cern.ch/accnet

Machine Design Options for LEP3, TLEP & SAPPHiRE

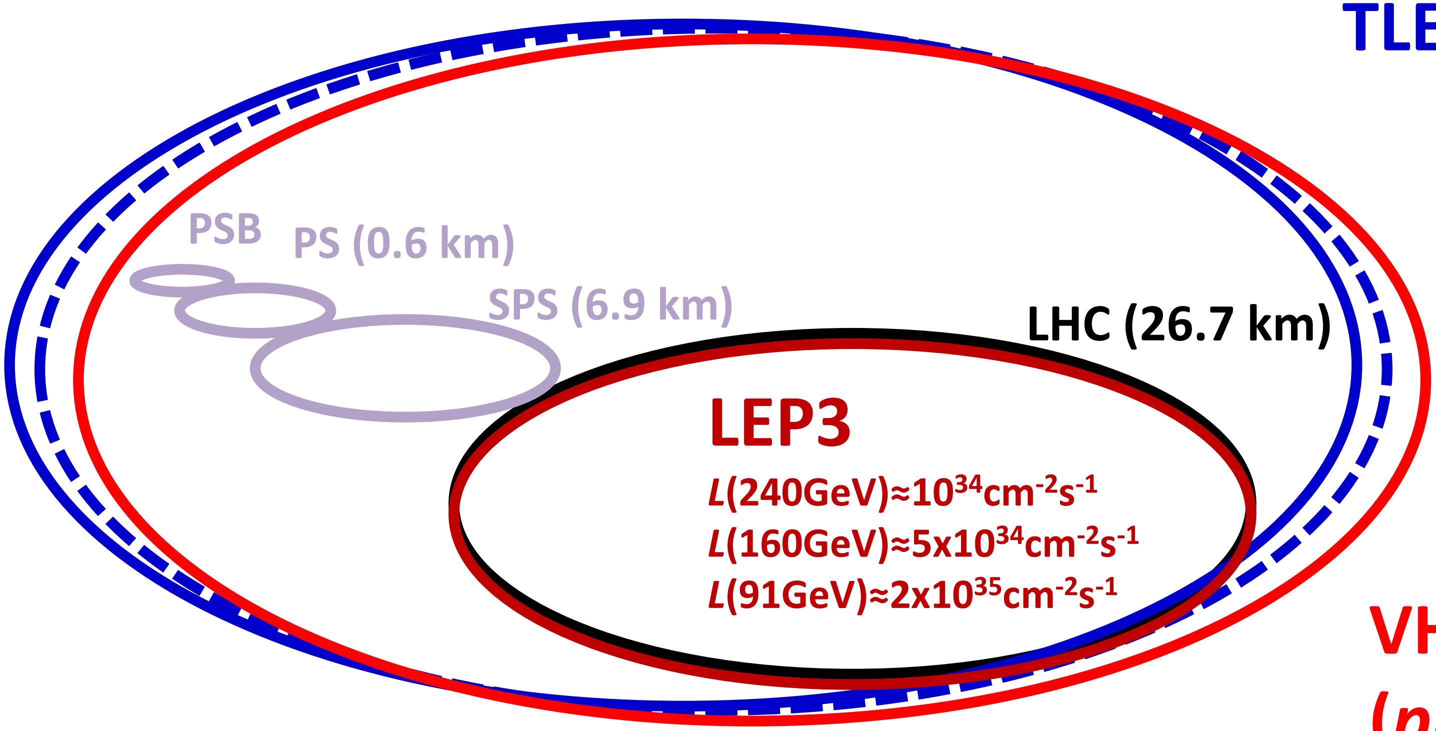
Frank Zimmermann

2nd LEP3 Day, 23 October 2012

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

Part 1 – LEP3 / TLEP

possible future projects



PSB

PS (0.6 km)

SPS (6.9 km)

LHC (26.7 km)

LEP3

L(240GeV)≈10^{34}cm^{-2}s^{-1}
L(160GeV)≈5x10^{34}cm^{-2}s^{-1}
L(91GeV)≈2x10^{35}cm^{-2}s^{-1}

TLEP (80 km,
e^+e^-, up to
400 GeV c.m.)

L(350GeV)≈7x10^{33}cm^{-2}s^{-1}
L(240GeV)≈5x10^{34}cm^{-2}s^{-1}
L(160GeV)≈1.5x10^{35}cm^{-2}s
L(91GeV)≈10^{36}cm^{-2}s^{-1}

VHE-LHC
(*pp*, up to
100 TeV c.m.)

also: **$e^{\pm}$ (200 GeV) – p (7 & 50 TeV)** collisions

LEP3/TLEP luminosity limits

$$L = \frac{f_{rev} n_b N_b^2}{4\pi\sigma_x\sigma_y} = (f_{rev} n_b N_b)\left(\frac{N_b}{\varepsilon_x}\right)\frac{1}{4\pi}\frac{1}{\sqrt{\beta_x\beta_y}}\frac{1}{\kappa_\varepsilon}$$

$$(f_{rev} n_b N_b) = \frac{P_{SR}\,\rho}{8.8575\times 10^{-5}\,\frac{\mathrm{m}}{\mathrm{GeV}^{-3}}\,E^4}$$

SR radiation power limit

$$\frac{N_b}{\varepsilon_x} = \frac{\xi_x 2\pi\gamma(1+\kappa_\sigma)}{r_e}$$

beam-beam limit

$$\frac{N_b}{\sigma_x\sigma_z}\frac{30\,\gamma r_e^2}{\delta_{acc}\,\alpha} < 1$$

>30 min beamstrahlung lifetime (Telnov) → N_b, β_x

boosting LEP3/TLEP luminosity

minimizing

$\kappa_\varepsilon=\varepsilon_y/\varepsilon_x$

$\beta_y\sim\beta_x(\varepsilon_y/\varepsilon_x)$

increases the luminosity independently of previous limits

however $\beta_y \geq \sigma_z$ (hourglass effect)

rf efficiency ($P_{wall} \rightarrow P_{SR}$)

compare **numbers from LHeC Conceptual Design Report**: J L Abelleira Fernandez et al, *"A Large Hadron Electron Collider at CERN Report on the Physics and Design Concepts for Machine and Detector,"* J. Phys. G: Nucl. Part. Phys. 39 075001 (2012):

conversion efficiency grid to amplifier RF output = 70%
transmission losses = 7%
feedbacks power margin = 15%
→ **total efficiency ~55%**

50% assumed for LEP3/TLEP at same frequency & gradient

LEP3/TLEP parameters -1

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
beam energy E_b [GeV]	104.5	60	120	45.5	120	175
circumference [km]	26.7	26.7	26.7	80	80	80
beam current [mA]	4	100	7.2	1180	24.3	5.4
#bunches/beam	4	2808	4	2625	80	12
#e–/beam [10^{12}]	2.3	56	4.0	2000	40.5	9.0
horizontal emittance [nm]	48	5	25	30.8	9.4	20
vertical emittance [nm]	0.25	2.5	0.10	0.15	0.05	0.1
bending radius [km]	3.1	2.6	2.6	9.0	9.0	9.0
partition number J_ε	1.1	1.5	1.5	1.0	1.0	1.0
momentum comp. α_c [10^{-5}]	18.5	8.1	8.1	9.0	1.0	1.0
SR power/beam [MW]	11	44	50	50	50	50
β^*_x [m]	1.5	0.18	0.2	0.2	0.2	0.2
β^*_y [cm]	5	10	0.1	0.1	0.1	0.1
σ^*_x [µm]	270	30	71	78	43	63
σ^*_y [µm]	3.5	16	0.32	0.39	0.22	0.32
hourglass F_{hg}	0.98	0.99	0.59	0.71	0.75	0.65
ΔE^{SR}_{loss}/turn [GeV]	3.41	0.44	6.99	0.04	2.1	9.3

LEP3/TLEP parameters -2

LEP2 was not beam-beam limited

	LEP2	LHeC	LEP3	TLEP-Z	TLEP-H	TLEP-t
$V_{RF,tot}$ [GV]	3.64	0.5	12.0	2.0	6.0	12.0
$\delta_{max,RF}$ [%]	0.77	0.66	5.7	4.0	9.4	4.9
ξ_x/IP	0.025	N/A	0.09	0.12	0.10	0.05
ξ_y/IP	0.065	N/A	0.08	0.12	0.10	0.05
f_s [kHz]	1.6	0.65	2.19	1.29	0.44	0.43
E_{acc} [MV/m]	7.5	11.9	20	20	20	20
eff. RF length [m]	485	42	600	100	300	600
f_{RF} [MHz]	352	721	700	700	700	700
δ^{SR}_{rms} [%]	0.22	0.12	0.23	0.06	0.15	0.22
$\sigma^{SR}_{z,rms}$ [cm]	1.61	0.69	0.31	0.19	0.17	0.25
L/IP[10^{32}cm^{-2}s^{-1}]	1.25	N/A	94	10335	490	65
number of IPs	4	1	2	2	2	2
Rad.Bhabha b.lifetime [min]	360	N/A	18	74	32	54
Υ_{BS} [10^{-4}]	0.2	0.05	9	4	15	15
n_γ/collision	0.08	0.16	0.60	0.41	0.50	0.51
$\Delta\delta^{BS}$/collision [MeV]	0.1	0.02	31	3.6	42	61
$\Delta\delta^{BS}_{rms}$/collision [MeV]	0.3	0.07	44	6.2	65	95

LEP data for 94.5 - 101 GeV consistently suggest a beam-beam limit of ~0.115 (R.Assmann, K. C.)

top-up injection

SPS as LEP injector accelerated $e^{\pm}$ from 3.5 to 20 GeV (later 22 GeV) on a very short cycle: acceleration time = 265 ms or about 62.26 GeV/s

Ref. K. Cornelis, W. Herr, R. Schmidt, "Multicycling of the CERN SPS: Supercycle Generation & First Experience with this mode of Operation," Proc. EPAC 1988

assuming injection from the SPS into the top-up accelerator at the same energy of 20 GeV and final energy of 120 GeV: acceleration time = 1.6 seconds

total cycle time = 10 s looks conservative (→ **refilling ~1% of the LEP3** beam, for τ_{beam}~16 min)

Ghislain Roy & Paul Collier

transverse impedance & TMCI

LEP bunch intensity was limited by TMCI: **$N_{b,thr}$~5x10^{11} at 22 GeV**

LEP3 with 700 MHz: **at 120 GeV we gain a factor 5.5 in the threshold**, **which almost cancels a factor $(0.7/0.35)^3$ ~ 8** arising from the change in wake-field strength due to the different RF frequency

LEP3 Q_s~0.2, LEP Q_s~0.15: further **25% increase** in TMCI threshold?

only ½ of LEP transverse kick factor came from SC RF cavities

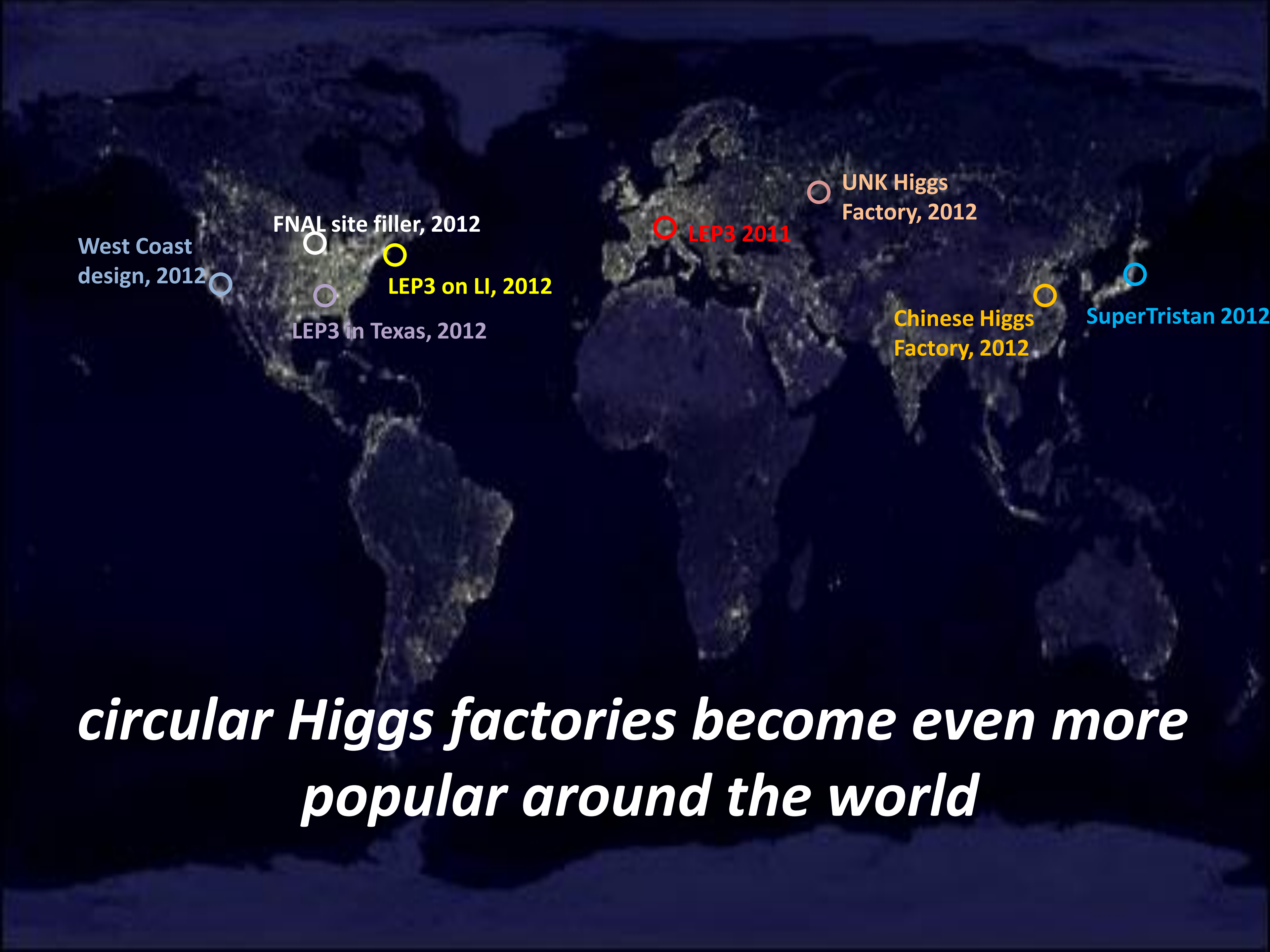
LEP3 beta functions at RF cavities might be smaller than in LEP

LEP3 bunch length (2-3 mm) is shorter than at LEP injection (5-9 mm)

M. Lamont, SL-Note-98-026 (OP)

beam-beam with large hourglass effect?

simulations by K. Ohmi – later at this meeting

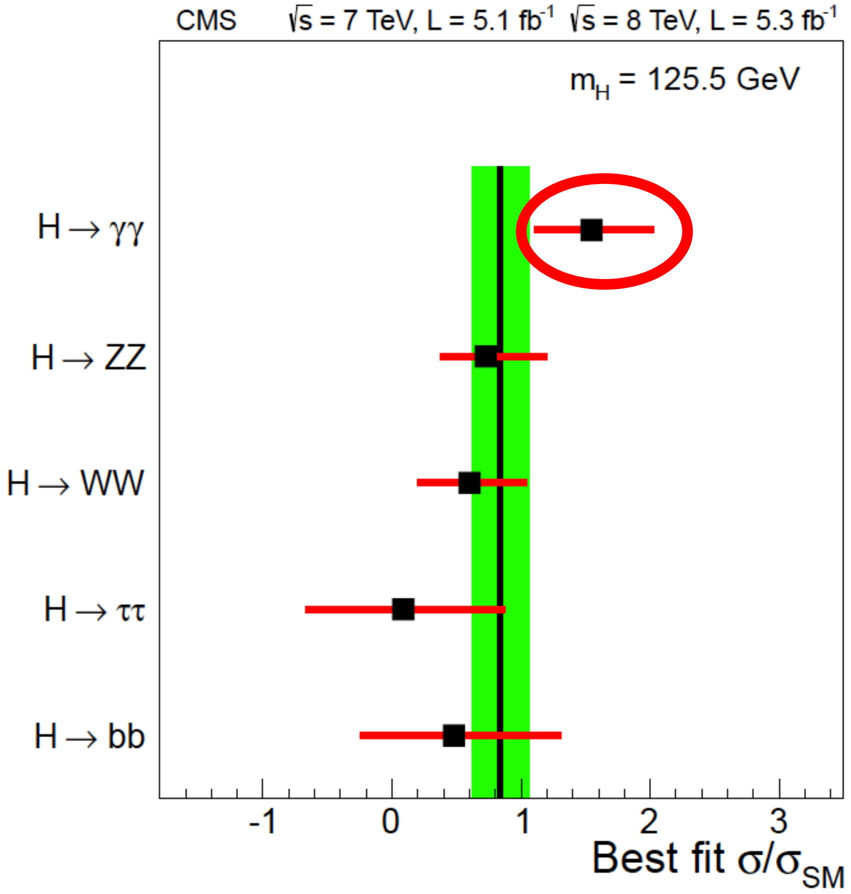


circular Higgs factories become even more popular around the world

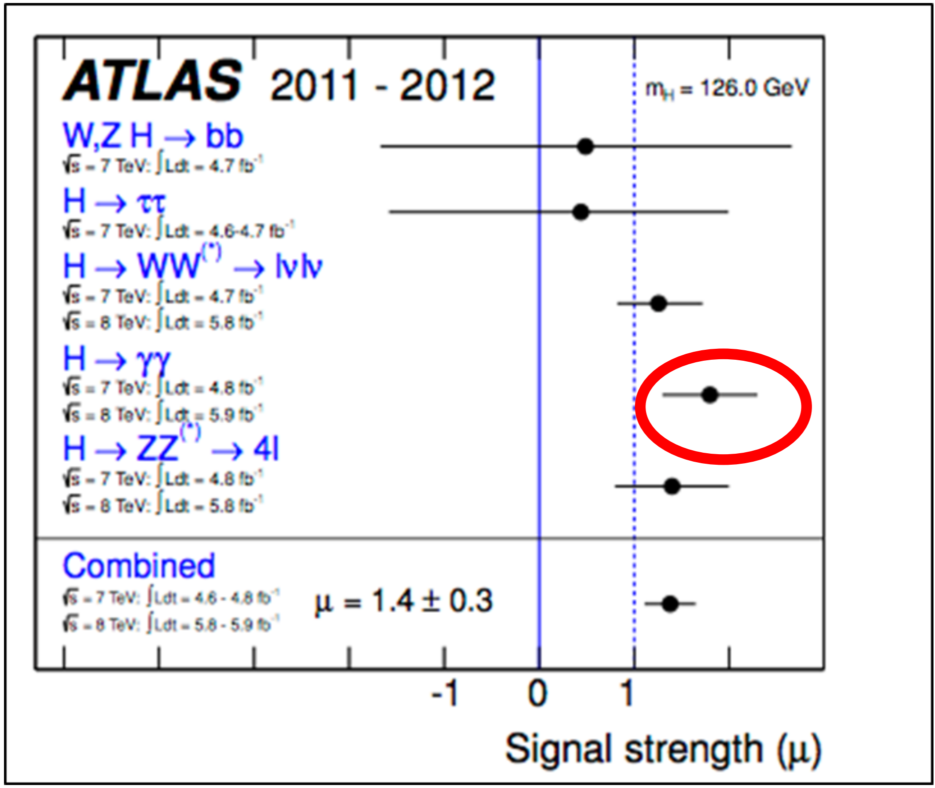
Part 2 - SAPPHiRE

“Higgs” strongly couples to $\gamma\gamma$

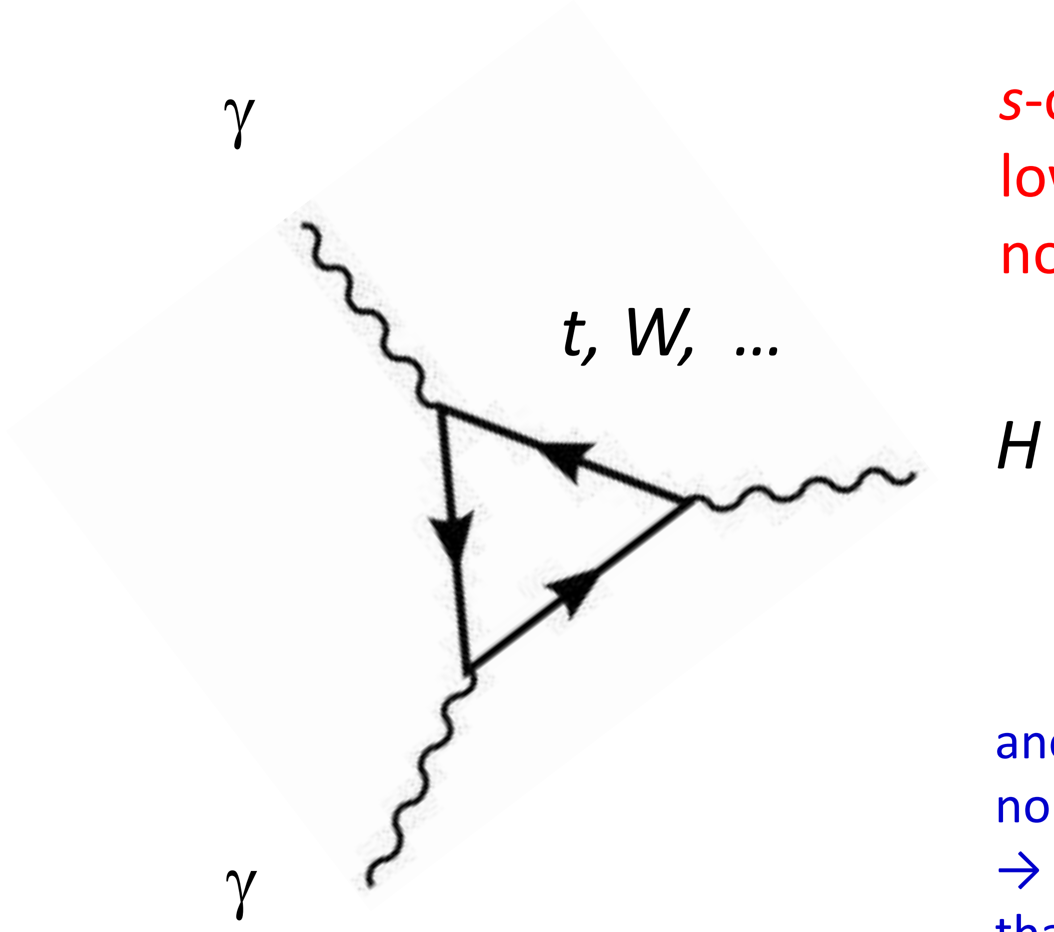
LHC CMS result



LHC ATLAS result



a new type of collider?

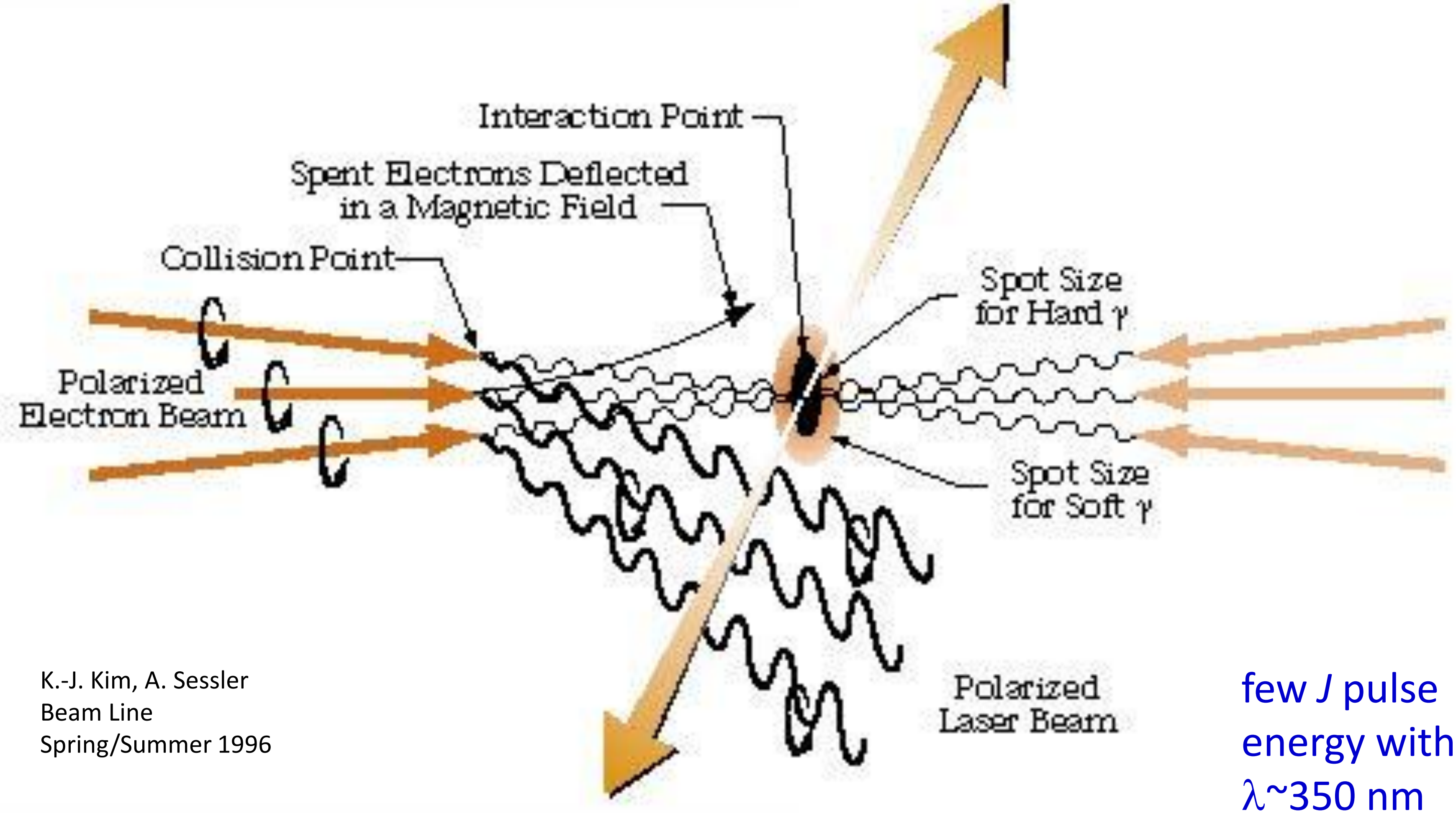


s-channel production;
lower energy;
no e^+ source

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

$\gamma\gamma$ collider Higgs factory

γγ collider



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?

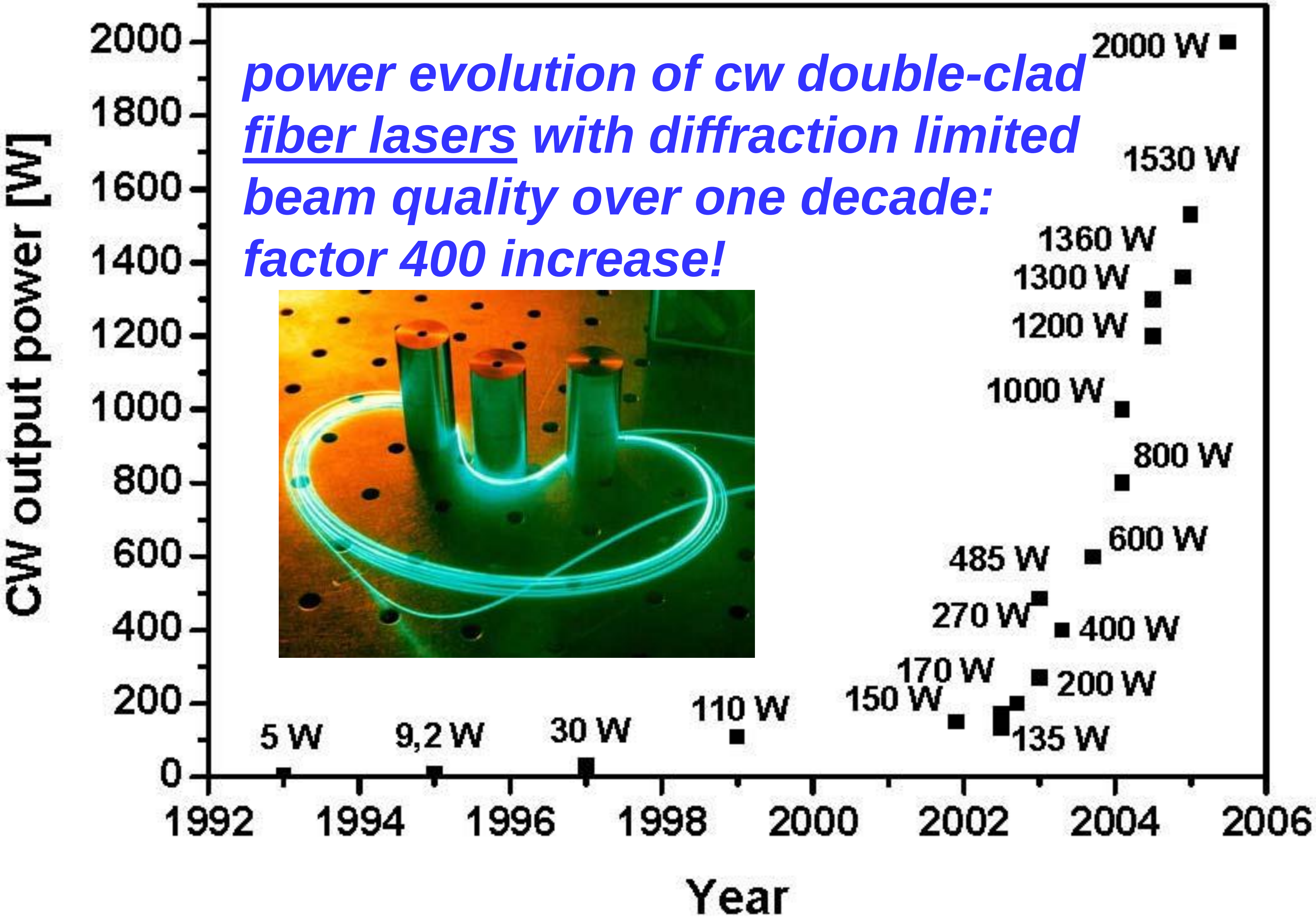
$$E_{\gamma,max} = \frac{x}{1+x} E_{beam}$$

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

laser progress: example fiber lasers



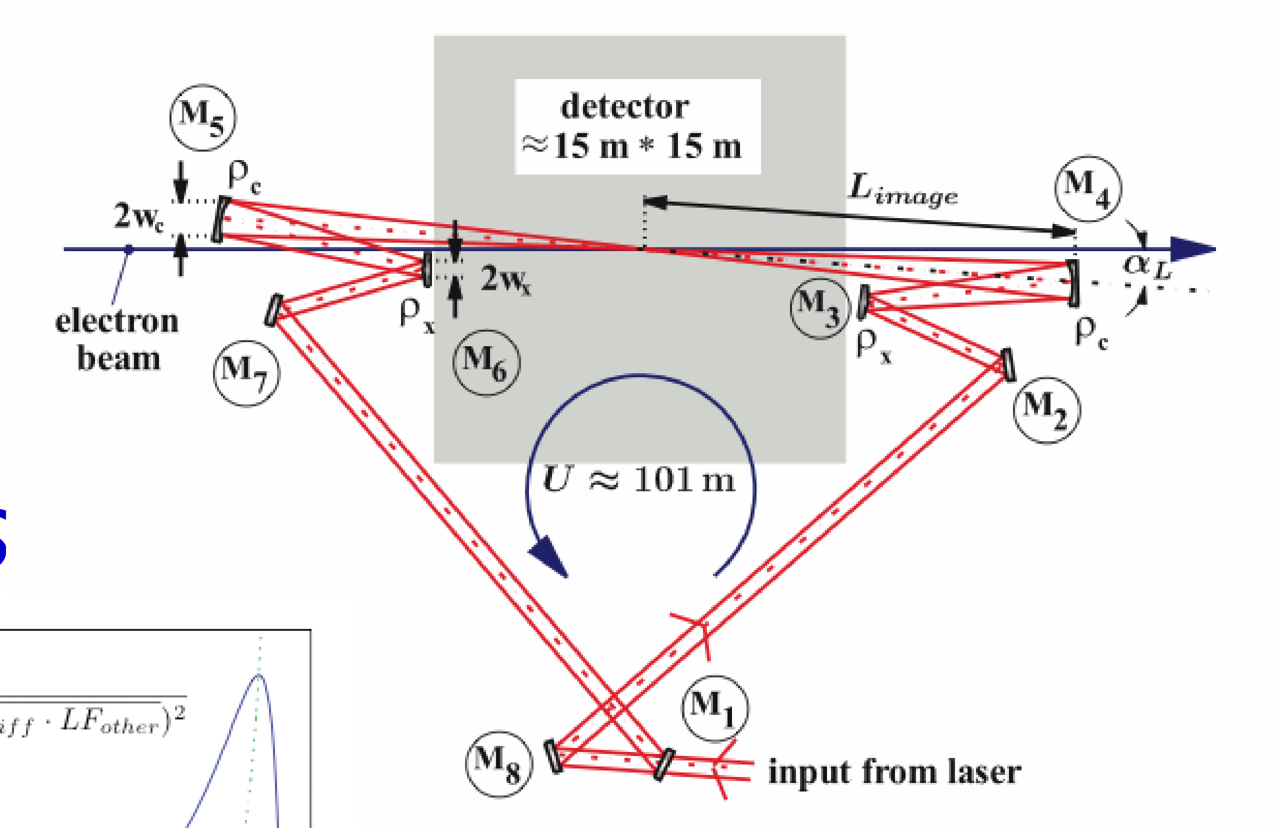
power evolution of cw double-clad <u>fiber lasers</u> with diffraction limited beam quality over one decade: factor 400 increase!

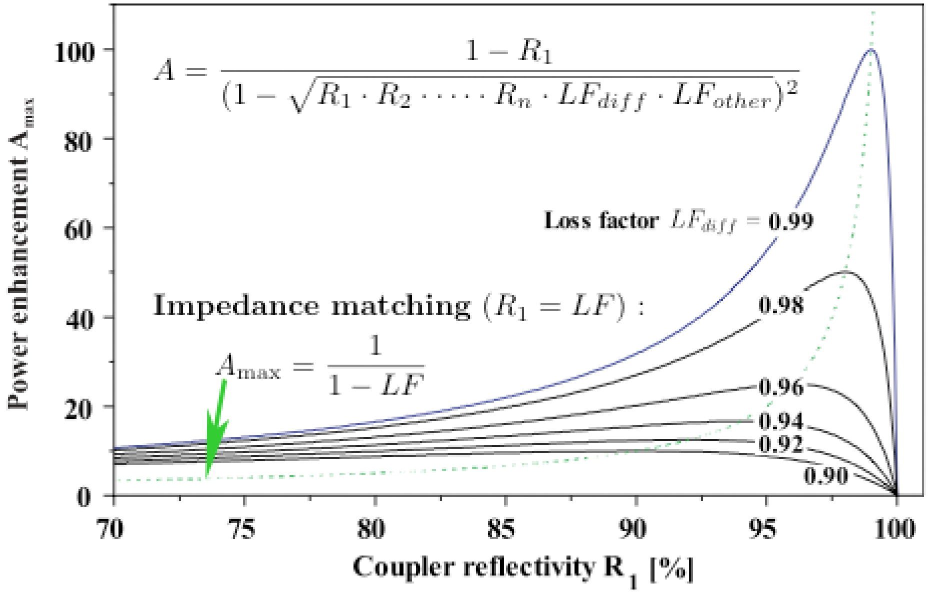
Source: Fiber Based High Power Laser Systems,
Jens Limpert, Thomas Schreiber, and Andreas Tünnermann

passive optical cavity

→

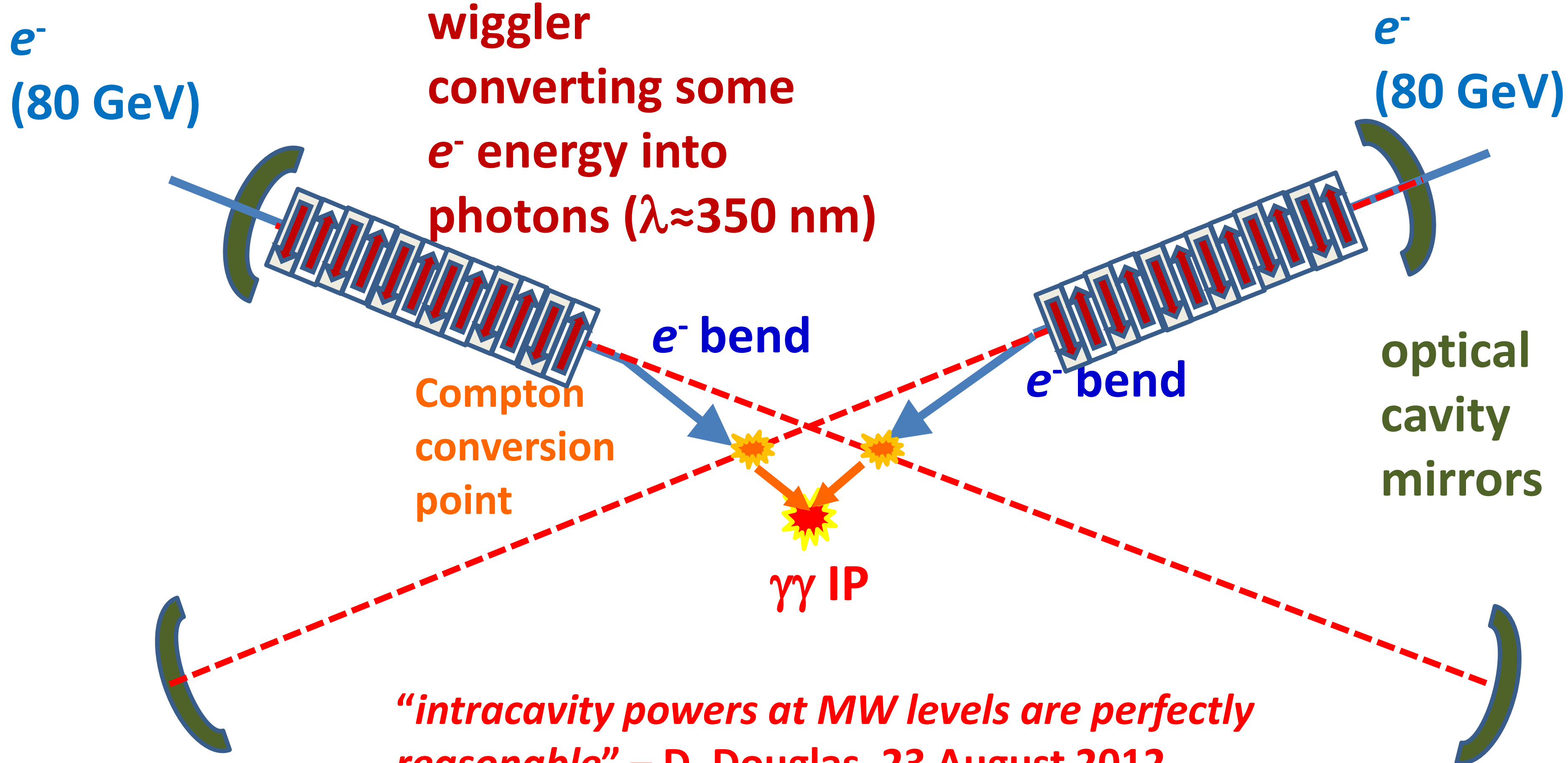
relaxed
laser
parameters





K. Moenig et al, DESY Zeuthen

self-generated FEL γ beams (instead of laser)?

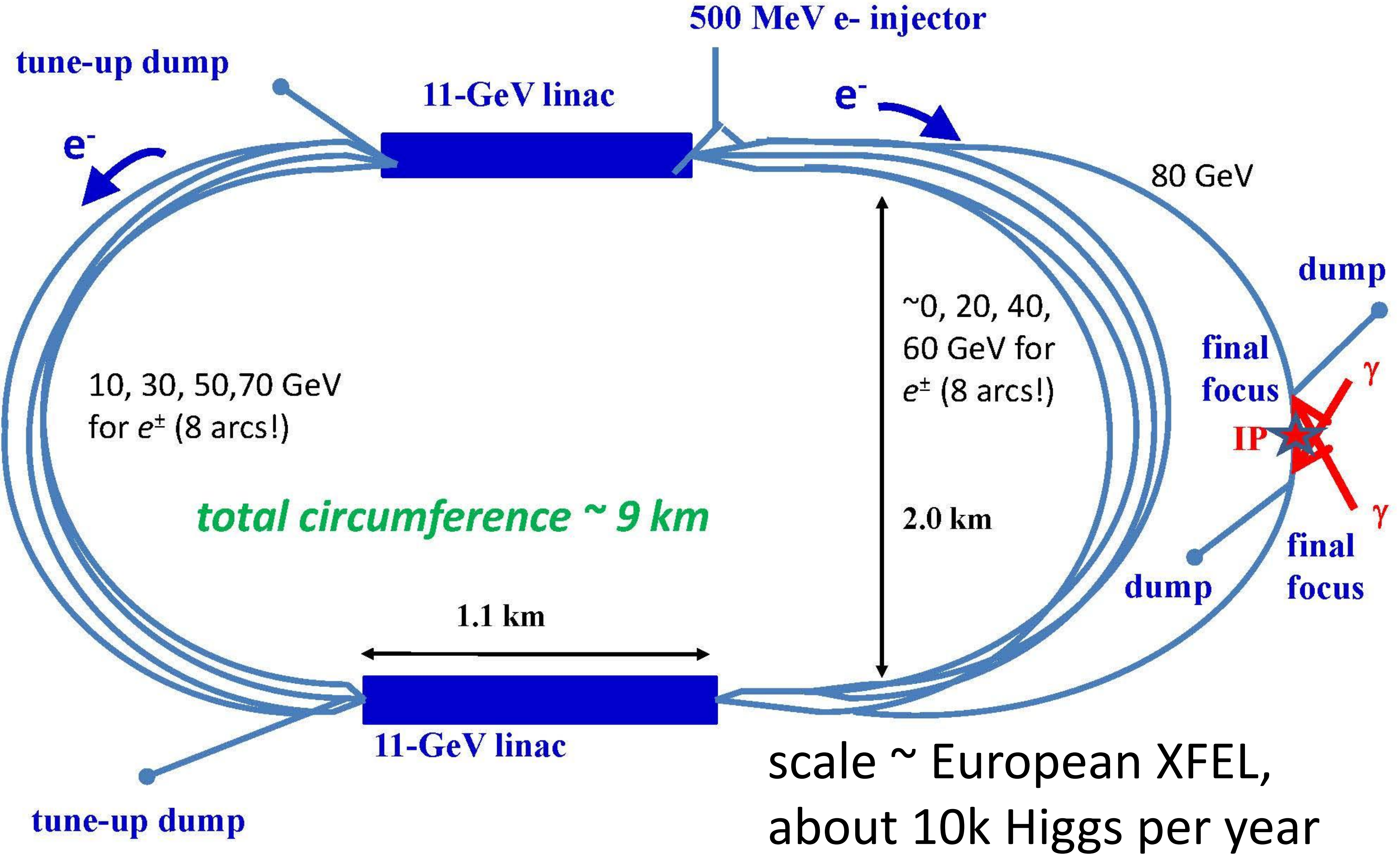


"intracavity powers at MW levels are perfectly reasonable" – D. Douglas, 23 August 2012

example: λ_u=50 cm, B=5 T, L_u=50 m, 0.1%$P_{beam}\approx$25 kW

scheme developed with Z. Huang

SAPPHiRE: a Small $\gamma\gamma$ Higgs Factory



scale ~ European XFEL,
about 10k Higgs per year

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

SAPPHiRE	symbol	value
total electric power	P	100 MW
beam energy	E	80 GeV
beam polarization	P_e	0.80
bunch population	Nb	10^{10}
repetition rate	f_{rep}	200 kHz
bunch length	σ_z	30 μm
crossing angle	θ_c	≥20 mrad
normalized horizontal emittance	$\gamma\varepsilon_x$	5 μm
normalized vertical emittance	$\gamma\varepsilon_y$	0.5 μm
horizontal IP beta function	β_x^*	5 mm
vertical IP beta function	β_y^*	0.1 mm
horizontal rms IP spot size	σ_x^*	400 nm
vertical rms IP spot size	σ_y^*	18 nm
horizontal rms CP spot size	σ_x^{CP}	400 nm
vertical rms CP spot size	σ_y^{CP}	180 nm

Valery Telnov's comments
(21 October 2012)

*"**SUPPHiRE will not work**. **I considered this approach many years ago**, thought about the usage of some existing ring for this purpose, but **the problem was clear - unacceptable increase of the emittance**"*

*"PLC needs polarized electrons (only in this case one can see the Higgs). **At present low emittance polarized electron guns do not exist.**"*

Energy loss

The energy loss per arc is $\Delta E_{arc}\ [\mathrm{GeV}] = 8.846 \times 10^{-5} \frac{(E\ [GeV])^4}{2\rho[\mathrm{m}]}$

For **ρ=764 m** (LHeC design) the energy loss in the various arcs is summarized in the following table. We lose about 4 GeV in energy, which can be compensated by increasing the voltage of the two linacs from 10 GV to 10.5 GV. We take 11 GV per linac to be conservative.

beam energy [GeV]	ΔE_{arc} [GeV]	$\Delta\sigma_E$ [MeV]
10	0.0006	0.038
20	0.009	0.43
30	0.05	1.7
40	0.15	5.0
50	0.36	10
60	0.75	20
70	1.39	35
80	1.19	27
total	**3.89**	**57**

Energy spread

The additional energy spread from the synchrotron radiation is given by

$$\Delta\sigma_E^2 = \frac{55\alpha(\hbar c)^2}{48\sqrt{3}}\gamma^7\frac{\pi}{\rho^2}$$

where *R*~1 km is the geometric radius, and ρ the bending radius of the arc. It is also listed in the table.

The **total rms energy spread induced by synchrotron radiation is only 0.071%**.

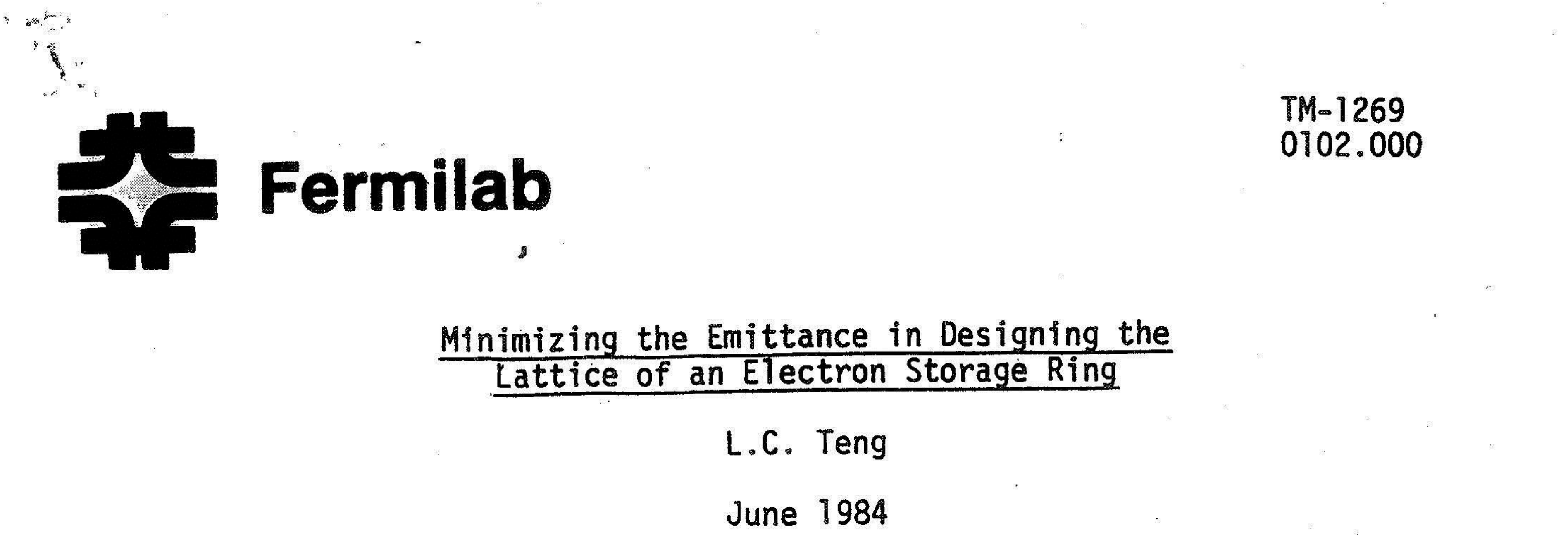
Emittance growth

The emittance growth is $\Delta\varepsilon_N = \frac{2\pi}{3}\frac{C_q r_e}{\rho^2}\gamma^6\langle H\rangle$

with C_q=3.8319x10^{-13} m, and ρ the bending radius.

For LHeC RLA design with l_{bend}~10 m, and ρ=764 m, <H>=1.2x10^{-3} m [Bogacz et al], close to the “useful and realistic” minimum emittance optics of Lee Teng. At 60 GeV the emittance growth of LHeC optics is 13 micron, too high fo our purpose, and extrapolation to 80 GeV is unfavourable with 6th power of energy. From Teng we also have **scaling law** $< H > \propto l_{bend}^3/\rho^2$. This suggests that **by reducing the cell length and dipole length by a factor of 4 we can bring the horiz. norm. emittance growth at 80 GeV down to 1 micron**.

reference



TM-1269
0102.000

Fermilab

Minimizing the Emittance in Designing the Lattice of an Electron Storage Ring

L.C. Teng

June 1984

“Sawtooth” orbit

The largest energy loss due to synchrotron radiation for beams in a common arc occurs at 70 GeV. It amounts to 1.39 GeV, or 2%. With a dispersion of 0.1 m (see [Bogacz et al]) the orbit change would be 2 mm. The two beams would certainly fit into a common beam pipe.

Flat electron source

We would like to operate with flat beams, with an emittance ratio of 10. Such flat beam can be produced with a flat-beam electron gun using the flat-beam transformer concept of Ref. [Derbenev et al]. Starting with a normalized uncorrelated emittance of 4-5 μm at a bunch charge of 0.5 nC, the injector test facility at the **Fermilab A0 line achieved emittances of 40 μm horizontally and 0.4 μm vertically**, with an emittance ratio of 100. For the gamma-gamma collider **we only need an emittance ratio of 10, but a three times larger charge (1.6 nC) and a smaller initial emittance of ~1.5 μm**. These parameters are within the present state of the art (e.g. the LCLS photoinjector routinely achieves 1.2 μm emittance at 1 nC charge). However, **we need a polarized beam**…

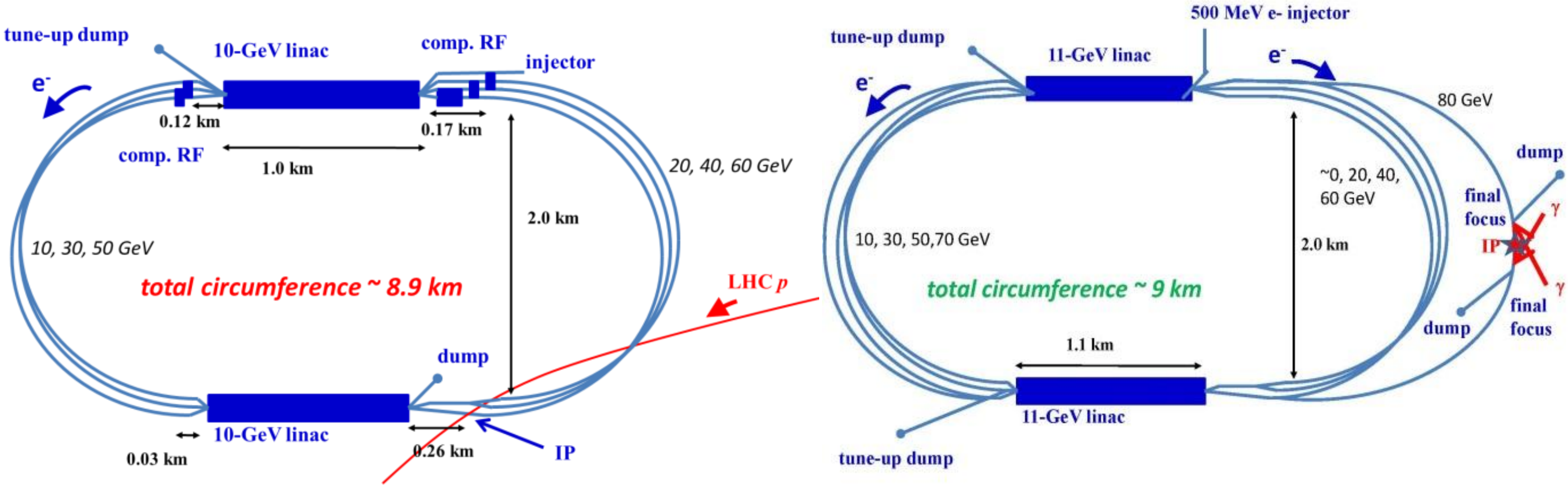
can we get ~ 1-nC polarized e^- bunches with ~1 μm emittance?

ongoing R&D efforts:

DC gun (MIT-Bates, Cornell, SACLA,…)

polarized SRF gun (FZD, BNL,…)

LHeC → SAPPHiRE

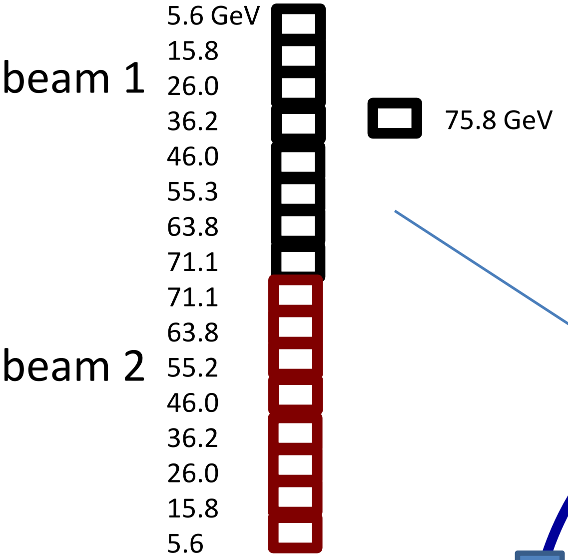


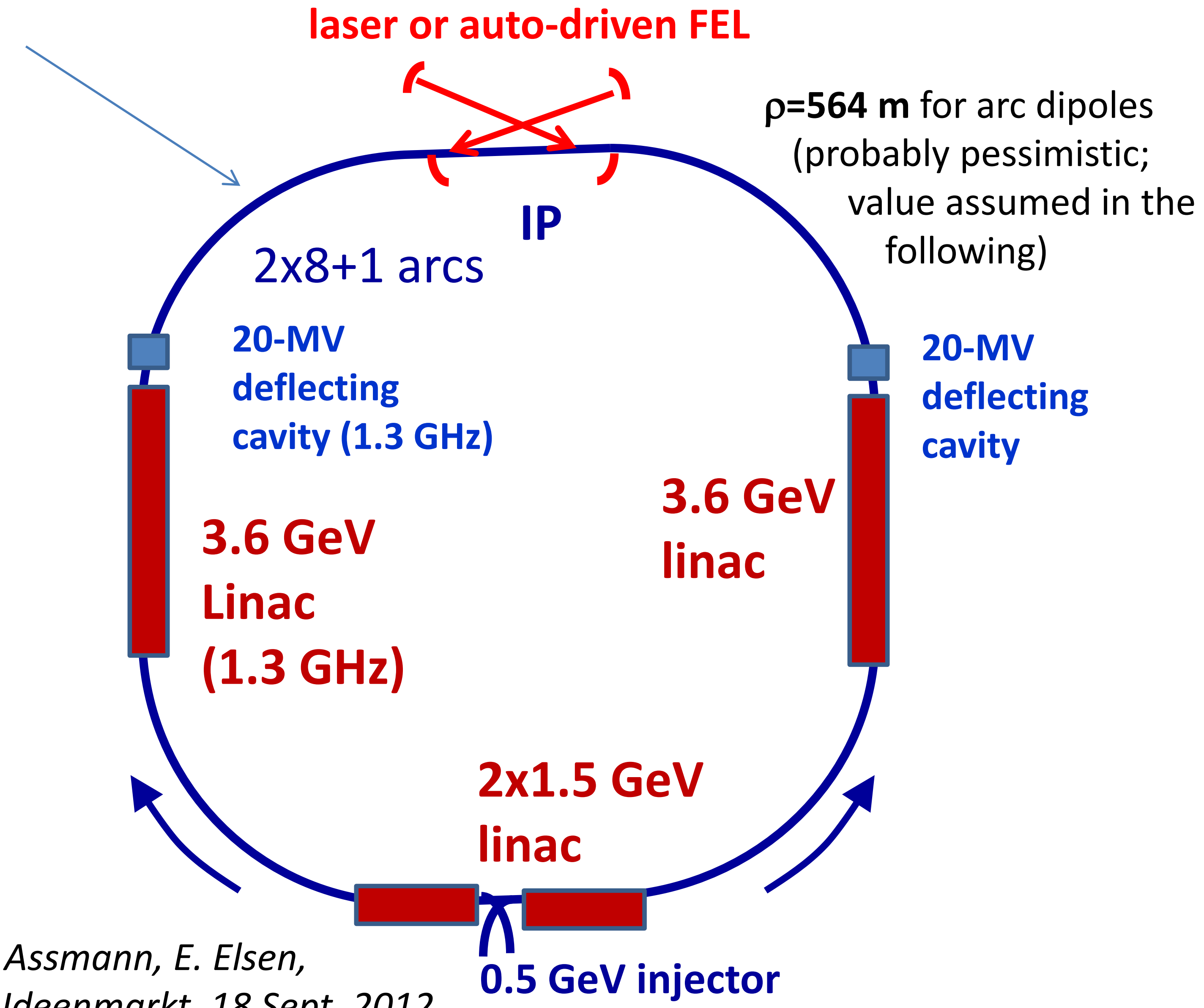
Schematic sketches of the layout for the LHeC ERL (left) and for a gamma-gamma Higgs factory based on the LHeC (right)

would it fit on SLAC site?

schematic of HERA-$\gamma\gamma$

arc magnets -17 passes!





ρ=**564 m** for arc dipoles (probably pessimistic; value assumed in the following)

real-estate linac
Gradient
~ 10 MV/m

total
SC RF =
10.2 GV

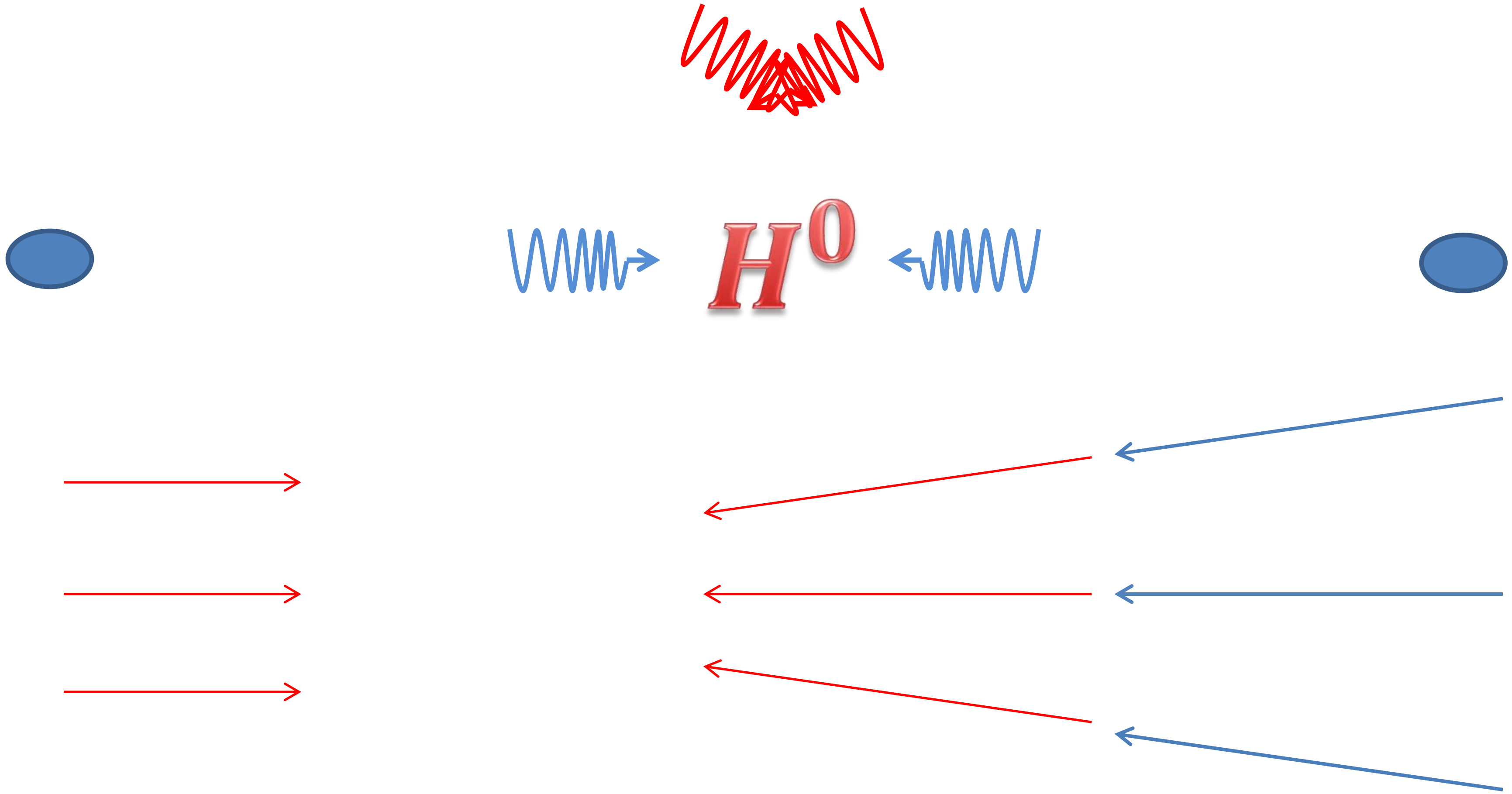
F. Zimmermann, R. Assmann, E. Elsen,
DESY Bschleuniger-Ideenmarkt, 18 Sept. 2012

similar ideas elsewhere

$\gamma\gamma$ Collider at J-Lab

By Edward Nissen

Town Hall meeting Dec 19 2011

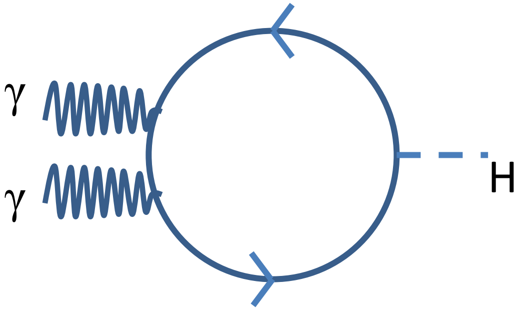


Background

Edward Nissen

$$x = \frac{12.3 E_e(TeV)}{\lambda_\gamma(\mu m)}$$

$$\hbar\omega_\gamma = \frac{x}{1+x} E_e$$



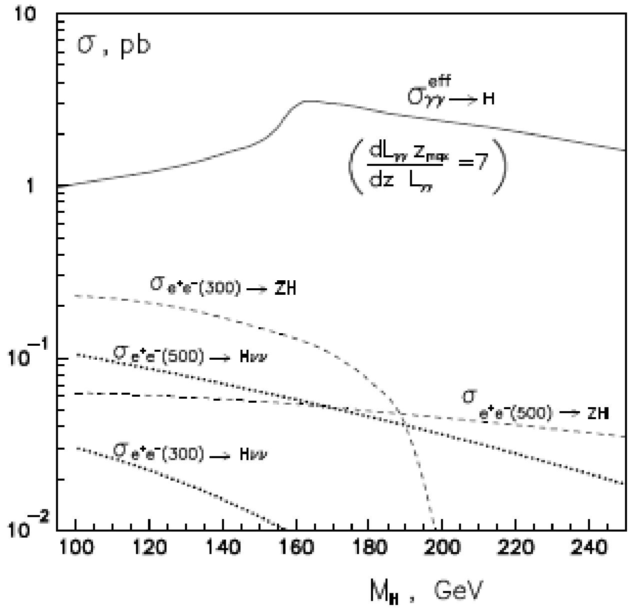


Figure 5: Cross sections for the Standard model Higgs in $\gamma\gamma$ and e^+e^- collisions.

arXiv:hep-ex/9802003v2

Possible Configurations at JLAB

85 GeV Electron energy
γ c.o.m. 141 GeV

103 GeV Electron energy
γ c.o.m. 170 GeV

LEP3, TLEP, and SAPPHiRE are moving forward

thank you for listening!