Lessons Learned from LEP and their Application to FCC/CEPC

(as asked by the organisers :) bit of history of the CERN

Large **E**lectron-**P**ositron Collider

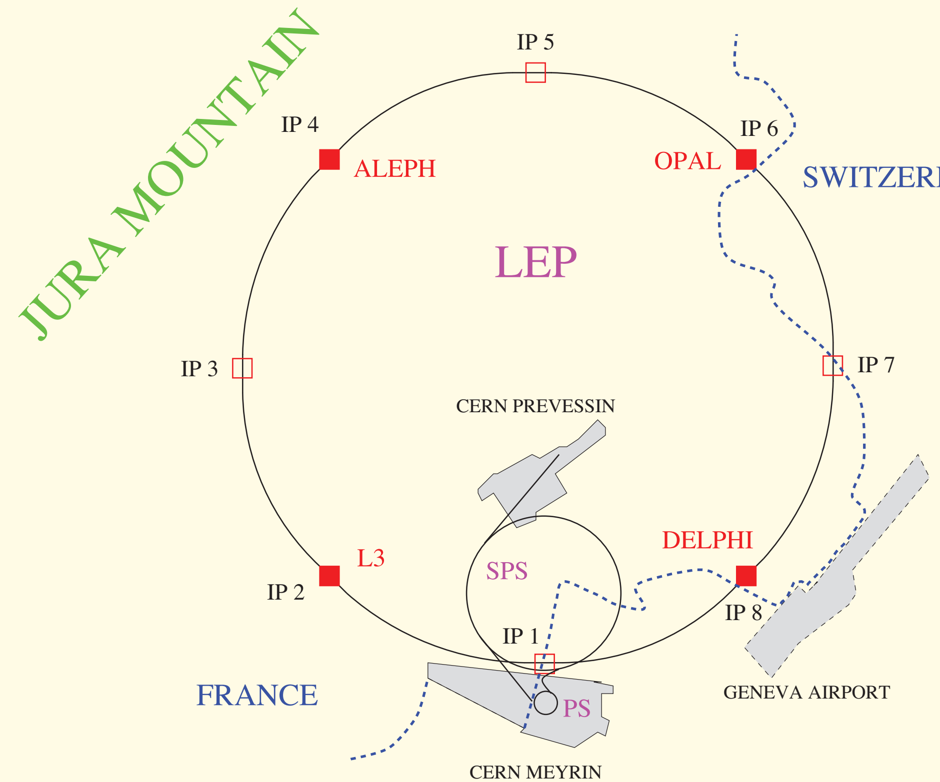
trying to illustrate and summarise key points, that we use as basis for the FCC-ee design and that should also be of interest for CEPC, with focus on MDI

L = 26.659 km **× 3**

Ecms 92 — 207 GeV **× 1.8**

SR Power 10 MW **× 5**

Luminosity **× 10^4**

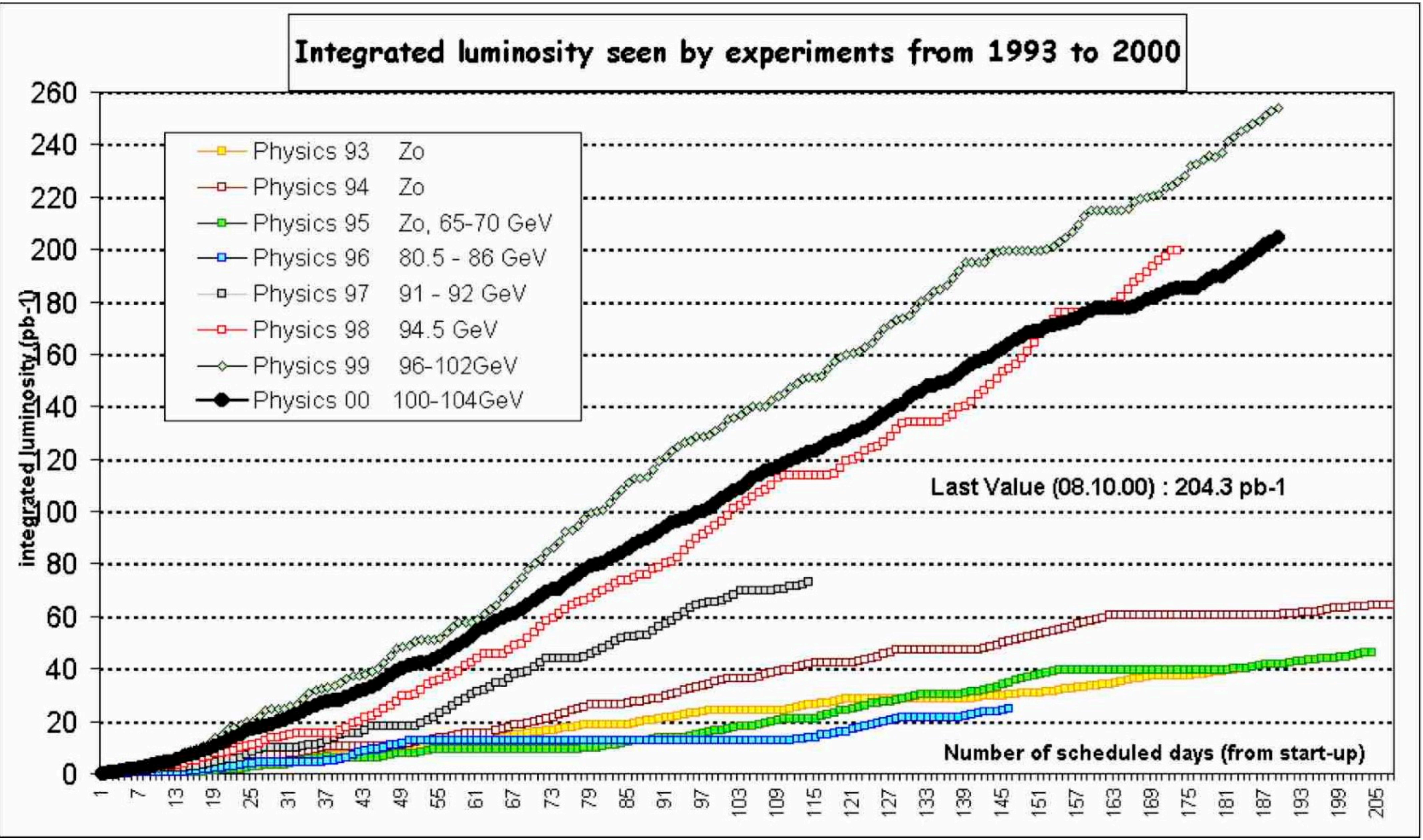


LEP : tunneling 13/9/1983 - 8/2/1988; installation largely in 1988 + sector test

Pilot run, first Z's, low L, superconducting final focus magnets off : August 1989

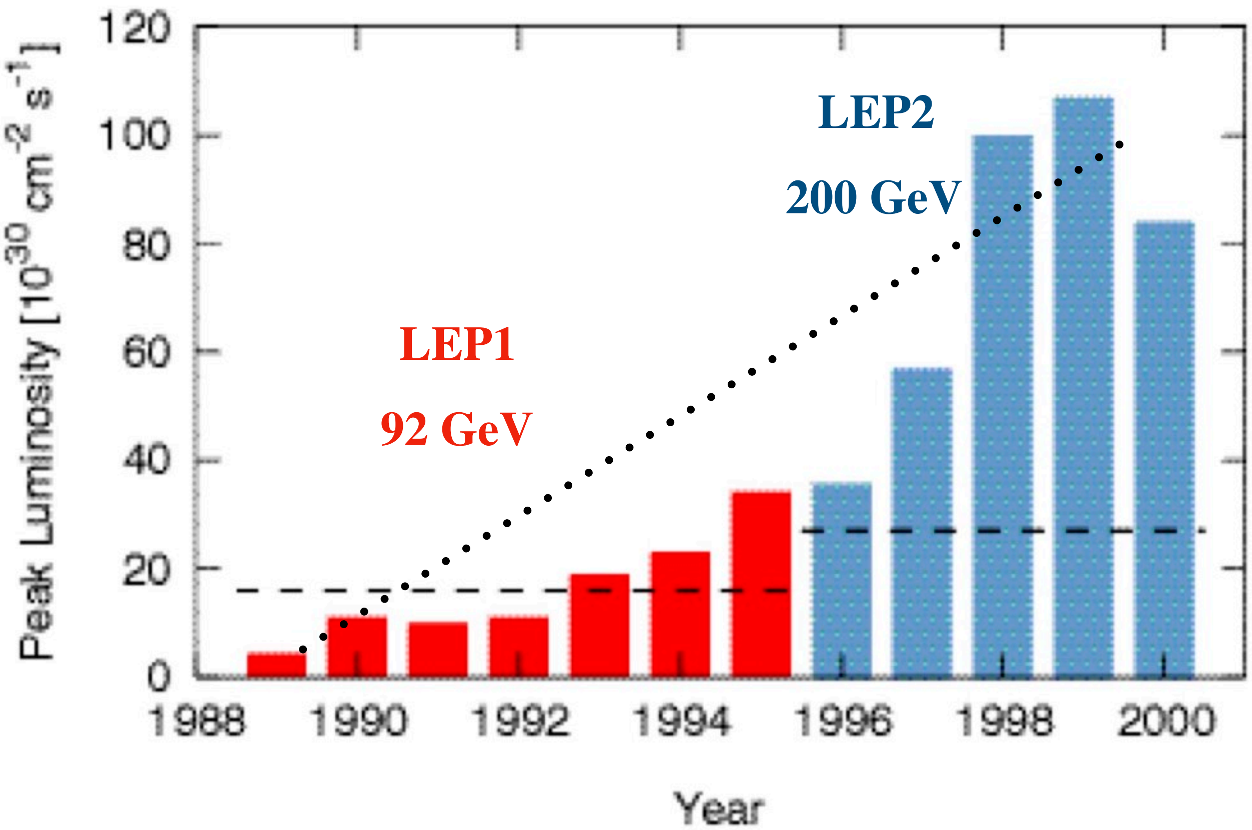
Operation : 1990 - 2000 ; then stopped and dismantled for LHC

Performance 1993 - 2000



$\int L\, dt$ / year increase by ~10 × over 10 years

Peak performance



Performance increases steadily (slowly) over many years

arguably **more than in pp machines where the beam brightness is made by the injectors**

here a key role in IR design / MDI

minimum β* and maximum tune shift were limited in LEP by the need for stable low background running conditions

LEP peak performance parameters

Table 1: LEP beam parameters corresponding to the best performances at three different energies. The luminosities and beam-beam tune shifts are averaged over a time interval of 15 minutes. For each beam energy, the first line corresponds to the horizontal, the second line to the vertical plane.

E_b (GeV)	N_b ($\times 10^{11}$)	k_b	$\mathcal{L}$ (cm^{-1}s^{-2})	Q_s	Q	β^* (m)	ϵ (nm)	σ (μm)	ξ
45.6	1.18	8	1.51×10^{31}	0.065	90.31	2.0	19.3	197	0.030
					76.17	0.05	0.23	3.4	0.044
65	2.20	4	2.11×10^{31}	0.076	90.26	2.5	24.3	247	0.029
					76.17	0.05	0.16	2.8	0.051
97.8	4.01	4	9.73×10^{31}	0.116	98.34	1.5	21.1	178	0.043
					96.18	0.05	0.22	3.3	0.079

Table 2: Overview of LEP (instantaneous) peak performance 1989-1999. $\int \mathcal{L}\, dt$ is the luminosity integrated per experiment over each year. The design luminosity at 45 GeV was $17\text{x}10^{30}$ cm^{-2}s^{-1}.

Year	$\int \mathcal{L}dt$ (pb^{-1})	E_b (GeV/c^2)	k_b	$2k_bI_b$ (mA)	$\mathcal{L}$ (10^{30} cm^{-2} s^{-1})	ξ_y
1989	1.74	45.6	4	2.6	4.3	0.017
1990	8.6	45.6	4	3.6	7	0.020
1991	18.9	45.6	4	3.7	10	0.27
1992	28.6	45.6	4/8	5.0	11.5	0.027
1993	40.0	45.6	8	5.5	19	0.040
1994	64.5	45.6	8	5.5	23.1	0.047
1995	46.1	45.6	8/12	8.4	34.1	0.030
1996	24.7	80.5 to 86	4	4.2	35.6	0.040
1997	73.4	90 to 92	4	5.2	47.0	0.055
1998	199.7	94.5	4	6.1	100	0.075
1999	253	98 to 101	4	6.2	100	0.083
2000	233.4	102 - 104	4	5.2	60	0.055

from Ref 6

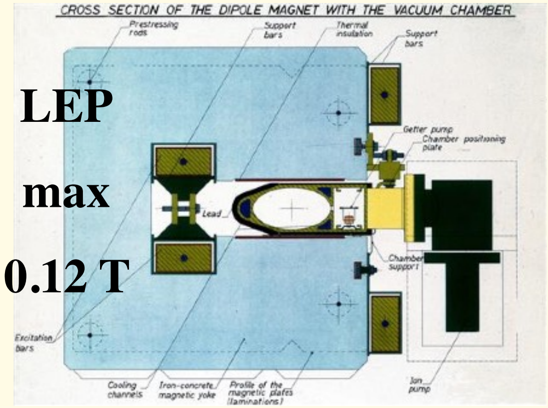
Basic geometry, magnets

LEP, LHC   built in the same tunnel, 26658.9 m circumference

LEP as single ring, single beam pipe

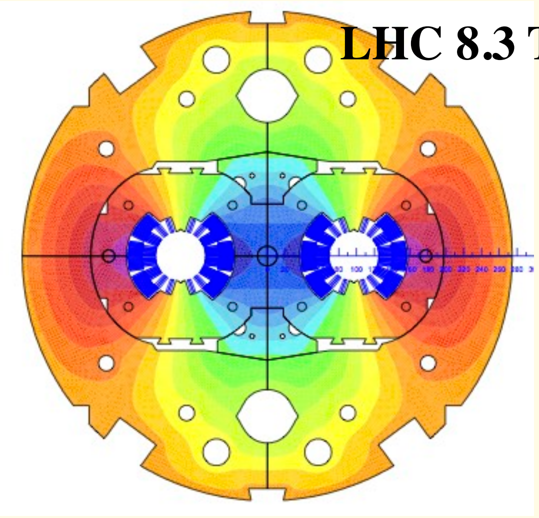
LHC two pipes in twin magnets separated by 19.4 cm

FCC-ee two rings   separated by 30 cm



8 straight sections, ± 284 m around IPs

4 used as interaction regions



distance IP to 1st superconducting Quadrupole (centre)

L* = 3.7 m for LEP

2.8 m FCC-ee

23 m for LHC

2 rings :   allow for many bunches without parasitic collisions

disadvantage : less evident to find collisions, need to frequently re-steer to centre collisions —>

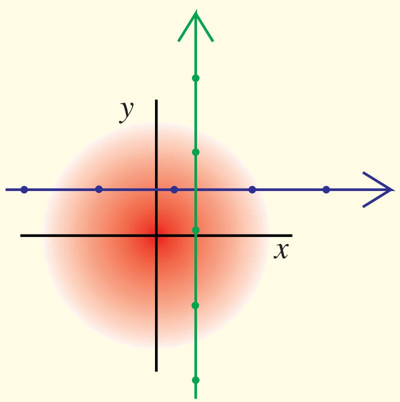
Optimize collisions (1/2)

LEP beam separated

during injection

ramp & squeeze

using electrostatic separators



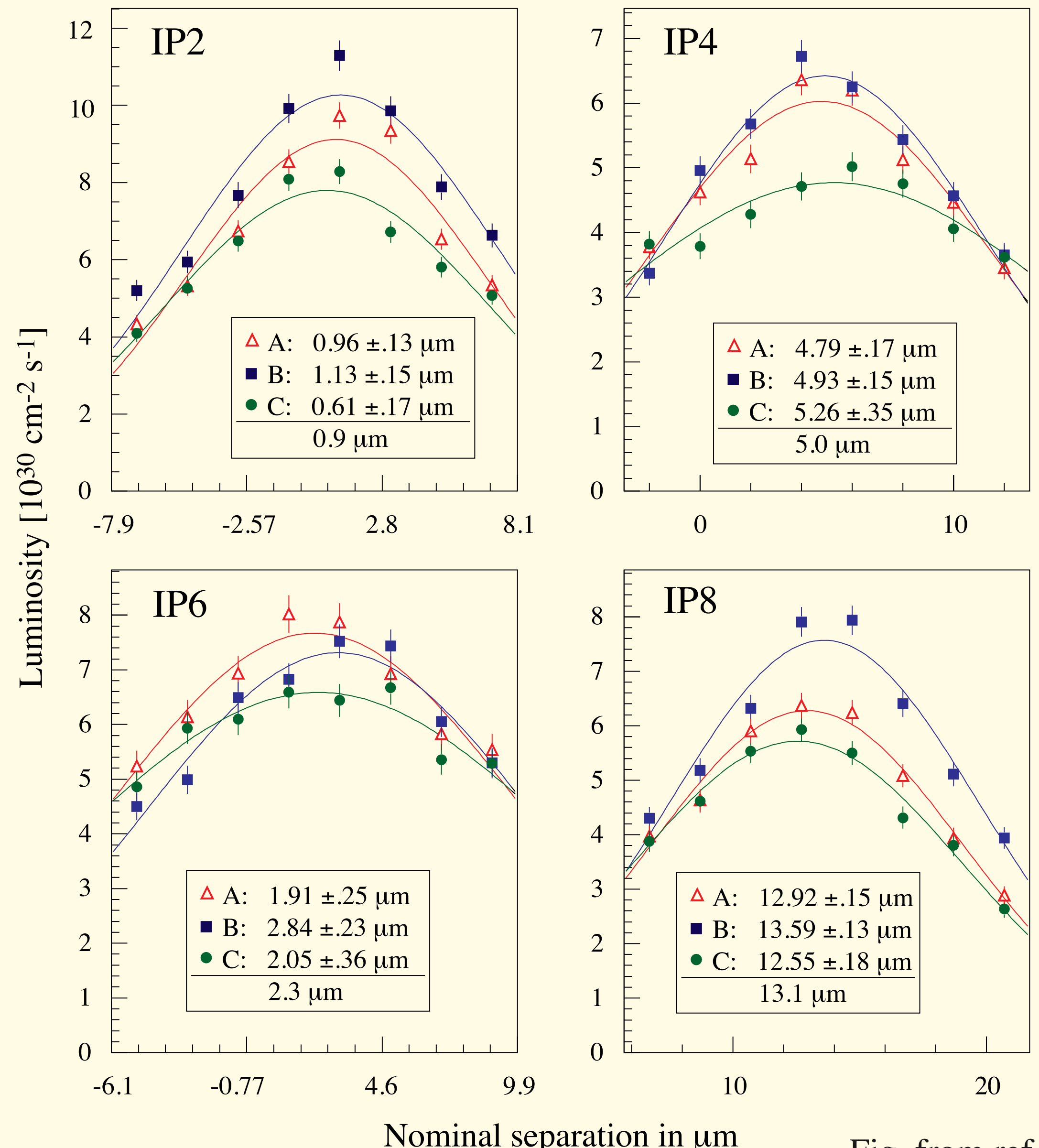


Fig. from ref. [5]

Collisions optimised by

separation scans

based on luminosity

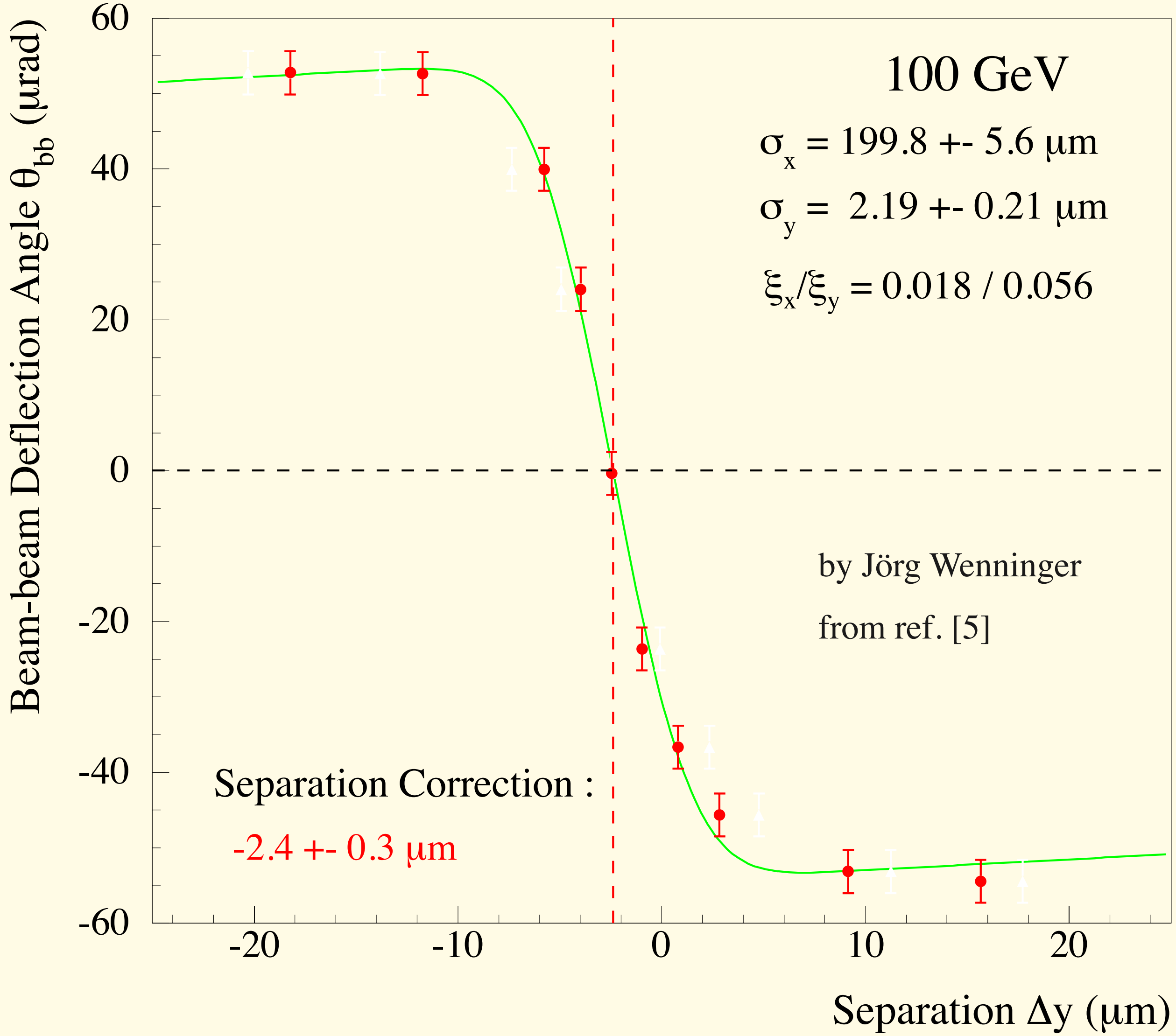
avoid partial separation :

reduces luminosity, can trigger coherent beam-beam, flip-flop, increase halo

Optimize collisions (2/2)

Later LEP operation with improved orbit monitoring and control :

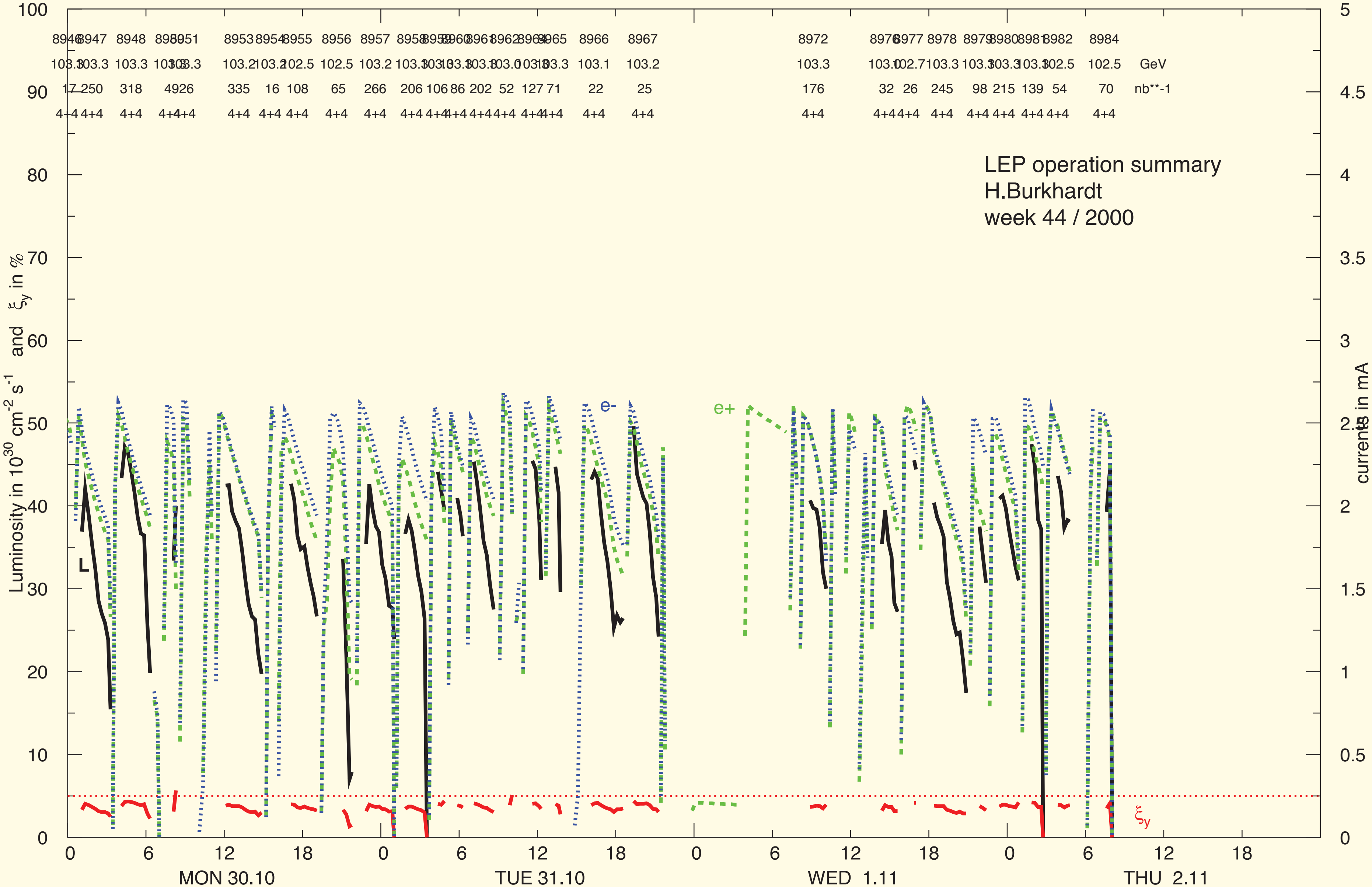
Fast centering using beam-beam deflections scans



additional challenges for FCC, CEPC : smaller beams large crossing angle, Beamstrahlung, high power — increase risk of damage by heating and beam losses

Operation cycles (1/2), LEP

betatron injection/accumulation at 20 GeV, later 22 GeV, synchrotron injection followed by ramp & squeeze with coarse collimation, physics with tight collimation



Operation cycles (2/2)

FCC-ee, CEPC instead plan to work with top-up injection

advantage :

no loss in physics time for injection, ramp squeeze

extra challenges :

- need for more aperture to efficiently capture beams
- background spikes by losses and lager amplitude (halo) from injection
  open collimators ? pause data taking ?
- continuously running at top maximum intensity and power

LEP beams were typically dumped after some hours when the luminosity had fallen

(at constant ξy linearly with current)

backgrounds and beam sizes decreased, stability increased

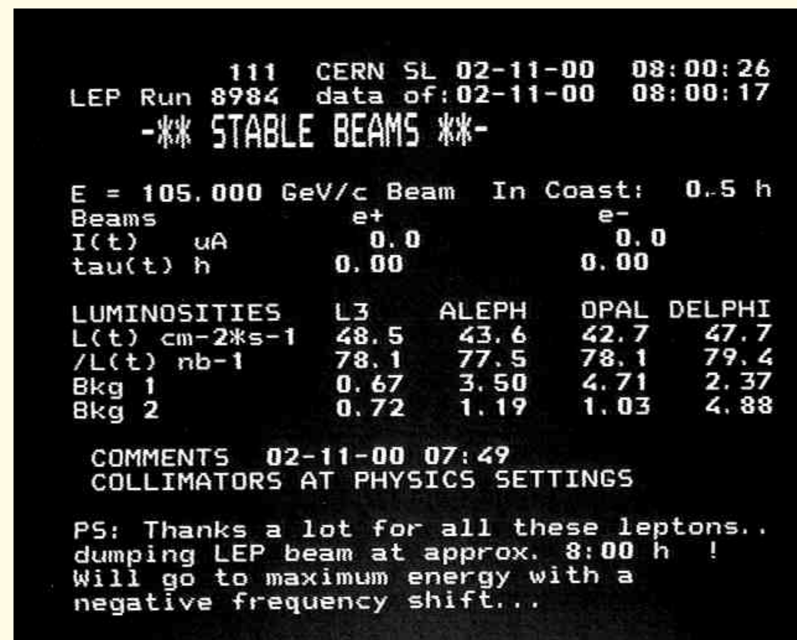
very useful for tuning (establish golden orbits for more luminosity / less background)

Signal exchange, logging and status displays

For good performance, LEP beams required continuous tuning — including hundreds of orbit corrections during a fill

Also here MDI essential

pioneered for SPS ppbar, also important for LHC —>



Using normalised background signals

5 : maximum tolerable

and upper limit to declare stable beam

1: and below meaning very good

allow for several background signals / experiment

BKG1 more sensitive to photon

BKG2 more beam loss or more beam 2

LEP performance workshops

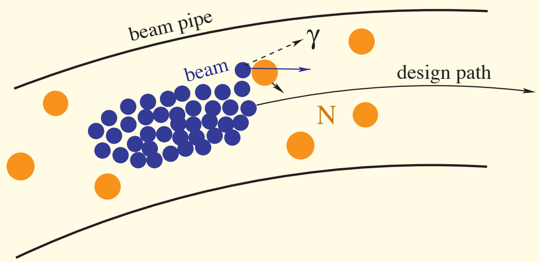
initiated by Steve Myers, critical review to further improve LEP, held during the winter stops

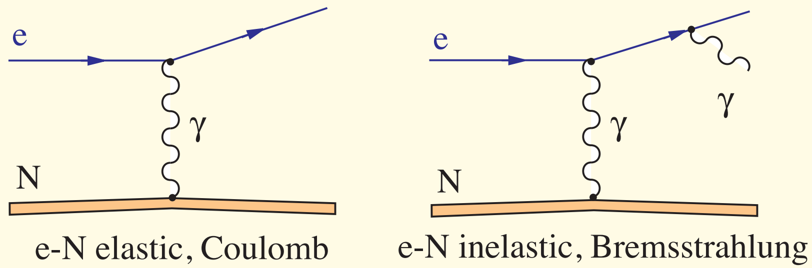
Photo courtesy John Jowett

LEP Performance workshop #1, Chamonix, January 13-19, 1991

numerous detailed improvements, new optics every year

Beam-gas, background source





Figs. from my contribution to
[Landolt-Börnstein New Series I/21C]

Well known in e+e– rings

and described in textbooks

At high energy elastic small

inelastic generator of off-momentum tail

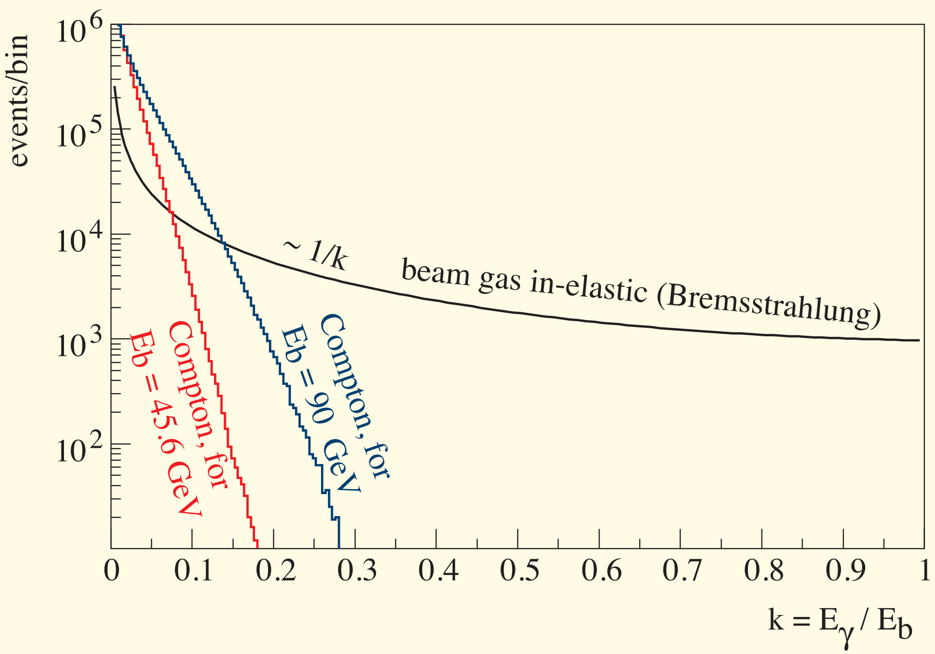
well visible in LEP

but not a major problem

(<< 1 electron lost at IR / crossing)

thanks to

- **excellent vacuum**
- **powerful momentum collimation**

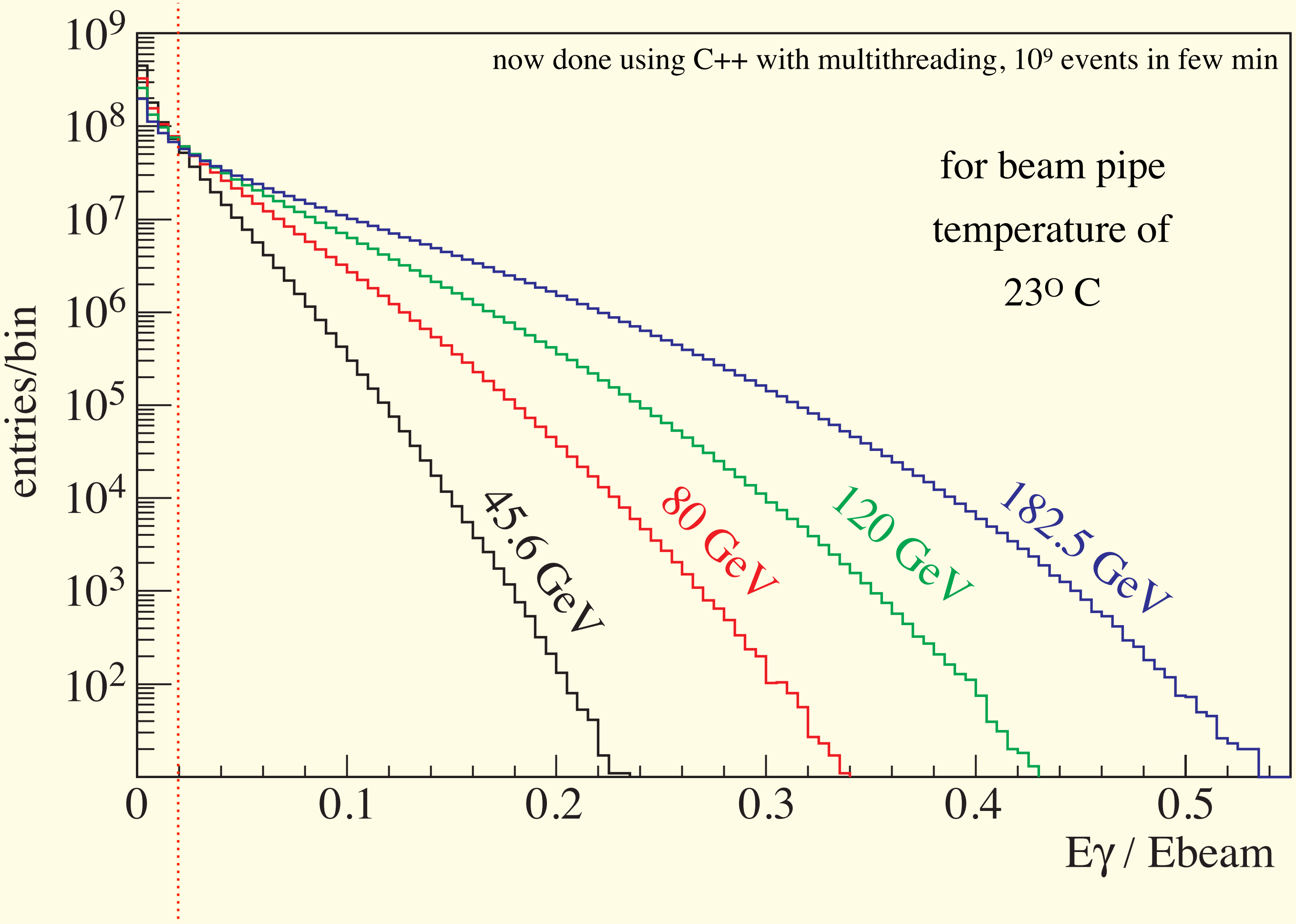


both in dedicated collimation section + local each IR

Thermal photon scattering

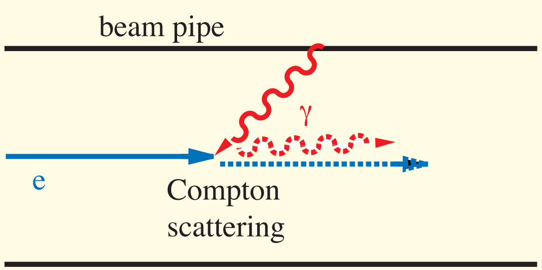
First described in [1987 by V. Telnov](#) , main single [beam lifetime limitation in LEP](#), [well measured](#) and simulated using the algorithm described in [SL/Note 93-73](#)

spectrum softer then beam-gas, only small fraction lost in low angle lumi. monitors



photon density

$\rho_\gamma = 5.3\times10^{14}\ m^{-3}$



very roughly

0.07 eV thermal photons

boosted by γ^2 to GeV

energy loss from beam

Fraction lost, at 2% energy acceptance,

19% at 45.6 GeV 54% at 182.5 GeV, lifetime τ = 54 h

LEP, example of background particle tracking

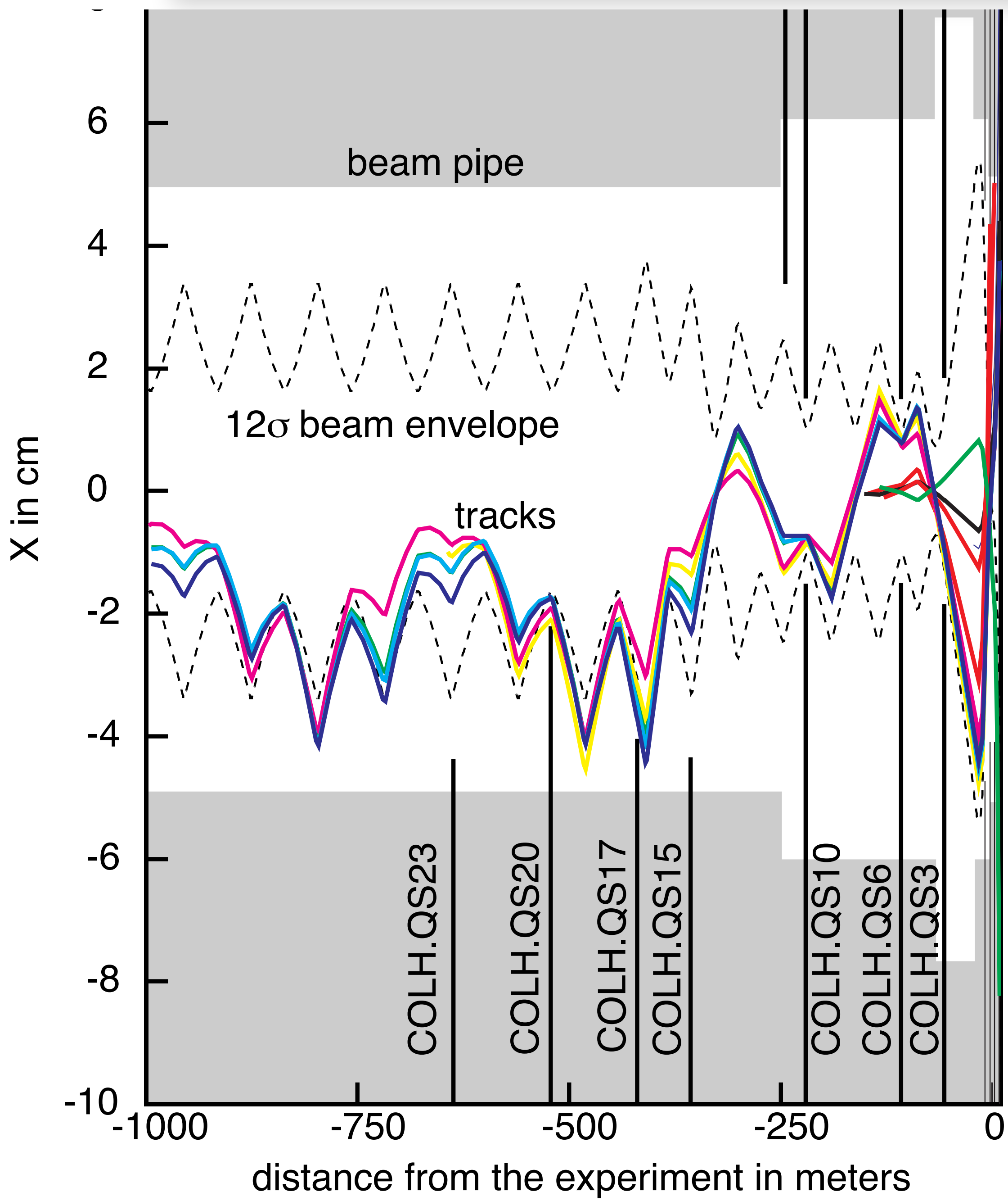
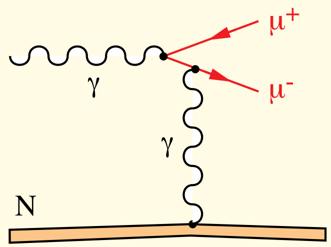


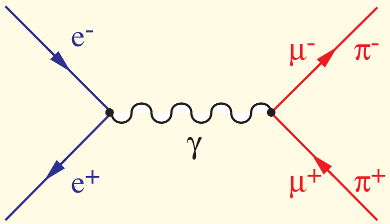
Illustration of beam particle tracking through the LEP lattice over 1000 meters up to an experimental region (cs coordinates).
The distance X from the nominal orbit is given in cm units.
The tracks are for particles that are lost within ±9 m from the interaction point.
The 12σ beam envelope is shown as broken line.
The physical aperture limitation given by the beam pipes is shaded.
The position of collimators (called COLH.QS15, COLH.QS17..) as used in LEP physics runs is shown as vertical straight lines.

LEP had ~ 100 collimators + IPs with local masks, r = 50 mm beam pipe at IP
plot from my simulation for the [1998 LEP background NIM paper]

Muon backgrounds

Collimating high energy e+, e– will generate muons, roughly at the 10^{-4} – 10^{-5} level





Came as a bad surprise to SLC

Carefully studied for CLIC, hard (long magnetise shielding) to reduce

CLIC Muon Sweeper Design, Aloev, H.B. et al. , and Belgin Pilicer thesis

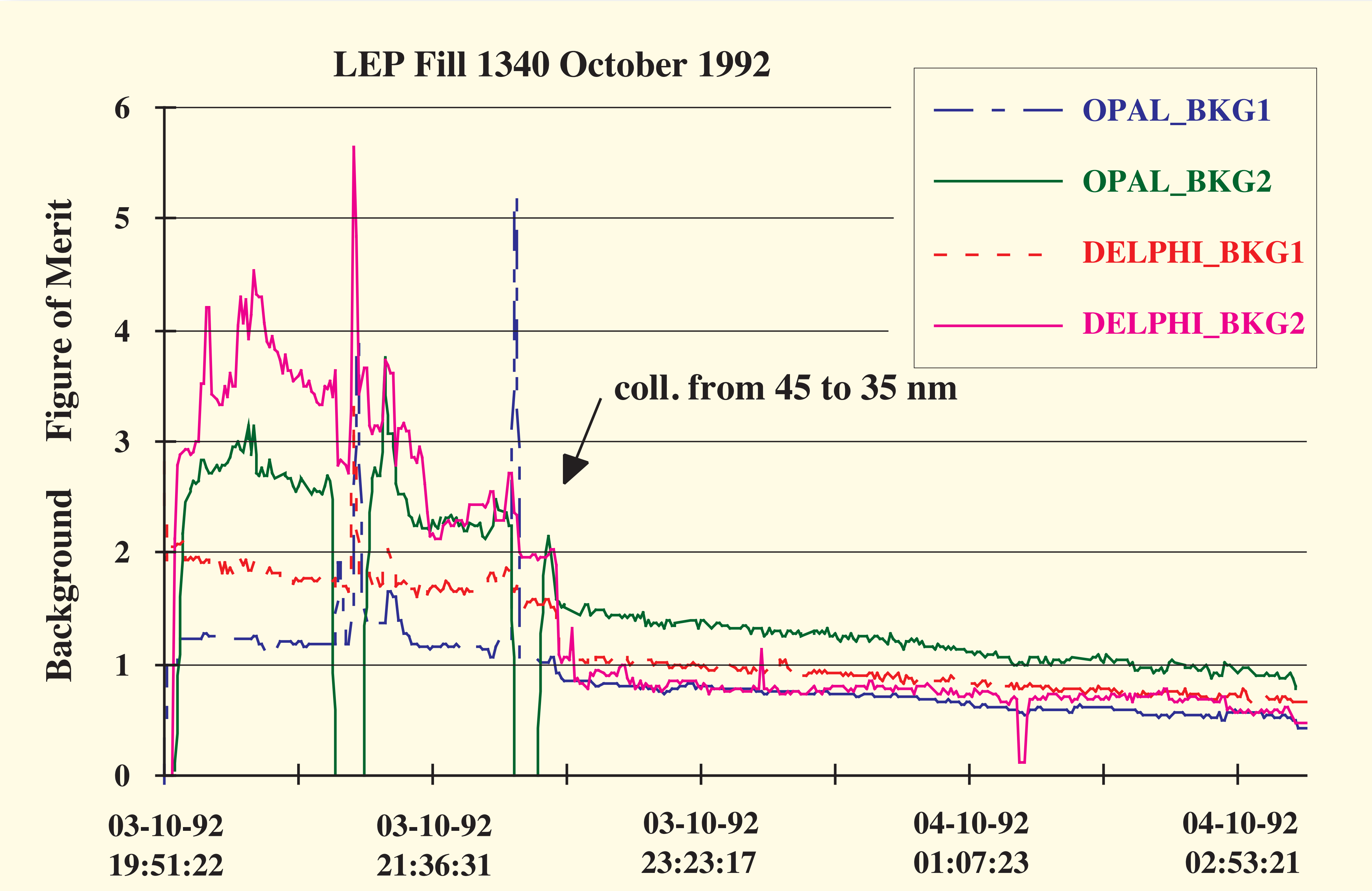
No problem in LEP where losses were collimated far from the experiments

the aperture limiting primary and secondary collimators were in a separate straight section (LEP IR5)

with up to 3.e15 e+, e- and lifetimes of ~ 200 minutes (FCC-ee-Z) we expect to lose 2.4e11 e+, e– per second generating millions of muons / second

—> avoid collimation of e+, e- in line of sight to experiments

LEP background observations



Evolution of key parameters, LEP1

Showing Fill 2420

one of our best

8+8 bunch (Pretzel)

fills from 9 October 1994

Luminosity

e+, e- currents

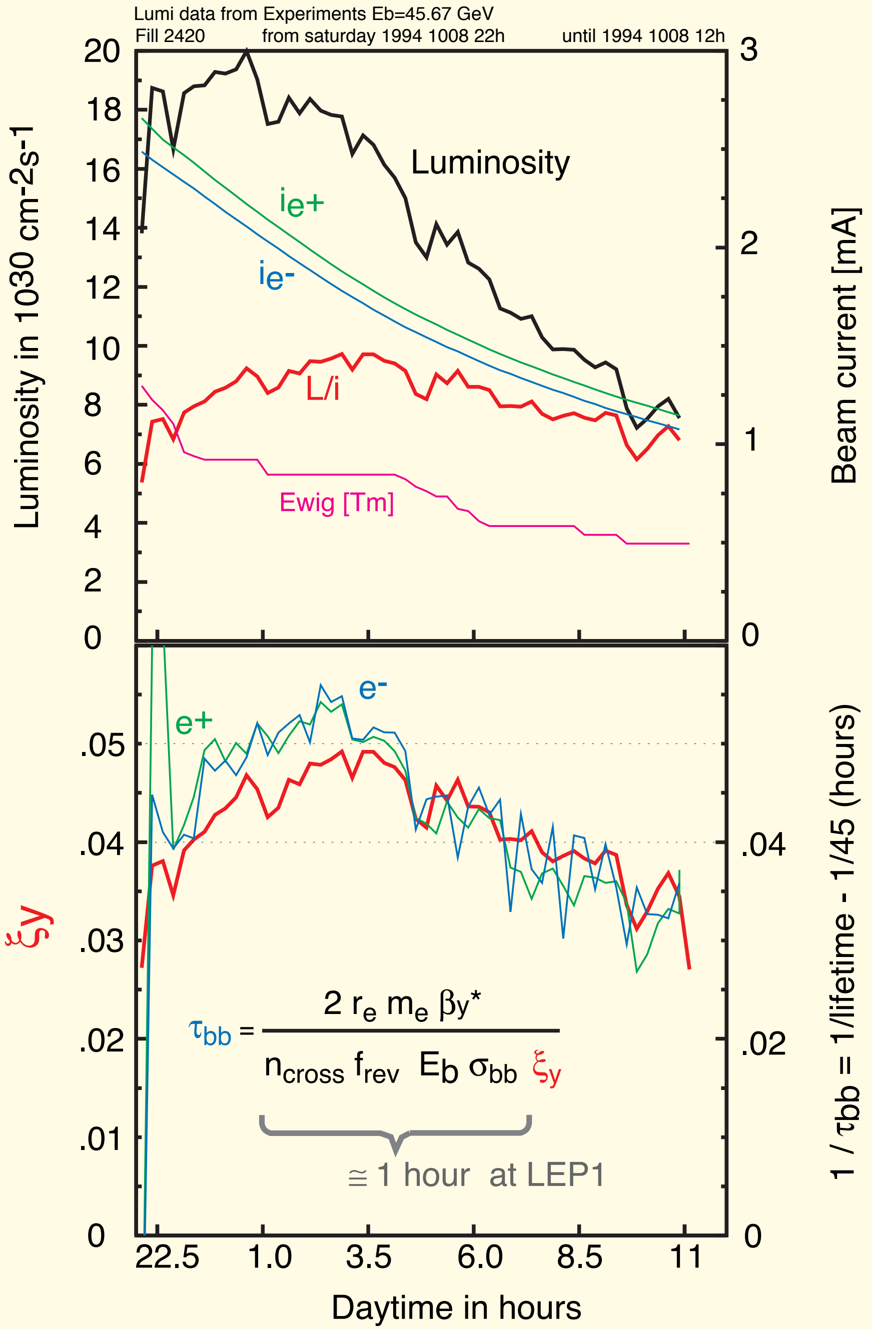
emittance wiggler strength (ε$_x$ adjust)

ξ_y vertical beam-beam tune shift ~ L / i

~ beam loss (inverse lifetime)

from radiative Bhabha

(Beam-beam Bremsstrahlung)



from my presentation / writeup for e+e- factories KEK 1999

Evolution of key parameters, LEP2

LEP2 :

more SR and damping

larger horizontal emittance

no more need to increase emittance

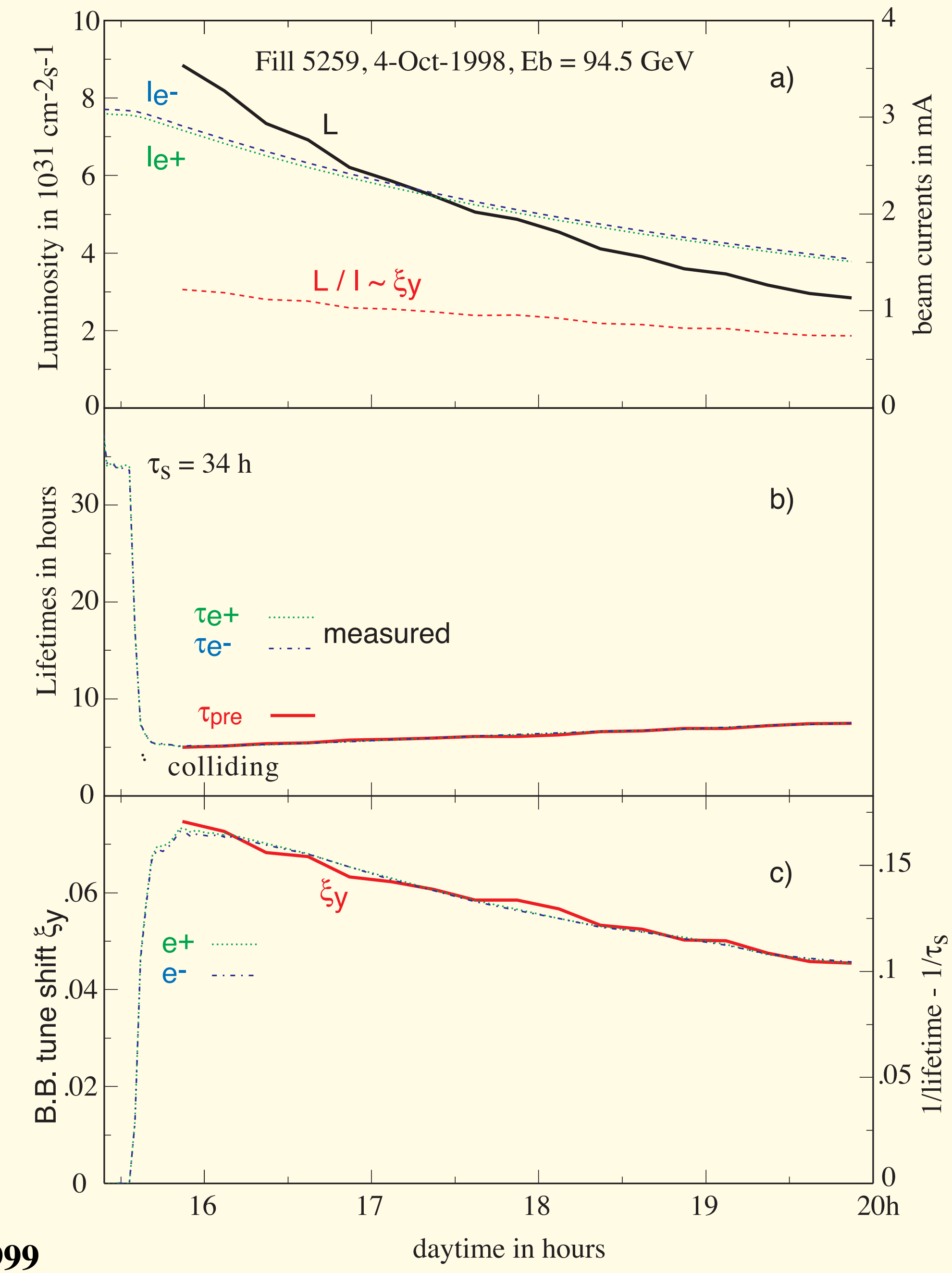
with wiggler

and ξ_y decreasing with current

emittance ratio

(coupling / dispersion limited)

and luminosity ~ 1 / current squared



from my presentation / writeup for e+e- factories KEK 1999

Beam Lifetime

Losses add —> inverse lifetimes add $1/\tau_{tot} = \sum \tau_i$

Example LEP2 fill 5259 4/10/1998, Eb = 94.5 GeV

τth = 60 h predicted for thermal photons

τ_{bg} = 80 h beam gas, 0.6 nTorr

— — — —

34 h as measured before collisions

Colliding :

Lifetime dropped from 34 h to 5 h

and slowly increased to 7.5 h towards the end of the fill

matching precisely with the expectation for a collision cross section of

σ_{bb} = 0.215 barn $\tau_{bb} = 0.44 / \xi_y$ ref : R. Kleiss, H.B. BBBrem

Lifetimes in LEP well accounted for by 3 loss processes

Thermal photon, beam-gas, radiative Bhabha (when colliding)

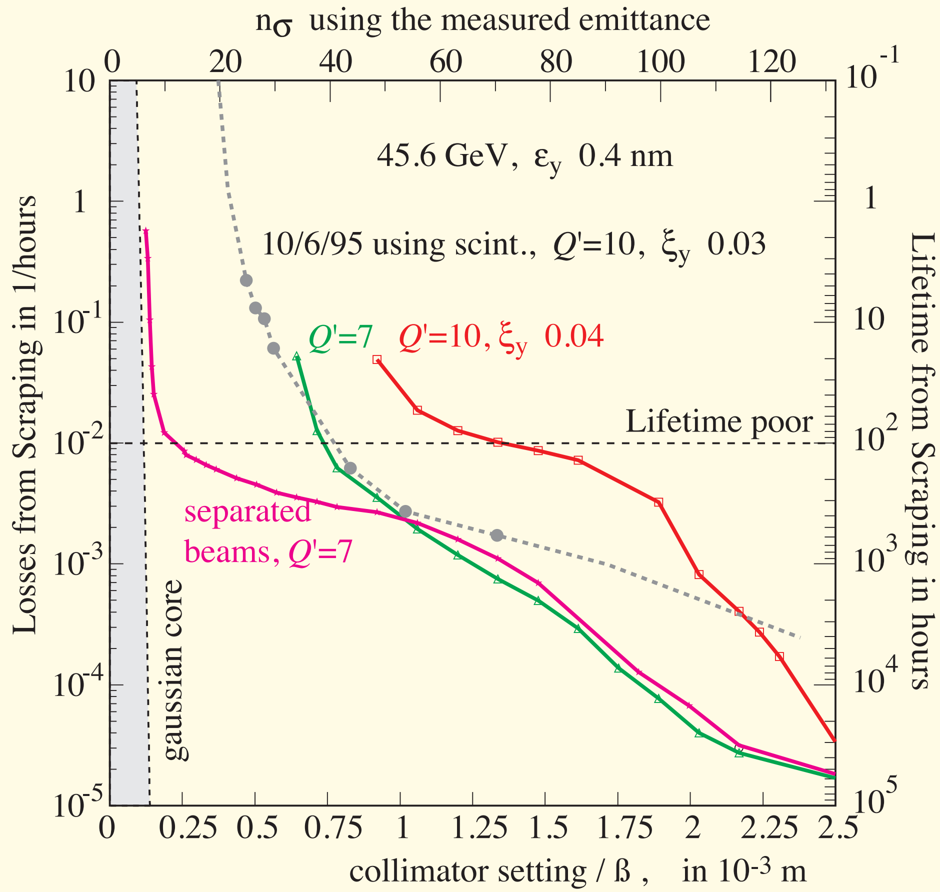
with occasionally (LEP1, high ξ_y) additional losses and background spikes

related to non-Gaussian tails and coherent instabilities

non-Gaussian tails, LEP

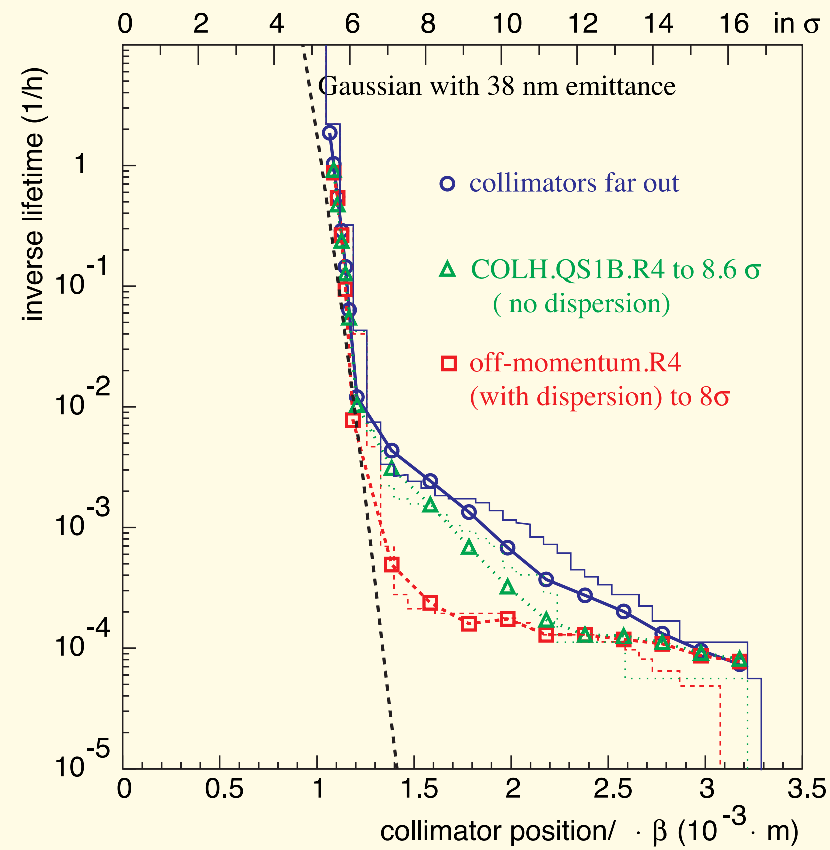
measured by scraping with loss monitors

vertical plane, colliding beams



horizontal plane

reproduced by simulation



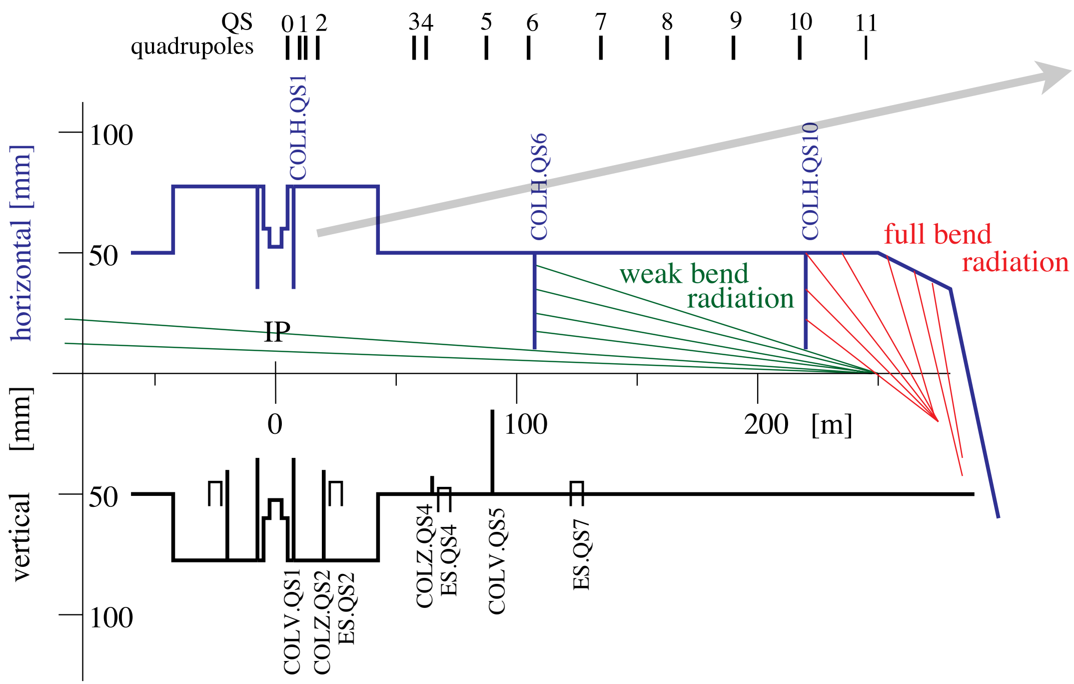
Tails from : beam-beam, high chromaticity, particle scattering

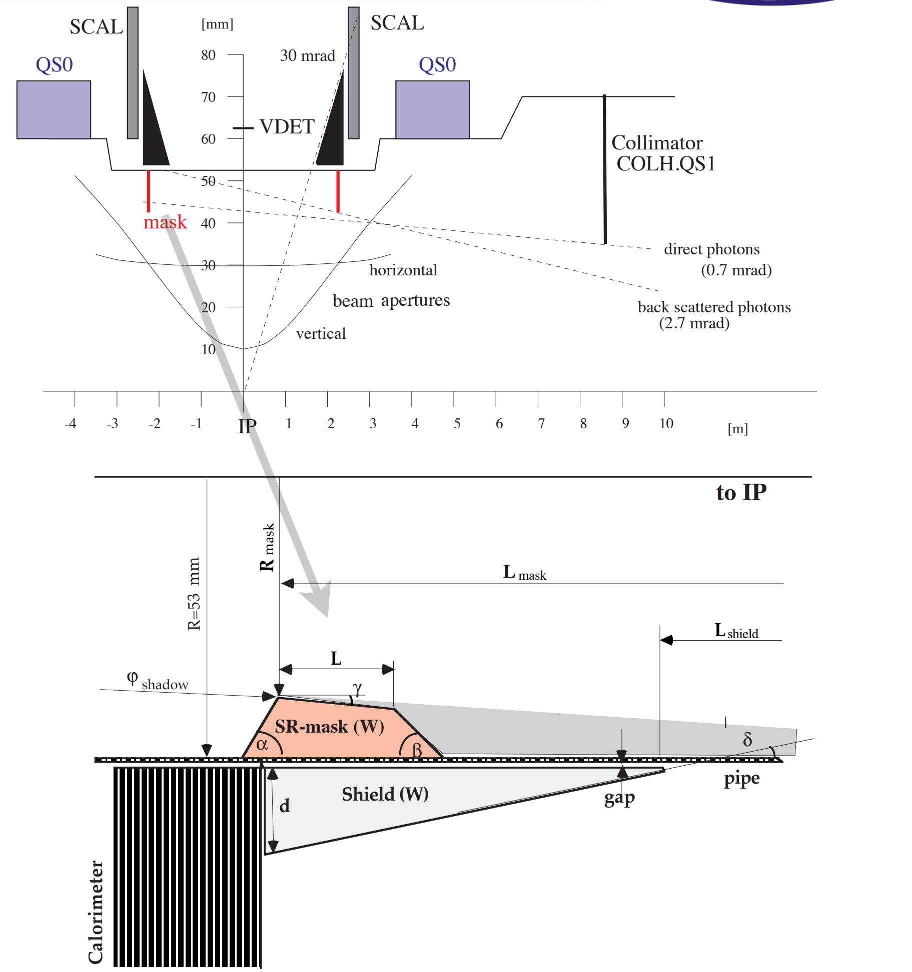
Background spikes, enhanced synchrotron radiation from quadruples

H.B. I. Reichel, G. Roy, Transverse beam tails due to inelastic scattering in LEP, PRSTAB, 3:091001, 2000; I. Reichel, CERN-Thesis-98-017

H.B. "Beam lifetime and beam tails in LEP." CERN-SL-99-061-AP and Proc. e+ e+ Factories 1999, KEK, Tsukuba 1999

LEP, as example of an IR optimized for SR





Georg von Holtey et al., [Nucl.Instrum.Meth.A403:205-246, 1998]

Eb = 45 GeV to 104 GeV **the closest we got to FCC-ee**

Machine induced backgrounds, MIB in LEP **~ 100 collimators to reduce MIB**

flat, symmetric machine, no crossing angle, few (4-12) bunches

Synchrotron radiation - **no direct and single reflected radiation to experiments in IP region**

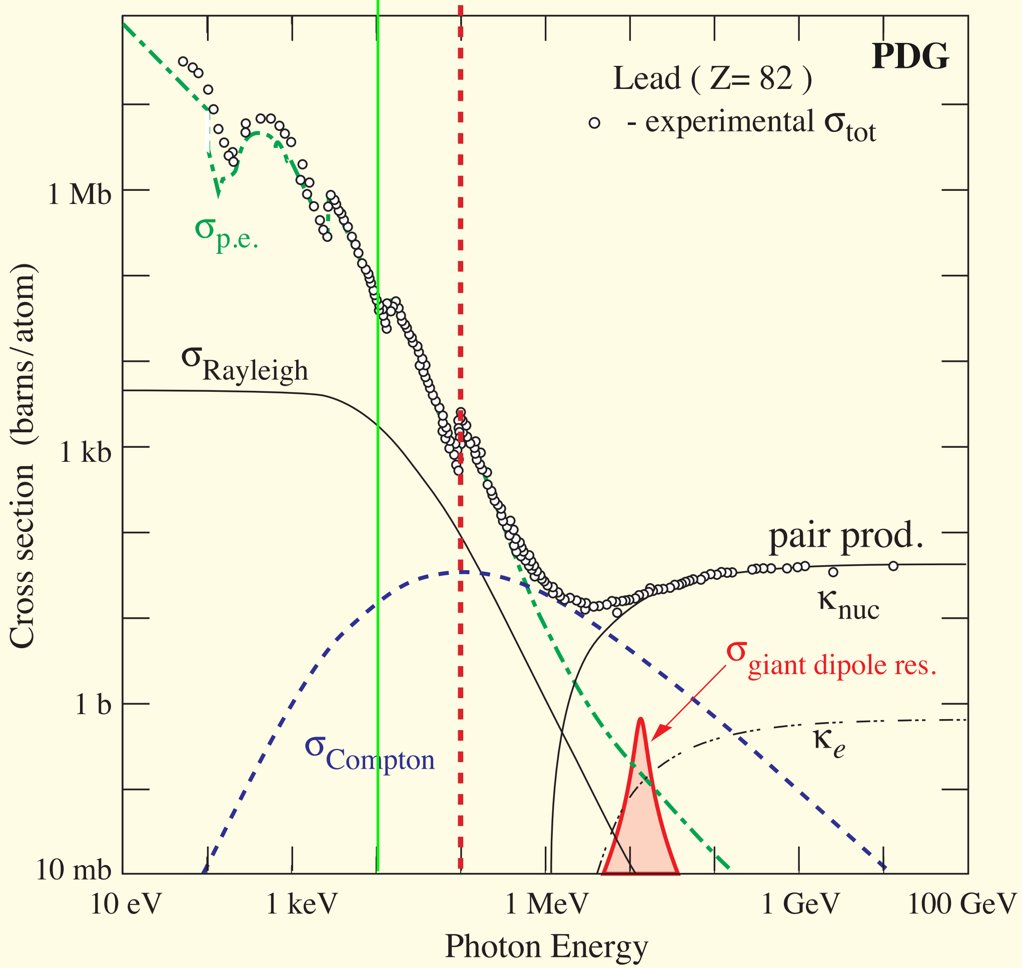
Off-momentum beam-gas and thermal photon

Major challenge synchrotron radiation : Photon shielding

✔ < 10 keV

> 100 keV very difficult

10 MeV significant neutron flux, giant dipole res.



Critical photon energies

SuperKEKB ~ 2 keV (LER)

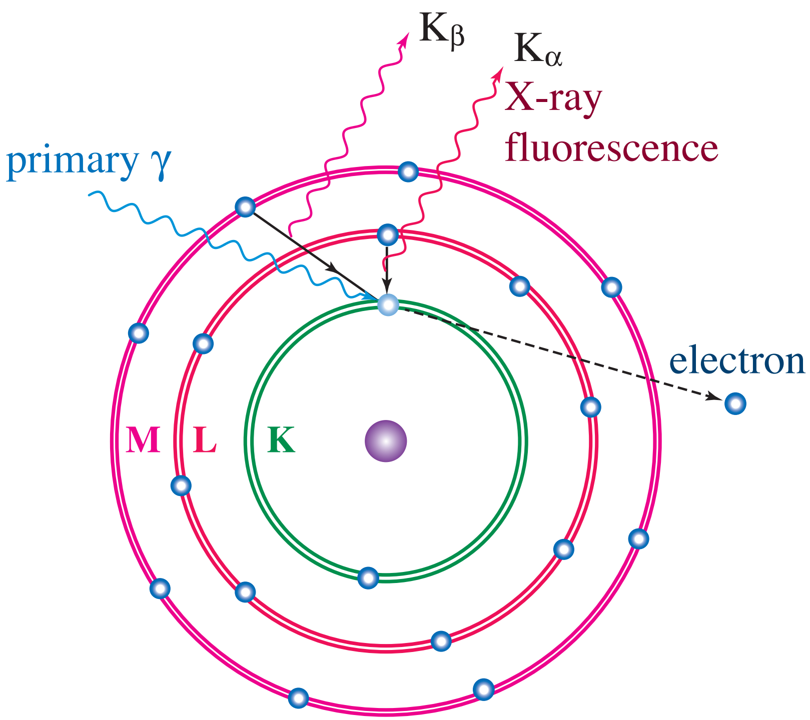
FCC-hh ~ 5 keV

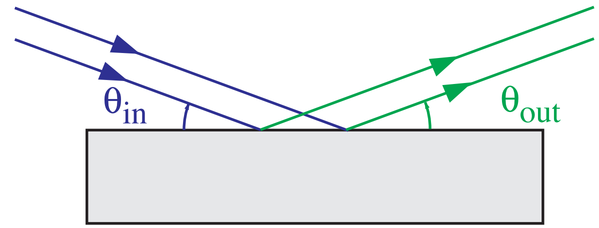
LEP1 : 69 keV

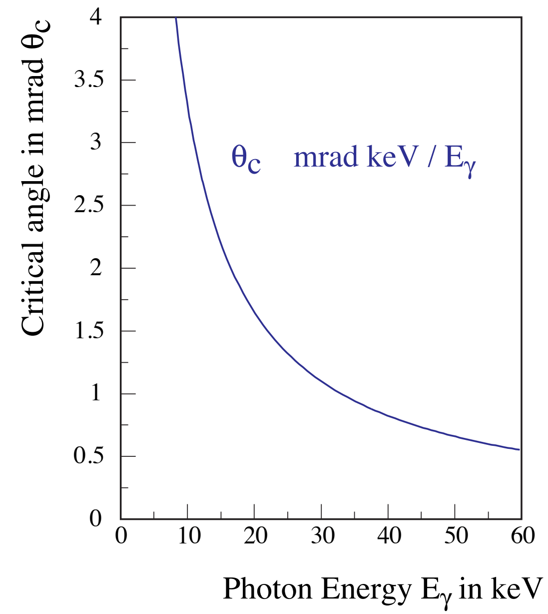
LEP2 : 725 keV (arc, last bend 10× lower)

FCC-ee : 1.3 MeV (arc, 182.5 GeV)

X-Ray - Fluorescence and Specular Reflection







below below θc
nearly 100 % very quickly dropping
above

i.e. :
at 1 mrad reflection up to ~ 33 keV
at 100 μrad (1cm in 100m)
up to ~ 330 keV

Important to take these into account

Fluorescence was expected, well simulated with Geant,

and was mitigated for absorbers by surface coating

Reflection in principle known from textbooks

like Batterman and Bilderback in Handbook on Synchrotron Radiation Vol.3 Eds G.S.Brown, D.E.Moncton

came as a surprise in LEP, mitigated with COLH.QS6 at 120 m

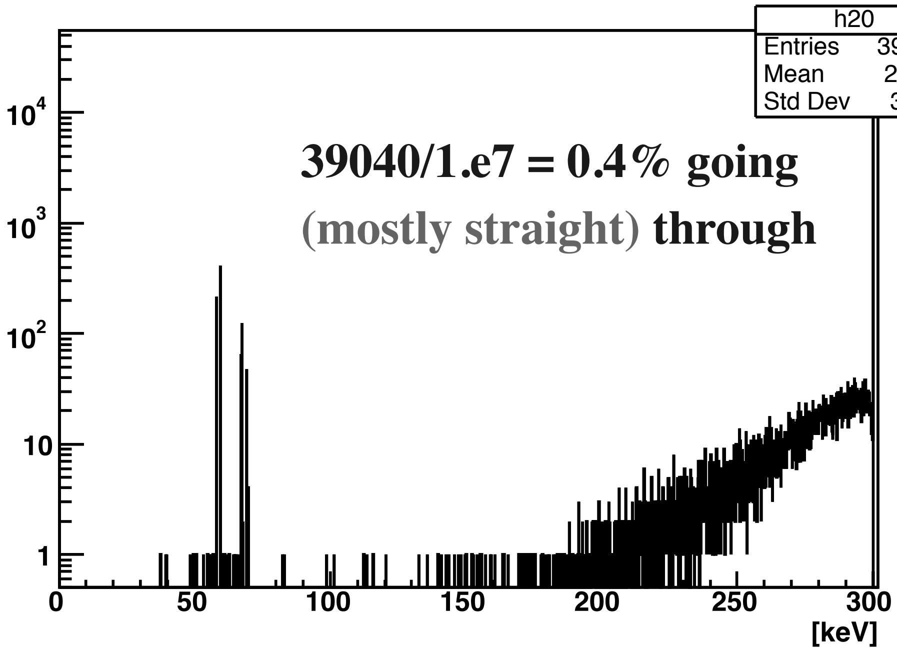
Shielding simulations

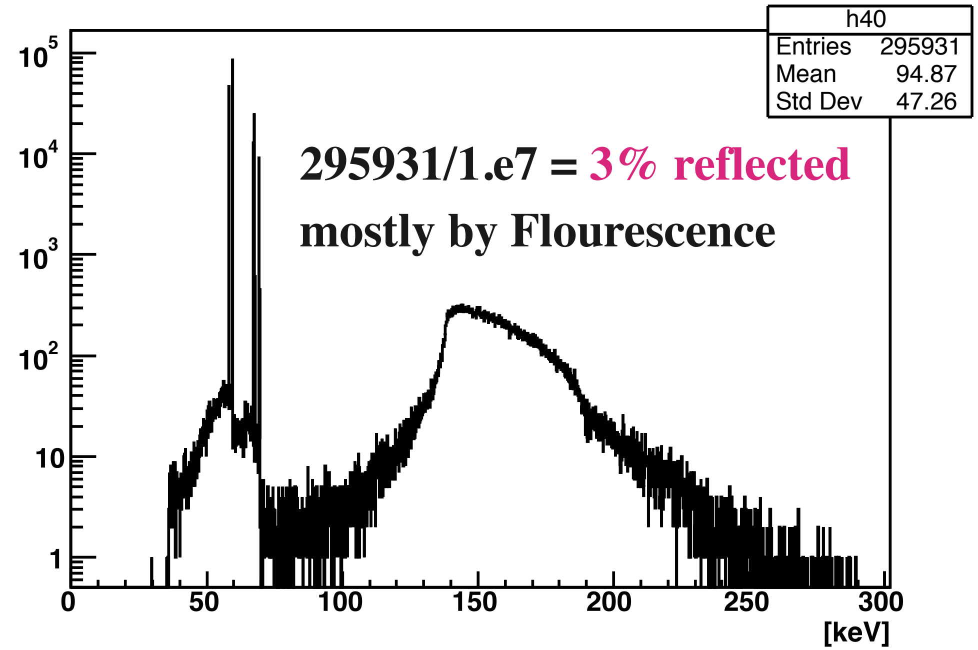
At LEP times done with dedicated codes

Motivated by work for CLIC [CLIC-Note-709](), 2007 integrated in GEANT4

GEANT4 simulation, 1.e7 photons of 300 keV perpendicular on 1 cm tungsten

Energy spectra



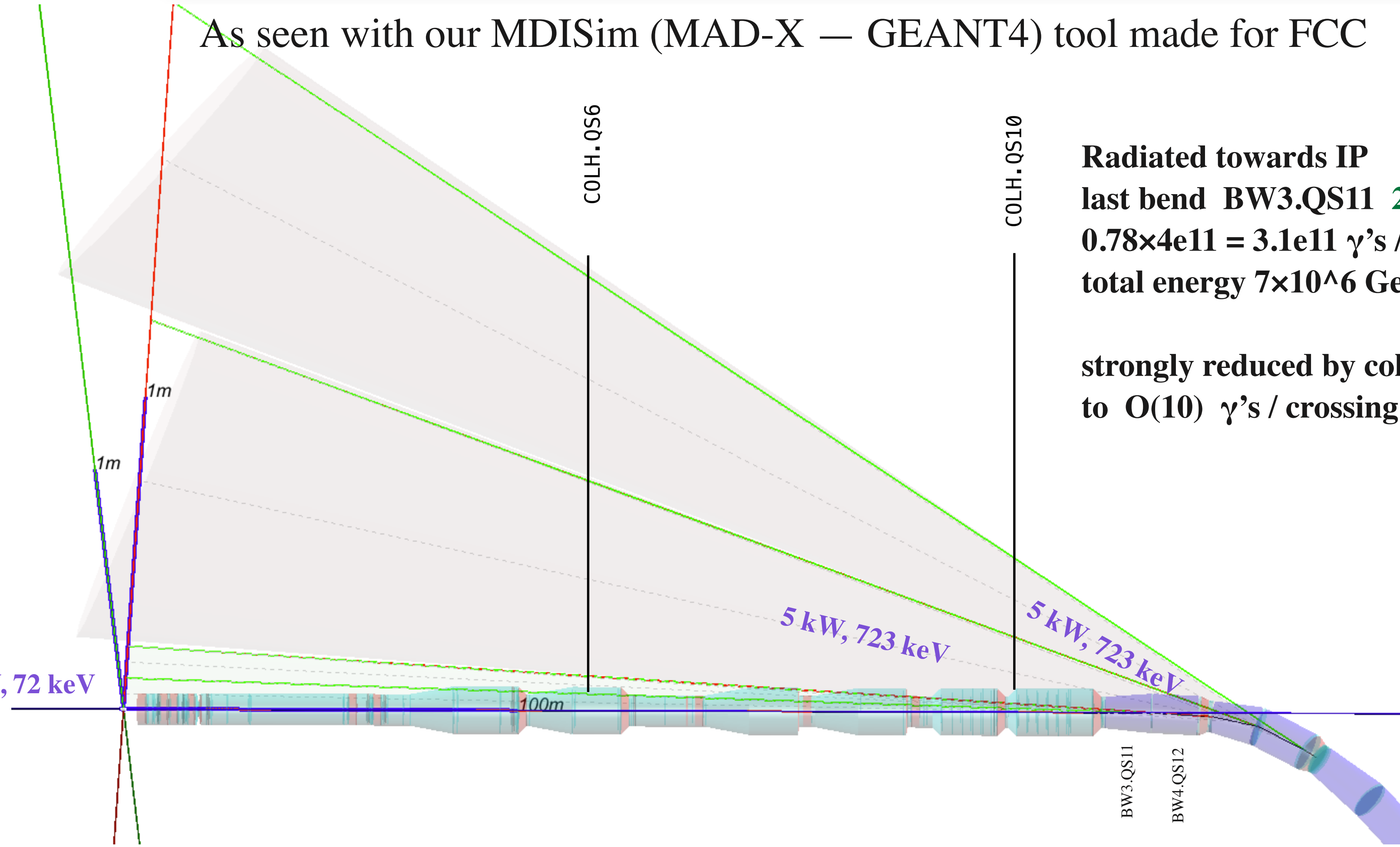


Increases to

~ 50% at small incident angle

IR, numbers for LEP2 Eb = 100 GeV

As seen with our MDISim (MAD-X — GEANT4) tool made for FCC



Radiated towards IP
last bend BW3.QS11 248.7 - 260.2 m
0.78×4e11 = 3.1e11 γ's / crossing
total energy 7×10^6 GeV

strongly reduced by collimation and masks to O(10) γ's / crossing interacting in TPC

iele	NAME	KEYWORD	S	L	Angle	Ecrit	ngamBend	rho	B	BETX	SIGX	divx	Power	frac>10MeV
			m	m		keV		m	T	m	mm	mrad	kW	
162	BW3.QS11.R2	RBEND	260.2	11.55	0.0003768	72.37	0.7767	30652.0	0.0109	45.5834	1.4262	0.0379	0.04989	2e-62
164	BW4.QS12.R2	RBEND	272.1	11.55	0.0003768	72.37	0.7767	30652.0	0.0109	33.8668	1.2293	0.0379	0.04989	2e-62
172	B2L.QS12.R2	RBEND	287.3	11.55	0.003768	723.7	7.767	3065.2	0.1088	88.0931	1.9827	0.0637	4.989	6.5e-08
174	B2R.QS13.R2	RBEND	299.2	11.55	0.003768	723.7	7.767	3065.2	0.1088	163.5957	2.7019	0.0636	4.989	6.5e-08

Quads, at 1 sigmax, horizontal

iele	Element	s	L	betx	sigx	divx	K1L	k0	x	Angle	Ecrit	ngam	Power
		m	m	m	mm	mrad	m-2	m-1	mm		keV		kW
2	QS0.R2	5.7	2	27.8	1.115	0.04003	-0.327	0.0003474	-0.0524	0.0006948	770.7	1.432	0.9798
10	QS1B.R2	11.2	2	226	3.176	0.01405	0.06314	0.0001918	-0.1377	0.0003836	425.5	0.7907	0.2987
12	QS1A.R2	13.7	2	278	3.523	0.01267	0.06314	0.0002129	-0.1509	0.0004259	472.4	0.8778	0.3681
20	QS2.R2	18	1.6	276	3.507	0.01272	0.01788	6.006e-05	-0.1471	9.61e-05	133.2	0.1981	0.023423
36	QS3.R2	59	2	39.4	1.326	0.03366	0.01879	2.45e-05	-0.02171	4.9e-05	54.35	0.101	0.004873

Selected references for LEP

[1] *Very High-Energy e+e- colliding beams..*, B. Richter, NIM 136:47 1976

[2] LEP design report, Vol II, CERN-LEP-81-01 1984; Vol III LEP2, CERN-AC/96-01, 1996

[3] *Test of EW theory at the Z resonance*, H.B., J.Steinberger, Annu.Rev.Nucl.Part.Sci.41 (1991) 55

[4] *Study of beam induced particle backgrounds..*, G.v. Holtey, A.Ball et al., NIM A403, 1998

[5] *Accelerator Physics at LEP*, D. Brandt, H.B., M. Lamont, S. Myers, J. Wenninger, Rept.Prog.Phys.63, 2000

[6] *A retrospective on LEP*, H. B., J. Jowett, ICFA Beam Dyn.Newslett.48:143-152, 2009

Pictures & Anecdotes :

Running the LEP Machine, Steve Myers, Mike Lamont, John Poole, H.B., The Aleph Experience, CERN 2005

The Greatest Lepton Collider, Steve Myers, Colloquium for the 30th anniversary of the start of LEP, 2019

https://home.cern/news/press-release/cern/lep-story

https://cerncourier.com/a/the-greatest-lepton-collider/

Concluding comments

FCC-ee, CEPC are very interesting and ambitious projects

designed as next major step in the evolution of colliders, combining and extending

- LEP as high energy e+e– collider combined with
- progress in luminosity on the e+e– factory front — two ring + crab waist

profiting from and stimulating technology further technology developments

(s.c. RF, computing, measurement / control..)

aiming at much higher luminosities (Z, W) and precision at LEP energies

and extending to higher limits to study Higgs and top

Much of the work is on details, MDI - IR design particularly important,

simulation, beam-dynamics, background — benchmarked with LEP and e+e– factories,

stimulating and profiting from further hardware / technology developments

Backup

Energy calibration

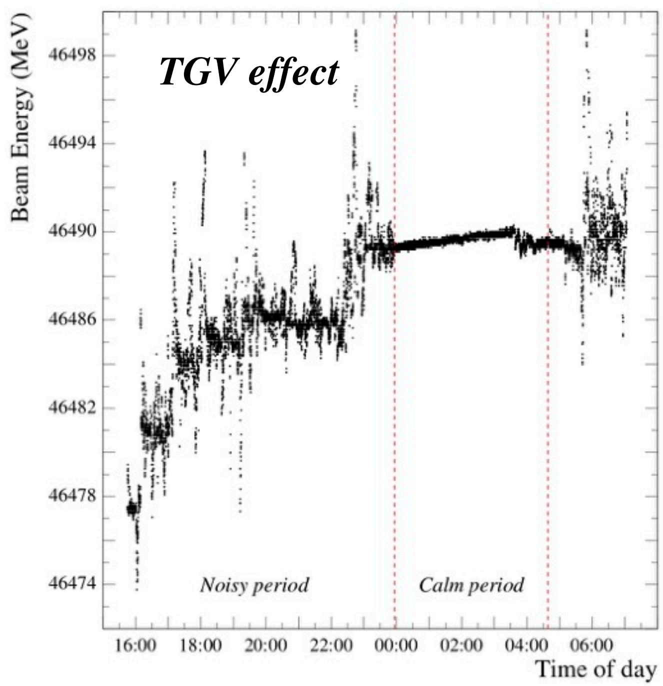


Figure 29. Magnetic field measured in a LEP dipole by an NMR probe over 10 h. For convenience, the magnetic field has been converted to an equivalent beam energy in MeV. Large short-term fluctuations and a slow rise in field are clearly visible. Between midnight and 4:30 am the field is stable while the fluctuations disappear.

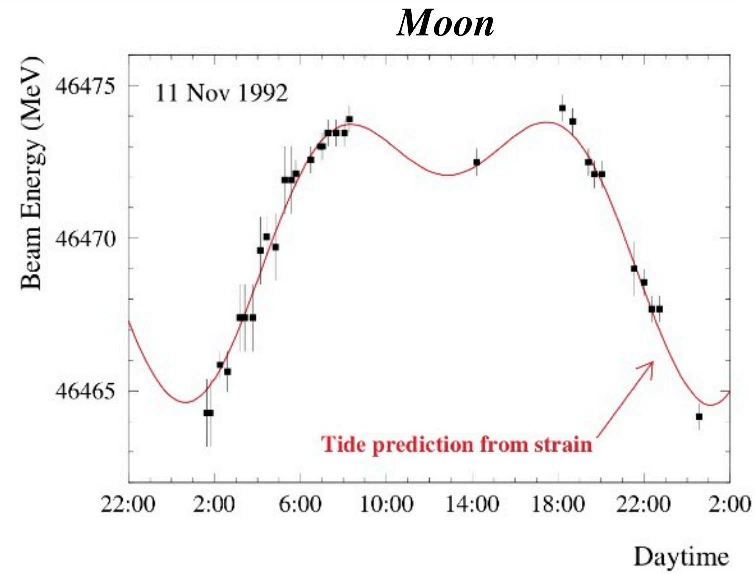


Figure 30. Energy variation of the LEP beams during a full moon day. The curve is the energy change predicted from the horizontal strain induced by the Earth tides.

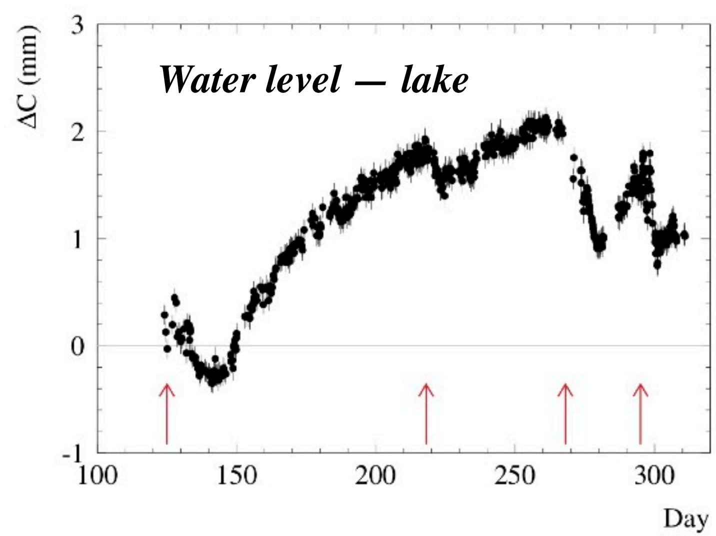


Figure 31. Evolution of the LEP circumference (corrected for tidal changes) as a function of the day in 1999. A drift of over to 2 mm is observed during the LEP run. In the summer months the circumference increases gradually. Following periods of heavy rainfall, indicated by the arrows, the circumference shrinks for some time before expanding again.

Figures from [5]

Amon the key persons on machine side :

J. Wenninger, Ralph Assmann,

Bernd Dehning (Polarimeter)