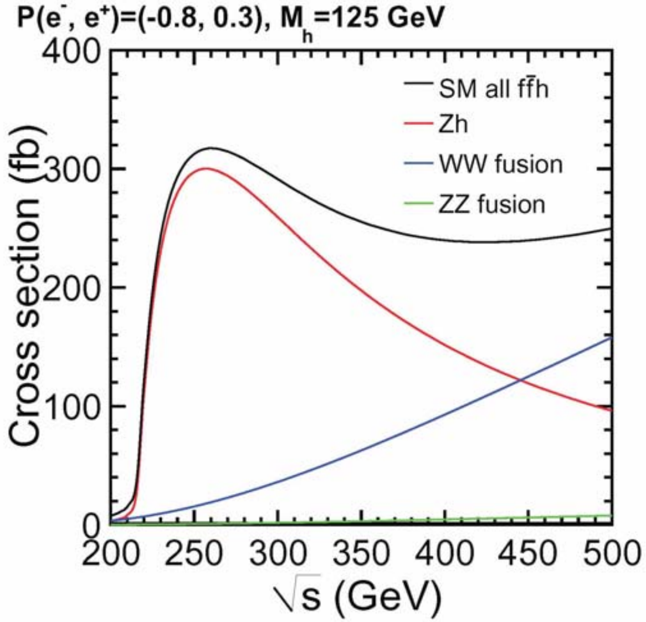
Photon colliders

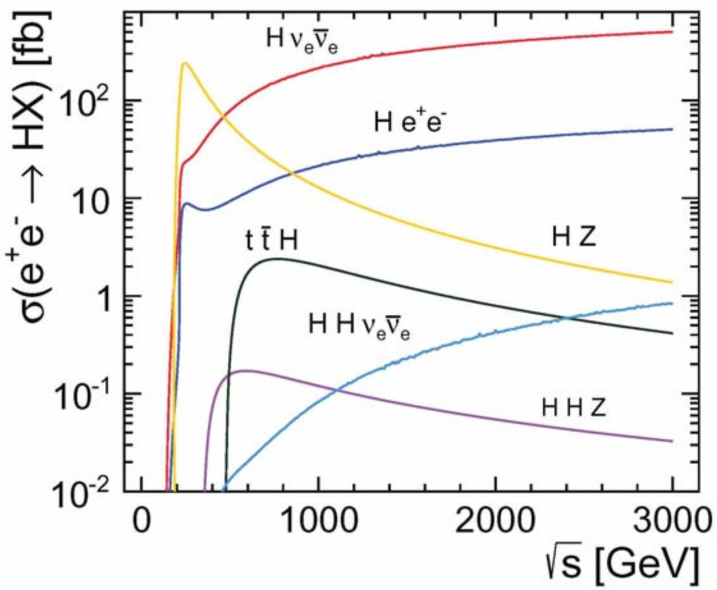
Muon collders

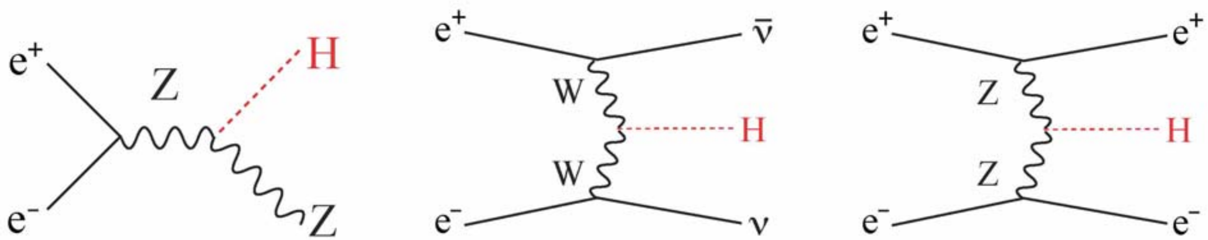
Higgs factory colliders (discussed at HF2012)

- Linear e+e- collider:
  - ILC
  - CLIC
  - X-band klystron based
- Circular e+e- collider:
  - LEP3
  - TLEP
  - SuperTRISTAN
  - Fermilab site-filler
  - China Higgs Factory (CHF)
  - SLAC/LBNL big ring
- Muon collider
  - Low luminosity
  - High luminosity
- $\gamma\gamma$ collider:
  - ILC-based
  - CLIC-based
  - Recircul. linac-based SAPPHiRE + HERA, Tevatron rings
  - SLC-type

Higgs physics in e+e- collisions







Tagging Z in e+e-→ZH one can measure all Br(H), even invisible decays width.
One can measure the Higgs total width:

$\Gamma(H) \sim \sigma(e^+e^- \to ZH)/Br(H \to ZZ)$ and $\Gamma(H) \sim \sigma(WW \to H)/Br(H \to WW)$

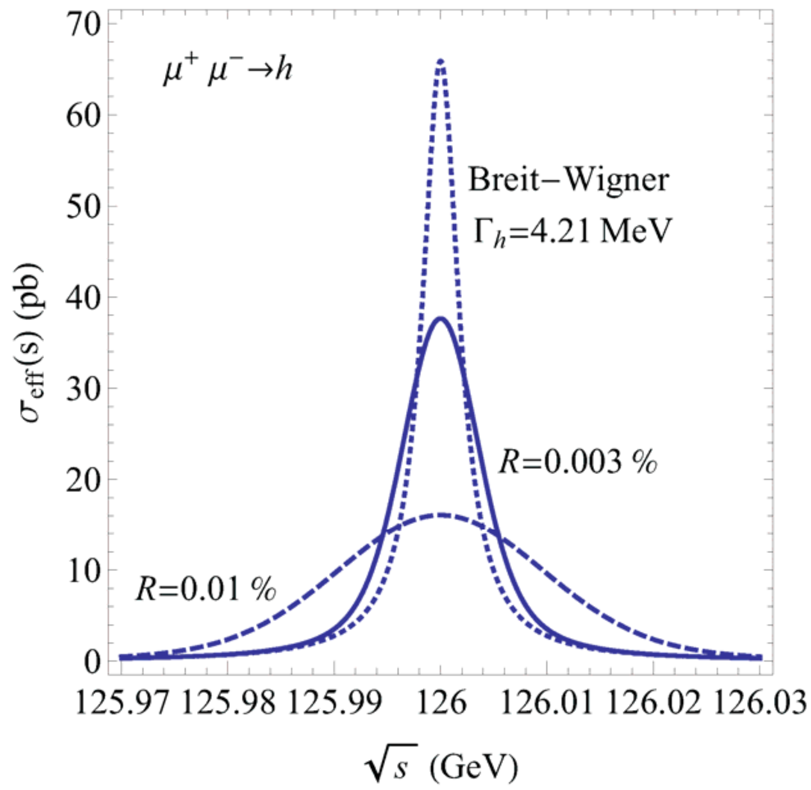
At linear colliders $L \sim 10^{34}$, $N_H \sim 20000$/year or 10^5 for life of the experiment;
At circular collider with C~100 km and several IP one can have $N_H \sim 10^6$.

Higgs physics at muon collider

Resonance H production:

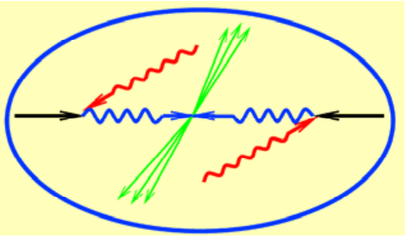
$\sigma(\mu^+\mu^- \to \mathrm{H}) \approx 40000\ \sigma(e^+e^- \to \mathrm{H}) \approx 70$ pb

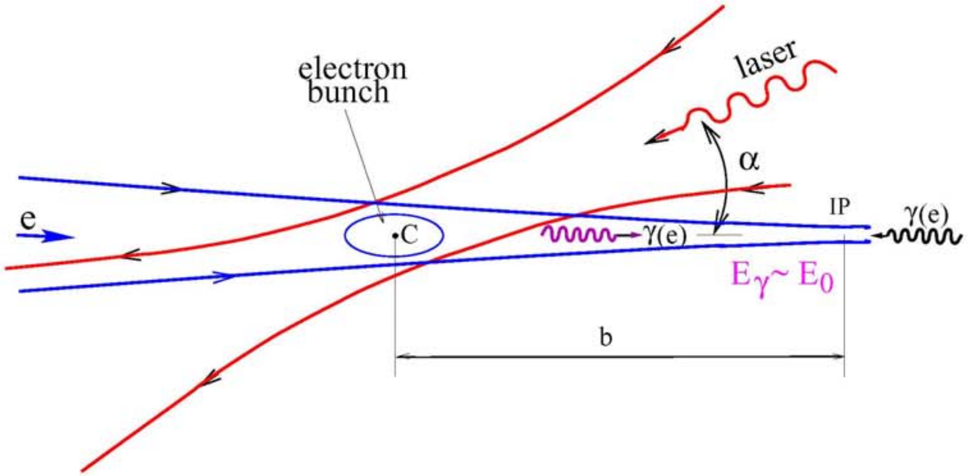
- The Higgs width is about 4 MeV, the muon collider with $\delta E/E$=0.003% can measure the Higgs width directly with an accuracy 5% (comparable that in e+e-).
- The Higgs mass can be measured with an accuracy 0.1 MeV, 100 times better than in e+e-.
- Coupling $\mathrm{H} \to \mu^+\mu^+$ can be measured with 1.5% accuracy.

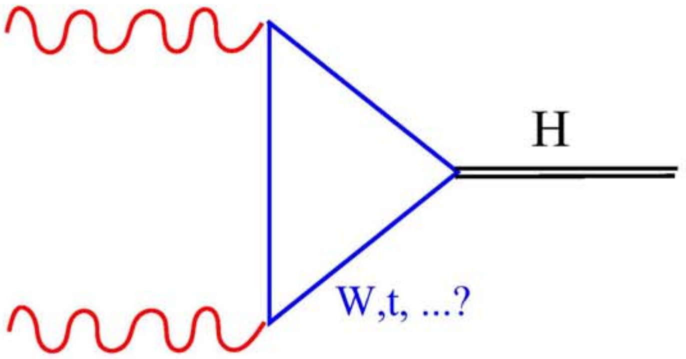


The number of Higgs boson is about 2500/year at expected L~10^{31} (small L due to transverse-longitudinal emittance exchange for obtaining a high monochromaticity).

Higgs study at photon colliders ($\gamma\gamma$, γe)







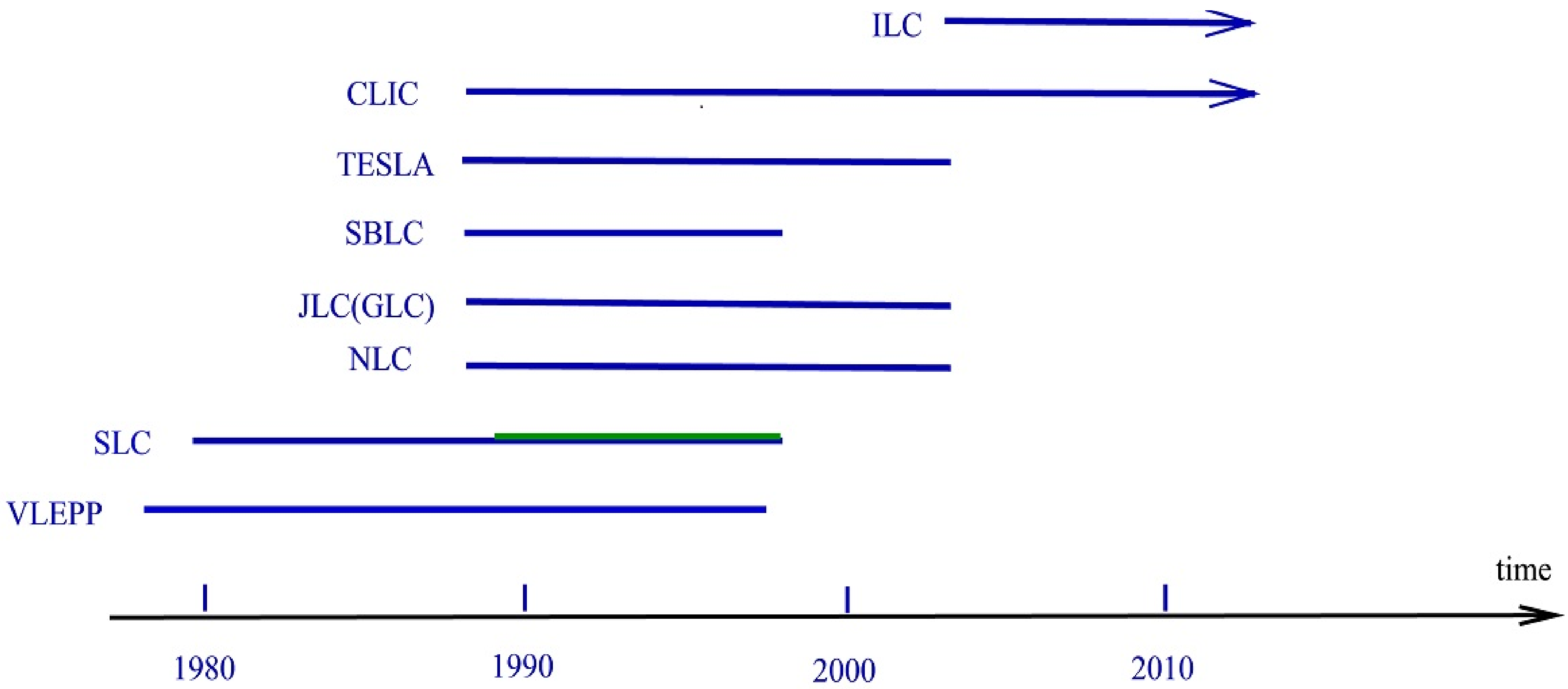
$\Gamma_{\gamma\gamma}$ is determited by contributions of all charge particles (even with $M>2E_0$), therefore this process is most sensitive to new physics!

In $\gamma\gamma$ collisions the $\Gamma(H\to\gamma\gamma)$ width can be measured with statistics ≈ 90 times higher than in e+e- collisions. This is the most important argument for the photon collider .

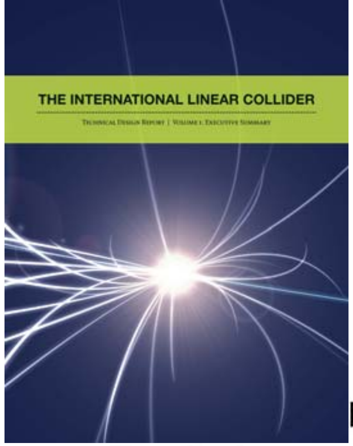
However, e+e- beams are much better for Higgs study (due to Z tagging). Therefore PLC has sense only in combination with e+e-: parallel work or second stage.

Linear colliders

History

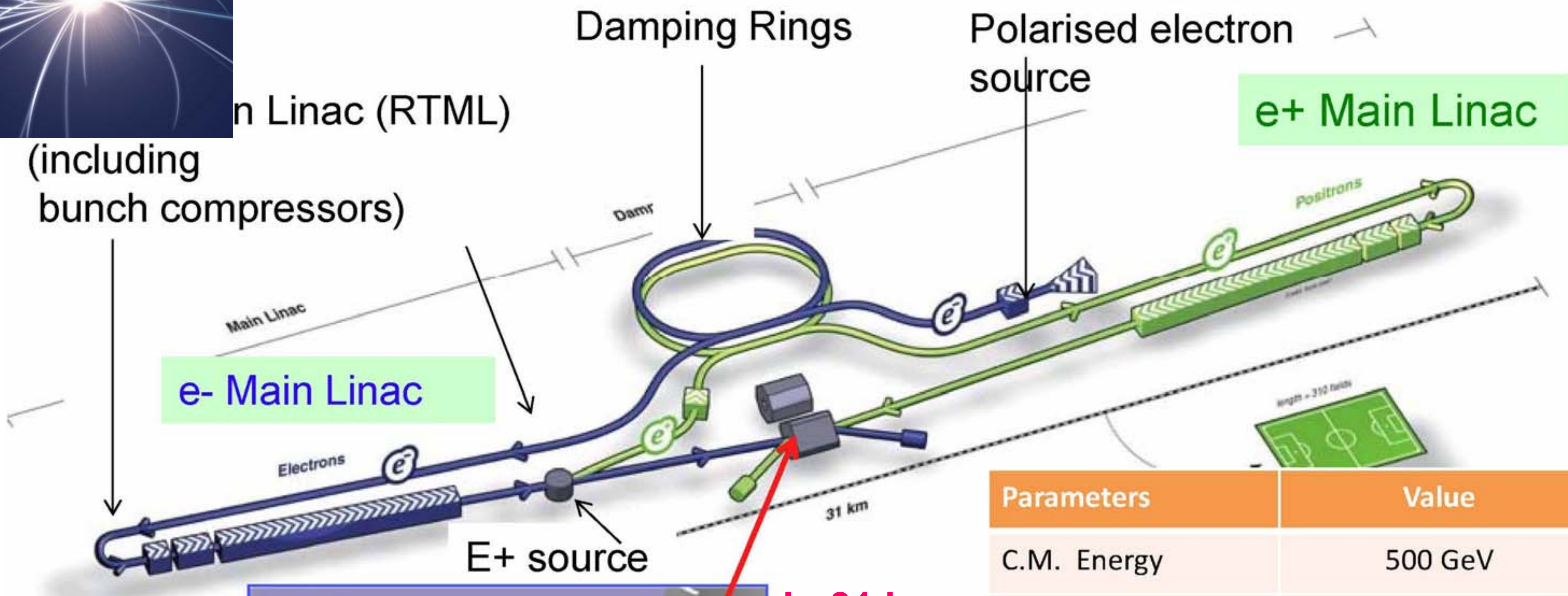


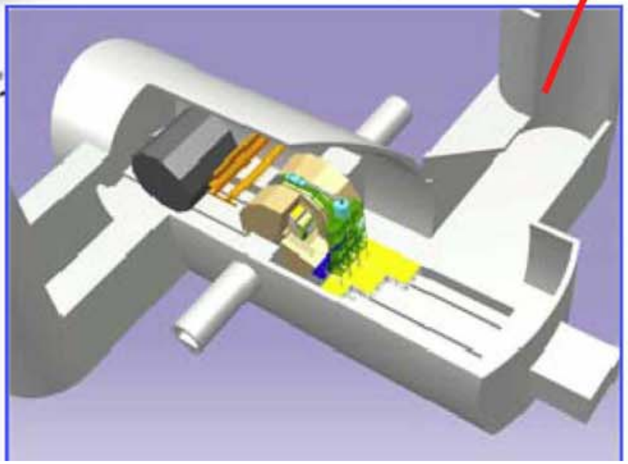
ILC Status



ILC TDR
6.2013

ILC TDR Layout





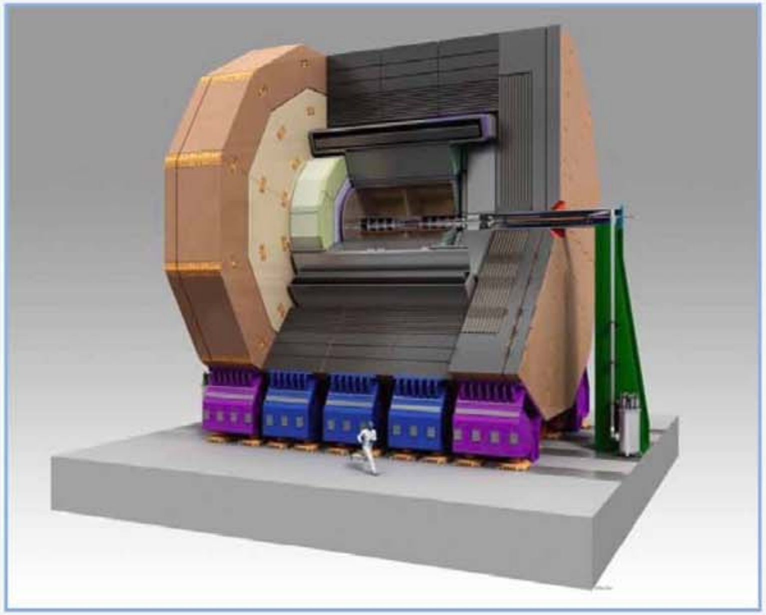
L=31 km
2E=500 GeV

Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

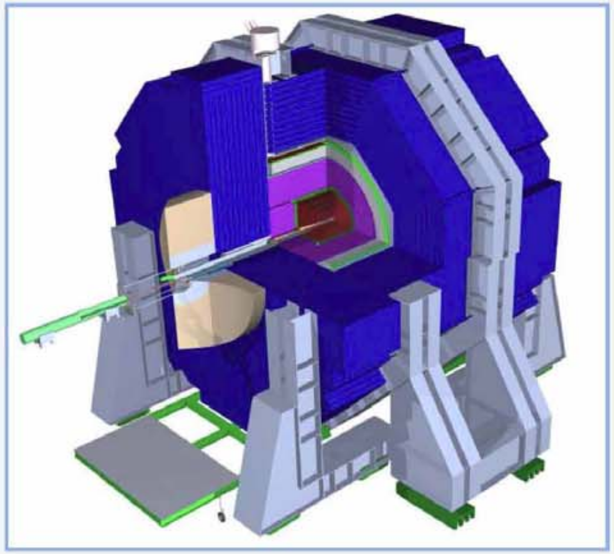
2E=250-500 GeV, upgradable to 1000 GeV

2 Detector Concepts: Detailed Baseline Design

ILD



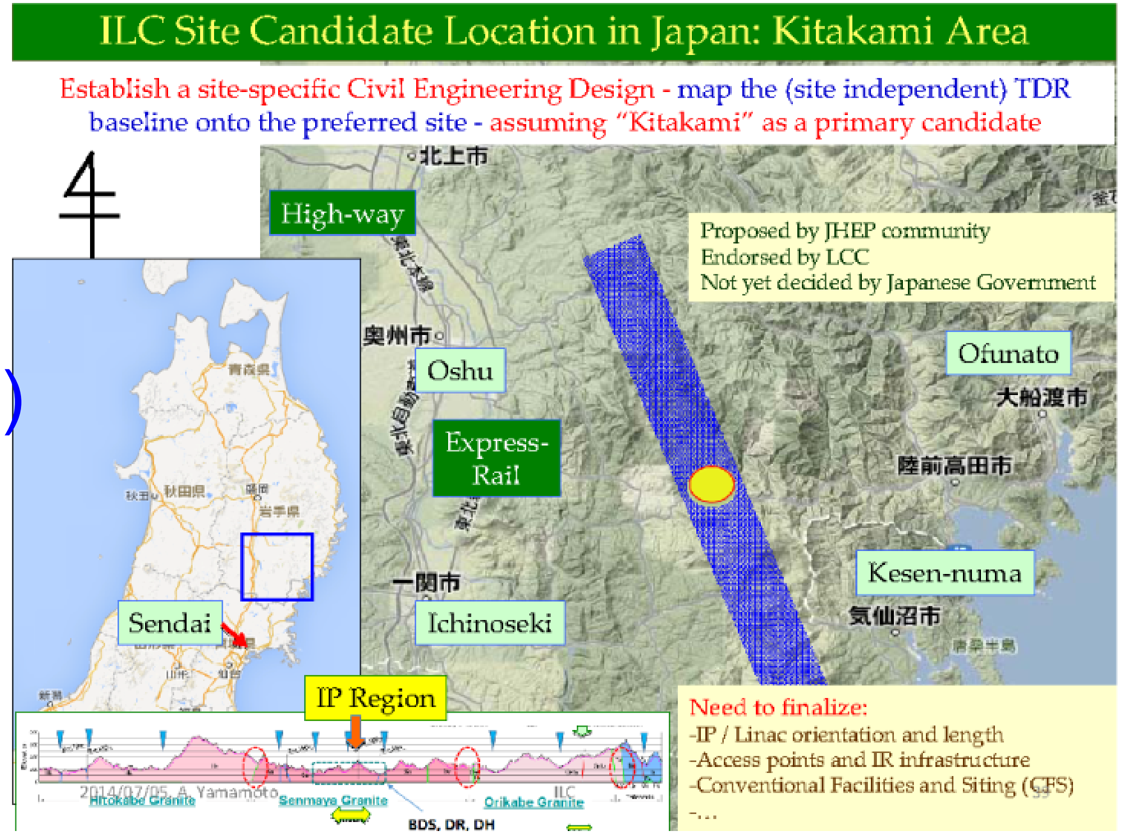
SiD

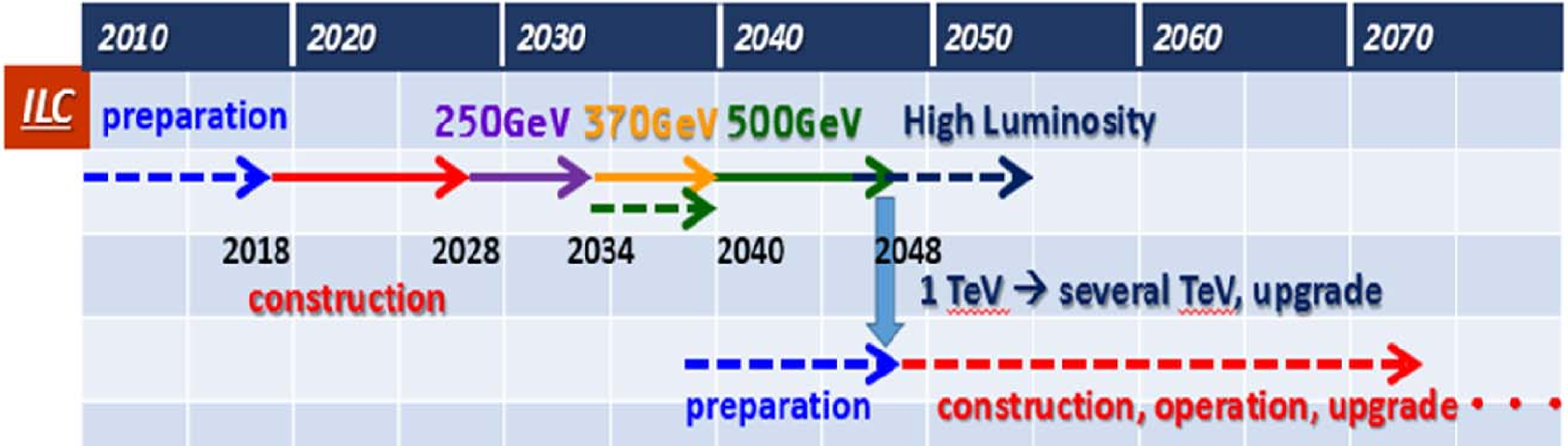


- Large R with TPC tracker
  - 32 countries,
  - 151 institutions,
  - ~700 members
- B=3.5T, TPC + Si trackers
- ECal: R=1.8m

- High B with Si strip tracker
  - 18 countries,
  - 77 institutions,
  - ~240 members
- B=5T, Si only tracker
- ECal : R=1.27m

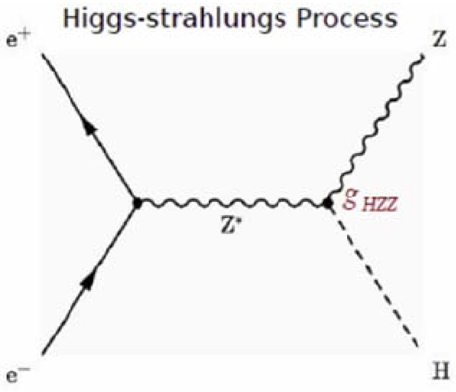
Japan is interested to host
-decision ~2018
-construction ~2019 (~10 years)
-physics ~2030



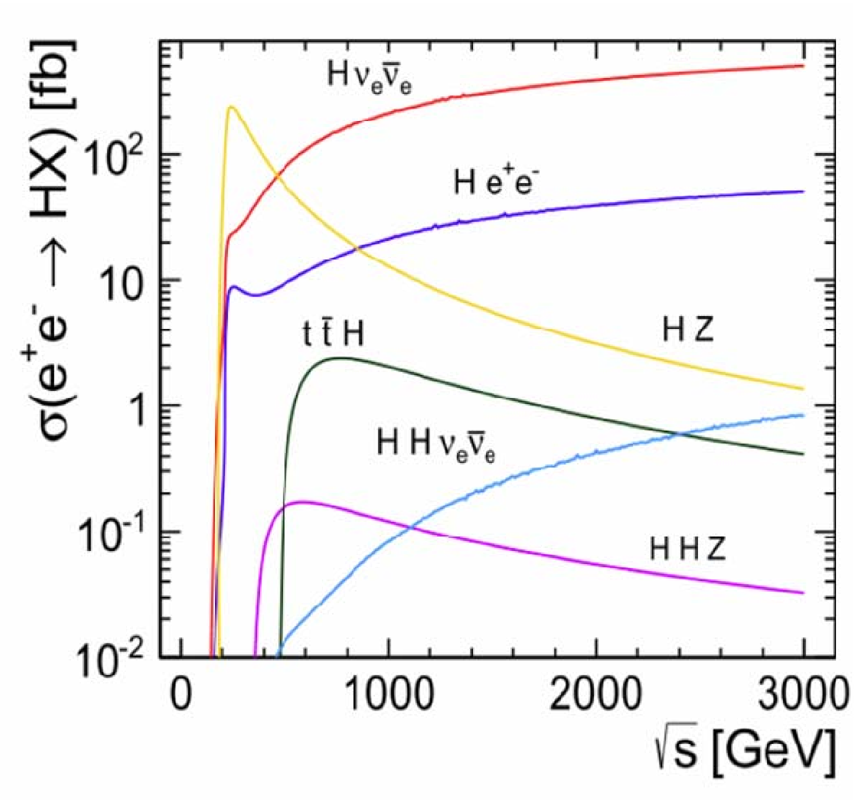


Known physics, ILC stages

- 2E=250 GeV Higgs boson
- 350 top quark
- 500 ZHH –Higgs self coupling
- 500 and higher ttH - top Yukawa coupling
- 1000 and higher Beyond

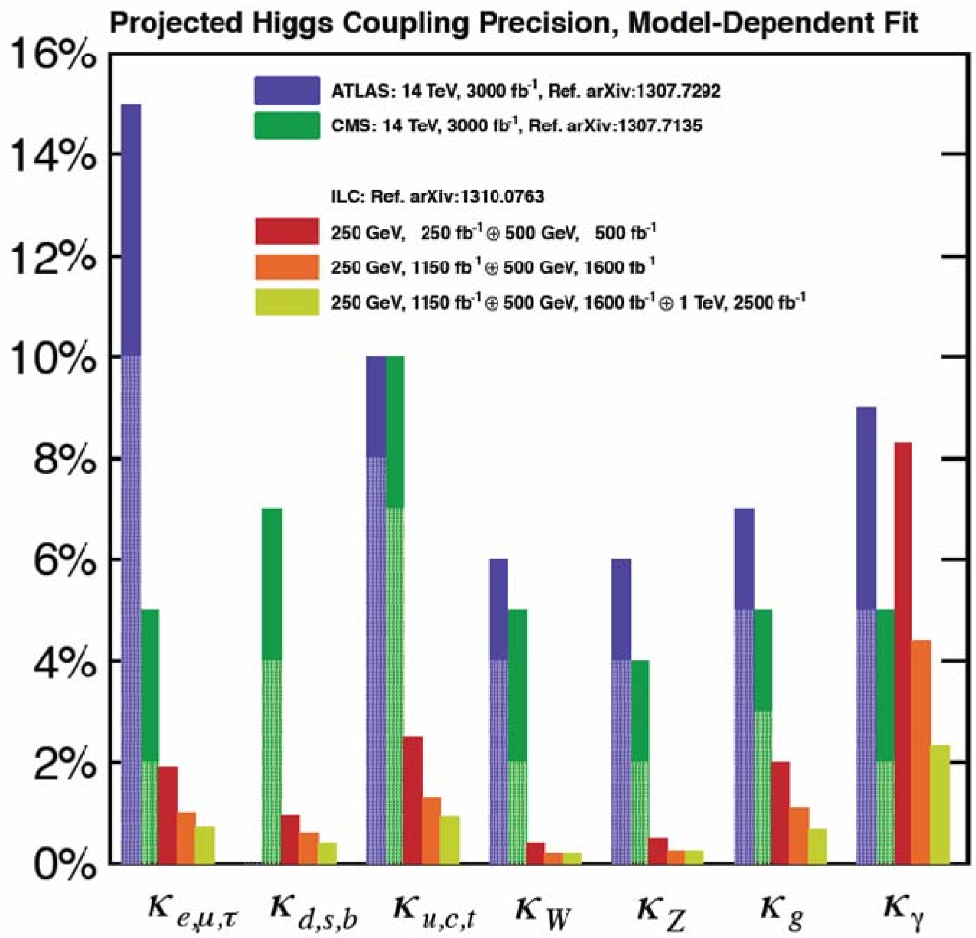


Higgs Studies at the ILC



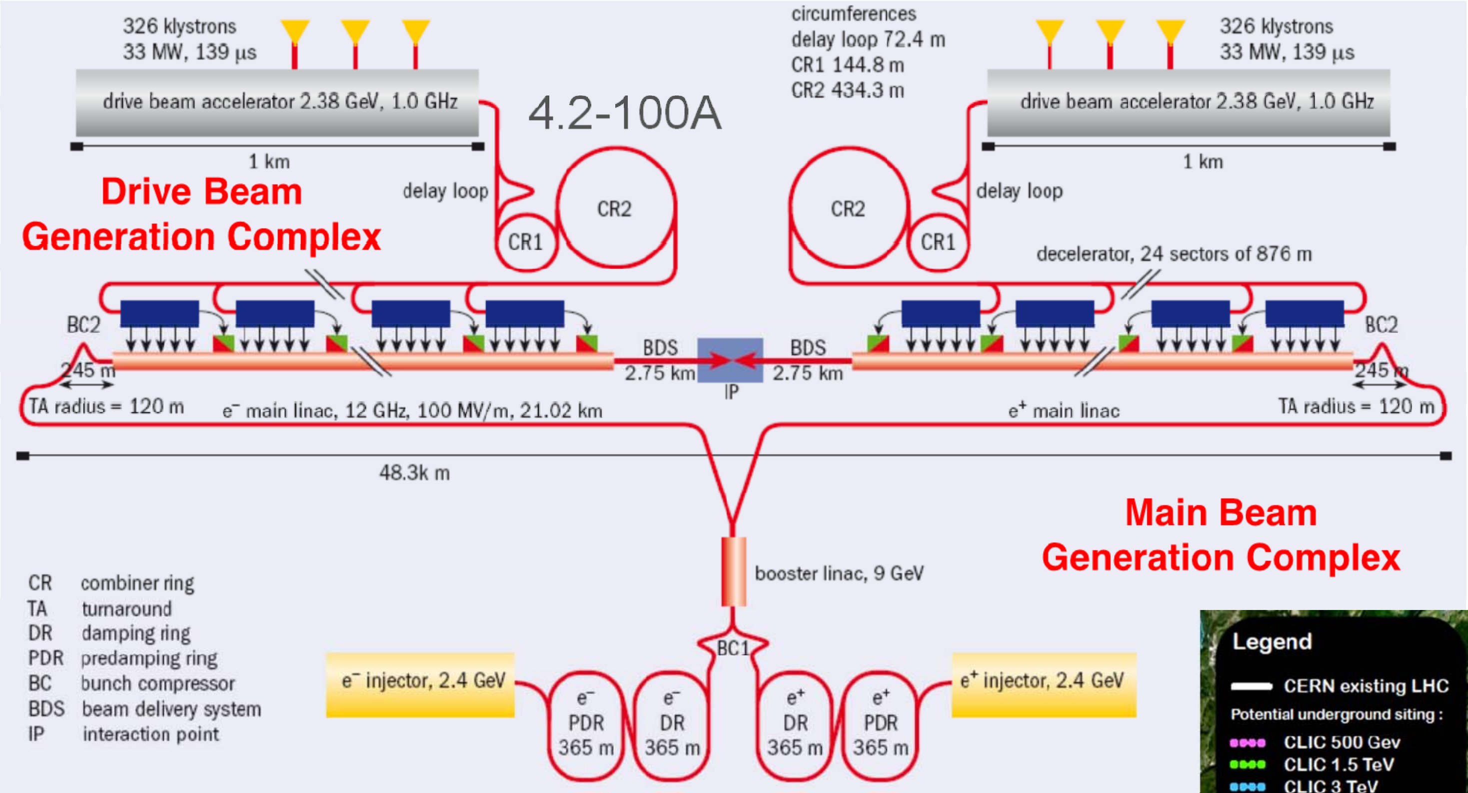
Higgs Couplings

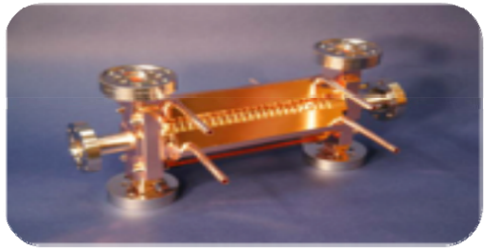
[With assumptions; not model-independent.]



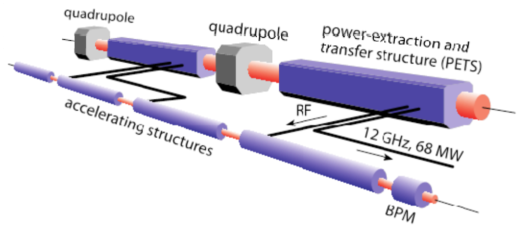
The coupling measurement at HL-LHC in 2-10% range can be reduced at the ILC by an order of magnitude

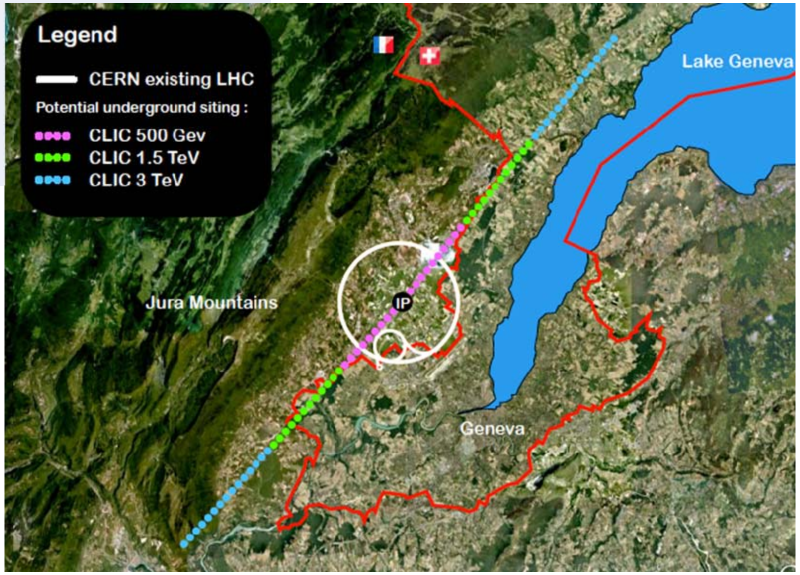
Compact LInear Collider (CLIC)





G_a ~ 100 MV/m



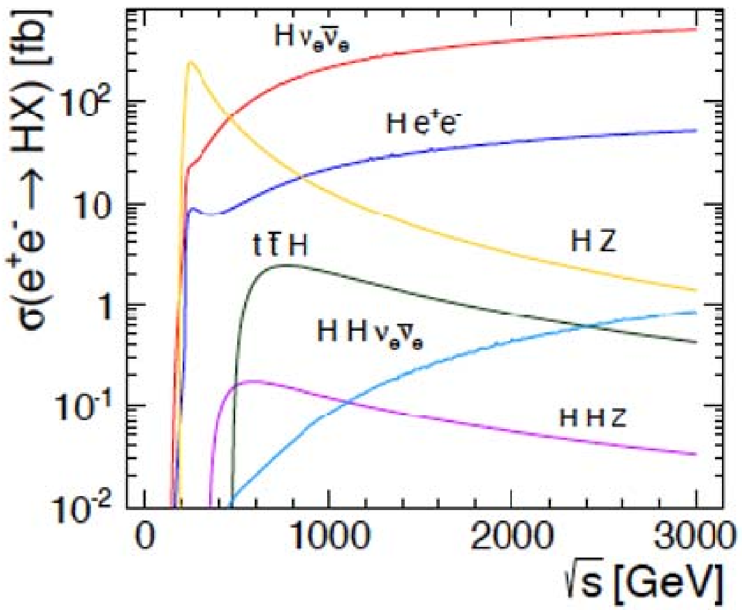


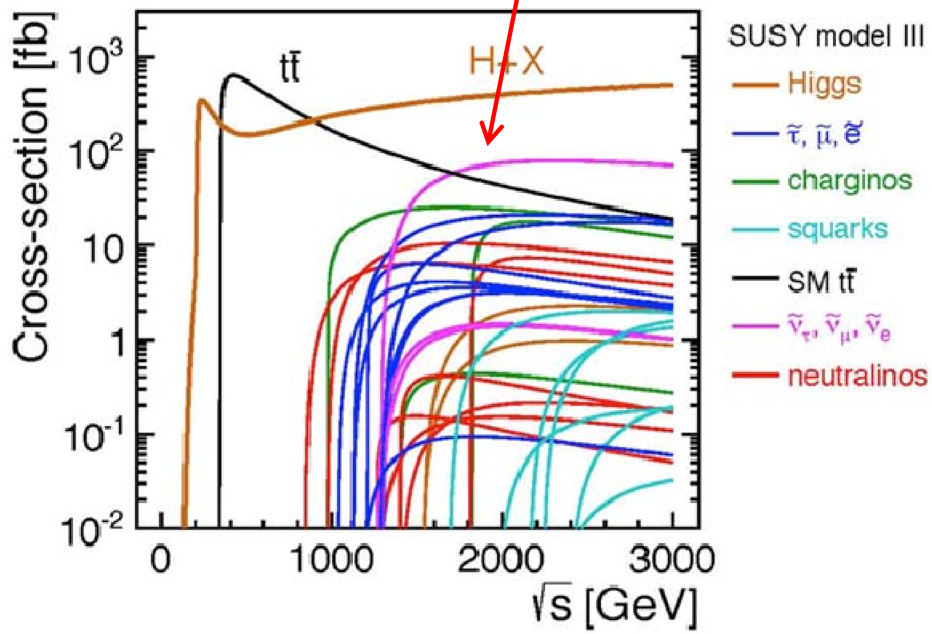
0.5 TeV: 8,300 MCHF ($\mathcal{L}$ ~ 1.4×10^{34})

CLIC
- e+e- 500 - 3000 GeV
- x-band accelerator technology
- 2-beam acceleration
- $\mathcal{L}$ ~ 2-6×10^{34}

CLIC projects

As usually, rich new physics is expected





The feasibility of the CLIC scheme has been established.
CLIC proposes a staged approach to reach 3 TeV:
Stages with 500fb-1 at <500 GeV, 1500fb-1 at 1-2 TeV, 2000 fb-1 at 3 TeV;
L= 2.3×10^{34} cm^{-2} s^{-1} at 500 GeV

Decision: 2018-2019
Preparation stage: ~5 years
Construction could start in 2024-25; commissioning in ~2033.

ILC and CLIC parameters

upgrage to (3-4)10^{34} is foreseen

	unit	ILC			CLIC		
$2E_0$	GeV	250	500	1000	250	500	3000
L_{tot}	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.75	1.8	4.9	1.37	2.3	5.9
L_{geom}	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.37	0.75	2.61	0.82	1.42	4.29
No. Higgs/yr(10^7 s)	1000	23	49	–	34	44	446
Length	km	21	31	48	13.2	13.2	48.3
P (wall)	MW	128	162	301	225	272	589
Pol. e^-/Pol. e^+	%	80/30	80/30	80/30	80/0	80/0	80/0
Accel. gradient	MV/m	31.5	31.5	31.5/45	40	80	100
N per bunch	10^{10}	2	2	1.74	0.34	0.68	0.372
Bunches per pulse		1312	1312	2450	842	354	312
Bunch distance	ns	554	554	366	0.5	0.5	0.5
Rep. rate	Hz	5	5	4	50	50	50
Norm. emit. $\varepsilon_{x,n}$	mm-mrad	10	10	10	0.66	2.4	0.66
Norm. emit. $\varepsilon_{y,n}$	mm-mrad	0.035	0.035	0.03	0.025	0.025	0.02
β_x at IP	mm	13	11	11	8	8	4
β_y at IP	mm	0.41	0.48	0.23	0.1	0.1	0.07
σ_x at IP	nm	729	474	335	150	200	40
σ_y at IP	nm	7.66	5.9	2.7	3.2	2.3	1
σ_z at IP	mm	0.3	0.3	0.225	0.072	0.072	0.044
Ener. loss. $\delta E/E$	%	0.95	4.5	10.5	1.5	7	28

Circular Higgs e+e-factories

Beginning:

1. A.Blondel and F.Zimmermann, A High Luminosity e+e- Collider in the LHC tunnel to study the Higgs Boson, arXiv:1112.2518 (Dec. 2011)
2. K.Oide, Super-Tristan, talk at KEK, Feb.2012 (crab-waist scheme)
3. V.Telnov, Restriction on the energy and luminosity of e+e- storage rings due to beamstrahlung, arXiv:1203.6563 (March 2012), PRL 110,114801 (2013).
4. A. Blondel…V.Telnov.., LEP3: A High Luminosity e+e- Collider to study the Higgs Boson, arXiv:1208.0504 (Aug.2012) (Triple-LEP (TLEP) with C=80 km is discussed)

HF2012-First Higgs factory workshop (November, 2012, FNAL) – already 7-8 proposals of Circular e+e- Higgs factories around the world on the energy 2E=230(H)-370(tt) GeV.


FNAL site filler, 2012
West Coast design, 2012
LEP3 on LI, 2012
LEP3 in Texas, 2012
LEP3 2011
TLEP 2012
UNK Higgs Factory, 2012
Chinese Higgs Factory, 2012
SuperTristan 2012
Many e^+e^- circular Higgs factories are being studied around the world

Circular e^+e^- Collider as a Higgs Factory

November 2012

- 16 km (Fermilab site-filler) USA
- 21 km (Protvino) Russia (free tunnel)
- 27 km (LEP3)
- 40 km (SuperTRISTAN-40)- Japan
- 50 km (CHF-1)- China
- 70 km (CHF-2)- China
- 80 km (TLEP, SuperTRISTAN-80)- Swiss, Japan
- 233 km (VLLC)- USA

At present: two projects are very seriously considered

FCC-ee, FCC-hh (CERN) C=100km, $2E_{e+e-}$=90-350 GeV, $2E_{pp}$=100 TeV

CEPC, SppC (China) C~54km, $2E_{e+e-}$= 240 GeV, $2E_{pp}$=70 TeV

FCC (ee, hh) – Future Circular Collider

CEPC – Circular Electron Positron Collider

SppC – Super proton proton Collider

Main arguments for circular e+e- colliders

During last 25 years linear colliders were considered as best candidates for the next collider for precision study below 1-3 TeV, why ring e+e- colliders again?

Advantages

1) No new physics is found up to now by LHC for exception of low mass Higgs boson. The energy 2E=230 GeV needed for study H in e+e- collision can be reached by circular e+e- colliders.

2) Ring colliders are easier and luminosity can be higher than at linear colliders at 2E=230 GeV (and much higher at Z), can provide higher accuracy needed for observation of new physics (in Higgs and Z decays). Top threshold 2E=350 GeV can be reached.

3) Ring tunnels (C~100 km) can be used further for highest energy pp (or muon) colliders. It is a very attractive long-term strategy.

Disadvantage: Presence of new physics in the region 2E=350-3000 is still not excluded, this region can be covered only by linear colliders

Beam lifetime due to beamstrahlung

The electron loses the beam after emission of beamstrahlung photon with an energy greater than the threshold energy $E_{th}=\eta E_0$, where a *ring energy acceptance* η~0.01-0.02.

The beam lifetime due to beamstrahlung (V. Telnov)

$$\tau \approx 6.\frac{2\pi R}{c}\frac{\sqrt{6\pi}\; r_e \gamma u^{3/2} e^{1.225u}}{\alpha^2 \eta \sigma_z}$$

$$u = \eta \frac{\alpha \sigma_x \sigma_z}{3\gamma r_e^2 N}, \qquad \alpha = e^2/\hbar c$$

The requirement of the lifetime 30 min imposes
a new restriction on the beam parameters

$$\boxed{\frac{N}{\sigma_x \sigma_z} < 0.1\eta \frac{\alpha}{3\gamma {r_e}^2}}$$

Head-on and "crab-waist" collision schemes

Below we consider two collision schemes: head-on and crab-waist.
In the crab-waist scheme the beams collide at an angle $\theta \gg \sigma_x/\sigma_z$.
This scheme allows a higher luminosity, if it is determined by the tune shift (beam-beam strength parameter characterizing instabilities).
For head-on collisions the tune shift ($\xi_y \le 0.1-0.15$) and the luminosity

(1) $$\xi_y = \frac{N r_e \beta_y}{2\pi\gamma\sigma_x\sigma_y} \approx \frac{N r_e \sigma_z}{2\pi\gamma\sigma_x\sigma_y} \text{ for } \beta_y \approx \sigma_z \qquad \mathcal{L} \approx \frac{N^2 f}{4\pi\sigma_x\sigma_y} \approx \frac{N f \gamma \xi_y}{2 r_e \sigma_z}$$

For the crab-waist scheme

(2) $$\xi_y = \frac{N r_e \beta_y^2}{\pi\gamma\sigma_x\sigma_y\sigma_z} \text{ for } \beta_y \approx \sigma_x/\theta \qquad \mathcal{L} \approx \frac{N^2 f}{2\pi\sigma_y\sigma_z\theta} \approx \frac{N^2 \beta_y f}{2\pi\sigma_x\sigma_y\sigma_z} \approx \frac{N f \gamma \xi_y}{2 r_e \beta_y}$$

In the crab-waist scheme one can make $\beta_y \sim \sigma_y/\theta \ll \sigma_z$, therefore the luminosity can be higher (>10 times)/ Nf is determined by SR power.
The only free parameters in L are σ_z (for head-on) and β_y (crab-waist), they are constrained by beamstrahlung condition

(3) $$\boxed{\frac{N}{\sigma_x\sigma_z} < 0.1\eta\frac{\alpha}{3\gamma r_e{}^2}}$$

Comparing (1),(2),(3) one can find the minimum beam energy when beamstrahlung becomes important.

For head-on collisions

$$\gamma_{\min} = \left(\frac{0.1\eta\alpha\sigma_z^2}{6\pi r_e \xi_y \sigma_y} \right)^{1/2} \propto \frac{\sigma_z^{3/4}}{\xi_y^{1/2}\varepsilon_y^{1/4}}$$

For "crab-waist" collisions

$$\gamma_{\min} = \left(\frac{0.1\eta\alpha\beta_y^2}{3\pi r_e \xi_y \sigma_y} \right)^{1/2} \propto \frac{2^{1/2}\beta_y^{3/4}}{\xi_y^{1/2}\varepsilon_y^{1/4}}$$

In the crab-waist scheme the beamstrahlung becomes important at much low energies because $\beta_y << \sigma_z$. For typical values of parameters (for $\eta=0.01$) $E_{min}>70$ GeV for head-on collisions and $E_{min}>20$ GeV for "crab-waist".

For considered colliders with $2E_0>240$ GeV beamstrahlung is important in both schemes.

Luminosities with account of beamstrahlung

It turns out that with account of beamstrahlung luminosities for head-on collisions and crab-waist collisions are practically equal

$$\boxed{\mathcal{L} \approx \frac{Nf}{4\pi} \left(\frac{0.1\eta\alpha}{3} \right)^{2/3} \left(\frac{2\pi\xi_y}{\gamma r_e^5 \varepsilon_y} \right)^{1/3}}$$

$$\sigma_{z,\mathrm{opt}} = \varepsilon_y^{1/3} \left(\frac{6\pi\gamma^2 r_e \xi_y}{0.1\eta\alpha} \right)^{2/3}$$ for head-on

$$\beta_{y,\mathrm{opt}} = \varepsilon_y^{1/3} \left(\frac{3\pi\gamma^2 r_e \xi_y}{0.1\eta\alpha} \right)^{2/3}$$ for crab-waist

Nf=n_bc/2πR is determined by the SR power in rings

$$P = 2\delta E \frac{cNn_{\mathrm{b}}}{2\pi R} = \frac{4e^2\gamma^4 cNn_{\mathrm{b}}}{3RR_{\mathrm{b}}}$$

Finally, the luminosity

$$\mathcal{L} \approx h\frac{(0.1\eta\alpha)^{2/3}PR}{32\pi^2\gamma^{13/3}r_e^3}\left(\frac{R_{\mathrm{b}}}{R}\right)\left(\frac{6\pi\xi_y r_e}{\varepsilon_y}\right)^{1/3}$$

(here h is the hourglass loss factor)

In practical units

$$\frac{\mathcal{L}}{10^{34}\,\mathrm{cm^{-2}s^{-1}}} \approx \frac{100h\eta^{2/3}\xi_y^{1/3}}{(E_0/100\,\mathrm{GeV})^{13/3}(\varepsilon_y/\,\mathrm{nm})^{\frac{1}{3}}}\left(\frac{P}{100\,\mathrm{MW}}\right)\left(\frac{2\pi R}{100\,\mathrm{km}}\right)\frac{R_{\mathrm{b}}}{R}$$

In order to increase luminosity one should increase the energy acceptance η

This formala is valid for high energies (for 2E=230, 350 GeV).
For Z factory beamstrahlung is not important.

FCC project (CERN)

FCC-hh hadron collider with 100TeV proton cms energy

~16 T ⇒ 100 TeV *pp* in 100 km
~20 T ⇒ 100 TeV *pp* in 80 km

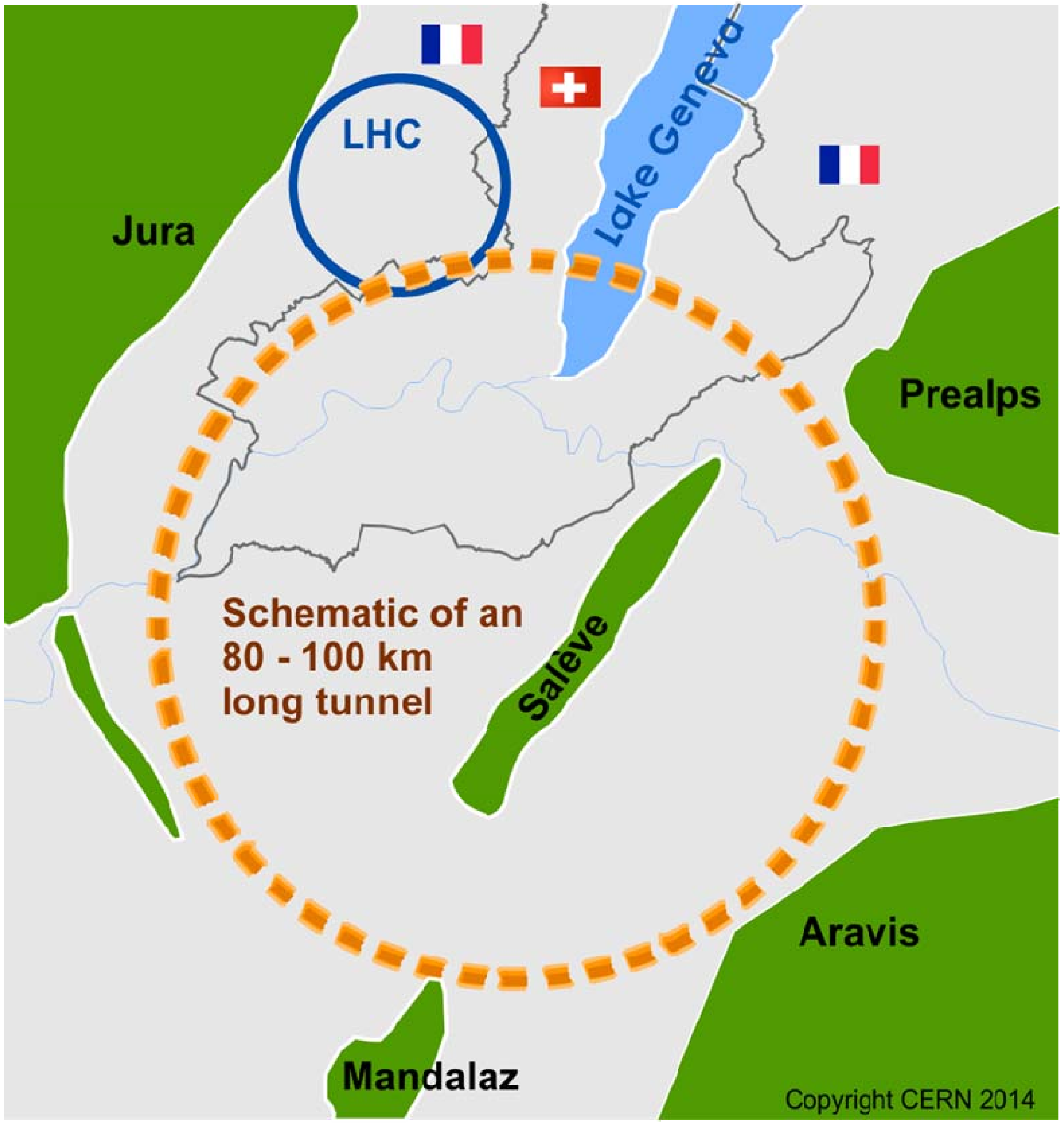
FCC-ee a lepton collider as a potential intermediate step

FCC-eh lepton hadron option

International collaboration

Site studies for Geneva area

CDR for EU strategy update in 2018



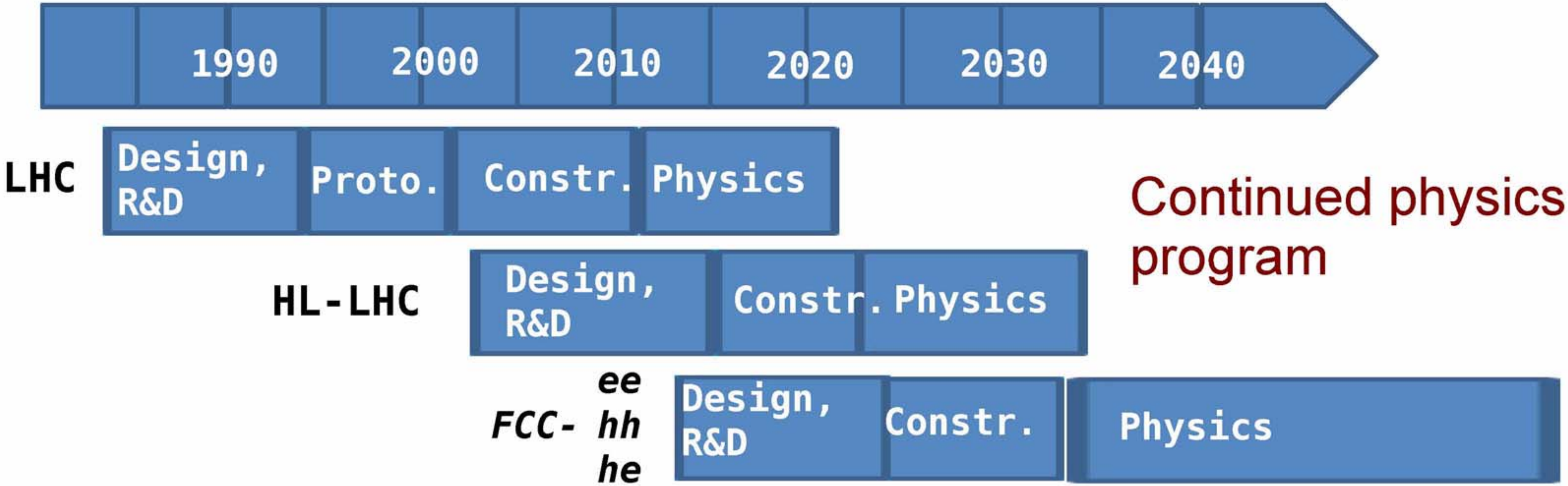
FCC Study Coordination Group

Study Coordination	M. Benedikt, F. Zimmermann
Hadron Collider Physics and Experiments	F. Gianotti, A. Ball, M. Mangano
Lepton Collider Physics and Experiments	A. Blondel, J. Ellis, P. Janot
e-p Physics, Experiments, IP Integration	M. Klein, O. Bruning
Hadron Injectors	B. Goddard
Hadron Collider	D. Schulte, M. Syphers, J.M. Jimenez
Lepton Injectors	Y. Papaphilippou (tbc)
Lepton Collider	J. Wenninger, U. Wienands, J.M. Jimenez
Accelerator R & D Technologies	M. Benedikt, F. Zimmermann
Infrastructures and Operation	P. Lebrun, P. Collier
Costing Planning	F. Sonnemann, P. Lebrun

M. Benedikt

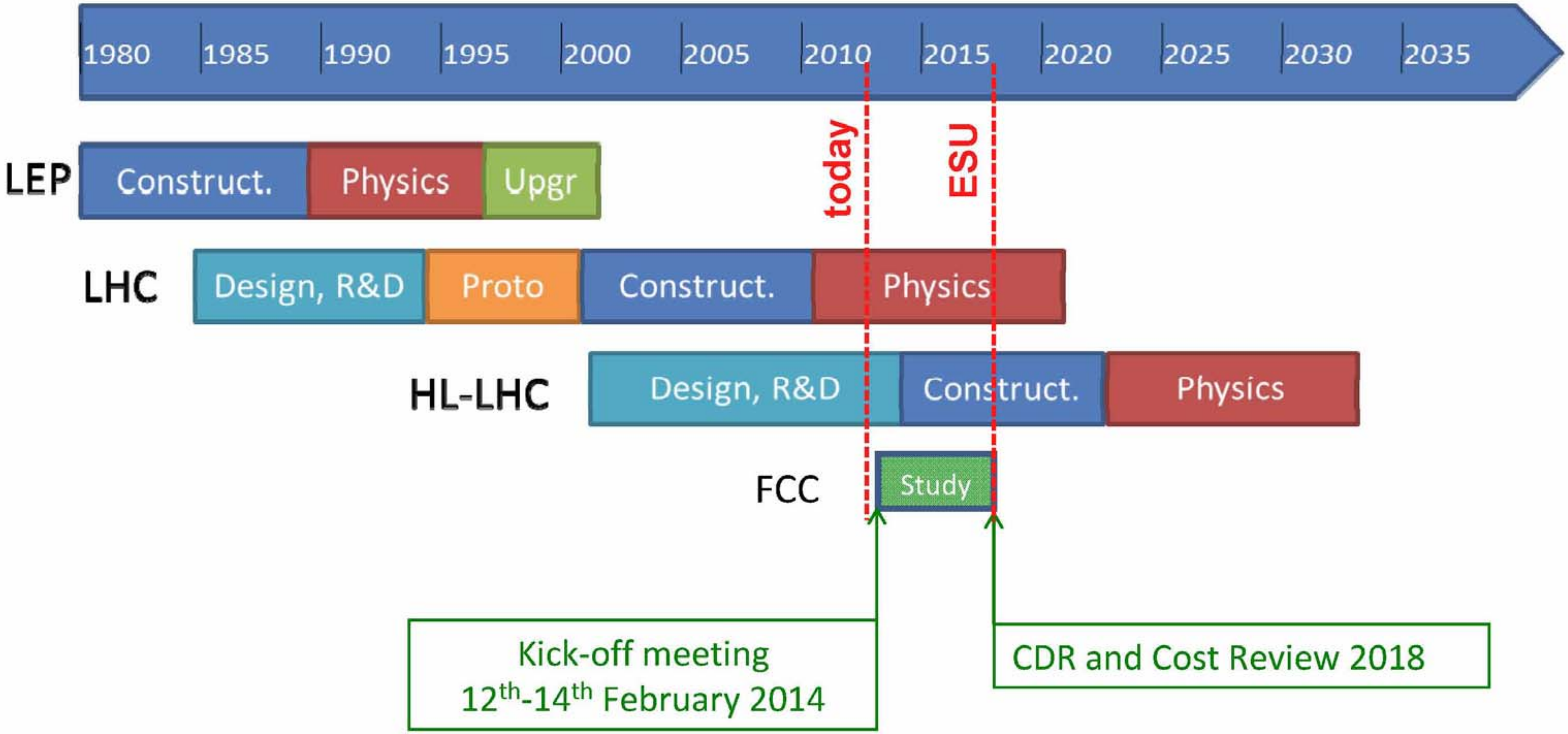
tentative time line and milestones

F. Zimmermann, IPAC14



Continued physics program

FCC study milestones



FCC-hh baseline parameters

parameter	LHC	HL-LHC	FCC-hh
c.m. energy [TeV]	14		100
dipole magnet field [T]	8.33		16 (20)
circumference [km]	36.7		100 (83)
luminosity [10^{34} $cm^{-2}s^{-1}$]	1	5	5 [→20?]
bunch spacing [ns]	25		25 {5}
events / bunch crossing	**27**	**135**	**170 {34}**
bunch population [10^{11}]	1.15	2.2	1 {0.2}
norm. transverse emitt. [μm]	3.75	2.5	2.2 {0.44}
IP beta-function [m]	0.55	0.15	1.1
IP beam size [μm]	16.7	7.1	6.8 {3}
synchrotron rad. [W/m/aperture]	0.17	0.33	28 (44)
critical energy [keV]	0.044		4.3 (5.5)
total syn.rad. power [MW]	**0.0072**	**0.0146**	**4.8 (5.8)**
longitudinal damping time [h]	**12.9**		**0.54 (0.32)**

Hadron collider FCC-hh parameters

- **Energy** — **100 TeV c.m.**
- **Circumference** — **~ 100 km (baseline) [80 km option]**
- **Dipole field (50 TeV)** — **~ 16 T (baseline) [20 T option]**
- **Dipole field (3 TeV inject.)** — **~ 1 T (baseline) [1.2 T option]**

- **Bunch spacing** — **25 ns [5 ns option]**
- Bunch population (25 ns) — 1×10^{11} p
- Emittance normalised — 2.15×10^{-6}m, normal.
- #bunches — 10500
- **Stored beam energy** — **8.2 GJ/beam**

Available from SPS/LHC today
→3 TeV injector baseline for FCC-hh

- # Interaction Points — 2 main experiments
- β^* — 1.1 m [baseline]
- **Luminosity** — **5×10^{34} cm^{-2}s^{-1}** [baseline]

- **Synchroton radiation arc** — **~30 W/m/aperture (fill. fact. ~78% in arc)**

machine protection

2 tons of TNT

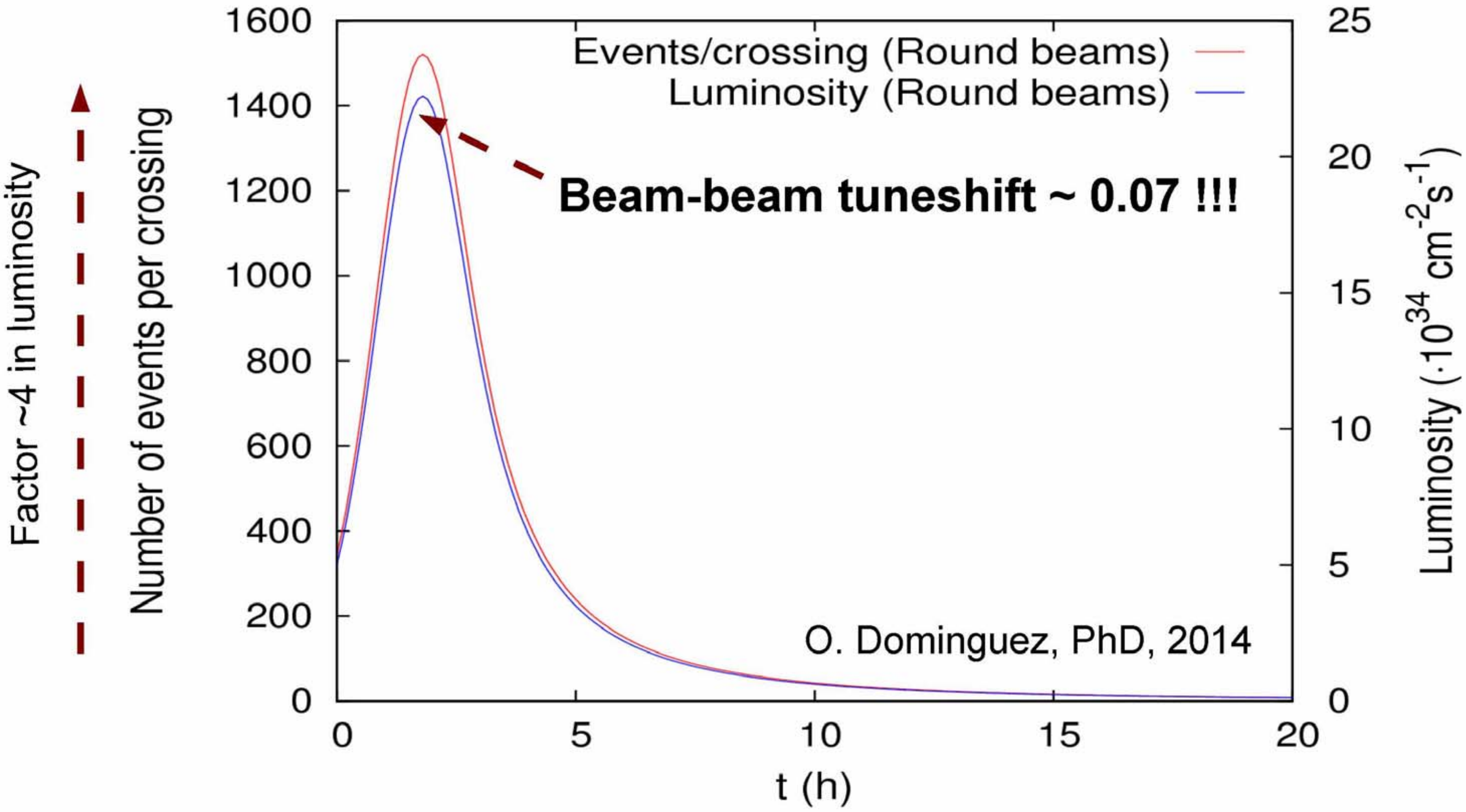
energy per proton beam

LHC: 0.4 GJ → *FCC-hh*: 8 GJ (20x more !)

– kinetic energy of Airbus A380 at 720 km/h

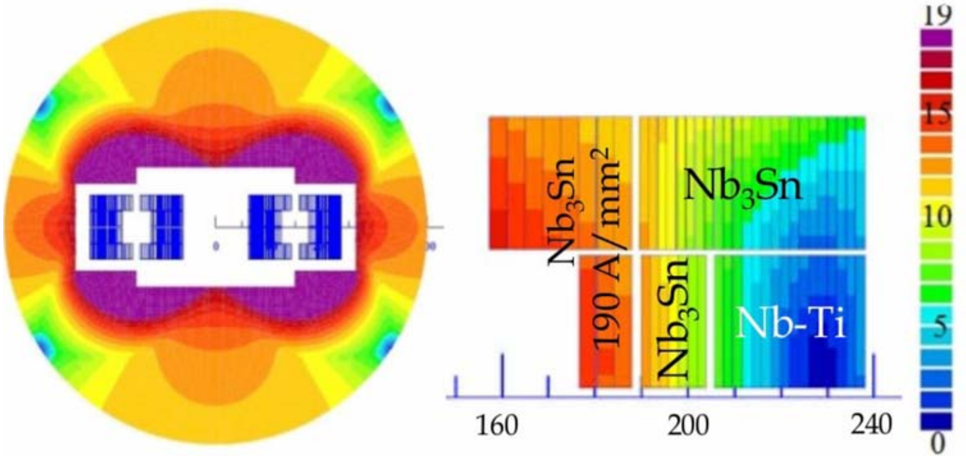
– can melt 12 tons of copper, or drill a 300-m long hole

Increasing luminosity during the FCC-hh fill thanks to SR

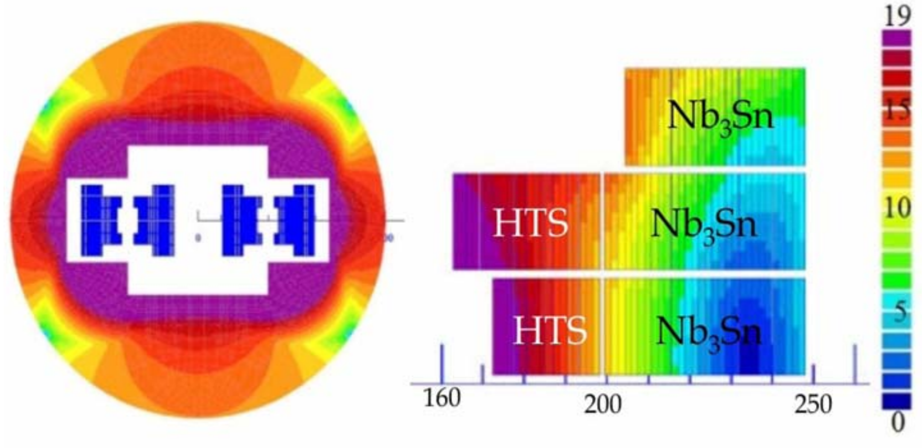


SR damping has never been observed in a hadron machine,
What to do?

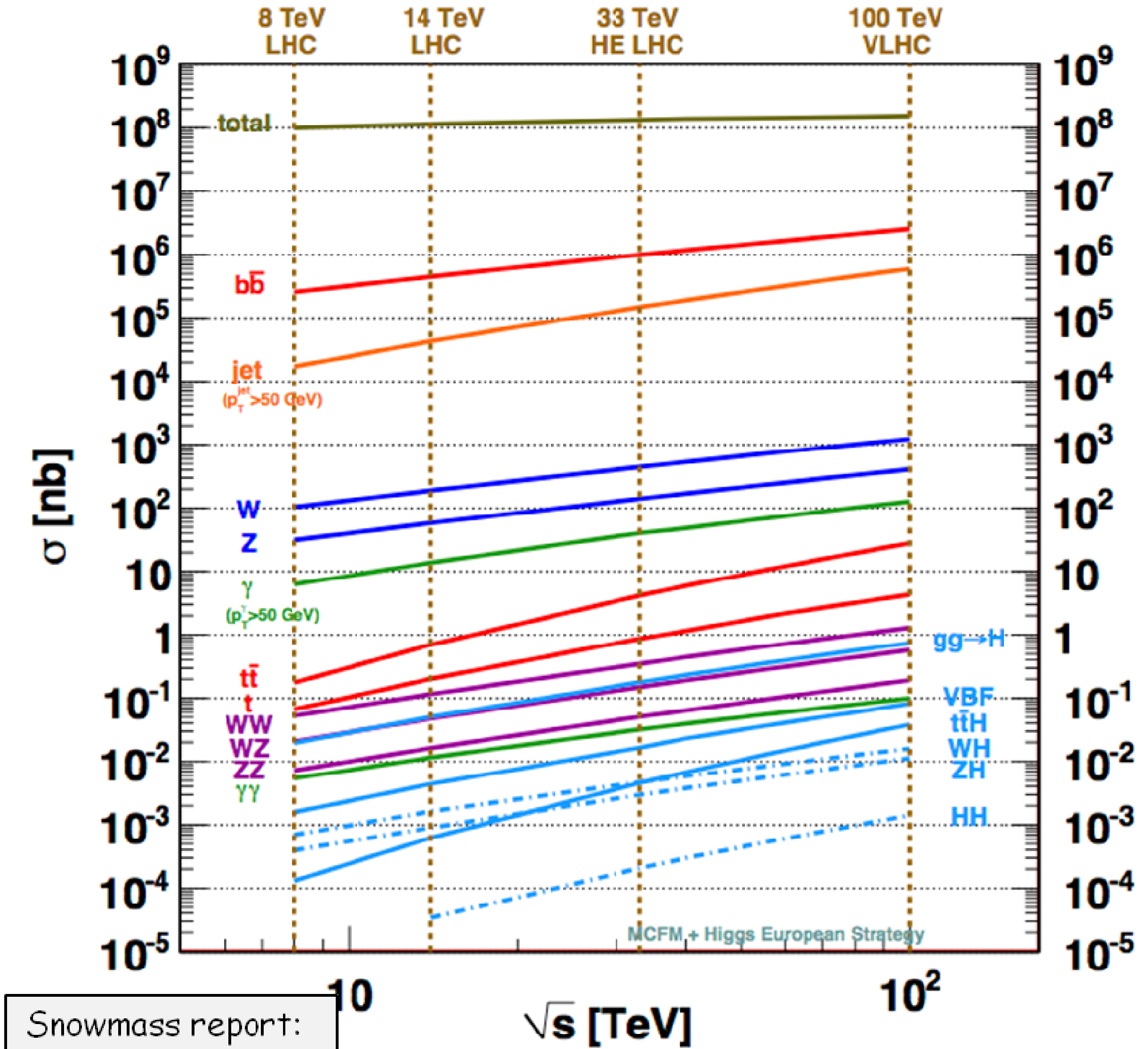
15 T with Nb_3Sn and Nb-Ti
(preliminary, project goal 16 T)



20 T with HTS and Nb_3Sn



Cross sections vs $\sqrt{s}$



Snowmass report:
arXiv:1310.5189

Process	σ (100 TeV)/σ (14 TeV)
Total pp	1.25
W	~7
Z	~7
WW	~10
ZZ	~10
tt	~30
H	~15 (ttH ~60)
HH	~40
stop (m=1 TeV)	$\sim 10^3$

→ With 10000/fb at $\sqrt{s}$=100 TeV expect: 10^{12} top, 10^{10} Higgs bosons, 10^8 m=1 TeV stop pairs, …

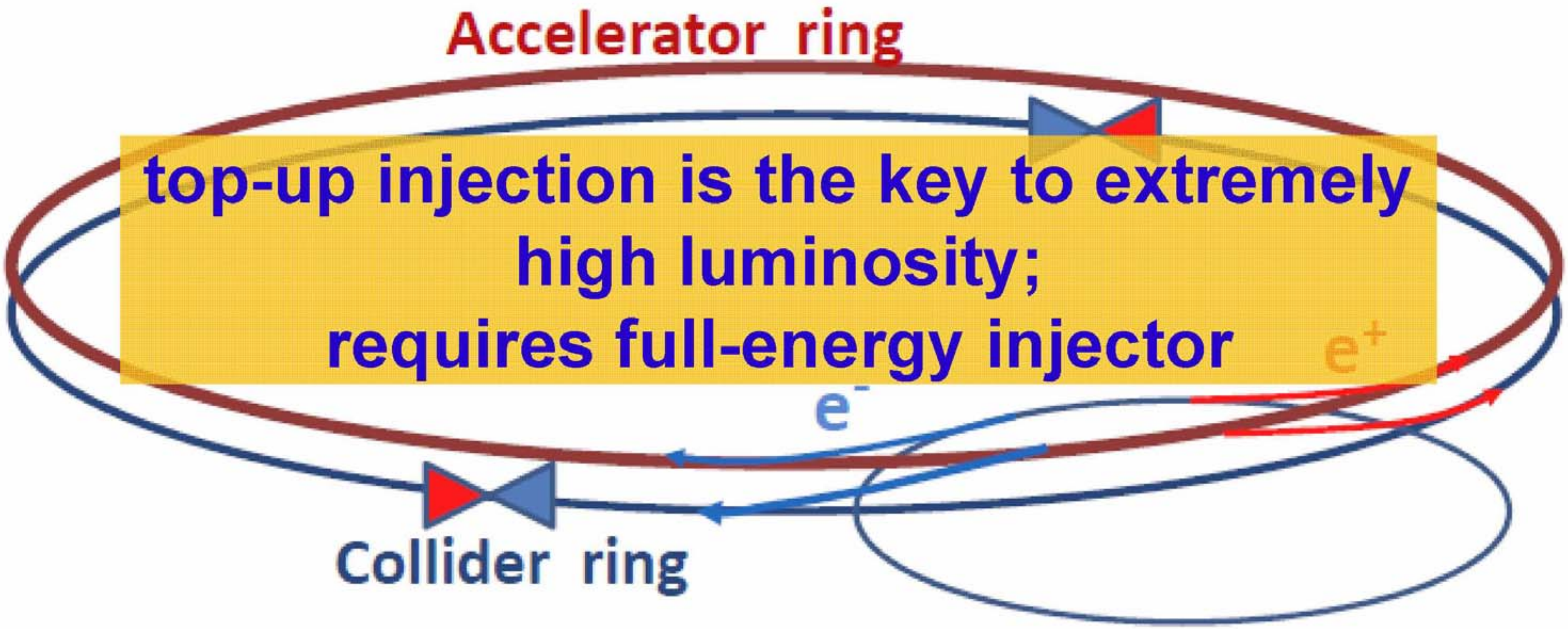
FCC-ee baseline parameters

parameter	LEP2	FCC-ee				
		Z	Z (c.w.)	W	H	t
E_{beam} [GeV]	104	45	45	80	120	175
circumference [km]	26.7	100	100	100	100	100
current [mA]	3.0	1450	1431	152	30	6.6
$P_{SR,tot}$ [MW]	22	100	100	100	100	100
no. bunches	4	16700	29791	4490	1360	98
N_b [10^{11}]	4.2	1.8	1.0	0.7	0.46	1.4
ε_x [nm]	22	29	0.14	3.3	0.94	2
ε_y [pm]	250	60	1	1	2	2
β^*_x [m]	1.2	0.5	0.5	0.5	0.5	1.0
β^*_y [mm]	50	1	1	1	1	1
σ^*_y [nm]	3500	250	32	84	44	45
$\sigma_{z,SR}$ [mm]	11.5	1.64	2.7	1.01	0.81	1.16
$\sigma_{z,tot}$ [mm] (w beamstr.)	11.5	2.56	5.9	1.49	1.17	1.49
hourglass factor F_{hg}	0.99	0.64	0.94	0.79	0.80	0.73
L/IP [10^{34} cm^{-2}s^{-1}]	0.01	28	212	12	6	1.7
τ_{beam} [min]	434	298	39	73	29	21

10^5 Z per sec

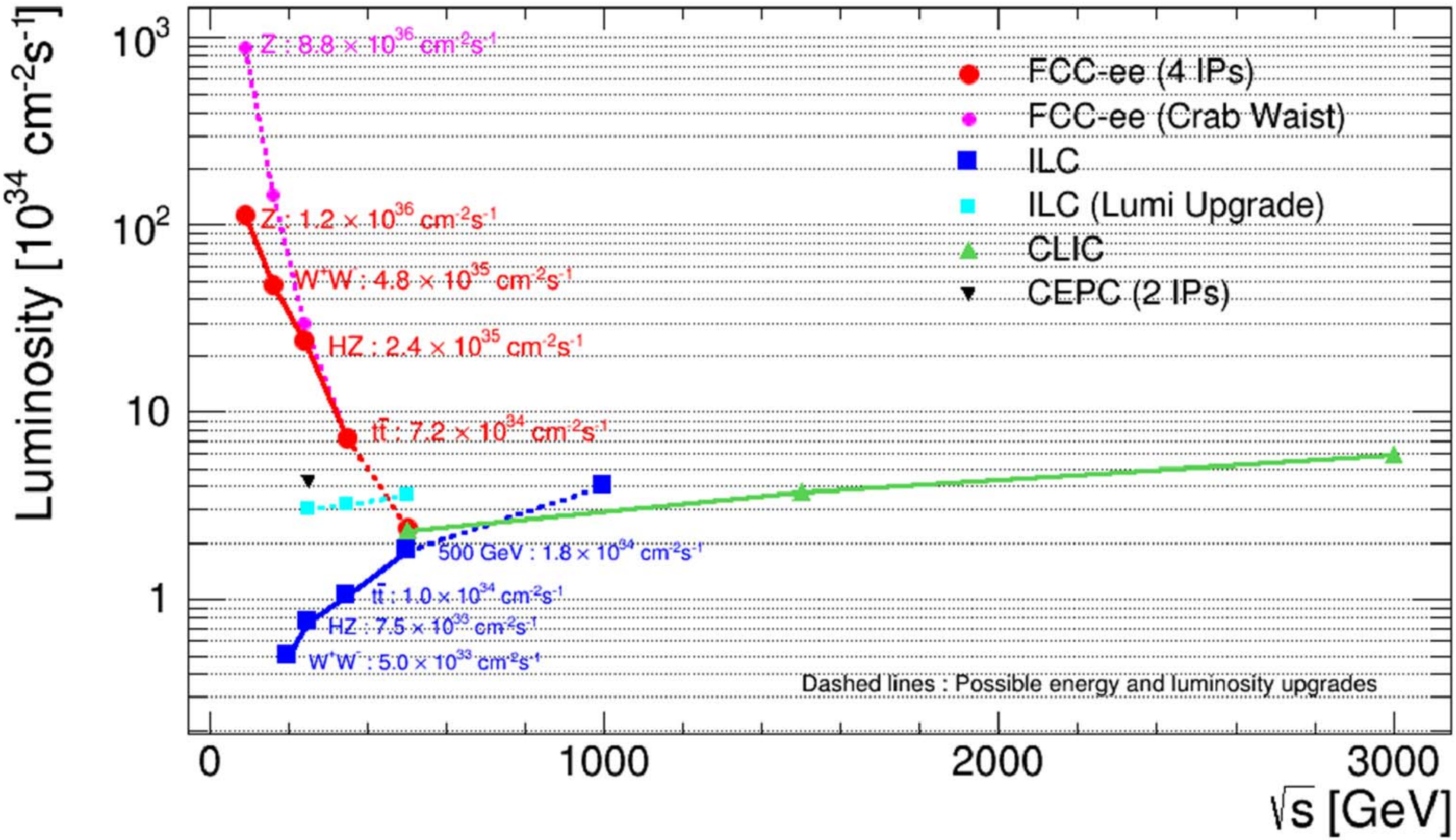
FCC-ee: e^+e^- collider up to 350 (500) GeV

circumference ≈100 km



top-up injection is the key to extremely high luminosity; requires full-energy injector

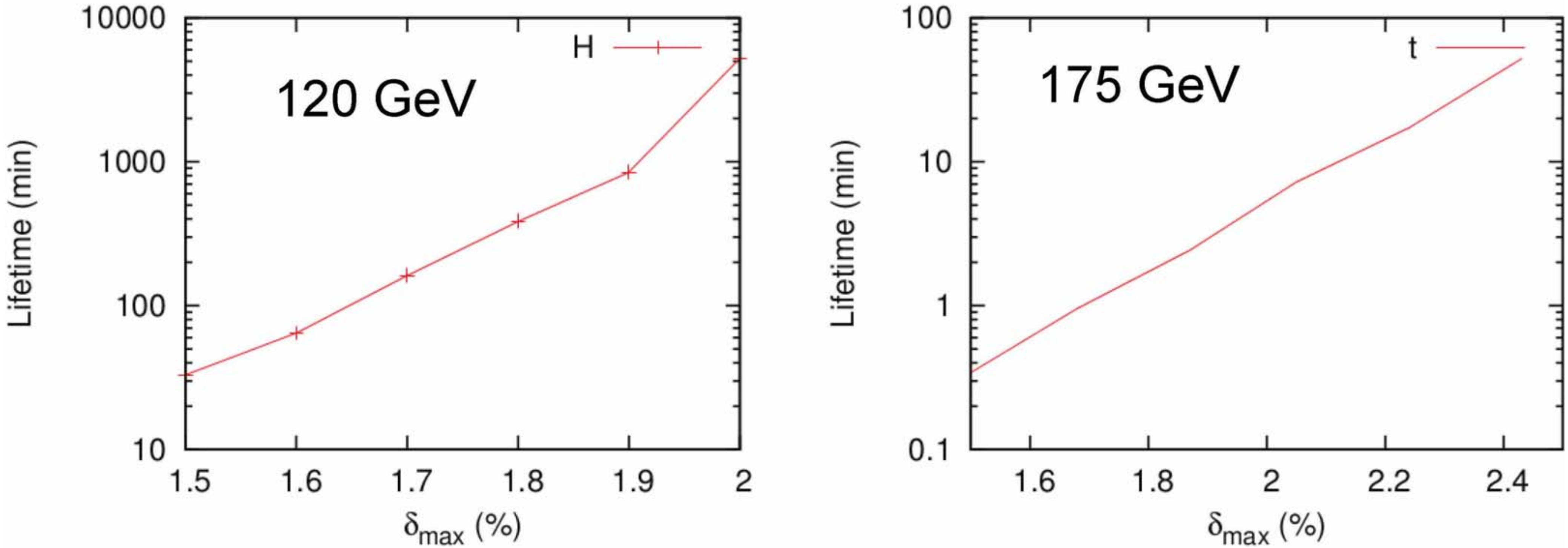
short beam lifetime ($\sim\tau_{LEP2}/40$) due to high luminosity
supported by top-up injection (used at KEKB, PEP-II, SLS,…);
top-up **also avoids ramping & thermal transients, + eases tuning**



Luminosity [10^{34} cm^{-2}s^{-1}]
10^3
10^2
10
1
0
1000
2000
3000
$\sqrt{s}$ [GeV]
Z : 8.8 × 10^{36} cm^{-2}s^{-1}
Z : 1.2 × 10^{36} cm^{-2}s^{-1}
W$^+$W : 4.8 × 10^{35} cm^{-2}s^{-1}
HZ : 2.4 × 10^{35} cm^{-2}s^{-1}
$t\bar{t}$: 7.2 × 10^{34} cm^{-2}s^{-1}
500 GeV : 1.8 × 10^{34} cm^{-2}s^{-1}
$t\bar{t}$: 1.0 × 10^{34} cm^{-2}s^{-1}
HZ : 7.5 × 10^{33} cm^{-2}s^{-1}
W$^+$W$^-$: 5.0 × 10^{33} cm^{-2}s^{-1}
FCC-ee (4 IPs)
FCC-ee (Crab Waist)
ILC
ILC (Lumi Upgrade)
CLIC
CEPC (2 IPs)
Dashed lines : Possible energy and luminosity upgrades

FCC-ee beamstrahlung and IR momentum acceptance

K. Oide & F. Zimmermann, IPAC 2014



- Very strong dependency of lifetime versus momentum acceptance
- Might be OK for Higgs but severe for Top

Physics requirements for FCC-ee

- highest possible luminosity for a wide physics program ranging from the *Z* pole to the $t\bar{t}$ production threshold
  - *beam energy range from 45 GeV to 175 (250?) GeV*
- main physics programs / energies:
  - *Z (45.5 GeV): Z pole, 'TeraZ' and high precision M_Z & Γ_Z,*
  - *W (80 GeV): W pair production threshold,*
  - *H (120 GeV): ZH production (maximum rate of H's),*
  - *t (175 GeV): $t\bar{t}$ threshold*
- some polarization up to ≥80 GeV for beam energy calibration
- optimized for operation at 120 GeV?!

Accuracy of Higgs coupling for LC and FCC-ee (Snowmass 2013)

Table 1-16. *Uncertainties on coupling scaling factors as determined in a completely model-independent fit for different e^+e^- facilities. Precisions reported in a given column include in the fit all measurements at lower energies at the same facility, and note that the model independence requires the measurement of the recoil HZ process at lower energies. ‡ILC luminosity upgrade assumes an extended running period on top of the low luminosity program and cannot be directly compared to TLEP and CLIC numbers without accounting for the additional running period. ILC numbers include a 0.5% theory uncertainty. For invisible decays of the Higgs, the number quoted is the 95% confidence upper limit on the branching ratio.*

Facility		ILC		ILC(LumiUp)	TLEP (4 IP)			CLIC	
$\sqrt{s}$ (GeV)	250	500	1000	250/500/1000	240	350	350	1400	3000
$\int \mathcal{L}dt$ (fb^{-1})	250	+500	+1000	1150+1600+2500‡	10000	+2600	500	+1500	+2000
$P(e^-, e^+)$	$(-0.8, +0.3)$	$(-0.8, +0.3)$	$(-0.8, +0.2)$	(same)	$(0, 0)$	$(0, 0)$	$(0, 0)$	$(-0.8, 0)$	$(-0.8, 0)$
Γ_H	12%	5.0%	4.6%	2.5%	1.9%	1.0%	9.2%	8.5%	8.4%
κ_γ	18%	8.4%	4.0%	2.4%	1.7%	1.5%	–	5.9%	<5.9%
κ_g	6.4%	2.3%	1.6%	0.9%	1.1%	0.8%	4.1%	2.3%	2.2%
κ_W	4.9%	1.2%	1.2%	0.6%	0.85%	0.19%	2.6%	2.1%	2.1%
κ_Z	1.3%	1.0%	1.0%	0.5%	0.16%	0.15%	2.1%	2.1%	2.1%
κ_μ	91%	91%	16%	10%	6.4%	6.2%	–	11%	5.6%
κ_τ	5.8%	2.4%	1.8%	1.0%	0.94%	0.54%	4.0%	2.5%	<2.5%
κ_c	6.8%	2.8%	1.8%	1.1%	1.0%	0.71%	3.8%	2.4%	2.2%
κ_b	5.3%	1.7%	1.3%	0.8%	0.88%	0.42%	2.8%	2.2%	2.1%
κ_t	–	14%	3.2%	2.0%	–	13%	–	4.5%	<4.5%
$BR_{\rm inv}$	0.9%	< 0.9%	< 0.9%	0.4%	0.19%	< 0.19%			

baseline ILC

FCC-ee

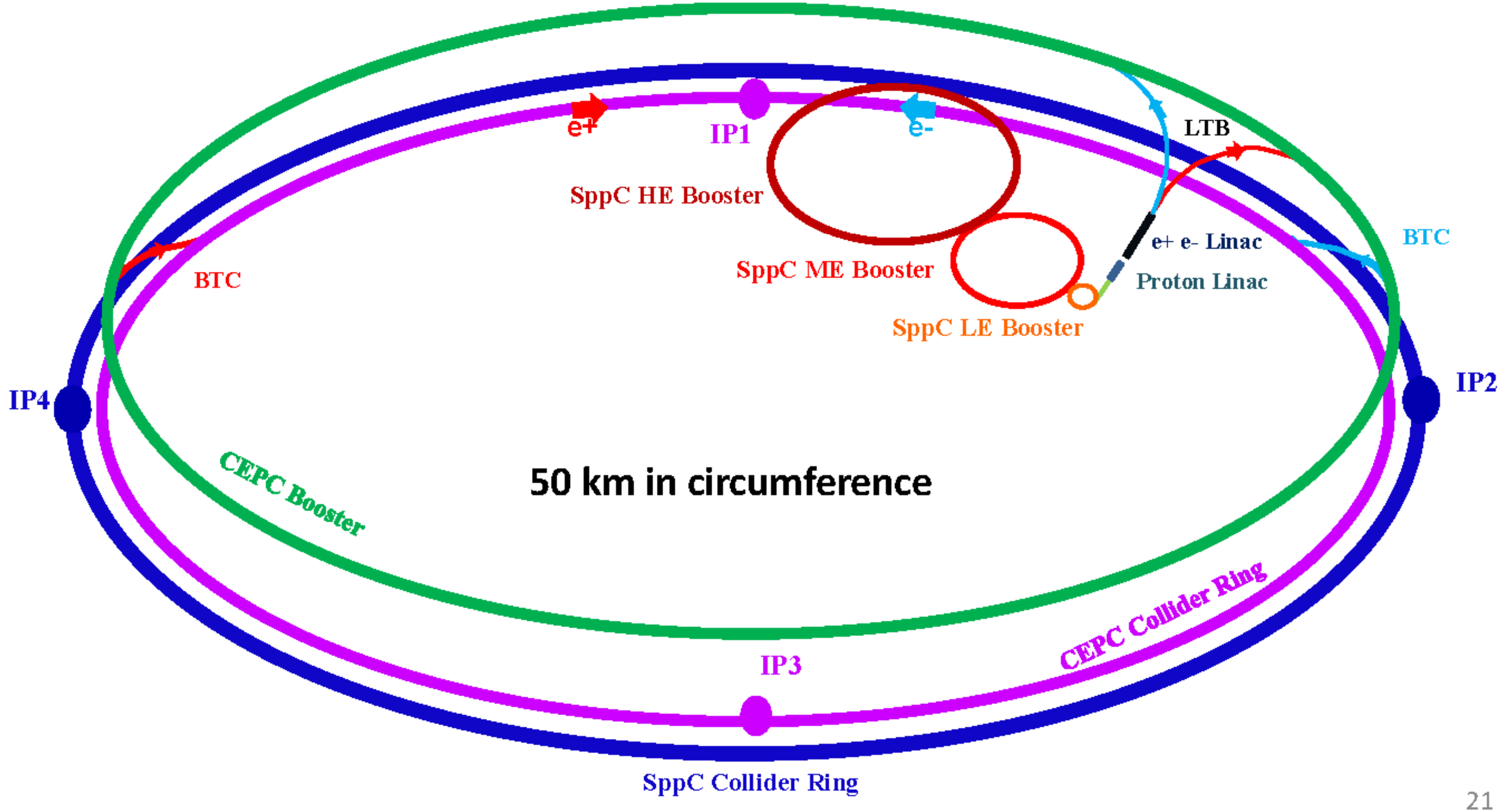
Accuracy of Higgs coupling for LHC, LC and FCC-ee (Snowmass 2013)

Table 1-20. *Expected precisions on the Higgs couplings and total width from a constrained 7-parameter fit assuming no non-SM production or decay modes. The fit assumes generation universality ($\kappa_u \equiv \kappa_t = \kappa_c$, $\kappa_d \equiv \kappa_b = \kappa_s$, and $\kappa_\ell \equiv \kappa_\tau = \kappa_\mu$). The ranges shown for LHC and HL-LHC represent the conservative and optimistic scenarios for systematic and theory uncertainties. ILC numbers assume (e^-, e^+) polarizations of $(-0.8, 0.3)$ at 250 and 500 GeV and $(-0.8, 0.2)$ at 1000 GeV, plus a 0.5% theory uncertainty. CLIC numbers assume polarizations of $(-0.8, 0)$ for energies above 1 TeV. TLEP numbers assume unpolarized beams.*

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 – 7%	2 – 5%	8.3%	4.4%	3.8%	2.3%	–/5.5/<5.5%	1.45%
κ_g	6 – 8%	3 – 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 – 6%	2 – 5%	0.39%	0.21%	0.21%	0.2%	1.5/0.15/0.11%	0.10%
κ_Z	4 – 6%	2 – 4%	0.49%	0.24%	0.50%	0.3%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 – 8%	2 – 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
$\kappa_d = \kappa_b$	10 – 13%	4 – 7%	0.93%	0.60%	0.51%	0.4%	1.7/0.32/0.19%	0.39%
$\kappa_u = \kappa_t$	14 – 15%	7 – 10%	2.5%	1.3%	1.3%	0.9%	3.1/1.0/0.7%	0.69%

CEPC-SppC

CEPC is an 240 GeV Circular Electron Positron Collider, proposed to carry out high precision study on Higgs bosons, which can be upgraded to a 70 TeV or higher pp collider **SppC**, to study the new physics beyond the Standard Model.



CepC/SppC study (CAS-IHEP), CepC CDR end of 2014, e^+e^- collisions ~2028; *pp* collisions ~2042

easy access

300 km from Beijing

3 h by car

1 h by train

"Chinese Toscana"

CEPC-SppC Project Timeline (dream)

CEPC

1[st] Milestone: pre-CDR (by the end of 2014) → R&D funding request to Chinese government in 2015
(China's 13[th] Five-Year Plan 2016-2020)

SppC

CEPC-SppC Schedule (Preliminary)

- CPEC
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-15 ➔ Pre-CDR by 2014
    - R&D: 2016-2020
    - Engineering Design: 2015-2020
  - Construction: 2021-2027
  - Data taking: 2030-2036

- SPPC
  - Pre-study, R&D and preparation work
    - Pre-study: 2013-2020
    - R&D: 2020-2030
    - Engineering Design: 2030-2035
  - Construction: 2036-2042
  - Data taking: 2042 -

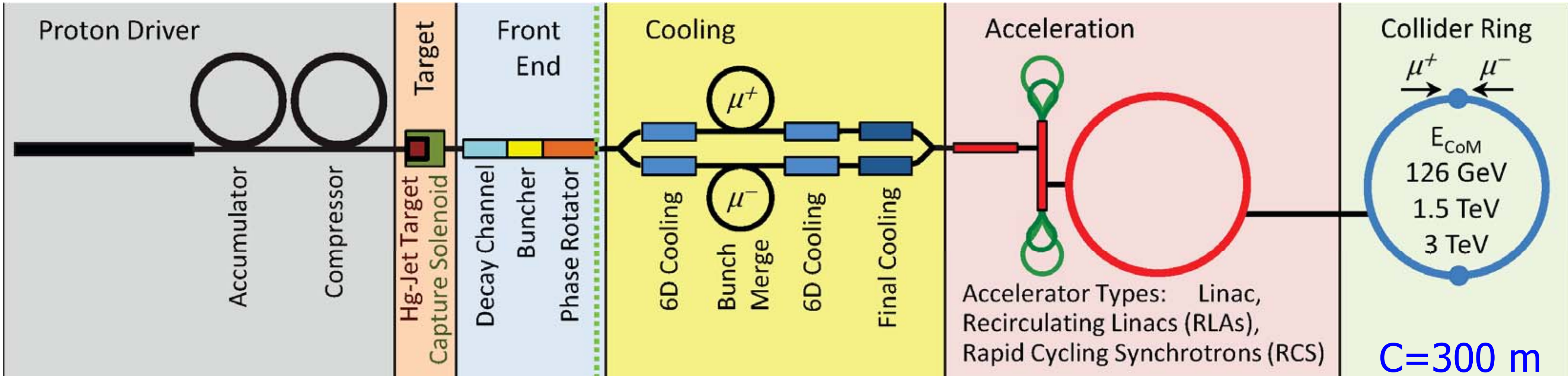
CEPC Design – Main Parameters

Parameter	Unit	Value	Parameter	Unit	Value
Beam energy [E]	GeV	120	**Circumference [C]**	m	54752
Number of IP[N_{IP}]		2	**SR loss/turn [U_0]**	GeV	3.11
Bunch number/beam[n_B]		50	**Bunch population [Ne]**		3.79E+11
SR power/beam [P]	MW	51.7	**Beam current [I]**	mA	16.6
Bending radius [ρ]	m	6094	**momentum compaction factor [α_p]**		3.36E-05
Revolution period [T_0]	s	1.83E-04	**Revolution frequency [f_0]**	Hz	5475.46
emittance (x/y)	nm	6.12/0.018	**β_{IP}(x/y)**	mm	800/1.2
Transverse size (x/y)	μm	69.97/0.15	**$\xi_{x,y}$/IP**		0.118/0.083
Bunch length SR [$\sigma_{s.SR}$]	mm	2.14	**Bunch length total [$\sigma_{s.tot}$]**	mm	2.65
Lifetime due to Beamstrahlung	min	47	**lifetime due to radiative Bhabha scattering [τ_L]**	min	51
RF voltage [V_{rf}]	GV	6.87	**RF frequency [f_{rf}]**	MHz	650
Harmonic number [h]		118800	**Synchrotron oscillation tune [ν_s]**		0.18
Energy acceptance RF [h]	%	5.99	**Damping partition number [Jε]**		2
Energy spread SR [$\sigma_{\delta.SR}$]	%	0.132	**Energy spread BS [$\sigma_{\delta.BS}$]**	%	0.096
Energy spread total [$\sigma_{\delta.tot}$]	%	0.163	**n_γ**		0.23
Transverse damping time [n_x]	turns	78	**Longitudinal damping time [n_ε]**	turns	39
Hourglass factor	Fh	0.68	**Luminosity /IP[L]**	$cm^{-2}s^{-1}$	2.04E+34

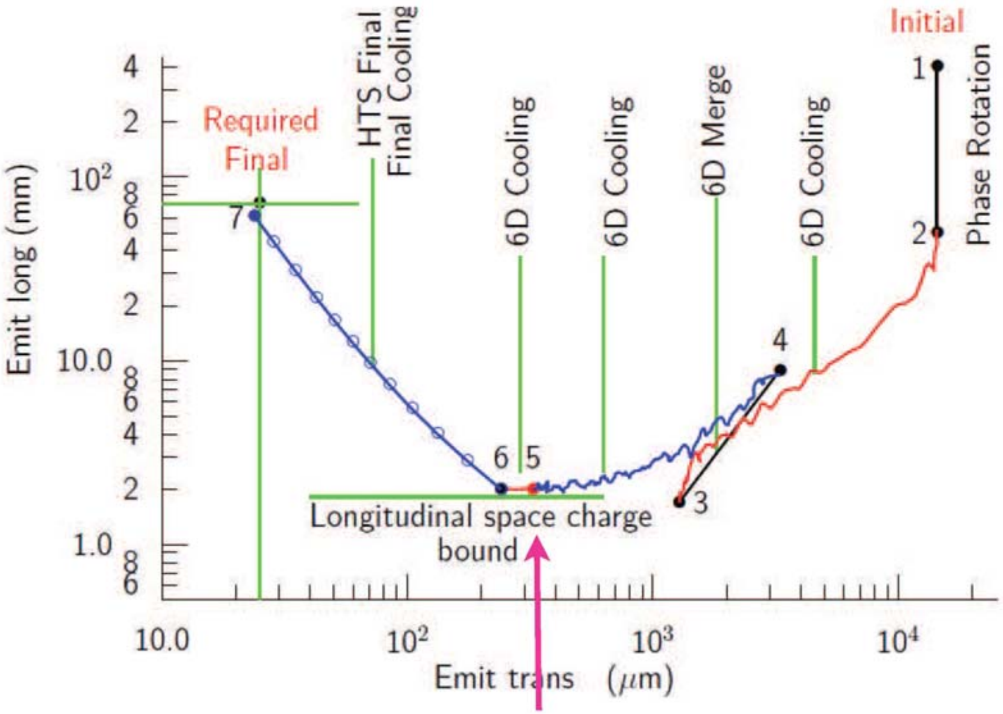
SppC Main Parameters (preliminary)

Parameter	Value	Unit
Circumference	52	km
Beam energy	35	TeV
Dipole field	20	T
Injection energy	2.1	TeV
Number of IPs	2 (4)	
Peak luminosity per IP	1.2E+35	$cm^{-2}s^{-1}$
Beta function at collision	0.75	m
Circulating beam current	1.0	A
Max beam-beam tune shift per IP	0.006	
Bunch separation	25	ns
Bunch population	2.0E+11	
SR heat load @arc dipole (per aperture)	56	W/m

Muon collider as a Higgs factory



C=300 m
~2000 turns



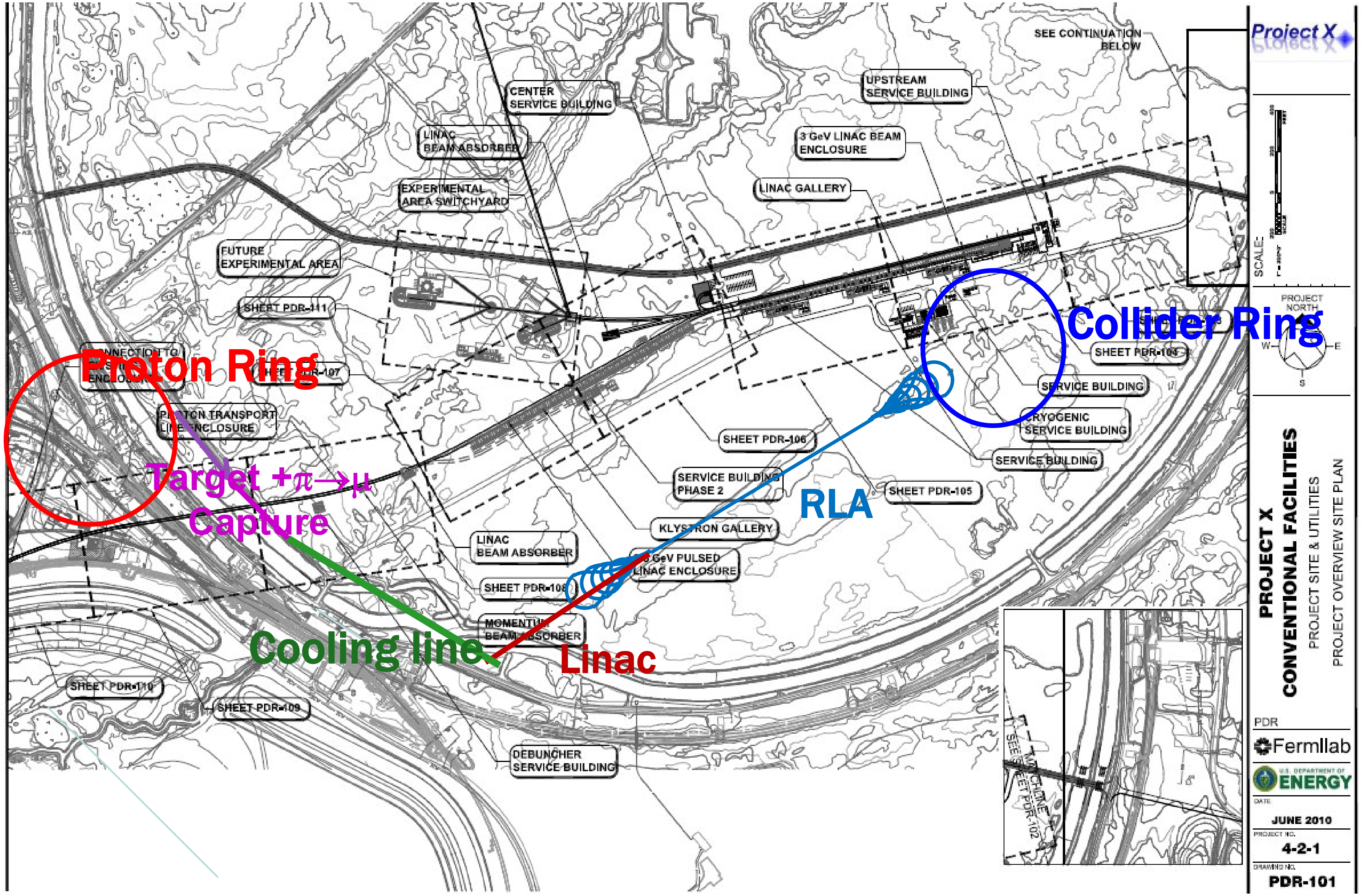
6D ionization cooling

Parameters of 126 GeV μ+μ- Higgs factory

	unit	Low L	High L
$2E_0$	GeV	126	126
Luminosity per IP	$10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$	0.001	0.01
Number of IPs		2	2
No. Higgs/yr(10^7 s) per IP	1000	5	50
Circumference	km	0.3	0.3
P (wall)	MW	100	125
Pol. μ^- and μ^+	%	10	10-20
N per bunch	10^{10}	200	500
Bunches per beam		1	1
Norm. emit. $\varepsilon_{x,n}$	mm-mrad	400	200
Norm. emit. $\varepsilon_{y,n}$	mm-mrad	400	200
β_x at IP	mm	60	40
β_y at IP	mm	60	40
σ_x at IP	μm	200	120
σ_y at IP	μm	200	120
σ_z at IP	mm	60	40
σ_E/E	%	0.003	0.003

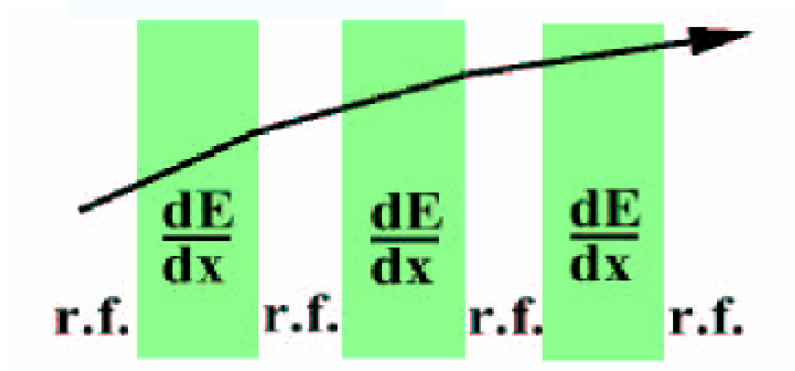
The luminosity is 2-3 orders of magnitude smaller than at e+e- colliders, but the Higgs production cross section is 200 times larger

Scale of facility

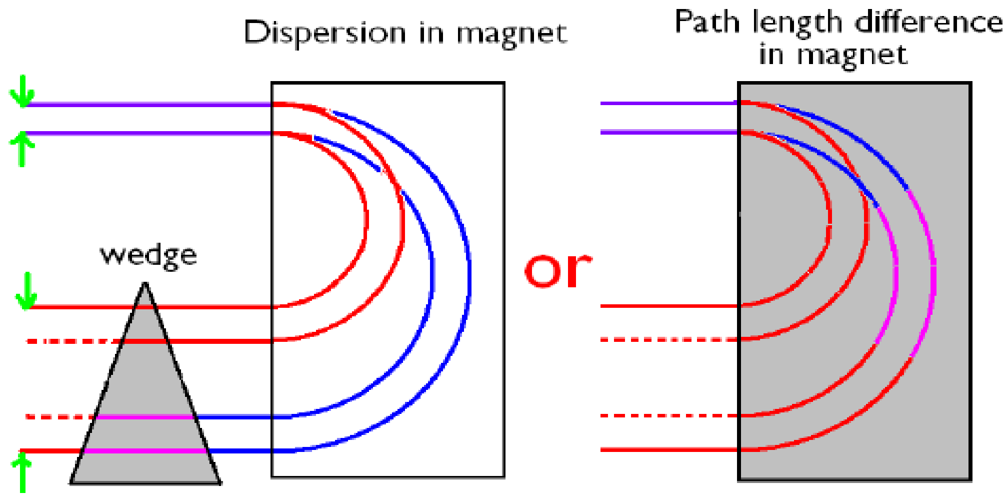


COOLING -- Principle is straightforward...

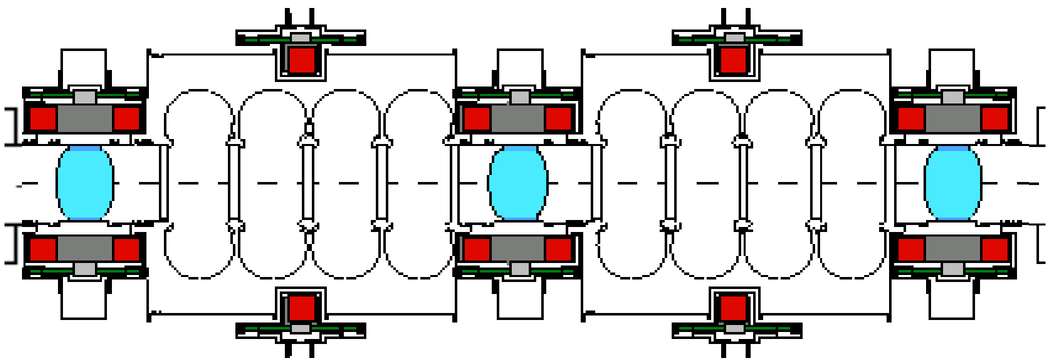
Transverse:



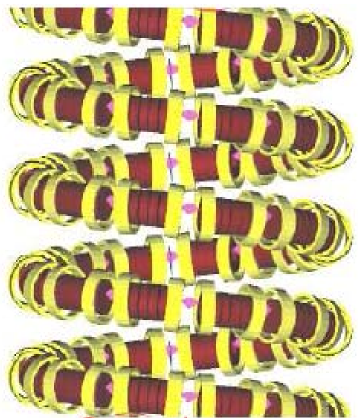
Longitudinal:



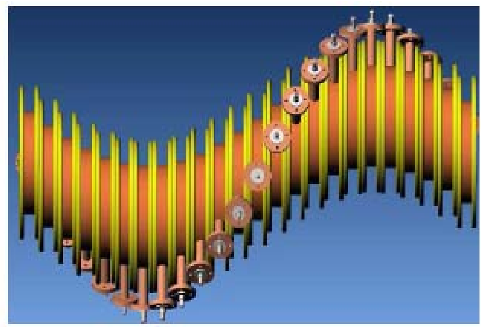
Practical realization is not!



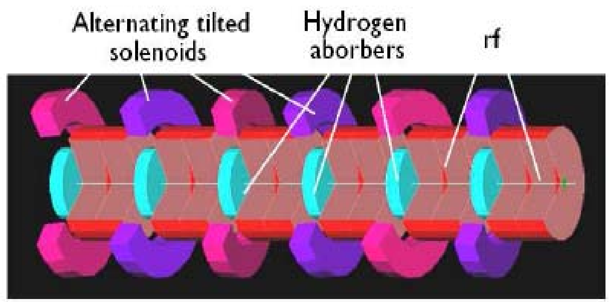
MICE cooling channel (4D cooling)



Guggenheim



Helical Cooling Channel



Snake

6D candidate cooling lattices

CERN next exits
GET IN LANE
China next right
HE-LHC
construction
2028+??
physics 2038+??
FCC-pp
(FCC-ee)
construction 2028+??
physics 2038+??
CLIC
construction 2028+??
physics 2038+??
SppS
construction 2028+??
physics 2038+??
Muon Collider
construction 2030+?
physics 2040+?
LHC
for the next 20 years
ILC in Japan
construction 2018?
physics 2028?
CepC in China
construction 2018?
physics 2028?
N. Walker

Conclusion

❖ A Higgs factory is needed for precision measurement of the Higgs properties. Possible candidates:

Linear e+e- Collider (2E=240-350 GeV→500-1000-3000 GeV)
Ring e+e- Collider (2E=240-350 GeV)
Muon collider (2E=126 GeV→3 -100 TeV)

The choice depends on LHC discoveries:

❖If new physics (like SUSY, etc) exists in 200-1000 GeV region, then ILC or CLIC.

❖If new physics exist in 1000-3000 GeV region, then CLIC.

❖If nothing, except H, is found, then a low energy e+e- Higgs factory, ring or LC. Ring Higgs factory with large R looks very attractive.

❖ Muon collider is always welcome (as potentially the highest energy collider)