Beam backgrounds at LEP

bit of history of the CERN **L**arge **E**lectron-**P**ositron Collider

trying to illustrate and summarize key points, that may be of interest for future (linear) e+e- colliders

L = 26.659 km

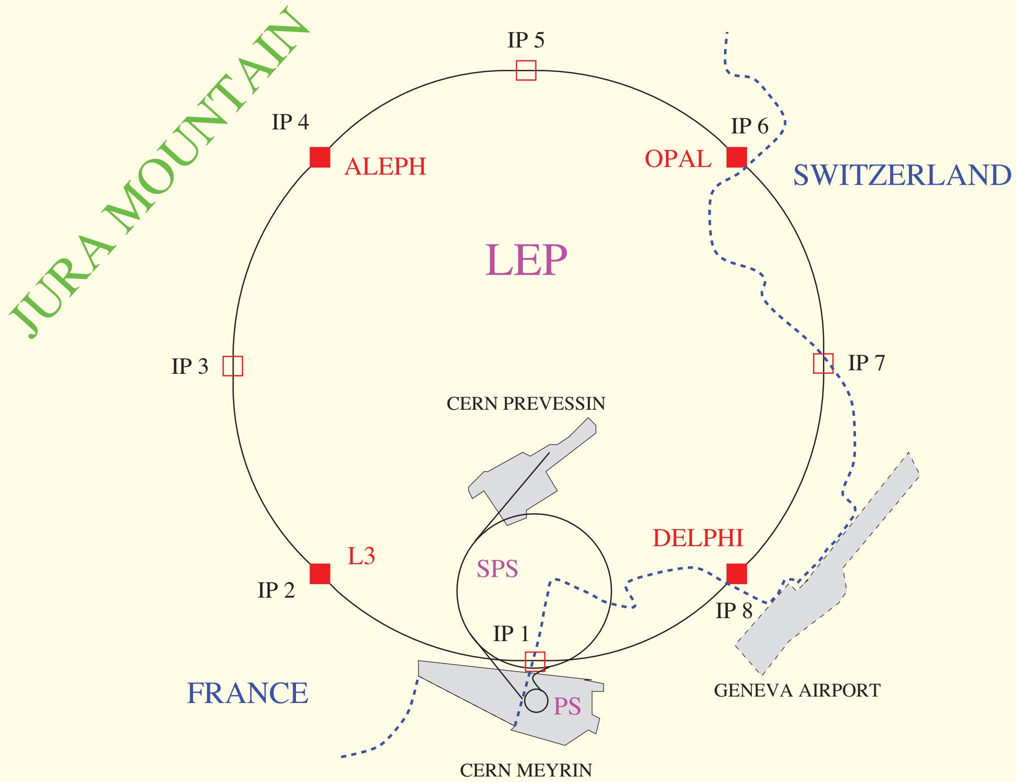
Ecms 89 — 209 GeV

SR Power ≲ 10 MW / beam

Luminosity ~ 10^{32} cm^{-2} s^{-1}

up to ~ 4×10^{11} e+, e- / bunch

min. $\sigma^*_{x,y}$ ~ 150 µm , 3 µm



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

Changing a lot and "devil in details"

Discussed in Chamonix meetings, well documented in proceedings

Had disappeared, ticket 8/1/2020 RQF1495759 created by me 8/1/2020

Resolved 11 month later : CERN Service Desk 11/12/2020, back online

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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
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Lesson #1 : seen with LEP — can expect as general feature for large, warm e+e- machines

Very dynamic, very complex, changing all the time, orbit, 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

adding off momentum collimators in dispersion suppressors - collimate off-momenum BKG

adding synchrotron masks

As a result : LEP2 backgrounds comparable to LEP1

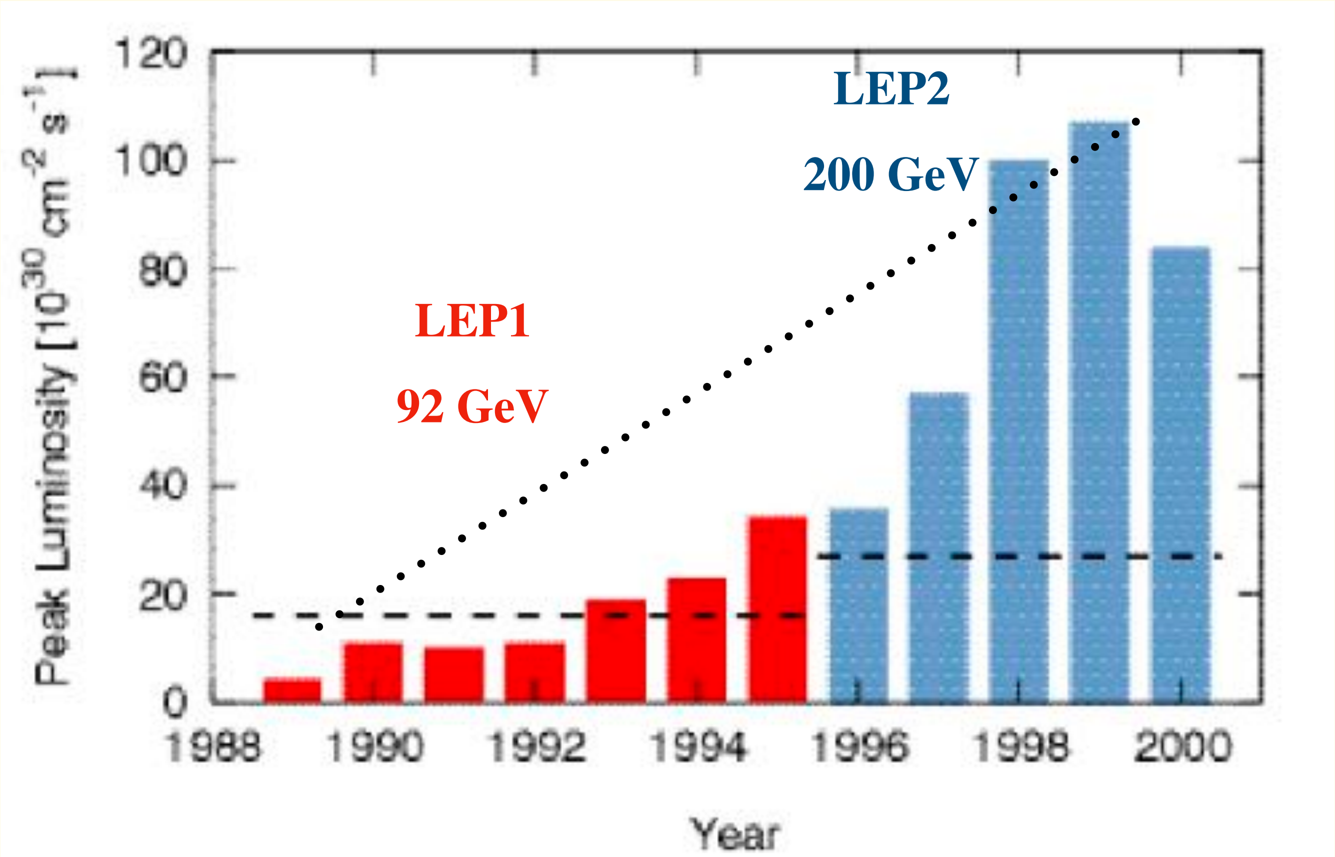
Just ~ 30 years ago

Photo
courtesy
John Jowett

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

numerous detailed improvements, new optics ~ every year

Peak performance



Performance increased steadily (slowly) over many years

not injector limited - beams accumulated, strong (SR) damping, equilibrium emittance

minimum β* and maximum tune shift were limited in LEP

by the need of the experiments for stable low background running conditions

LEP peak performance parameters

Table 3. 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 min. For each beam energy, the first line corresponds to the horizontal, the second line to the vertical plane.

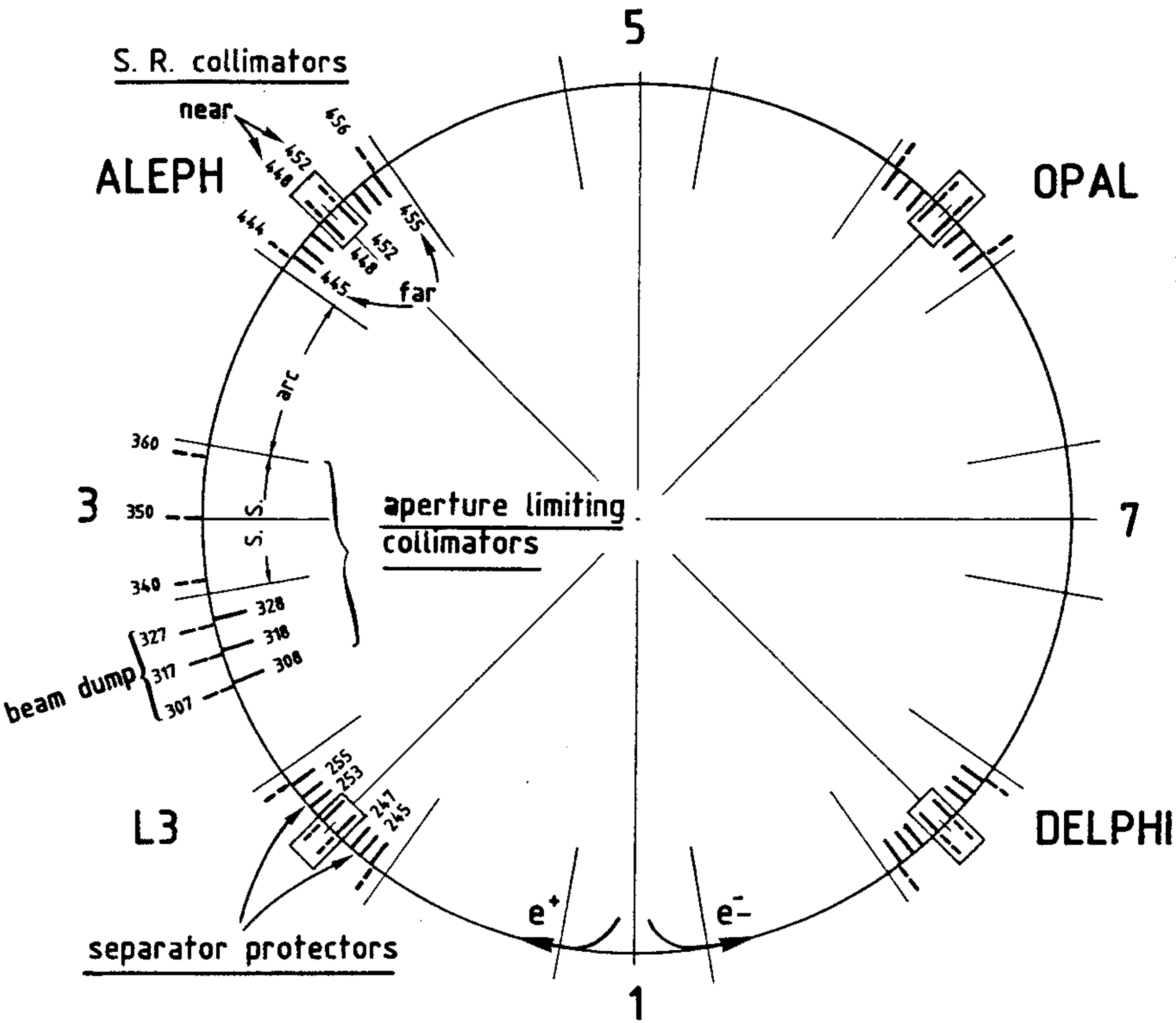
E_b (GeV)	N_b ($\times 10^{11}$)	k_b	$\mathcal{L}$ (cm^{-1} s^{-2})	Q_s	Q	β^* (m)	ϵ (nm)	σ (μm)	ξ
45.6	1.18	8	1.51×10^{31}	0.065	90.31	2.0	19.3	197	0.030
					76.17	0.05	0.23	3.4	0.044
65	2.20	4	2.11×10^{31}	0.076	90.26	2.5	24.3	247	0.029
					76.17	0.05	0.16	2.8	0.051
97.8	4.01	4	9.73×10^{31}	0.116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

Table 6. Overview of LEP (instantaneous) peak performance 1989–99. $\int \mathcal{L}\,dt$ is the luminosity integrated per experiment over each year. The design luminosity at 45 GeV is 17×10^{30} cm^{-2} s^{-1}.

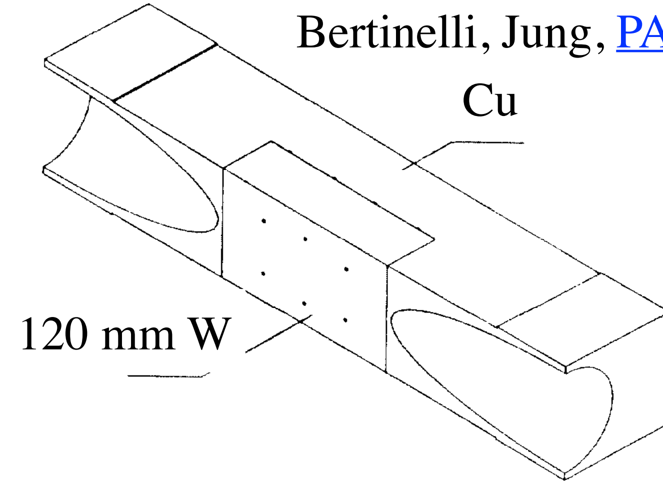
Year	$\int \mathcal{L}\,dt$ (pb^{-1})	E_b (GeV/c^2)	k_b	$2k_b I_b$ (mA)	$\mathcal{L}$ (10^{30} cm^{-2} s^{-1})	ξ_y
1989	1.74	45.6	4	2.6	4.3	0.017
1990	8.6	45.6	4	3.6	7	0.020
1991	18.9	45.6	4	3.7	10	0.27
1992	28.6	45.6	4/8	5.0	11.5	0.027
1993	40.0	45.6	8	5.5	19	0.040
1994	64.5	45.6	8	5.5	23.1	0.047
1995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

from Ref 7

LEP movable collimators, essential for background



Bertinelli, Jung, [PAC97]



as originally designed,

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

later modified (AP. limit IP5) and upgraded

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

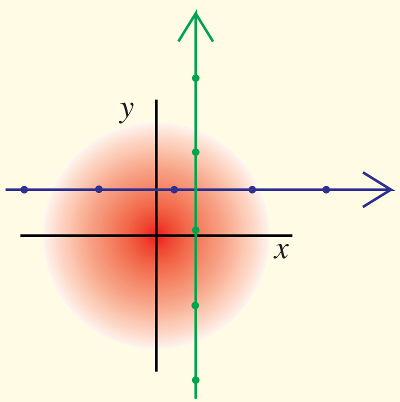
Optimize collisions (1/2)

LEP beam separated

during injection

ramp & squeeze

using electrostatic separators



Collisions optimized initially

by separation scans

based on luminosity

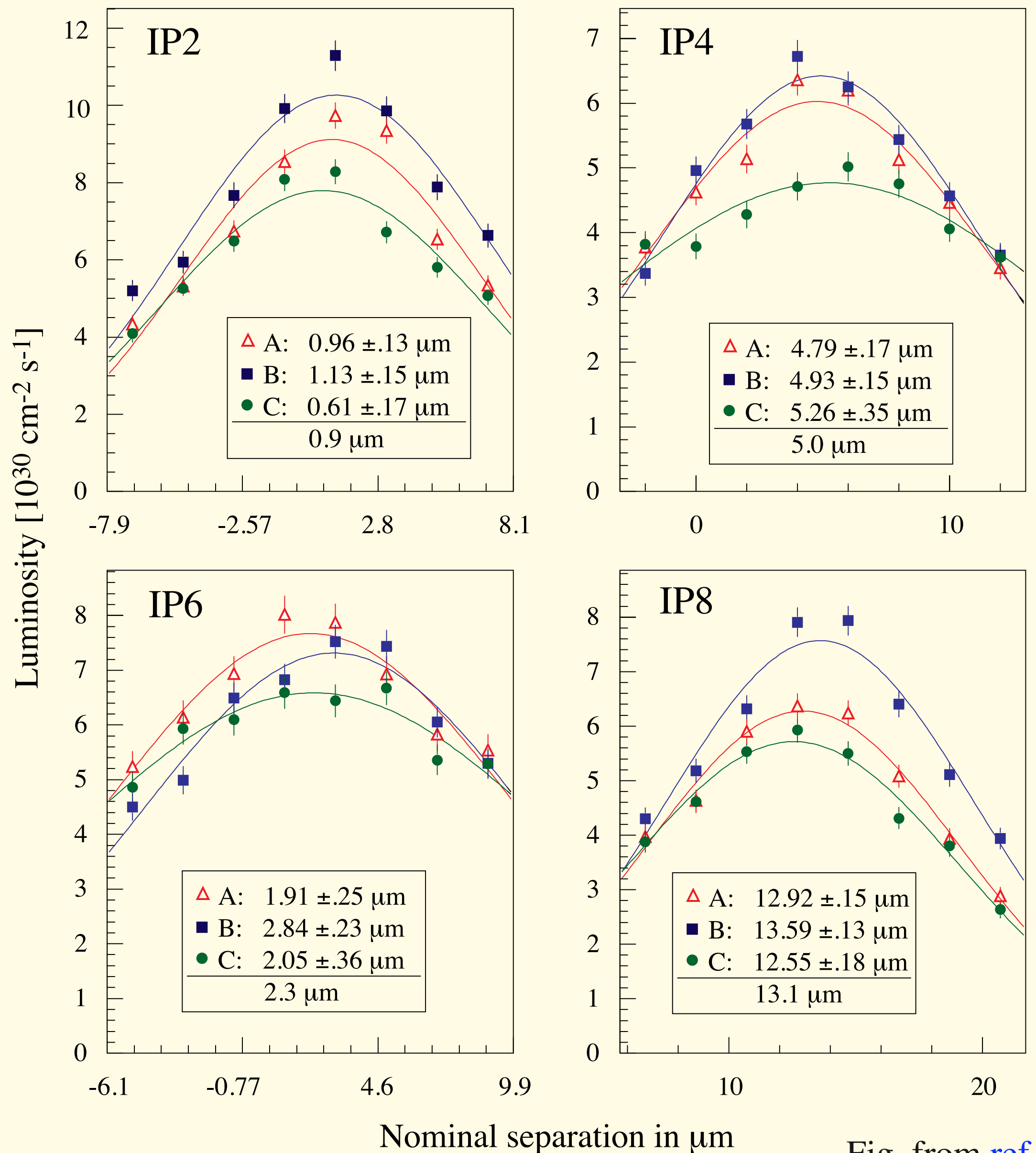


Fig. from ref. [7]

avoid partial separation :

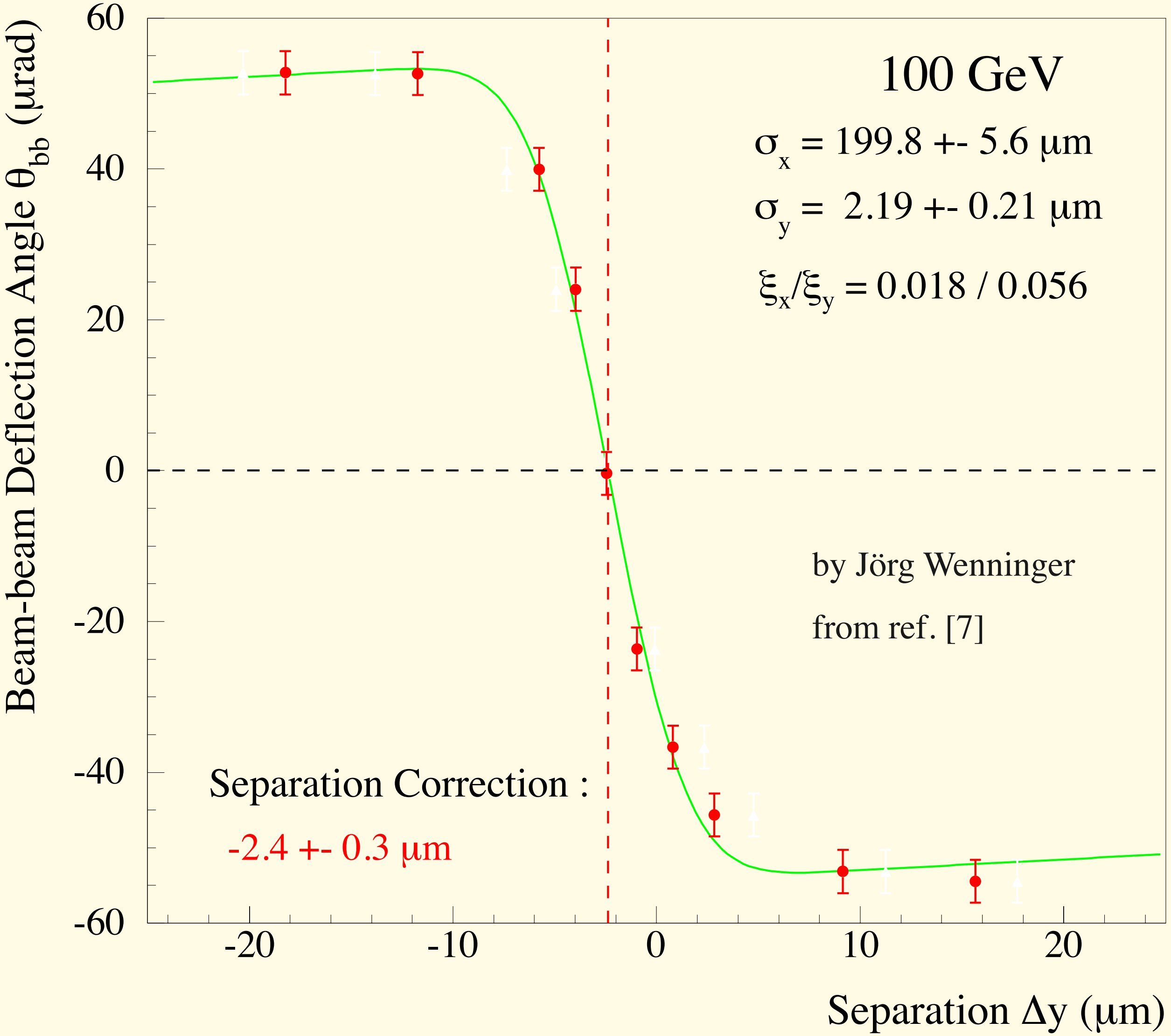
reduces luminosity, can trigger coherent beam-beam, flip-flop, increase halo

Optimize collisions (2/2)

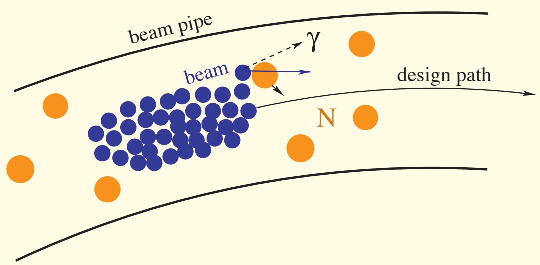
Later LEP operation with improved orbit monitoring and control :

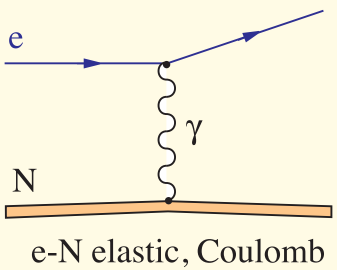
Fast centering using beam-beam deflections scans

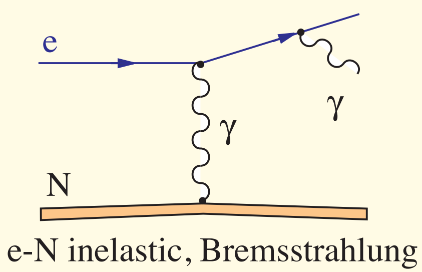
also providing good estimate of core beam sizes (emittance, bb tune shift)

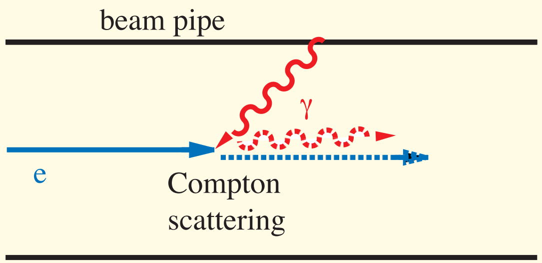


background sources for loss of e+, e-









elastic scattering very small

at LEP energies

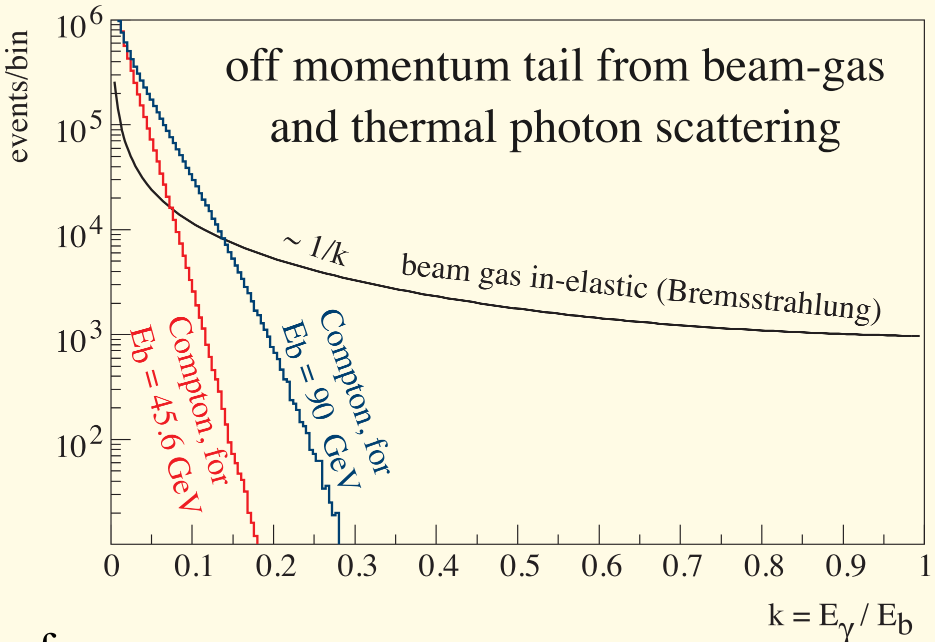
inelastic generated by beam-gas

and thermal photon well visible

but not a major problem

(<< 1 electron lost at IR / crossing)

thanks to



- **excellent vacuum** — SR helps to back out surfaces
- **powerful momentum collimation** both in dedicated collimation section + local each IR

Thermal γ : 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

LEP, example of background particle tracking

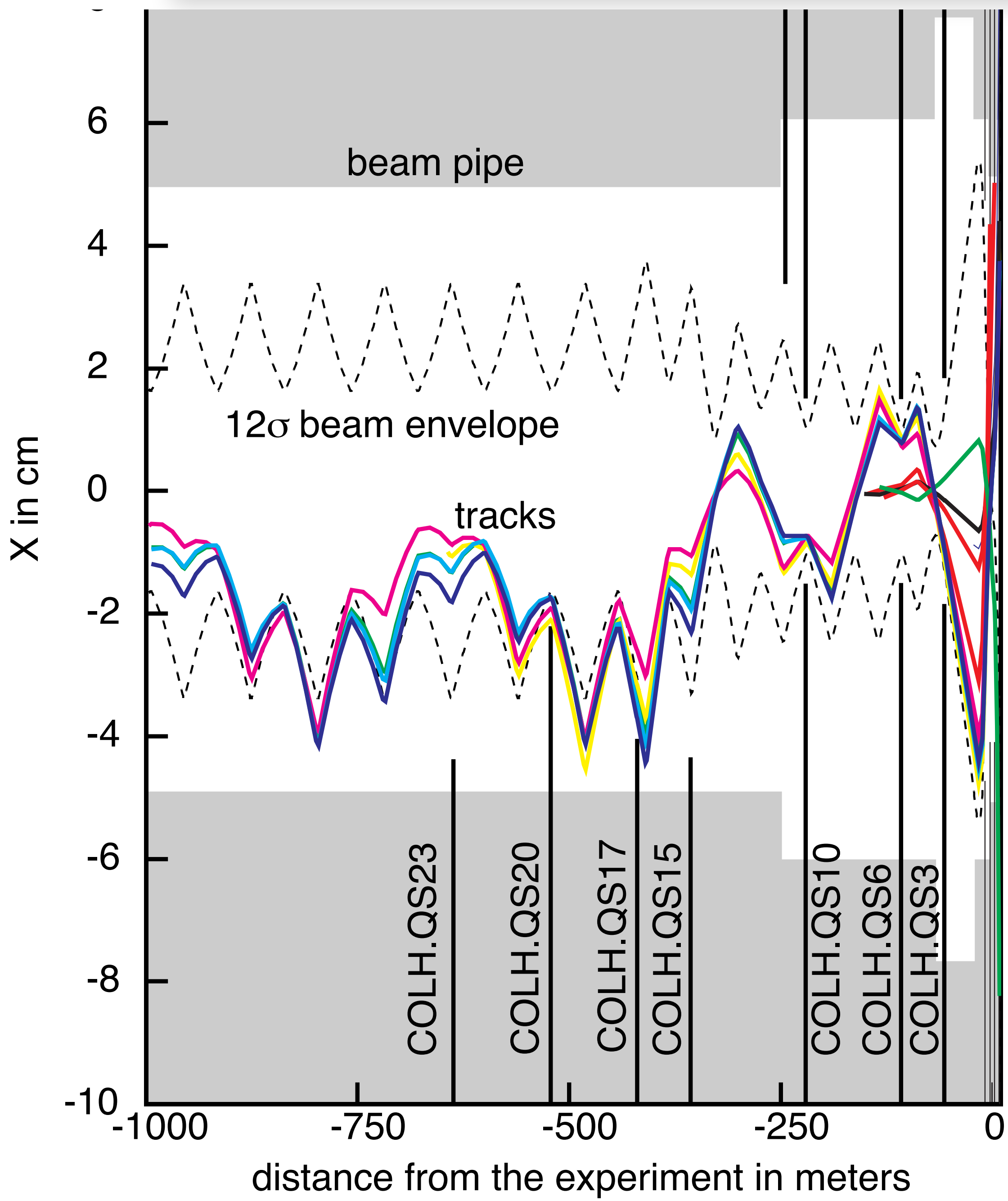


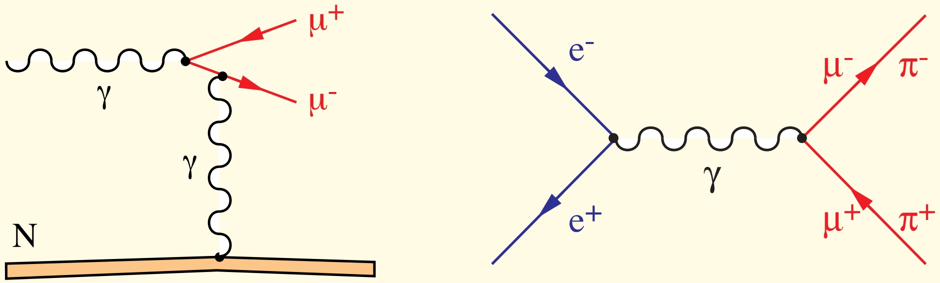
Illustration of beam particle tracking through the LEP lattice over 1000 meters up to an experimental region (cs coordinates).
The distance X from the nominal orbit is given in cm units.
The tracks are for particles that are lost within ±9 m from the interaction point.
The 12σ beam envelope is shown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

plot from my simulation for the 1998 LEP background paper Ref [6]

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

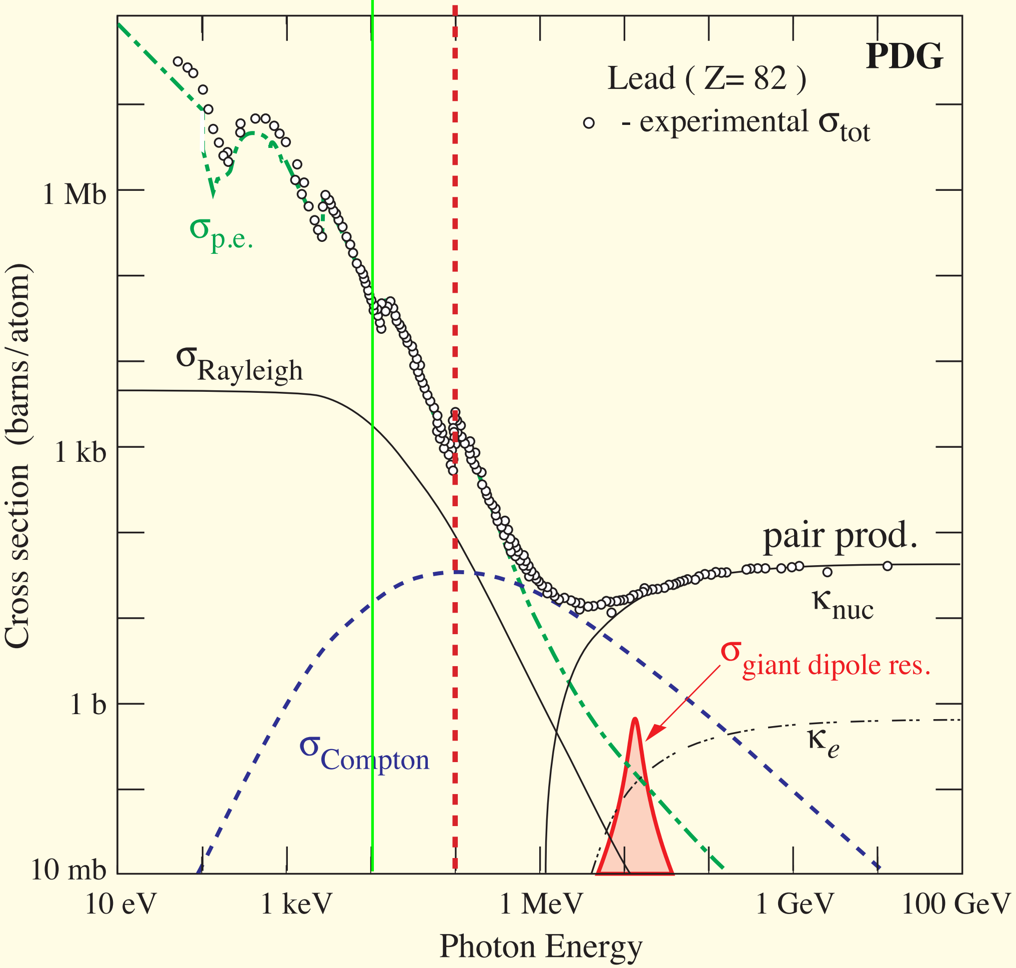
the aperture limiting primary and secondary collimators were in a separate straight section (LEP IR5)

Major challenge synchrotron radiation : Photon shielding

✔ < 10 keV

\> 100 keV very difficult

10 MeV significant neutron flux, giant dipole res.



Critical photon energies - bending magnets

SuperKEKB ~ 2 keV (LER)

FCC-hh ~ 5 keV

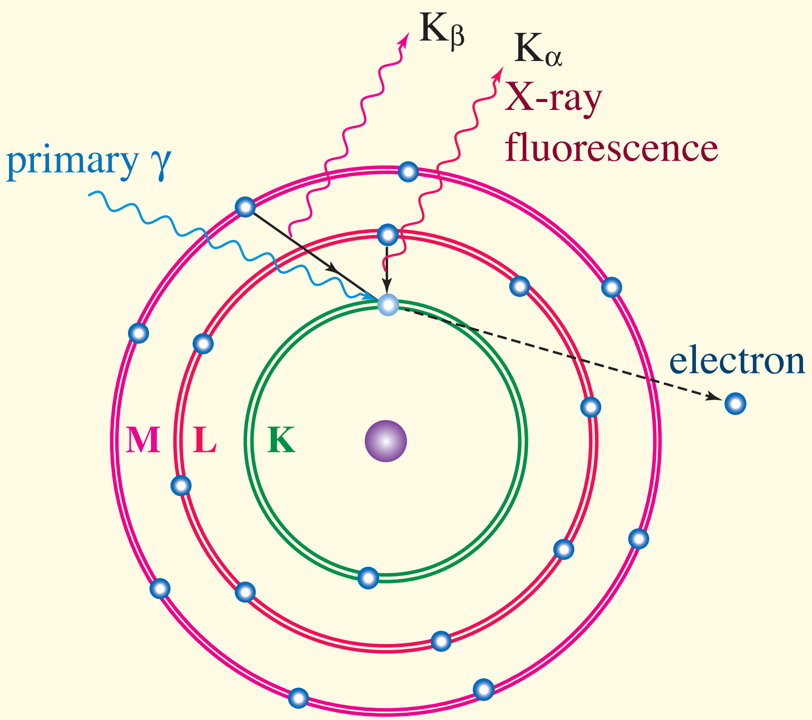
LEP1 : 69 keV

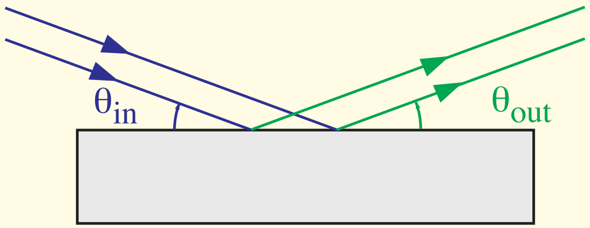
LEP2 : 725 keV (arc, last bend 10× lower)

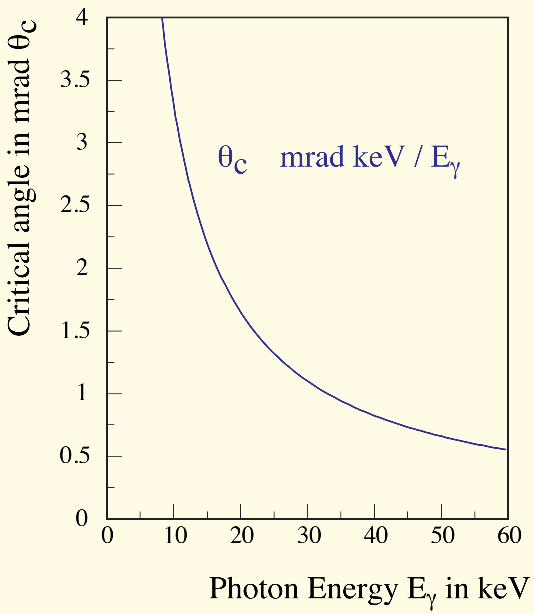
FCC-ee : 1.3 MeV (arc, 182.5 GeV)

important for LEP - and linear colliders :
SR from quadrupoles, dominated by non-Gaussian tails

X-Ray - Fluorescence and Specular Reflection







below below θc
nearly 100 %
very quickly dropping above

Make sure these are included in simulations

Fluorescence was expected and is well simulated with Geant,

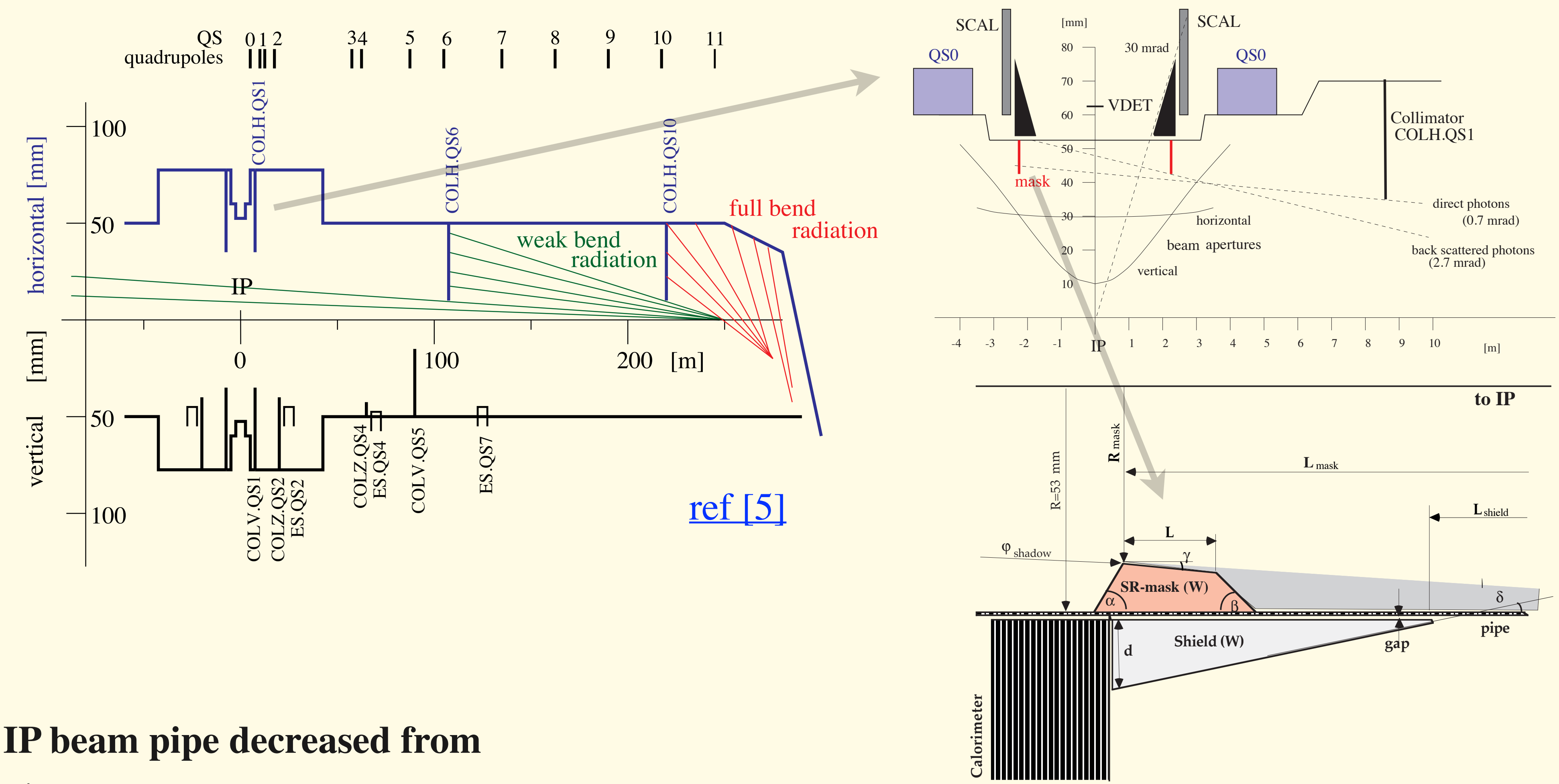
was mitigated for LEP absorbers by surface coating

Reflection in principle known from textbooks (less known for hard γ, depends on surface quality)

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

LEP IR by design minimizing SR backgrounds



ref [5]

IP beam pipe decreased from

Ø = 156 mm Al to 106 mm Be after 1y runnig

~ 100 movable collimators to reduce machine induced backgrounds

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

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

Experiments providing continuous background monitoring to LEP control room ref [3]

Evolution of key parameters, LEP1

Showing Fill 2420

one of our best

8+8 bunch (Pretzel)

fills from 9 October 1994

injection energy   22 GeV / beam

physics 45.6 GeV / beam

Luminosity

e+, e- currents

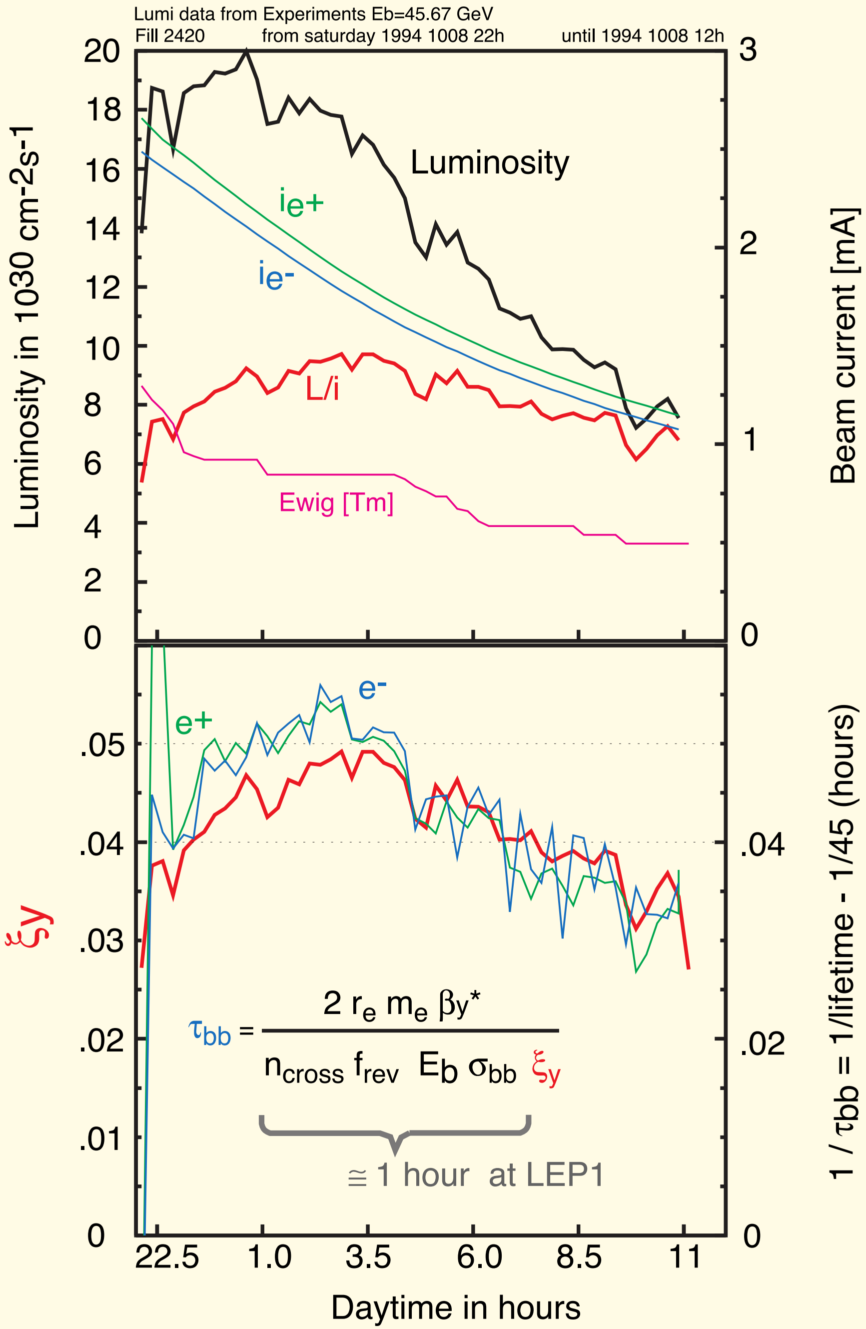
emittance wiggler strength (ε_x adjust)

ξ_y vertical beam-beam tune shift   ~ L / i

~ beam loss (inverse lifetime)

from *"burn-off"* by radiative Bhabha

(Beam-beam Bremsstrahlung)

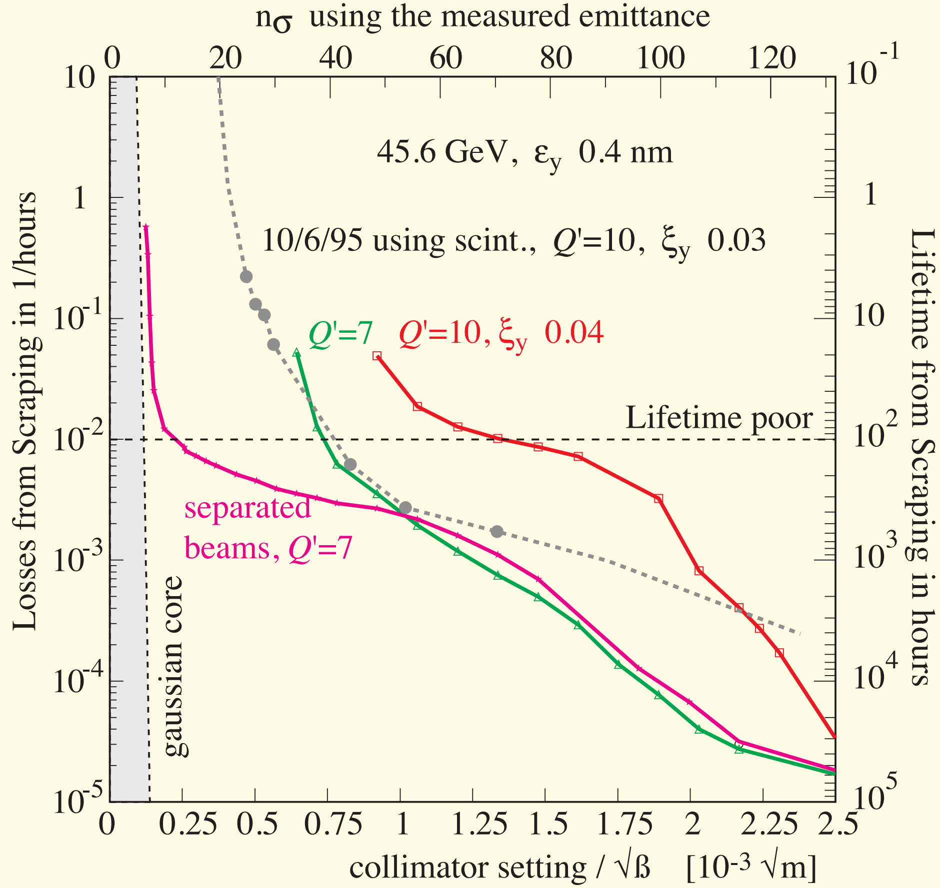


from my presentation / writeup for e+e- factories KEK 1999

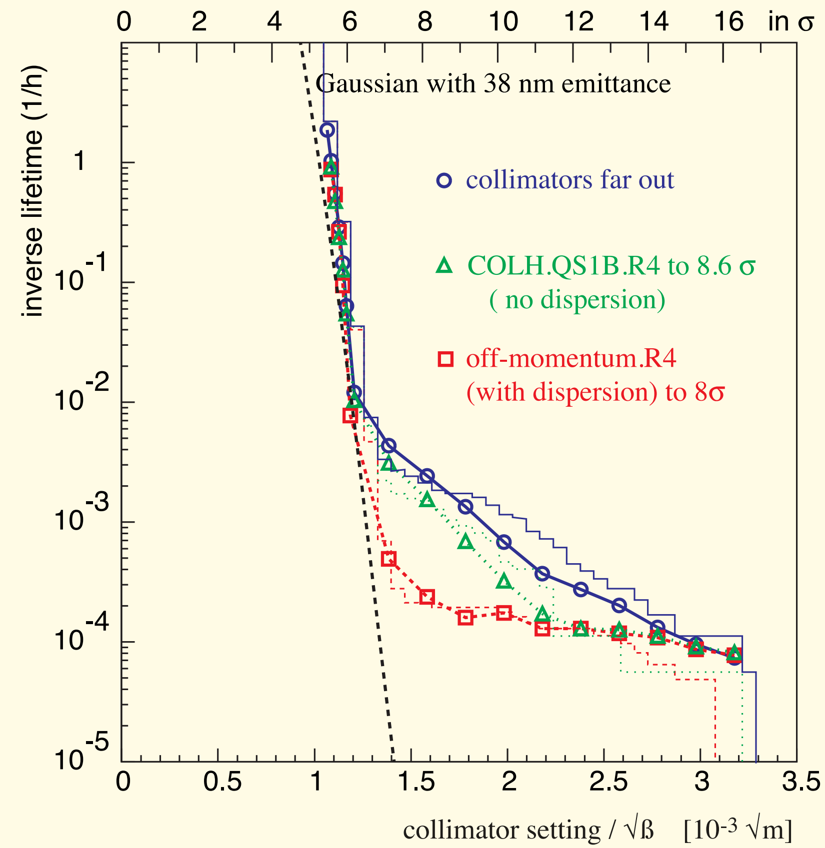
non-Gaussian tails, LEP

measured with loss monitors; scraping with aperture collimators

vertical plane, colliding beams



horizontal plane
reproduced by simulation

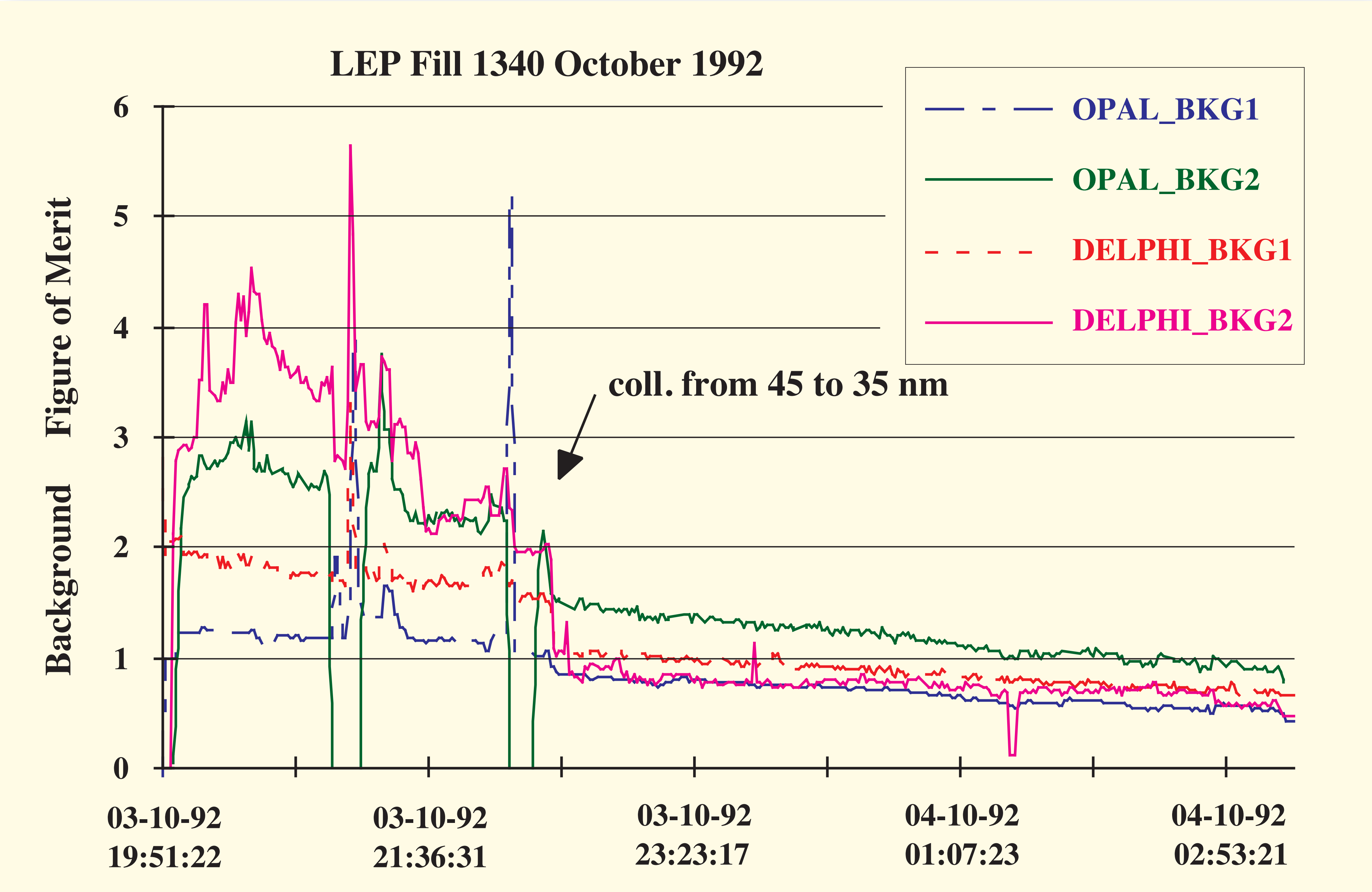


Tails from : beam-beam, high chromaticity, particle scattering

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." Ref [6]

LEP background observations



my selection of interesting **aspects we learned**

on the not so good side : (initially very poor) machine coupling by the nickel layer
poor stability (girder, concrete magnets), missing OP - software, lack of reliable monitoring
electrostatic separator sparking

wigglers important for injection, LEP1 controlled emittance increase — rather than coupling
correct frequently orbit (towards golden orbit), coupling, dispersion as best as you can
make sure that the collimators do not reduce the lifetime
LEP2 : major heating by SR - melting beampipes, BEUV mirrors, .. avoid steps/transitions

good side : superconducting RF - took a while to get ready, then working really well
higher energy - more damping - larger emittance helped a lot
beam-lifetimes better than predicted — vacuum improved a lot - backing out by SR
"total e+e-" cross section ~ 200 mb, not 300 mb as initially predicted
better than predicted quantum lifetime; no limitation from SR within beam scattering
generally excellent collaborative spirit from ~ all sides; lumi+background online from experiments
good support for machine studies + hardware & software improvements
small effects, initially not well known :
earth tides & rain changing circumferce, TGV - earth currents changing bending / LEP energy

Selected LEP references

[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] *Proposal for Background monitoring with ALEPH*, H.B., J.Rotherg, ALEPH 88-144, 1988

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

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

[6] *Beam Lifetime and Beam Tails in LEP*, H.B., SL-99-061-AP, Proc. e+e- Factories, 1999

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

[8] *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 remards

LEP experiments required low backgrounds

≪ **e+, e- / crossing, low SR photon flux** (≲ 100 / crossing , almost invisible in event displays)

which limited pushing up luminosities, particularly at LEP1

Beamstrahlung + muon backgrounds were negligible for LEP — important for linear colliders

Important to have a continuous, close experiment + machine collaboration

with background monitoring by the experiments + signal exchange

Even in a well (MDI) optimized IR with movable collimators + fixed masking

this can be expected to be essential to minimize synchrotron radiation + off momentum

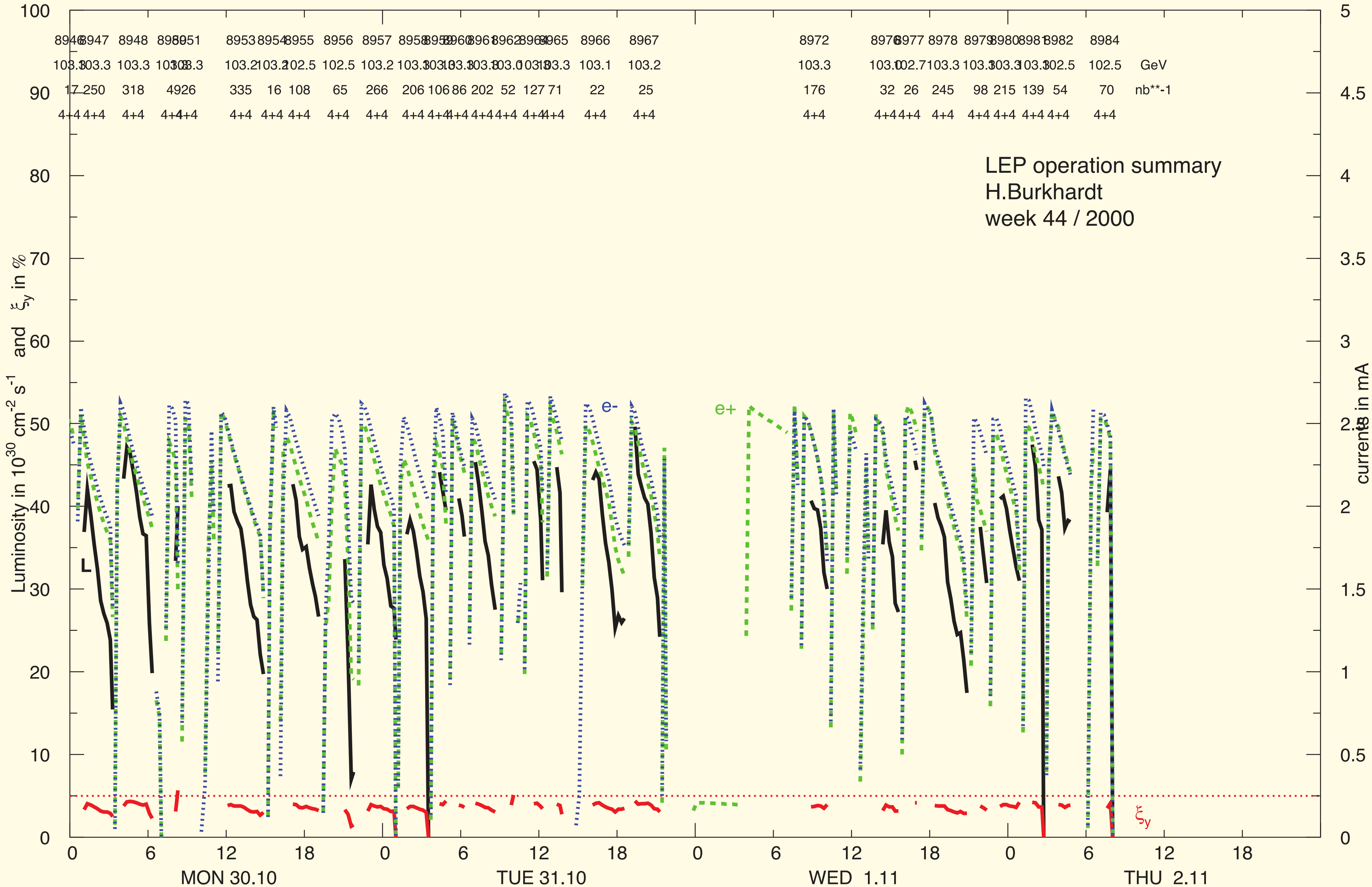
backgrounds and maximise the precision physics potential reachable with an e+e- collider

Backup

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



Evolution of key parameters, LEP2

LEP2 :

more SR and damping

larger horizontal emittance

no more need to increase emittance

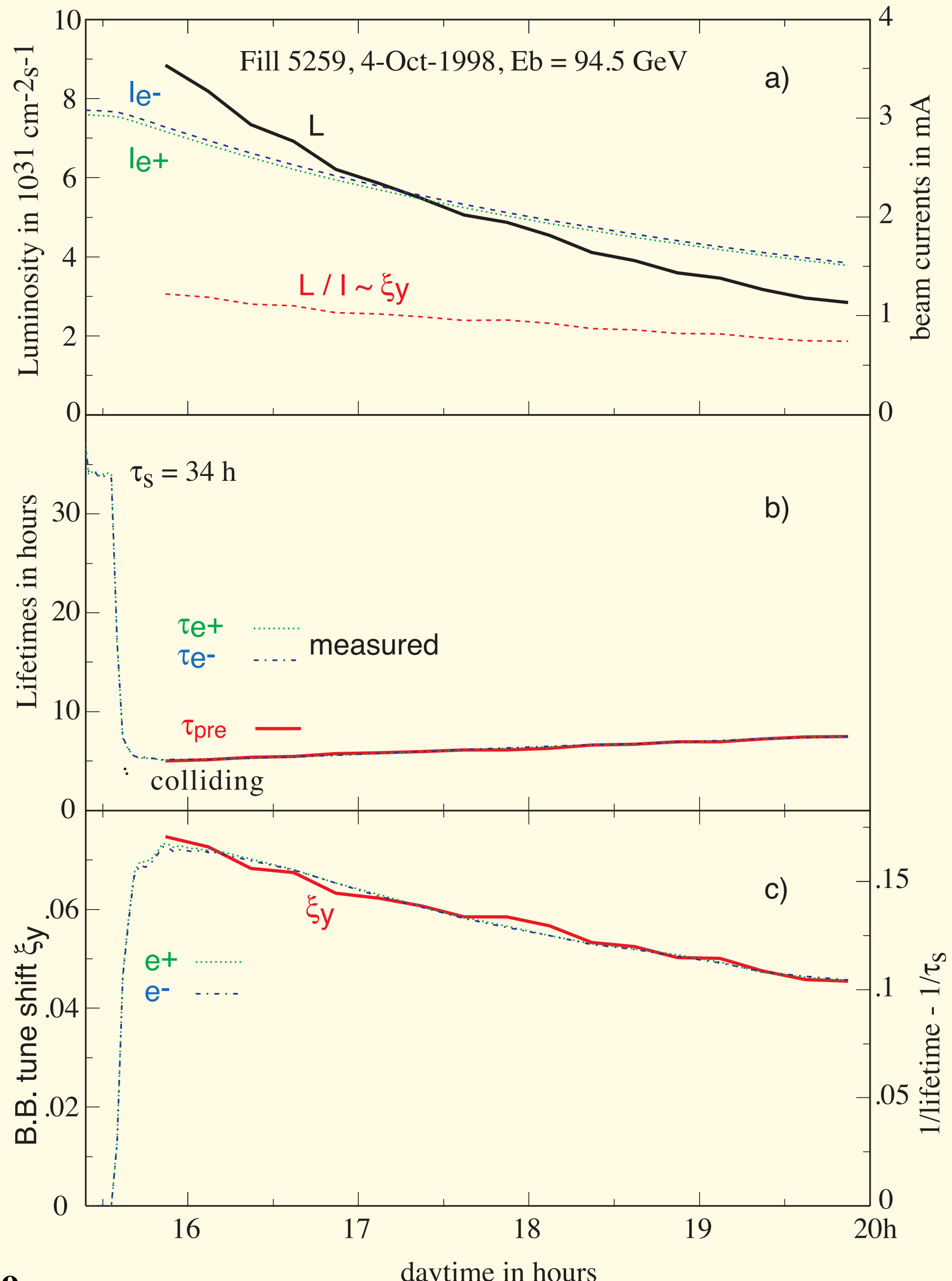
with wiggler

and ξ_y decreasing with current

emittance ratio

(coupling / dispersion limited)

and luminosity ~ 1 / current squared



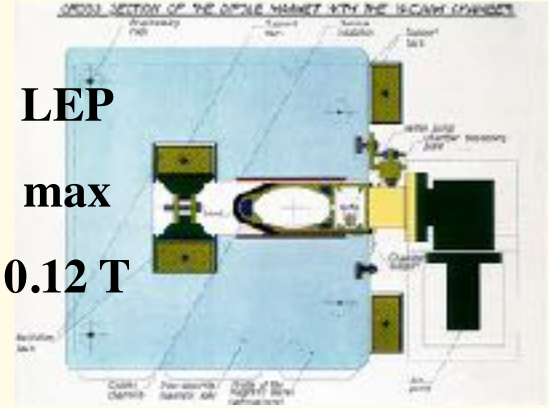
from my presentation / writeup for e+e- factories KEK 1999

Basic geometry, magnets

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

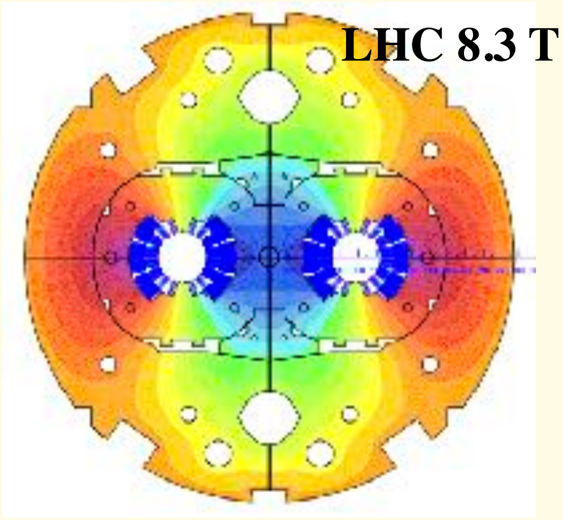
LEP as single ring, single beam pipe

LHC two pipes in twin magnets separated by 19.4 cm



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