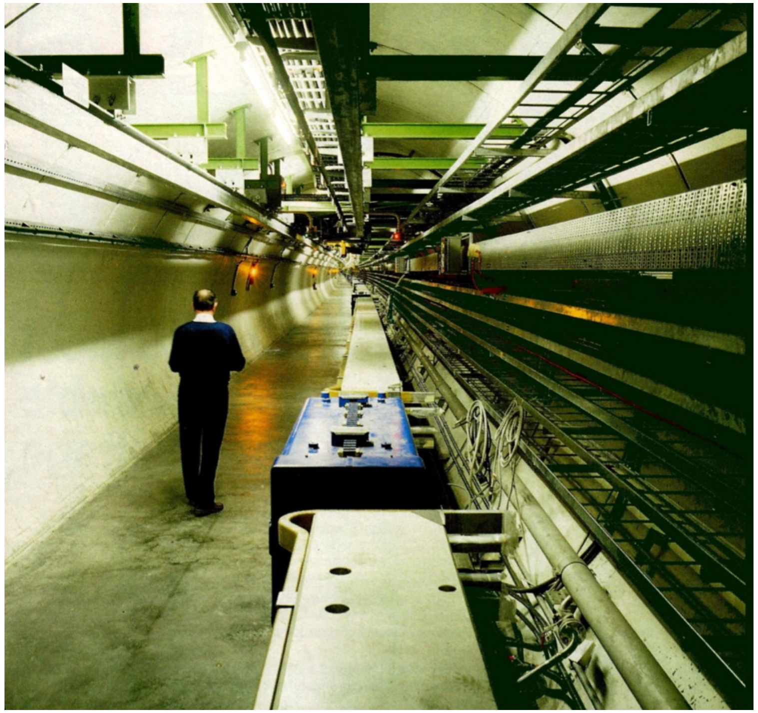
Fast luminosity monitor for FCC-ee based on the LEP experience

Antonio Di Domenico
Dipartimento di Fisica, Sapienza Università di Roma
e INFN sezione di Roma, Italy



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 10

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

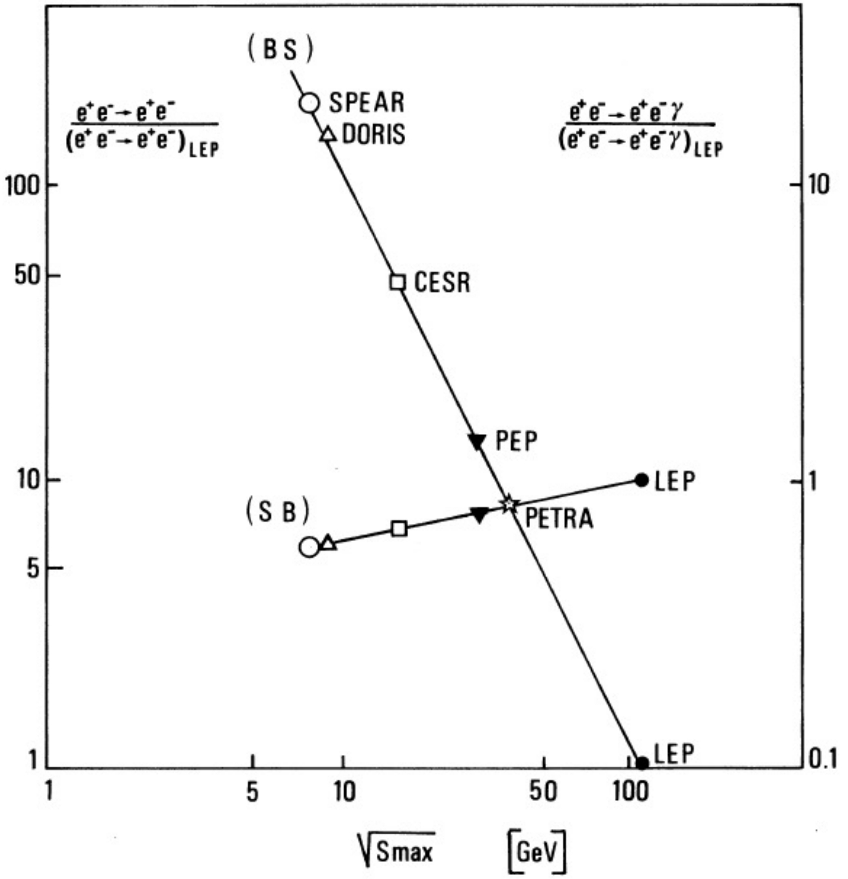
Luminosity measurement using single Bremsstrahlung

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))

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

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

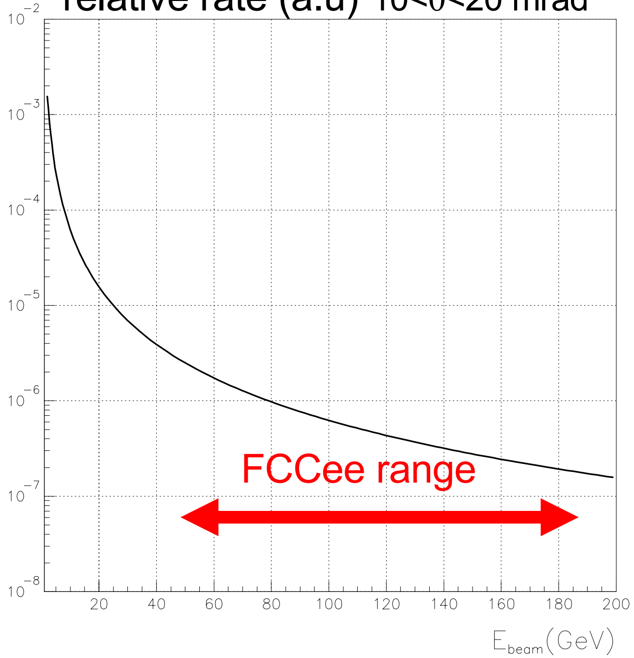


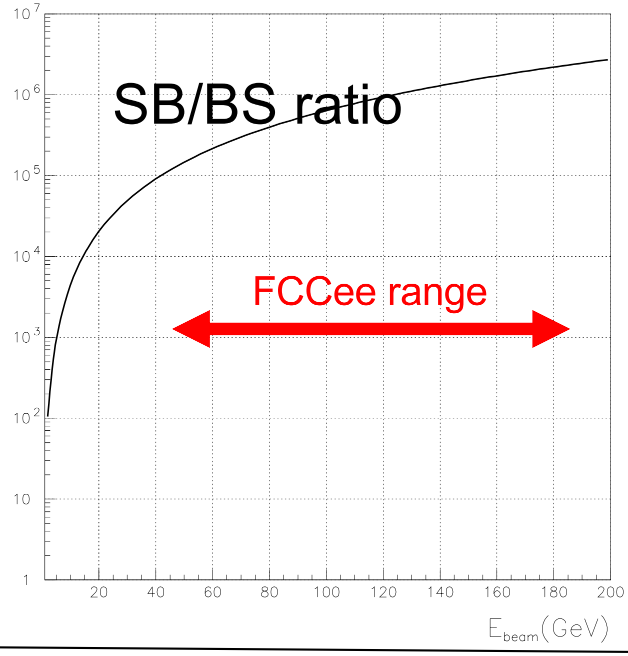
	SPEAR	PETRA	LEP
Luminosity ($cm^{-2}\ s^{-1}$)	10^{31}	10^{30}	10^{31}
Beam energy (GeV)	2.6	8.5	55
Rate Bhabha evts.(Hz) $10<\theta<20$ mrad	$3.5 \cdot 10^3$	30	6.5
Rate SB evts.(Hz) $E_\gamma > 500$ MeV	$6.7 \cdot 10^5$	$1.5 \cdot 10^5$	$3.3 \cdot 10^6$

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

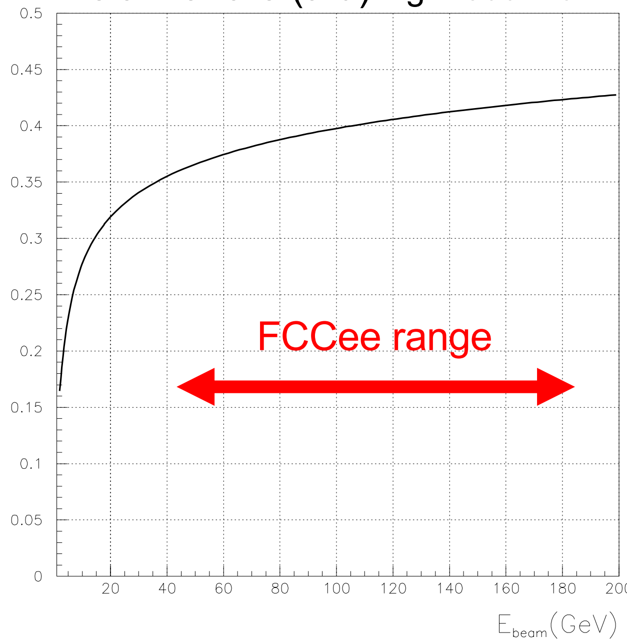
Single Bremsstrahlung vs Bhabha scattering at FCCee

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





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



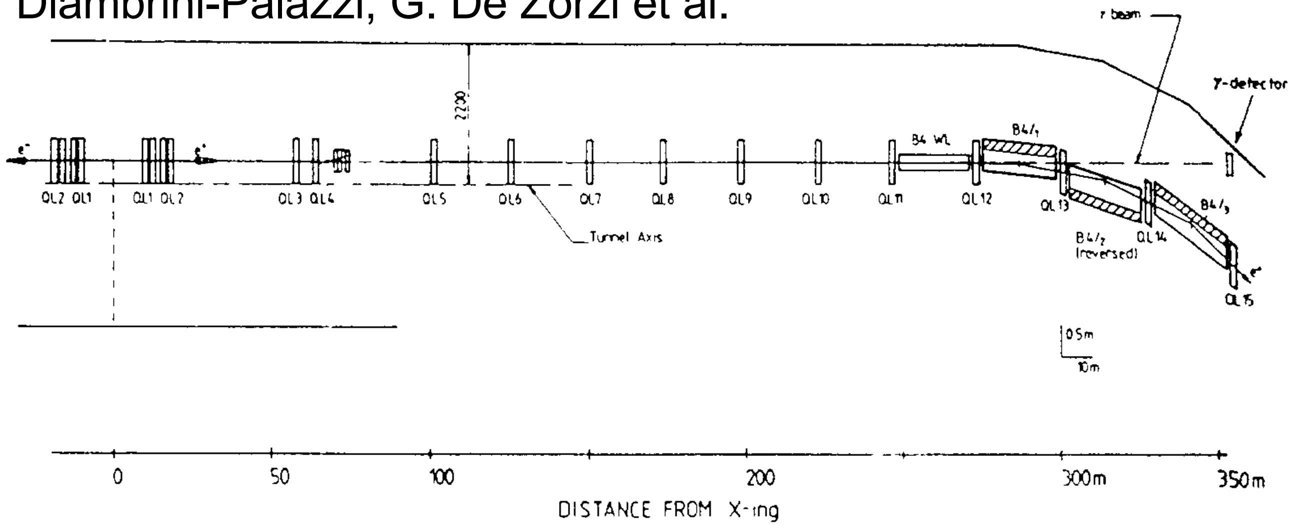
Taking into account FCCee parameters

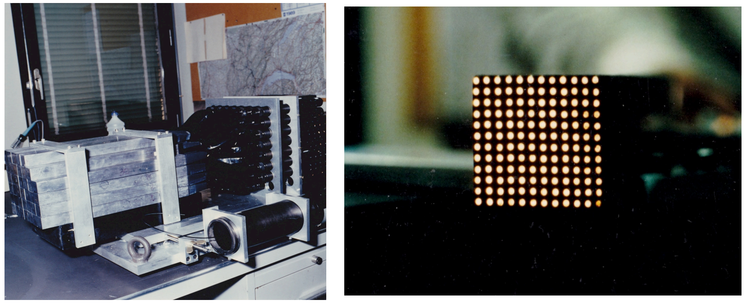
E beam (GeV)	BS rate (Hz)	BS evts per bunch crossing
45	$2\ 10^6$	$5\ 10^{-2}$
80	$5\ 10^4$	$2\ 10^{-2}$
120	$8\ 10^3$	$1\ 10^{-2}$
182.5	$6\ 10^2$	$5\ 10^{-3}$

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.

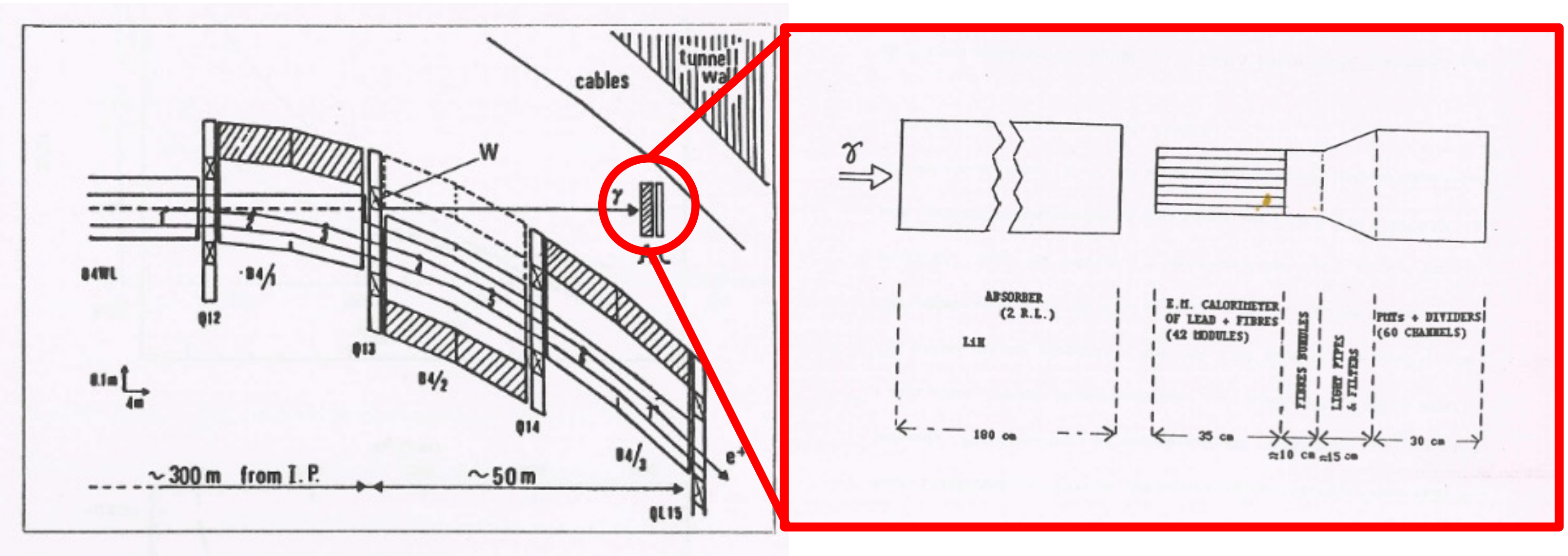




Lead scintillating fiber calorimeter
Spatial resolution ~ 1 mm @ 10-50 GeV

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

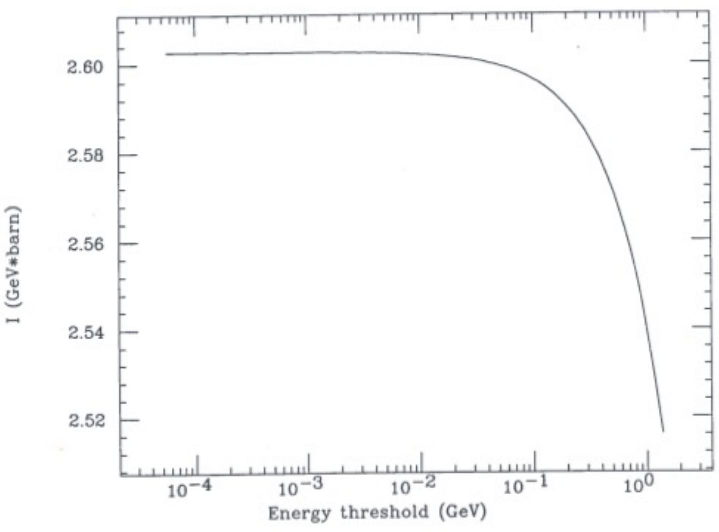
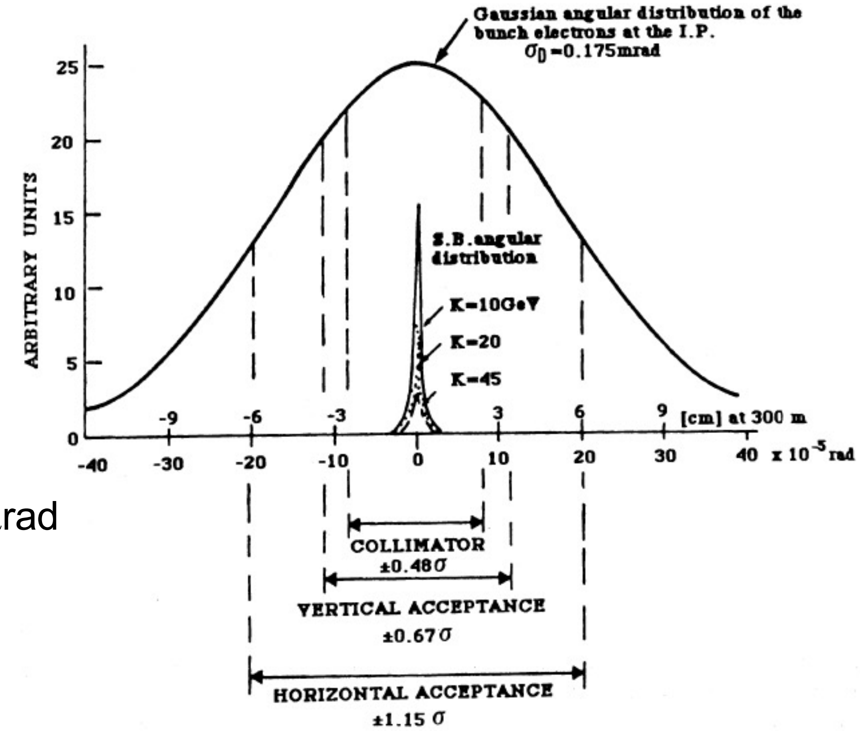


Fig. 1

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

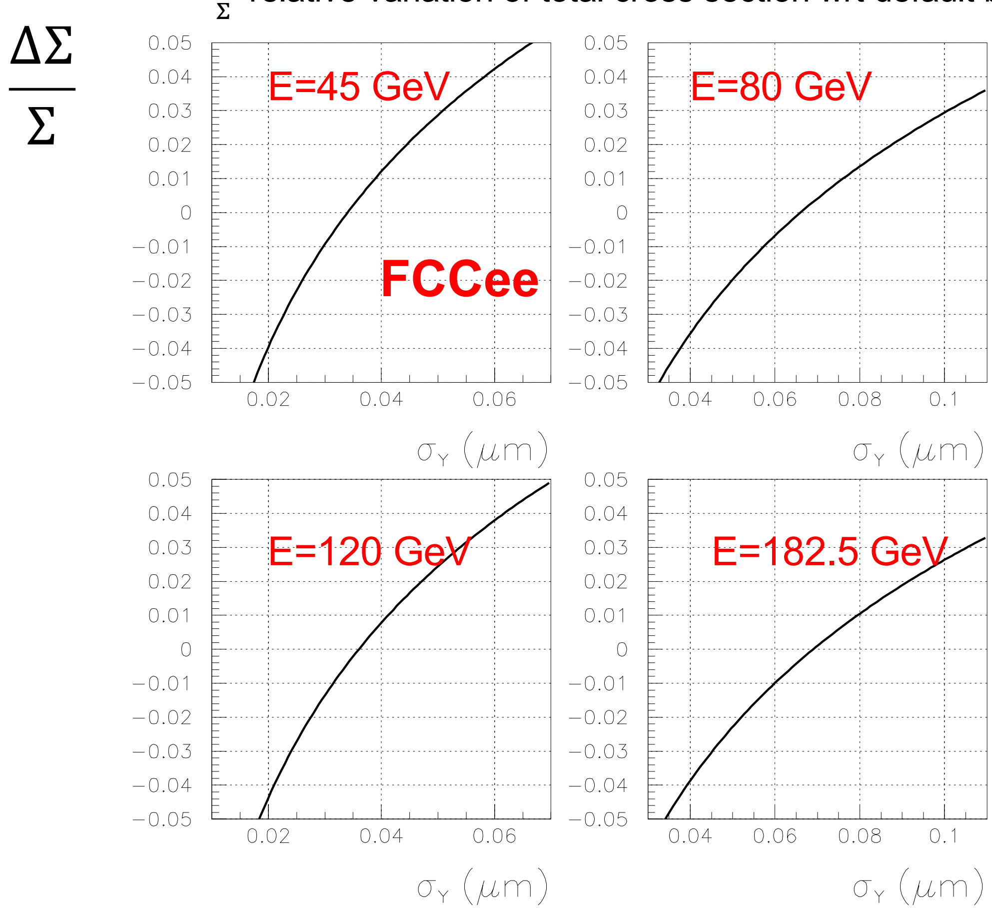
Large impact parameter for the emission of SB photons (it can be O(cm)) => dependence of the total cross section on the finite beam transverse dimensions

At LEP SB cross section reduction of ~25%

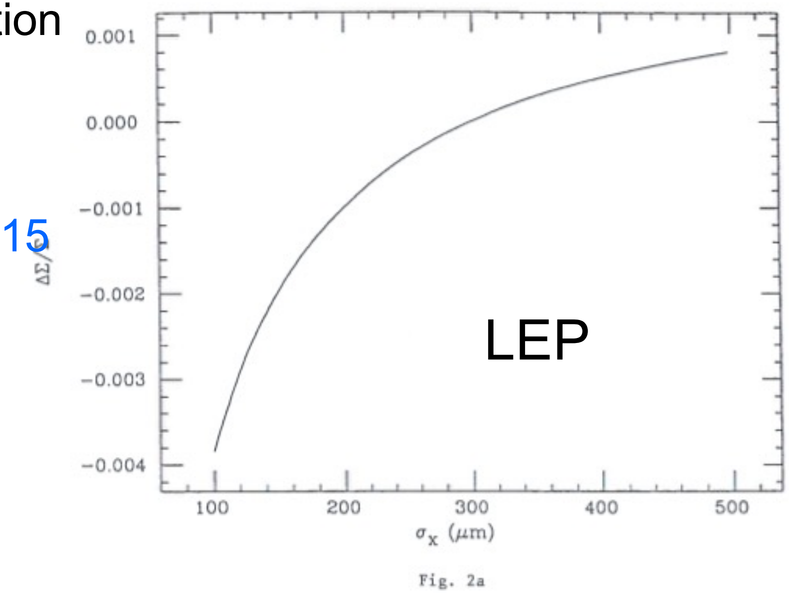
Blinov et al. NIM A273(1988); PLB113(1982)423

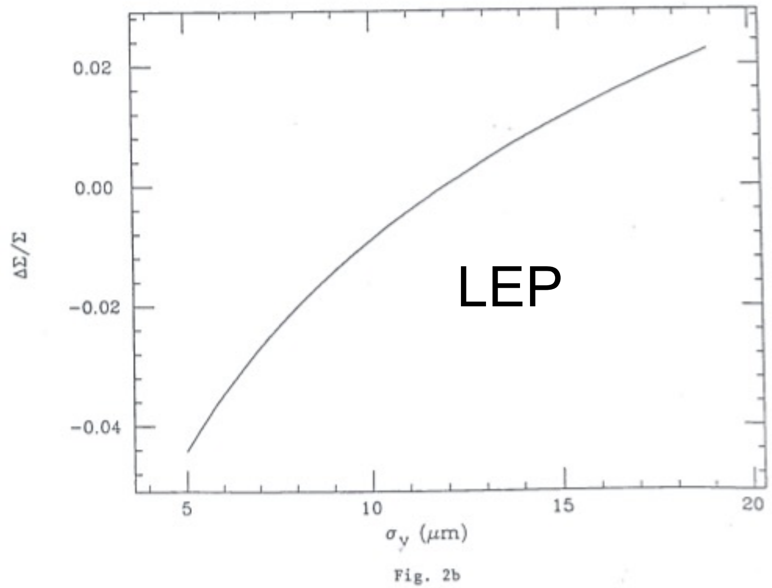
See also Kotkin et al. PLB 227 (2005) 137; JINST 4 (2009) P06015

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



<u>the smallest dimension σ_Y is the more critical</u>





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)

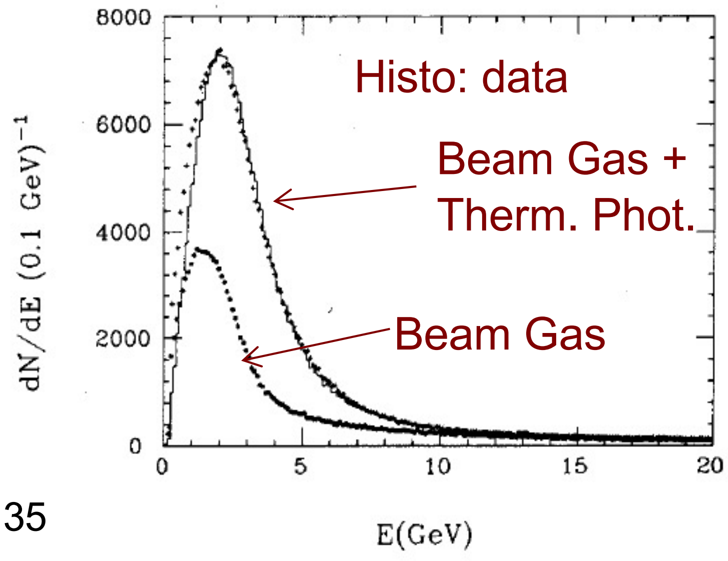
Window	Beam-gas (BG)	SR	SB	SR /(SR+SB)	BG /(BG+SB)
2 x 5 cm^2 SS-1		6×10^{-3}	0.5	1.2 %	
7 x 5 cm^2 SS-even		2×10^{-2}	2.2	0.9 %	

Beam gas bremss. and thermal photons measurement

Compton scattering of 50 GeV beam electrons on thermal photons

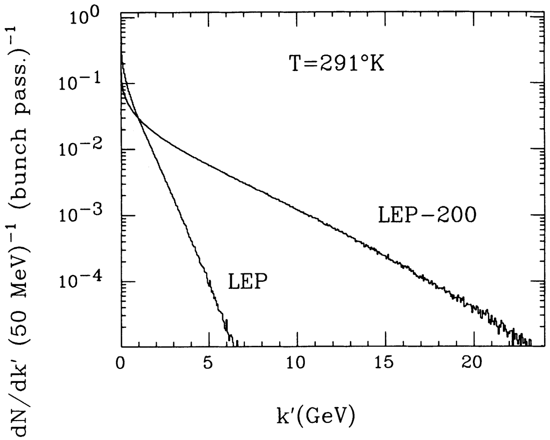
After scattering:
0.07 eV photon => up to 2.8 GeV photon

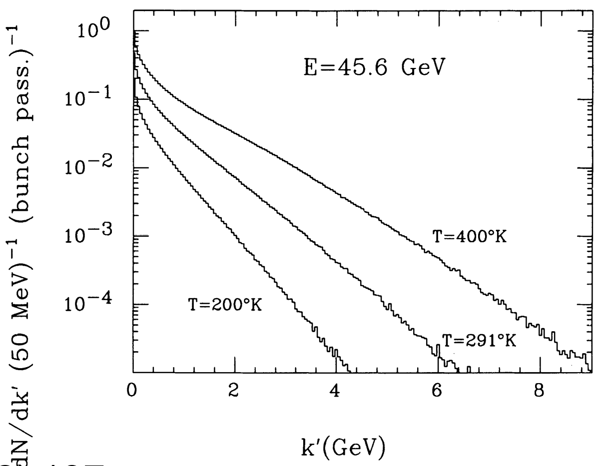
$\mu_{BG} = 0.44$; $\mu_{TP} = 1.47$ γ multiplicities
$\Rightarrow P \approx 2.2 \times 10^{-10}$ torr
$T \approx 291$ K

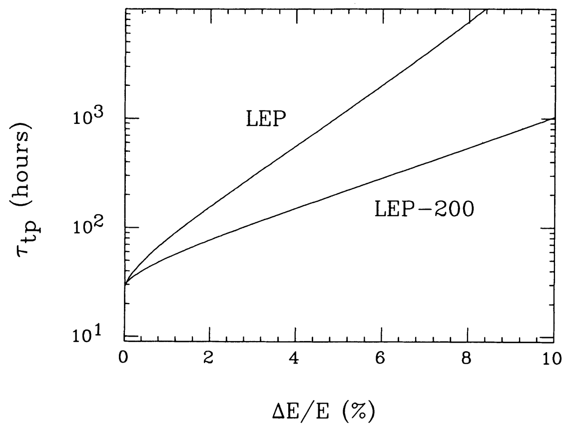


C.Bini et al., PLB **262** (1991) 135

Inverse Compton scattering evaluation

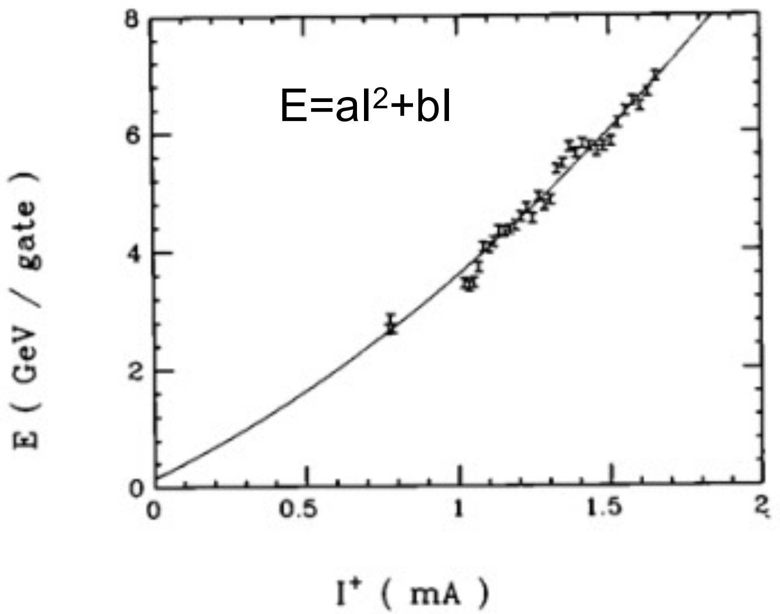


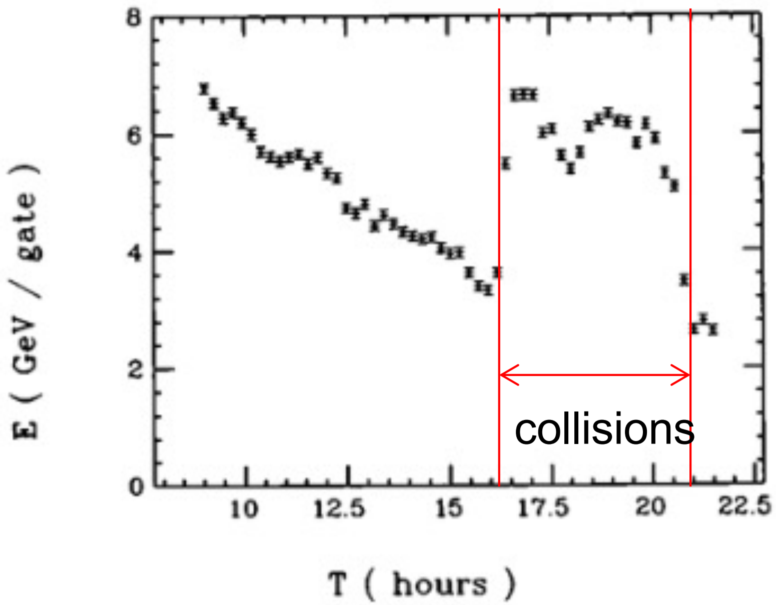




A.Di Domenico, Particle Accelerators **39** (1992) 137

Single bremsstrahlung and background measurement





Separate beams for background measurement

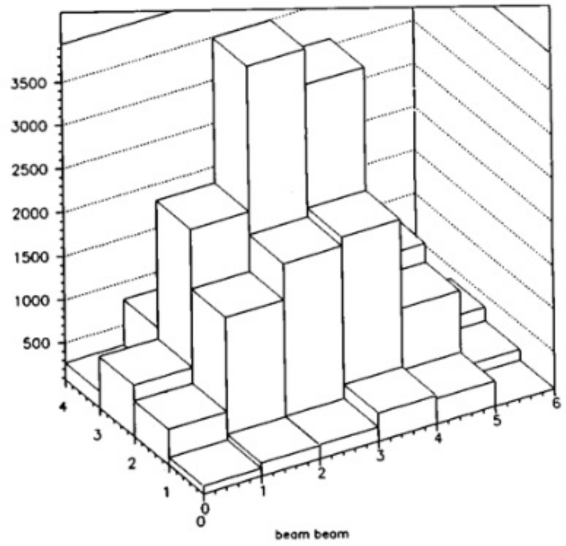
1) Beam-gas Bremsstrahlung
2) Compton scattering of thermal photons

ADC gate = 1 μs T_{LEP}= 22 μs

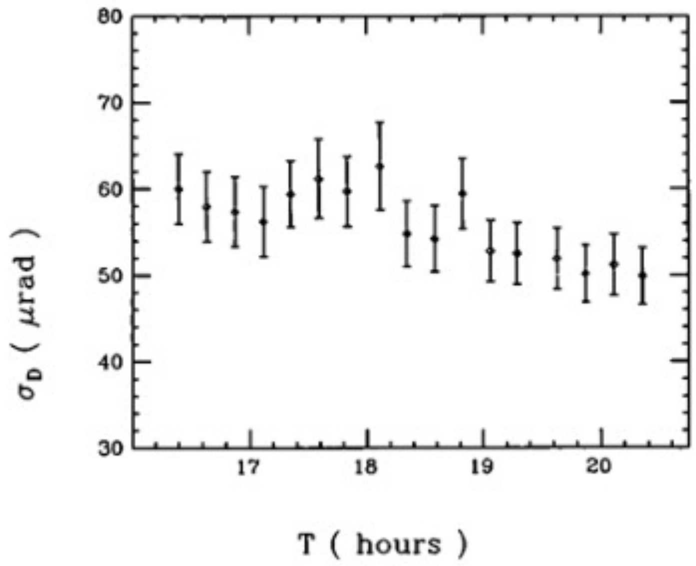
3) Synchrotron radiation
Energy deposited in the calorimeter downstream LiH absorber from MC: SR/SB <1% at LEP nominal luminosity (IP even)

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

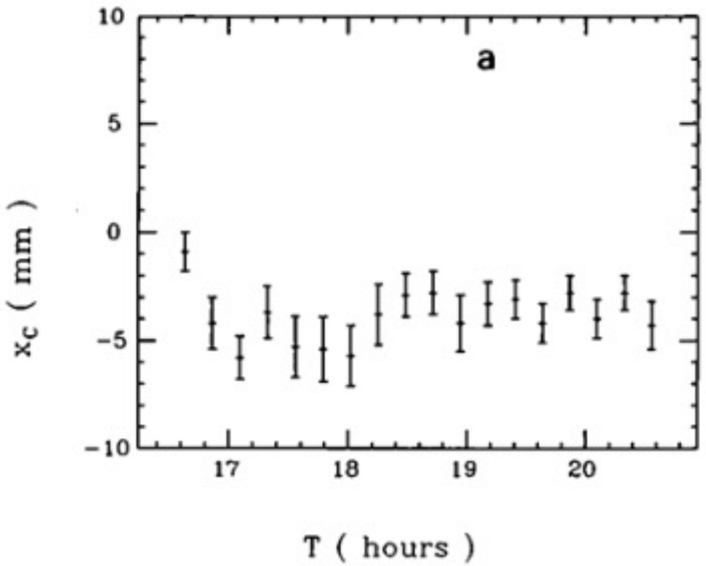
Acceptance



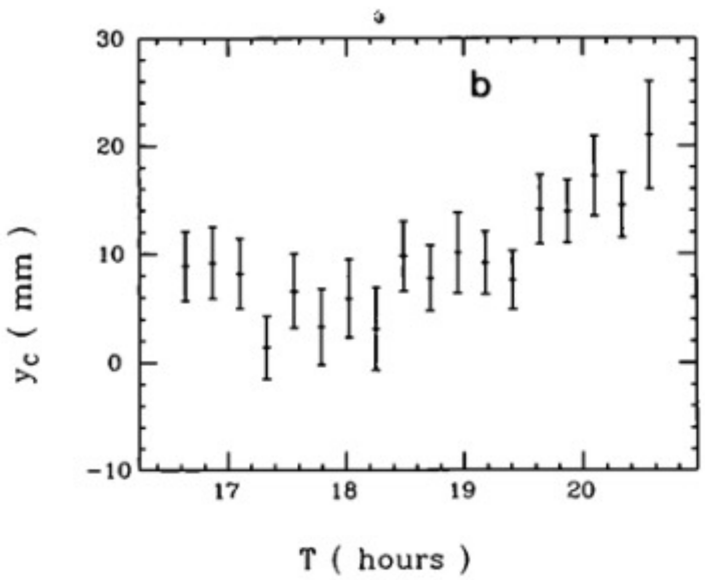
3500
3000
2500
2000
1500
1000
500
beam beam



σ_D (μrad)
T (hours)

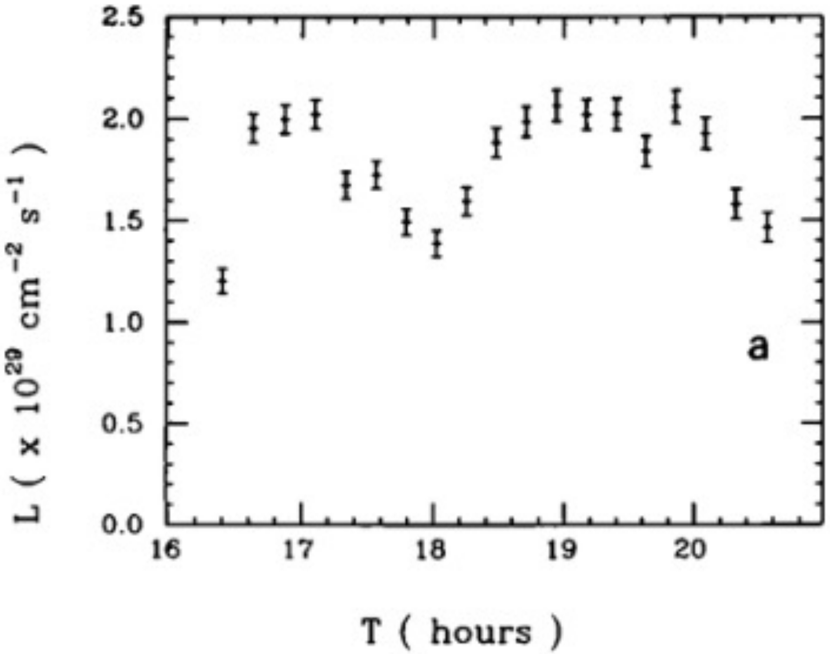


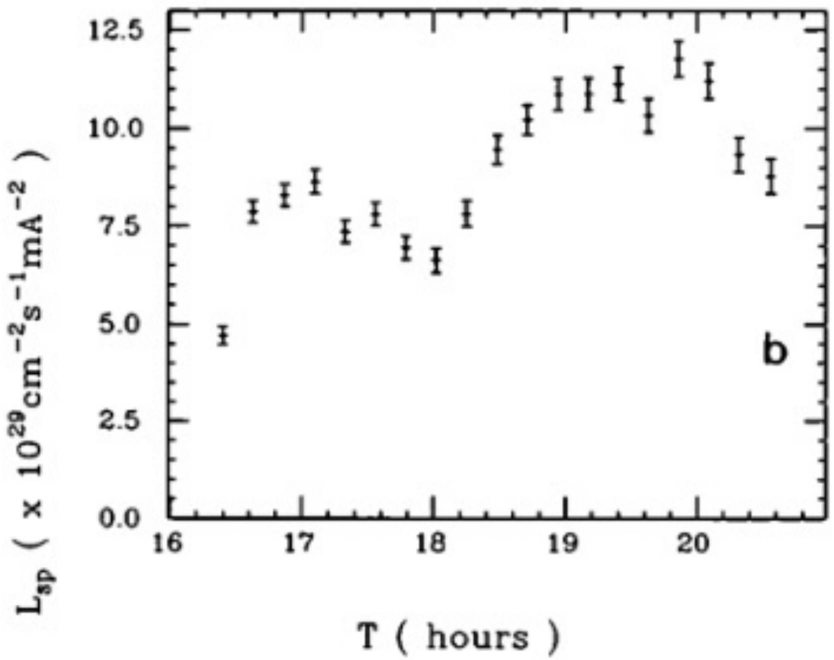
a
x_c (mm)
T (hours)



b
y_c (mm)
T (hours)

Luminosity measurement





Each point ~ 10 min data taking
Statistical 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%

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

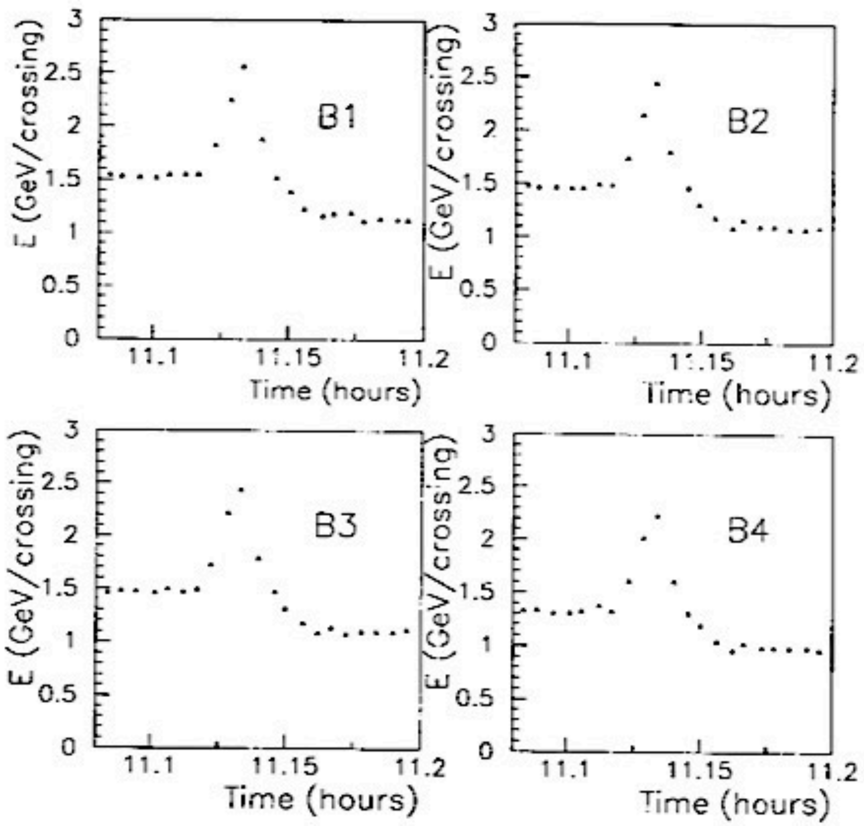
C. Bini at al. NIM **A306** (1991) 467

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

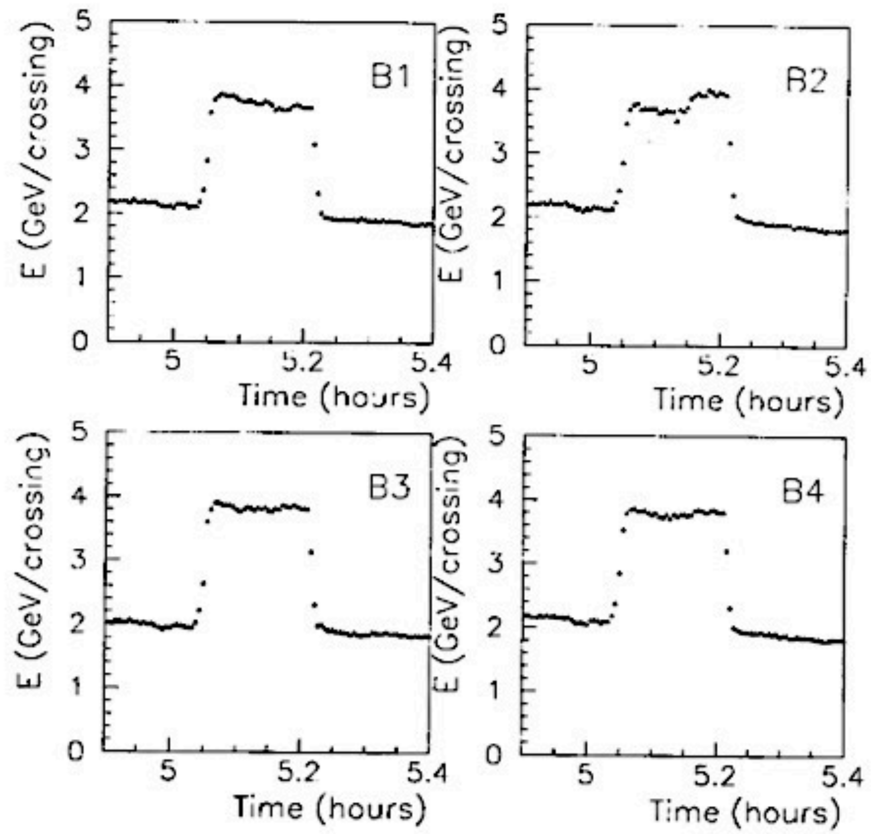
LEP-5 DAQ upgrade

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

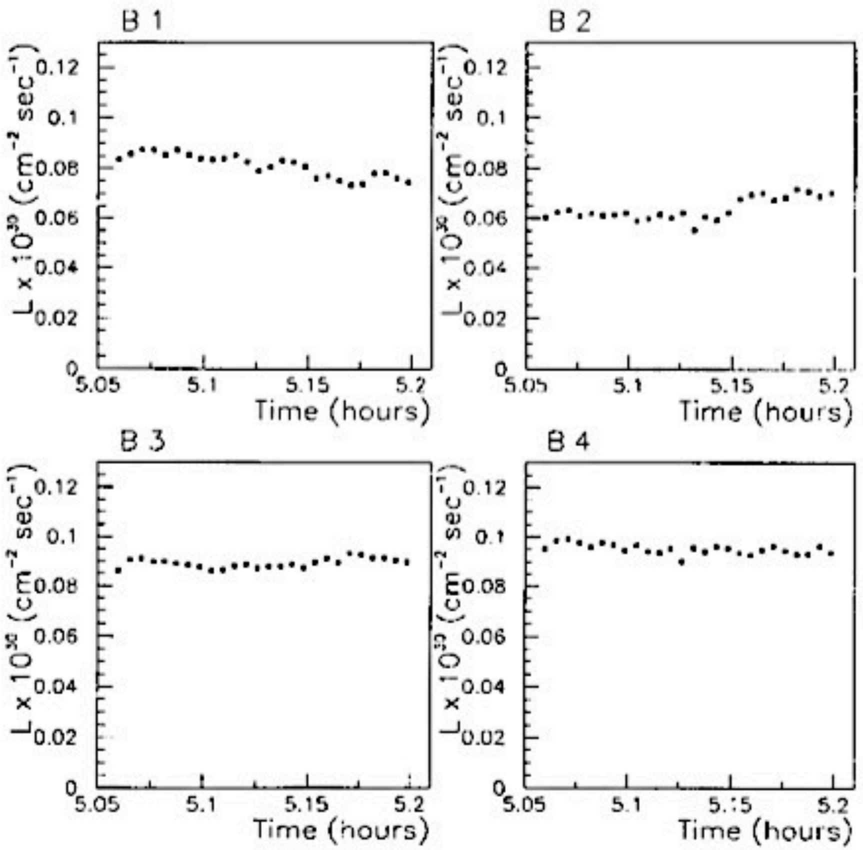


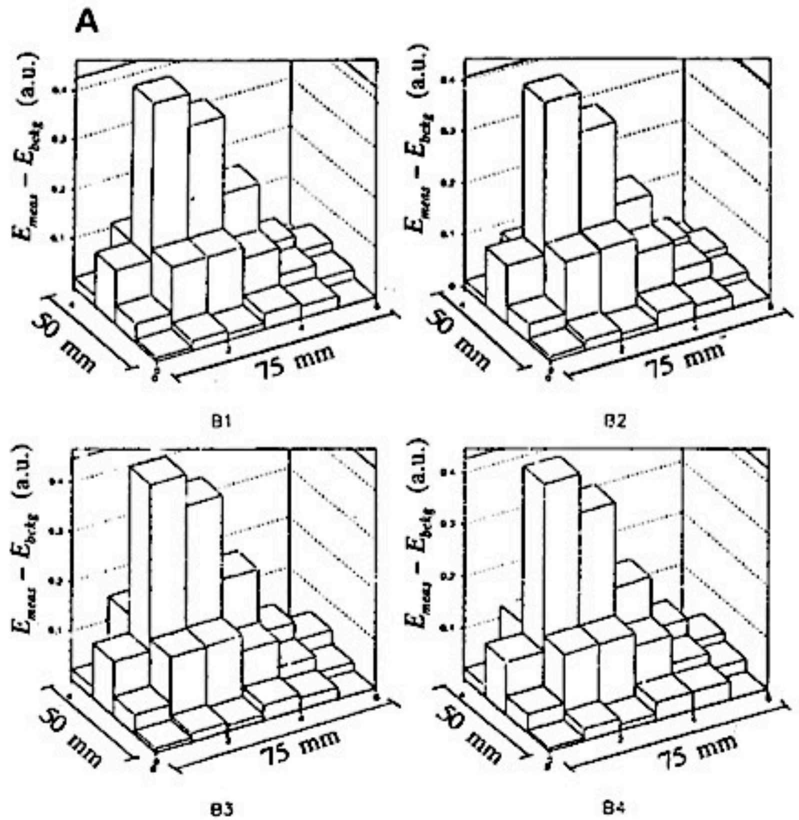
Collisions only for 40 s



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.

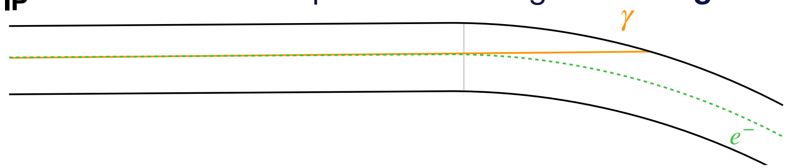
$$\Upsilon \sim \frac{5}{6}\frac{r_e^2 \gamma N_e}{\alpha \sigma_z (\sigma_x + \sigma_y)}$$

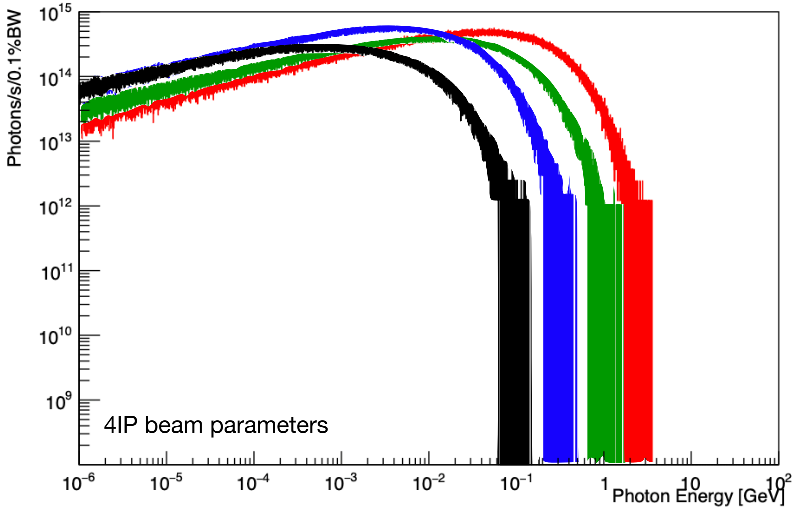
$$< E_\gamma > \sim E \times 0.462\Upsilon$$

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

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++**.



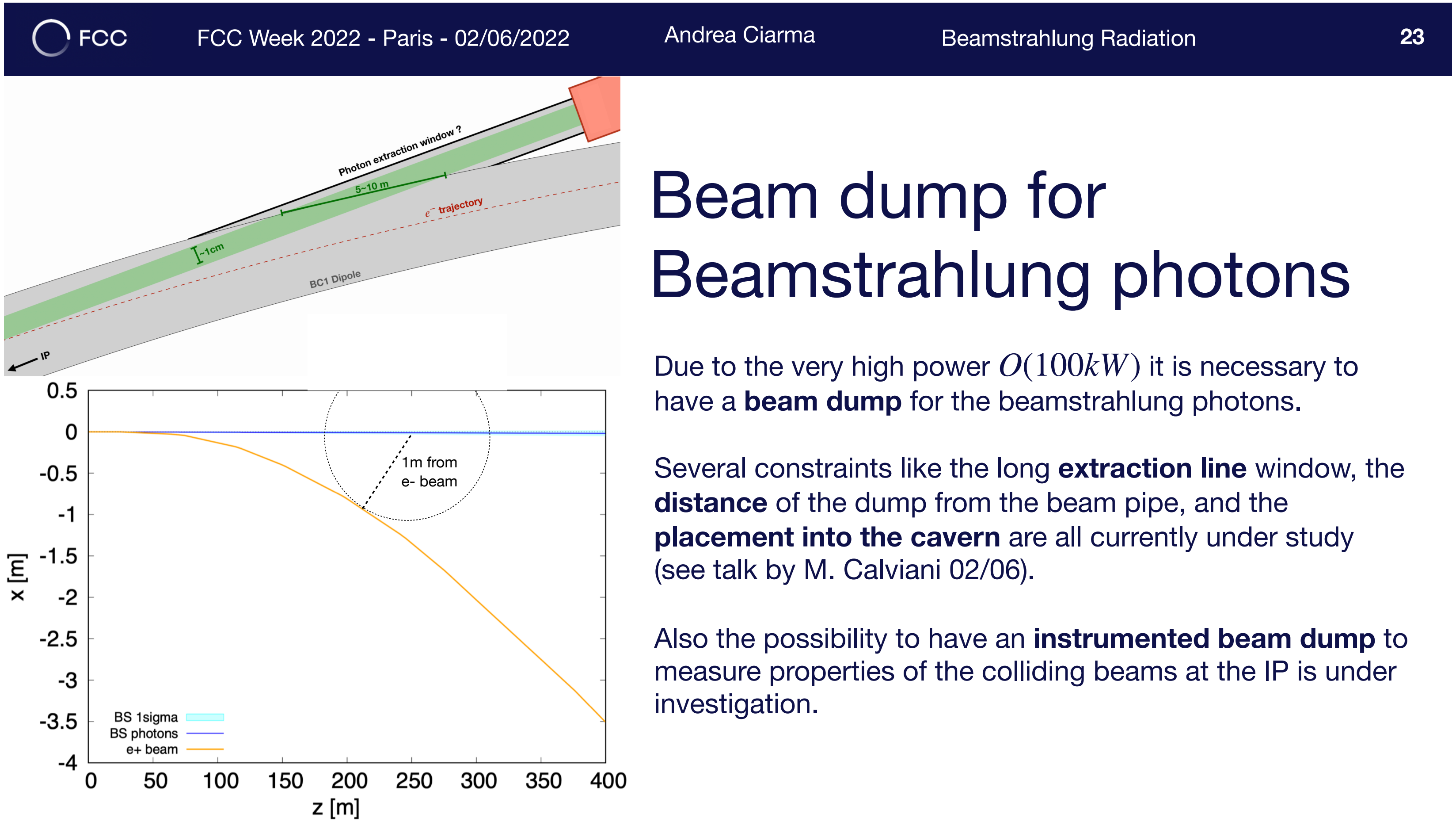


	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

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.



SPARE SLIDES

FCCee basic design choices

Double ring e+e- collider

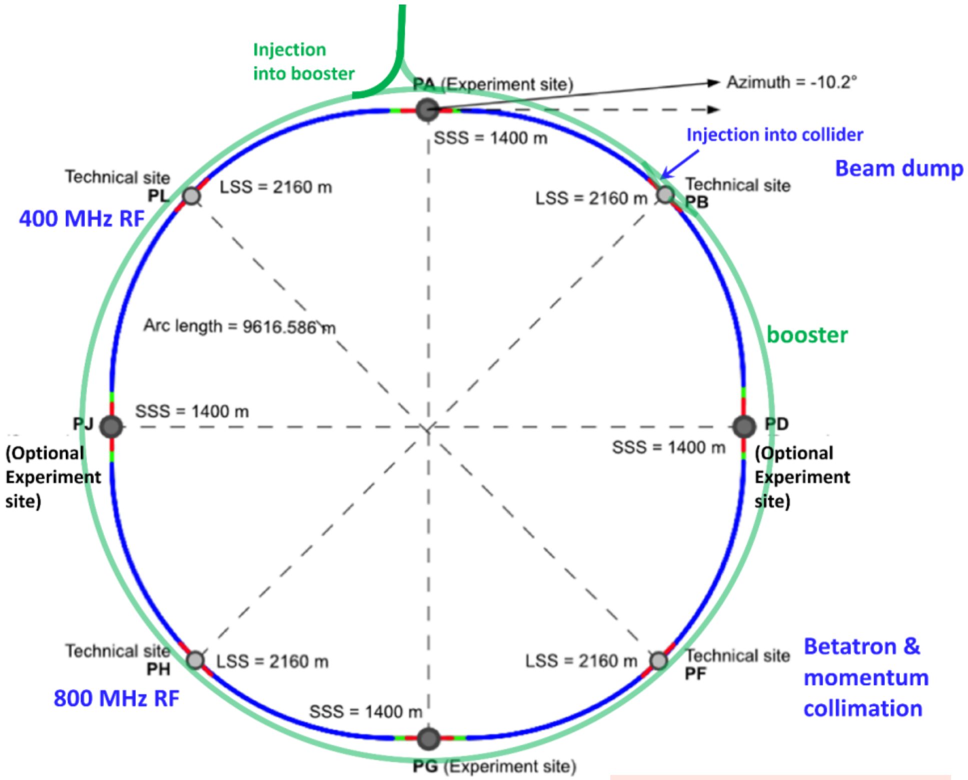
Common footprint with FCC-hh,
except around IPs

Asymmetric IR layout and optics to limit synchrotron radiation towards the detector

Perfect 4-fold superperiodicity allowing 2 or 4 IPs; large horizontal crossing angle **30 mrad, crab-waist collision optics**

Synchrotron radiation power 50 MW/beam at all beam energies

Top-up injection scheme for high luminosity
Requires **booster synchrotron in collider tunnel**



K. Oide, J. Gutleber

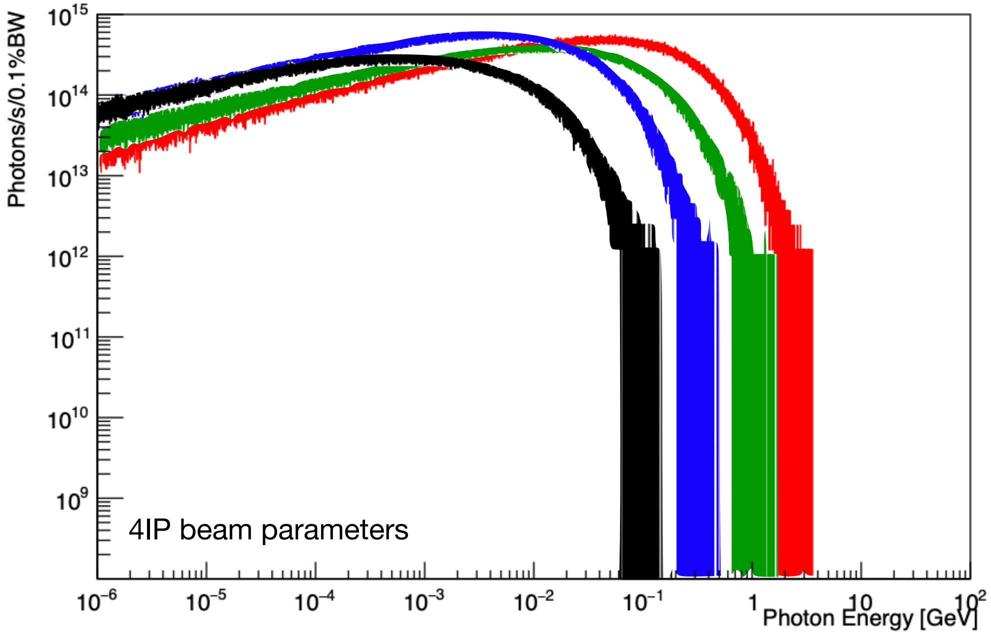
Beamstrahlung radiation Characterisation

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

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

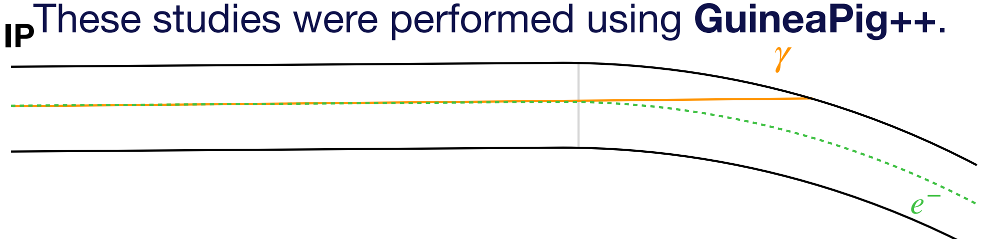
$$< E_\gamma > \sim E \times 0.462\Upsilon$$

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



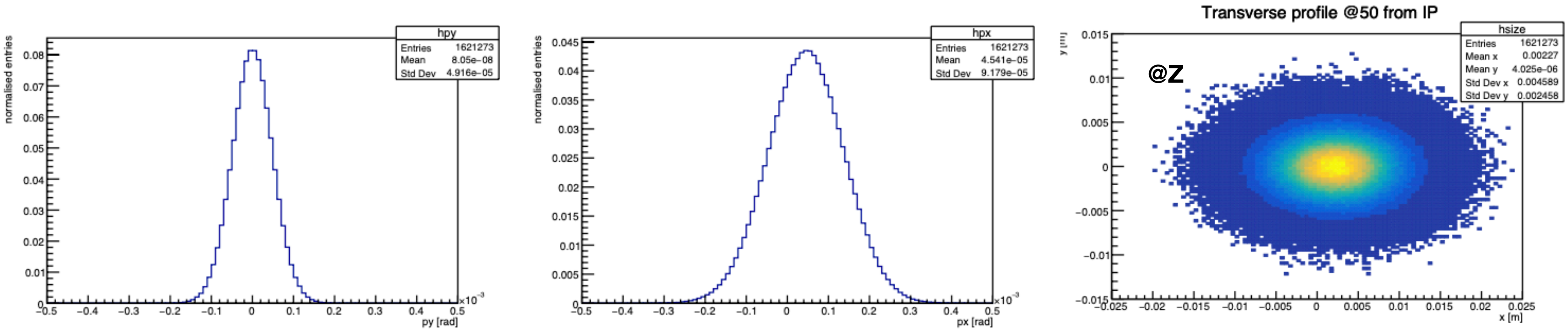
The photons are emitted **collinear to the beam** with an angle proportional to the beam-beam kick. This radiation is extremely intense **O(100kW)** and **hits the beam pipe** at the end of the first downstream dipole.

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

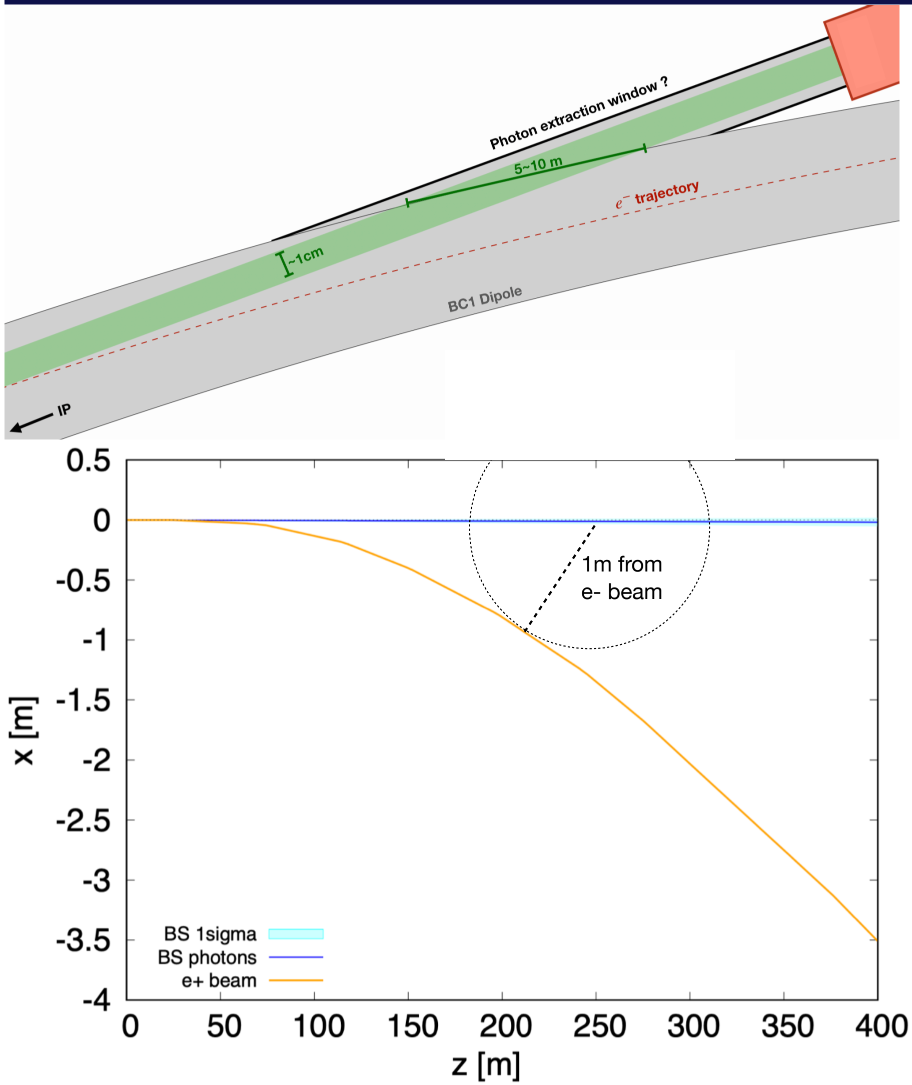


	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

Photons are emitted in a **very narrow cone** ($\propto 1/\gamma$) in the direction of the particle which produced them. As the beam divergence is $O(10 \sim 100\mu rad)$, the **transverse spot size** at few hundred meters from the IP will remain in the order of $O(cm^2)$



	$\sigma_{px}(\gamma)\ [\mu rad]$	$\sigma_{py}(\gamma)\ [\mu rad]$	$\sigma_{px}(e^-)\ [\mu rad]$	$\sigma_{py}(e^-)\ [\mu rad]$	$\sigma_x(\gamma)\ [mm]@50m$	$\sigma_y(\gamma)\ [mm]@50m$
Z	91.8	49.2	84.3	42.1	4.59	2.46
WW	110	73.0	103.4	65.7	5.50	3.65
ZH	51.7	41.3	46.2	35.9	2.58	2.06
Top	44.6	50.3	38.6	43.2	2.23	2.51



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.

FCCee parameters (CDR)

Table 1. Machine parameters of the FCC-ee for different beam energies.

	Z	**WW**	**ZH**	**$t\bar{t}$**	
Circumference (km)	97.756				
Bending radius (km)	10.760				
Free length to IP l^* (m)	2.2				
Solenoid field at IP (T)	2.0				
Full crossing angle at IP θ (mrad)	30				
SR power/beam (MW)	50				
Beam energy (GeV)	45.6	80	120	175	182.5
Beam current (mA)	1390	147	29	6.4	5.4
Bunches/beam	16 640	2000	328	59	48
Average bunch spacing (ns)	19.6	163	994	2763	3396
Bunch population (10^{11})	1.7	1.5	1.8	2.2	2.3
Horizontal emittance ε_x (nm)	0.27	0.84	0.63	1.34	1.46
Vertical emittance ε_y (pm)	1.0	1.7	1.3	2.7	2.9
Horizontal β^*_x (m)	0.15	0.2	0.3	1.0	
Vertical β^*_y (mm)	0.8	1.0	1.0	1.6	
Energy spread (SR/BS) σ_δ (%)	0.038/0.132	0.066/0.131	0.099/0.165	0.144/0.186	0.150/0.192
Bunch length (SR/BS) σ_z (mm)	3.5/12.1	3.0/6.0	3.15/5.3	2.01/2.62	1.97/2.54
Piwinski angle (SR/BS) ϕ	8.2/28.5	3.5/7.0	3.4/5.8	0.8/1.1	0.8/1.0
Energy loss/turn (GeV)	0.036	0.34	1.72	7.8	9.2
RF frequency (MHz)	400			400/800	
RF voltage (GV)	0.1	0.75	2.0	4.0/5.4	4.0/6.9
Longitudinal damping time (turns)	1273	236	70.3	23.1	20.4
Energy acceptance (DA) (%)	±1.3	±1.3	±1.7	-2.8 +2.4	
Polarisation time t_p (min)	15000	900	120	18.0	14.6
Luminosity/IP (10^{34}/cm^{2}s)	230	28	8.5	1.8	1.55
Beam-beam ξ_x/ξ_y	0.004/0.133	0.010/0.113	0.016/0.118	0.097/0.128	0.099/0.126
Beam lifetime by rad. Bhabha scattering (min)	68	59	38	40	39
Actual lifetime incl. beam-strahlung (min)	>200	>200	18	24	18

Notes. For $t\bar{t}$ operation a common RF system is used.