Fast luminosity monitor for FCC-ee based on the LEP experience

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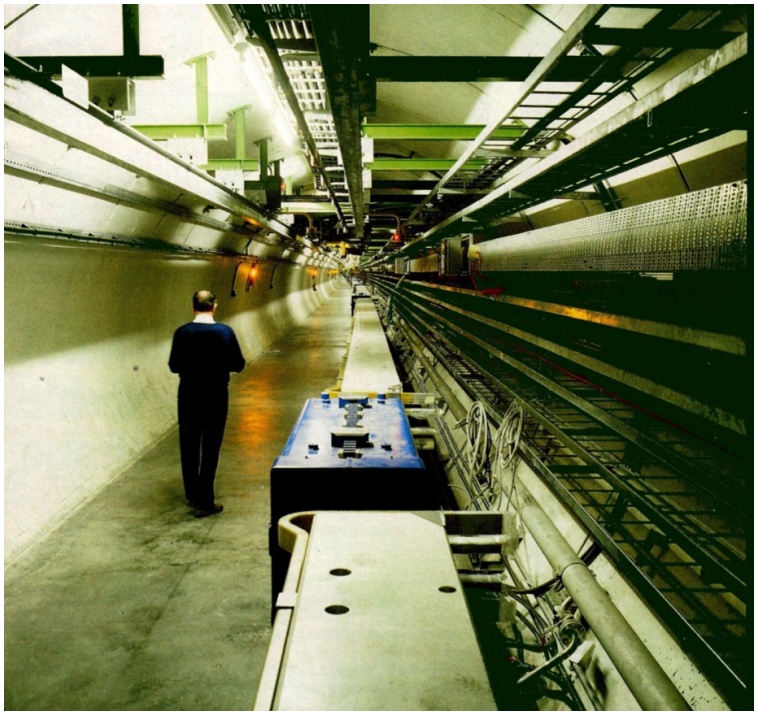

65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e+e- Colliders (eeFACT2022), 13 September 2022, INFN-LNF

FCCee parameters

FCC

FCC-ee Parameters

K. Oide, D. Shatilov

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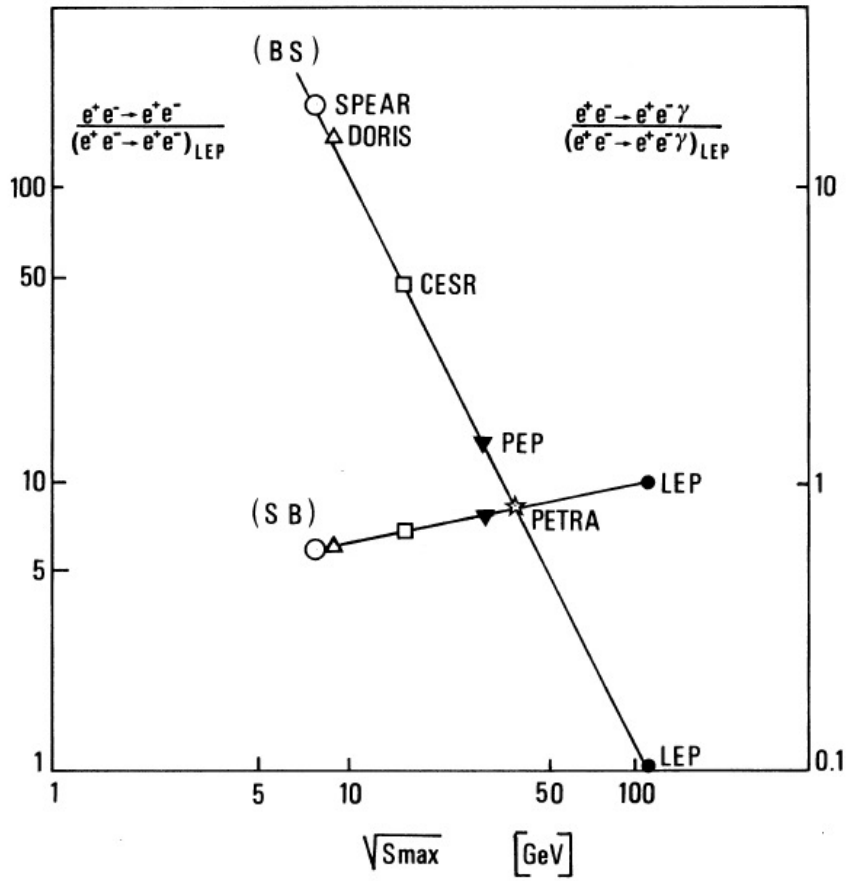
Parameter [4 IPs, 91.1 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	40
bunch intensity [10^{11}]	2.43	2.91	2.04	2.37
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400 / 800 MHz [GV]	0.120 / 0	1.0 / 0	2.08 / 0	2.5 / 8.8
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004 / 0.159	0.011 / 0.111	0.0187 / 0.129	0.093 / 0.140
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	1.95 / 2.75
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.26	1.25
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

From talk “Accelerator overview” by Tor Raubenheimer presented at FCC Week 2022

Luminosity measurement using single Bremsstrahlung

Luminosity and beam angular divergence have been measured at LEP with a fast monitor based on the single bremsstrahlung process $e^+e^- \to e^+e^- \gamma$.

(ADONE: H.C.Dehne, M.Preger, S.Tazzari, G.Vignola NIM 116 (1974) 345
VEPP: Blinov et al. NIM A273(1988))



$$\sigma_{SB} \sim \ln s$$

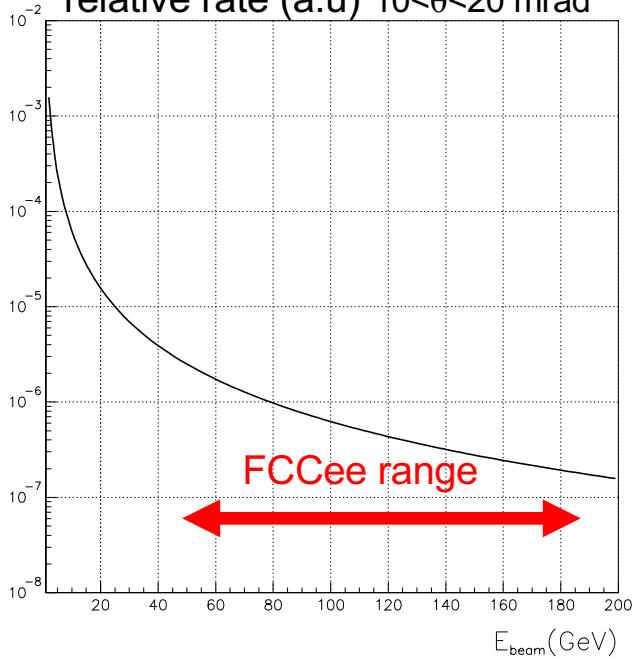
$$\vartheta \simeq \frac{m}{E} \simeq 10\ \mu rad \text{ a LEP}$$

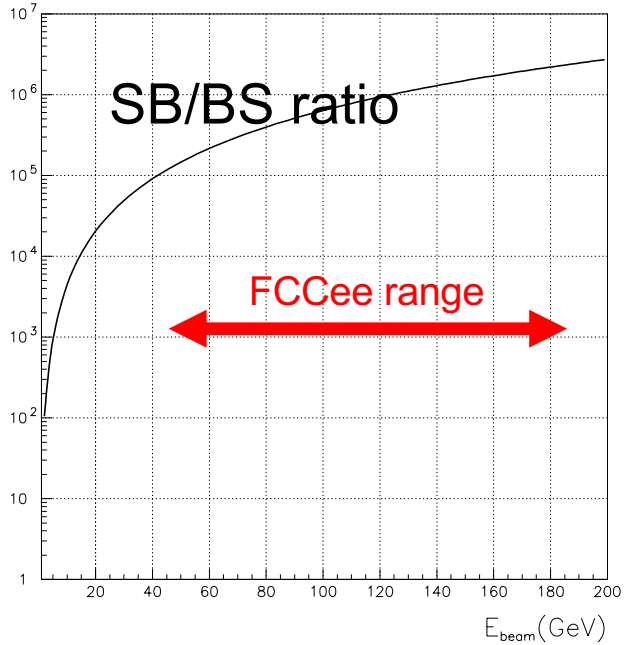
	SPEAR	PETRA	LEP
Luminosity ($cm^{-2}\ s^{-1}$)	10^{31}	10^{30}	10^{31}
Beam energy (GeV)	2.6	8.5	55
Rate Bhabha evts.(Hz) $10<\theta<20$ mrad	$3.5 \cdot 10^3$	30	6.5
Rate SB evts.(Hz) $E_\gamma > 500$ MeV	$6.7 \cdot 10^5$	$1.5 \cdot 10^5$	$3.3 \cdot 10^6$

~ 100 photons / bunch crossing
O(100 GeV /bunch crossing)

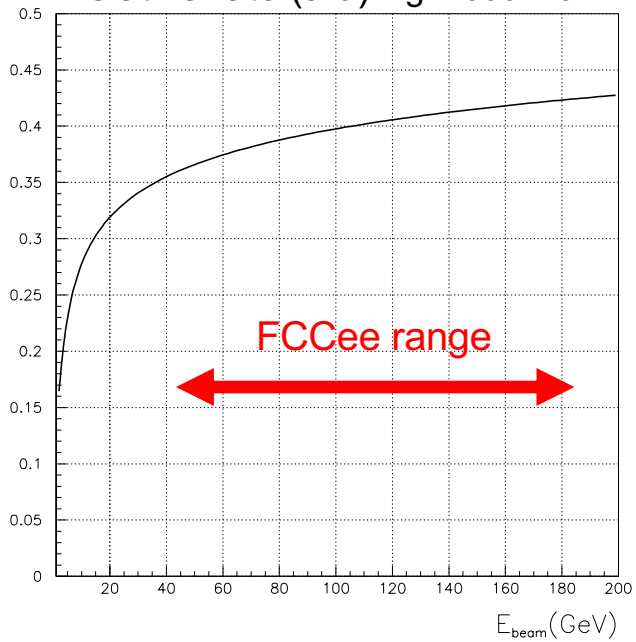
Single Bremsstrahlung vs Bhabha scattering at FCCee

Bhabha scattering (BS)
relative rate (a.u) 10<θ<20 mrad





Single Bremsstrahlung (SB)
relative rate (a.u) Eg > 500 MeV



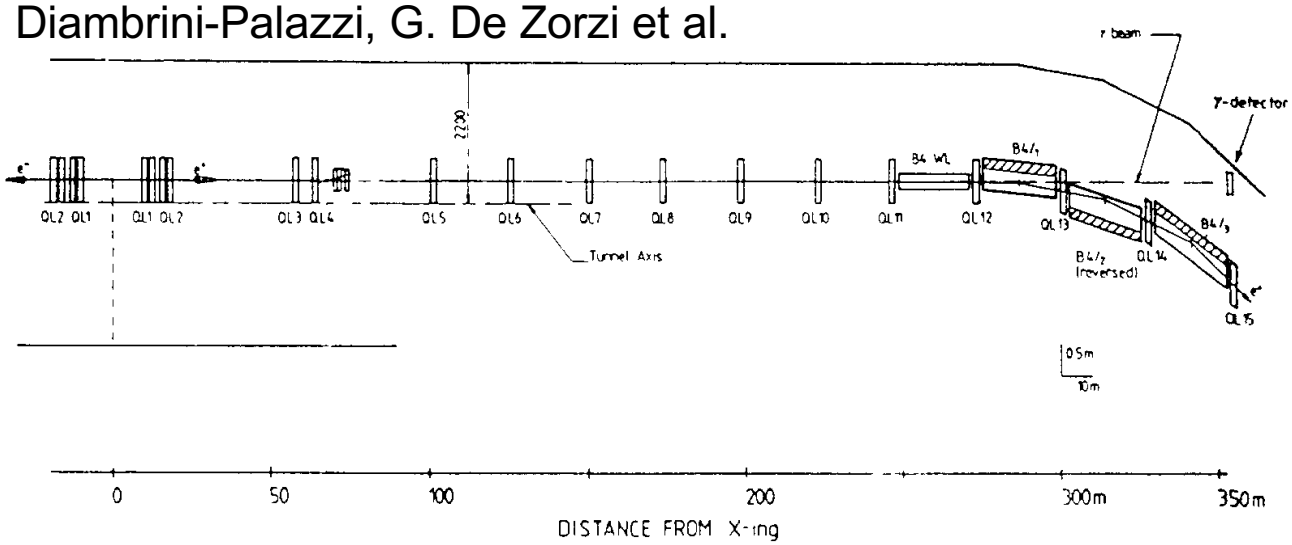
Taking into account FCCee parameters

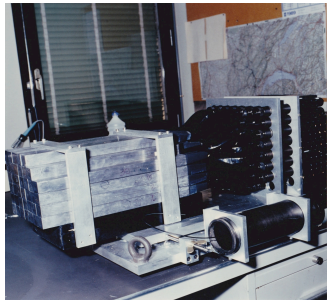
E beam (GeV)	BS rate (Hz)	BS evts per bunch crossing
45	$2\ 10^{6}$	$5\ 10^{-2}$
80	$5\ 10^{4}$	$2\ 10^{-2}$
120	$8\ 10^{3}$	$1\ 10^{-2}$
182.5	$6\ 10^{2}$	$5\ 10^{-3}$

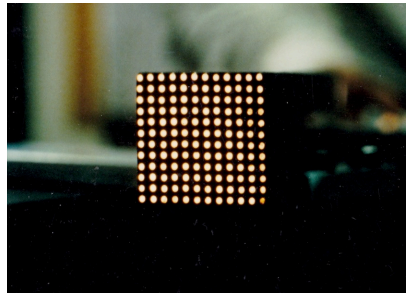
E beam (GeV)	SB rate (MHz)	SB evts per bunch crossing
45	$6\ 10^{5}$	$2\ 10^{4}$
80	$6\ 10^{4}$	$2\ 10^{4}$
120	$2\ 10^{4}$	$3\ 10^{4}$
182.5	$9\ 10^{3}$	$3\ 10^{4}$

LEP-5 experiment (1987-1992)

G. Diambrini-Palazzi, G. De Zorzi et al.



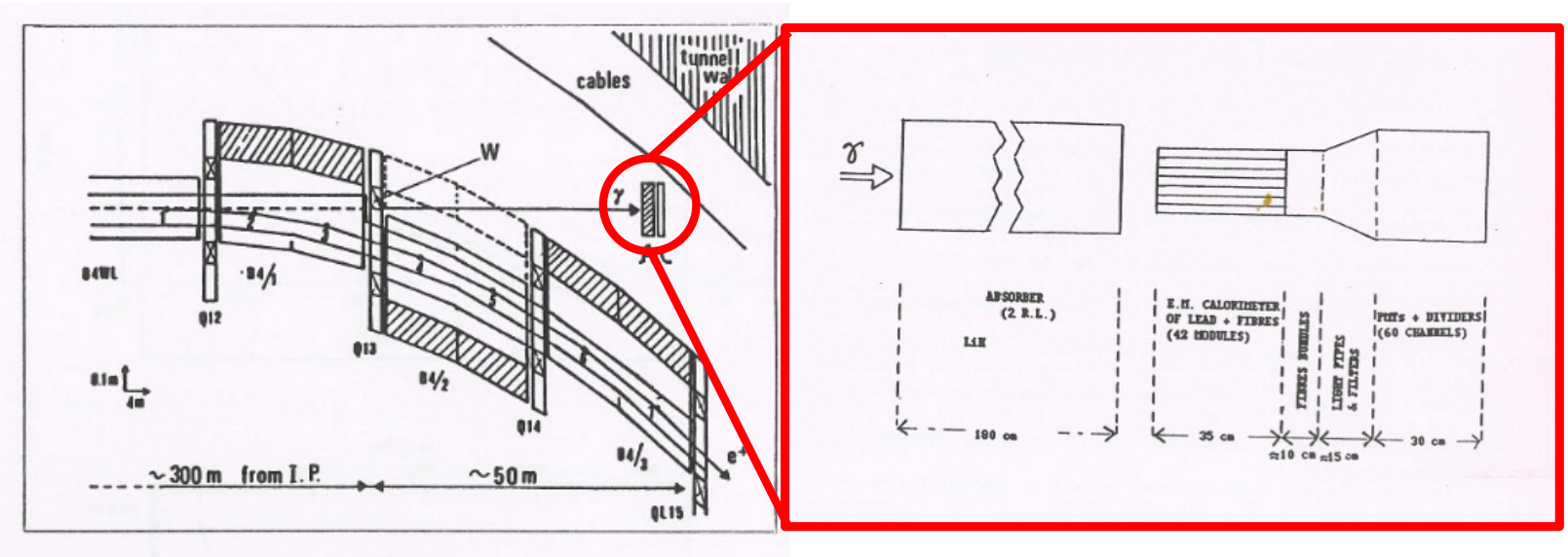




Lead scintillating fiber calorimeter
Spatial resolution ~ 1 mm @ 10-50 GeV

M. Bertino et al. NIM **A315** (1992) 327

Experimental set-up in IP-1 (no other expts at that time)



W = thin AL window, 2 × 5 cm^2

2 X_0 of LiH (180 cm)
in front of the calorimeter to absorb synchrotron radiation

Counting room near IP-1
⇒ 420 m long cables

LEP-5 luminosity measurement: the method

High rate ⇒ multiphoton regime ⇒ measurement of integrated energy rather than photon counts

$$I = E_{meas} - E_{bckg} = AL\int_0^{E_{beam}} \epsilon(k)\, k \frac{d\Sigma}{dk}\, dk$$

Dependence of I on the effective detection energy threshold

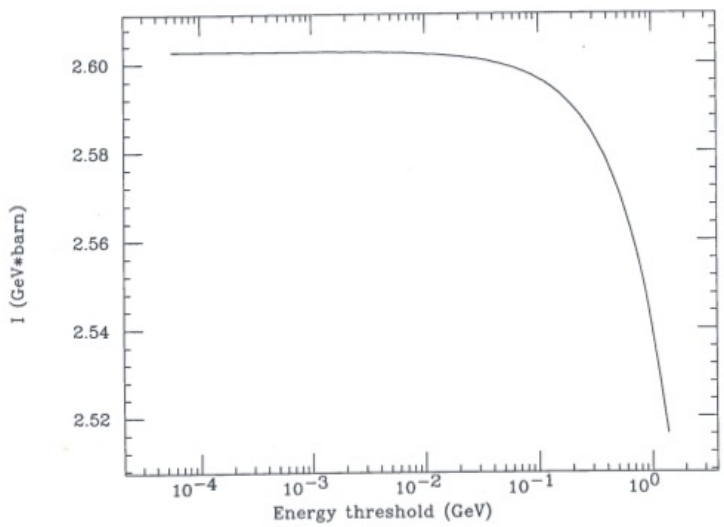
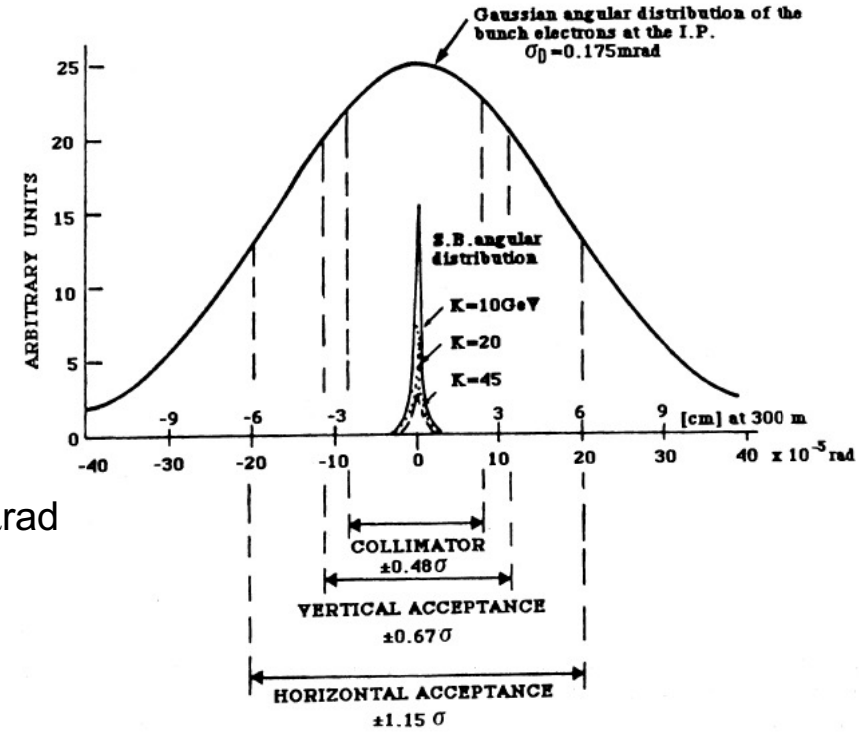


Fig. 1

SB photons emitted in a very narrow cone

$$\vartheta \simeq \frac{m}{E} \simeq 10\ \mu rad \text{ a LEP}$$

from 10 to 3 μrad at FCCee



LEP beam divergence 175 μrad (55 μrad at IP 1)
At FCCee
O(10-100 μrad)

Acceptance A from a fit to the energy space distribution on the detector (space resolution + e.m. shower transverse size to be taken into account)
⇒ measurement of position and angular divergence of beams at IP.

Beam size effect

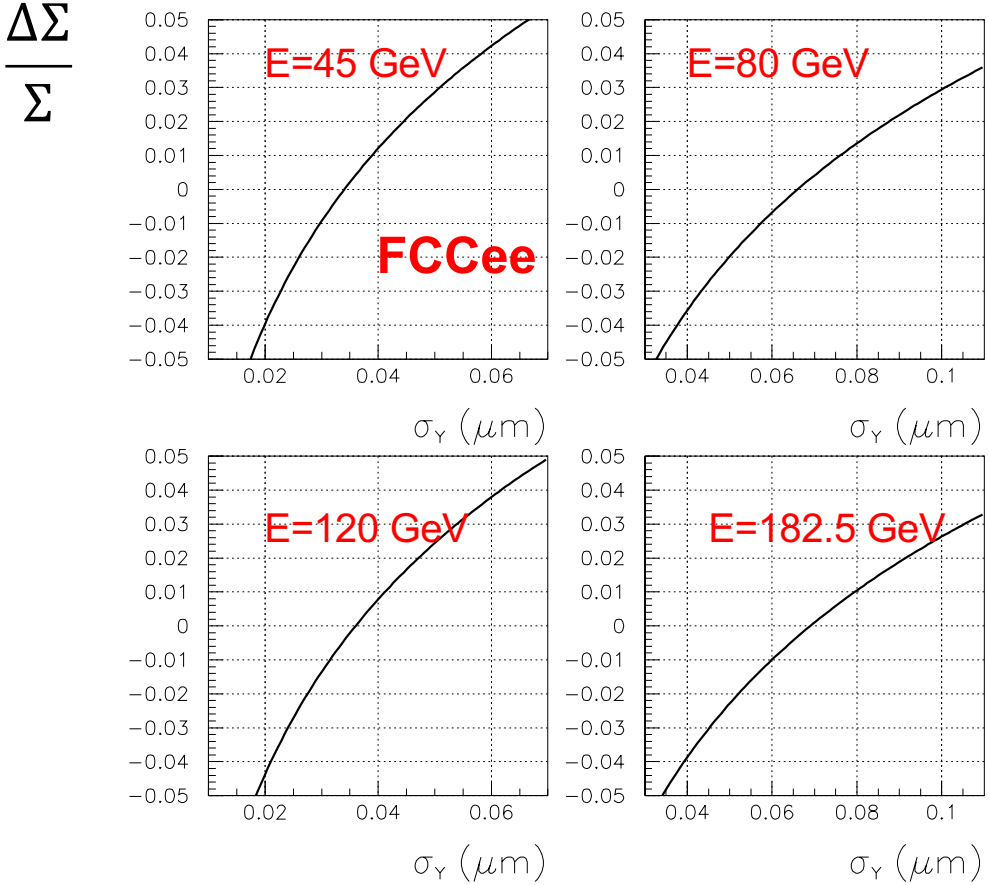
Large impact parameter for the emission of SB photons (it can be O(cm)) => dependence of the total cross section on the finite beam transverse dimensions

At LEP SB cross section reduction of ~25%

Blinov et al. NIM A273(1988); PLB113(1982)423

See also Kotkin et al. PLB 227 (2005) 137; JINST 4 (2009) P06015

$\frac{\Delta\Sigma}{\Sigma}$ relative variation of total cross section wrt default beam sizes



the smallest dimension σ_Y is the more critical

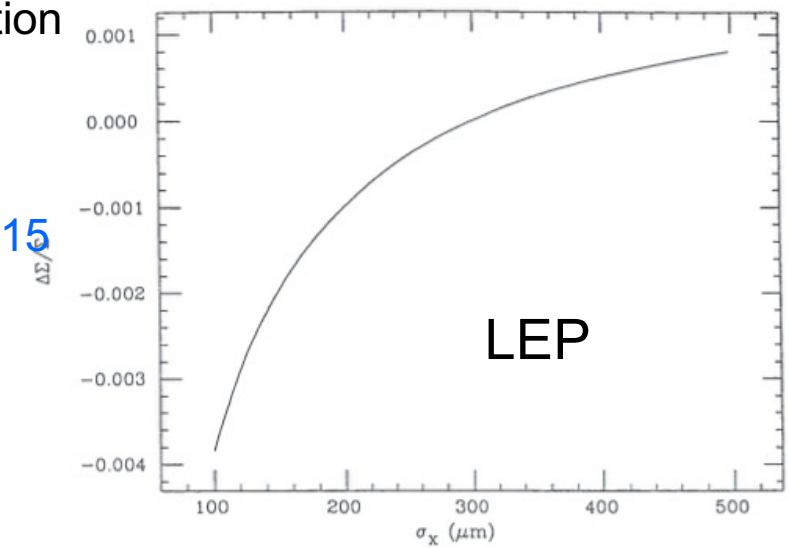


Fig. 2a

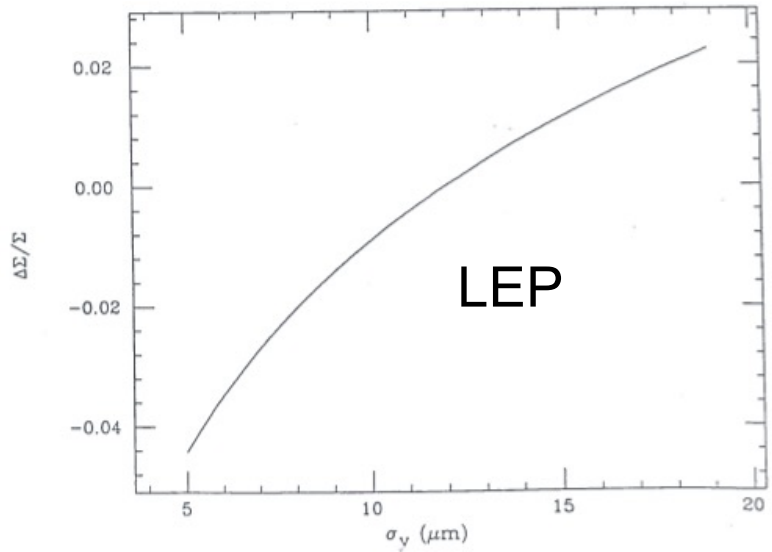


Fig. 2b

Background estimates at LEP

SR=synchrotron radiation

Table 3

Energy from the window (GeV / crossing)

Window	Beam-gas (BG)	SR	SB	SR /(SR+SB)	BG /(BG+SB)
2 x 5 cm^2 SS-1	45	3×10^6	40		53 %
7 x 5 cm^2 SS-even	3	4×10^6	170		1.8 %

Energy deposited in the calorimeter fibres after 2 R. L. of LiH absorber (GeV / crossing)

2 x 5 cm^2 SS-1		6×10^{-3}	0.5	1.2 %
7 x 5 cm^2 SS-even		2×10^{-2}	2.2	0.9 %

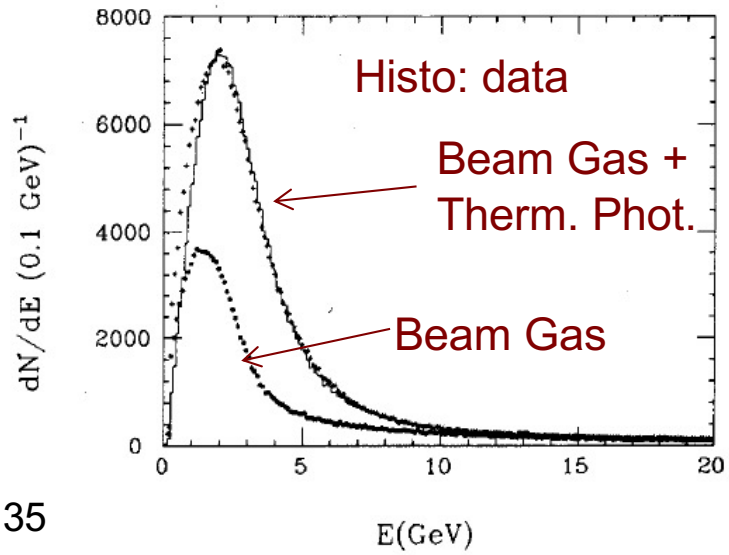
Beam gas bremss. and thermal photons measurement

Compton scattering of 50 GeV beam electrons on thermal photons

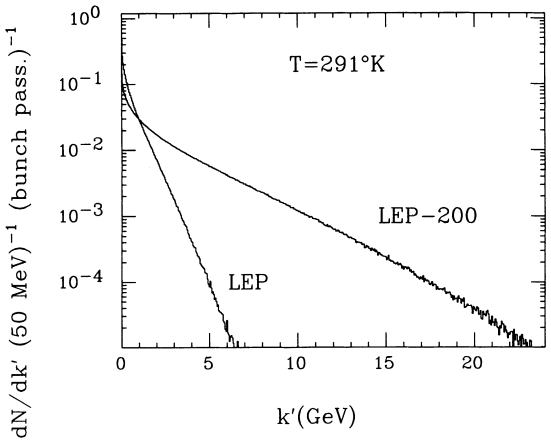
After scattering:
0.07 eV photon => up to 2.8 GeV photon

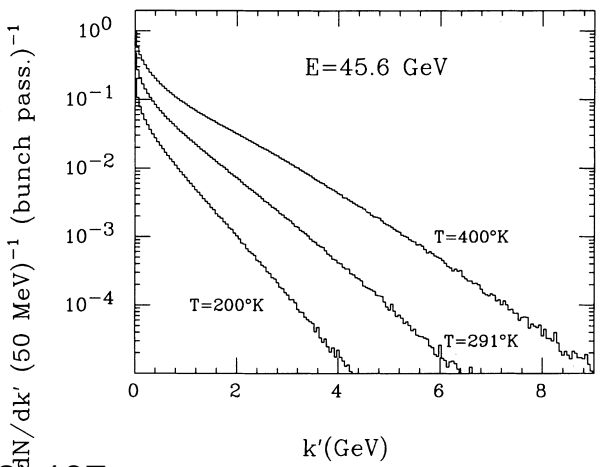
$\mu_{BG} = 0.44$; $\mu_{TP} = 1.47$ γ multiplicities
$\Rightarrow P \approx 2.2 \times 10^{-10}$ torr
$T \approx 291$ K

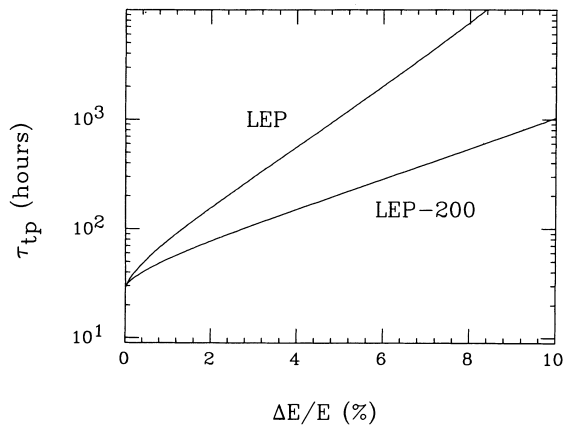
C.Bini et al., PLB **262** (1991) 135



Inverse Compton scattering evaluation

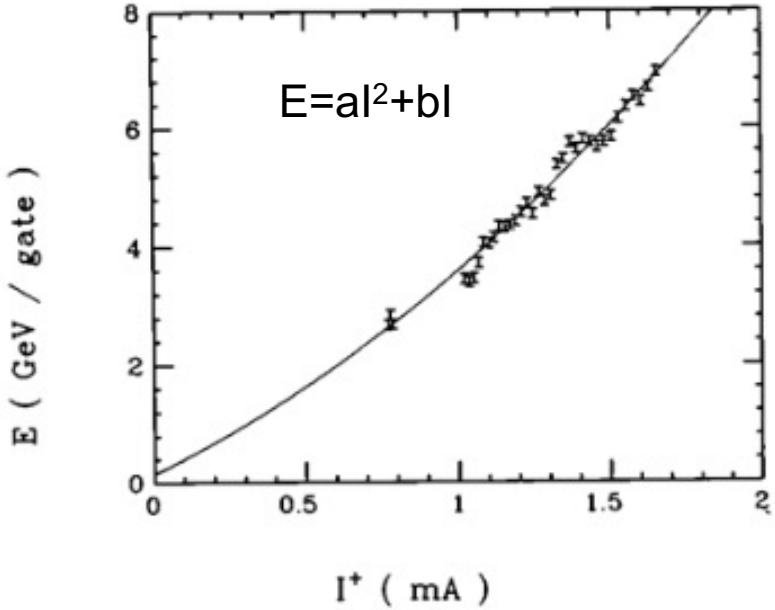


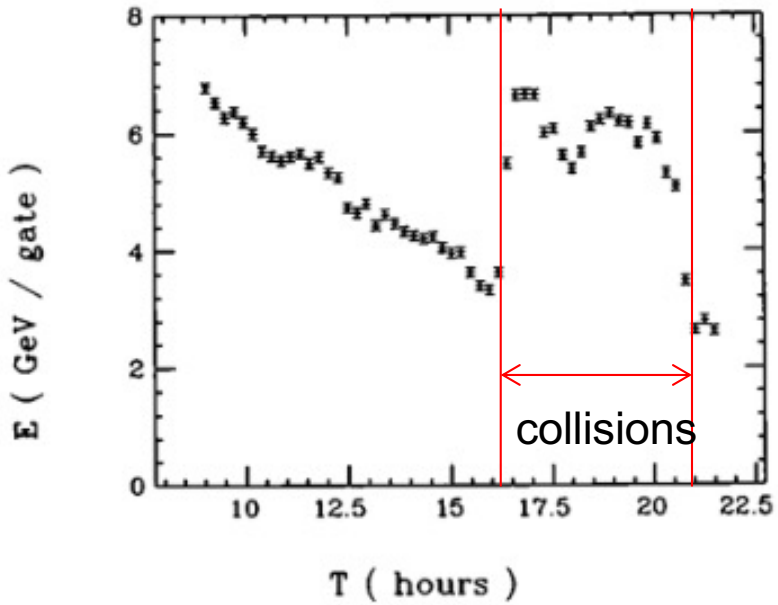




A.Di Domenico, Particle Accelerators **39** (1992) 137

Single bremsstrahlung and background measurement





Separate beams for background measurement

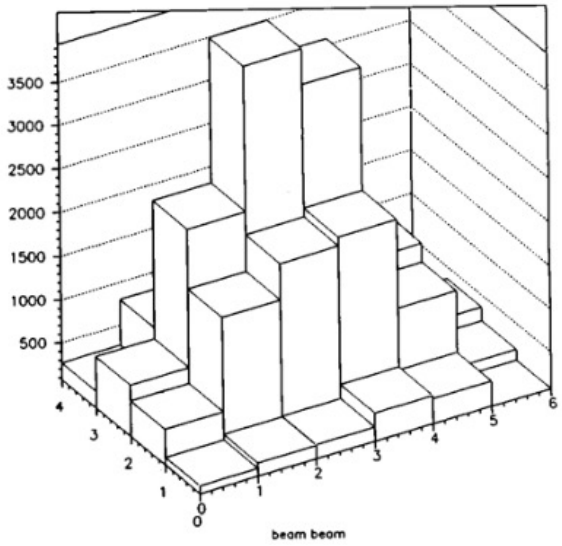
1) Beam-gas Bremsstrahlung
2) Compton scattering of thermal photons

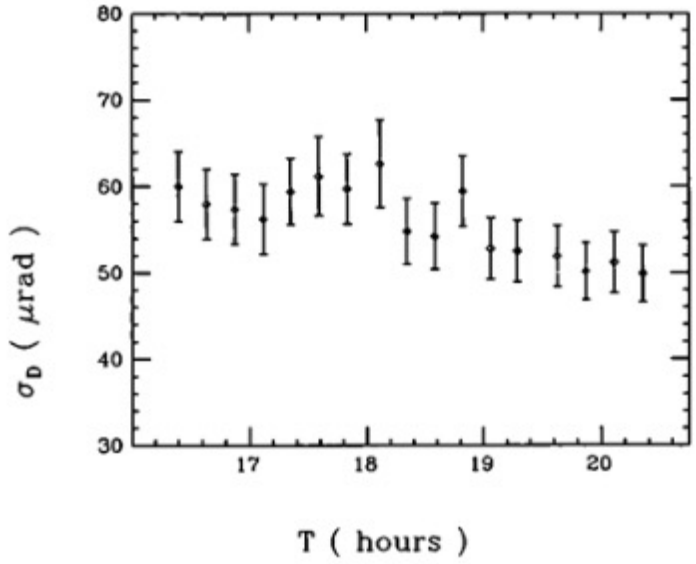
ADC gate = 1 μs T_{LEP}= 22 μs

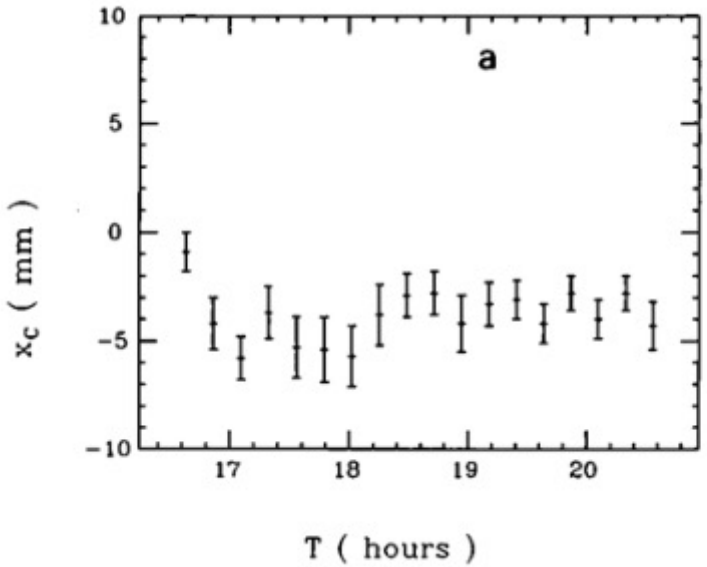
3) Synchrotron radiation
Energy deposited in the calorimeter downstream LiH absorber from MC: SR/SB <1%
at LEP nominal luminosity (IP even)

DAQ event rate before upgrade ~ 100 Hz ; after 45 kHz (see next slides)

Acceptance


3500
3000
2500
2000
1500
1000
500
beam beam


80
70
60
50
40
30
17
18
19
20
σ_D (μrad)
T (hours)


a
10
5
0
−5
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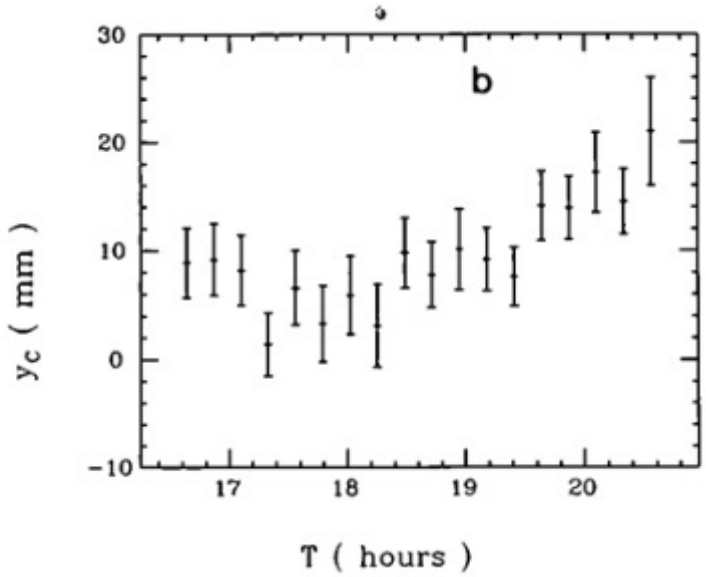
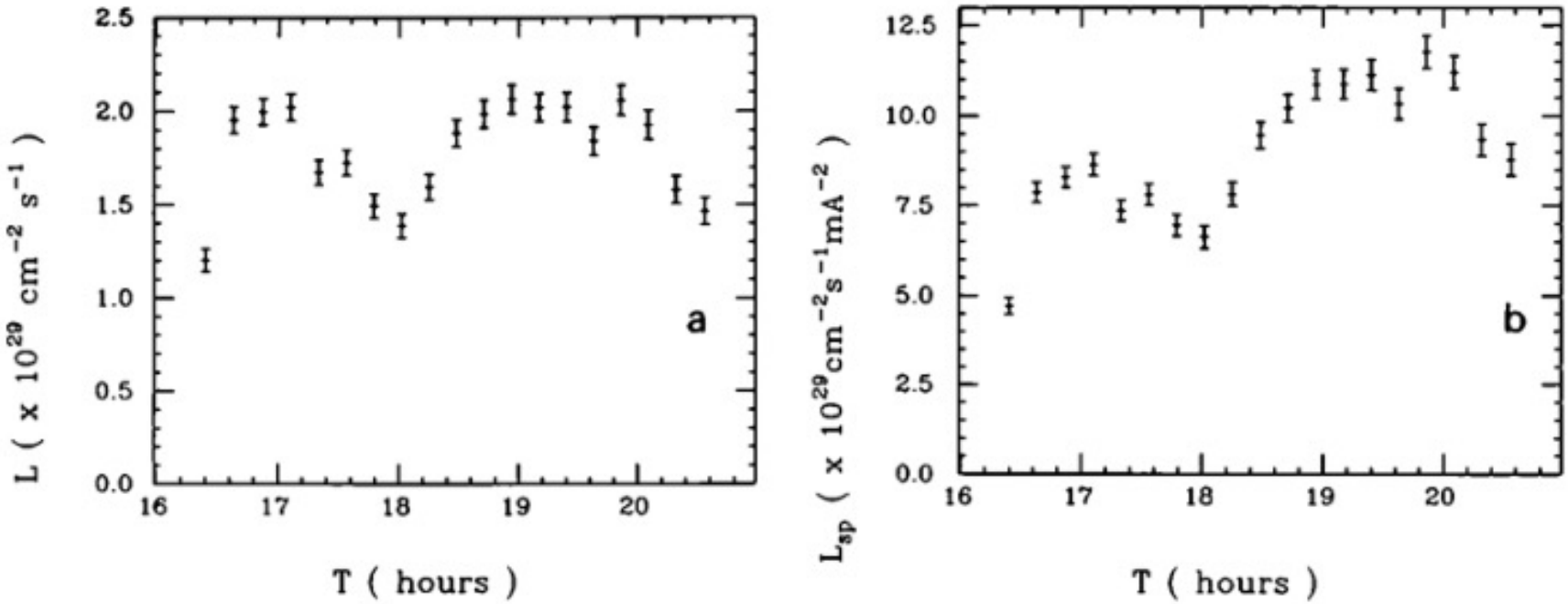
17
18
19
20
x_c (mm)
T (hours)


b
30
20
10
0
−10
17
18
19
20
y_c (mm)
T (hours)

Luminosity measurement



Each point ~ 10 min data taking
Statististical error: 1%

Sytematic errors:
Background and signal noise subtraction: 2%
(420 m long signal cables - noise induced in LEP tunnel)
Acceptance: 1.5%
SB cross-section – theory: < 1%
SB cross-section - beam sizes: 1%
Lower energy threshold (efficiency): 1%
TOTAL ~ 3.2%

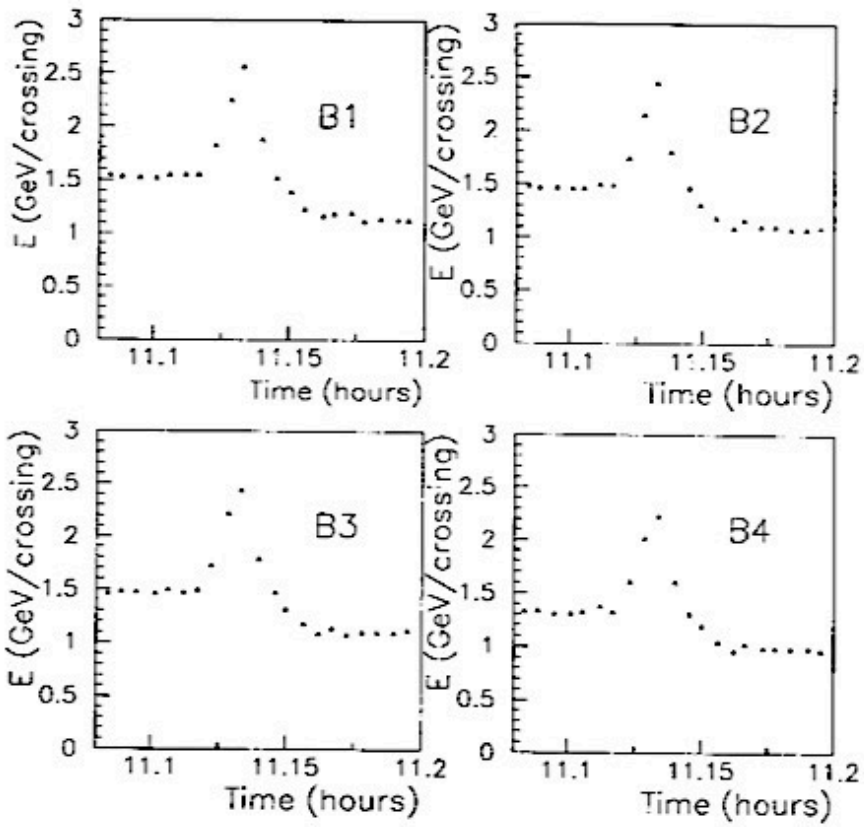
$$L_{sp} = \frac{L}{\sum_i I_i^+ I_i^-}$$

C. Bini at al. NIM **A306** (1991) 467

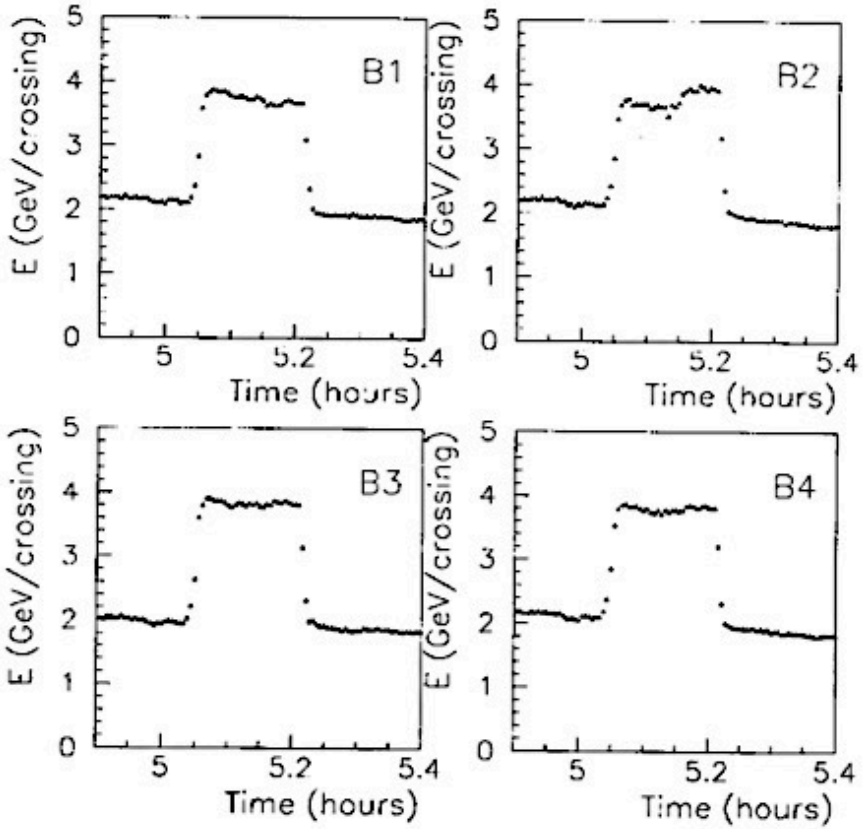
Sysyt. Uncert. can be reduced to 1-2% with:
Higher luminosity, larger acceptance
Noise shielding

LEP-5 DAQ upgrade

Upgrade with a new fast processor able to reach the maximum intrinsic rate and to store information separately for the 4 bunches
Unstable beams for collisions in IP-1 ⇒ few data collected

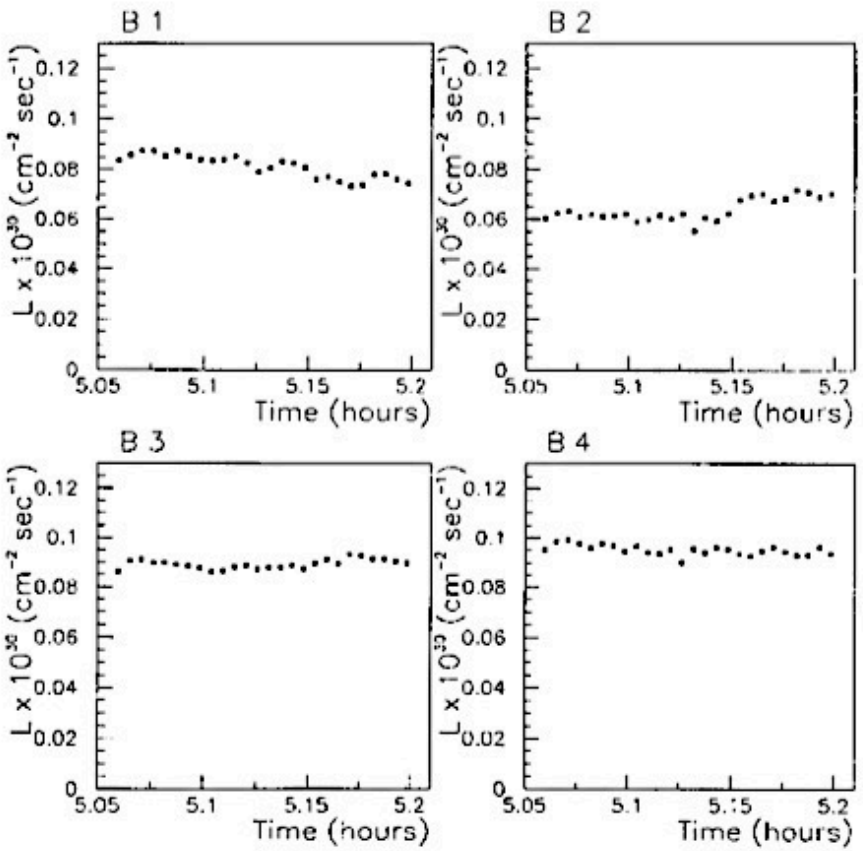


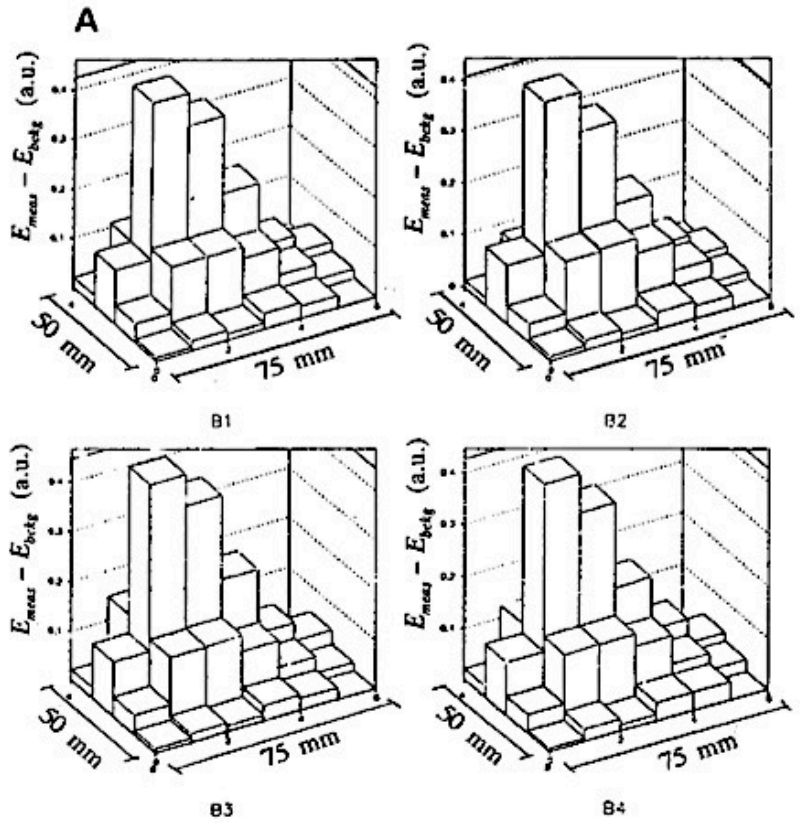
Collisions only for 40 s



Collisions for 10 min

Luminosity measurement per bunch





Each point ⇒ 20 s data taking
Statistical error : 0.2%

C. Bini et al. NIM **A349** (1994) 27

Beam centered outside the window => increased uncertainty on acceptance determination

SB luminosity monitor at FCCee: some considerations (I)

- A SB luminosity monitor can be very fast at FCCee.
- Beam size and low energy threshold (efficiency) control required for cross-section determination.
- Precision of theoretical cross section calculation <~1%.
  Beam size effect revised for e.g super B-factories, beam gaussian shape assumed
  Theory calculations could be further improved.

- Difficult to reach a precision of $10^{-3} \div 10^{-4}$ of the much slower Bhabha monitor
  (see Dam, EPJ Plus (2022) 137:81)

- In case of a photon exit window at 50 m from IP, the beam spot can be few mm:
  Pros: easier to get ~full acceptance, reduced systematic uncertainty
  Cons: difficult to measure beam divergence and position at IP,
  mm space resolution needed, e.m. shower transverse dimension

- Huge SB+background energy flux implies a very robust and radiation hard detector

SB luminosity monitor at FCCee: some considerations (II)

Background:

- beam gas bremsstrahlung $\propto I^2$
  extrapolating from LEP (P~2x10^{-10} Torr) beam gas/SB < 10^{-4} => negligible
  Residual gas pressure at LEP IP-1 was exceptionally good (P~2 x 10^{-10} Torr)
  At FCCee at Z peak P ~ 1x10^{-9} Torr is expected
  => could worsen beam gas bremsstrahlung background

- Inverse Compton scattering of thermal photons
  extrapolating from LEP (Temp=291 K) ther.phot./SB < 10^{-4} => negligible

- Synchrothron radiation: absorber and collimator required =>
  worsening of downstream detector performance => attenuation
  depends also on the detector characteristics => to be studied

SB luminosity monitor at FCCee: some considerations (III)

Background:

- Beamstrahlung (negligible at LEP) has to be taken into account
  The huge energy flux must be attenuated (at Z peak Beamstrah./SB O(10^3)).
  To be studied the compatibility of a SB luminosity monitor with a beam dump.

FCC | FCC Week 2022 - Paris - 02/06/2022 | Andrea Ciarma | Beamstrahlung Radiation | 17

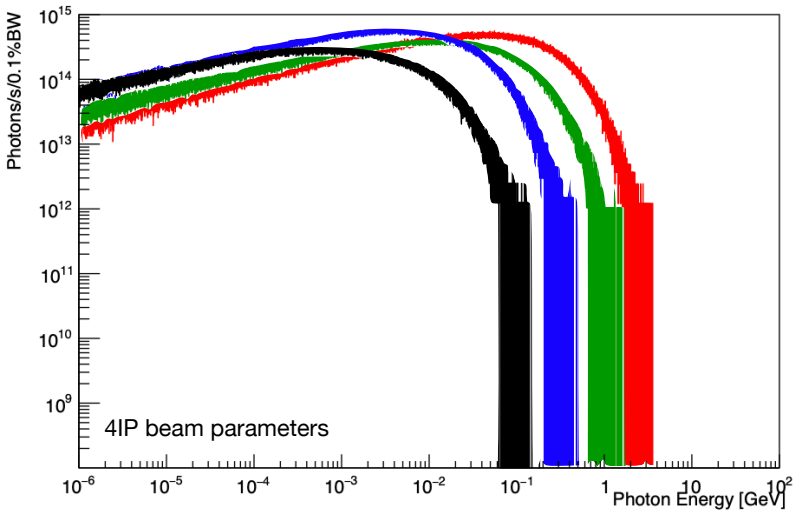
Beamstrahlung radiation Characterisation

Beamstrahlung is a **dominant process** for the lifetime at FCCee due to the small beam size and high population.

$$\Upsilon \sim \frac{5}{6}\frac{r_e^2 \gamma N_e}{\alpha \sigma_z(\sigma_x+\sigma_y)}$$

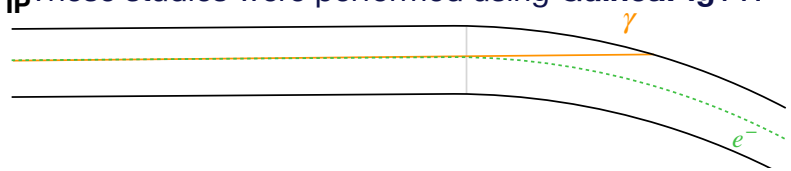
$$< E_\gamma > \sim E \times 0.462\Upsilon$$

$$n_\gamma \sim 2.54\left[\frac{\alpha^2\sigma_z}{r_e\gamma}\Upsilon\right]\frac{1}{[1+\Upsilon^{2/3}]^{1/2}}$$



The photons are emitted **collinear to the beam** with an angle proportional to the beam-beam kick. This radiation is extremely intense **O(100kW)** and **hits the beam pipe** at the end of the first downstream dipole.

These studies were performed using **GuineaPig++**.



	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

SB luminosity monitor at FCCee: some considerations (III)

Background:

- Beamstrahlung (negligible at LEP) has to be taken into account
  The huge energy flux must be attenuated (at Z peak Beamstrah./SB O(10^3)).
  To be studied the compatibility of a SB luminosity monitor with a beam dump.

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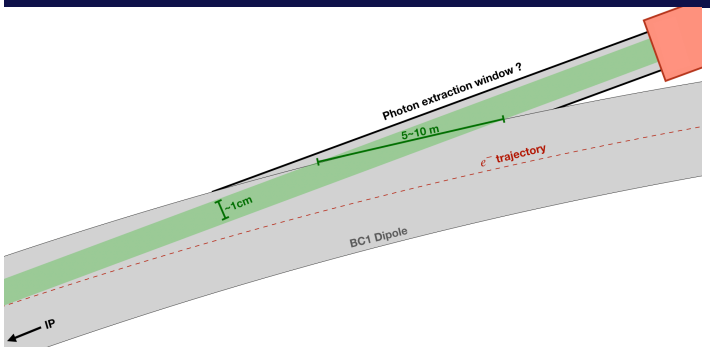

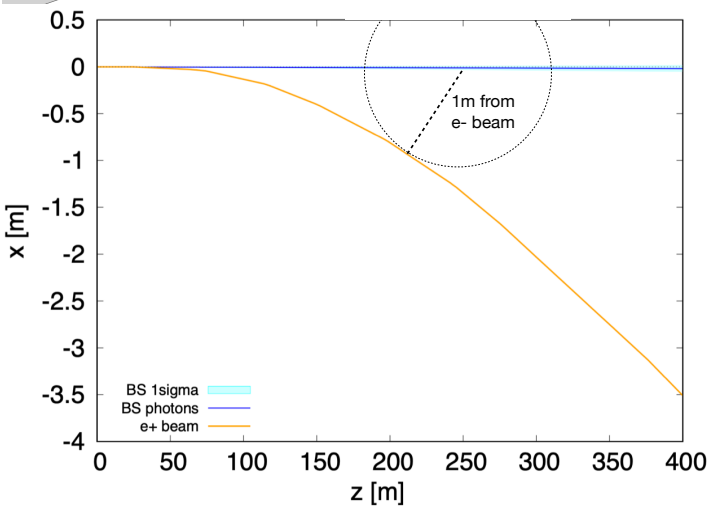

Beam dump for Beamstrahlung photons

Due to the very high power $O(100kW)$ it is necessary to have a **beam dump** for the beamstrahlung photons.

Several constraints like the long **extraction line** window, the **distance** of the dump from the beam pipe, and the **placement into the cavern** are all currently under study (see talk by M. Calviani 02/06).

Also the possibility to have an **instrumented beam dump** to measure properties of the colliding beams at the IP is under investigation.