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PUBLICATION

Circular Higgs Factories & Possible Long-Term Strategy

Zimmermann, F (CERN)

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Circular Higgs Factories & Possible Long-Term Strategy

Frank Zimmermann, CERN/BE

oPAC Grand Challenge workshop, CERN, 26 June 2013

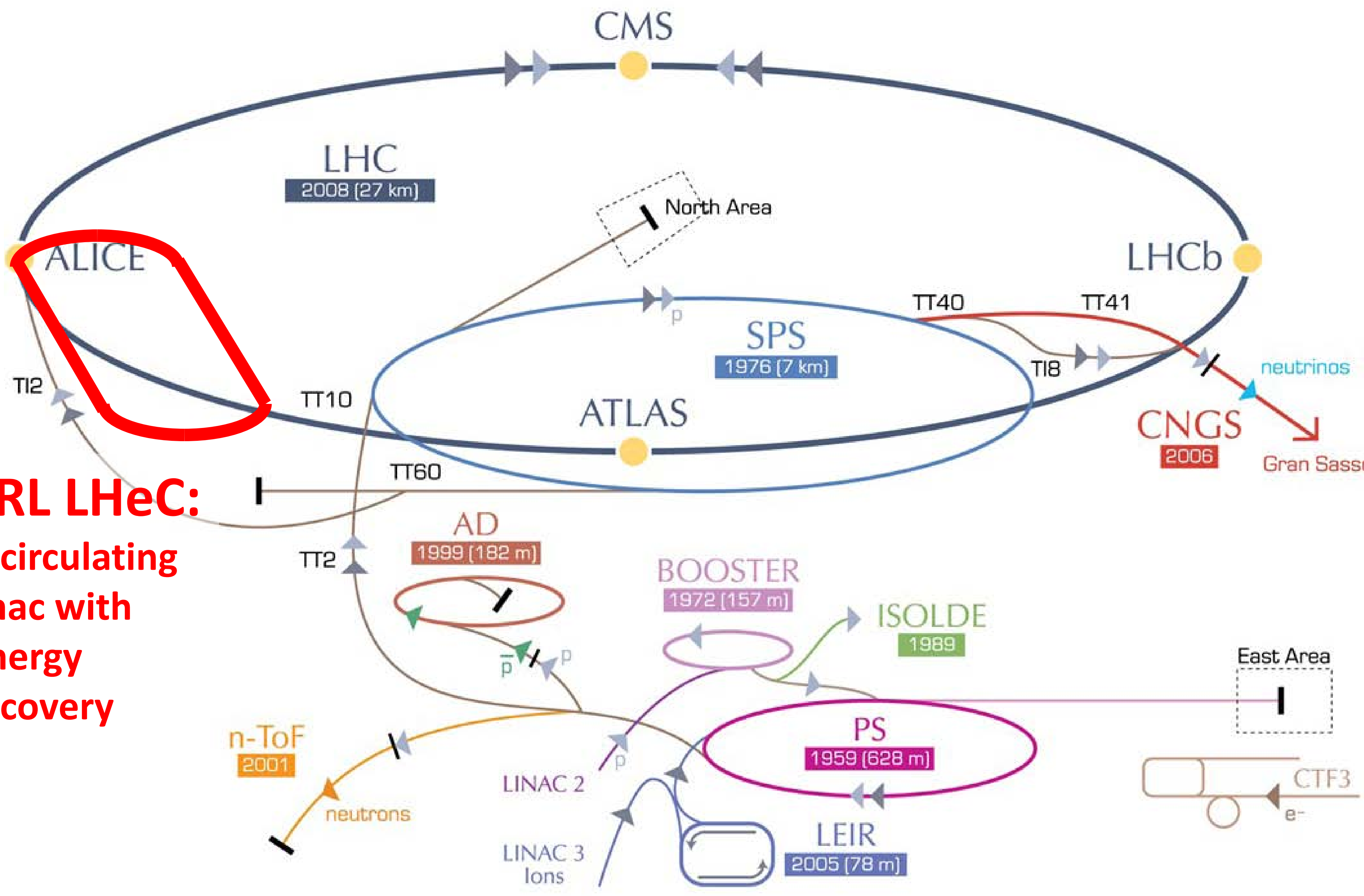
*Work supported by the **European Commission** under the FP7 Research Infrastructures project **EuCARD**, grant agreement no.~227579*

possible future circular colliders

- LHeC & SAPPHiRE
- HE-LHC or VHE-LHC
- LEP3 or TLEP
- even higher-energy *pp* collider?
- ultimate limits

LHeC

Large Hadron electron Collider (LHeC)



ERL LHeC:

recirculating linac with energy recovery

LHeC Conceptual Design Report

DRAFT 1.0
Geneva, September 3, 2011
CERN report
ECFA report
NuPECC report
LHeC-Note-2011-003 GEN

A Large Hadron Electron Collider at CERN

Report on the Physics and Design
Concepts for Machine and Detector

LHeC Study Group

THIS IS THE VERSION FOR REFEREEING, NOT FOR DISTRIBUTION

LHeC CDR published in J. Phys. G: Nucl. Part. Phys. 39 075001 (2012)

http://cern.ch/lhec

LHeC Study Group

J. Abelleira Fernandez[10,15], C.Adolphsen[39], S.Alekhin[40,11], A.N.Akai[01], H.Aksakal[30], P.Allport[17], J.L.Albacete[37], V.Andreev[25], R.B.Appleby[23], N.Armesto[38], G.Azuelos[26], M.Bai[47], D.Barber[11], J.Bartels[12], J.Behr[11], O.Behnke[11], S.Belyaev[10], I.BenZvi[47], N.Bernard[16], S.Bertolucci[10], S.Bettoni[10], S.Biswal[32], J.Bluemlein[11], H.Boettcher[11], H.Braun[48], S.Brodsky[39], A.Bogacz[28], C.Bracco[10], O.Bruening[10], E.Bulyak[08], A.Bunyatian[11], H.Burkhardt[10], I.T.Cakir[54], O.Cakir[53], R.Calaga[47], E.Ciapala[10], R.Ciftci[01], A.K.Ciftci[01], B.A.Cole[29], J.C.Collins[46], J.Dainton[17], A.De.Roeck[10], D.d'Enterria[10], A.Dudarev[10], A.Eide[43], E.Eroglu[45], K.J.Eskola[14], L.Favart[06], M.Fitterer[10], S.Forte[24], P.Gambino[42], T.Gehrmann[50], C.Glasman[22], R.Godbole[27], B.Goddard[10], T.Greenshaw[17], A.Guffanti[09], V. Guzey[28], C.Gwenlan[34], T.Han[36], Y.Hao[47], F.Haug[10], W.Herr[10], B.Holzer[10], M.Ishitsuka[41], M.Jacquet[33], B.Jeanneret[10], J.M.Jimenez[10], H.Jung[11], J.M.Jowett[10], H.Karadeniz[54], D.Kayran[47], F.Kocac[45], A.Kilic[45], K.Kimura[41], M.Klein[17], U.Klein[17], T.Kluge[17], G.Kramer[12], M.Korostelev[23], A.Kosmicki[10], P.Kostka[11], H.Kowalski[11], D.Kuchler[10], M.Kuze[41], T.Lappi[14], P.Laycock[17], E.Levichev[31], S.Levonian[11], V.N.Litvinenko[47], A.Lombardi[10], C.Marquet[10], B.Mellado[07], K.H.Mess[10], S.Moch[11], I.I.Morozov[31], Y.Muttoni[10], S.Myers[10], S.Nandi[26], P.R.Newman[03], T.Omori[44], J.Osborne[10], Y.Papaphilippou[10], E.Paoloni[35], C.Pascaud[33], H.Paukkunen[38], E.Perez[10], T.Pieloni[15], E.Pilicer[45], A.Polini[04], V.Ptitsyn[47], Y.Pupkov[31], V.Radescu[13], S.Raychaudhuri[27], L.Rinolfi[10], R.Rohini[27], J.Rojo[24], S.Russenschuck[10], C.A.Salgado[38], K.Sampei[41], E.Sauvan[19], M.Sahin[01], U.Schneekloth[11], A.N.Skrinsky[31], T.Schoerner Sadenius[11], D.Schulte[10], H.Spiesberger[21], A.M.Stasto[46], M.Strikman[46], M.Sullivan[39], B.Surrow[05], S.Sultansoy[01], Y.P.Sun[39], W.Smith[20], I.Tapan[45], P.Taels[02], E.Tassi[52], H.Ten.Kate[10], J.Terron[22], H.Thiesen[10], L.Thompson[23], K.Tokushuku[44], R.Tomas.Garcia[10], D.Tommasini[10], D.Trbojevic[47], N.Tsoupas[47], J.Tuckmantel[10], S.Turkoz[53], K.Tywoniuk[18], G.Unel[10], J.Urakawa[44], P.VanMechelen[02], A.Variola[37], R.Veness[10], A.Vivoli[10], P.Vobly[31], R.Wallny[51], G.Watt[10], G.Weiglein[12], C.Weiss[28], U.A.Wiedemann[10], U.Wienands[39], F.Willeke[47], V.Yakimenko[47], A.F.Zarnecki[49], F.Zimmermann[10], F.Zomer[33]

About 150 Experimentalists and Theorists from 50 Institutes
Tentative list

Thanks to all and to
CERN, ECFA, NuPECC

~600 pages

L-R LHeC road map to $\geq 10^{33}$ $cm^{-2}s^{-1}$

luminosity of LR collider:

(round beams)

H_D~1.3

D. Schulte
LHeC2010

$$L = \frac{1}{4\pi e} \frac{N_{b,p}}{\varepsilon_p} \frac{1}{\beta_p^*} I_e H_{hg} H_D$$

highest proton beam brightness "permitted" (ultimate LHC values)

$\gamma\varepsilon$=3.75 μm

N_b=1.7x10^{11}

bunch spacing 25 or 50 ns

smallest conceivable proton β* function:

- **reduced *l** (23 m → 10 m)**
- **squeeze only one *p* beam**
- **new magnet technology Nb_3Sn**

β^*_p=0.1 m

average e^- current limited by energy recovery efficiency

I_e=6.4 mA

maximize geometric overlap factor

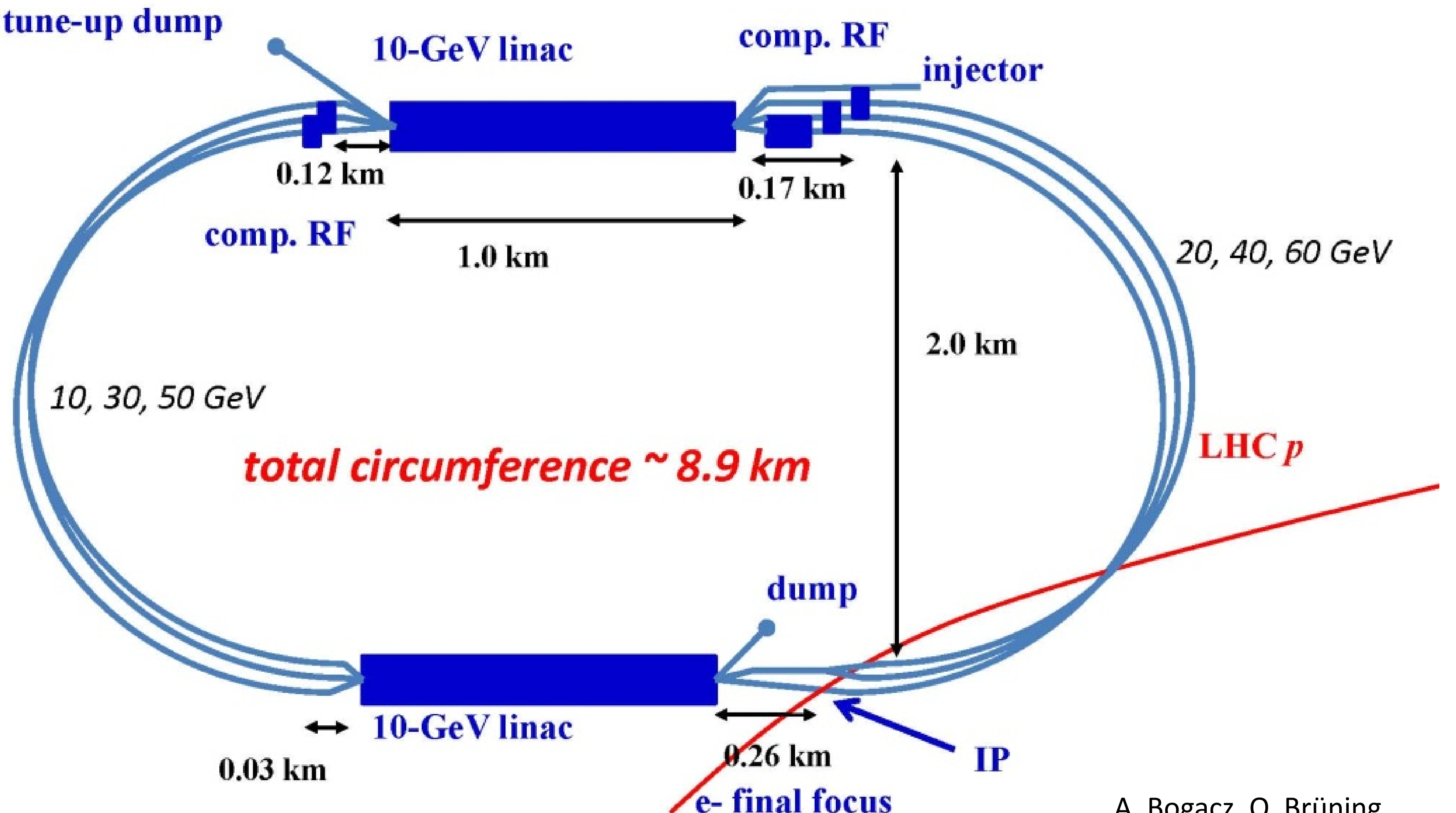
- **head-on collision**
- **small e- emittance**

θ_c=0

$H_{hg}\geq$0.9

LHeC ERL layout

two SC linacs, 3-pass up, 3-pass down; 6.4-mA 60-GeV *e*⁻'s collide w. LHC *p*/ions, *e*⁻ RF grad ~20 MV/m, 800 MHz



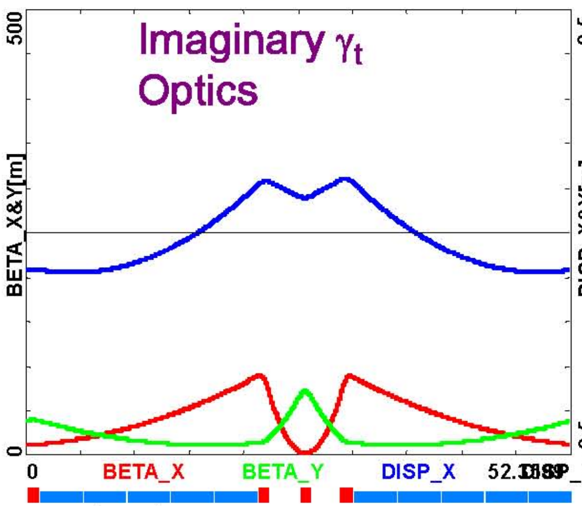
(C=1/3 LHC allows for ion clearing gaps)

A. Bogacz, O. Brüning, M. Klein, D. Schulte, F. Zimmermann, et al

LHeC: 3 passes, flexible momentum compaction arc lattice building block: 52 m long cell with 2 (10) dipoles & 4 quadrupoles

LHeC flexible momentum compaction cell; tuned for small beam size (low energy) or low $\Delta\varepsilon$ (high energy)

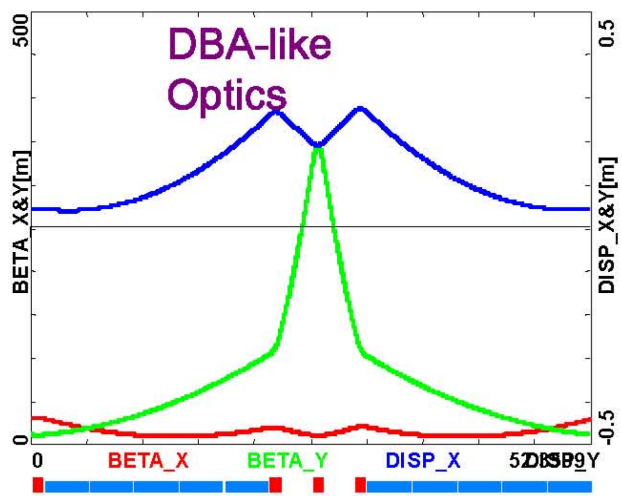
Arc 1 , Arc2



$$\langle H \rangle = 8.8 \times 10^{-3}\ m$$

limit chamber size
(>12 σ at 25 mm diameter)

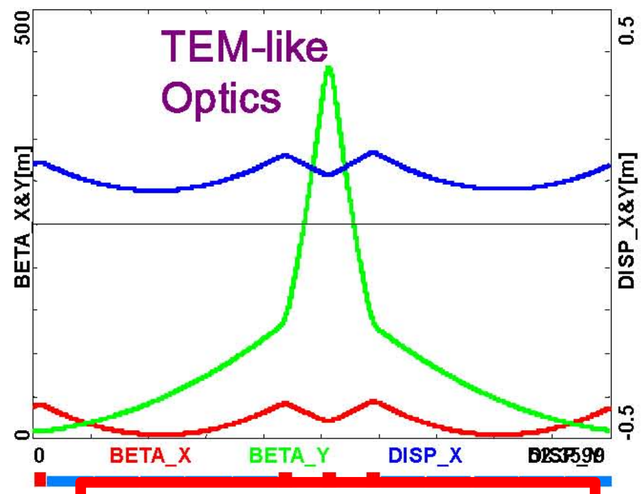
Arc 3, Arc 4



$$\langle H \rangle = 2.2 \times 10^{-3}\ m$$

Alex Bogacz

Arc5, Arc 6



$$\langle H \rangle = 1.2 \times 10^{-3}\ m$$

factor of 18 smaller than FODO

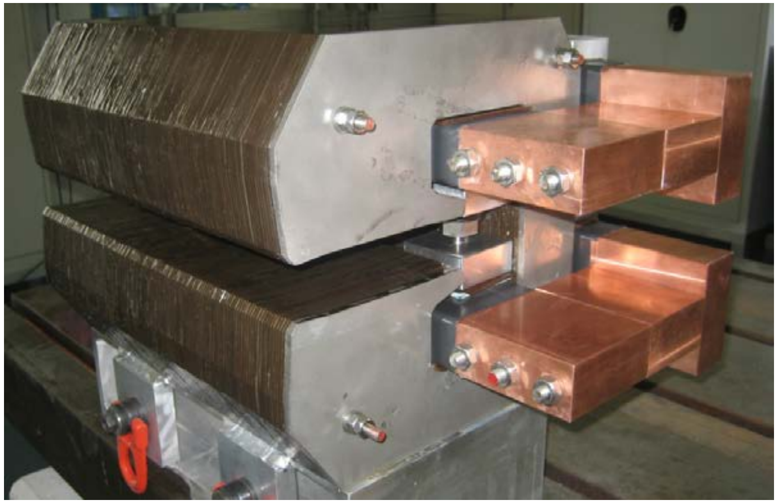
limit emittance growth

prototype arc magnets

eRHIC dipole model (BNL)

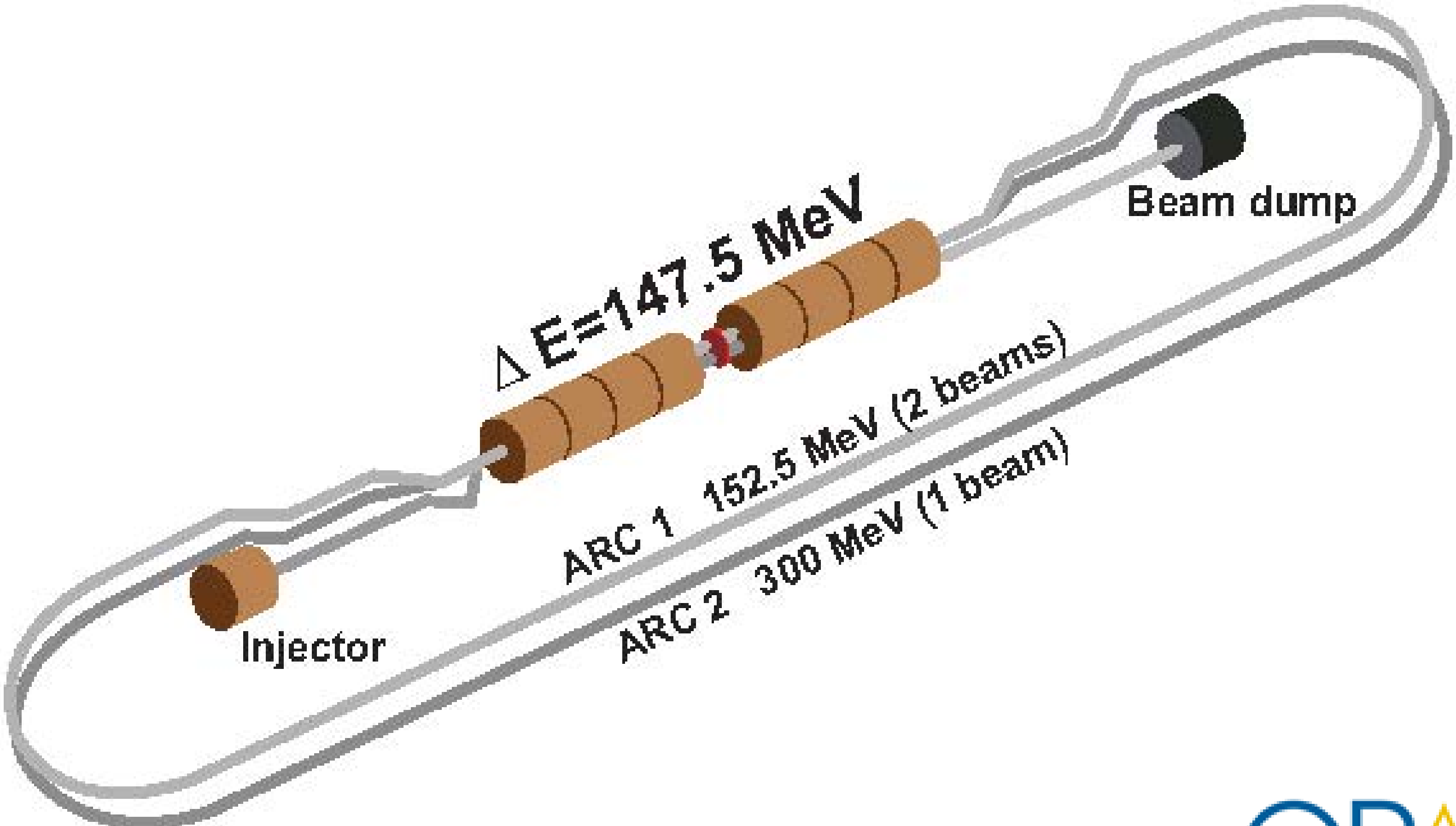
5 mm gap
max. field 0.43 T (30 GeV)

LHeC dipole models
(BINP & CERN)



25 mm gap
max. field 0.264 T (60 GeV)

LHeC test facility @ CERN



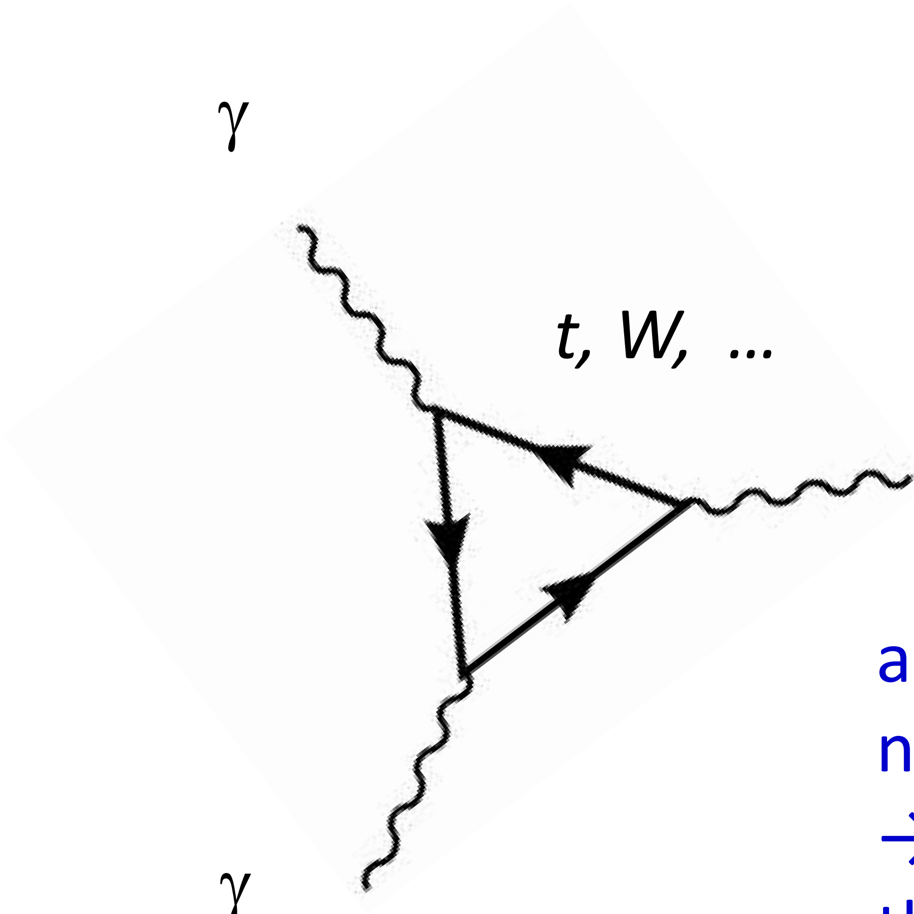
being designed by oPAC fellow Alessandra Valloni

LHeC baseline & Higgs factory parameters

parameter [unit]	LHeC baseline		LHeC Higgs factory	
species	e^-	p	e^-	p
beam energy (/nucleon) [GeV]	60	7000	60	7000
bunch spacing [ns]	25 (50)	25 (50)	25 (50)	25 (50)
bunch intensity (nucleon) [10^{10}]	0.1 (0.2)	17	0.4 (0.8)	22 (35)
beam current [mA]	6.4	860	25.6	1110 (883)
rms bunch length [mm]	0.6	75.5	0.6	75.5
polarization [%]	90	none	90	none
normalized rms emittance [μm]	50	3.75	50	2.5 (3.0)
geometric rms emittance [nm]	0.43	0.50	0.43	0.34
IP beta function $\beta^*_{x,y}$ [m]	0.12	0.1	0.039	0.05
IP spot size [μm]	7.2	7.2	4.1	4.1
synchrotron tune Q_s	—	1.9×10^{-3}	—	1.9×10^{-3}
hadron beam-beam parameter	0.0001 (0.0002)		0.0004 (0.0008)	
lepton disruption parameter D	6		23 (31)	
crossing angle	0		0	
hourglass reduction factor H_{hg}	0.91		0.70 (0.73)	
pinch enhancement factor H_D	1.35		1.35	
c.m. energy [GeV]	1300		1300	
luminosity / nucleon [10^{33} cm^{-2}s^{-1}]	1.3		L_{ep} ~2 10^{34} cm^{-2}s^{-1}	


SAPPHiRE

a different type of collider

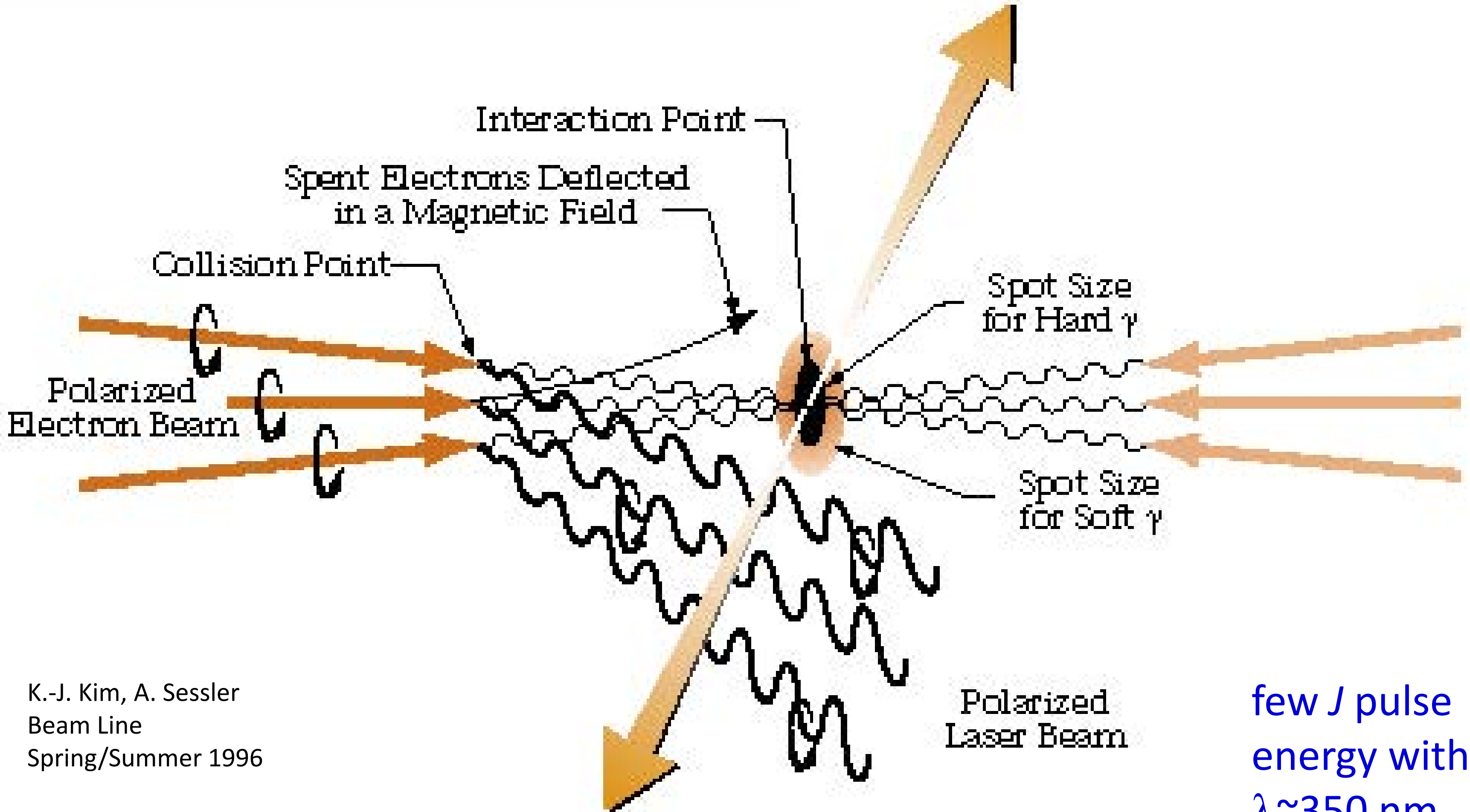


s-channel production;
lower energy;
no e^+ source

another advantage:
no beamstrahlung
→ higher energy reach
than e^+e^- colliders

γγ collider Higgs factory

γγ collider based on e^-



K.-J. Kim, A. Sessler
Beam Line
Spring/Summer 1996

few *J* pulse energy with λ~350 nm

combining photon science & particle physics!

which beam & photon energy / wavelength?

$$E_{\gamma,max} = \frac{x}{1+x} E_{beam}$$

$$x = \frac{4E_e\omega_L}{m_e^2}\cos^2\frac{\theta}{2}$$

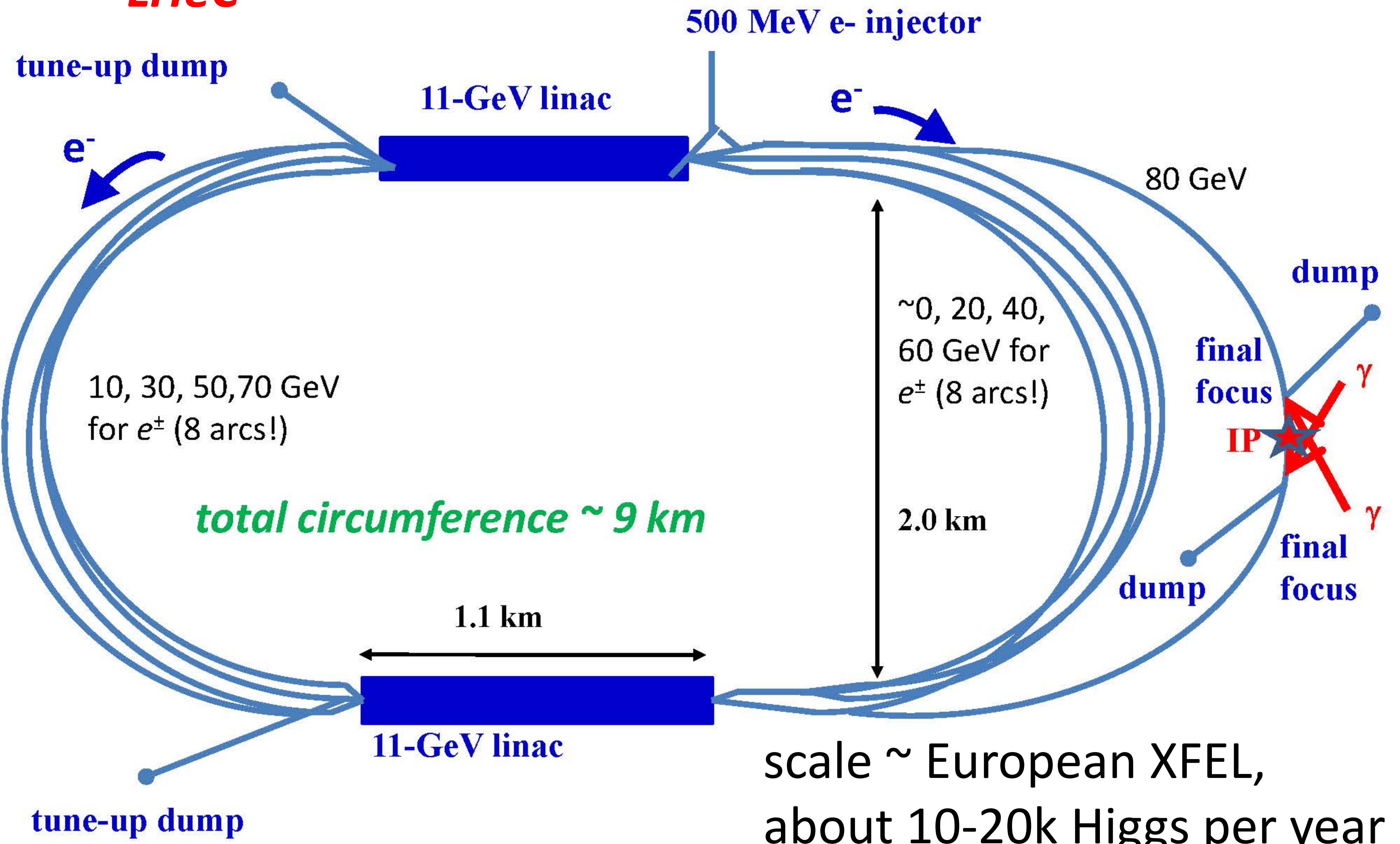
example $x \approx 4.3$
(for x>4.83 coherent pair production occurs)

with $E_{beam} \approx 80$ GeV: $E_{\gamma,max} \approx$66 GeV
$E_{CM,max} \approx 132$ GeV

E_{photon} ~3.53 eV , λ~351 nm

Reconfigured *LHeC*

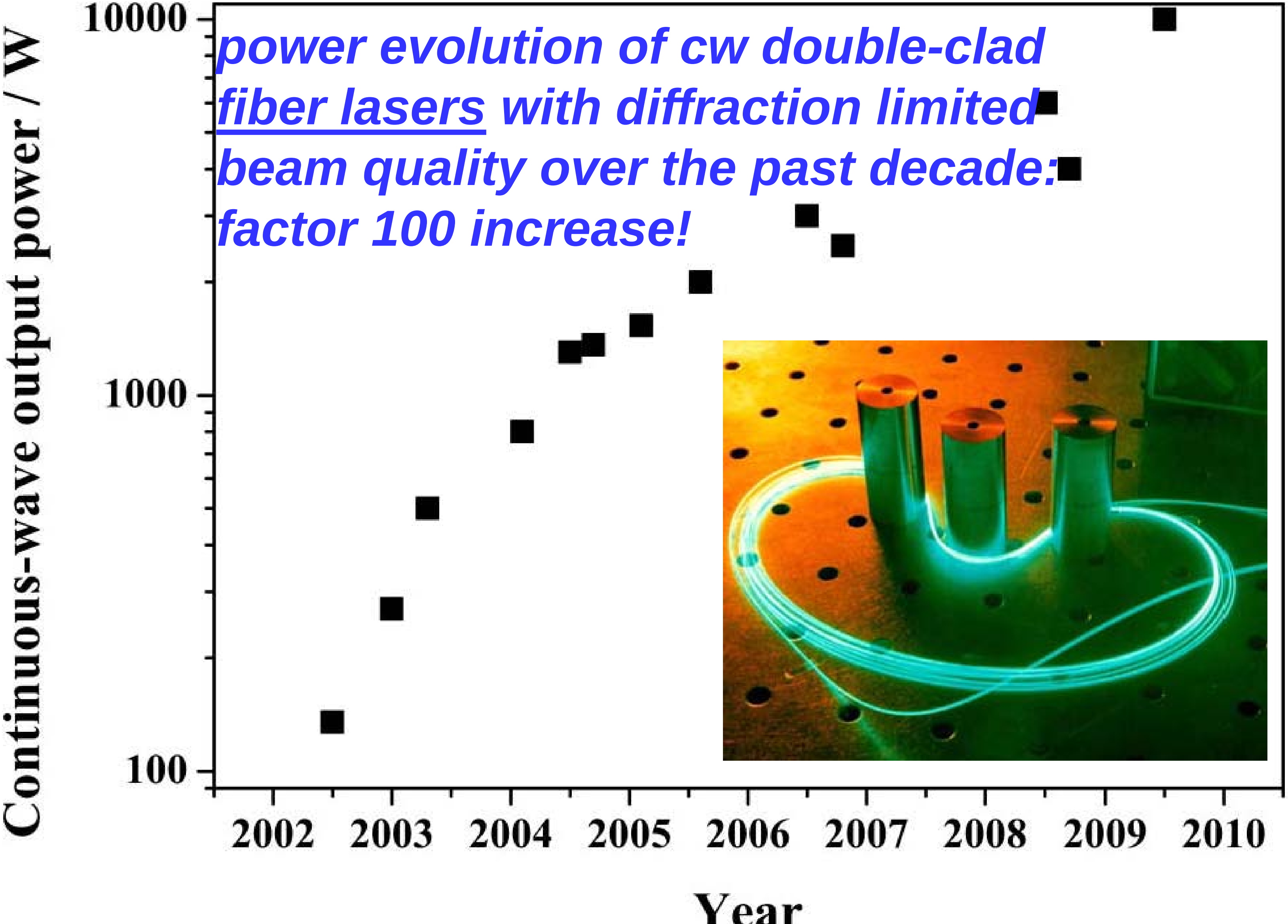
SAPPHiRE γγ Higgs Factory



scale ~ European XFEL,
about 10-20k Higgs per year

SAPPHiRE: Small Accelerator for Photon-Photon Higgs production using Recirculating Electrons

laser progress: example fiber lasers

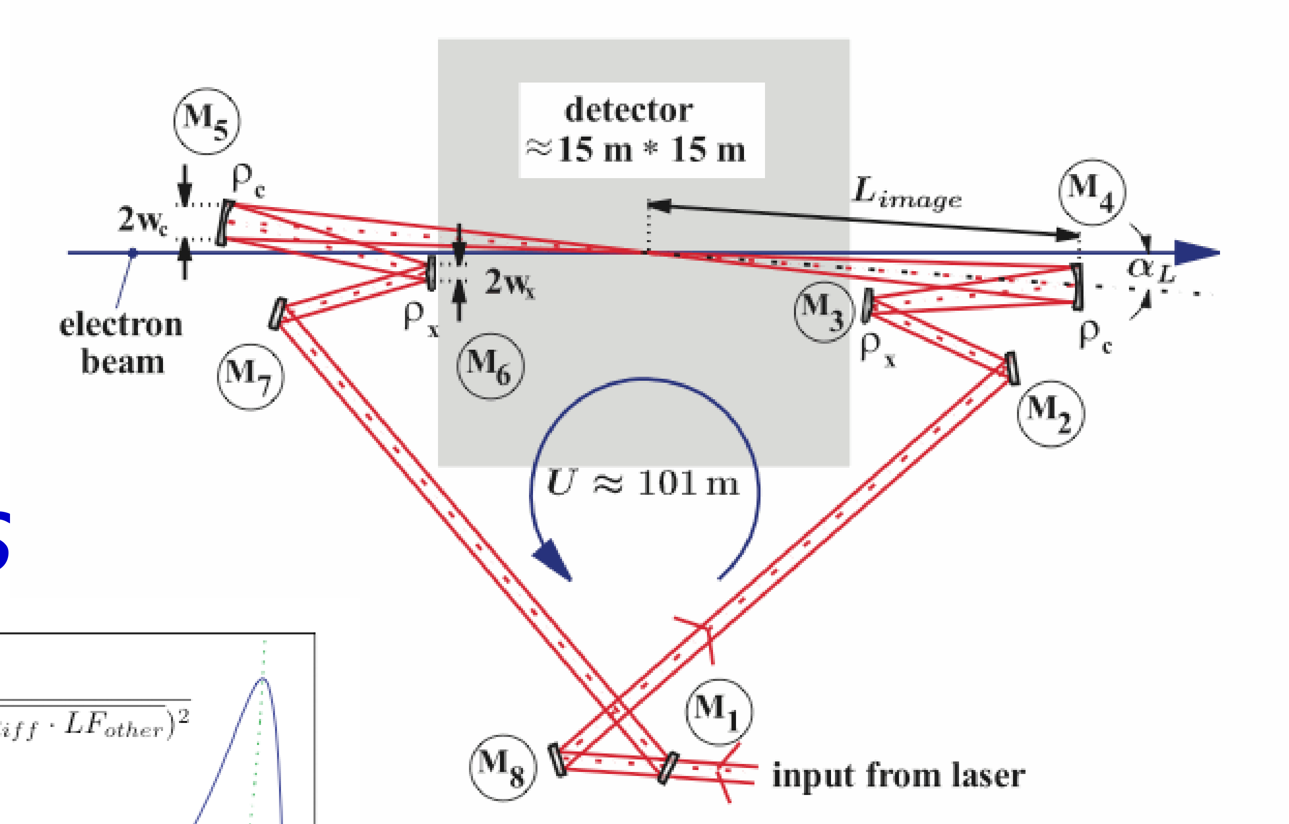


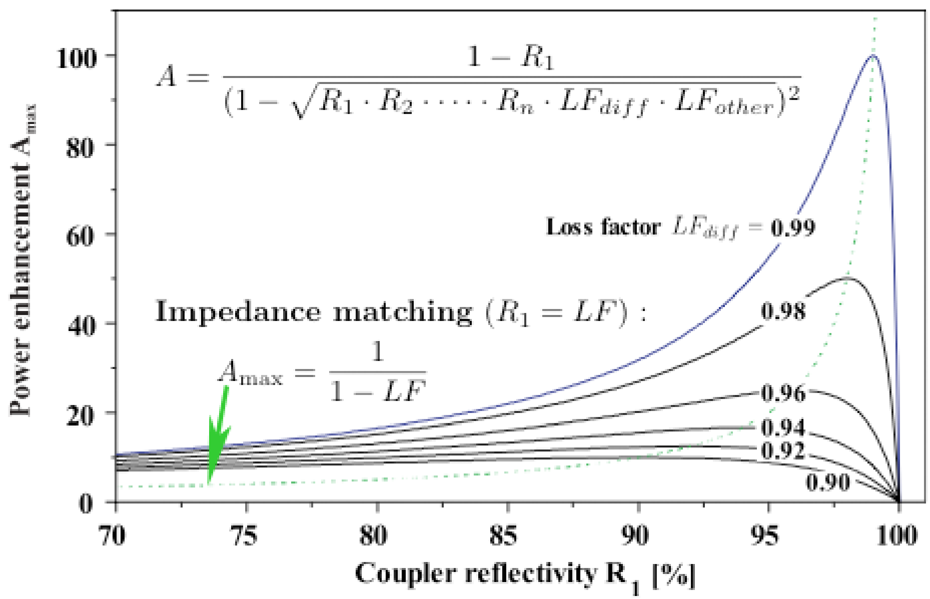
Source: Fiber lasers and amplifiers: an ultrafast performance evolution, Jens Limpert, Thomas Schreiber, and Andreas Tünnermann, Applied Optics, Vol. 49, No. 25 (2010)

passive optical cavity

→

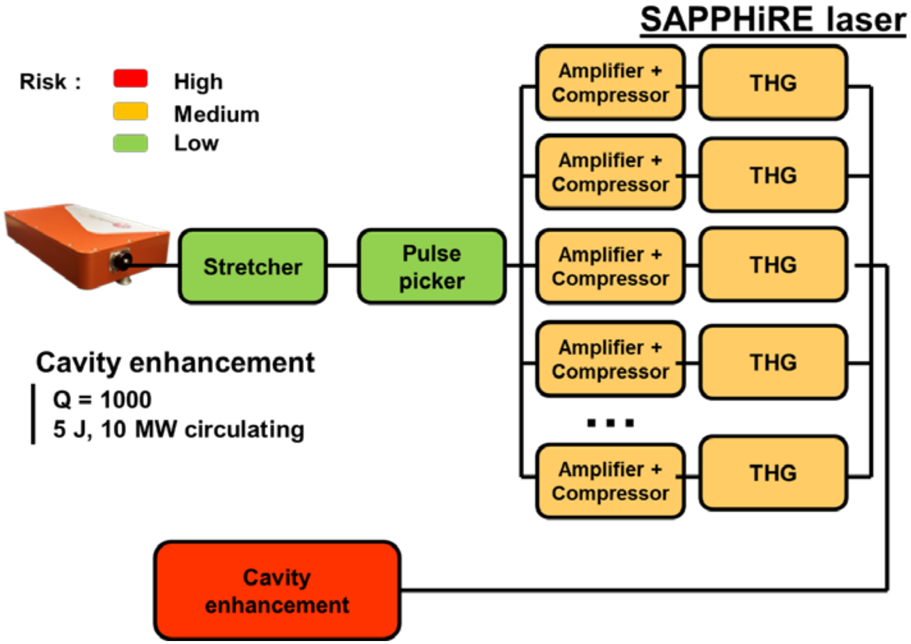
relaxed laser parameters



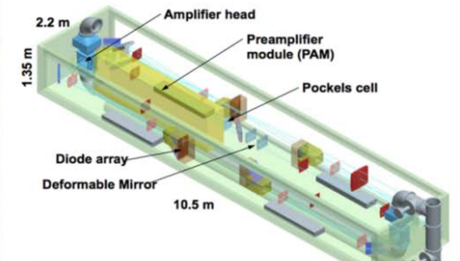


K. Moenig et al, DESY Zeuthen

laser options for SAPPHiRE



Y. Zaouter, Amplitude Systems



LIFE beam line :
- Pulses at 16 Hz
- 8.125 kJ / pulse
- 130 kW average power
- ns pulse width

J. Gronberg, LLNL

Gerard Mourou et al., *"The future is fiber accelerators," Nature Photonics, vol 7, p.258 (April 2013).*

10 J at 10 kHz

Figure 2: Principle of a coherent amplifier network (CAN) based on fiber laser technology. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of 10 kHz (7). [3]

G. Mourou, LOA;
M. Velasco,
Northwestern U.

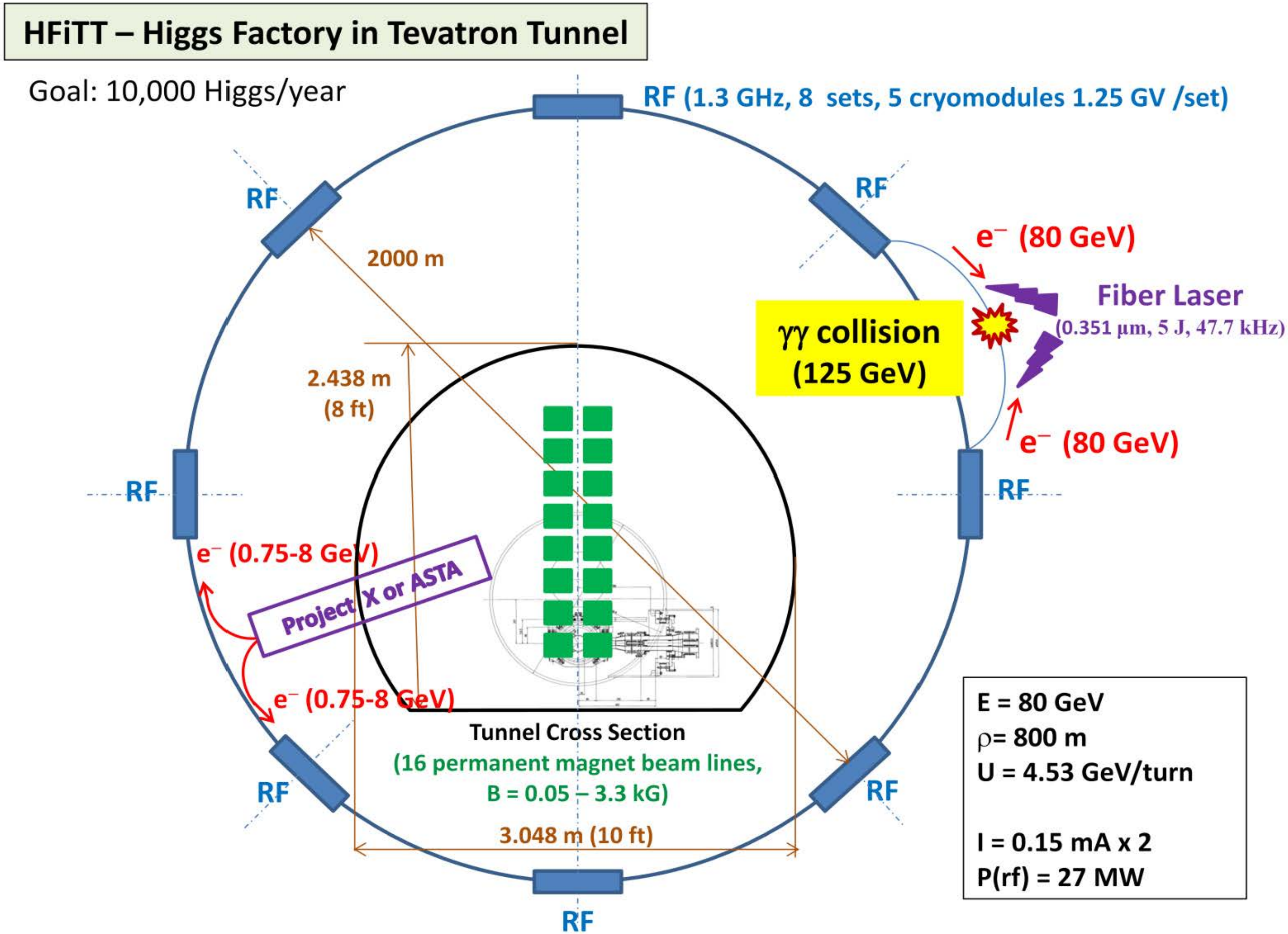
LHeC Higgs factory comparison

(1 year = 10^7 s at design luminosity).

machine	LHeC	LHeC-HF	SAPPHiRE
luminosity [10^{34} cm^{-2}s^{-1}]	0.1 (*ep*)	2 (*ep*)	0.06 ($\gamma\gamma$ >125 GeV)
cross section	~200 fb	~200 fb	>1.7 pb
no. Higgs/yr	2k	40k	>10k

HFITT – HF in Tevatron tunnel

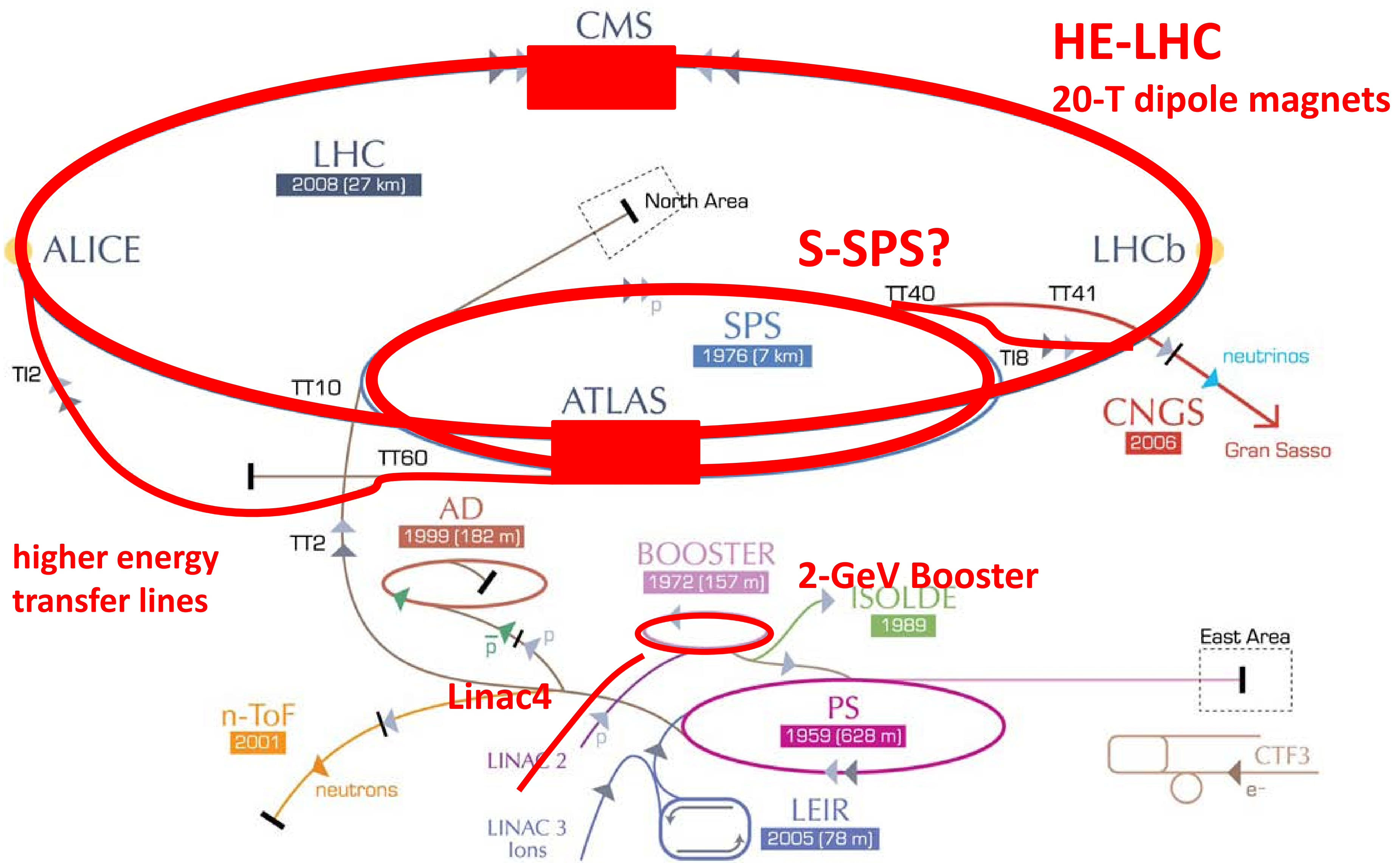
$\gamma\gamma$ collider inspired by SAPPHIRE



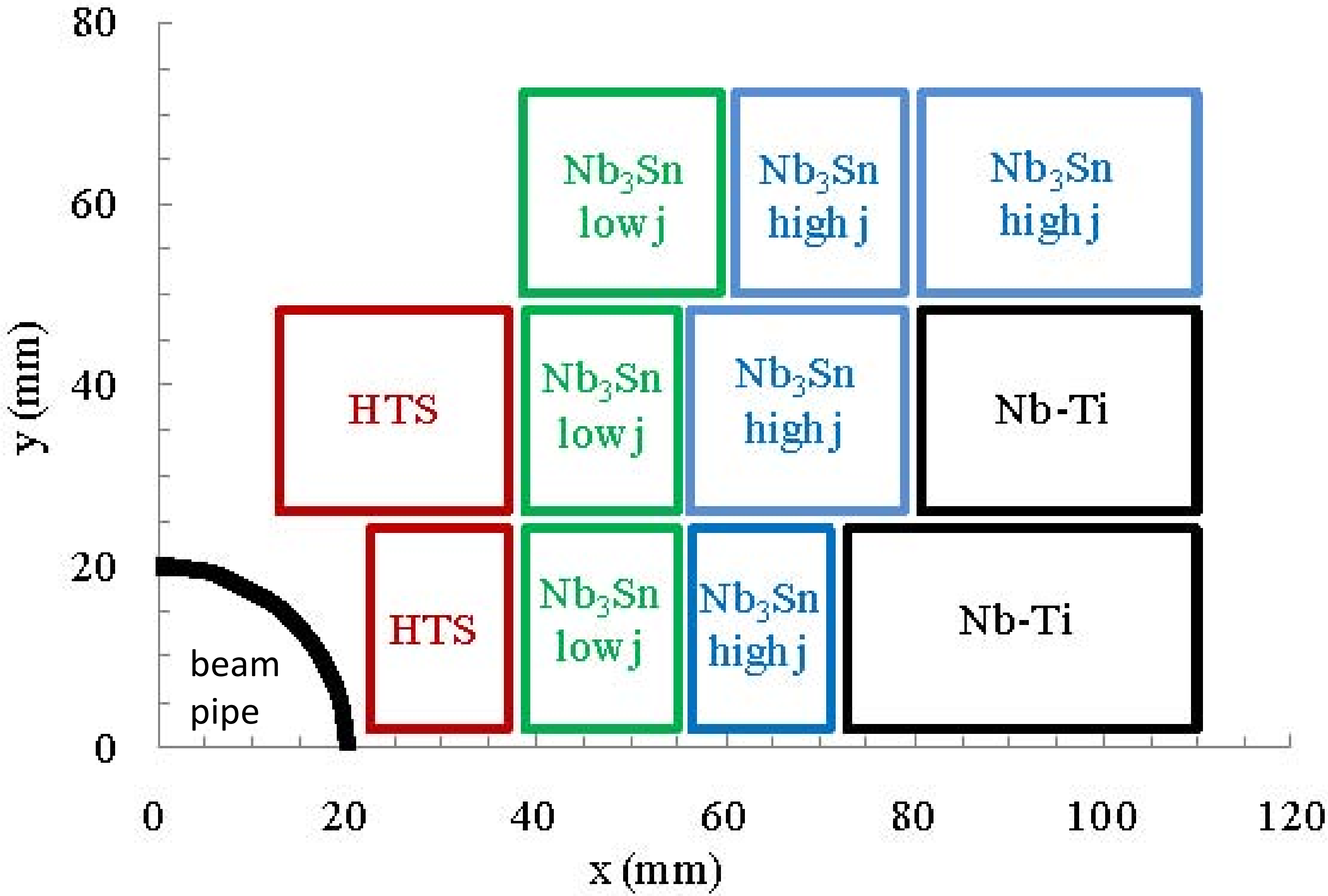
Weiren Chou, Gerard Mourou, Nikolay Solyak, Toshiki Tajima, Mayda Velasco, 20 May 2013

higher-energy *pp* colliders

High-Energy LHC

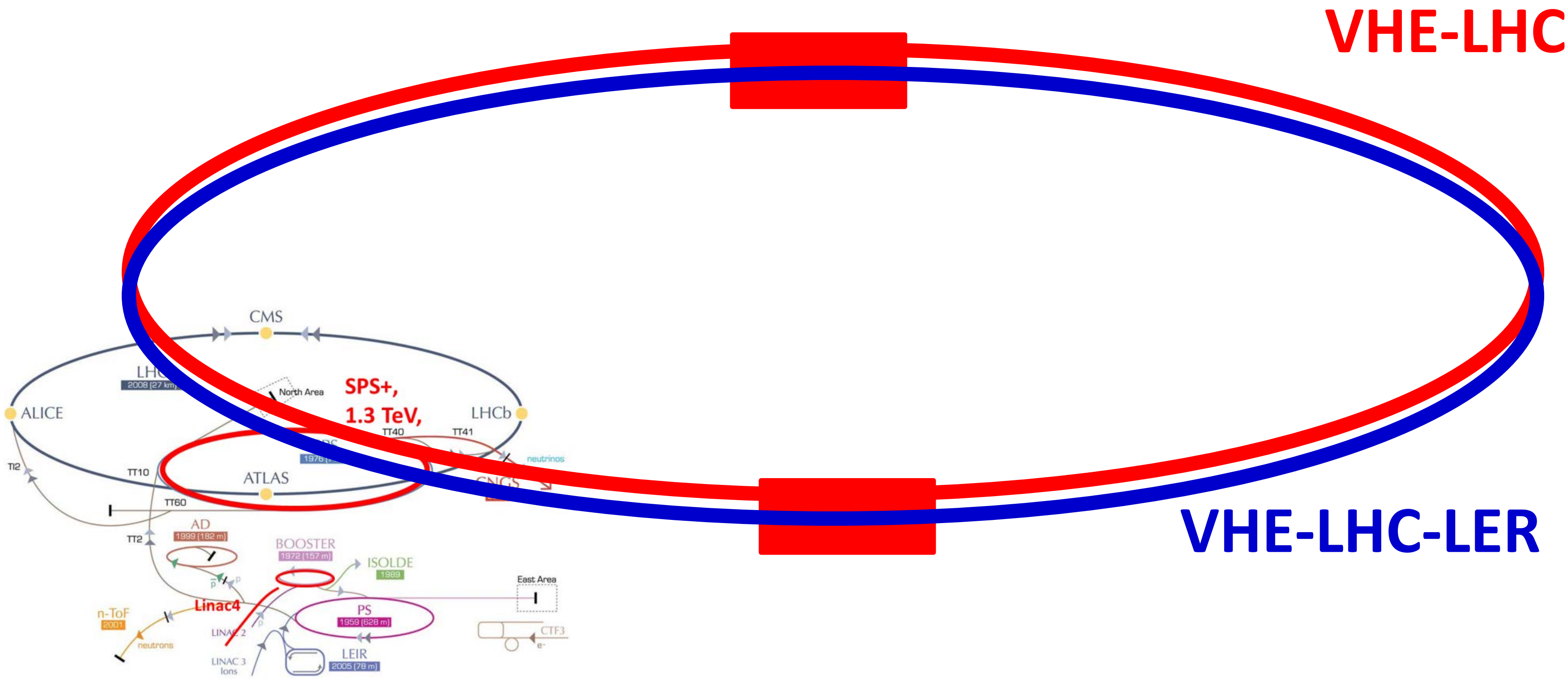


20-T dipole magnet



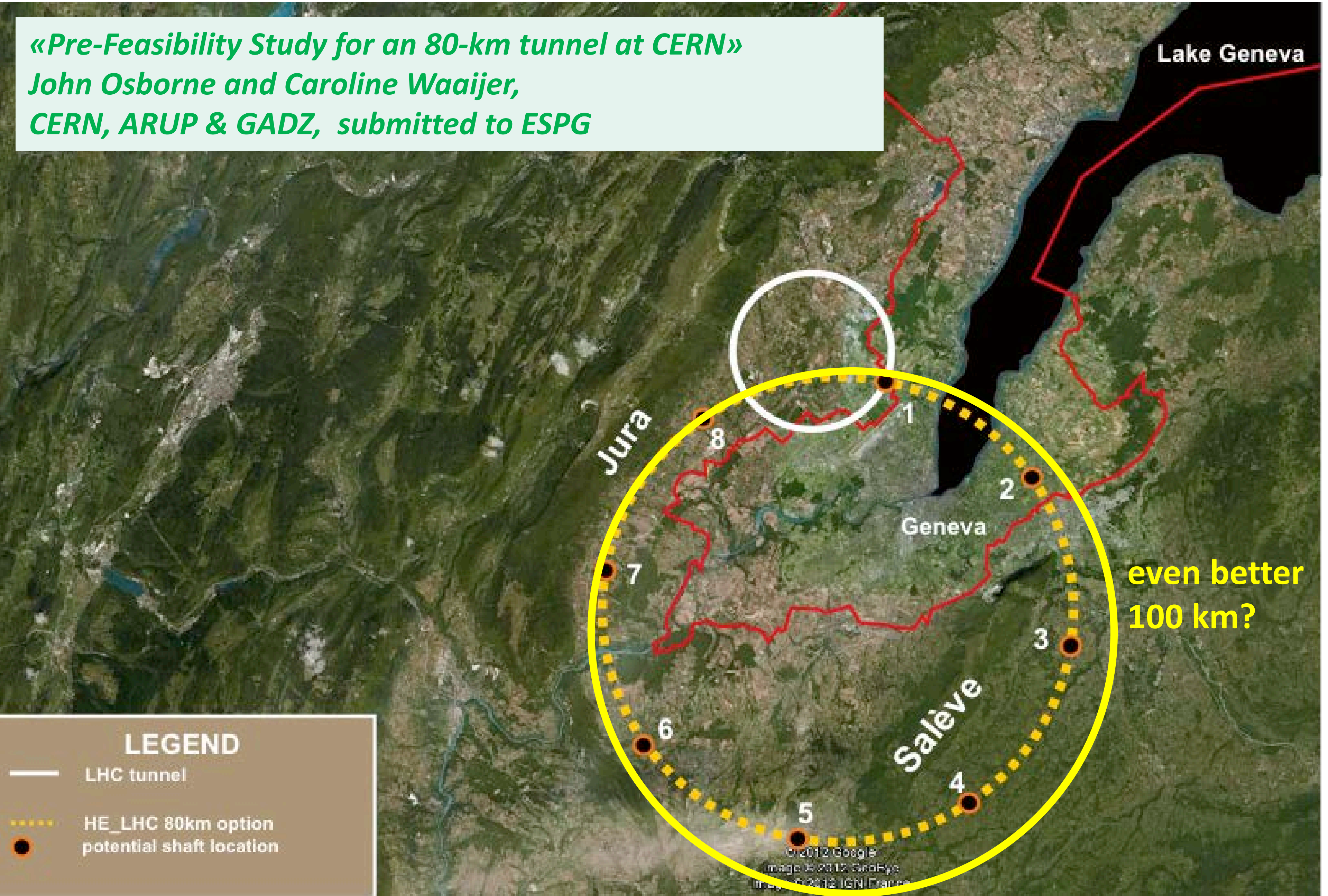
E. Todesco, L. Rossi, P.. McIntyre

VHE-LHC


VHE-LHC
VHE-LHC-LER
CMS
ALICE
LHCb
ATLAS
SPS+,
1.3 TeV,
North Area
TT40
TT41
TT10
TT60
TI2
TT2
neutrinos
CNGS
AD
1999 (182 m)
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
Linac4
n-ToF
2001
neutrons
PS
1959 (628 m)
CTF3
LEIR
2005 (78 m)
LINAC 3
Ions

80-km tunnel for VHE-LHC – “best” option

«Pre-Feasibility Study for an 80-km tunnel at CERN»
John Osborne and Caroline Waaijer,
CERN, ARUP & GADZ, submitted to ESPG



HE-LHC & VHE-LHC parameters – 1

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
c.m. energy [TeV]	14	14	33	100
circumference C [km]	26.7	26.7	26.7	80
dipole field [T]	8.33	8.33	20	20
dipole coil aperture [mm]	56	56	40	≤ 40
beam half aperture [cm]	~ 2	~ 2	1.3	≤ 1.3
injection energy [TeV]	0.45	0.45	>1.0	>3.0
no. of bunches n_b	2808	2808	2808	8420
bunch population N_b [10^{11}]	1.15	2.2	0.94	0.97
init. transv. norm. emit. [μm]	3.75	2.5	1.38	2.15
initial longitudinal emit. [eVs]	2.5	2.5	3.8	13.5
no. IPs contributing to tune shift	3	2	2	2
max. total beam-beam tune shift	0.01	0.015	0.01	0.01
beam circulating current [A]	0.584	1.12	0.478	0.492
rms bunch length [cm]	7.55	7.55	7.55	7.55
IP beta function [m]	0.55	0.15 (min.)	0.35	1.1
rms IP spot size [μm]	16.7	7.1 (min.)	5.2	6.7
full crossing angle [μrad]	285	590	185	72
stored beam energy [MJ]	362	694	701	6610

O. Dominguez, L. Rossi, F.Z.

HE-LHC & VHE-LHC parameters – 2

parameter	LHC	HL-LHC	HE-LHC	VHE-LHC
SR power per ring [kW]	3.6	7.3	96.2	2900
arc SR heat load [W/m/aperture]	0.17	0.33	4.35	43.3
energy loss per turn [keV]	6.7	6.7	201	5857
critical photon energy [eV]	44	44	575	5474
photon flux [10^{17}/m/s]	1.0	2.0	1.9	2.0
longit. SR emit. damping time [h]	12.9	12.9	1.0	0.32
horiz. SR emit. damping time [h]	25.8	25.8	2.0	0.64
init. longit. IBS emit. rise time [h]	57	23.3	40	396
init. horiz. IBS emit. rise time [h]	103	10.4	20	157
peak events per crossing	27	135 (lev.)	147	171
total/inelastic cross section [mb]	111 / 85		129 / 93	153 / 108
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.0	5.0	5.0	5.0
beam lifetime due to burn off [h]	45	15.4	5.7	14.8
optimum run time [h]	15.2	10.2	5.8	10.7
opt. av. int. luminosity / day [fb^{-1}]	0.47	2.8	1.4	2.1

HE-LHC &VHE-LHC luminosities could greatly improve for bunch spacings < 25 ns, e.g. by factor 5 for 5 ns, and make better use of strong radiation damping!

are 5 ns spacing & 2.5x10^{35}cm^{-2}s^{-1} acceptable for detectors?

O. Dominguez, L. Rossi, F.Z.

pp Higgs factories

LHC is the 1st Higgs factory!
E_{CM}=8-14 TeV, $\widehat{L} \sim 10^{34} cm^{-2}s^{-1}$

1 M Higgs produced so far – more to come!
15 H bosons / min – and more to come

HL-LHC (~2022-2030):
E_{CM}=14 TeV, $L \sim 5x10^{34} cm^{-2}s^{-1}$ (leveled)

10x more Higgs

HE-LHC: in LHC tunnel (2035-?)
E_{CM}=33 TeV, $L = 5x10^{34} cm^{-2}s^{-1}$

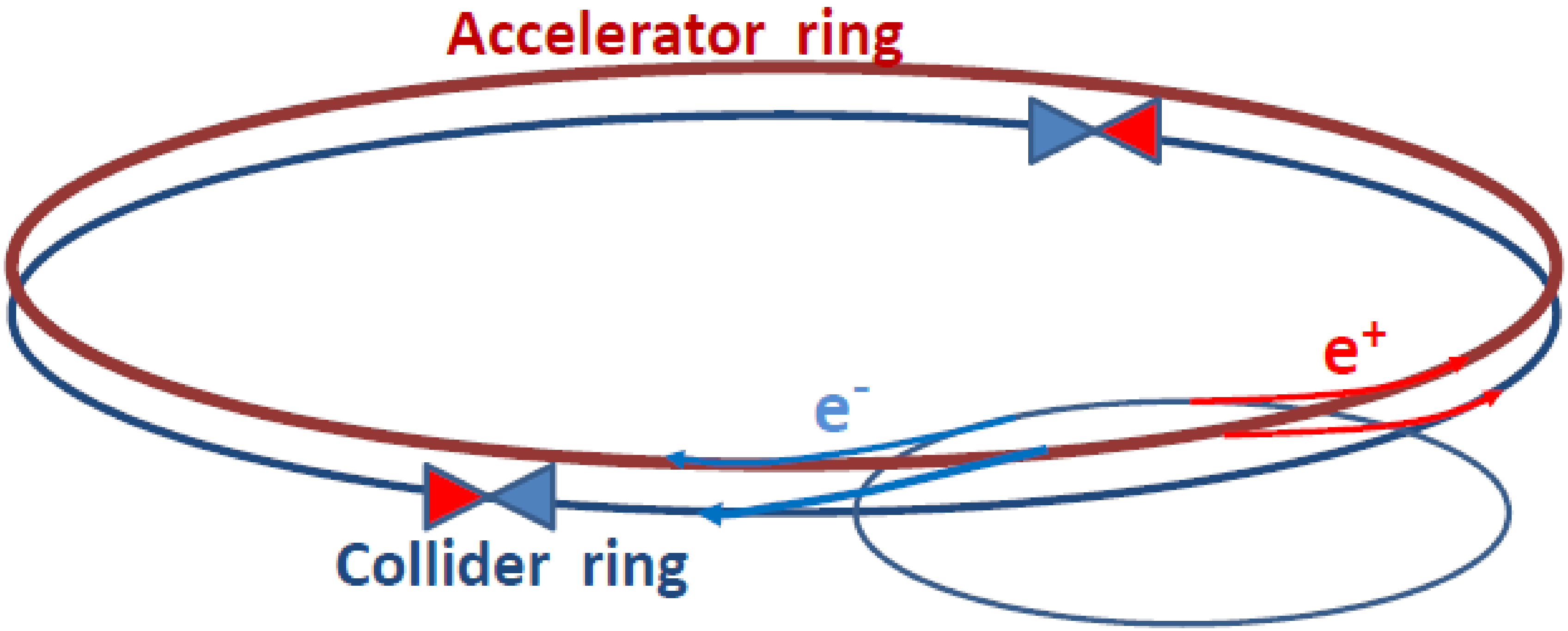
6x higher cross section for *H* self coupling

VHE-LHC in new 80-100 km tunnel (2040?)
E_{CM}=84-104 TeV, $L = 5x10^{34} cm^{-2}s^{-1}$

42x higher cross section for *H* self coupling

circular e^+e^- Higgs factories

circular e^+e^- colliders to study the «Higgs boson» X(126)

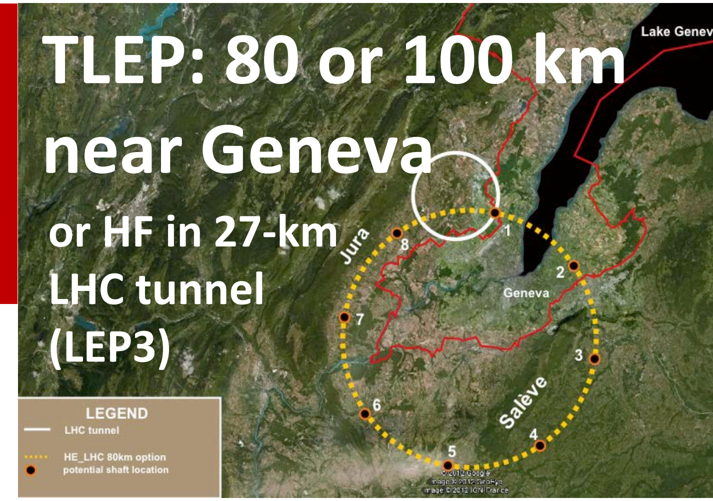


A. Blondel

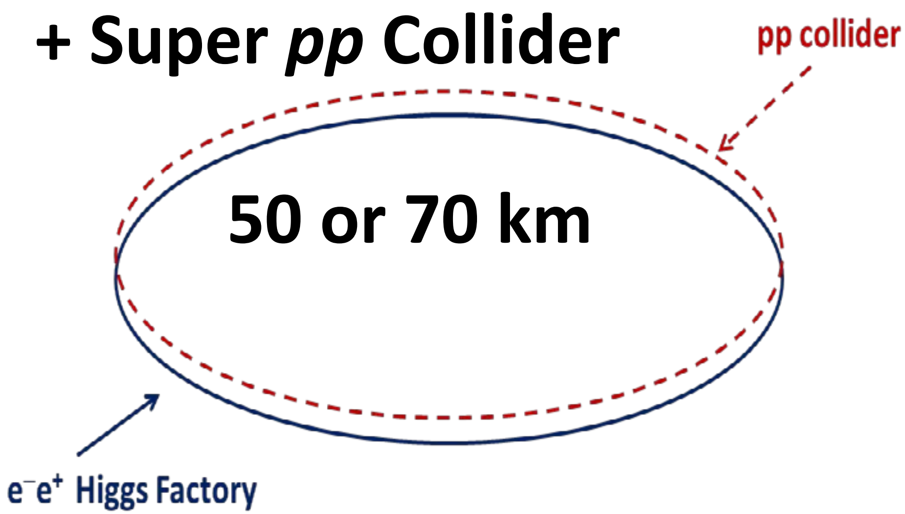
a relatively young concept (2011)

proposed circular e^+e^- Higgs factories

SLAC/LBNL design: 27 km



Chinese Higgs Factory + Super *pp* Collider



circular e^+e^- Higgs factories LEP3 & TLEP

option 1: installation in the LHC tunnel **"LEP3"**

+ inexpensive (only pay for new accelerator -- <~2B CHF)
+ tunnel exists
+ reusing ATLAS and CMS detectors
+ reusing LHC cryoplants
- interference with LHC and HL-LHC

option 2: in new 80 or 100-km tunnel **"TLEP"**

+ higher energy reach, 5-10x higher luminosity
+ decoupled from LHC/HL-LHC operation & construction
+ tunnel can later serve for VHE-LHC 100 TeV machine

long term vision

- more expensive because of tunnel

LEP3, TLEP

(e^+e^- -> ZH, $e^+e^- \rightarrow W^+W^-$, $e^+e^- \rightarrow Z$,[$e^+e^- \rightarrow t\bar{t}$])

key parameters

	LEP3	TLEP
circumference	26.7 km	80 km
max beam energy	120 GeV	175 GeV
max no. of IPs	4	4
Luminosity/IP at 350 GeV c.m.	-	1.3×10^{34} cm^{-2}s^{-1}
Luminosity/IP at 240 GeV c.m.	10^{34} cm^{-2}s^{-1}	4.8×10^{34} cm^{-2}s^{-1}
Luminosity/IP at 160 GeV c.m.	5×10^{34} cm^{-2}s^{-1}	1.6×10^{35} cm^{-2}s^{-1}
Luminosity/IP at 90 GeV c.m.	2×10^{35} cm^{-2}s^{-1}	5.6 10^{35} cm^{-2}s^{-1}

at the *Z* pole repeat the LEP physics programme in a few minutes…

TLEP parameters – 1

	TLEP Z	TLEP W	TLEP H	TLEP t
E_{beam} [GeV]	**45**	80	120	**175**
circumf. [km]	80	80	80	80
beam current [mA]	**1180**	124	24.3	**5.4**
#bunches/beam	4400	600	80	12
#$e-$/beam [10^{12}]	1960	200	40.8	9.0
horiz. emit. [nm]	30.8	9.4	9.4	10
vert. emit. [nm]	0.07	0.02	0.02	0.01
bending rad. [km]	9.0	9.0	9.0	9.0
κ_ε	440	470	470	1000
mom. c. α_c [10^{-5}]	9.0	2.0	1.0	1.0
$P_{loss,SR}$/beam [MW]	50	50	50	50
β^*_x [m]	0.5	0.5	0.5	1
β^*_y [cm]	0.1	0.1	0.1	0.1
σ^*_x [μm]	124	78	68	100
σ^*_y [μm]	0.27	0.14	0.14	0.10

TLEP parameters – 2

	TLEP Z	**TLEP W**	**TLEP H**	**TLEP t**
hourglass F_{hg}	0.71	0.75	0.75	0.65
E^{SR}_{loss}/turn [GeV]	0.04	0.4	2.0	9.2
V_{RF},tot [GV]	2	2	6	12
$\delta_{max,RF}$ [%]	4.0	5.5	9.4	4.9
ξ_x/IP	0.07	0.10	0.10	0.10
ξ_y/IP	0.07	0.10	0.10	0.10
f_s [kHz]	1.29	0.45	0.44	0.43
E_{acc} [MV/m]	3	3	10	20
eff. RF length [m]	600	600	600	600
f_{RF} [MHz]	700	700	700	700
δ^{SR}_{rms} [%]	0.06	0.10	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	0.19	0.22	0.17	0.25
$\mathcal{L}$ /IP[10^{32}cm^{-2}s^{-1}]	5600	1600	480	130
number of IPs	4	4	4	4
beam lifet. [min]	**67**	**25**	**16**	**20**

circular HFs: synchroton-radiation heat load

	PEPII	SPEAR3	LEP3	TLEP-Z	TLEP-H	TLEP-t
E (GeV)	9	3	120	45.5	120	175
I (A)	3	0.5	0.0072	1.18	0.0243	0.0054
rho (m)	165	7.86	2625	9000	9000	9000
Linear Power (W/cm)	101.8	92.3	30.5	8.8	8.8	8.8

TLEP has >10 times less SR heat load per meter than PEP-II or SPEAR! (though higher photon energy)

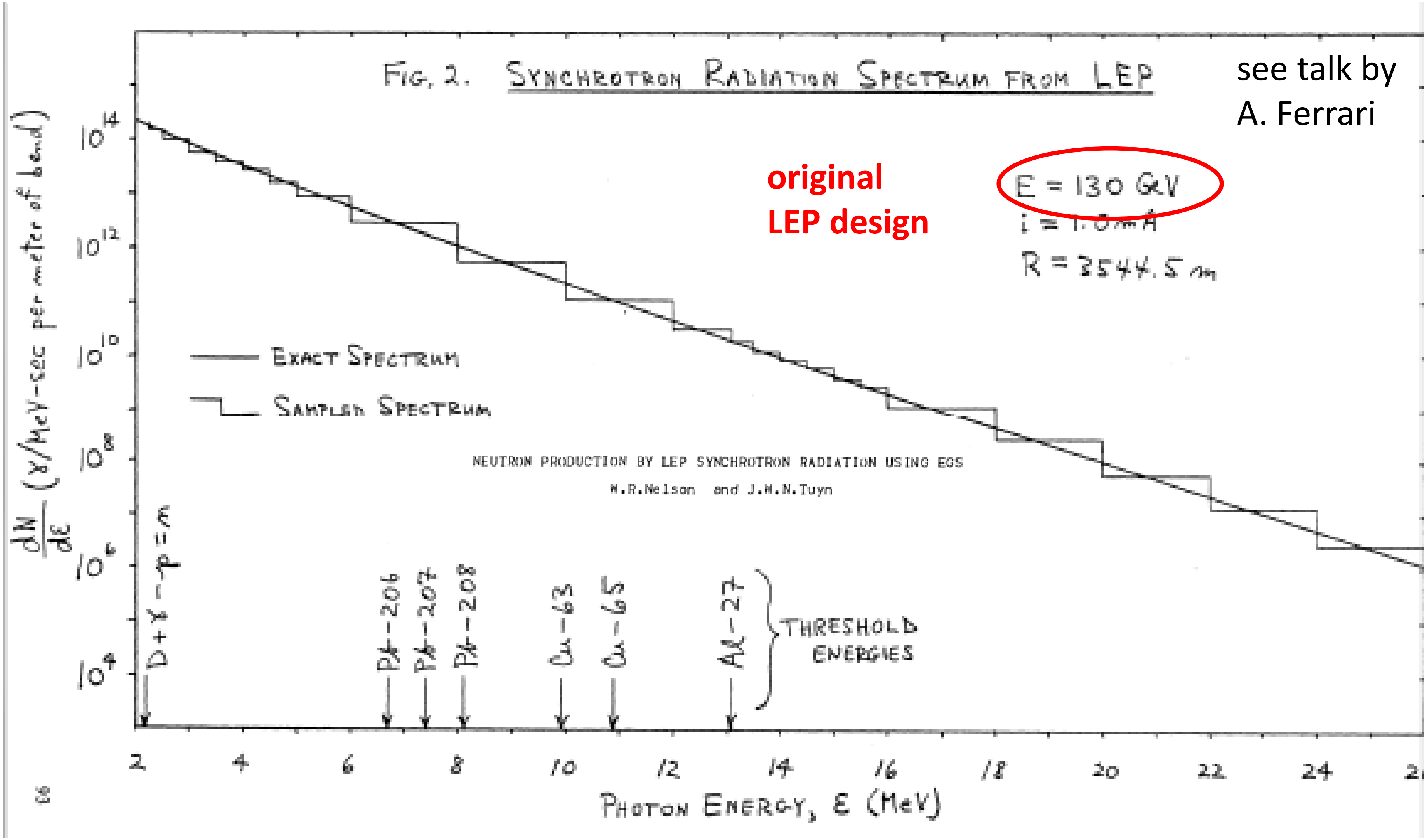
N. Kurita, U. Wienands, SLAC

synchrotron radiation - activation

NEUTRON PRODUCTION BY LEP SYNCHROTRON RADIATION USING EGS

N.R.Nelson and J.H.N.Tuyn

A. Fasso
3rd TLEP3 Day

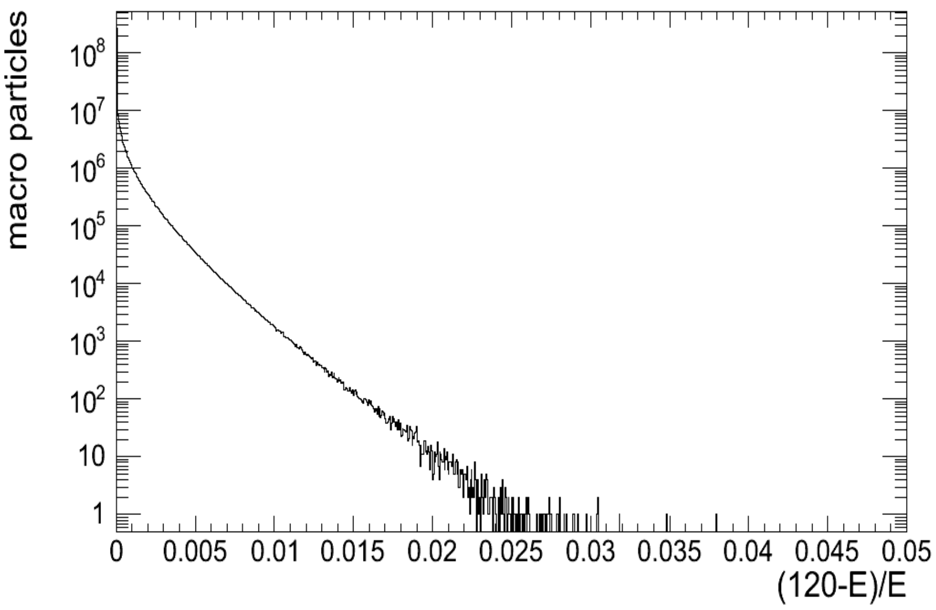


beamstrahlung lifetime

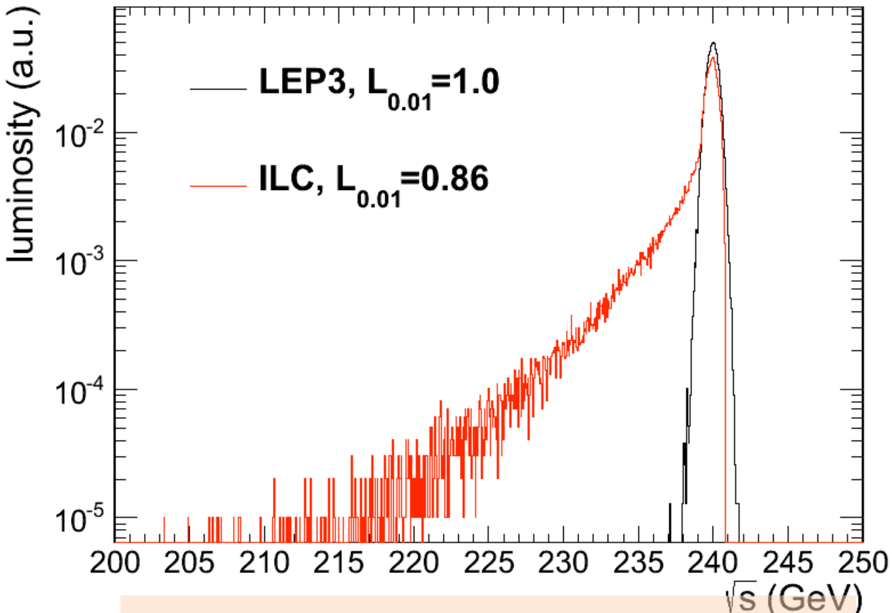
- simulation w 360M macroparticles (guinea-pig)
- τ varies exponentially with momentum acceptance η

M. Zanetti (MIT)

TLEP at 240 GeV post-collision
E tail → lifetime τ



luminosity *E* spectrum

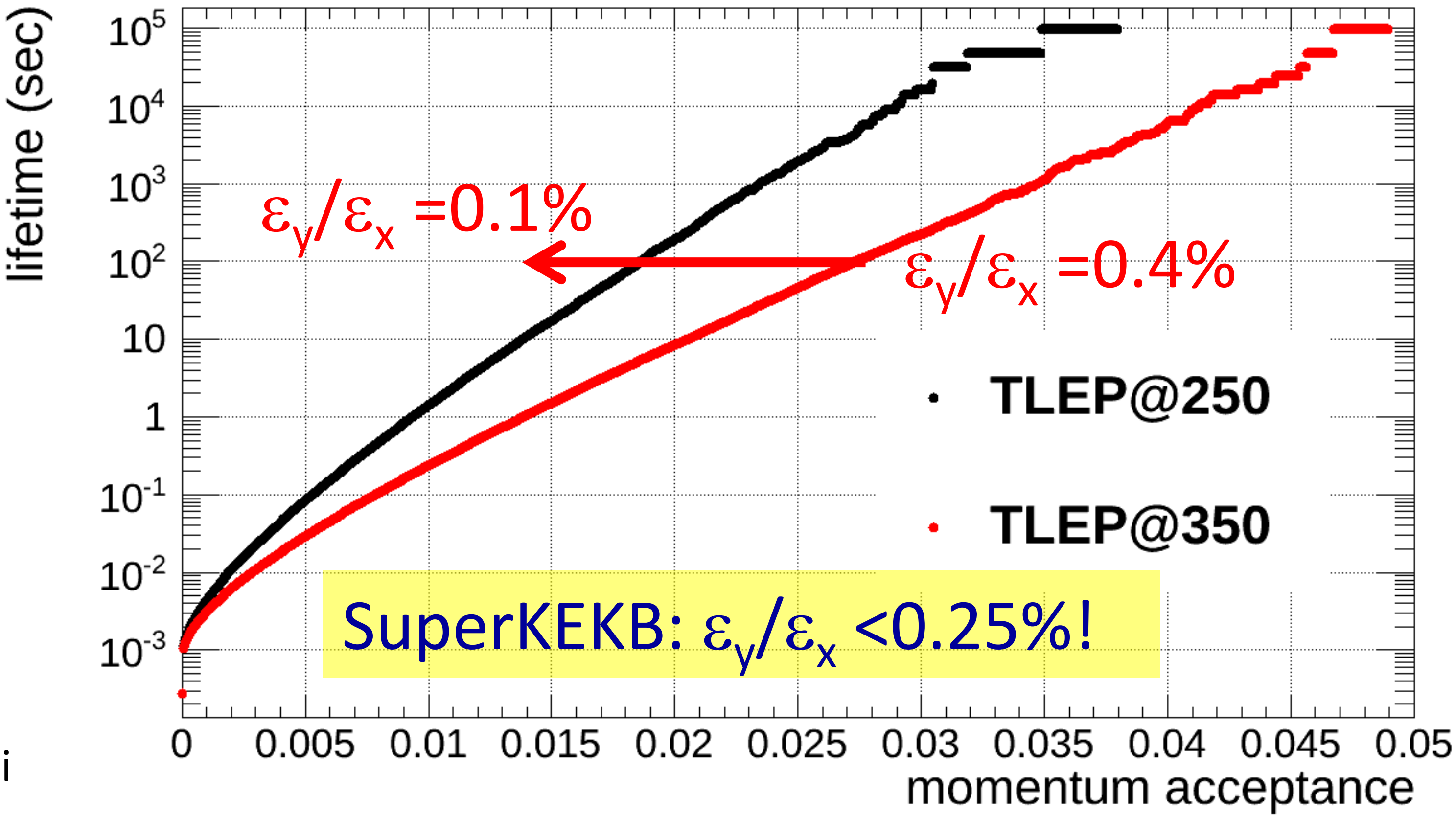


R-HF beamstrahlung more benign than for linear collider

beamstrahlung lifetime

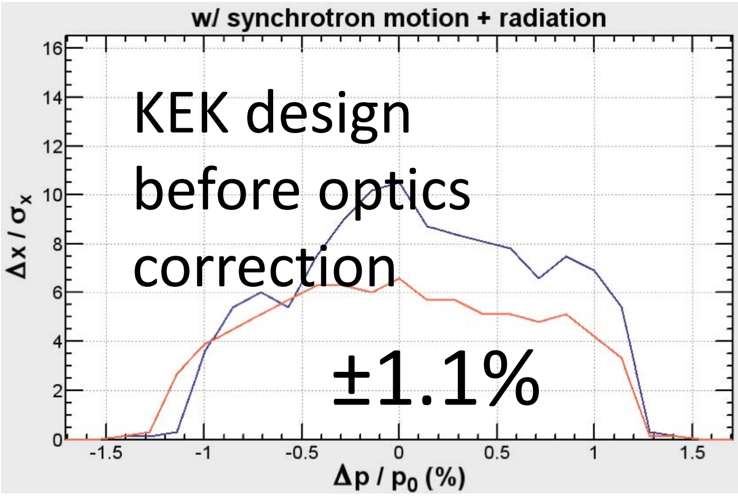
- simulation w 360M macroparticles
- τ varies exponentially w energy acceptance η
- post-collision *E* tail → lifetime τ

beam lifetime versus acceptance δ_{max} for 4 IPs:

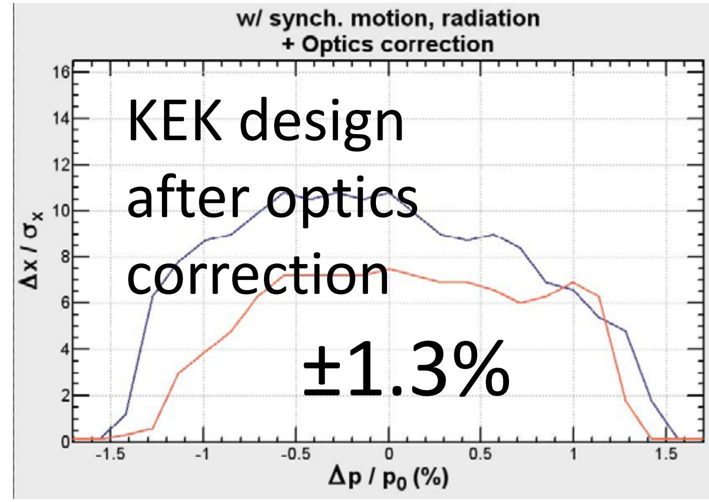


M. Zanetti

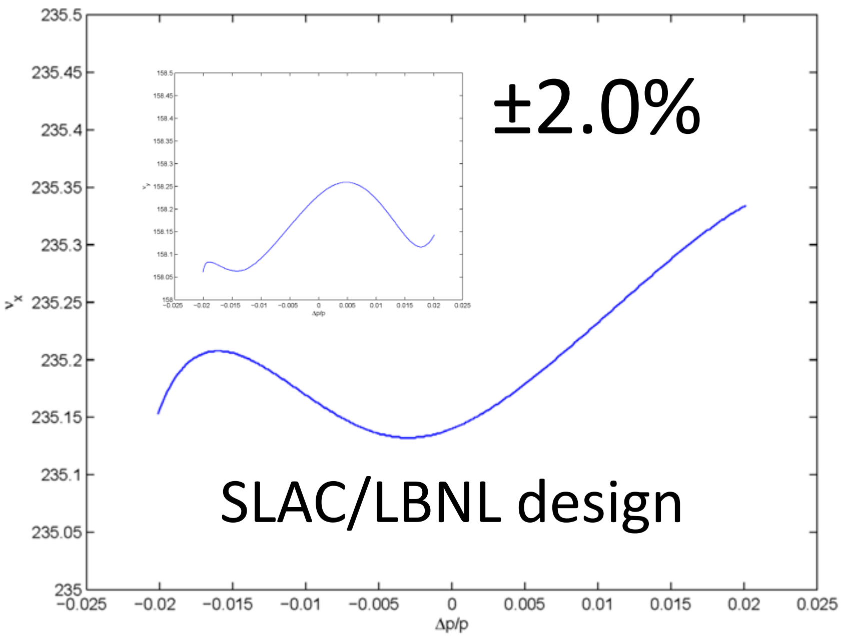
circular HFs - momentum acceptance

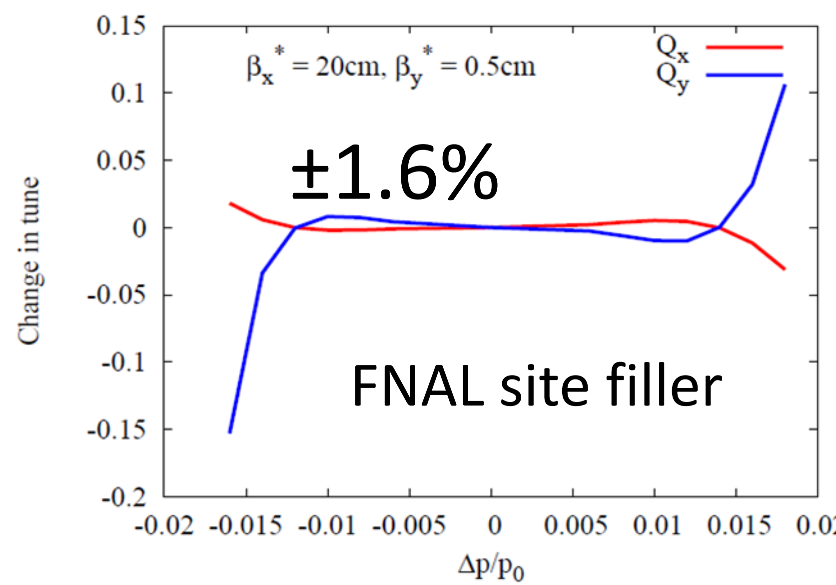


with synchrotron motion & radiation (sawtooth)



K. Oide

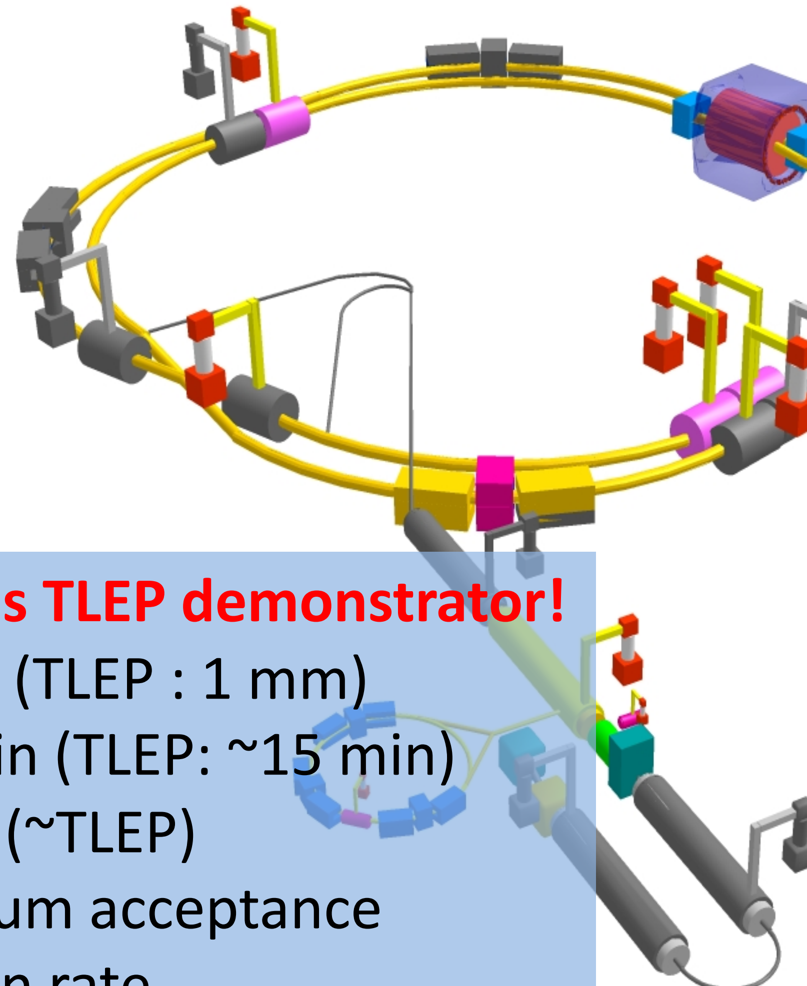




Y. Cai

T. Sen, E. Gianfelice-Wendt, Y. Alexahin

Next Collider: SuperKEKB



SuperKEKB is TLEP demonstrator!

β_y*=300 μm (TLEP : 1 mm)

lifetime 5 min (TLEP: ~15 min)

$\varepsilon_y/\varepsilon_x$=0.25% (~TLEP)

off momentum acceptance

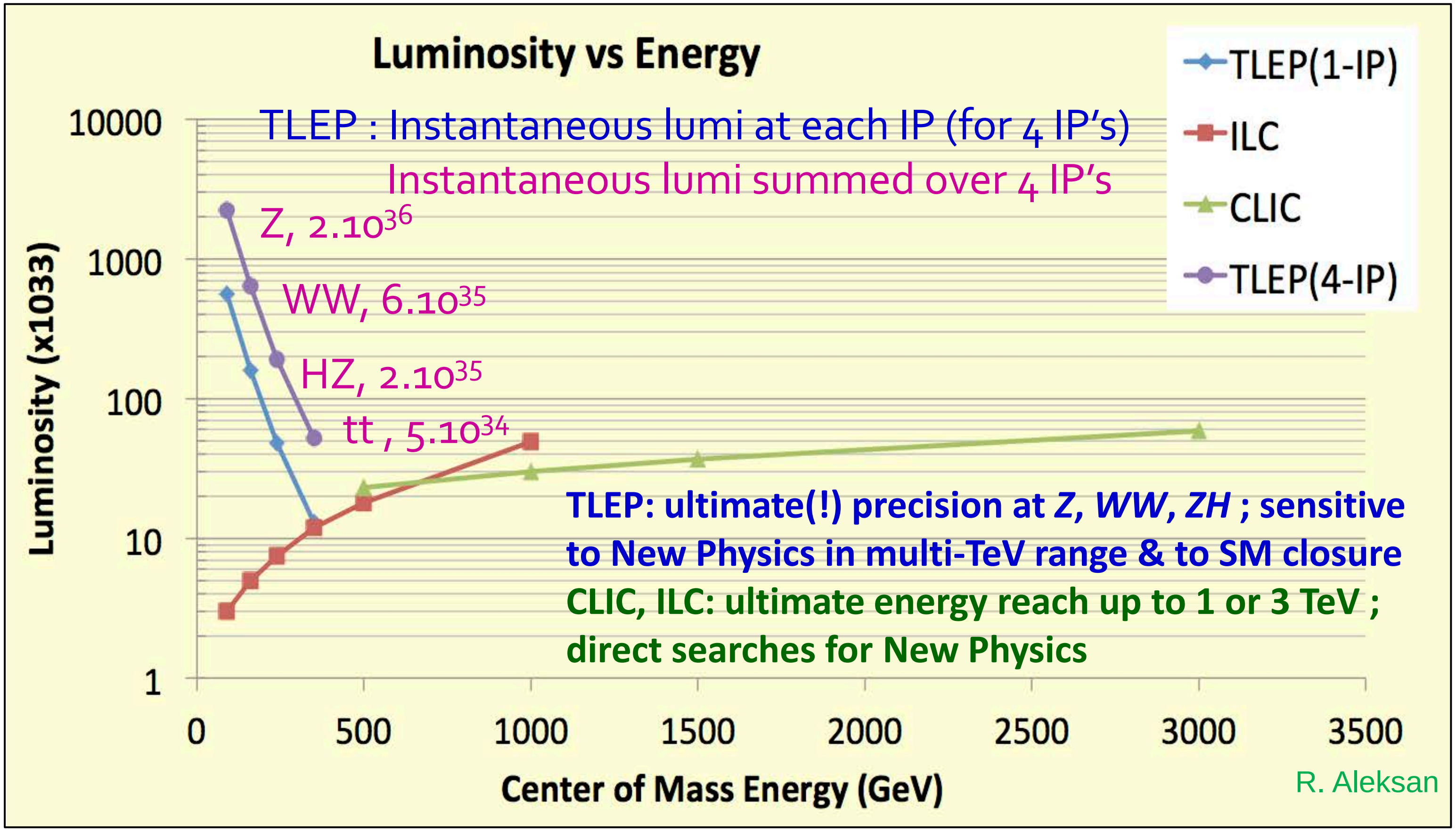
e^+ production rate

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

beam commissioning will start early 2015

Luminosity Performance of e^+e^- colliders

Circular colliders have several IP's



- Lumi upgrade (×3) now envisioned at ILC : luminosity is key at low energy!
- Crossing point between circular and linear colliders ~ 400 GeV
- With fewer IP's expect total luminosity of facility to scale approx as $(N_{IP})^{0.5}$

Higgs factory performances

Precision on couplings, cross sections, mass, width, Summary of the ICFA HF2012 workshop (FNAL, Nov. 2012) arxiv1302:3318

Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. Many studies are quite recent and still ongoing.

Accelerator → Physical Quantity ↓	**LHC** 300 fb^{-1} /expt	**HL-LHC** 3000 fb^{-1} /expt	**ILC** 250 GeV 250 fb^{-1} 5 yrs	**Full ILC** 250+350+ 1000 GeV 5yrs each	**CLIC** 350 GeV (500 fb^{-1}) 1.4 TeV (1.5 ab^{-1}) 5 yrs each	**LEP3, 4 IP** 240 GeV 2 ab^{-1} (*) 5 yrs	**TLEP, 4 IP** 240 GeV 10 ab^{-1} 5 yrs (*) 350 GeV 1.4 ab^{-1} 5 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν	7.5×10^4 ZH 4.7×10^5 Hνν	4×10^5 ZH	2×10^6 ZH 3.5×10^4 Hνν
m_H (MeV)	100	50	35	35	100	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	ongoing	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	ongoing	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	ongoing	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	< 3%	2.2%	0.7%
$\Delta g_{Hww} / g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	~1%	1.5%	0.25%
$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	~1%	0.65%	0.2%
$\Delta g_{HHH} / g_{HHH}$	--	< 30% (2 expts)	--	~30%	~22% (~11% at 3 TeV)	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	10%	14%	7%
$\Delta g_{H\tau\tau} / g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	≤ 3%	1.5%	0.4%
$\Delta g_{Hcc} / g_{Hcc}$	--	--	3.7%	2%	2%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	1%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	5%	3%	--	30%

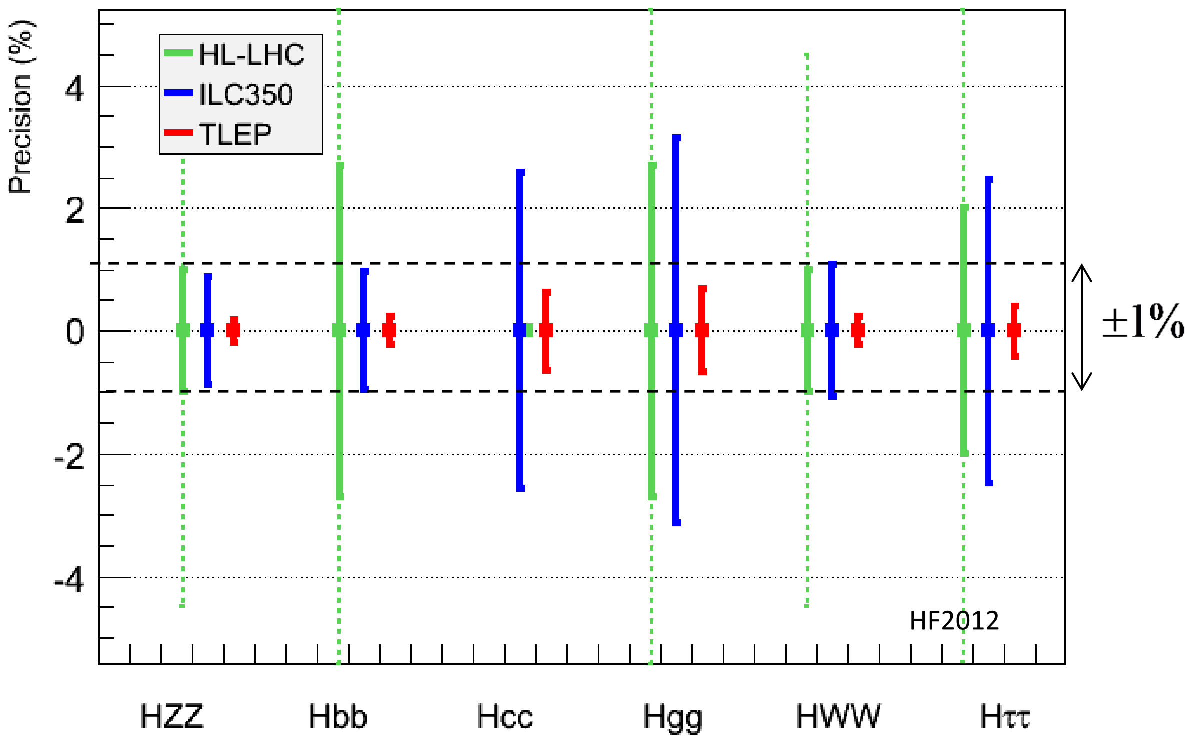
(*) The total luminosity is the sum of the integrated luminosity a

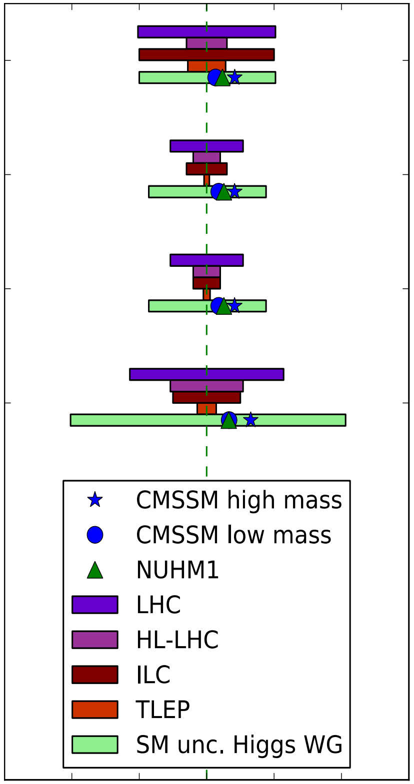
Circular Higgs Factory really goes to precision at few permil level.

Performance Comparison

Need sub-percent precision for sensitivity to multi-TeV New Physics

– Compare (LHC), HL-LHC, ILC, TLEP





- **TLEP reaches the needed sub-percent accuracy**
- **much theoretical work also needed**

J. Ellis et al.

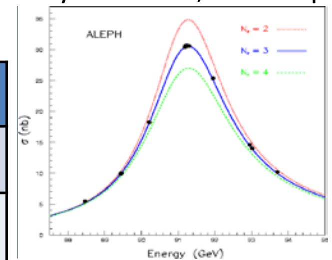
P. Janot

TLEP TeraZ, Oku-W & Mega-Top

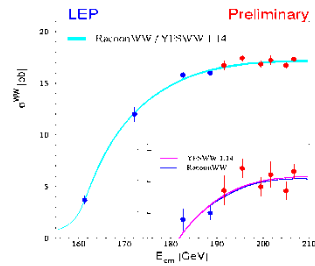
- Precision tests of EWSB

	LEP	ILC	TLEP
√s ~ m_Z	Mega-Z	Giga-Z	Tera-Z
#Z / year Polarization **Precision vs LEP1** **Error on m_Z, Γ_Z**	2×10^7 Yes (T) **1** **2 MeV**	Few 10^9 Easy **1/5 to 1/10** **–**	10^{12} (>10^{11} b,c,τ) Yes (T,L) **~1/100** **< 0.1 MeV**
√s ~ $2m_W$			
#W pairs / year Polarization **Error on m_W**	Few dozens No **220 MeV**	2×10^5 Easy **7 MeV**	2.5×10^7 Yes (T) **0.5 MeV**
√s = 240 GeV			Oku-W
# W pairs / 5 years **Error on m_W**	4×10^4 **33 MeV**	4×10^6 **3 MeV**	2×10^8 **0.5 MeV**
√s ~ 350 GeV			Mega-Top
# top pairs / 5 years **Error on m_{top}** **Error on λ_t**	– **–** **–**	100,000 **30 MeV** **40%**	500,000 **13 MeV** **15%**

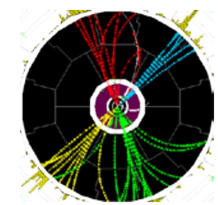
Asymmetries, Lineshape



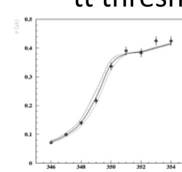
WW threshold scan

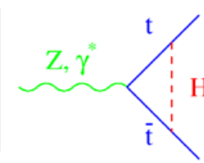


WW production



$t\bar{t}$ threshold scan





TLEP : Repeat the LEP1 physics programme every 15 min

Transverse polarization up to the WW threshold

➤ Exquisite beam energy determination (10 keV)\

Longitudinal polarization at the Z pole

➤ Measure $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}

– measure m_Z, Γ_Z to < 0.1 MeV, m_W to < 1 MeV, $\sin^2\theta_W$ to 2.10^{-6} from A_{LR}

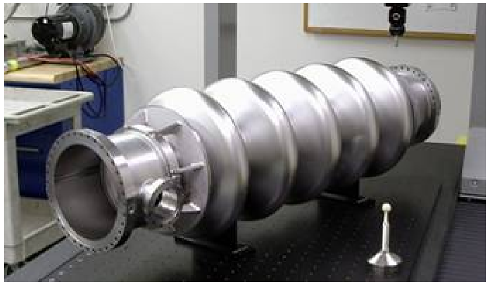
– **TLEP beam polarization up to *W* threshold, for energy calibration**

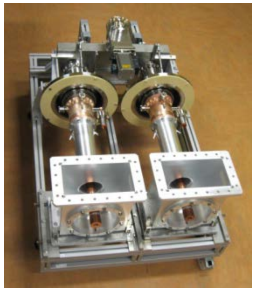
P. Janot

other TLEP challenges

- **Efficient RF system**
  - Need 12 GeV/turn at 350 GeV
    - **~600 m of SC RF cavities @ 20 MV/m**
      - **LEP2 had 600 m at 7 MV/m**
  - Very high power : up to 200 kW / cavity in collider ring
    - **Power couplers similar to ESS** – 700-800 MHz preferred

BNL 5-cell 700 MHz cavity





RF Coupler (ESS/SPL)

- **Operation at the Z pole**
  - 4400 bunches : e^+ source, impedance effects, parasitic collisions
    - **May need two rings designed to separate e^+ and e^- beams**

TLEP design study: http://cern.ch/tlep

where you can subscribe for work, information, newsletter , etc…

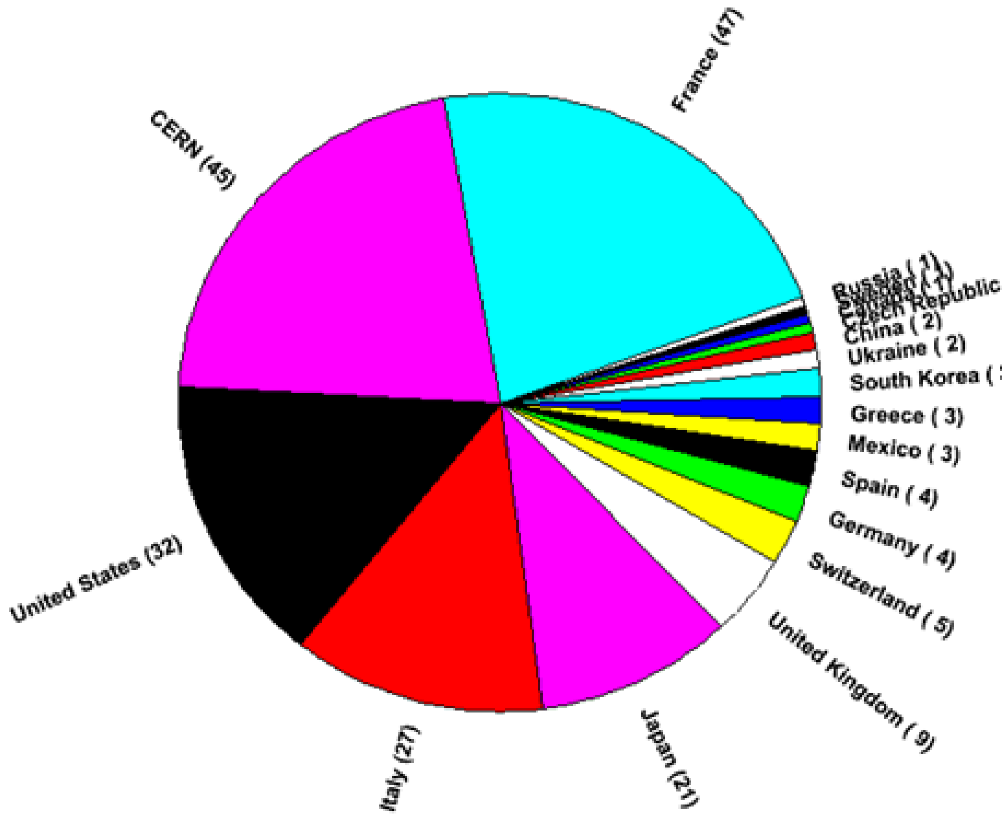
R. Aleksan,
A. Blondel,
P. Janot,
M. Koratzinos,
et al

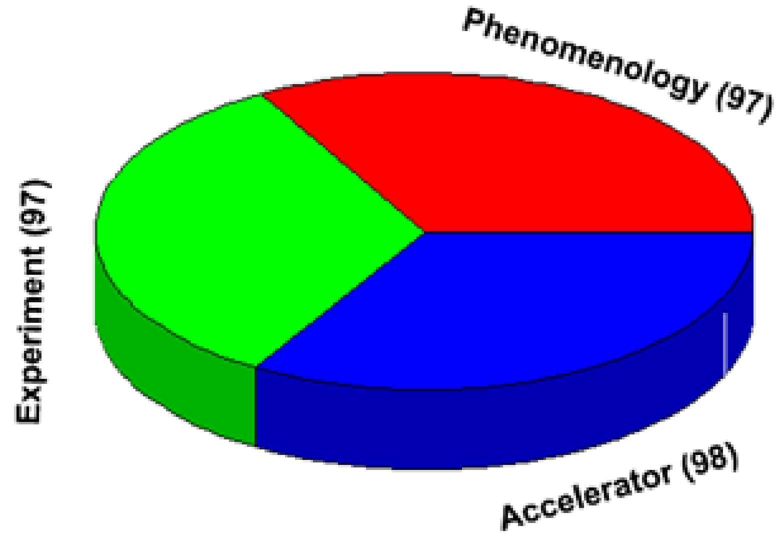
Global endeavour: collaborators from Europe, US, Japan, China ,…

Next events: TLEP workshops 25-26 July 2013, Fermilab
16-18 October, CERN
Joint VHE-LHC+ TLEP kick-off meeting in February 2014

First 200 subscribers:

P. Janot





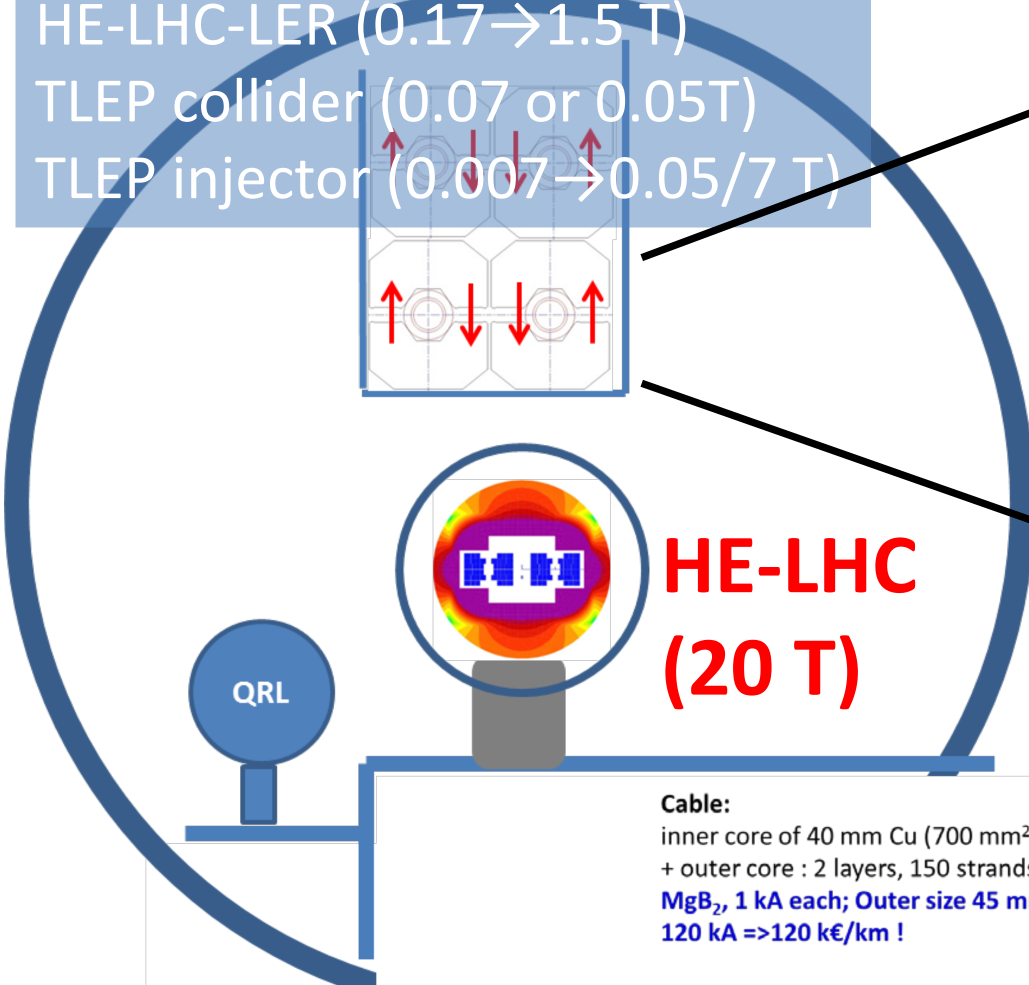
Distribution of countries of origin reflects the youth of the TLEP project and the very different levels of awareness in the different countries.

Audience is remarkably well balanced between Accelerator, Experiment, and Phenomenology -- the agreement with the three colour model is too good to be a statistical fluctuation!

VHE-LHC + TLEP

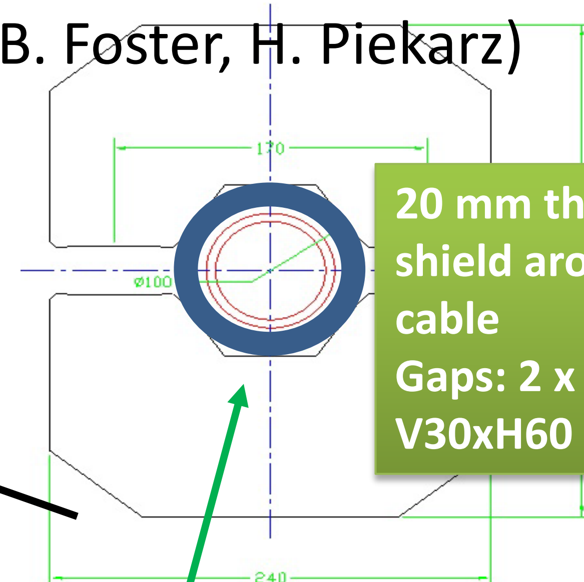
L. Rossi

HE-LHC-LER (0.17→1.5 T)
TLEP collider (0.07 or 0.05T)
TLEP injector (0.007→0.05/7 T)



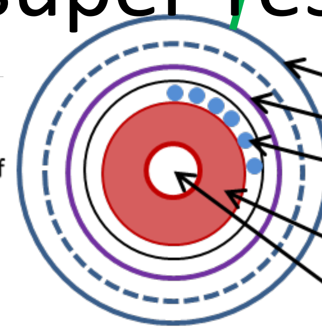
multipurpose tunnel

transmission line magnet (B. Foster, H. Piekarz)



20 mm thick shield around cable
Gaps: 2 x V30xH60 mm

super-resistive cable



- Cryostat : 60 mm
- He envelope : 50 mm
- SC part: 2 layers MgB_2 (Bi2212)150x∅1mm
- Cu inner core 40 mm
- Cooling hole: 10 mm

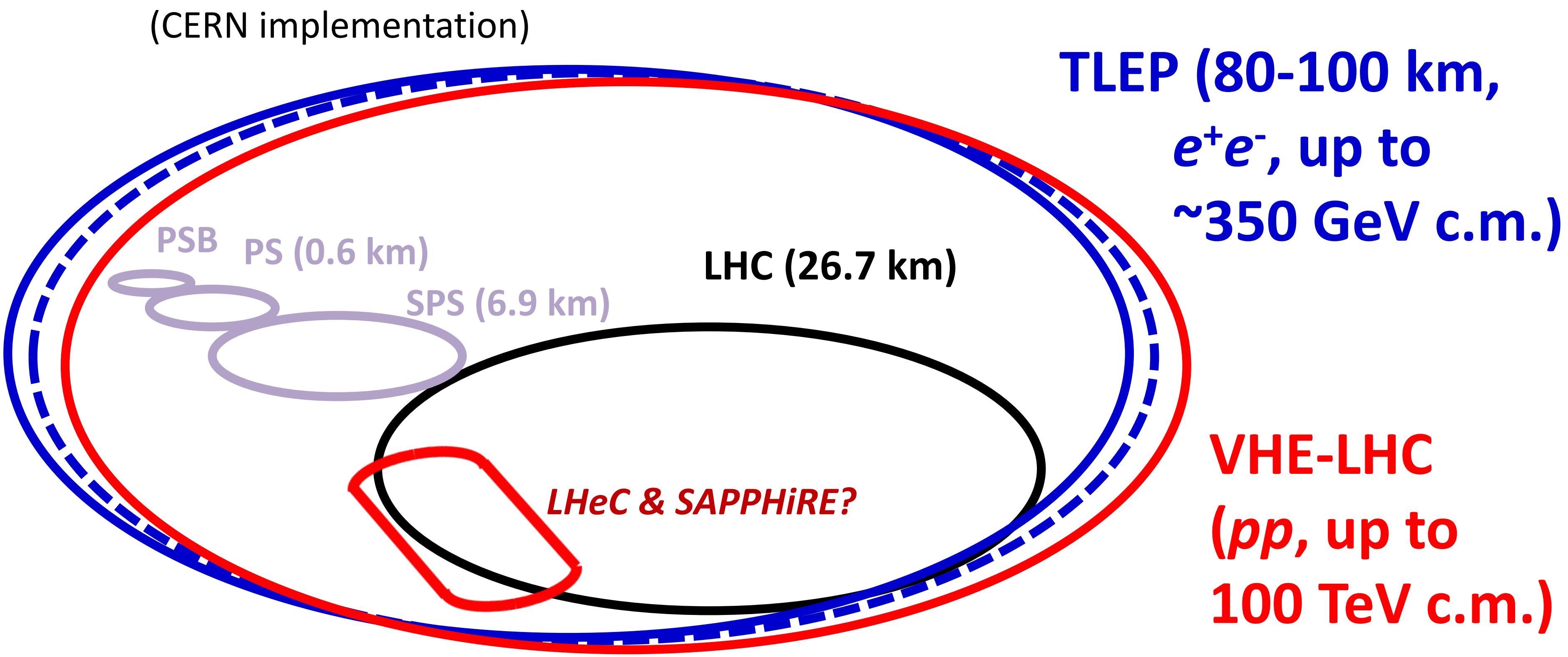
Cable:
inner core of 40 mm Cu (700 mm²)
+ outer core : 2 layers, 150 strands of **MgB_2, 1 kA each; Outer size 45 mm.**
120 kA =>120 k€/km !

For electrons: Cu water cooled, J_{ov} 2.5 A/mm²

For protons: 800 A/strands
120 kA (for >2.1 T); central copper acts as stabilizer

based on *MgB_2* SC
only 12 MEuro/100 km!

possible long-term strategy



& $e^{\pm}$ **(120 GeV) – *p* (7, 16 & 50 TeV)** collisions (**[(V)HE-]TLHeC)**

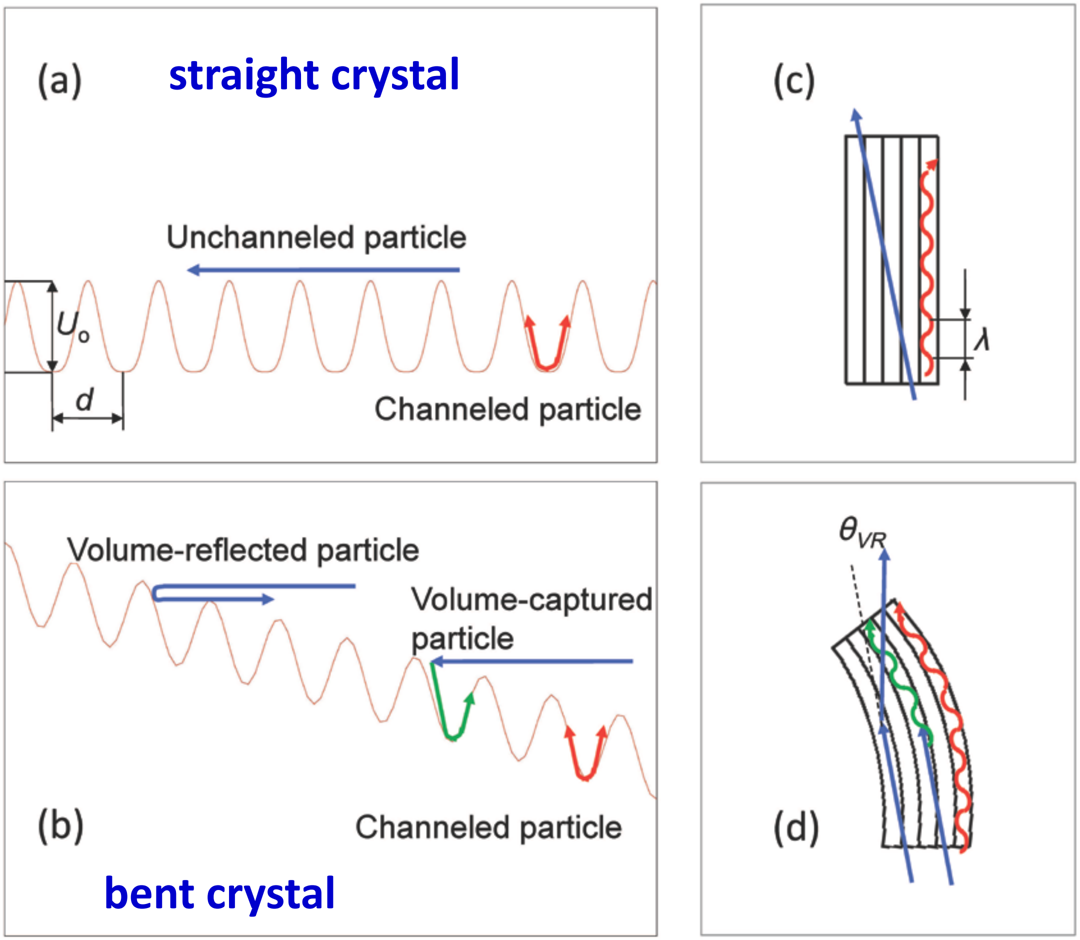
≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

BUT - what if 100 TeV *pp* collider is not enough ?!?

how to go beyond VHE-LHC?

the really grand challenge!

one possibility –
crystal: world's strongest magnets



crystal focusing strength

ϕ~20-60 eV/Å^2

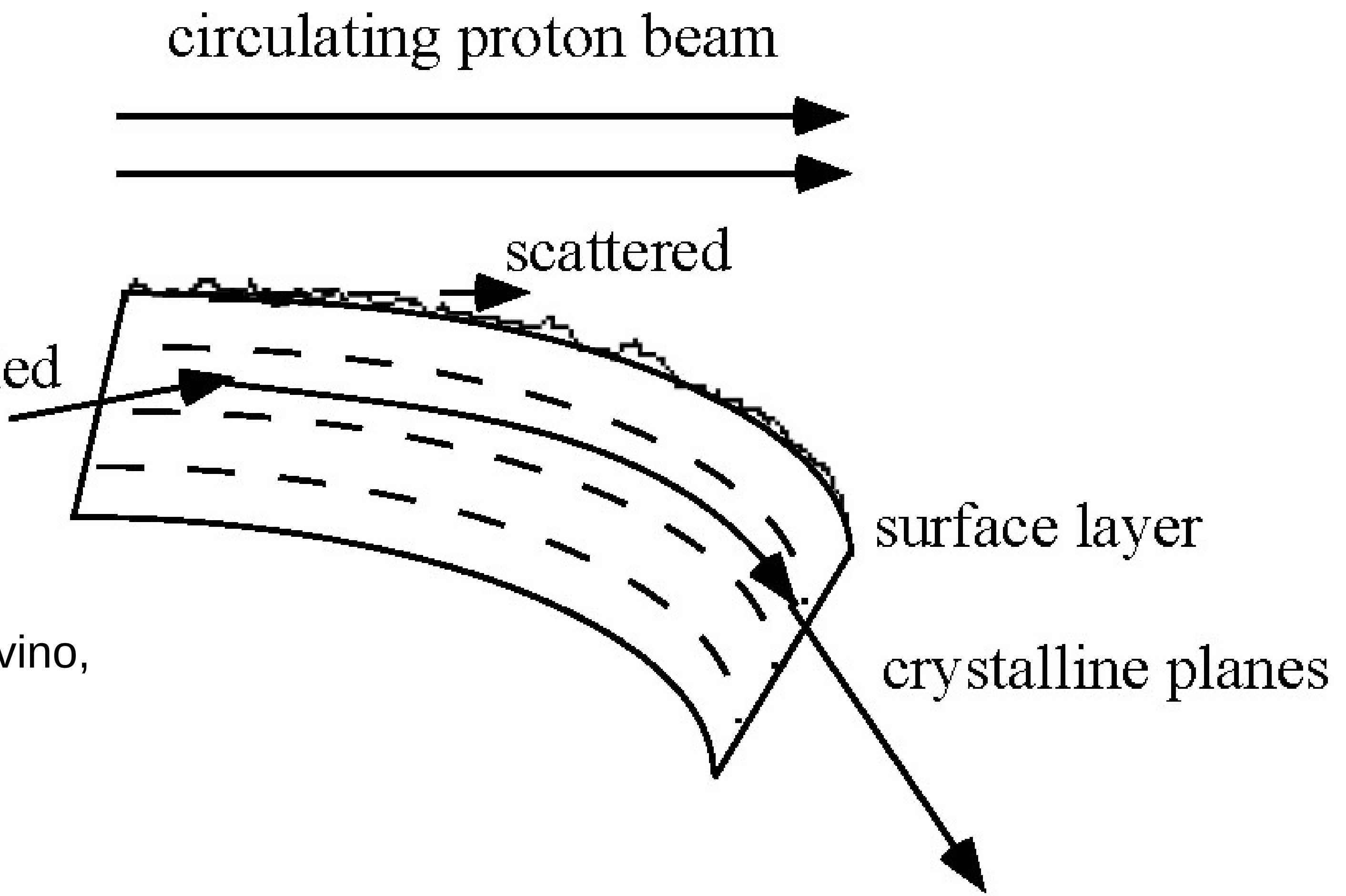
B_{max}≈2000 T !

$\lambda = 2\pi\beta = 2\pi\ (E/\phi)^{1/2}$

S.A. Bogacz, D. Cline, 1997

W. Scandale, MPL A (2012)

crystal extraction from stored proton/ion beam



Dubna, Protvino,
CERN SPS,
Tevatron

since 1978 crystals are used for extracting high-energy protons or ions from storage rings;

can they also be used for a circular collider?!

crystal channeling & dechanneling

channeling condition: angle of incidence < Lindhard **critical angle ~5 μrad (*Z*/*p* [TeV/*c*])$^{1/2}$**

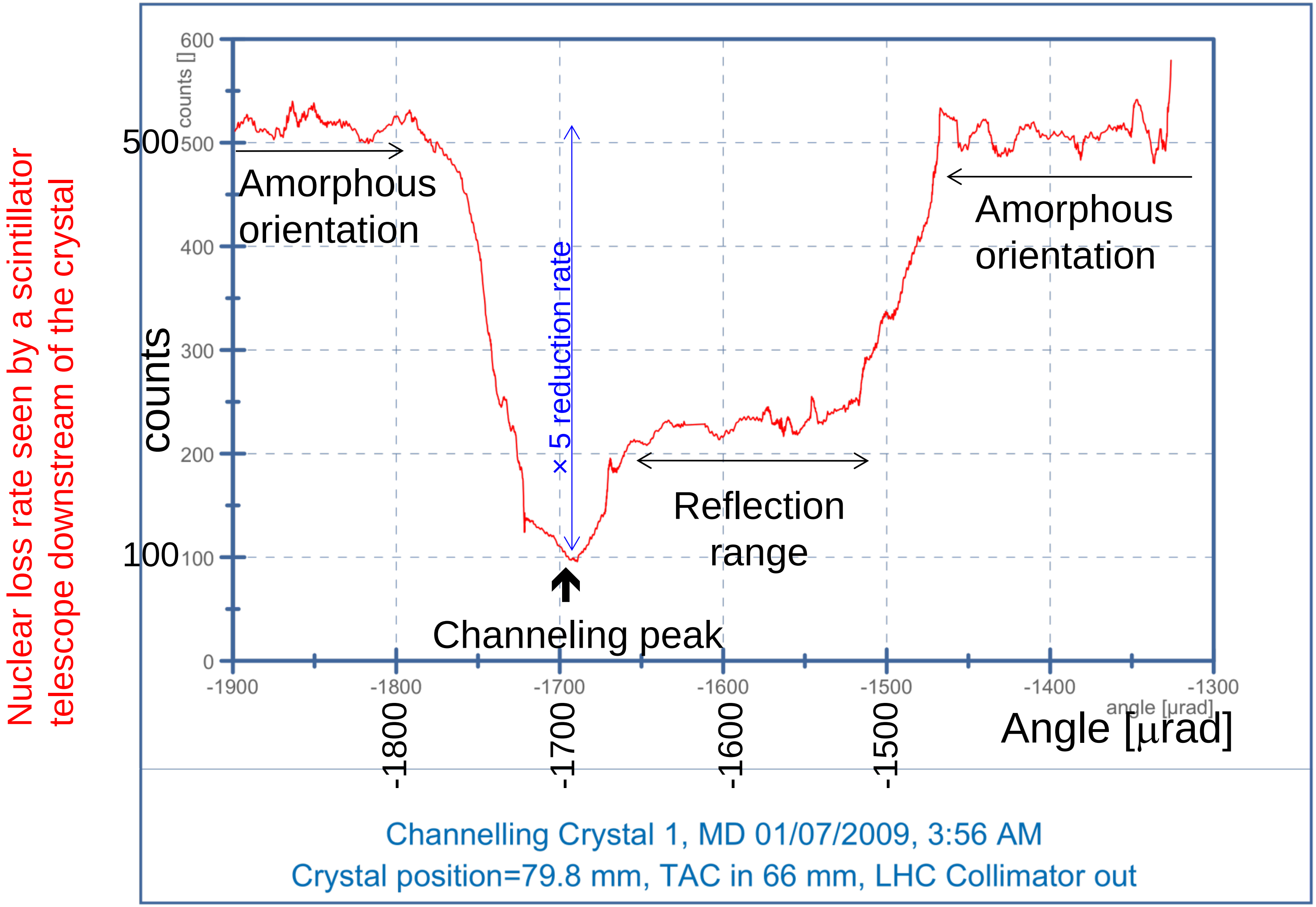
thermal vibrations, discreteness of lattice, electrons → **dechanneling** (exponential decrease of channeled protons)

dechanneling length L_0~0.9 m *p*[TeV/c]

cooling of crystal increases L_0

minimum bending radius for channeling
R_c~0.4 *p* [TeV/c] meter

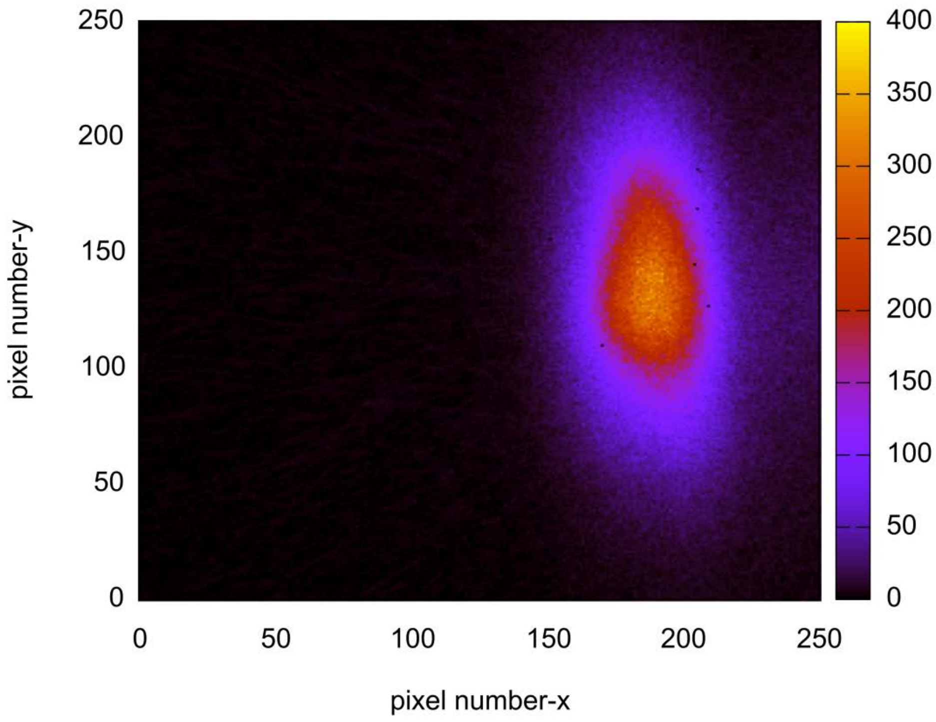
crystal extraction experiment UA9 at SPS (2009)

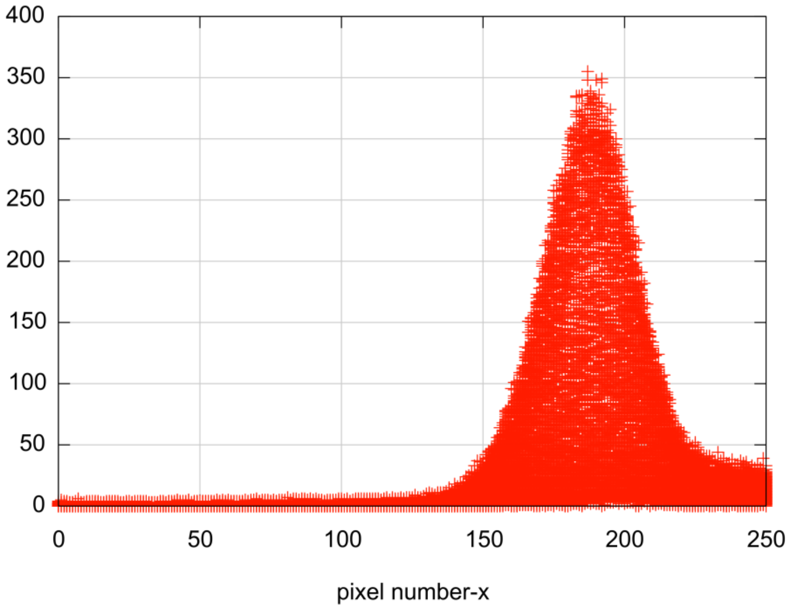


- *Nuclear loss rate* (including diffractive) strongly depressed

W. Scandale

profile of "beam" deflected by crystal

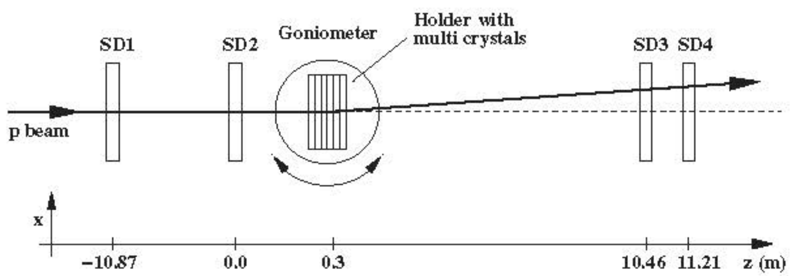


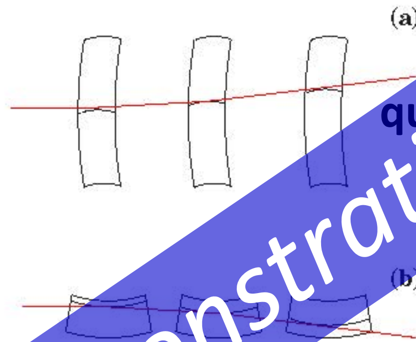


- 256×256 square pixels
- 1 pixel size = 55 μm
- 1 frame integration time 1 s

W. Scandale

staging of crystal deflectors



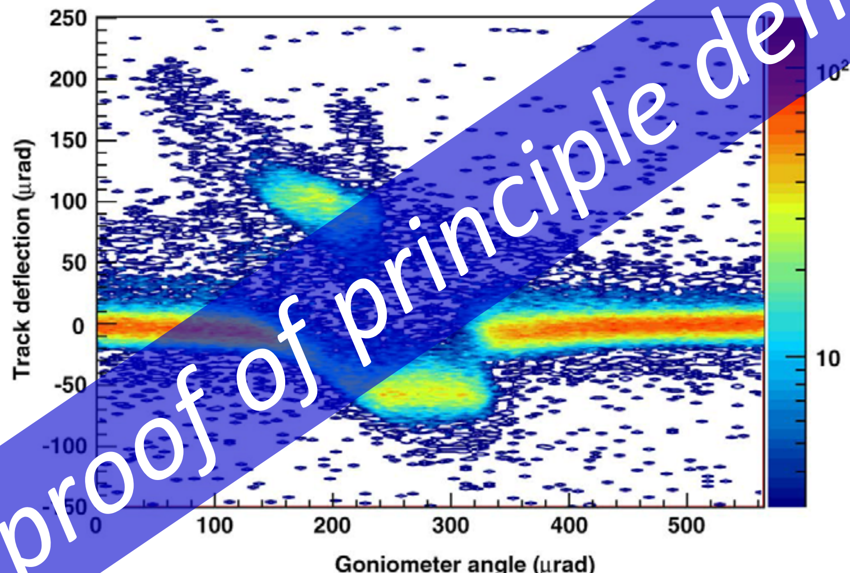


quasimosaic

strip crystals

schematic layout of the experimental setup used to study multiple volume reflection at the H8 beam line of the CERN SPS

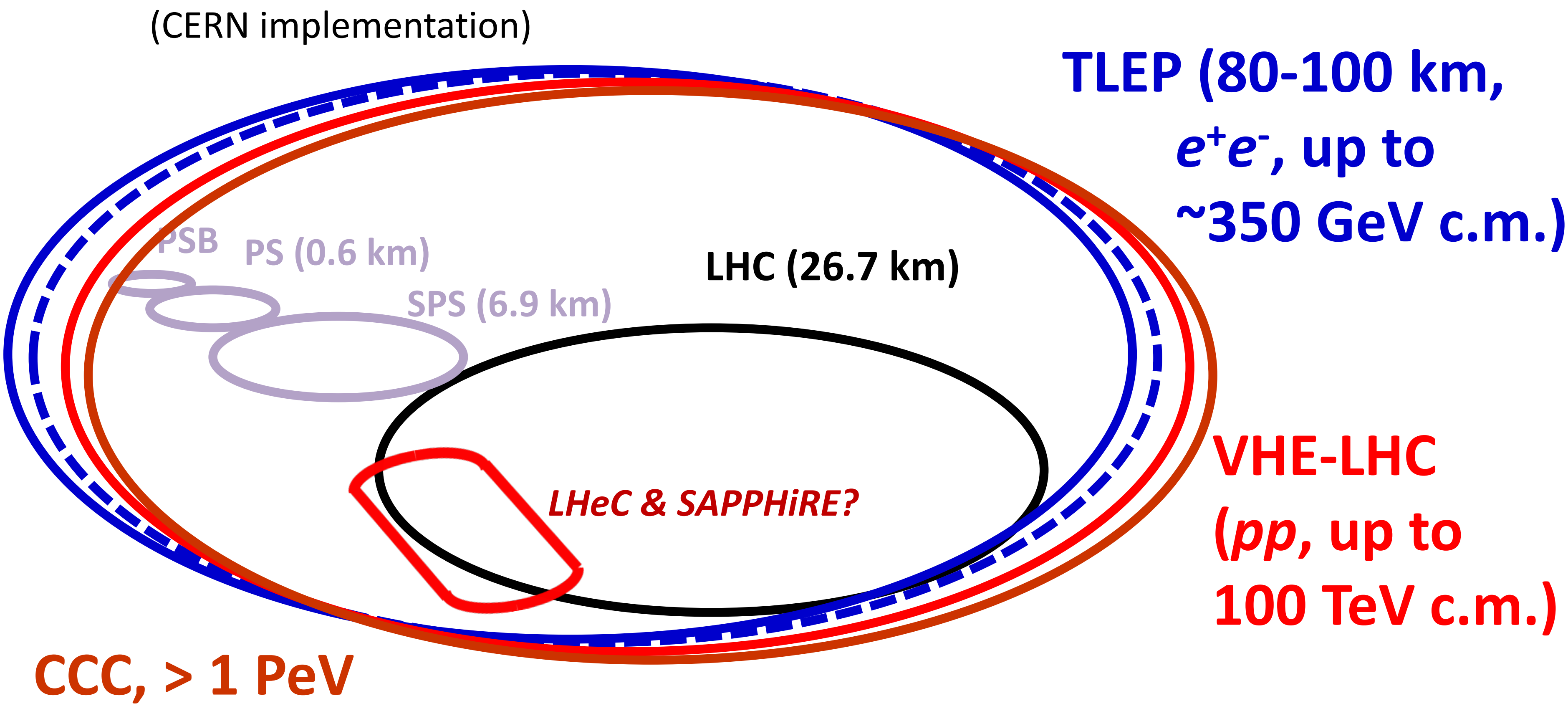
proof of principle demonstration!



6 strip crystals in series
(each 2 mm long):
400 GeV/*c* protons
reflected by 40±2 μrad
[effective field **16 T**]
with **efficiency 0.93±0.04**

W. Scandale et al, Observation of Multiple Volume Reflection of Ultrarelativistic Protons by a Sequence of Several Bent Silicon Crystals, Phys.Rev.Lett. 102 (2009) 084801

possible longer-term strategy

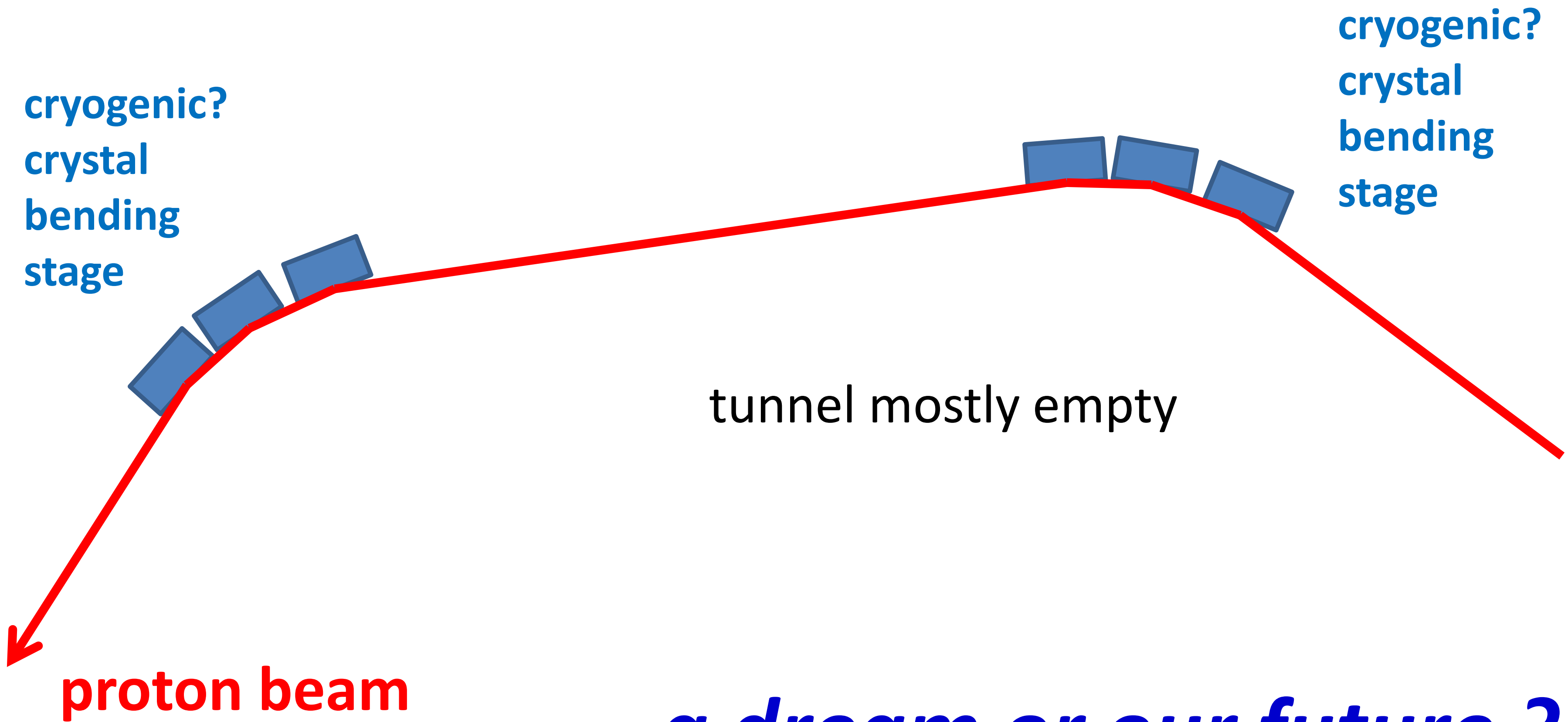


& $e^{\pm}$ **(120 GeV) – *p* (7, 16 & 50 TeV)** collisions (**[(V)HE-]TLHeC)**

≥50 years of e^+e^-, *pp*, *ep/A* physics at highest energies

followed by >1 PeV circular crystal collider (CCC)?!?

circular crystal collider?



a dream or our future ?

energy ramp using induction acceleration?

highest-energy particles

4 July 2012 CERN, Geneva, Switzerland

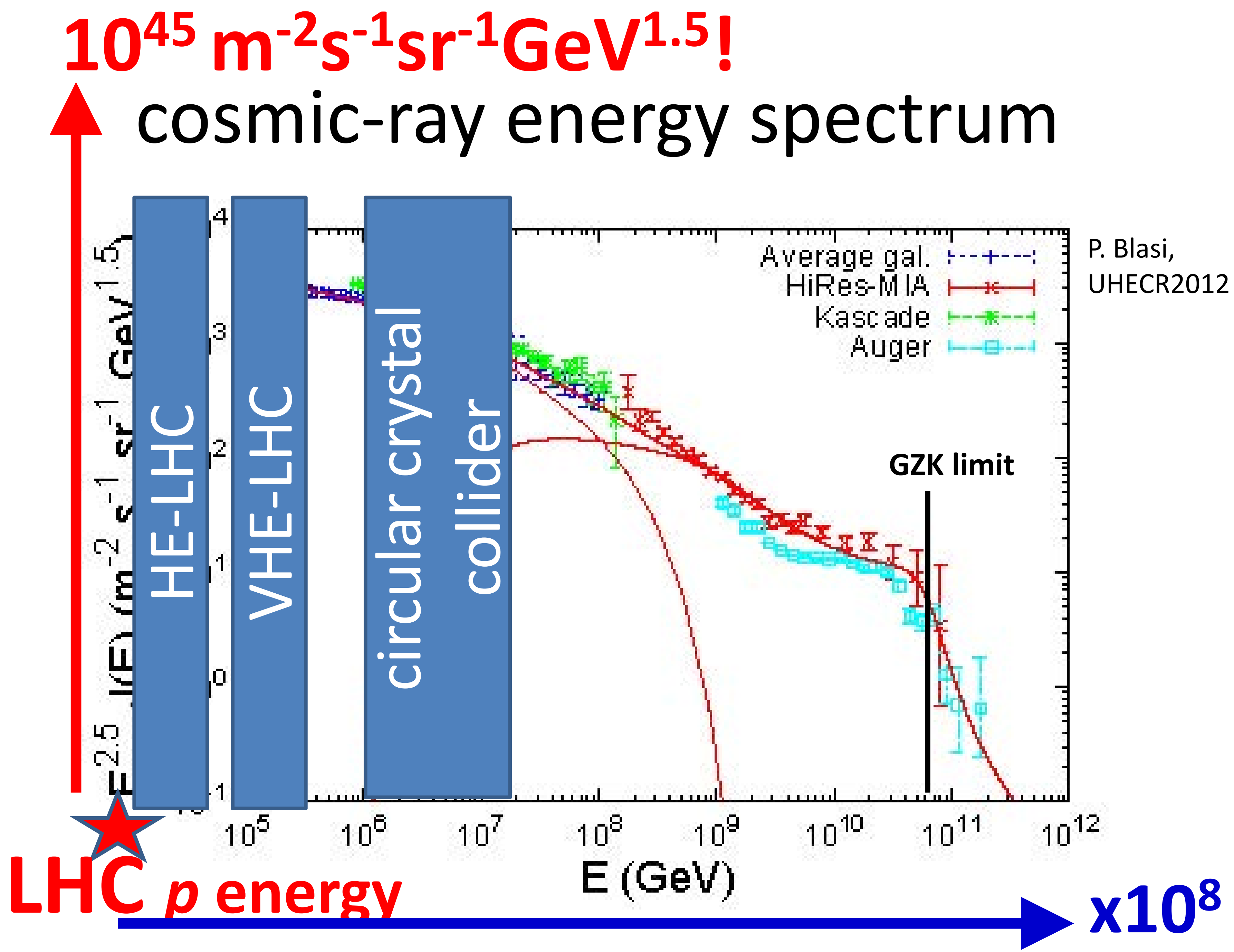
Higgs boson – “God particle”? – mass 1.25×10^{11} eV, neither matter nor force!

15 October 1991 Dugway Proving Ground, Utah, U.S.A.

“Oh-my-God-particle”!

(kinetic) energy 3×10^{20} eV

($= 3 \times 10^{11}$ GeV = 300 EeV)!



10^45 m^-2s^-1sr^-1GeV^1.5!
cosmic-ray energy spectrum
HE-LHC
VHE-LHC
circular crystal collider
Average gal.
HiRes-MIA
Kascade
Auger
GZK limit
P. Blasi, UHECR2012
E (GeV)
LHC p energy
x10^8

ultimate limit of electromagnetic acceleration

$E_{cr} \approx 10^{18}$ V/m critical field for e^+e^- pair creation - $\hbar/(m_e c)\, e\, E_{cr} \sim m_e c^2$

reaching Planck scale of 10^{28} eV would need 10^{10} m long accelerator [10^{10} m= 1/10th of distance earth-sun]

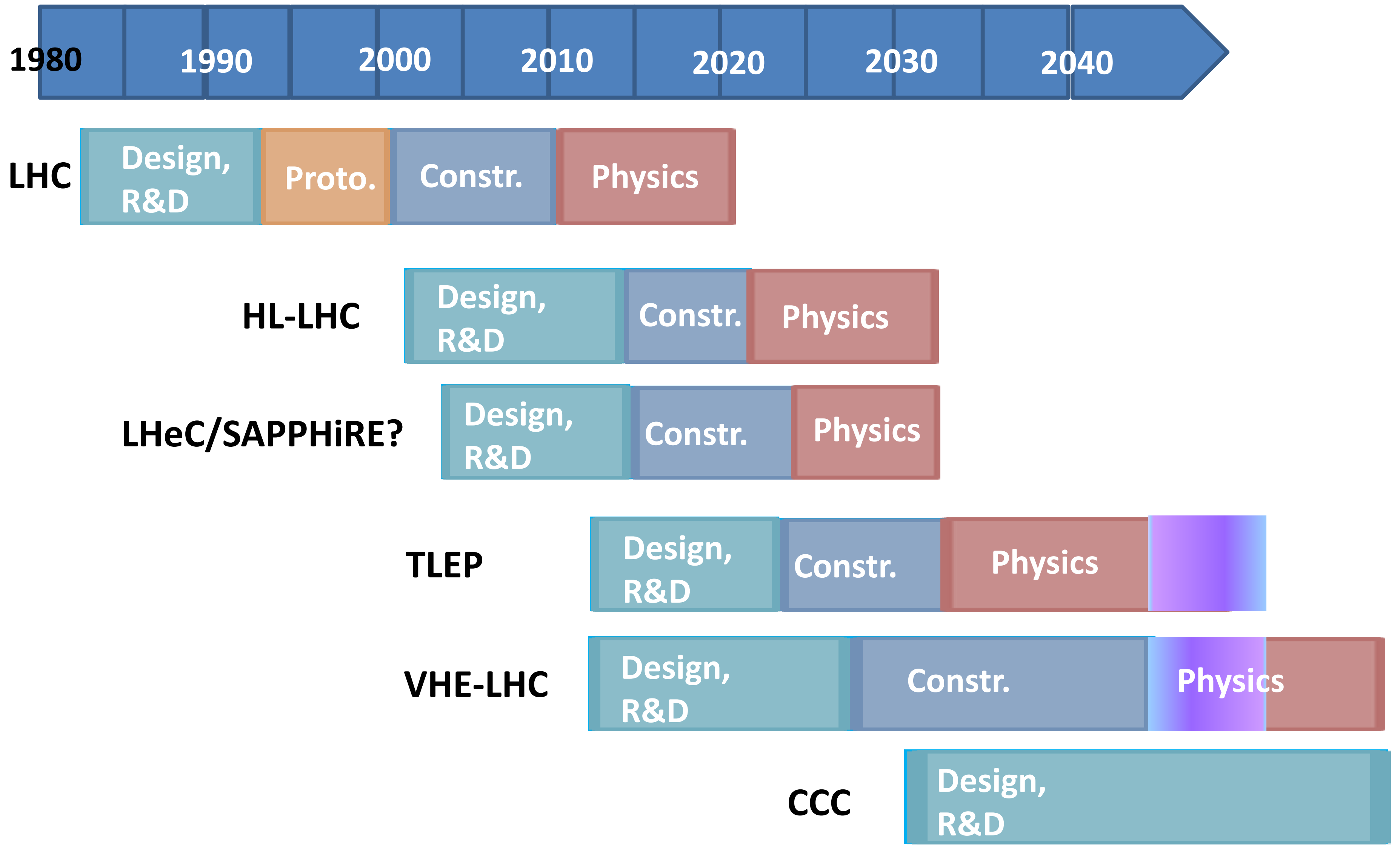
"*not an inconceivable task for an advanced technological society*"

P. Chen, R, Noble, SLAC-PUB-7402, April 1998

summary

- proposed **circular Higgs factories**:
  LHeC (*ep*), SAPPHiRE (γγ) as intermediate HF's & TLEP [or LEP3] as highest-luminosity e^+e^- Higgs factory - **staged**: LHeC/SAPPHiRE concurrent with HL-LHC; TLEP after HL-LHC; note: LHeC/SAPPHiRE's RF system identical to TLEP's – can be recycled
- **HL-LHC** is developing **technology** (*Nb_3Sn* magnets, 20-kA *HTS* cables) for & **TLEP shares tunnel with VHE-LHC *pp* collider** (100 TeV c.m.); **VHE-TLHeC**
- **coherent long-term strategy** emerging, based on sharing, staging & synergies (high performance, minimum total cost)
- next next next machine: **circular crystal collider?**

possible long-term time line



short LHC history

1983 *LEP Note 440* - S. Myers and W. Schnell propose twin-ring *pp* collider in LEP tunnel with 9-T dipoles

1991 CERN Council: LHC approval in principle

1992 EoI, LoI of experiments

1993 SSC termination

1994 CERN Council: LHC approval

1995-98 cooperation w.Japan,India,Russia,Canada,&US

2000 LEP completion

2006 last s.c. dipole delivered

2008 first beam

2010 first collisions at 3.5 TeV beam energy

2015 collisions at ~design energy (plan)

LEP Note 440
11.4.1983
PRELIMINARY PERFORMANCE ESTIMATES FOR A LEP PROTON COLLIDER
S. Myers and W. Schnell

>30 years!

we are already very late if we want to get a new machine by ~2040!

oPAC help urgently needed!

- SAPPHiRE laser & optical cavity system
- IR designs for $\gamma\gamma$, *ep,* and e^+e^- colliders
- highly efficient RF system for TLEP
- TLEP polarization up to 350 GeV?
- economical 20-T dipole
- >100-T magnets?
- efficient crystal channeling
- path to the Planck scale (10^{16} TeV)?

thank you for your attention