Long Range Quantum Electrodynamical Effects in High Energy Bremsstrahlung

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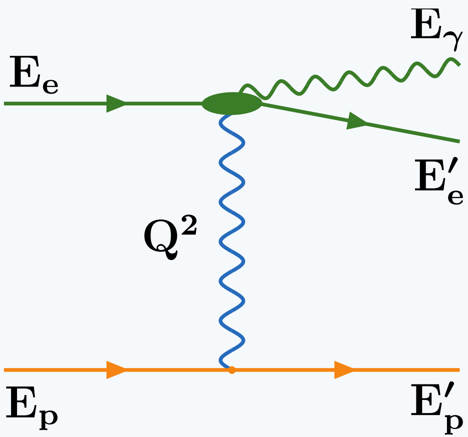
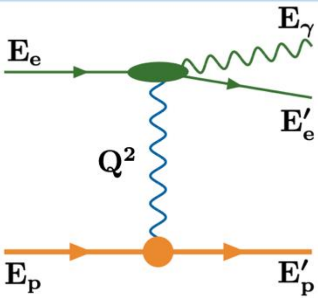


PHE Seminaire, 13 Novembre 2025

Bremsstrahlung *aka* braking radiation is truly unique at high energies



Bremsstrahlung process was first studied by Hans Bethe and Walter Heitl*er* – hence the *Bethe-Heitler* reference still used today – however, its "macroscopically" long-range nature has been quite elusive ever since…

On the Stopping of Fast Particles and on the Creation of Positive Electrons

By H. Bethe, Manchester, and W. Heitler, Bristol

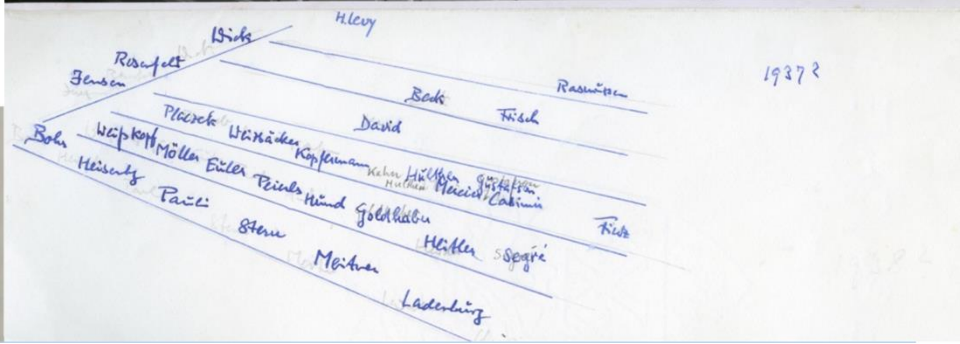
(Communicated by P. A. M. Dirac, F.R.S.—Received February 27, 1934)

For energies large compared with mc^2, *i.e.*, for

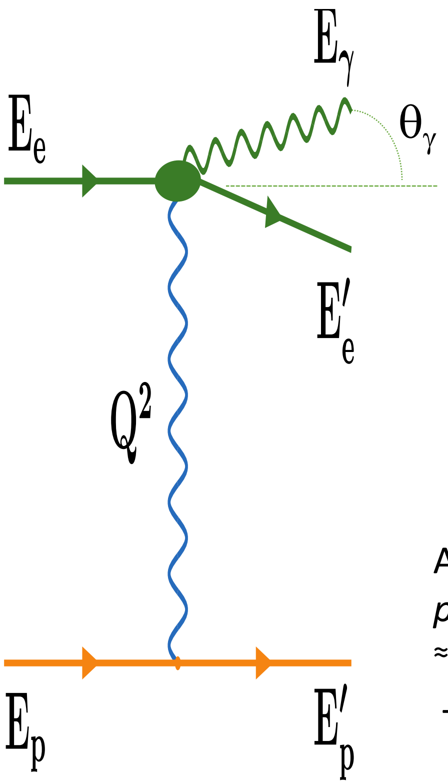
$$E_0 \gg mc^2, \qquad E \gg mc^2, \qquad k \gg mc^2,$$

(15) reduces to

$$\Phi = \frac{Z^2}{137}\left(\frac{e^2}{mc^2}\right)^2 \frac{dk}{k} \frac{4}{E_0^2}\left(E_0^2 + E^2 - \tfrac{2}{3}E_0E\right)\left(\log\frac{2E_0E}{k\mu} - \tfrac{1}{2}\right).$$



e^+e^- bremsstrahlung *aka* radiative Bhabha scattering at high energies



Bremsstrahlung signatures in ***electron-positron collisons*** $e^- + e^+ \rightarrow e^{-\prime} + \gamma + e^+$:

$E'_e + E_\gamma = E_e$ with very (very) high accuracy, and it is "zero-angle process"

$\Rightarrow$ typ. polar angles for photons/scattered electrons, $\theta_\gamma \approx \theta_e \approx m_e/E_e$

It is kinematically allowed that $\theta_\gamma = \theta_{e'} = \theta_p = 0$ hence there is no transverse momentum transfer, which results in (for variables in LAB):

$$|q_{min}| = m_e^3\, E_\gamma/(4\, E_p\, E_e\, E'_e),$$ where

$$Q^2 = -q^2 \simeq -q^2_{min} + p_T^2$$

At FCC/CEPC, for $E_e = E_p = 180$ GeV and $E_\gamma = 2$ GeV, minimal momentum transfer, *in positron rest-frame*, $\Delta p_z = |q_{min}|/c \approx 10^{-8}$ eV/c ! Corresponding to kin. energy transfer $= (\Delta p)^2/2M \approx 10^{-22}$ eV !

That corresponds to coherence length $l_c = \hbar/\Delta p_z \approx$ **20 m** whereas in transverse plane impact parameters can be even larger

Higher beam energies/lower photon energy $\Rightarrow$ **more** extreme it becomes!

Bremsstrahlung and *Beam Size Effect(s)*

$$d^3\sigma/dE_\gamma\, d\theta_e d\theta_\gamma \propto Q^{-4}$$

hence cross-section integrated over angles, that is bremsstrahlung spectrum, is dominated by large distance contributions

$p_T = 0$ → infinite impact parameter!

Beam-Size Effect – *apparent* bremsstrahlung *suppression* at colliders, at low E_γ, due to finite lateral beam-sizes

Discovered at VEPP-4 [Phys. Lett. B113 (1982) 423], measured also at HERA I [Z. Phys. C67 (1995) 577]

Nota bene: This has nothing to do with "environmental effects" – it is present in proper "binary" processes ⇒ collisions of single particles

BSE is directly related to ("text-book") **definition** of cross-sections:

Event rate = Luminosity × σ

where colliding particles are represented by plane waves. But this assumption is **invalid** if lateral sizes of both beams are comparable to relevant impact parameter of process.

⇓

In this case *wave-packet formalism* must be used ⇒ Int. J. Mod. Phys. A7 (1992) 4707

Bremsstrahlung in electron-hadron colliders

Paradoxically, bremsstrahlung was and will be used for luminosity measurements at electron-hadron colliders – HERA at DESY and Electron-Ion Collider (EIC) at BNL

Example: Bremsstrahlung at the EIC

https://arxiv.org/abs/2510.05259

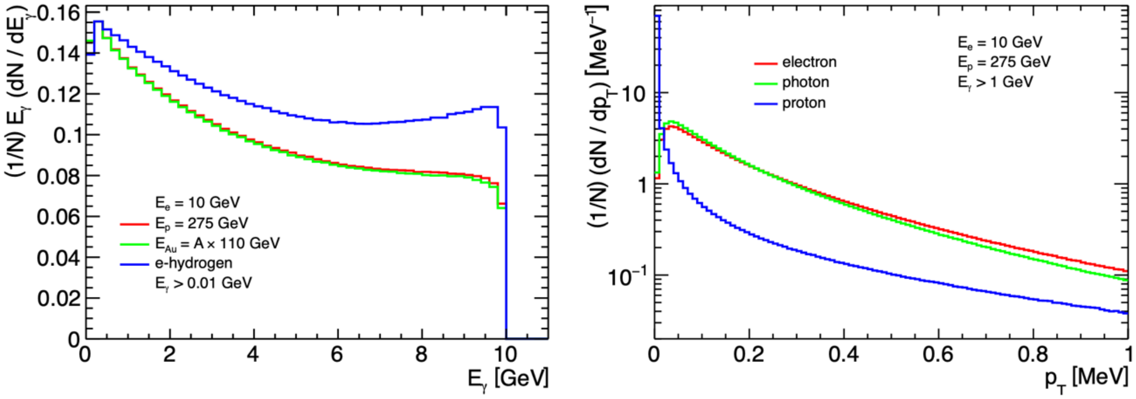
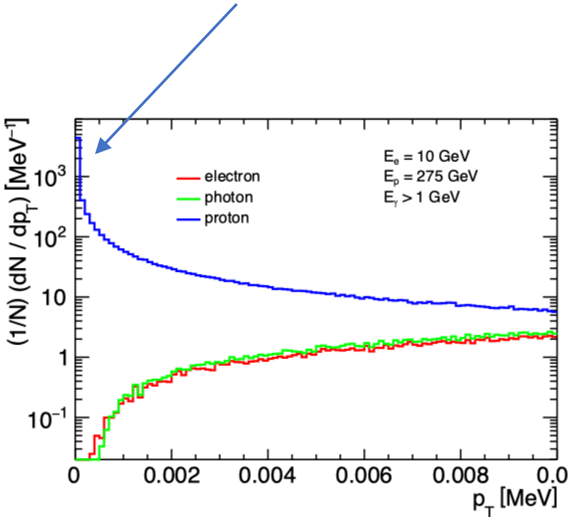


Fig. 9. Normalized photon spectra $\frac{E_\gamma}{N}\frac{dN}{dE_\gamma}$ (left) for the 10 GeV electron beam *ep*, *e*Au and *e*-hydrogen (*e*-gas) collisions, and $\frac{1}{N}\frac{dN}{dp_T}$ (right) for the radiated photons and the scattered electrons and protons for the *ep* collisions; no beam-size effect is considered and 100 million events were generated for each sample.



Note: Screening effect in *e-gas* bremsstrahlung was first manifestation of its microscopically long-range nature

Bremsstrahlung at HERA: Observation of Beam Size Effect

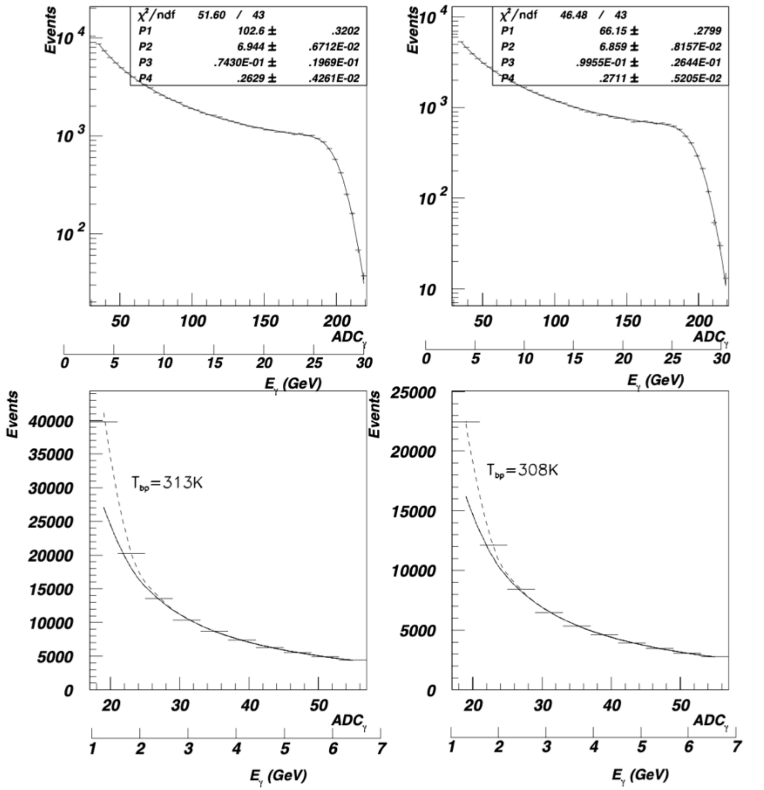
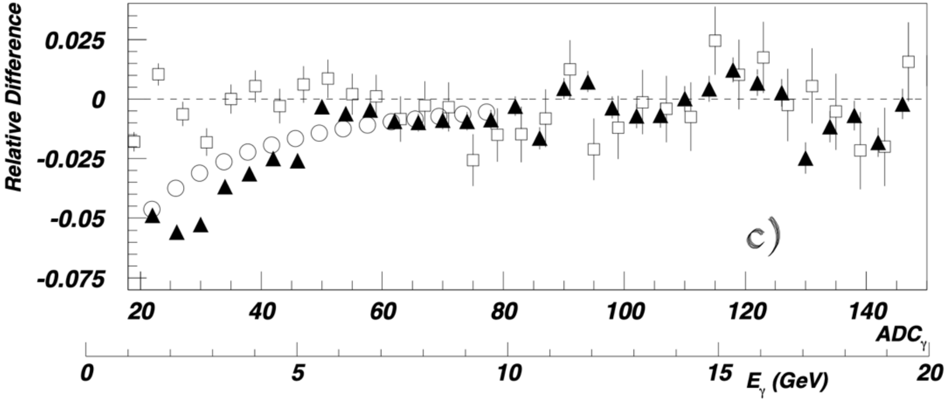


Figure 3: Two spectra of eN bremsstrahlung measured in the luminosity monitor using the electron pilot bunches. The histograms represent the data and the curves are results of fitting the function F (from Eq.1) for $E_\gamma > 3.5$ GeV; in the lower plots the low energy parts of the spectra are shown with extrapolations of the curves obtained from the fits - the excess of events with $2 > E_\gamma > 1$ GeV is well described by adding a contribution from Compton scattering of the blackbody photons off the beam electrons (dashed curves, T_{bp} is the beam-pipe temperature).

K. Piotrzkowski, Zeit. für Physik C **67** (1995) 577,
https://arxiv.org/abs/hep-ex/9504003

Measured *electron-gas* bremsstrahlung agreed with Bethe-Heitler formula but significant suppression of *electron-proton* brems-strahlung was observed at low photon energies – it was found to agree at 30% level with BSE calculations by G. Kotkin *et al.*, Z. Phys. C **39**, 61 (1988):



Letter Open Access

When invariable cross sections change: The Electron-Ion Collider case

Krzysztof Piotrzkowski and Mariusz Przybycien
Phys. Rev. D **103**, L051901 – Published 5 March 2021

Article | References | No Citing Articles | Supplemental Material | PDF | HTML | Export Citation

ABSTRACT

In everyday research, it is tacitly assumed that scattering cross sections have fixed values for a given particle species, center-of-mass energy, and particle polarization. However, this assumption has been called into question after several observations of suppression of high-energy bremsstrahlung. This process will play a major role in experiments at the future Electron-Ion Collider, and we show how variations of the bremsstrahlung cross section can be profoundly studied there using the lateral beam displacements. In particular, we predict a very strong increase of the observed cross sections for large beam separations. We also discuss the relation of these elusive effects to other quantum phenomena occurring over macroscopic distances. In this context, spectacular and possibly useful properties of the coherent bremsstrahlung at the Electron-Ion Collider are also evaluated.

BSE @ EIC

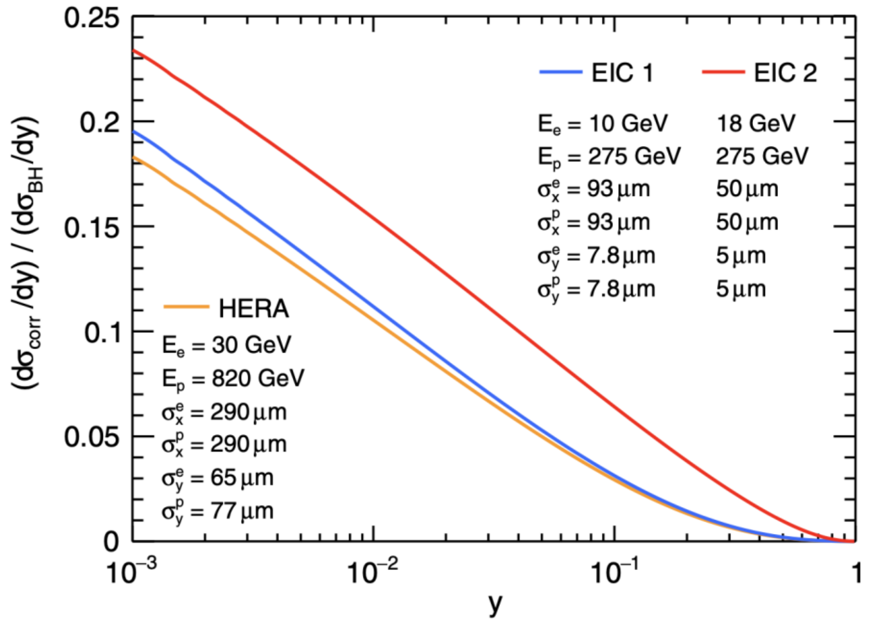


FIG. 2. Relative corrections to the standard Bethe-Heitler cross sections due to the beam-size effect. Relative suppression due to the beam-size effect $(d\sigma_{corr}/dy)/(d\sigma_{BH}/dy)$ is shown as a function of $y = E_\gamma/E_e$ for three cases of electron-proton bremsstrahlung.

https://doi.org/10.1103/PhysRevD.103.L051901

Due to very small **vertical** beam sizes bremsstrahlung suppression at the EIC is **stronger** than at HERA – BSE must be carefully studied and understood to get required precision on the EIC luminosity

$$\sigma_{obs} = \sigma_{BH} - \sigma_{corr}$$

BSE @ EIC

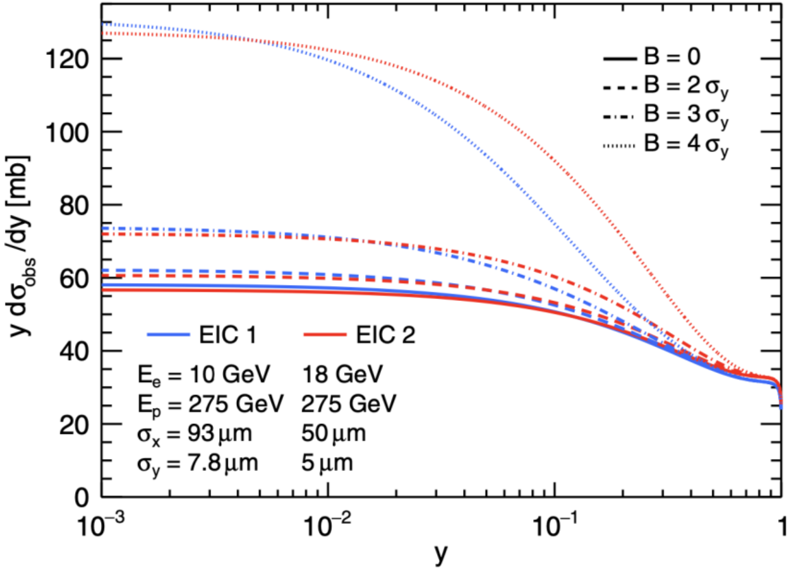


FIG. 4. The predicted spectra of ep bremsstrahlung at the EIC for several vertical beam displacements. The standard Bethe-Heitler cross section $d\sigma_{BH}/dy$ is modified due to the beam-size effect and beam displacements B. The effective cross sections (multiplied by y for better visibility) are shown for two cases of electron-proton collisions at the EIC—the corresponding beam energies and Gaussian lateral beam sizes at the interaction point are listed.

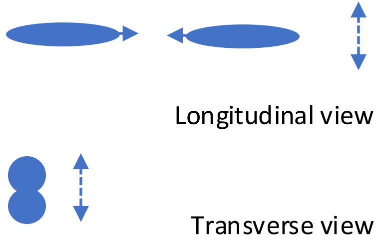
https://doi.org/10.1103/PhysRevD.103.L051901

Powerful test of BSE was proposed by measuring bremsstrahlung spectrum while making beam van der Meer scans (vertically).

This will allow for direct studies/demonstration of very long-range nature of bremsstrahlung process – for large **lateral** beam displacements strong effective **increase** of its cross-section is expected!

(see backup slide for part of actual derivation/calculations)

Vertical *Van der Meer scans*:



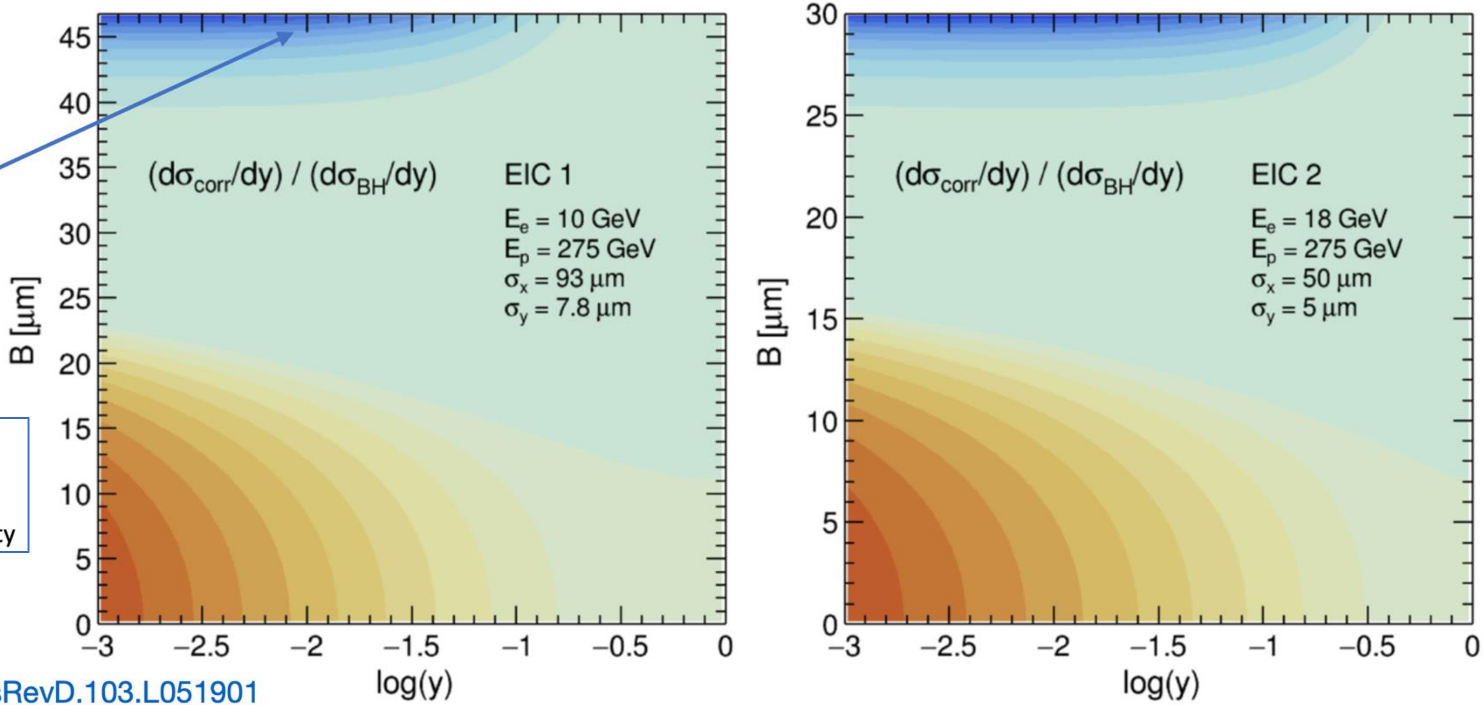
BSE @ EIC

$\sigma \times 80$

Reminder:

$$L(B) = L(0)\exp(-B^2/4\sigma^2)$$

where $L(0)$ is the nominal luminosity



https://doi.org/10.1103/PhysRevD.103.L051901

FIG. 5. Relative corrections to the standard Bethe-Heitler cross sections, due to both the beam-size effect and vertical beam displacements, as a function of B and y. The ratios $(d\sigma_{\rm corr}/dy)/(d\sigma_{\rm BH}/dy)$ are shown as a function of the vertical beam displacement B and the logarithm of the relative photon energy $y = E_\gamma/E_e$ for the two sets of EIC parameters: EIC 1 and EIC 2. The corresponding beam energies and Gaussian lateral beam sizes at the interaction point are listed. Shown are ten equidistant (in the third dimension) contours for the values above zero (displayed in brown) and ten equidistant contours for values below zero (displayed in blue). For the EIC 1 case, the distribution extends in the third dimension between approximately −84 and +0.2, whereas for the EIC 2 case this range

Bremsstrahlung in electron-positron colliders

Bremsstrahlung *aka* radiative Bhabha scattering limits fundamentally beam lifetimes (→ positron sources!)

<u>BSE is very beneficial</u>

BSE @ FCC-ee (and CEPC)

Eur. Phys. J. C (2023) 83:802
https://doi.org/10.1140/epjc/s10052-023-11981-2

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

High energy bremsstrahlung at the FCC-ee, FCC-eh and LHeC

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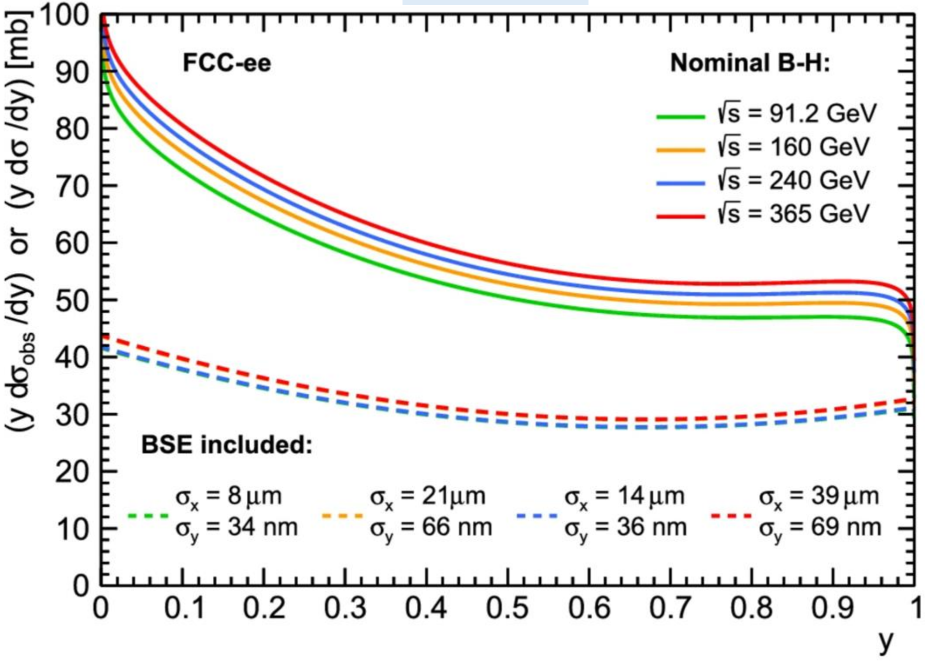
At very high energies, for small flat beams, bremsstrahlung spectra are very strongly distorted and depend only on vertical beam sizes! ⇒

NB: In calculations head-on collisions are assumed, and no hour-glass effects (both effects found very small)

$y = E_\gamma / E_e$



Bremsstrahlung spectra at the $\sqrt{s} = 91.2$ GeV, 160 GeV, 240 GeV and 365 GeV FCC-ee – solid lines $y\,\mathrm{d}\sigma/\mathrm{d}y$ are for the Bethe–Heitler nominal case and dashed ones $y\,\mathrm{d}\sigma_{\mathrm{obs}}/\mathrm{d}y$ when the BSE is included. Note that the spectra with the BSE included overlap due to similar σ_y: those at $\sqrt{s} = 160$ GeV and 365 GeV, as well as those at $\sqrt{s} = 91.2$ GeV and 240 GeV

Beam lifetimes @ FCC-ee

$$\tau_b = N_b/(L_{\rm tot}\sigma_a)$$

Table 2 FCC-ee beam lifetimes due to bremsstrahlung, assuming the most recent beam parameters as given in Table 1 in Ref. [11]

$E_{\rm beam}$ [GeV]	45.6	80	120	182.5
N_b [10^{13}]	242	25.5	5.05	0.945
$L_{\rm tot}$ [10^{35} cm^{-2}s^{-1}]	74.8	7.64	2.92	0.5
σ_a [mb] for $a = 0.01(0.02)$	166 (137)	174 (144)	167 (138)	175 (145)
$\sigma_{\rm BH}$ [mb] for $a = 0.01(0.02)$	319 (260)	333 (271)	343 (280)	353 (288)
τ_b [min] for $a = 0.01(0.02)$	32 (39)	32 (39)	17 (21)	18 (22)

Beam lifetimes @ CEPC

Radiation Detection Technology and Methods (2024) 8:1–1105
https://doi.org/10.1007/s41605-024-00463-y

IHEP-CEPC-DR-2023-01

Received: 7 March 2024 / Revised: 7 March 2024 / Accepted: 9 March 2024 / Published online: 3 June 2024

IHEP-AC-2023-01

CEPC

Technical Design Report

Accelerator

Table 4.1.1: CEPC baseline parameters in TDR

	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	30			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	150/150/75	13.2/13.2/6.6
Piwinski angle	4.88	24.23	5.98	1.23
Bunch number	268	11934	1297	35
Bunch spacing (ns)	591 (53% gap)	23 (18% gap)	257	4524 (53% gap)
Bunch population (10^{11})	1.3	1.4	1.35	2.0
Beam current (mA)	16.7	803.5	84.1	3.3
Phase advance of arc FODO (°)	90	60	60	90
Momentum compaction (10^{-5})	0.71	1.43	1.43	0.71
Beta functions at IP β_x^*/β_y^* (m/mm)	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Betatron tune ν_x/ν_y	445/445	317/317	317/317	445/445
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.5/8.7	2.5/4.9	2.2/2.9
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.13	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) (%)	1.6/2.2	1.0/1.7	1.05/2.5	2.0/2.6
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.004/0.127	0.012/0.113	0.071/0.1
RF voltage (GV)	2.2	0.12	0.7	10
RF frequency (MHz)	650			
Longitudinal tune ν_s	0.049	0.035	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	40/40	90/2800	60/195	81/23
Beam lifetime requirement (min)	18	77	22	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	5.0	115	16	0.5

BSE and beam lifetime @ CEPC

E_{beam} [GeV]	45.5	80	120	180
N_b [10^{13}]	167	17.5	3.5	0.7
L_{tot} [10^{35} cm^{-2}s^{-1}]	23	3.2	1.0	0.1
σ_a [mb] for $a = 0.01$ (0.02)	169 (140)	172 (142)	170 (141)	184 (152)
τ_a [minutes]	71 (86)	53 (64)	34 (41)	63 (77)

Reminder: At very high energies, for very small flat beams, bremsstrahlung spectrum depends (logarithmically) only on vertical beam size ⇒

The integrated cross-section $\sigma_{a,\mathrm{p}} = \int_a^1 \mathrm{d}\sigma_{\mathrm{obs,p}} = 41.77 \times C(r)(a - 5/8 - 3a^2/8 - \ln a)$ [mb], where $a = y_{\min}$ and $C(r) = (1 + 0.074 \ln r)$, $r = \sigma_y/36$ nm

Bremsstrahlung in electron-positron colliders

Large beam lifetime increase was observed at LEP and KEKB, but no proper BSE studies were performed (as luminosity was measured using elastic Bhabha scattering)

SuperKEKB offers unique opportunity to improve our understanding of long-distance effects in bremsstrahlung!

Conclusions

- Bremsstrahlung has truly exceptional properties due its long-range nature
- At high energies, these distances reach macroscopic values, resulting in important "practical" consequences for beam lifetimes and luminosity determination at colliders involving electrons/positrons
- Belle II has a unique possibility to largely improve understanding of these elusive long-range effects!
- Such studies are of interest at fundamental level too – giving new evidence and insights into quantum interactions at **macroscopically** large distances; with possible consequences for understanding origins of UHE cosmic photons, for example.

Thank you for attention!

Backup slide

$$\frac{d\sigma_{\text{corr}}}{dy} = 2\,\frac{\alpha^3}{m_e^2}\,\frac{1}{y}\int_0^\infty F(y,z)\,G(\omega)\,\frac{dz}{(1+z)^2} \qquad (6.7^\star)$$

which is twice as big as the correction in Eq. (6.7) in Ref. [11] due to summing over photon helicities, and

where $\omega = \frac{m_e^2 y(1+z)}{4E_e(1-y)}$ and $\rho_m = E_p/(m_p\omega)$

$$F(y,z) = 2 - y - 4\frac{(1-y)z}{(1+z)^2} - y(1-y) \qquad (6.3)$$

$$G(\omega) = 2\int_0^\infty \frac{\rho_\perp}{\rho_m} K_1^2\left(\frac{\rho_\perp}{\rho_m}\right)\left[1 - \frac{e^{-v_+}}{\pi}\int_0^\pi e^{v_-\cos\varphi}\cosh\left(t_x\cos\left(\frac{\varphi}{2}\right)\right)d\varphi\right]\frac{d\rho_\perp}{\rho_m} \qquad (1)$$

where $t_x = \rho_\perp B/a_x^2$ and $v_\pm = \rho_\perp^2(1 \pm a_y^2/a_x^2)/(4a_y^2)$, where $a_x^2 = \sigma_{x1}^2 + \sigma_{x2}^2$ and $a_y^2 = \sigma_{y1}^2 + \sigma_{y2}^2$ and σ_{x1}, σ_{y1} and σ_{x2}, σ_{y2} are, respectively, the horizontal and vertical beam sizes at the interaction point (that is, at $z = 0$) for two colliding beams; K_1 is the modified Bessel function of the second (third) kind.

The plots in Fig. 1 (left) below are effectively obtained by making cross-sections of the two-dimensional distributions shown in Fig. 5 at fixed B - shapes of the obtained curves are driven by the beam displacement effect at high y, and by the beam-size effect at low y. In Fig. 1 (right) the corresponding plots are shown for the horizontal displacement B at the EIC, according to Eq. (1) above. Finally, for completeness, in Figs. 2 and 3 we show modifications of the photon angular distributions due to the vertical beam displacements and lateral beam-sizes.

All plots have been produced using the `ROOT` analysis framework [20]. Numerical integrations were performed using GNU Scientific Library [21] interfaced to `ROOT`. The library reimplements the algorithms used in `QUADPACK` which are described in Ref. [22].