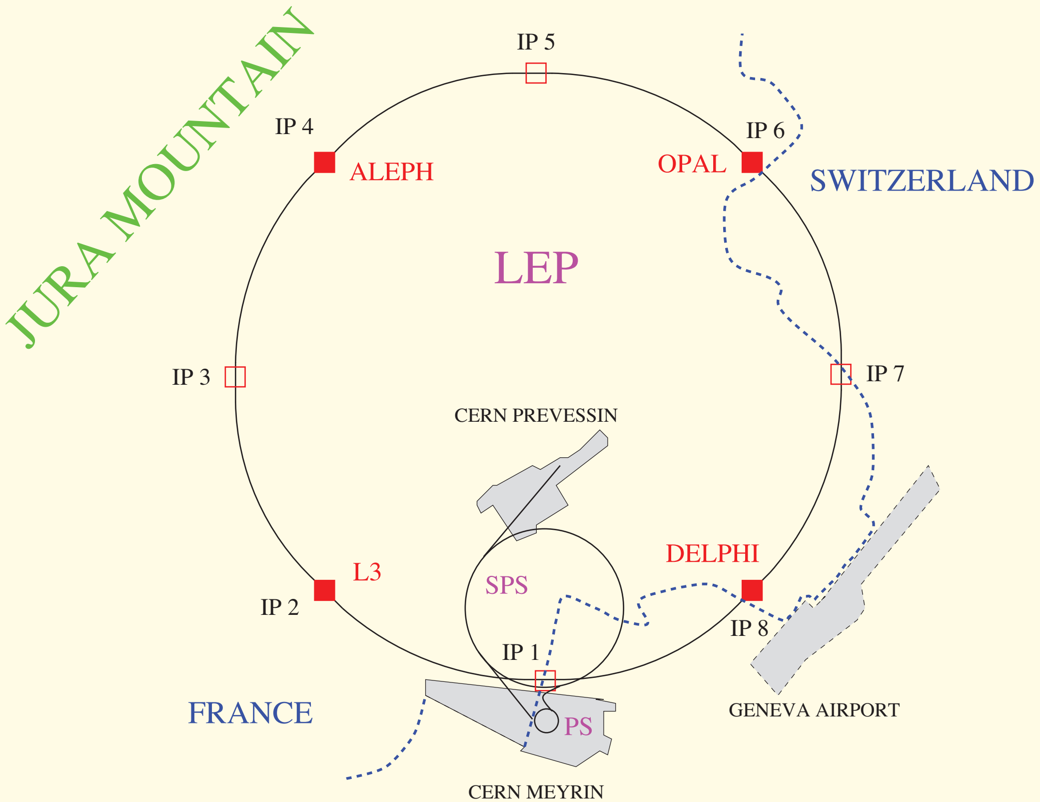
Learning from the Large Electron-Positron Collider LEP

in many respects within factor 3 or pretty close to CEPC / FCC

L = 26.659 km × 3
Max SR Power 18 MW × 2.8
Max RF Voltage 3.7 MV × 2.6
Lumi / x-ing 2.5e11 $cm^{-2}s^{-1}$ × 3
Ecms 92 — 209 GeV × 1.8
Intens 4×10^{11} e+, e- / bunch × 0.4



LEP : tunneling 13/9/1983 - 8/2/1988; installation largely in 1988 + octant test
Pilot run, first Z's, low L, superconducting final focus magnets off : August 1989
Operation : 1990 - 2000 after tough discussions stopped and dismantled for LHC
then busy with **LHC** + CLIC, LHeC, ELFE
renewed e+e- ring interest more recent

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

Changing a lot and "devil in details"

Discussed in Chamonix meetings, well documented in proceedings

Had disappeared, restored in 2020 following my request inspired by the [Jan'20 IAS MDI workshop]

```
1st Workshop on LEP Performance, Chamonix 1991:        https://cds.cern.ch/record/256125
2nd Workshop on LEP Performance, Chamonix 1992:        https://cds.cern.ch/record/260389
3rd Workshop on LEP performance, Chamonix 1993:        https://cds.cern.ch/record/248984
4th Workshop on LEP Performance, Chamonix 1994:        https://cds.cern.ch/record/265955
5th Workshop on LEP Performance, Chamonix 1995:        https://cds.cern.ch/record/277821
6th LEP Performance Workshop, Chamonix 1996:           https://cds.cern.ch/record/289995
7th LEP Performance Workshop, Chamonix 1997:           https://cds.cern.ch/record/312024
8th LEP Performance Workshop, Chamonix 1998:           https://cds.cern.ch/record/330057
9th LEP-SPS Performance Workshop, Chamonix 1999:       https://cds.cern.ch/record/359023
10th Workshop on LEP-SPS Performance, Chamonix 2000:   https://cds.cern.ch/record/394989
```

Lesson #1 :

Very dynamic, very complex, changing all the time, orbit, (vertical) **emittance,**

major beam-beam tune shift ($\xi_y = 0.08$/IP) **and** (vertical) **tails; core/halo see different machine**

Requiering continous efforts and follow up

LEP optics changed a lot : 60/60 ('89-'91), 90/90 ('92), 90/60 ('93/97), 102/90 ('98-'00)

Collimation and operational procedures improved, including

As a result : LEP2 backgrounds comparable to LEP1

Detailed info, example of my records

```
Macintosh   HD:Helmut:fortran:MAD:worktwiss.out                                         Page: 1
Friday, 18 July 1997 / 9:27
 twiss=n0520p97v2 Ebeam=45.60 GeV assumed from twiss file name
 IPs at          .000    3332.360    6664.720    9997.080  13329.400  16661.800  19994.200  23326.500 EndLep   2(
 emittance in x= 45.000   in y=  4.500 nm    deltaE/E= 1.000E-03
 sawtooth, sign is for positrons, opposite for electrons,  collimator position increased by ABS(SAWT)
 Collimator     dist to IP    beta   disp number of     sawtooth  sigmabeam opening  nsig  opening /
                    [m]        [m]    [m]  B2 BI bends    [mm]        [mm]     [mm]          disp
 IP1"               .000      25.3   .00   612   12       .00       1.066
 COLH.QL8.R1"    175.458      57.3   .00   612   12       .00       1.605     23.3   14.5
 COLH.QF23.L2"  -637.260     115.7  1.11   782   24      -.74       2.537     32.4   12.5   .029
 COLH.QD20.L2"  -522.170      26.4   .60   791   24      -.41       1.245     16.0   12.5   .027
 COLH.QS17.L2"  -419.630      67.3   .84   798   24      -.58       1.931     24.7   12.5   .030
 COLH.QS15.L2"  -356.600     146.9   .94   802   24      -.66       2.738     34.9   12.5   .037
 COLH.QS10.L2"  -220.540       9.1   .00   808   24       .00        .640      9.3   14.5
 COLH.QS6.L2"   -129.440      31.3   .00   808   24       .00       1.187     17.2   14.5
 COLV.QS5.L2"    -98.660      36.6   .00   808   24       .00        .406     12.2   30.0
 COLZ.QS4.L2"    -66.110     132.0   .00   808   24       .00        .771     23.1   30.0
 COLH.QS4.L2"    -61.970      20.9   .00   808   24       .00        .969     14.0   14.5
 COLZ.QS2.L2"    -21.320      33.1   .00   808   24       .00        .386     11.6   30.0
 COLV.QS2.L2"    -15.150      63.8   .00   808   24       .00        .536     16.1   30.0
 COLH.QS1B.L2"    -8.750     131.1   .00   808   24       .00       2.429     35.2   14.5
 IP2"               .000       2.0   .00     0    0       .00        .300
 COLH.QS1B.R2"     8.750     131.1   .00     0    0       .00       2.429     35.2   14.5
 COLV.QS2.R2"     15.150      63.8   .00     0    0       .00        .536     16.1   30.0
 COLZ.QS2.R2"     21.310      33.1   .00     0    0       .00        .386     11.6   30.0
 COLH.QS4.R2"     61.970      20.9   .00     0    0       .00        .969     14.0   14.5
 COLZ.QS4.R2"     66.110     132.0   .00     0    0       .00        .771     23.1   30.0
 COLV.QS5.R2"     98.660      36.6   .00     0    0       .00        .406     12.2   30.0
 COLH.QS6.R2"    129.440      31.3   .00     0    0       .00       1.187     17.2   14.5
 COLH.QS10.R2"   220.540       9.1   .00     0    0       .00        .640      9.3   14.5
 COLH.QS15.R2"   356.600     146.9   .94     6    0       .64       2.738     34.9   12.5   .037
 COLH.QS17.R2"   419.630      67.3   .84    10    0       .56       1.931     24.7   12.5   .030
 COLH.QD20.R2"   522.170      26.4   .60    17    0       .40       1.245     16.0   12.5   .027
 COLH.QF23.R2"   637.260     115.7  1.11    26    0       .71       2.537     32.4   12.5   .029
 IP3"               .000      25.3   .00   208    0       .00       1.066
 COLH.QF23.L4"  -637.260     115.6  1.11   390    0       .06       2.536     31.8   12.5   .029
 COLH.QD20.L4"  -522.170      26.4   .60   399    0       .02       1.245     15.6   12.5   .026
 COLH.QS17.L4"  -419.640      62.2   .79   406    0       .02       1.850     23.1   12.5   .029
 COLH.QS15.L4"  -356.600     136.8   .88   410    0       .02       2.633     32.9   12.5   .037
 COLH.QS10.L4"  -220.490      17.3   .00   416    0       .00        .883     12.8   14.5
 COLH.QS6.L4"   -108.000      16.8   .00   416    0       .00        .870     12.6   14.5
 COLV.QS5.L4"    -79.180      42.7   .00   416    0       .00        .438     13.1   30.0
 COLZ.QS3A.L4"   -66.110      70.8   .00   416    0       .00        .565     16.9   30.0
 COLH.QS3B.L4"   -56.280      46.9   .00   416    0       .00       1.452     21.1   14.5
 COLZ.QS2.L4"    -21.320      28.8   .00   416    0       .00        .360     10.8   30.0
 COLV.QS2.L4"    -15.150      63.9   .00   416    0       .00        .536     16.1   30.0
 COLH.QS1B.L4"    -8.550     120.1   .00   416    0       .00       2.325     33.7   14.5
 IP4"               .000       2.0   .00   416    0       .00        .300
 COLH.QS1B.R4"     8.520     120.2   .00   416    0       .00       2.326     33.7   14.5
 COLV.QS2.R4"     15.120      63.5   .00   416    0       .00        .535     16.0   30.0
 COLZ.QS2.R4"     21.320      28.2   .00   416    0       .00        .356     10.7   30.0
 COLH.QS3B.R4"    56.320      46.9   .00   416    0       .00       1.452     21.1   14.5
 COLZ.QS3A.R4"    66.120      73.8   .00   416    0       .00        .576     17.3   30.0
 COLV.QS5.R4"     79.220      43.6   .00   416    0       .00        .443     13.3   30.0
 COLH.QS6.R4"    108.020      16.8   .00   416    0       .00        .871     12.6   14.5
 COLH.QS10.R4"   220.520      17.3   .00   416    0       .00        .883     12.8   14.5
 COLH.QS15.R4"   356.620     136.6   .88   422    0       .00       2.632     32.9   12.5   .037
 COLH.QS17.R4"   419.620      62.1   .79   426    0      -.01       1.850     23.1   12.5   .029
 COLH.QD20.R4"   522.120      26.4   .60   433    0      -.01       1.245     15.6   12.5   .026
 COLH.QF23.R4"   637.220     115.8  1.11   442    0      -.04       2.537     31.7   12.5   .029
 COLH.QL13.L5"  -299.100      87.3   .13   622    0      -.04       1.987     24.9   12.5   .187
 IP5"               .000      25.2   .00   624    0       .00       1.066
 COLH.IP5"          .200      25.2   .00   624    0       .00       1.066     13.3   12.5
 COLV1.QL8.R5"   168.400      50.5   .00   624    0       .00        .477     11.9   25.0
 COLV2.QL8.R5"   176.100      60.2   .00   624    0       .00        .520     13.0   25.0
 COLV.QL9.R5"    195.400      20.6   .00   624    0       .00        .305      7.6   25.0
 COLH.QL13.R5"   299.200      87.5   .13   626    0      -.04       1.989     24.9   12.5   .187
 COLV.QD20.R5"   519.300     153.5   .00   641    0       .00        .831     20.8   25.0
 COLV.QD30.R5"   914.300     149.1   .00   671    0       .00        .819     20.5   25.0
 COLV.QD40.R5"  1309.300     142.6   .00   701    0       .00        .801     20.0   25.0
 COLH.QF23.L6"  -637.300     115.5  1.11   806    0      -.69       2.535     32.4   12.5   .029
 COLH.QD20.L6"  -522.200      26.4   .60   815    0      -.38       1.245     16.0   12.5   .027
 COLH.QS17.L6"  -419.600      79.0   .93   822    0      -.61       2.102     26.9   12.5   .029
 COLH.QS15.L6"  -356.600     107.1   .89   826    0      -.59       2.370     30.2   12.5   .034
 COLH.QS10.L6"  -220.500      11.3   .00   832    0       .00        .714     10.4   14.5
 COLH.QS6.L6"   -129.500      26.7   .00   832    0       .00       1.096     15.9   14.5
 COLV.QS5.L6"    -98.700      33.2   .00   832    0       .00        .386     11.6   30.0
 COLZ.QS4.L6"    -66.100     127.7   .00   832    0       .00        .758     22.7   30.0
 COLH.QS4.L6"    -62.000      20.9   .00   832    0       .00        .970     14.1   14.5
 COLZ.QS2.L6"    -21.300      36.2   .00   832    0       .00        .403     12.1   30.0
 COLV.QS2.L6"    -15.300      67.9   .00   832    0       .00        .553     16.6   30.0
 COLH.QS1B.L6"    -8.700     124.6   .00   832    0       .00       2.368     34.3   14.5
 IP6"               .000       2.0   .00     0    0       .00        .300
 COLH.QS1B.R6"     8.700     124.6   .00     0    0       .00       2.368     34.3   14.5
 COLV.QS2.R6"     15.300      67.9   .00     0    0       .00        .553     16.6   30.0
 COLZ.QS2.R6"     21.300      36.2   .00     0    0       .00        .403     12.1   30.0
 COLH.QS4.R6"     62.000      20.9   .00     0    0       .00        .970     14.1   14.5
 COLZ.QS4.R6"     66.100     127.7   .00     0    0       .00        .758     22.7   30.0
 COLV.QS5.R6"     98.700      33.2   .00     0    0       .00        .386     11.6   30.0

Macintosh   HD:Helmut:fortran:MAD:worktwiss.out                                         Page: 2
Friday, 18 July 1997 / 9:27
 COLH.QS6.R6"    129.400      26.7   .00     0    0       .00       1.096     15.9   14.5
 COLH.QS10.R6"   220.500      11.3   .00     0    0       .00        .714     10.4   14.5
 COLH.QS15.R6"   356.600     107.1   .89     6    0       .60       2.370     30.2   12.5   .034
 COLH.QS17.R6"   419.600      79.0   .93    10    0       .62       2.102     26.9   12.5   .029
 COLH.QD20.R6"   522.200      26.4   .60    17    0       .40       1.245     16.0   12.5   .027
 COLH.QF23.R6"   637.300     115.5  1.11    26    0       .71       2.535     32.4   12.5   .029
 IP7"               .000      25.2   .00   208    0       .00       1.066
 COLH.QF23.L8"  -637.200     115.8  1.11   390    0       .06       2.537     31.8   12.5   .029
 COLH.QD20.L8"  -522.200      26.4   .60   399    0       .02       1.245     15.6   12.5   .026
 COLH.QS17.L8"  -419.600      62.1   .79   406    0       .02       1.850     23.1   12.5   .029
 COLH.QS15.L8"  -356.600     136.6   .88   410    0       .02       2.632     32.9   12.5   .037
 COLH.QS10.L8"  -220.500      17.3   .00   416    0       .00        .883     12.8   14.5
 COLH.QS6.L8"   -108.000      16.8   .00   416    0       .00        .871     12.6   14.5
 COLV.QS5.L8"    -79.200      43.6   .00   416    0       .00        .443     13.3   30.0
 COLZ.QS3A.L8"   -66.100      73.8   .00   416    0       .00        .576     17.3   30.0
 COLH.QS3B.L8"   -56.300      46.9   .00   416    0       .00       1.452     21.1   14.5
 COLZ.QS2.L8"    -21.300      28.2   .00   416    0       .00        .356     10.7   30.0
 COLV.QS2.L8"    -15.100      63.5   .00   416    0       .00        .535     16.0   30.0
 COLH.QS1B.L8"    -8.500     120.2   .00   416    0       .00       2.326     33.7   14.5
 IP8"               .000       2.0   .00   416    0       .00        .300
 COLH.QS1B.R8"     8.600     120.1   .00   416    0       .00       2.325     33.7   14.5
 COLV.QS2.R8"     15.200      63.9   .00   416    0       .00        .536     16.1   30.0
 COLZ.QS2.R8"     21.300      28.8   .00   416    0       .00        .360     10.8   30.0
 COLH.QS3B.R8"    56.300      46.9   .00   416    0       .00       1.452     21.1   14.5
 COLZ.QS3A.R8"    66.100      70.8   .00   416    0       .00        .564     16.9   30.0
 COLV.QS5.R8"     79.200      42.6   .00   416    0       .00        .438     13.1   30.0
 COLH.QS6.R8"    108.000      16.8   .00   416    0       .00        .870     12.6   14.5
 COLH.QS10.R8"   220.500      17.3   .00   416    0       .00        .883     12.8   14.5
 COLH.QS15.R8"   356.600     136.8   .88   422    0       .00       2.633     32.9   12.5   .037
 COLH.QS17.R8"   419.600      62.2   .79   426    0      -.01       1.850     23.1   12.5   .029
 COLH.QD20.R8"   522.200      26.4   .60   433    0      -.01       1.245     15.6   12.5   .026
 COLH.QF23.R8"   637.300     115.6  1.11   442    0      -.04       2.536     31.7   12.5   .029
 COLH.QL8.L1"   -175.500      57.2   .00   612   12       .00       1.605     23.3   14.5
 end of LEP NB2,NBI=   612   12
 there were in total NB2tot=  1640 standard  bends called B2L or B2M or B2R or B2S
 there were in total NBItot=    24 injection bends called BI
 there were in total NBWtot=    32 weak bends called BW1 or BW2 or BW3 or BW4
```

Also kept : full set of LEP mad8 optics files
my logging of LEP snapshots avery 15 min, used 2019 to re-analyze lumi calibration, σ_Z , # Neutrinos, see doi

```
FILL     TIME          Ie+         Ie-      EWIG    e+x    e+y    e-x    e-y     L3  ALEPH   OPAL DELPHI
6811  11.3794      1.60178     1.63328      .813   .000   .000   .000   .000  3.965  5.047  1.795  5.310
```

```
 FILL TIME              LEP_MODE      ENERGY BETA_Y TWISS_NAME   BUN
----- ----------------- ------------ ------- ------ ------------ ---
 6811 03-04-00 09:52:04 filling       22.100     10 g1020b99_v1    8
 6811 03-04-00 10:41:14 acceleration  22.100     10 g1020b99_v1    8
 6811 03-04-00 10:45:26 acceleration  45.620      5 g0520b99_v1    8
 6811 03-04-00 10:45:33 adjust        45.620      5 g0520b99_v1    8
 6811 03-04-00 11:14:57 physics       45.620      5 g0520b99_v1    8
```

High energy e+e- rings "touchy and potentially non-reproducible"

LHC (proton, ion, cold machine) much more stable and reproducible than LEP

Synchrotron Radiation, Beamstrahlung, HOM source of major local heating

Weak magnetic fields as needed to limit SR
Spurious fields : earth field and leakage-(earth) currents, magnetic materials
Flat beams — by design very small V/H emittance ratio, can easily be spoiled by
coupling and spurious vertical dispersion ; dispersion free steering / golden orbit
need to re-align LEP every year

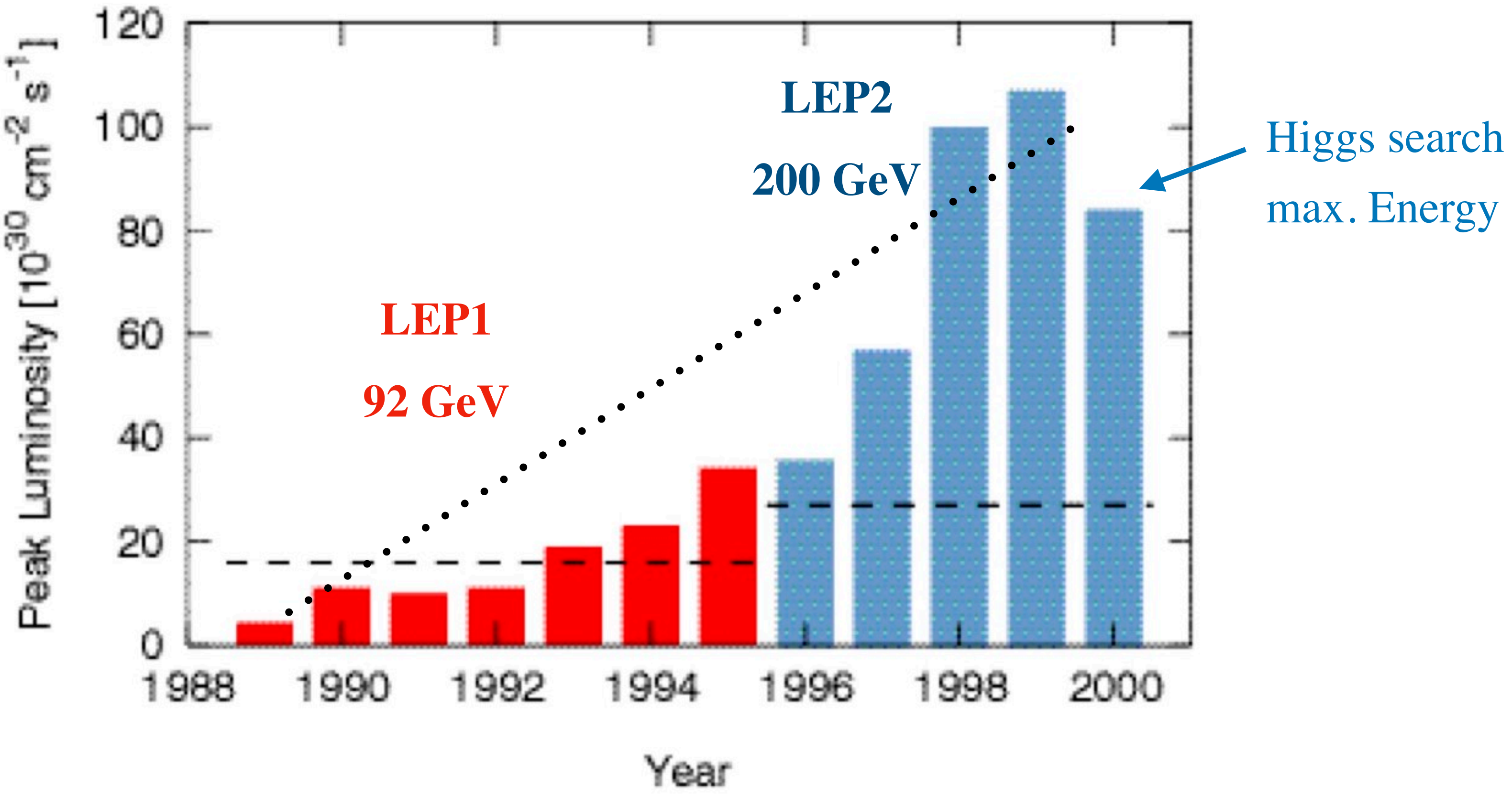
large size and number of components : hard to exclude polarity / cables / poor contact issues

Lifetime/background with strong beam-beam very tune sensitive $\sim 10^{-4}$

A major source of coupling observed in the early LEP octant test :
identified as caused by Ni-component in glue used for Pb-shielding around pipe
minimized by de-magnetization + choice of coupling friendly optics
choice of integer part of tunes and H/V difference important

Very small momentum-compaction
— tiny changes in circumference change energy (earth tides, rain / water level)

Peak performance



Performance increases steadily (slowly) over many years

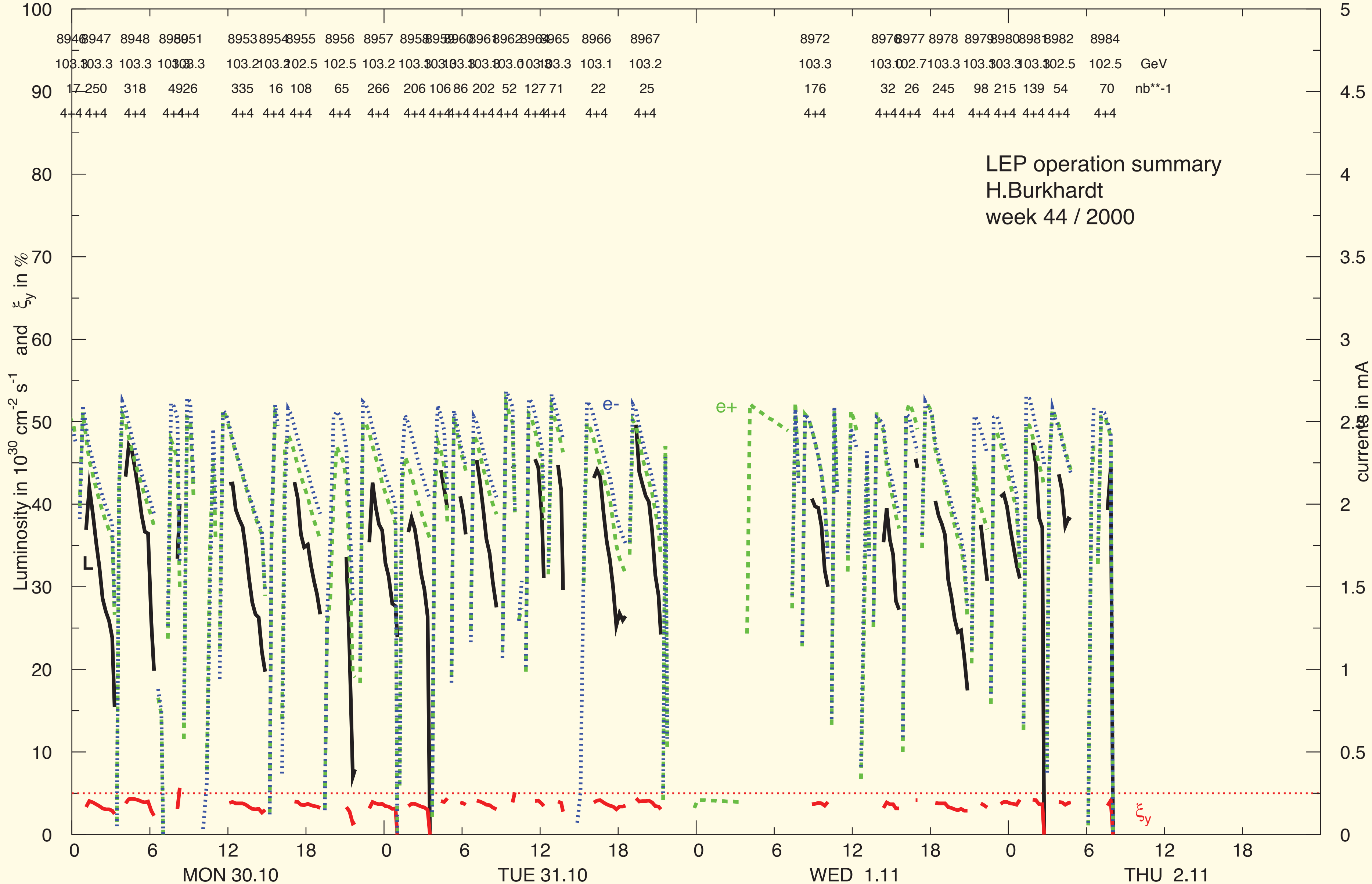
arguably more than in pp machines where the beam brightness is made by the injectors

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

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
- continuously running at top maximum intensity and power

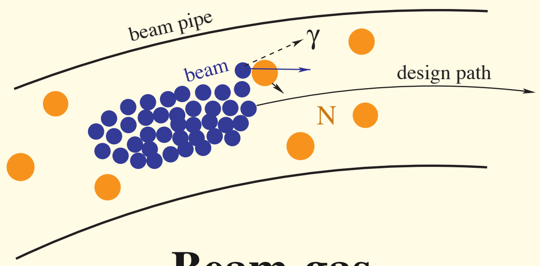
LEP beams were typically dumped after some hours when the luminosity had fallen

(at constant ξy linearly with current)

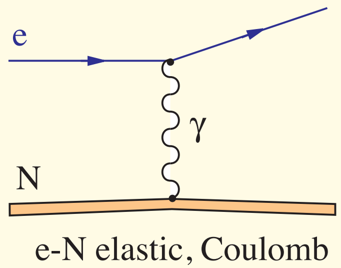
backgrounds and beam sizes decreased, stability increased

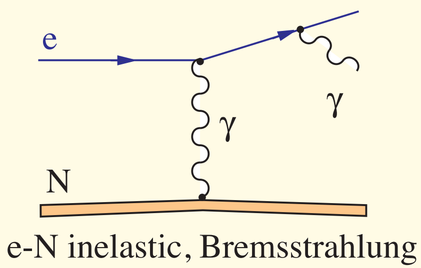
end of fill very useful for tuning improve golden orbits more luminosity / less background

Beam-gas, thermal photons, off momentum background



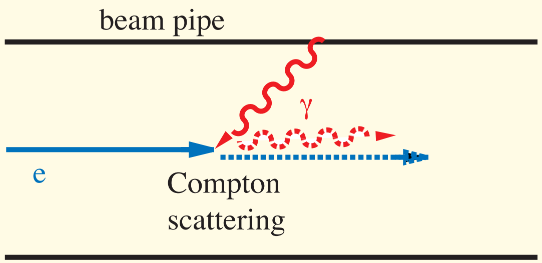
Beam-gas





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

thermal photon scattering



Beamstrahlung ~ negligible @ LEP

at high energy elastic scattering small

inelastic generator of off-momentum tail

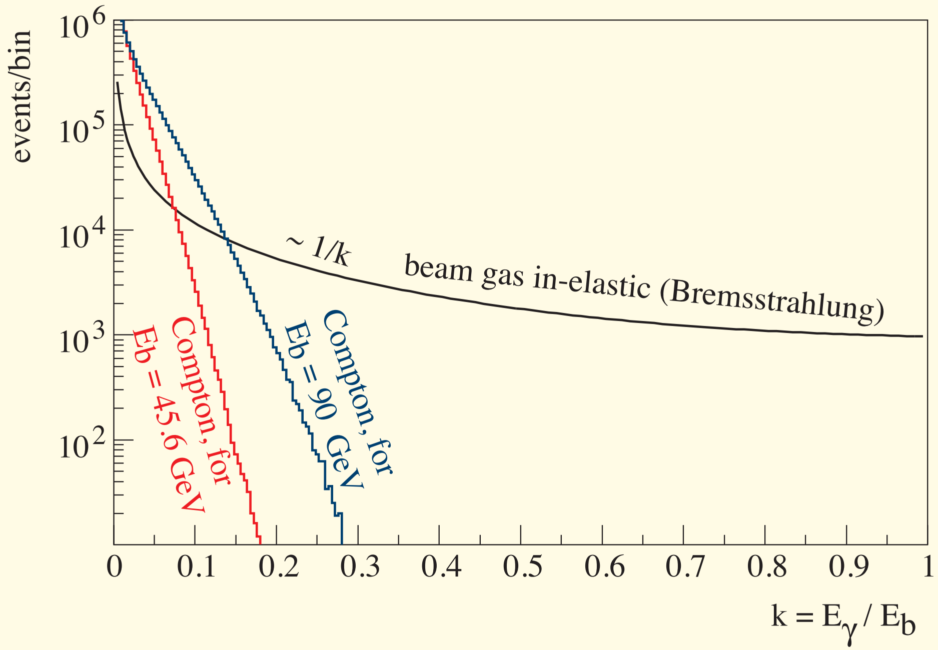
well visible in LEP

generally 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



LEP, example of background particle tracking

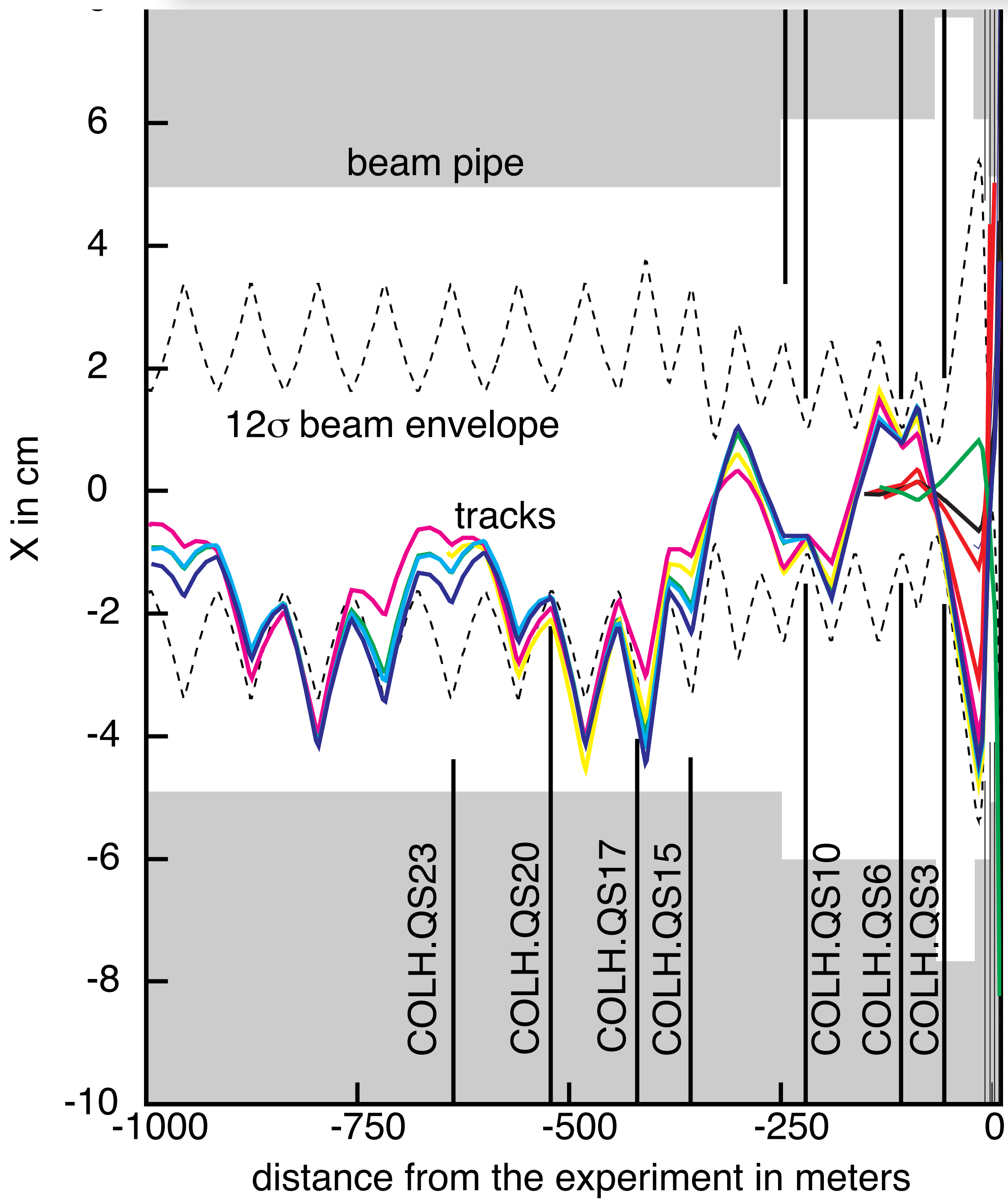
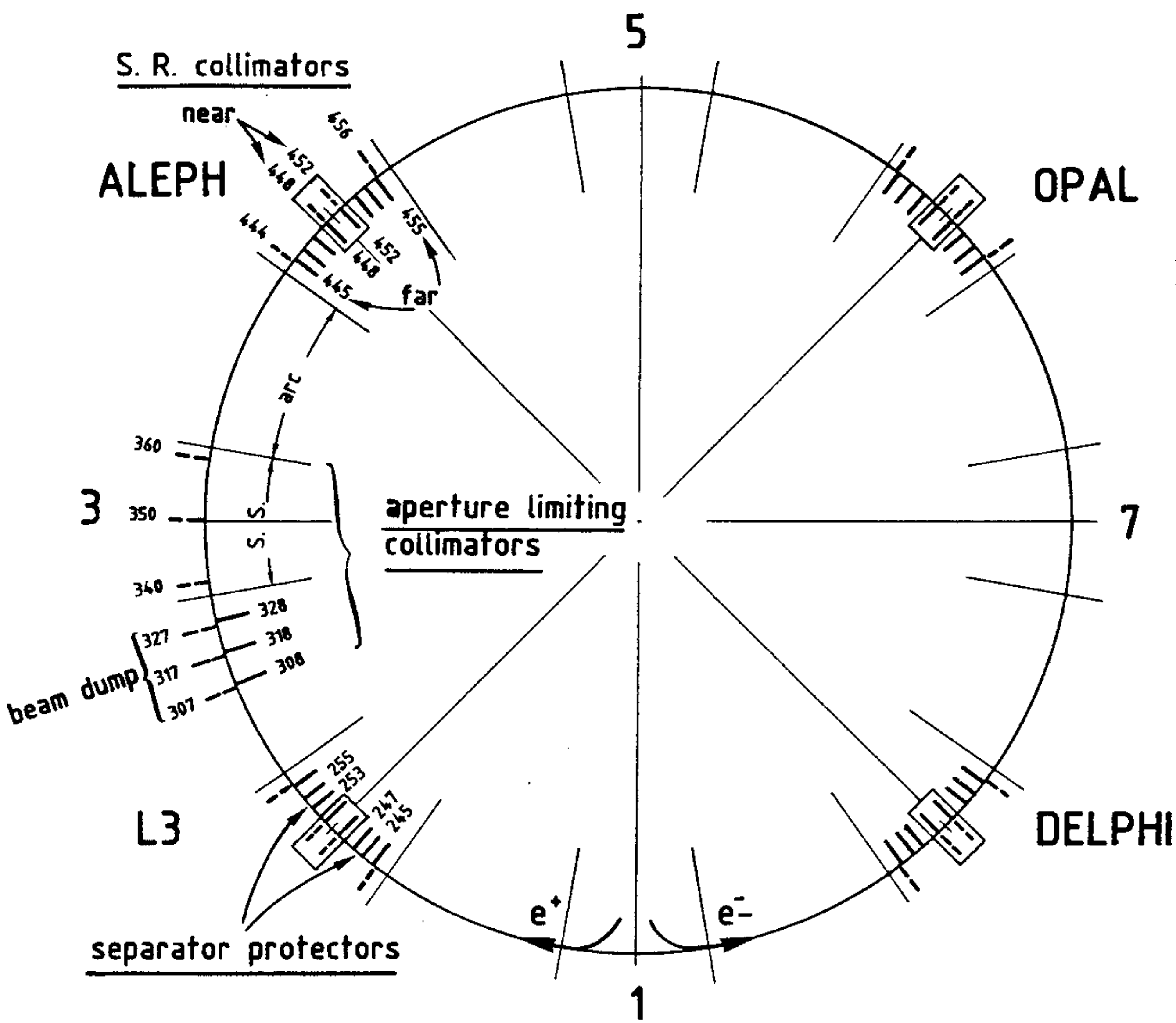


Illustration of beam particle tracking through the LEP lattice over 1000 meters up to an experimental region (cs coordinates).
The distance X from the nominal orbit is given in cm units.
The tracks are for particles that are lost within ±9 m from the interaction point.
The 12σ beam envelope is shown 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.

Codes : MAD8, Turtle, DIMAD, EGS
+ “own generators” beam gas, thermal, SR, radiative Bbhabha

plot from my simulation for the 1998 LEP background paper Ref [1]

LEP movable collimators, essential for background

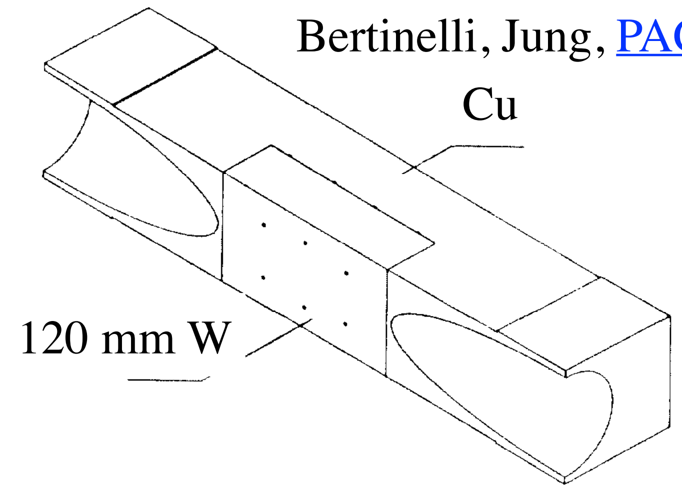


shown here as originally designed,

G. von Holtey. LEP main ring collimators. [EP-BI-87-03]

later upgraded (AP. limit IP5) masks, QD20 coll around IRs

Bertinelli, Jung, [PAC97]



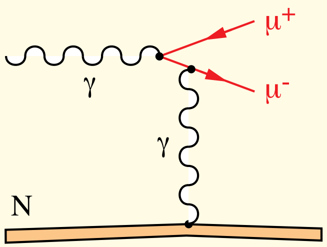
settings of order
Aperture H 15.5 σ
Experim. H 18 σ

Vertical
~ 30 nominal σ
~ 100 measured σ

nominal :
10% coupling
σ E = 1.e-3

Muon backgrounds

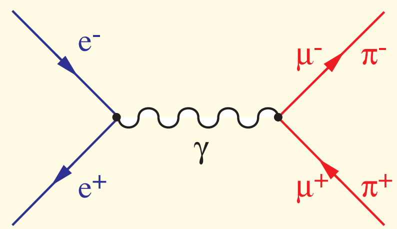
Collimating high energy e+, e– will generate muons, roughly at the 10^{-4} – 10^{-5} level



G4GammaConversionToMuons

beam e+

on atomic e-



G4AnnihiToMuPair

implemented in GEANT4 in 2002

Came as a bad surprise to SLC, hard to avoid in linear colliders

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

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

Not an issue for LEP-MDI since losses were collimated far from the experiments

In CEPC, FCC-Z we expect to lose several 10^{11} e+, e– per second generating millions of muons / second —> minimize collimation of e+, e- in line of sight to experiments

Signal exchange, monitoring, logging and status displays

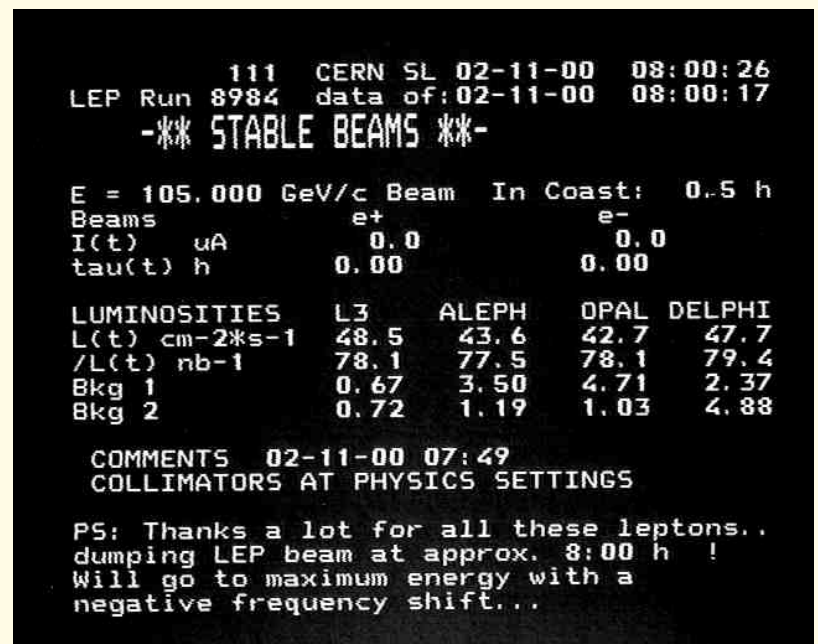
For good performance, LEP beams required

continuous monitoring and 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

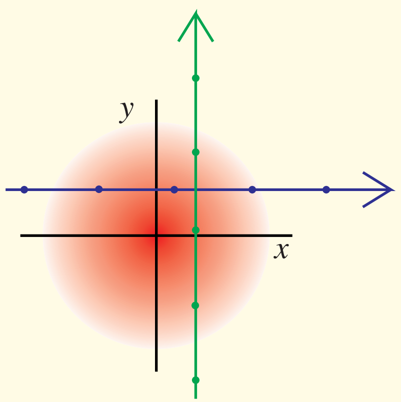
Optimize collisions (1/2)

LEP beam separated

during injection

ramp & squeeze

using electrostatic separators



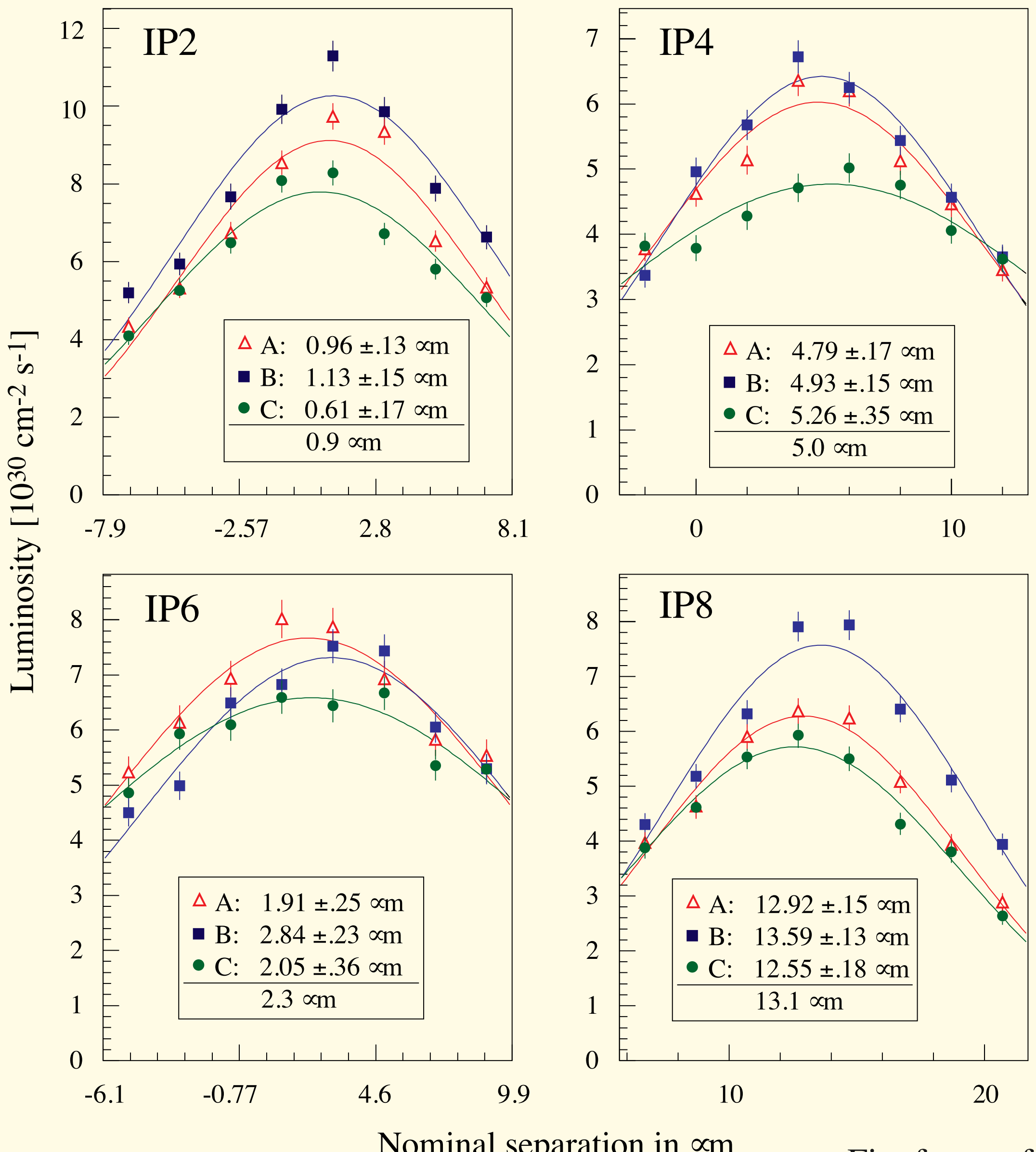


Fig. from ref. [5]

Collisions optimised by

separation scans

based on luminosity

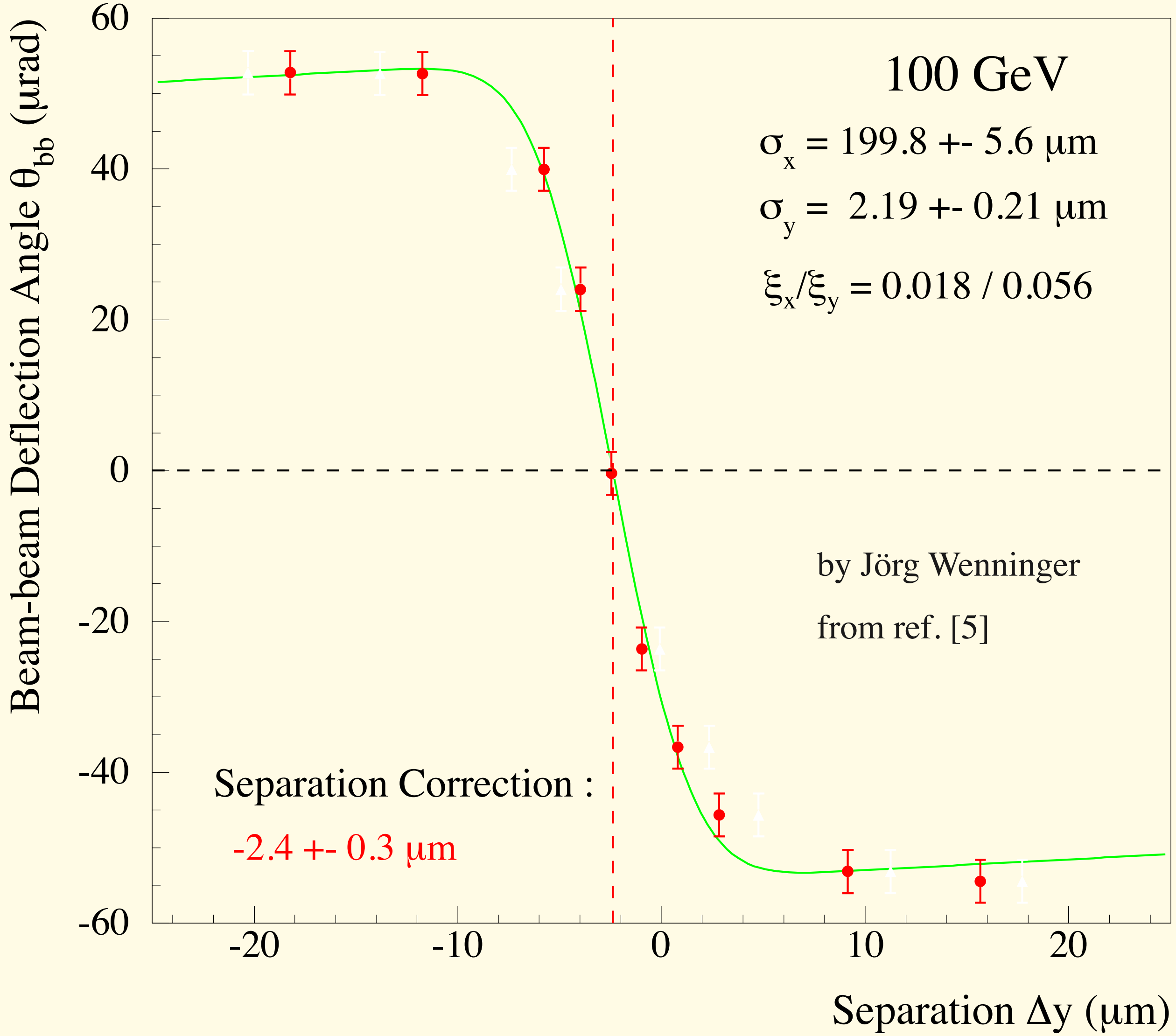
avoid partial separation :

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 beam power — increased for small separation, risk of damage

Beam Lifetime

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

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

τ_{th} = 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 well 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

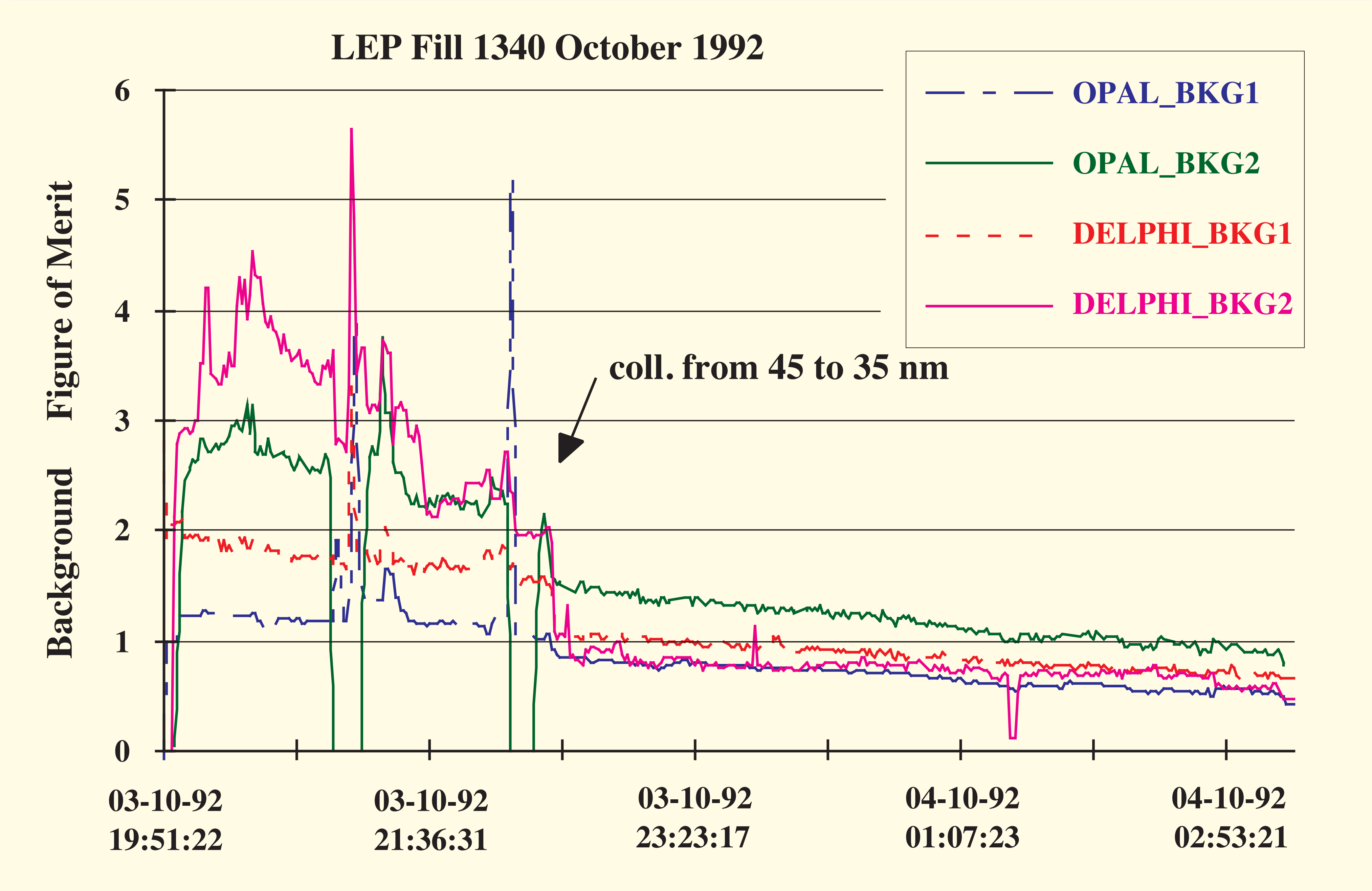
Lifetimes in LEP well accounted for by 3 loss processes

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

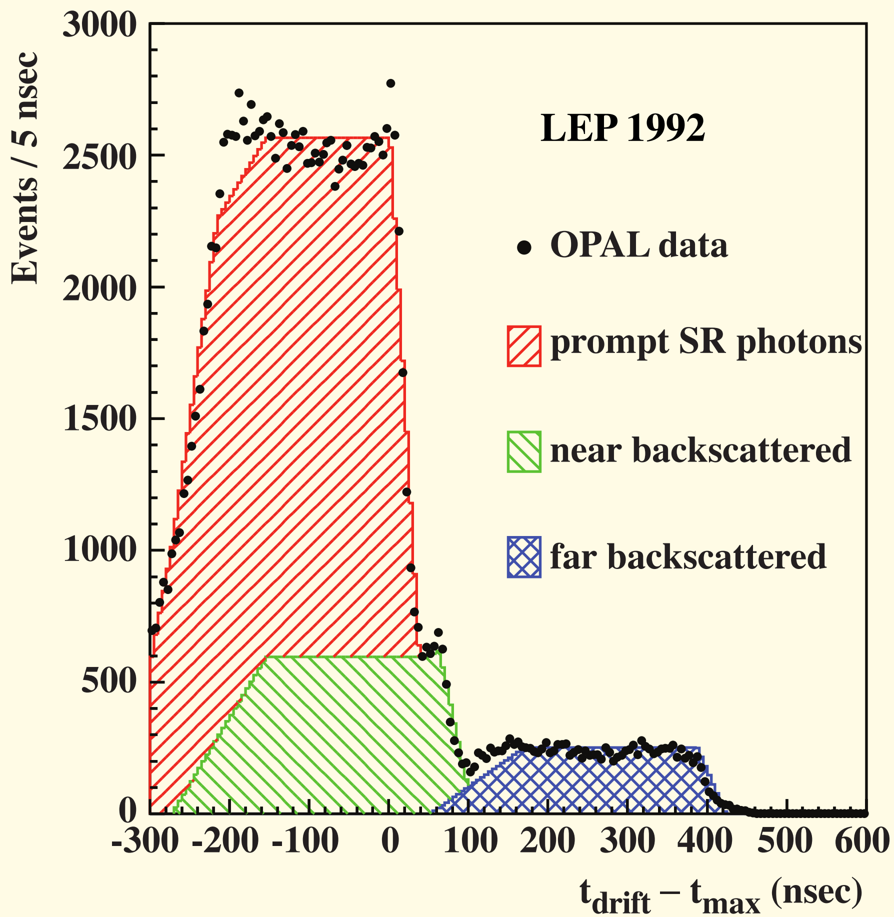
with occasionally (LEP1, high ξ_y) additional losses and background spikes

related to non-Gaussian tails and coherent instabilities

LEP background observations



LEP background observations



incoming

~ 9 m from IP

~ 60 m from IP

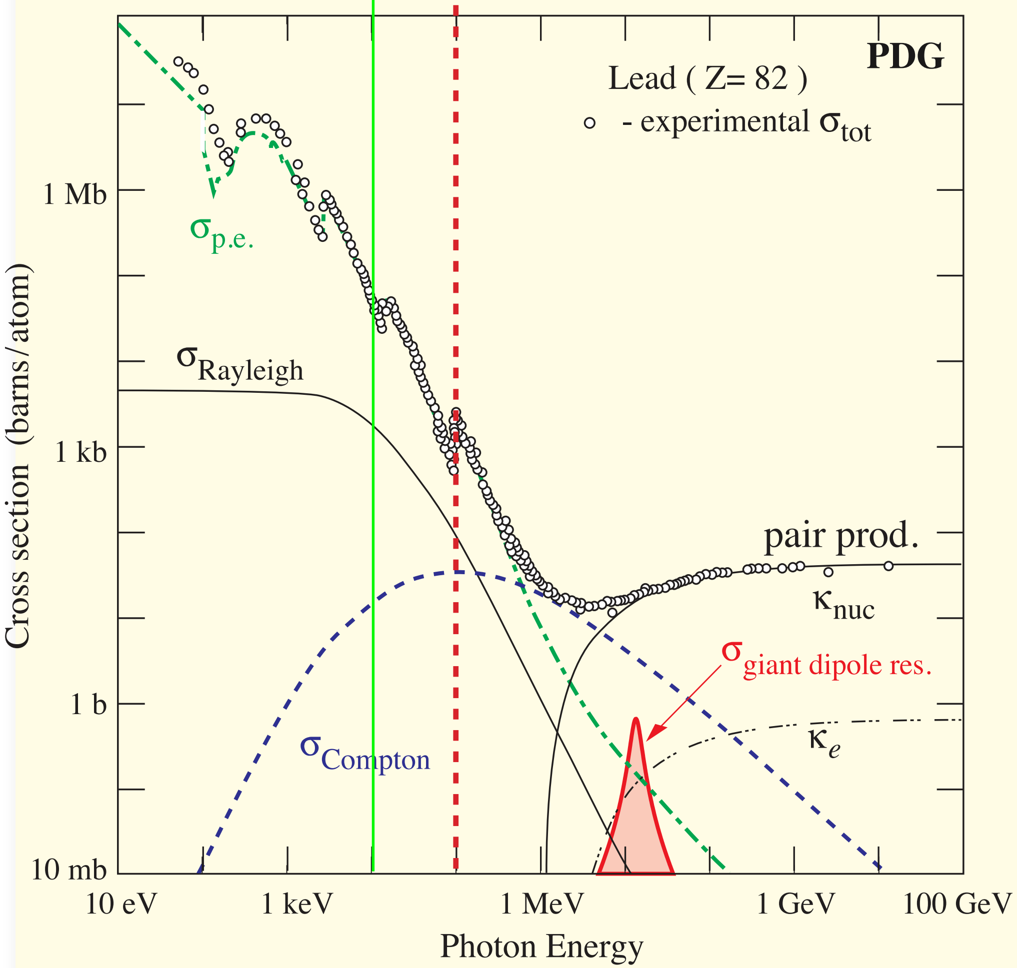
Distribution of arrival times relative to the maximum drift time for the hit wire of SR photons in the OPAL vertex drift chamber

Major challenge : synchrotron radiation

✔ < 10 keV

> 100 keV very difficult

10 MeV significant neutron flux, giant dipole res.



Critical photon energies

SuperKEKB ~ 2 keV (LER)

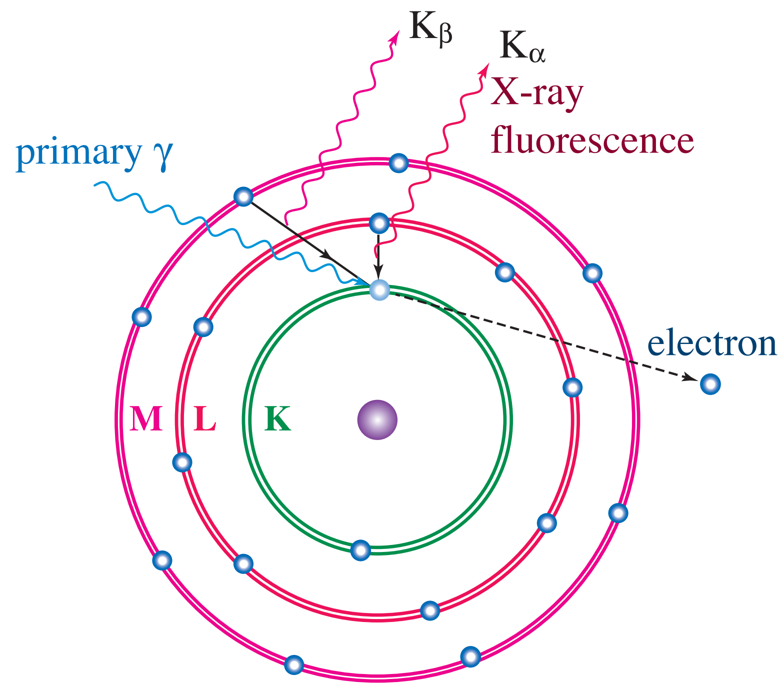
FCC-hh ~ 5 keV

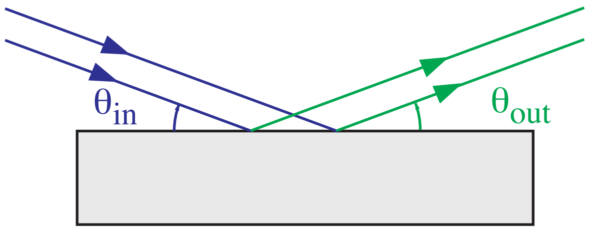
LEP1 : 69 keV

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

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

X-Ray - Fluorescence and Specular Reflection





Fluorescence was known and mitigated for absorbers by surface coating in LEP
Fluorescence + Auger cascade are implemented in GEANT4
make sure materials well defined
and these processes activated

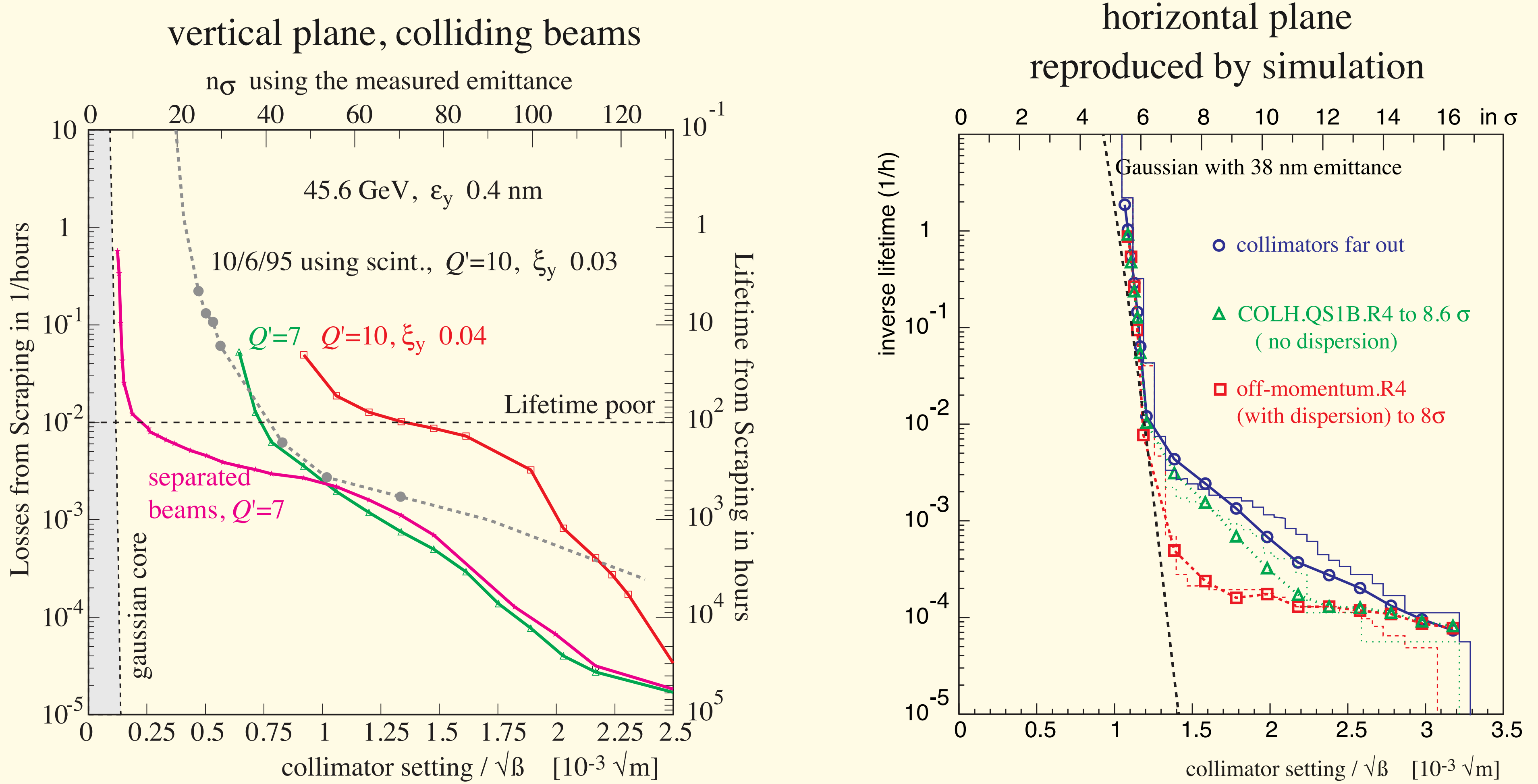
X-Ray specular reflection came as a surprise in LEP mitigated with far coll. like COLH.QS6 at 120 m

currently working hard to (finally) implement this in GEANT4
presented at annual G4 meeting end Sept.
meanwhile merged into G4 developer repository
checks ongoing for upcoming public Geant4 Release 11.2, also of more general interest including x-ray mirrors, space science

Important to take these properly into account
Requires good knowledge and optimization of materials, geometry, surfaces (roughness) and tight control of orbit / alignment tolerances
Ideally addressed by dedicated work with benchmarking measurents + simulation

non-Gaussian tails, LEP

measured with loss monitors; scraping with aperture collimators

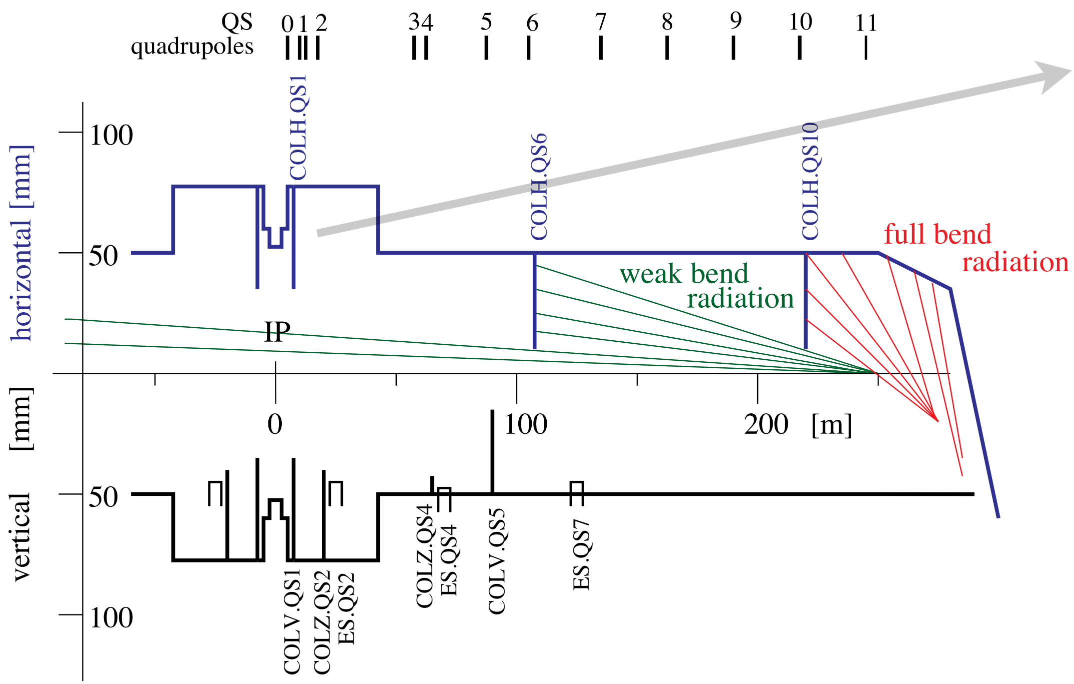


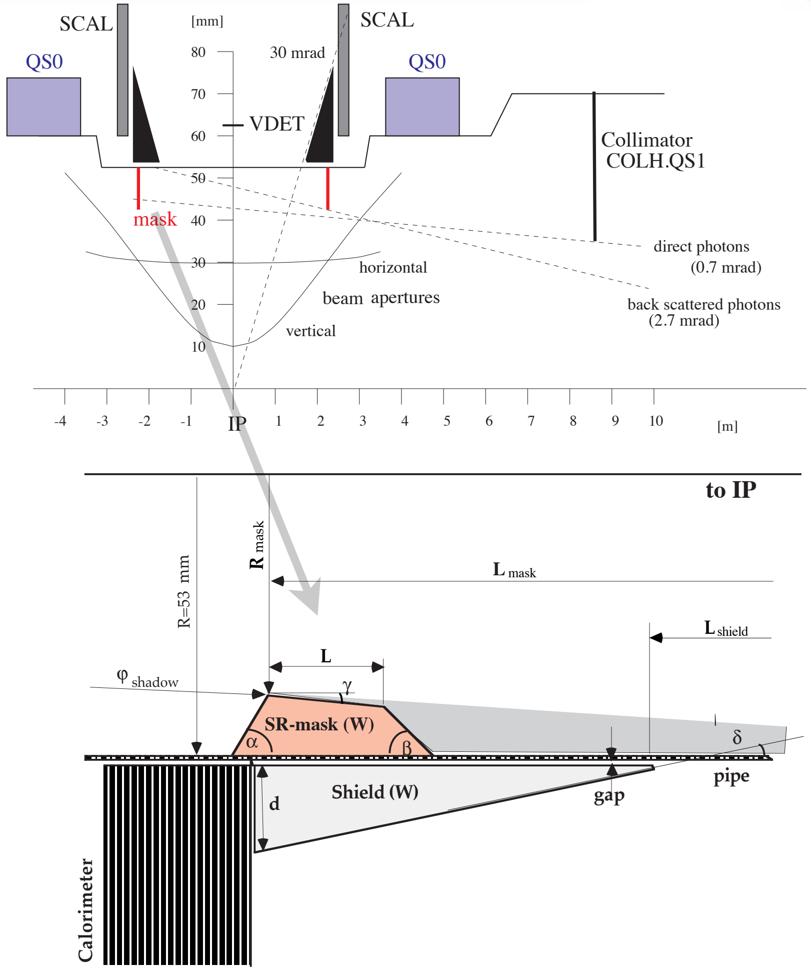
Tails from :   beam-beam, high chromaticity, particle scattering

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." Ref [2]

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 last bend 260 m, from IP 10 × weaker

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

8.5 m COLH.QS1 instrumented as compact Si-tungsten calorimeter - loss and IR rate monitor

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

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] *Ultimate performance of the LEP RF system*, P. Brown et al. PAC-2001-MPPH123

[7] *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

LEP worked very well, in many respects and particular energy precision better than anticipated

encouraging as demonstrator for CEPC / FCC feasibility

Much of the work is on details

MDI - IR design particularly important

— minimize SR and losses towards IR

— last upstream bend aim for Ecr < 100 keV, keep bend SR and loss collimation far from IP

Importance of excellent continuous monitoring + frequent correction + alignment

close collaboration with experiments, minimize vertical dispersion + coupling;

LEP had a octant test 2 years and modest pilot run 1 year before start of proper operation

A larger (inner) **r = 78 mm Al beam pipe at the IR for the first year, later r = 53 mm Be**

Goals very ambitious — need for testing & ramp-up strategy

Backup

Energy calibration

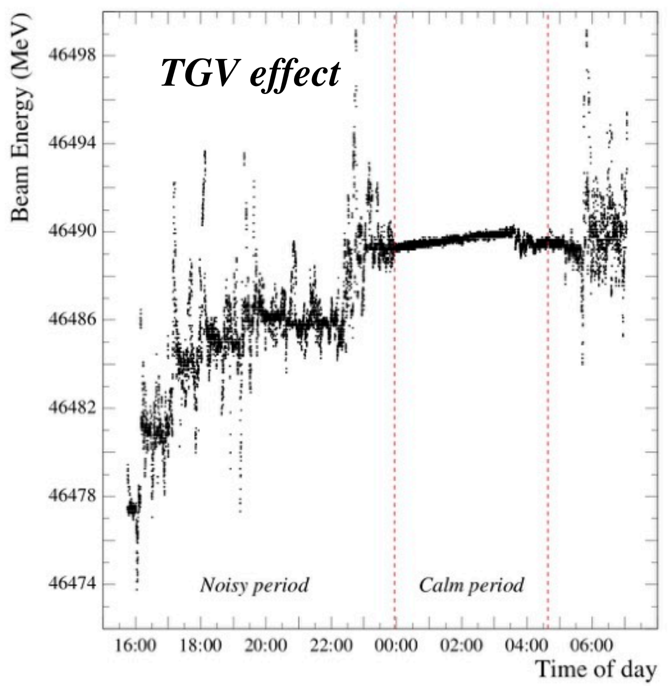


Figure 29. Magnetic field measured in a LEP dipole by an NMR probe over 10 h. For convenience, the magnetic field has been converted to an equivalent beam energy in MeV. Large short-term fluctuations and a slow rise in field are clearly visible. Between midnight and 4:30 am the field is stable while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

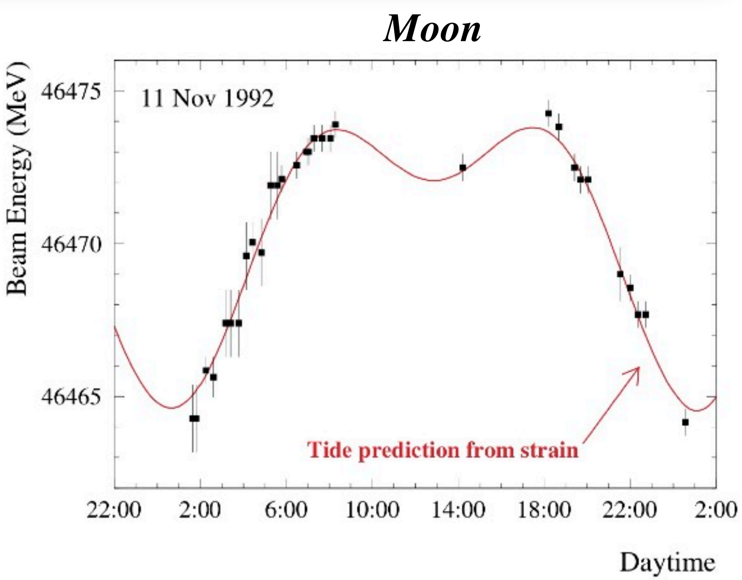


Figure 30. Energy variation of the LEP beams during a full moon day. The curve is the energy change predicted from the horizontal strain induced by the Earth tides.

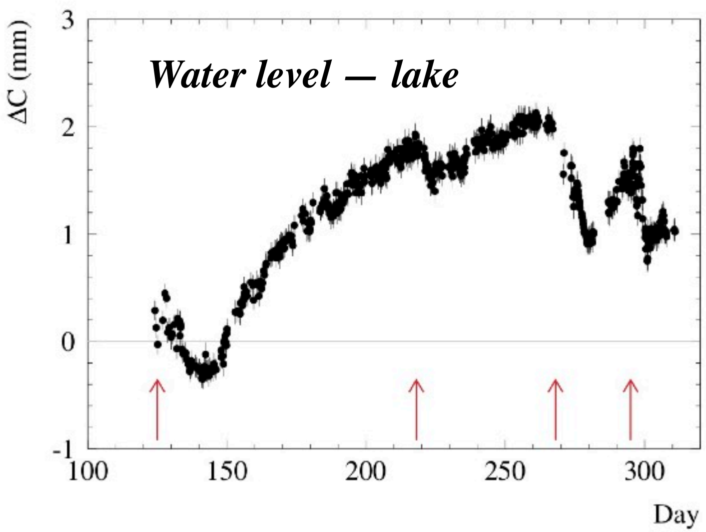


Figure 31. Evolution of the LEP circumference (corrected for tidal changes) as a function of the day in 1999. A drift of over to 2 mm is observed during the LEP run. In the summer months the circumference increases gradually. Following periods of heavy rainfall, indicated by the arrows, the circumference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

Figures from [5]

Amon the key persons on machine side :

J. Wenninger, Ralph Assmann,

Bernd Dehning (Polarimeter)

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	$\mathcal{L}$ ($\mathrm{cm}^{-1}\mathrm{s}^{-2}$)	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 $17\mathrm{x}10^{30}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Year	$\int \mathcal{L}dt$ (pb^{-1})	E_b ($\mathrm{GeV/c}^2$)	k_b	$2k_bI_b$ (mA)	$\mathcal{L}$ ($10^{30}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$)	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 7

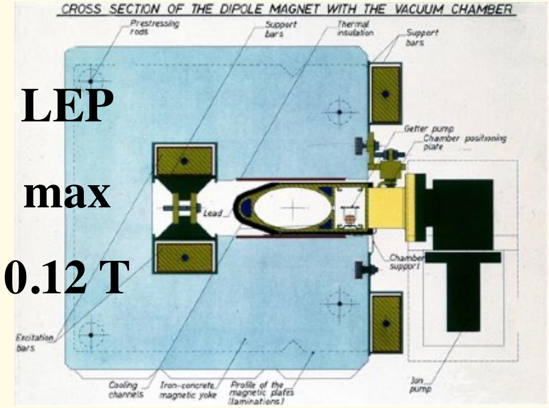
Basic geometry, magnets

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



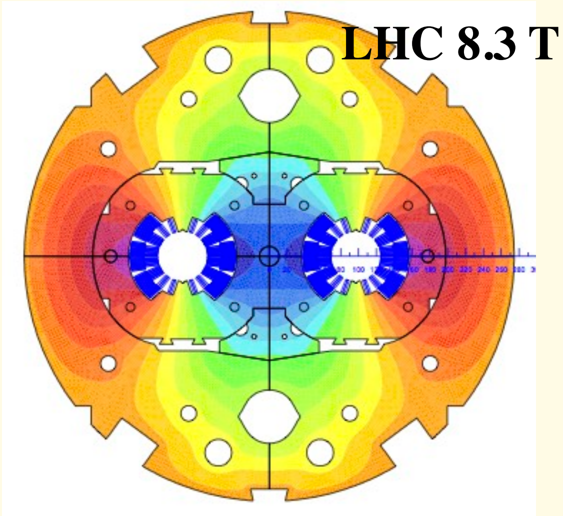
LEP

max

0.12 T

8 straight sections, ± 284 m around IPs

4 used as interaction regions



LHC 8.3 T

distance IP to 1st superconducting Quadrupole (centre)

L* = 3.7 m for LEP

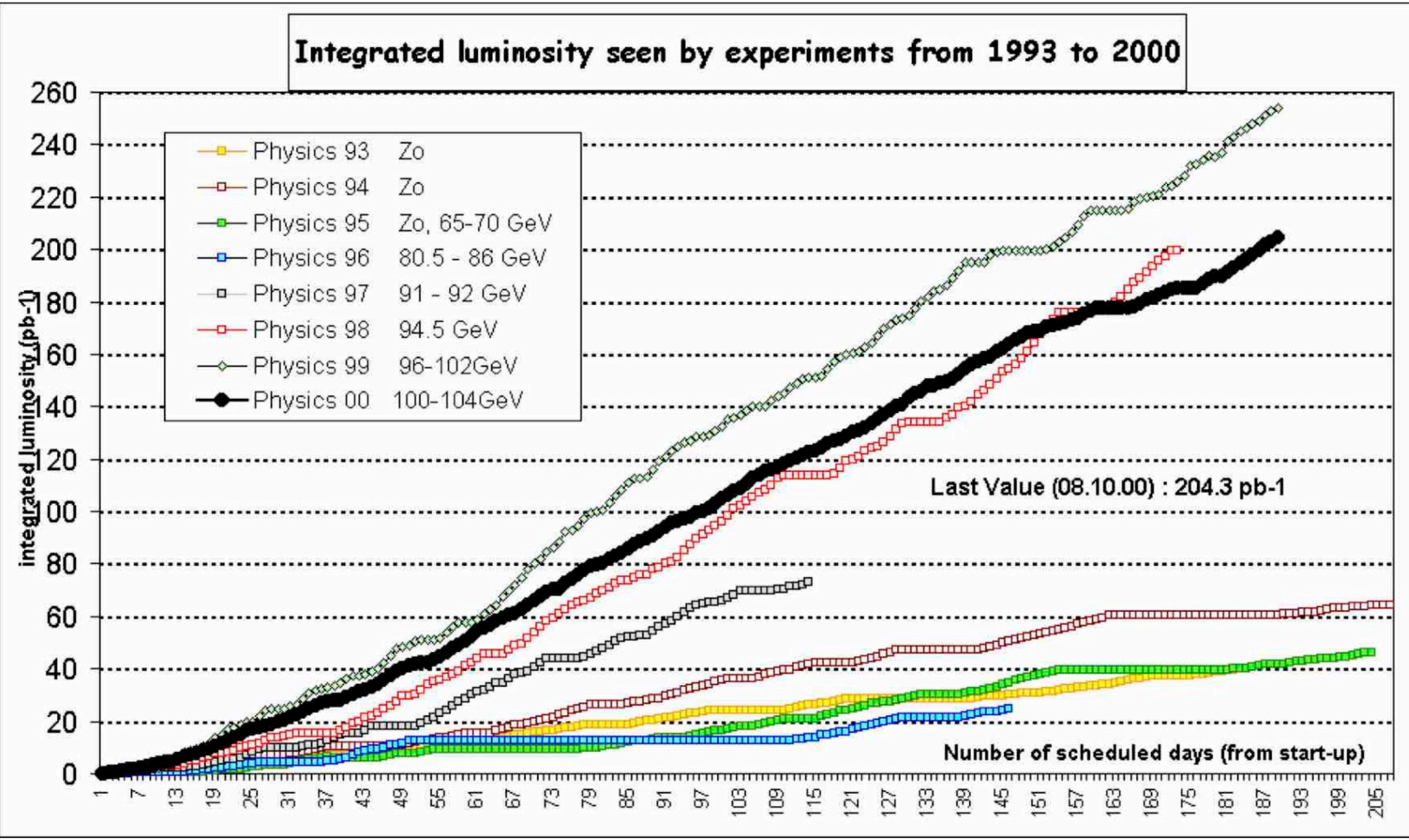
2.8 m FCC-ee

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 —>

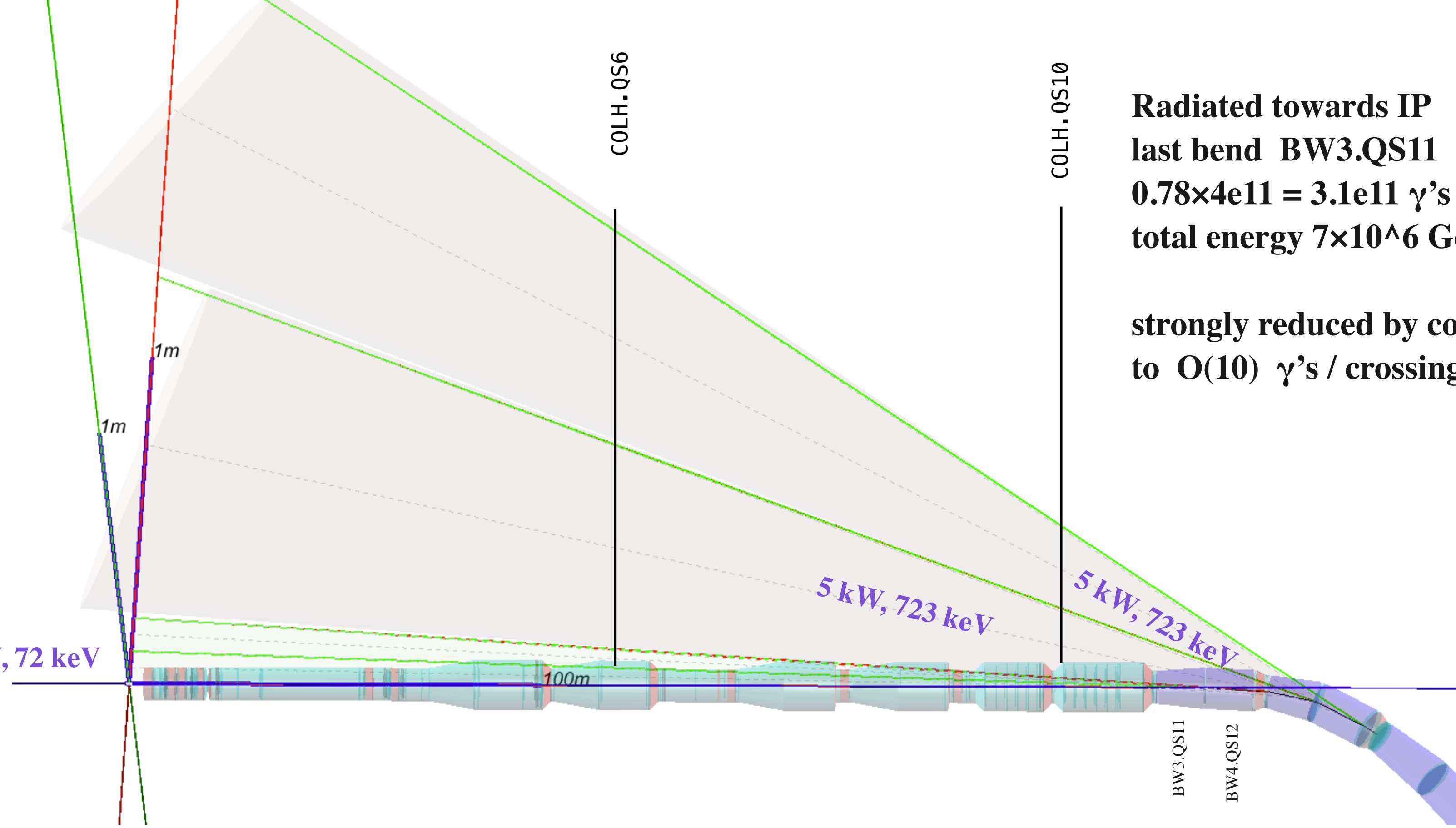
Performance 1993 - 2000



$\int L\,dt$ / year increase by $\sim 10\times$ over 10 years

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