Challenges on detectors operation in early running at FCC-ee

FCC-ee, focusing on the initial Z-running

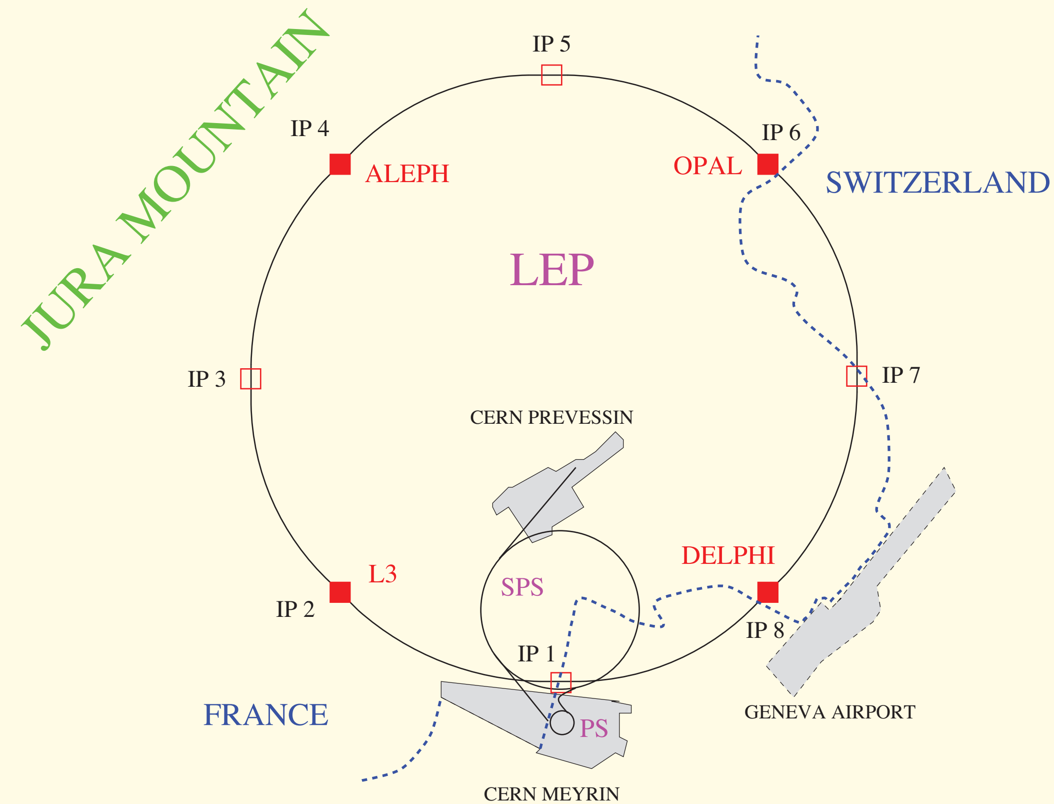
- comparison with known machines :
- parameters, challenges
- startup
- layout and losses in the interaction regions

to see what we may expect in early running
and what could help for safe + efficient early operation

Key Parameters, compared

in many respects within factor 3 or pretty close to LEP

L = 26.659 km **× 3**
Max SR Power 18 MW **× 2.8**
Max RF Voltage 3.7 MV **× 2.6**
Lumi / bunch 2.8e30 cm^{-2}s^{-1} **× 4**
Ecms 92 — 209 GeV **× 1.8**
Intens 4×10^{11} e+, e- / bunch × 0.5



+ challenges of LHC

#bunches 2800 —> **11200**, similar spacing

energy stored in beam 400 MJ —> **30 MJ** showers more concentrated

#particles stored /beam 4.e14 —> **4e15** ×10

~ 10 shorter lifetime, FCC-ee losing **~ 100 ×** more beam particles / second

+ very tight interaction region similar to SuperKEKB

LEP :

1988 octant test, essential to identify magnetization / coupling issue

1989 pilot run, proven technology - without superconducting magnets/RF

1990 first year larger beam pipe

LHC : many steps, increasing beam-power

initially no crossing angle

not possible in FCC-ee

from Ref [3]

Event	E_b TeV	β^* m	n_b	$N_{1,2}$	$E_{\rm tot}$ MJ	n_c	L $\rm cm^{-2}s^{-1}$	Date
1	3.5	10	2	1×10^{10}	0.01	1	8.9×10^{26}	30/03/2010
2	3.5	10	2	$\mathbf{2 \times 10^{10}}$	0.02	1	3.6×10^{27}	02/03/2010
3	3.5	**2**	2	2×10^{10}	0.02	1	1.8×10^{28}	10/04/2010
4	3.5	2	**4**	2×10^{10}	0.05	2	3.6×10^{28}	19/04/2010
5	3.5	2	**6**	2×10^{10}	0.07	4	7.1×10^{28}	15/05/2010
6	3.5	2	**13**	2.6×10^{10}	0.19	8	2.4×10^{29}	22/05/2010
7	3.5	**3.5**	**3**	$\mathbf{1.1 \times 10^{11}}$	0.19	2	6.1×10^{29}	26/06/2010
8	3.5	3.5	**6**	1.0×10^{11}	0.34	4	1.0×10^{30}	02/07/2010
9	3.5	3.5	**8**	9.0×10^{10}	0.41	6	1.2×10^{30}	12/07/2010
10	3.5	3.5	**13**	9.0×10^{10}	0.66	8	1.6×10^{30}	15/07/2010
11	3.5	3.5	**25**	1.0×10^{11}	1.41	16	4.1×10^{30}	30/07/2010
12	3.5	3.5	**48**	1.0×10^{11}	2.71	36	9.1×10^{30}	14/08/2010

with crossing angle

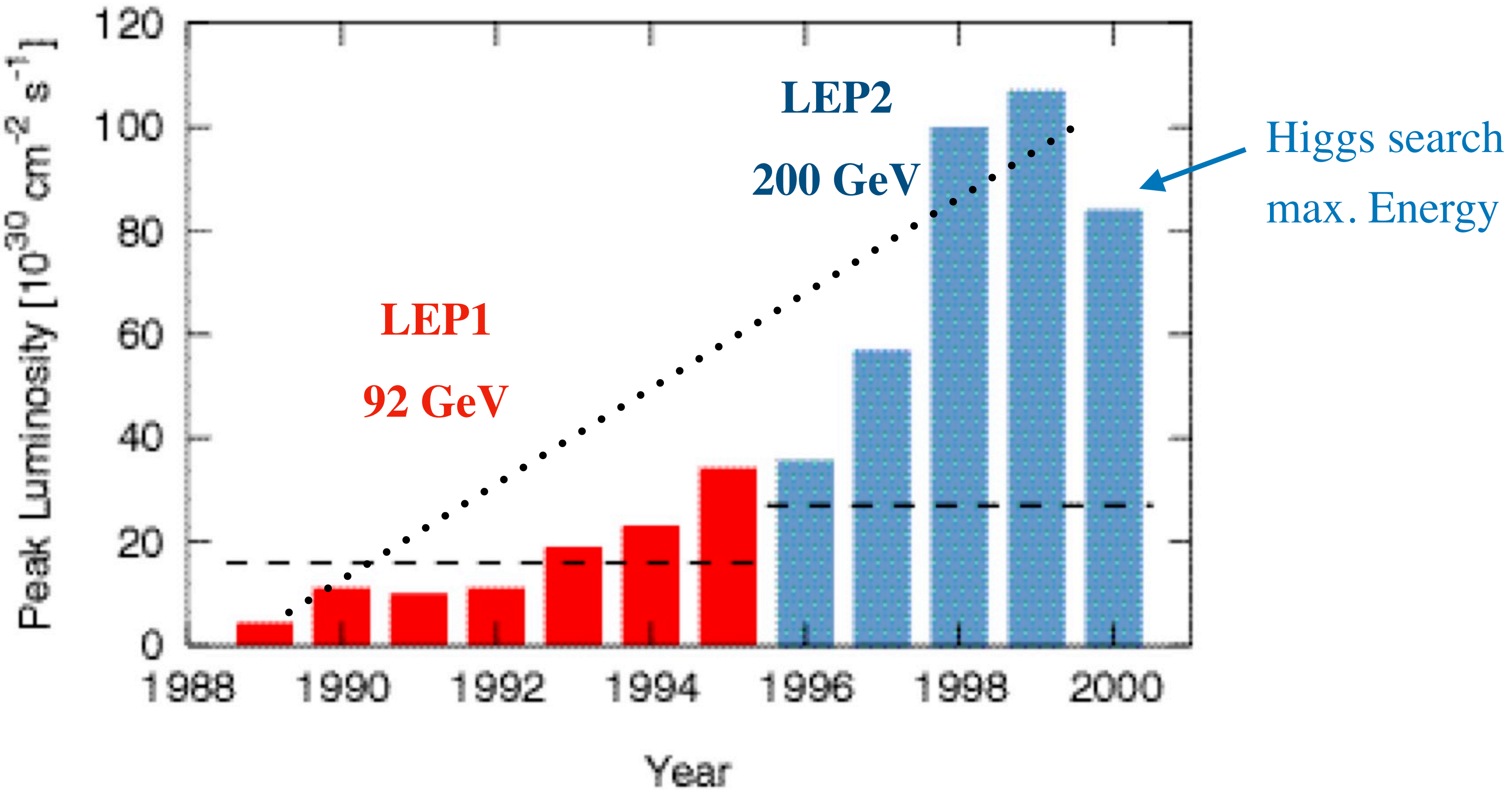
n_b	$N_{1,2}$	$E_{\rm tot}$ MJ	n_c	L $\rm cm^{-2}s^{-1}$	Pile up	Date
56	1.10×10^{11}	3.5	47	2.0×10^{31}	1.91	30/03/2010
104	1.10×10^{11}	6.5	93	3.5×10^{31}	1.80	25/09/2010
152	1.10×10^{11}	9.4	140	5.0×10^{31}	1.76	29/09/2010
204	1.10×10^{11}	12.7	186	7.0×10^{31}	1.83	04/10/2010
248	1.10×10^{11}	15.4	233	1.03×10^{32}	2.22	14/10/2010
312	1.10×10^{11}	19.4	295	1.50×10^{32}	2.57	16/10/2010
368	1.15×10^{11}	23.9	348	2.05×10^{32}	2.97	25/10/2010

design luminosity

1.e34 cm-2s-1 June 2016

doubled in 2017

LEP Peak performance



Performance increases steadily over many years, flat beams,

importance of tuning/correctiong coupling, dispersion

different from pp machines with round beams, where 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

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

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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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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**

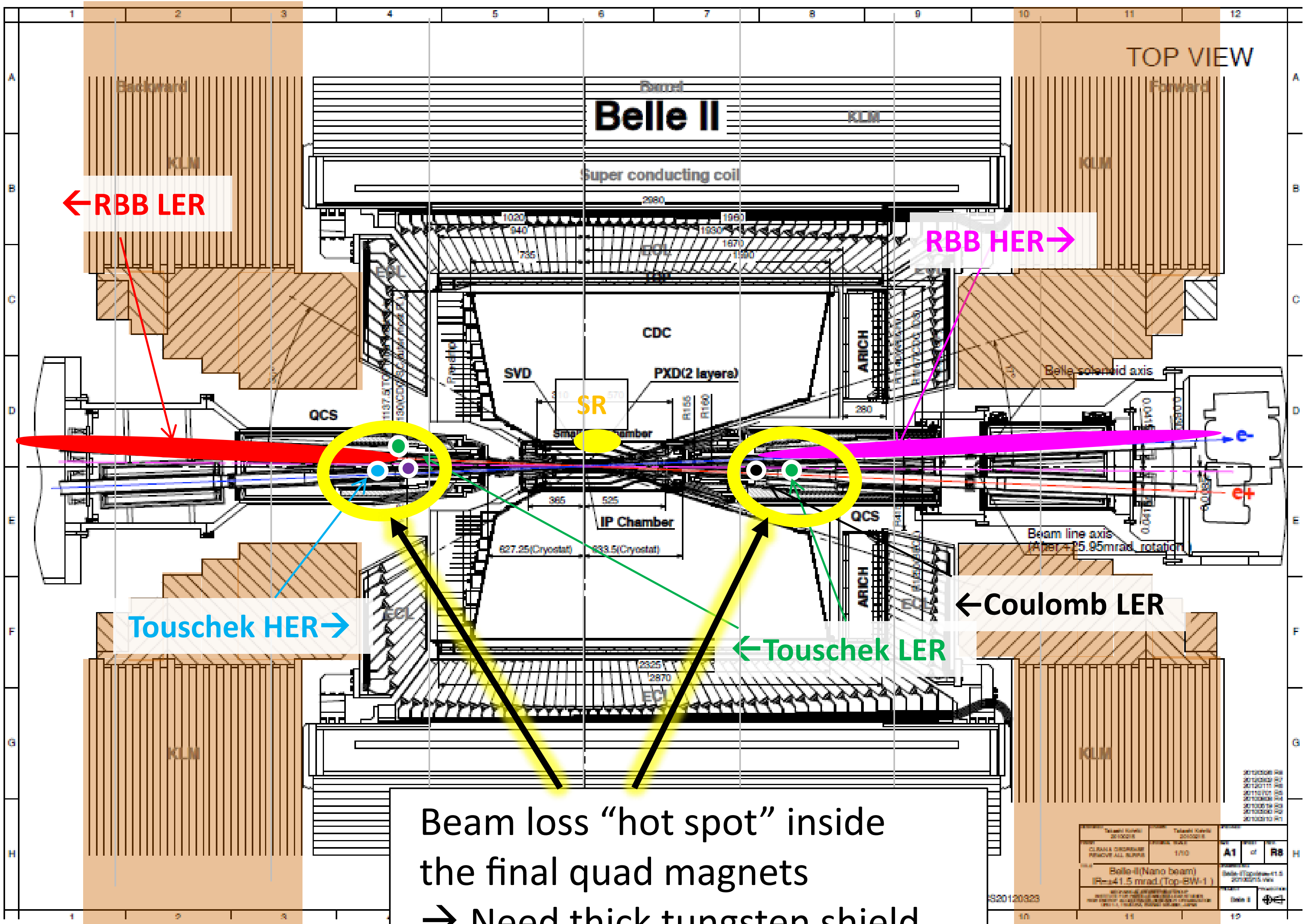
Requiring continuous efforts and follow up

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

As a result : LEP2 backgrounds comparable to LEP1

SuperKEKB, Belle II



Beam loss "hot spot" inside the final quad magnets
→ Need thick tungsten shield

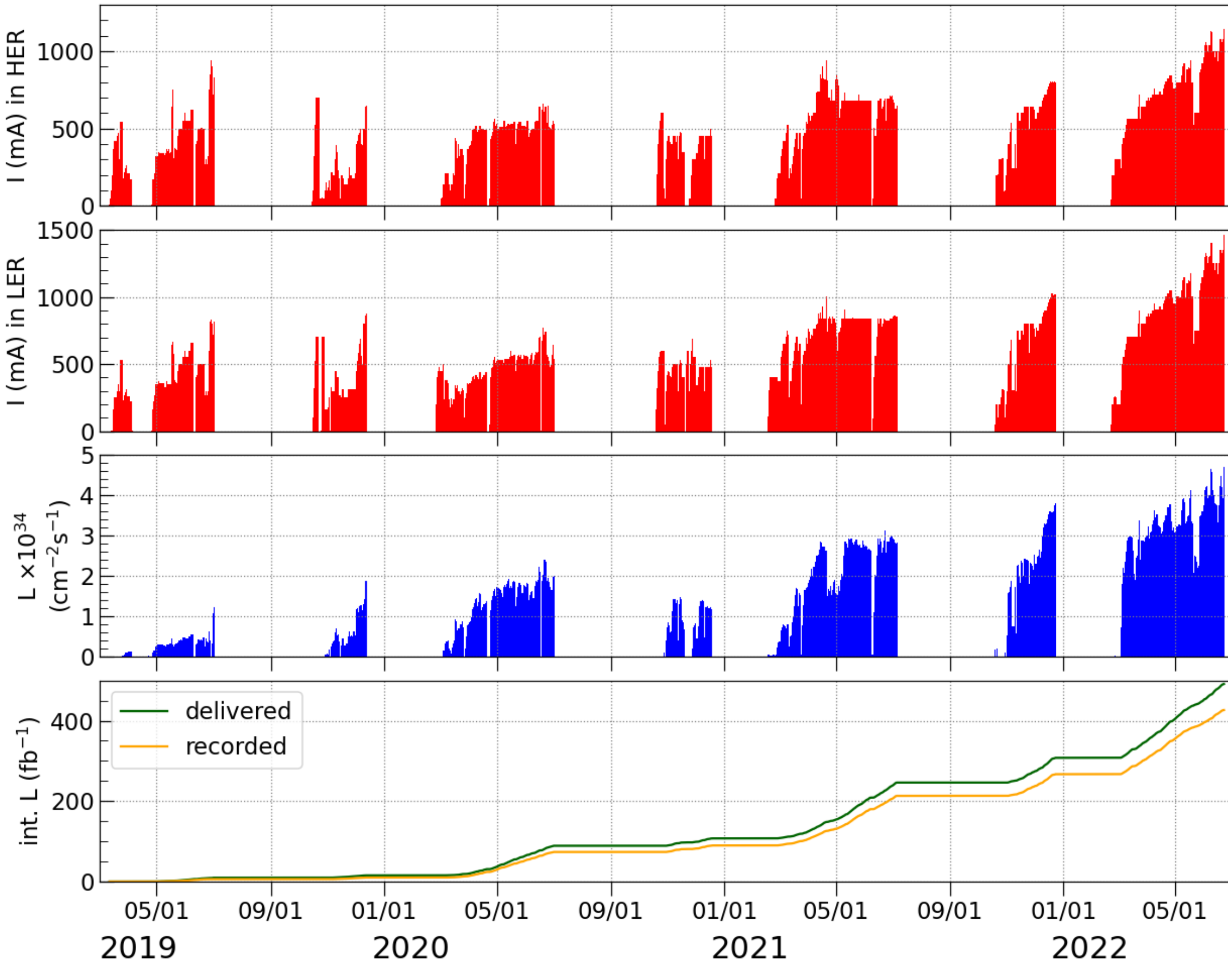
Hiroyuki Nakayama @ Oct. 2023 International Circular Collider "CEPC" workshop

SuperKEKB performance

2018 first collisions

2020 world record in e+e- luminosity 2.22×10^{34} cm^{-2}s^{-1}

Target Luminosity of 6.5×10^{35} cm^{-2}s^{-1}



LHC

LHC   rather different the major source of radiation in the IR are the pp-collisions produced at the IP + contribution from halo collimation + local beam gas

major ingredients of going from LHC to High Lumi LHC :

lighter beam-pipe + Al2219 support structures at IR

new much larger aperture final focus quadrupoles

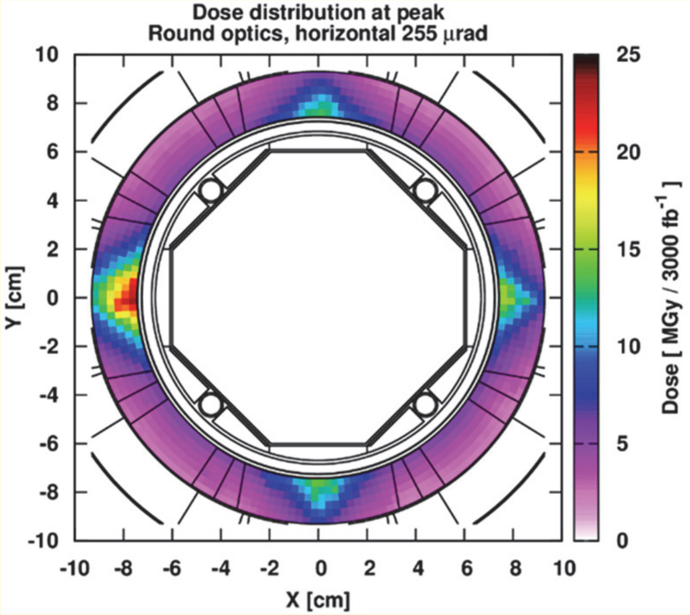
inner diameter 70 mm → 150 mm

final focus quadrupoles starting 23 m from the IP

behind a 1.8 m thick Cu - absorber

with reinforced tungsten alloy shielding in beam screens

16 mm thick in first quad, then 6 mm



Energy Deposition and Radiation
F. Cerutti et al. High Lumi LHC book, 2nd Ed.

Still surprises

ALICE background issue in LHC PbPb operation end of 2023

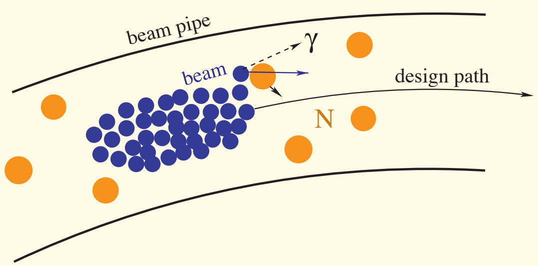
Main source halo hitting the vertical collimator TCTPV.4L2.B1 at 117 m in front of ALICE

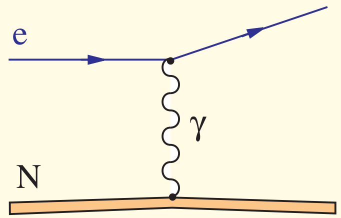
Pb208 ions losing one neutron Pb207 appearing as 0.5 % off-momentum particle

2024 IR1 crossing polarity + optics changes doubling of forward muon backgrounds

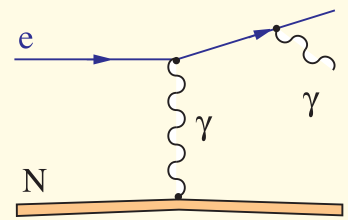
Off momentum tails, primary / secondary collimator hierarchy compromised

single beam sources of e+, e- losses

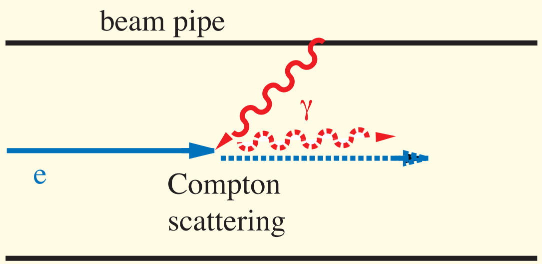




e-N elastic, Coulomb



e-N inelastic, Bremsstrahlung

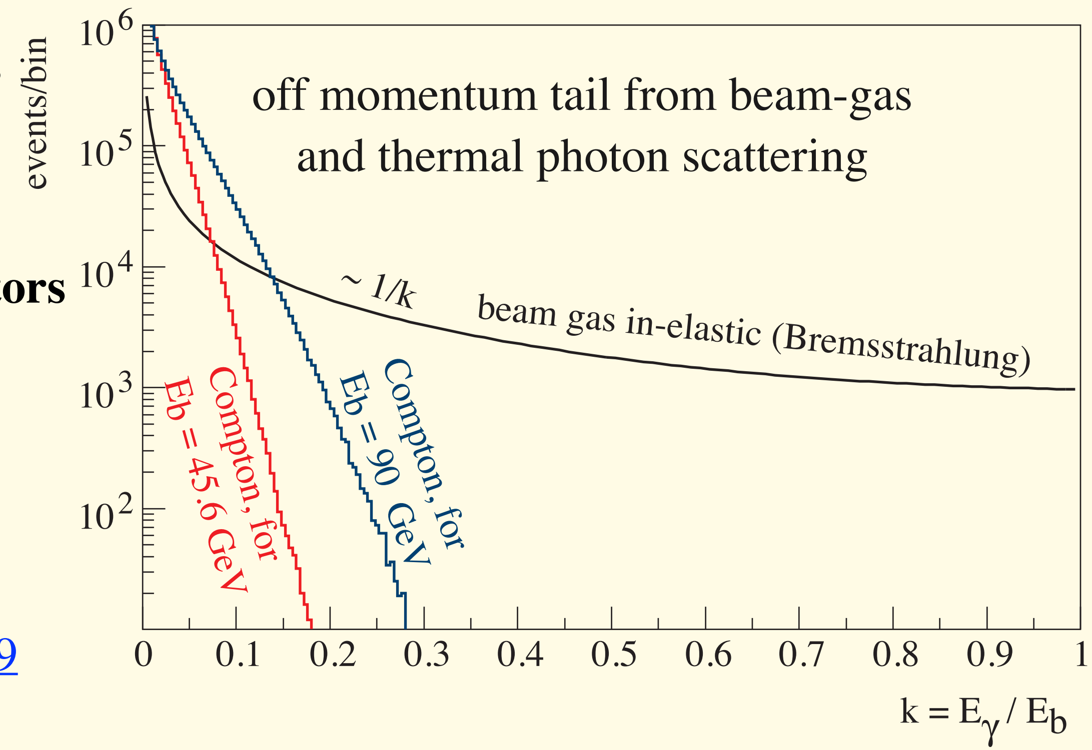


elastic scattering very small at FCC energies

inelastic beam-gas and thermal photon

generating broad off-momentum tails

well visible at LEP in low angle (lumi) detectors



first estimates have been per performed

for FCC

Francesco Collamati 2018 beam gas

Thermal photon H.B. FCC-week Brussels 2019

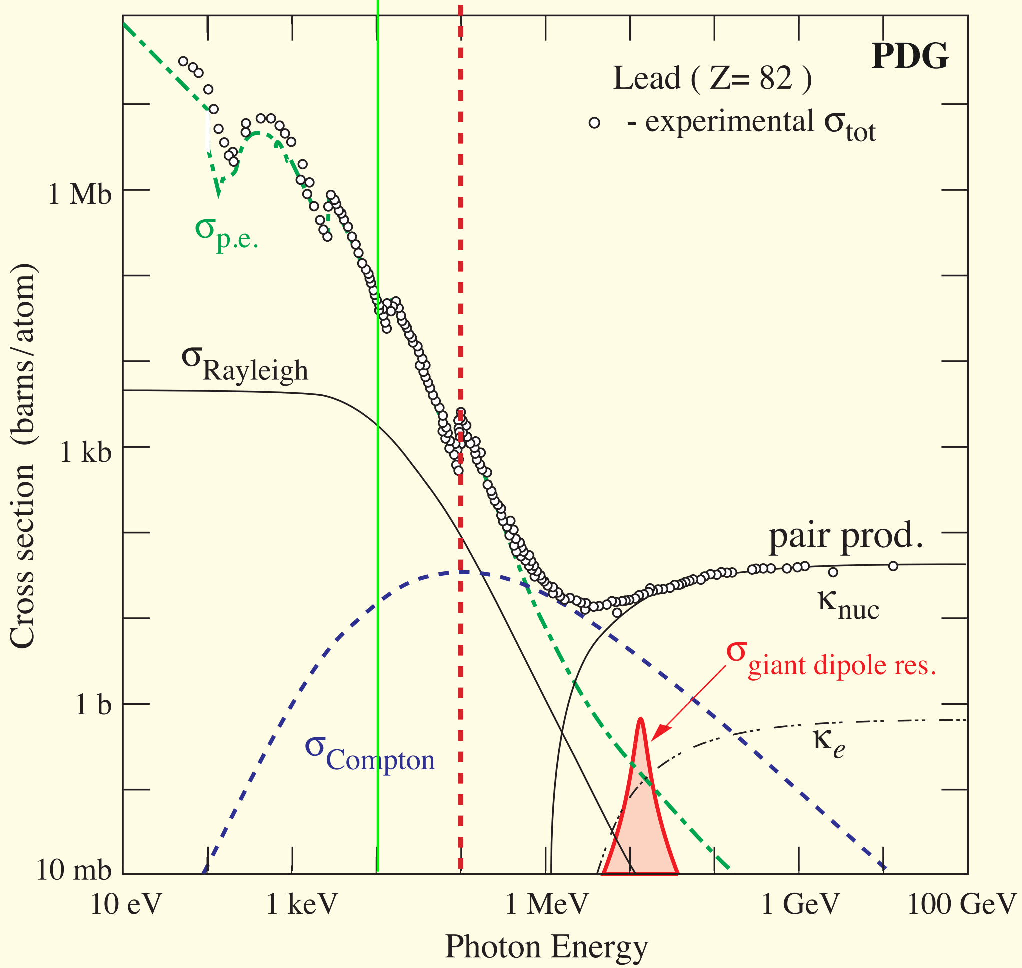
updates planned / in progress

Major FCC-ee challenge : 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

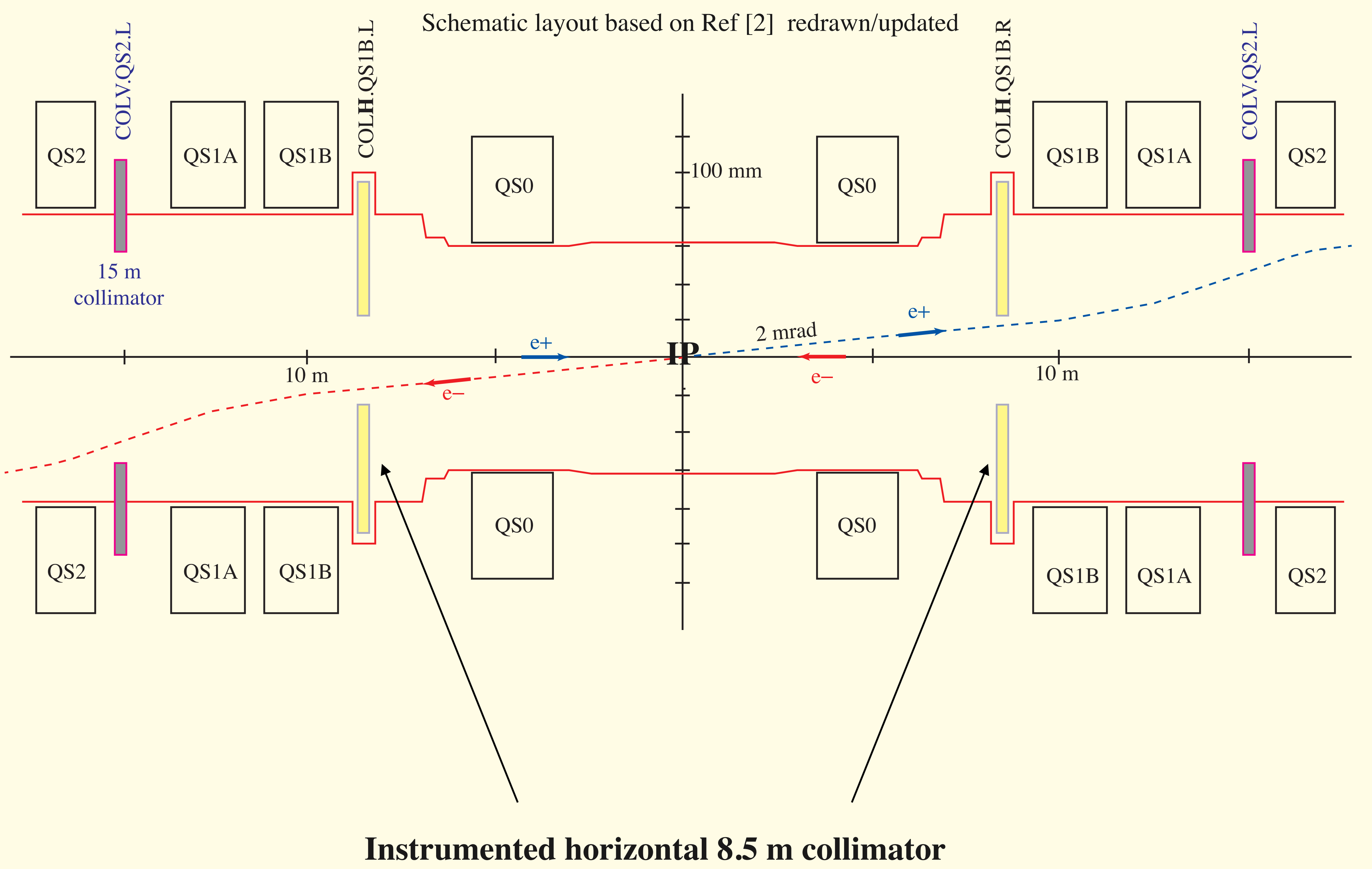
LEP1 : 69 keV

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

HERA upgrade : ~ 100 keV C.Niehbuhr / CERN-2009-003

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

LEP machine low angle Bhabha monitor, layout



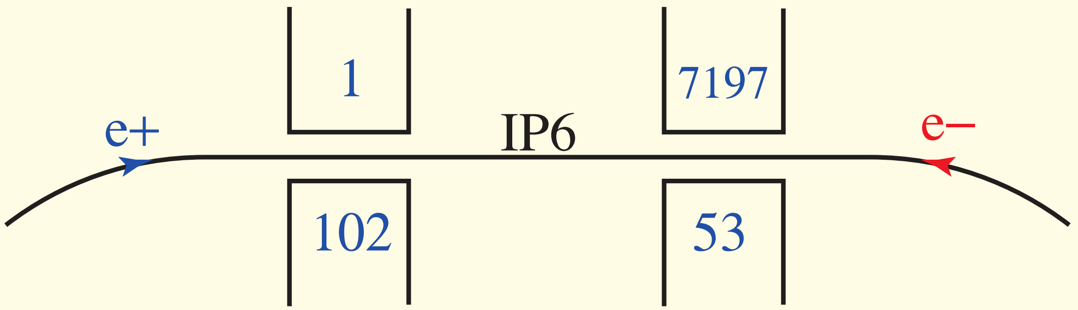
Off-momentum backgrounds at small angle

Studied in detail in 1993
Eb = 45.6 GeV, G05P46MT optics

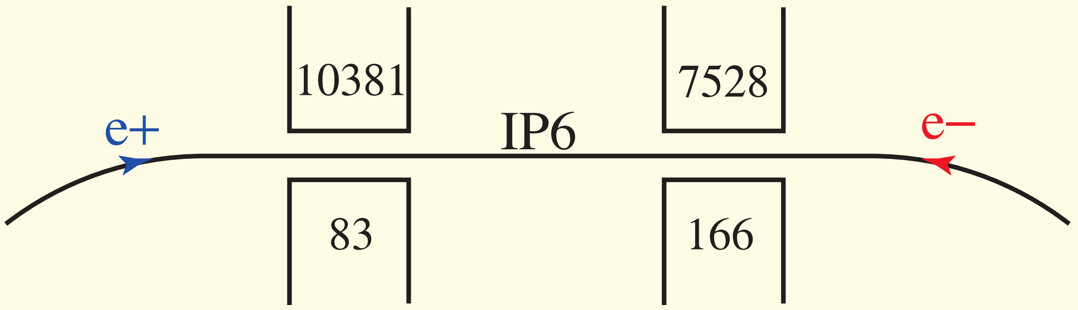
thermal photon simulation Ref 3

Rates [Hz] / beam current [mA]

prediction
single beam, thermal photon scattering
detectors at ± 32 mm
or ~ 15 nominal σ, < E > = 43 GeV
mainly hitting outside downstream IP



example **measured**
both beams
detectors at ± 30 mm



~ few % off-momentum particles typically dominate losses around IR
generated by thermal photon scattered beam particles, beam-gas and collisions

MD study, vs collimator settings

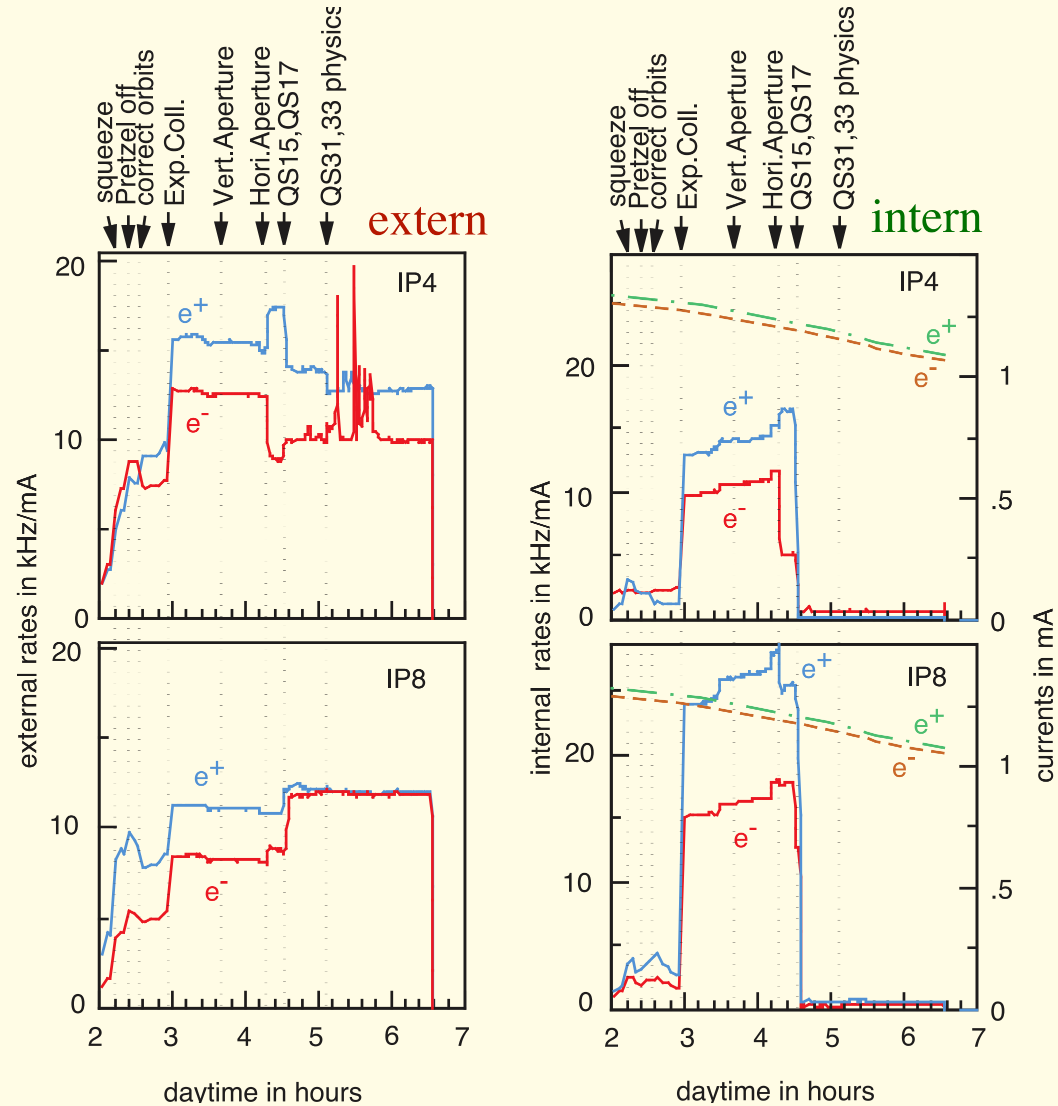
Details in MD-notes 107, 111 Ref 4-5 performed in 1993

main conclusion :

backgrounds from IR losses at small angles well reproduced by simulations simulations

internal rates can be strongly reduced by collimation
external not without reduction of aperture

aperture collimators important but not sufficient to eliminate off-momentum from last arc's

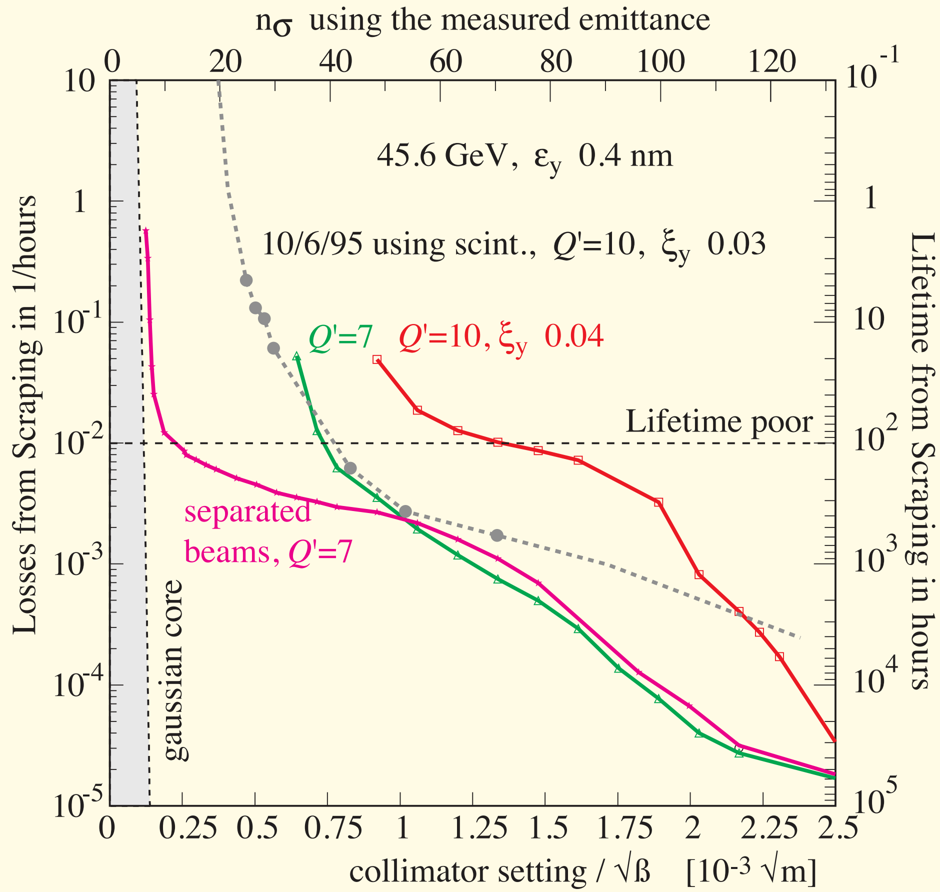


following theses studies much improved in later LEP operation by extra off-momentum QD20 collimators around each IP

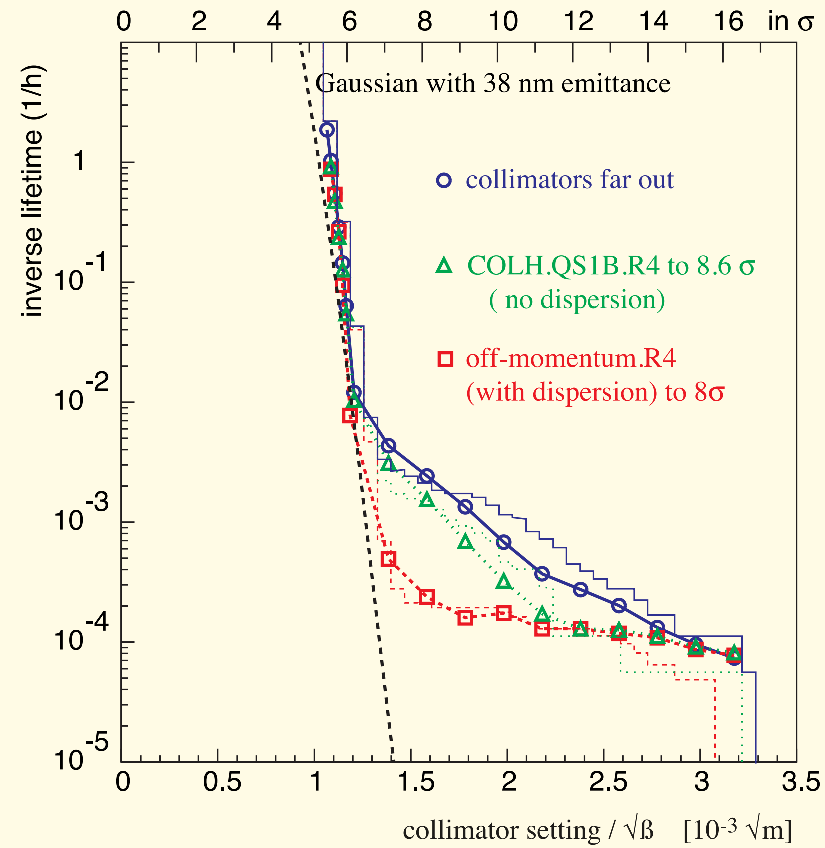
non-Gaussian tails, LEP

measured with loss monitors; scraping with aperture collimators

vertical plane, colliding beams



horizontal plane
reproduced by simulation

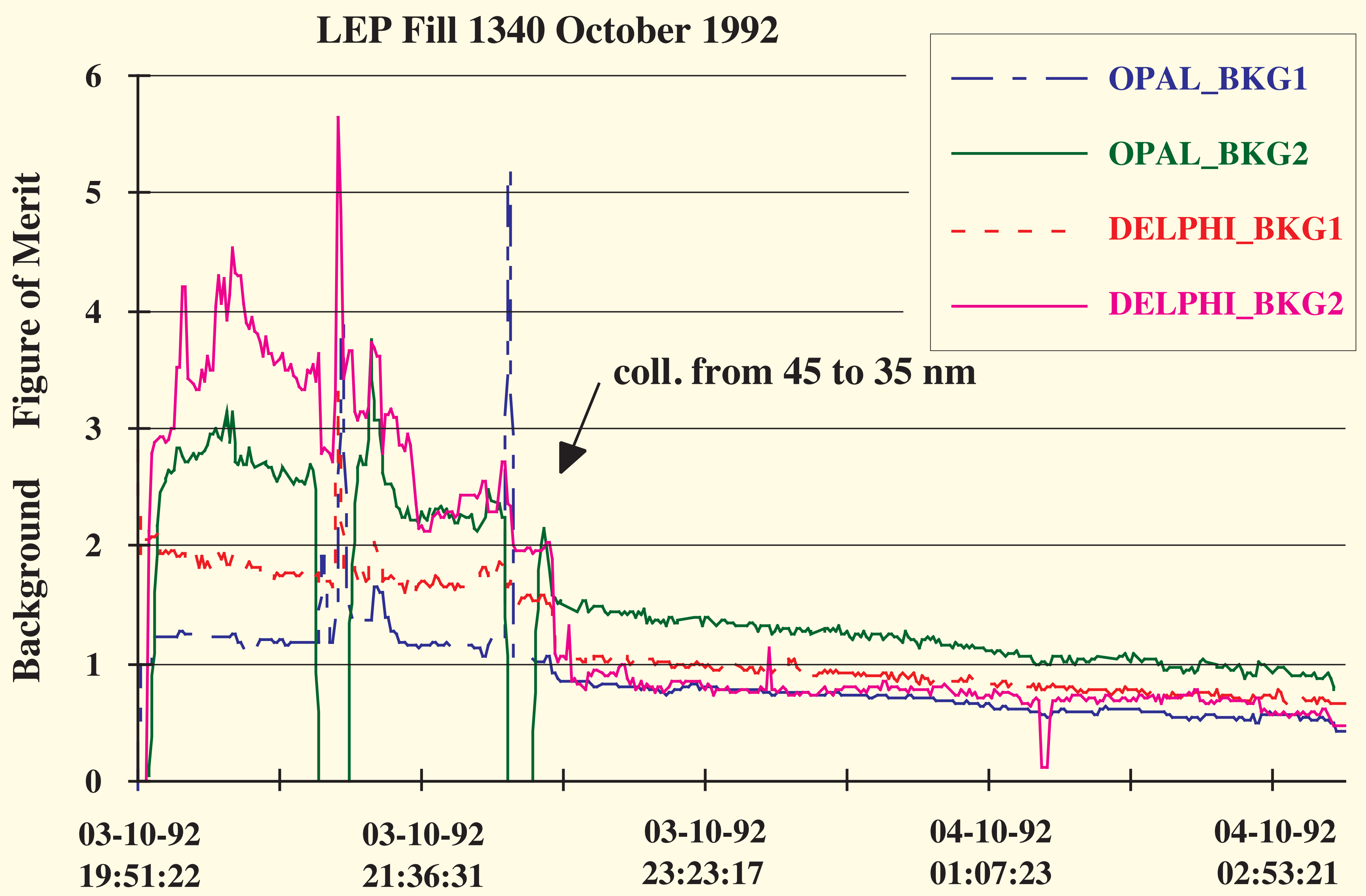


Tails from : beam-beam, high chromaticity, particle scattering

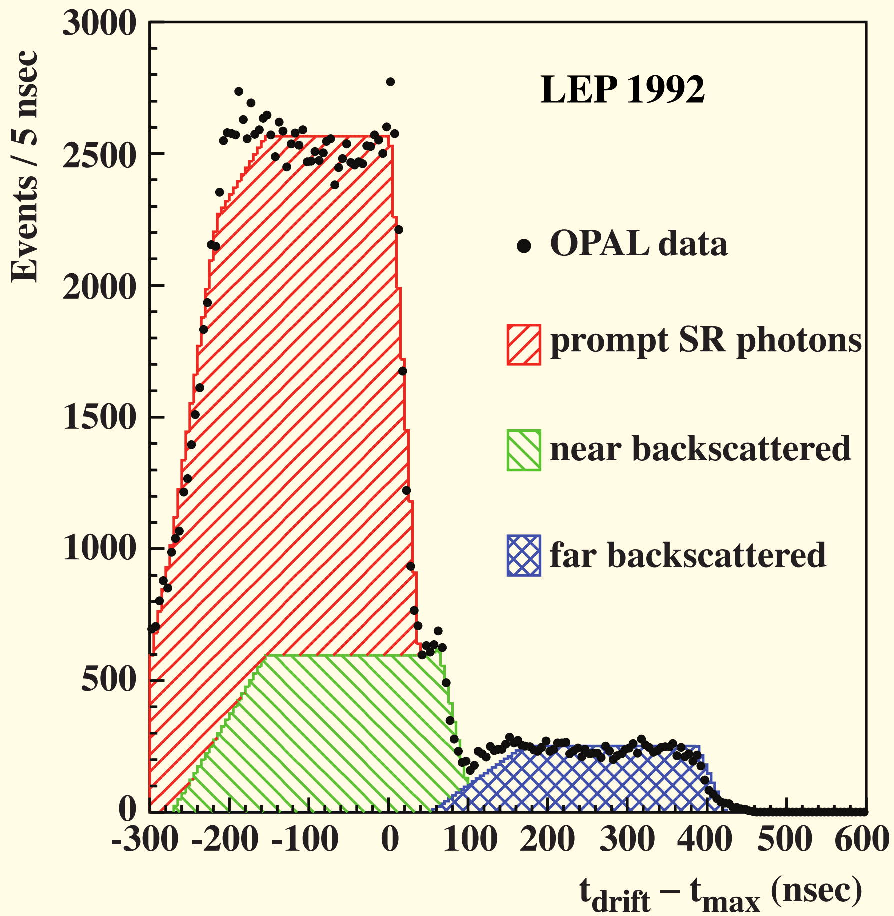
Background spikes, enhanced synchrotron radiation from quadruples

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." CERN-SL-99-061-AP

LEP background observations



LEP example, importance of timing information



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

Beam pipe radius at IP

complex subject

- small radius makes operation/background/commissioning time more difficult
- beam-cone/optics relevant in energy e+,e-   off momentum / photons   different
- has to work for any mode — commissioning, injection, steering, squeezing
- depends on limits of parameters hard to quantify non-gaussian tails, stability, tolerances

LEP, LHC started with larger pipes, decreased later

LEP/ALEPH 78 mm Al —> 53 mm Be after 1y

CMS   29 mm   —> 21.7 mm LS1

FCC-ee   10 mm   very challenging

Selected references

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

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

[3] *The Large Hadron Collider LHC*, O. Brüning, H.B., S.Myers, PPNP 67, 2012

[4] *The High Luminosiy Large Hadron Collider,* O. Brüning et al. World Scientific 2nd Edition 2024

ideas related to vertex detectors — for discussion

LEP+LHC in many respects within factor 3 of FCC-ee

both got beyond design luminosity within few years

FCC-ee Z much more dynamic and less reproducible than LHC

IR region very tight — kind of ultimate

Prepare for changes and stepwise approach

beam pipe radius — start larger, insert innermost layers later

also useful later when going to Higgs, top operation

built in beam-condition monitoring, safe mode(s) ?

alignment, possible IP offsets

Challenges / experience

Single beam backgrounds + SR in collisions (beamstrahlung) **backgrounds will certainly be there and can be simulated with some confidence**

Experience :

real life backgrounds are often much higher than the unavoidable/predicted backgrounds

seen in LEP and in particular LEP1, issue for the HERA upgrade,

LHC RUN1 Alice

Collimation of backgrounds close to IP essential — as last line of defence

Shielding not always helping (PETRA/TASSO Sn shield), going to lighter LHC structures

Minimize background production - minimal bending before IP, excellent vacuum

Continuous monitoring / study / analysis of backgrounds essential in close collaboration machine + experiments

FCC-ee Parameter table

FCC-ee collider parameters for the GHC lattice as of May 29, 2024. Katsunobu Oide

Beam energy	[GeV]	45.6	80	120	182.5
Layout		PA31-3.0			
# of IPs		4			
Circumference	[km]	90.658728			
Bend. radius of arc dipole	[km]	10.021			
Energy loss / turn	[GeV]	0.0390	0.369	1.86	9.94
SR power / beam	[MW]	50			
Beam current	[mA]	1283	135	26.8	5.0
Colliding bunches / beam		11200	1852	300	64
Colliding bunch population	[10^{11}]	2.16	1.38	1.69	1.48
Hor. emittance at collision ε_x	[nm]	0.70	2.16	0.66	1.51
Ver. emittance at collision ε_y	[pm]	1.9	2.0	1.0	1.36
Lattice ver. emittance $\varepsilon_{y,\text{lattice}}$	[pm]	0.87	1.20	0.57	0.94
Arc cell		Long 90/90		90/90	
Momentum compaction α_p	[10^{-6}]	29.2nx		7.52	
Arc sext families		75		146	
$\beta^*_{x/y}$	[mm]	110 / 0.7	220 / 1	240 / 1	900 / 1.4
Transverse tunes $Q_{x/y}$		218.158 / 222.220	218.185 / 222.220	398.150 / 398.220	398.148 / 398.215
Chromaticities $Q'_{x/y}$		0 / +5	0 / +5	0 / 0	0 / 0
Energy spread (SR/BS) σ_δ	[%]	0.039 / 0.110	0.069 / 0.105	0.102 / 0.176	0.152 / 0.184
Bunch length (SR/BS) σ_z	[mm]	5.57 / 15.6	3.46 / 5.28	3.26 / 5.59	1.91 / 2.32
RF voltage 400/800 MHz	[GV]	0.079 / 0	1.00 / 0	2.09 / 0	2.1 / 9.20
Harm. number for 400 MHz		121200			
RF frequency (400 MHz)	MHz	400.787129			
Synchrotron tune Q_s		0.0289	0.0809	0.0334	0.0881
Long. damping time	[turns]	1171	218	65.4	19.4
RF acceptance	[%]	1.06	3.32	2.06	3.06
Energy acceptance (DA)	[%]	±1.0	±1.0	±1.9	-2.8/+2.5
Beam crossing angle at IP θ_x	[mrad]	±15			
Crab waist ratio	[%]	70	55	50	40
Beam-beam ξ_x/ξ_y [a]		0.0022 / 0.0977	0.013 / 0.129	0.0108 / 0.130	0.065 / 0.136
Piwinski angle $(\theta_x \sigma_{z,\text{BS}})/\sigma^*_x$		26.6	3.6	6.6	0.94
Lifetime (q + BS + lattice)	[sec]	11800	4500	6000	7700
Lifetime (lum) [b]	[sec]	1330	960	600	670
Luminosity / IP	[10^{34}/cm^{2}s]	143	20	7.5	1.38

[a] incl. hourglass.
[b] only the energy acceptance is taken into account for the cross section, no beam size effect.

3