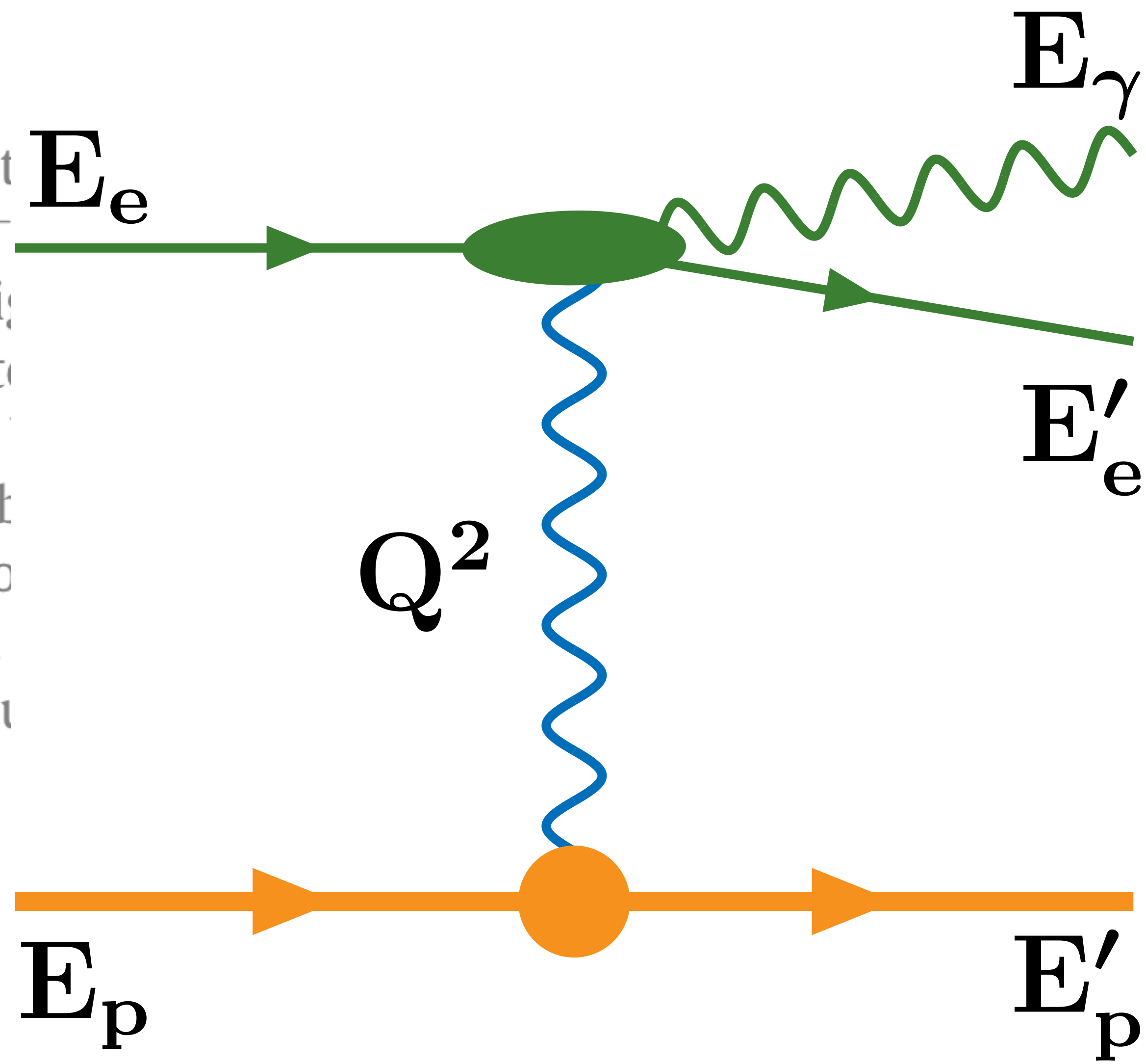
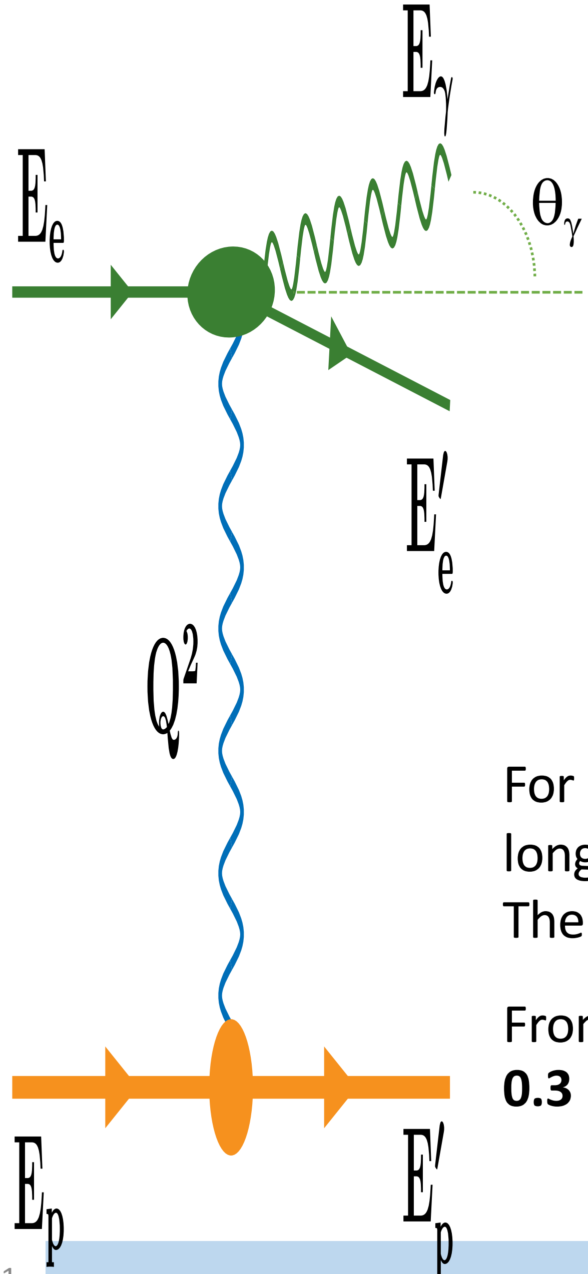
Luminosity measurement challenge at the EIC

Krzysztof PIOTRZKOWSKI – *UCLouvain & AGH UST (Kraków)*

In e^+e^- collisions, the int… the rate of low-angle Bhabha
interactions $e^+e^- \to e^+e^-$ … oretical uncertainty of ±0.061%
on the predicted rate is si… al uncertainties. We present an
updated and more accurat… letter, which is found to reduce
the Bhabha cross section … 7%. When accounted for, these
changes modify the numb…), as determined from the LEP
measurement of the hadro… ± 0.0074. The 20-years-old 2σ
tension with the Standard



ep Bremsstrahlung at High Energy



electron-proton bremsstrahlung ***e + p → e′ + γ + p′*** unique signatures:

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

⇒ 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 transfer of transverse momentum, which results in (for LAB variables):

$$|q_{min}| = m_e^2\, m_p\, E_\gamma/(4\, E_p\, E_e\, E'_e),$$ where

$$Q^2 = -q^2 \approx -q^2{}_{min} + q_T{}^2$$

For example, at the EIC, for $E_e = 18$ GeV, $E_p = 275$ GeV and $E_\gamma = 1$ GeV, one gets the minimal longitudinal momentum transfer, *in the proton rest-frame*, $\Delta p_z = |q_{min}|/c = 0.00073$ eV/c. The corresponding (kinetic) energy transfer = $(\Delta p)^2/2M \approx 3.10^{-16}$ eV!

From the uncertainty principle Δp_z corresponds to the longitudinal distance $\approx \hbar/\Delta p_z$ of **0.3 mm** whereas in the transverse plane the impact parameters can be even larger.

Higher beam energies/lower photon energy ⇒ **more** extreme it becomes!

Bremsstrahlung at HERA: Observation of Beam-Size Effect

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

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

$p_T = 0 \rightarrow$ infinite impact parameter,

$p_{T,typ} \approx |q_{min}|/c \rightarrow$ **Beam-Size Effect –** *effective* bremsstrahlung *suppression* at colliders, at low E_γ, due to small lateral beam-sizes of **two** beams

At HERA I, for E_γ = 1 GeV $|q_{min}| \approx 0.0001$ eV $\Rightarrow$ it corresponded to a 2 mm impact parameter, whereas the **both** HERA colliding beam lateral sizes were $\ll$ 1 mm

Nota bene: This has nothing to do with the "environmental effects" – it is present in proper "binary" processes

BSE is effectively related to the "textbook" **definition** of a cross-section:

$$\text{Event rate} = \text{Luminosity} \times \sigma$$

where colliding particles are represented by PLANE waves – but this *assumption* breaks down if the lateral beam sizes are **comparable** to relevant impact parameter of a process.

Bremsstrahlung at HERA: Observation of Beam-Size Effect

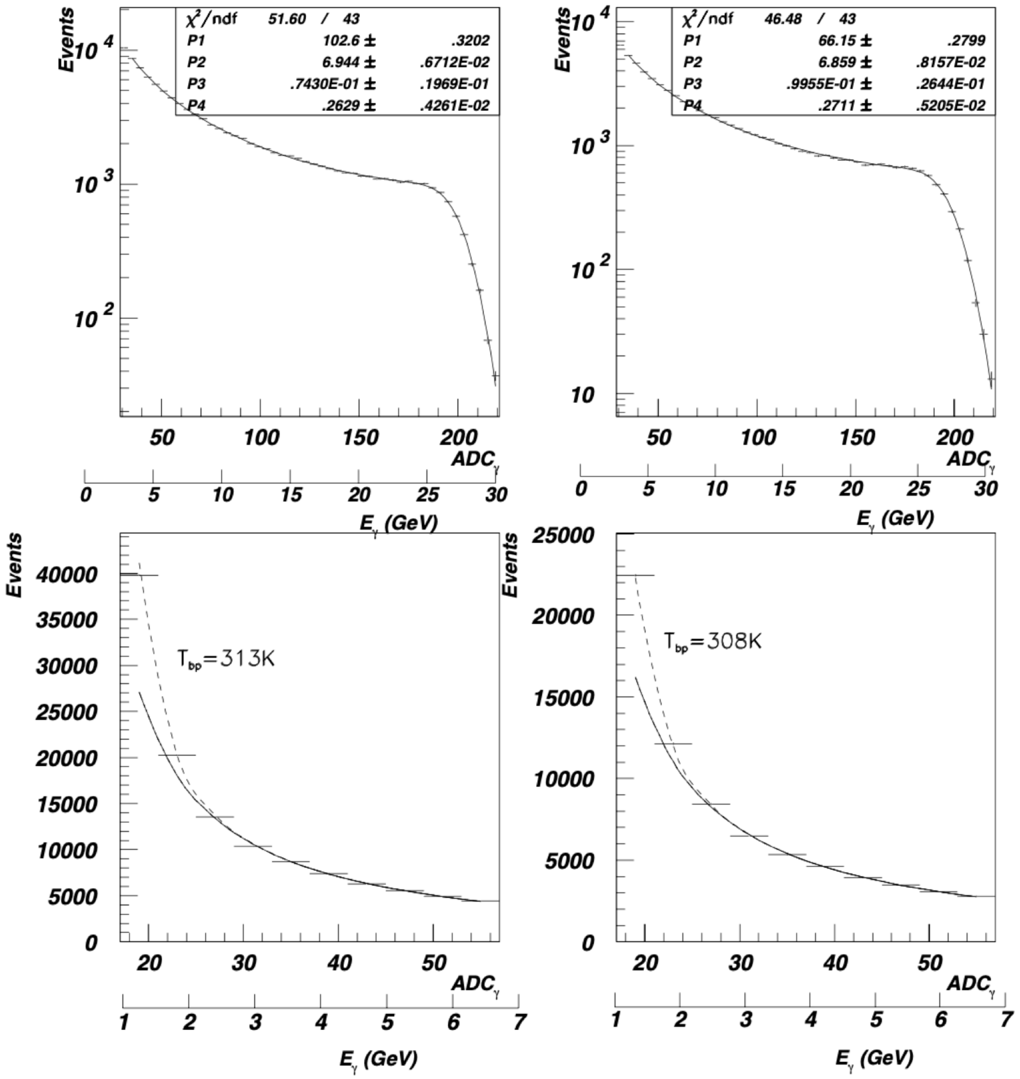
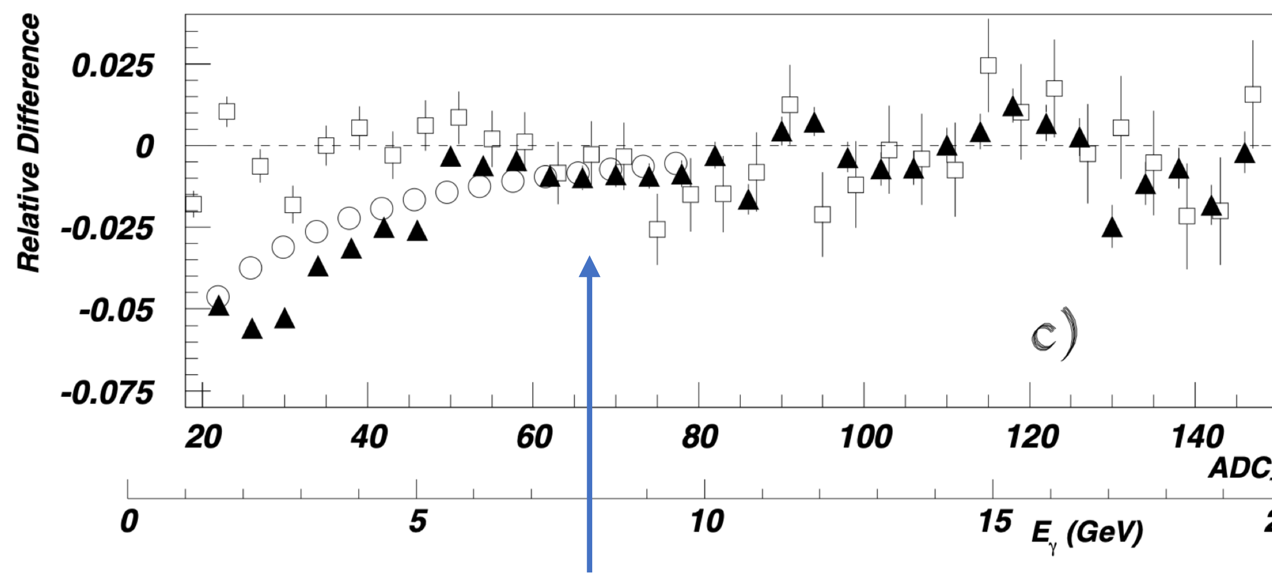


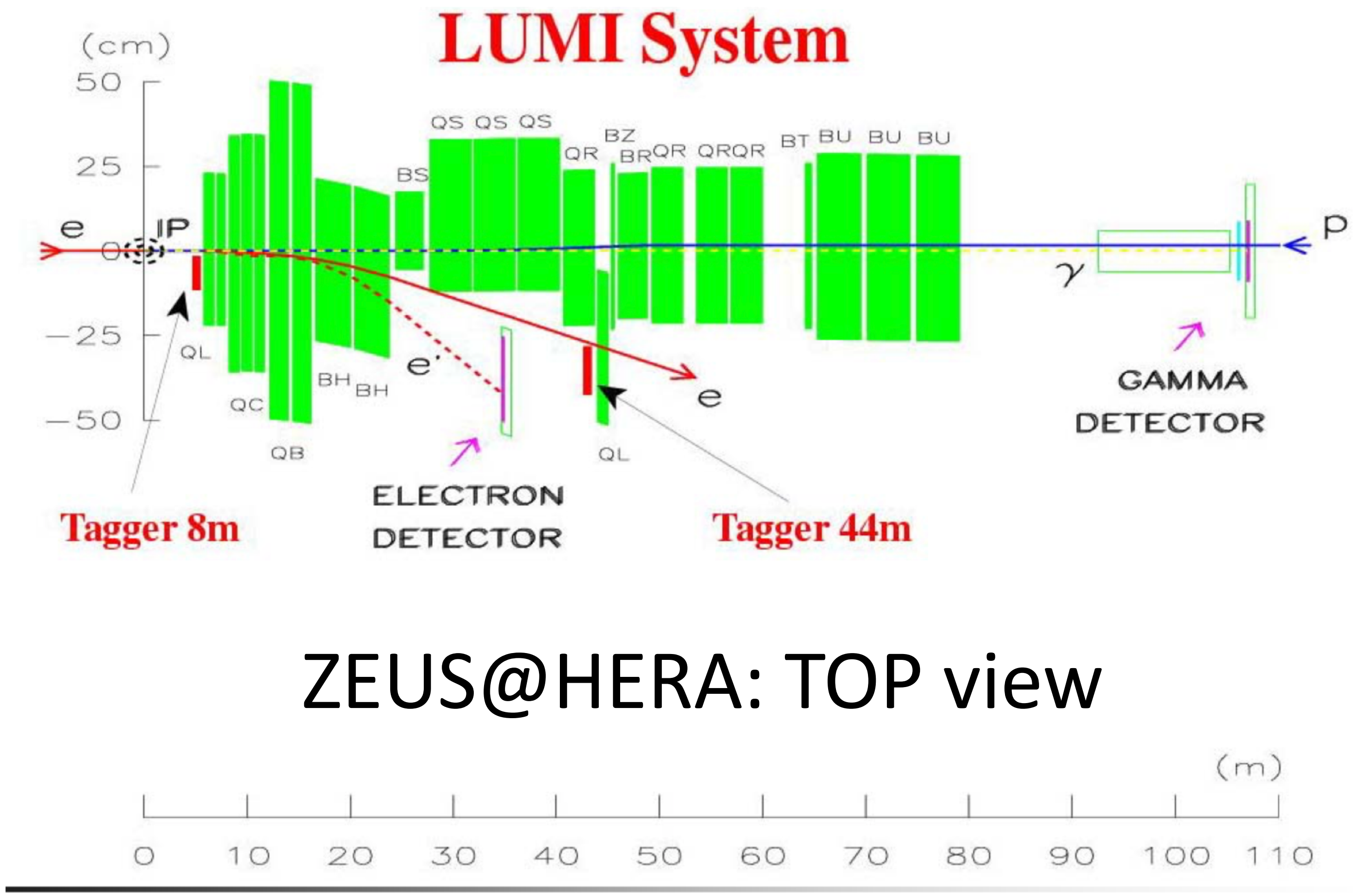
Figure 3: Two spectra of eN bremsstrahlung measured in the luminosity monitor using the electron pilot bunches. The histograms represent the data and the curves are results of fitting the function F (from Eq.1) for $E_\gamma > 3.5$ GeV; in the lower plots the low energy parts of the spectra are shown 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).

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

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



ep Bremsstrahlung: Luminosity measurement (w/ photons) at HERA I

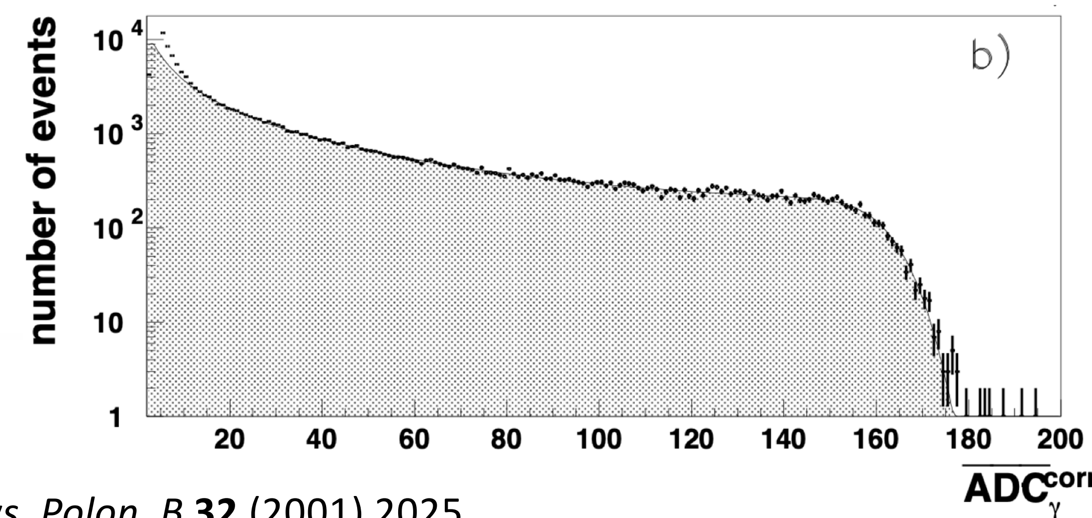


ZEUS@HERA: TOP view

(H1 used similar photon detectors)

27.5 GeV *e* × 820 GeV *p*

Acceptance error	0.8%
Cross section calculation	0.5% ←
e gas background substr.	0.1%
Multiple event correction	0.03%
Energy scale error	0.5%
Total error	1.05%

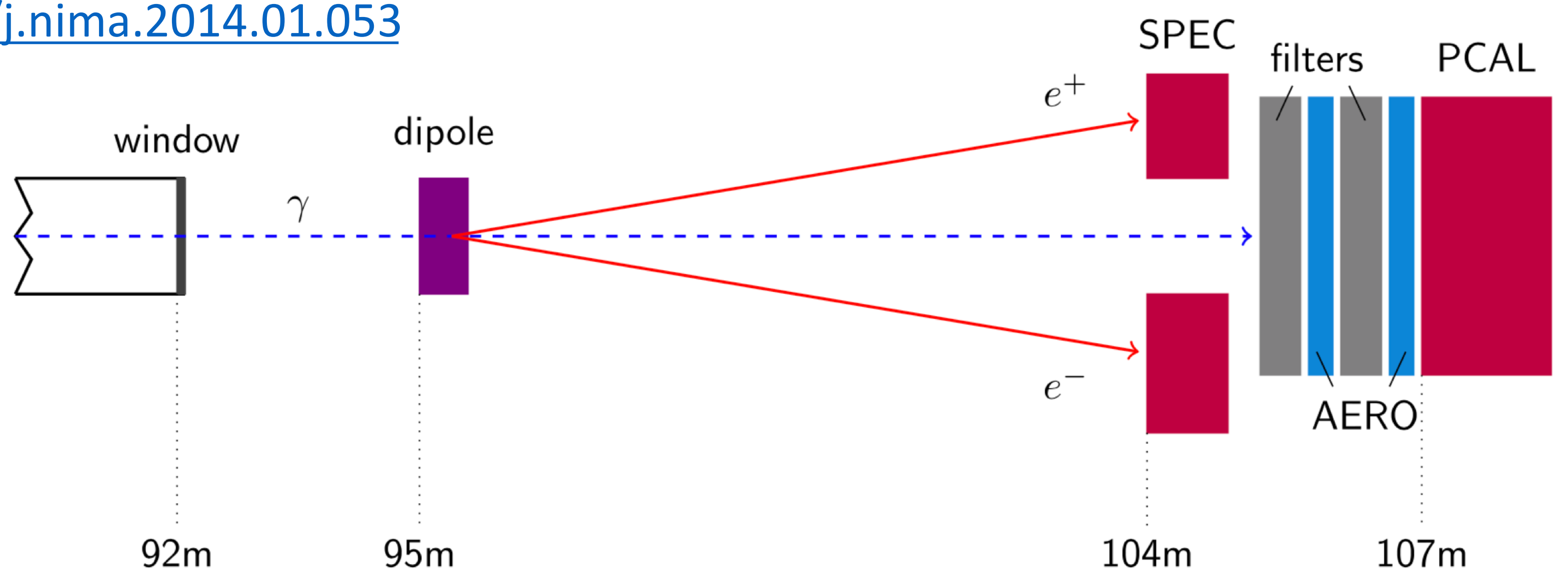


Acta Phys. Polon. B **32** (2001) 2025

ep Bremsstrahlung: Luminosity measurement at HERA II

https://doi.org/10.1016/j.nima.2014.01.053

ZEUS: SIDE view



27.5 GeV *e*
×
920 GeV *p*

Fig. 2. The layout of the luminometers in the ZEUS experiment. The IP was on the left side in the ZEUS detector. A dipole magnet just downstream of the beam-exit window deflected electrons originating from converted photons to the two electromagnetic calorimeters of the spectrometer SPEC. PCAL denotes the photon calorimeter and filters the carbon absorber blocks. AERO are Cherenkov counters not used for the luminosity measurement.

HERA II big challenges: luminosity > 5 × higher (→ event pileup) + **very hard synchrotron radiation** (→ strong SR filtering needed) ⇒ two complementary methods used by ZEUS, but still only 2% precision achieved

H1 using only one ("PCAL") bremsstrahlung measurement, https://doi.org/10.1016/j.nima.2010.12.219, achieved 3% absolute precision – for overall normalization the Compton scattering was used, https://dx.doi.org/10.1140/epjc/s10052-012-2163-2, resulting in final uncertainty of 2.7%

EIC luminosity challenge: electron-ion Bremsstrahlung

Precise cross-section measurements are the corner stone of physics program at the EIC, hence very demanding requirements for the EIC luminosity measurement:

- **Absolute $\mathcal{L}$ precision of 1%,** or better
- "Bunch-to-bunch" relative measurements with very high precision of $\delta(\mathcal{L}_1/\mathcal{L}_2) \approx \mathbf{10^{-4}}$

HERA recipe: very precisely measure bremsstrahlung rate R + use the "definition relation" $R = \mathcal{L}\,\sigma$

However: nominal EIC *ep* luminosity will be almost **1000 times bigger** than that at HERA I, and thanks to 10 times smaller bunch spacing the event pileup will be partially mitigated – for $E_\gamma/E_e > 1\%$, $\sigma_{BH} = 0.23$ b at $E_e = 10$ GeV; **as event pileup scales roughly as $Z^2/2A$** hence for *eAu* case, instead of **23** hard photons every 10 ns, more than **300** photons ($\sigma_{BH} = 1.4$ kb) will hit detectors, what corresponds to >**30 GHz total event rate**!

electron-ion **bremsstrahlung,** $e + i \rightarrow e' + \gamma + i$

- (very) large cross-sections ($\propto \mathbf{Z^2}$), with very small HO corrections
- σ_{BH} is *insensitive* to the beam polarizations, but what is the polarization sensitivity (limit) according to the HO calculations – **is it $\ll 10^{-4}$?**
- unique signatures:
  $E_{e'} + E_\gamma = E_e$ to a very high accuracy and
  it is a truly "zero-angle process"

⇒ OK, but **what about the beam-size effect?**

Measurements of the Beam-Size Effect @ EIC

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

Letter Open Access

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

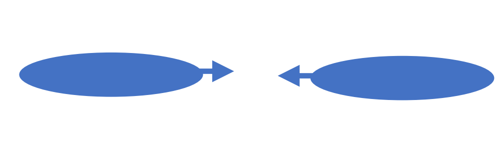
Krzysztof Piotrzkowski and Mariusz Przybycien
Phys. Rev. D **103**, L051901 – Published 5 March 2021

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

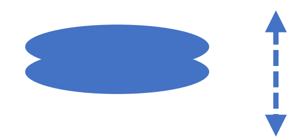
ABSTRACT

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.

Using *Van der Meer scans*:



Longitudinal view



Transverse view

BSE @ EIC

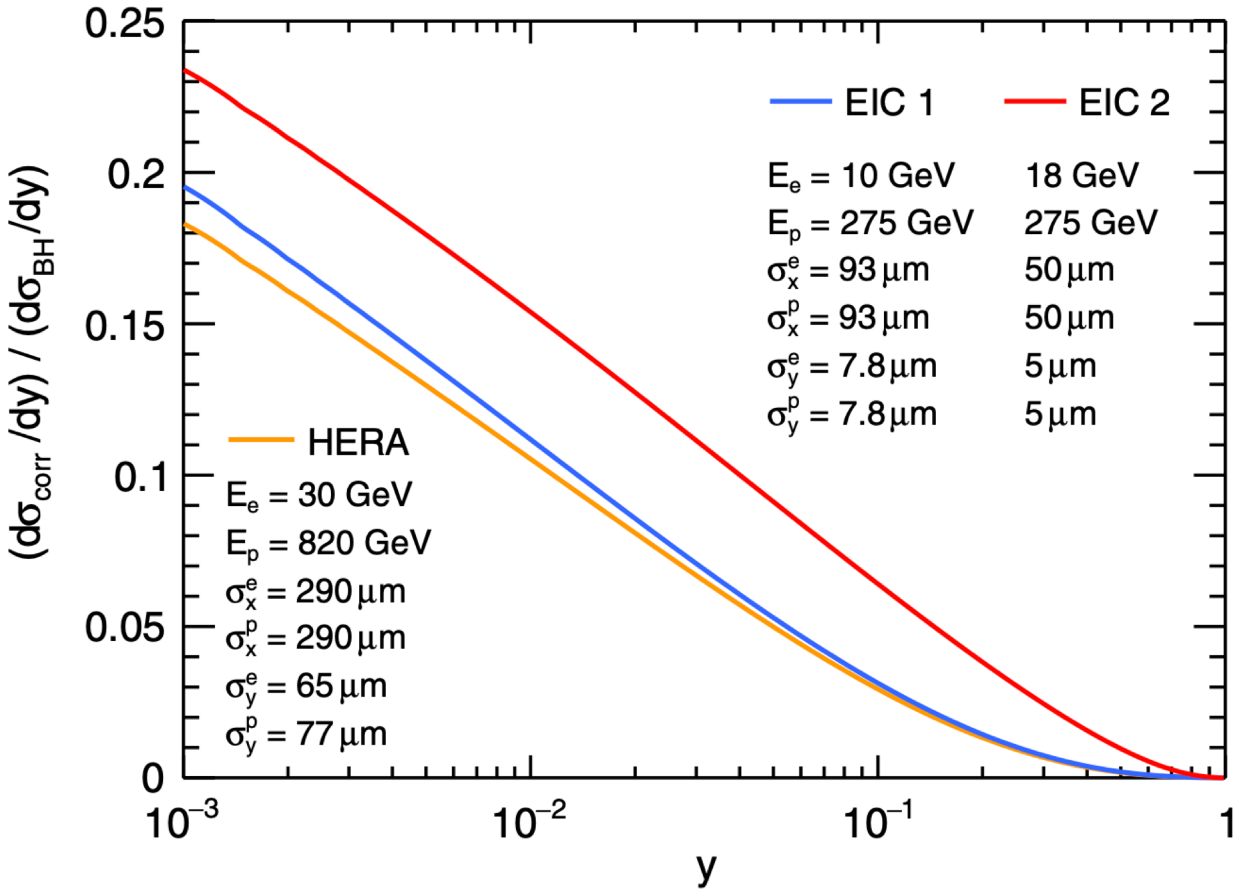


FIG. 2. Relative corrections to the standard Bethe-Heitler cross sections due to the beam-size effect. Relative suppression due to the beam-size effect $(d\sigma_{\rm corr}/dy)/(d\sigma_{\rm BH}/dy)$ is shown as a function of $y = E_\gamma/E_e$ for three cases of electron-proton bremsstrahlung.

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 has to be carefully studied and understood to get the required precision on the EIC luminosity (also in case of electron-ion collisions).

BSE @ EIC

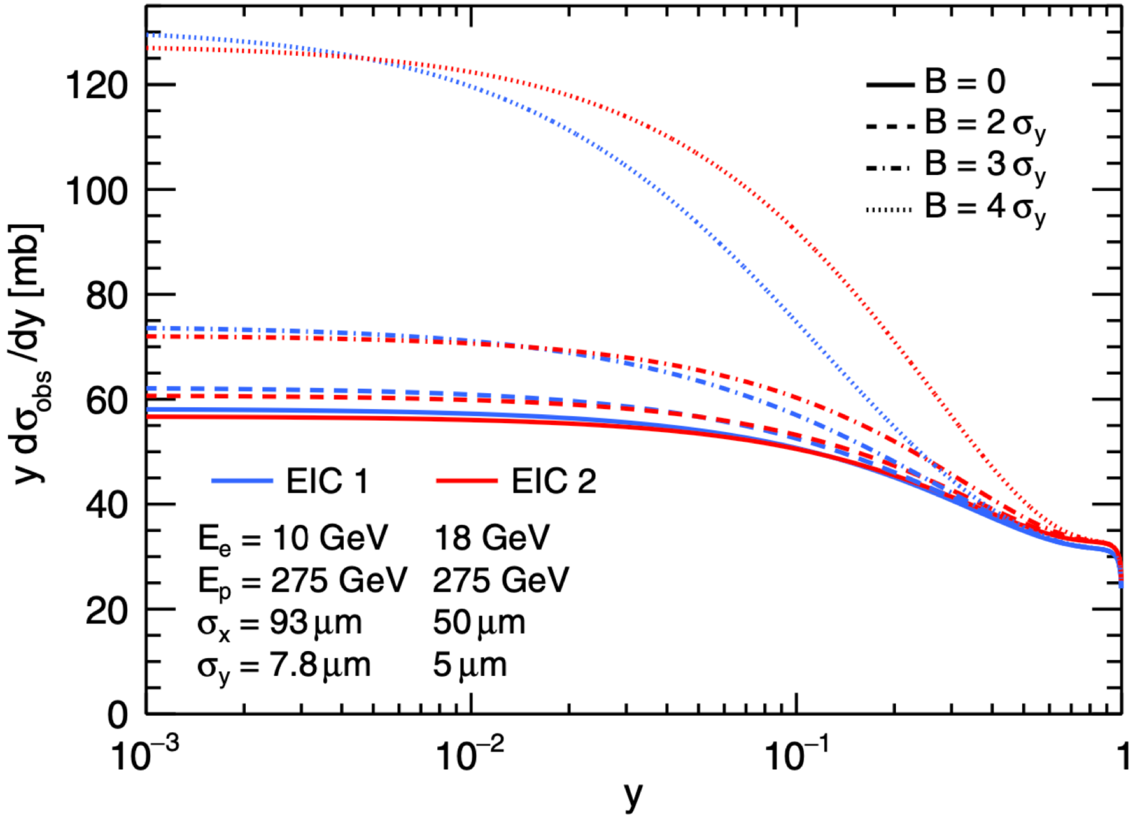


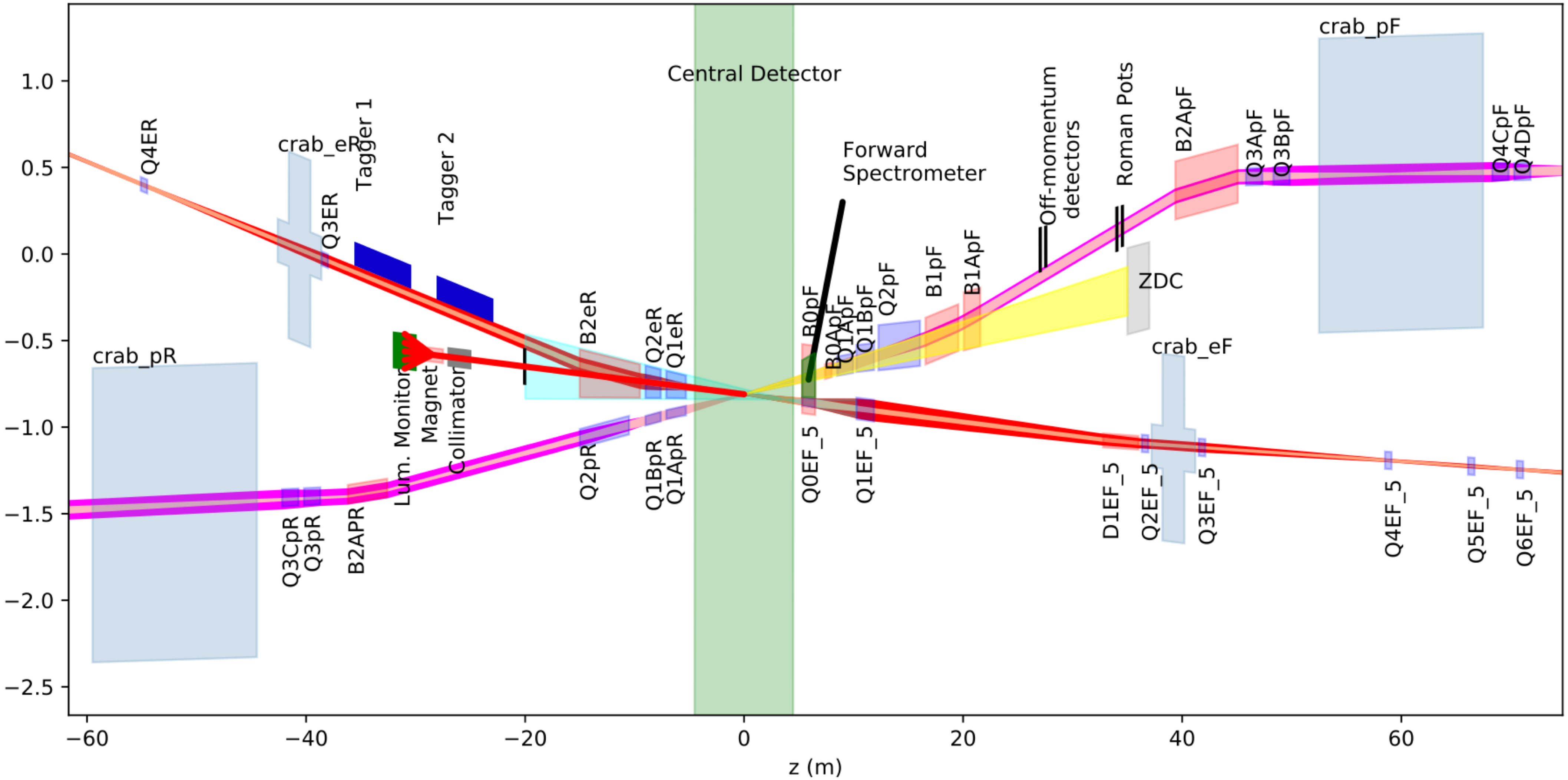
FIG. 4. The predicted spectra of $e\,p$ bremsstrahlung at the EIC for several vertical beam displacements. The standard Bethe-Heitler cross section $d\sigma_{\mathrm{BH}}/dy$ is modified due to the beam-size effect and beam displacements B. The effective cross sections (multiplied by y for better visibility) 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

We propose an original and powerful test of the BSE by measuring the bremsstrahlung spectrum while scanning (vertically) using one (hadron) beam.

This will be at the same time an exciting direct study/demonstration of very long-range nature of bremsstrahlung process – for large **lateral** beam displacements we predict a strong **effective increase** of its cross-section!

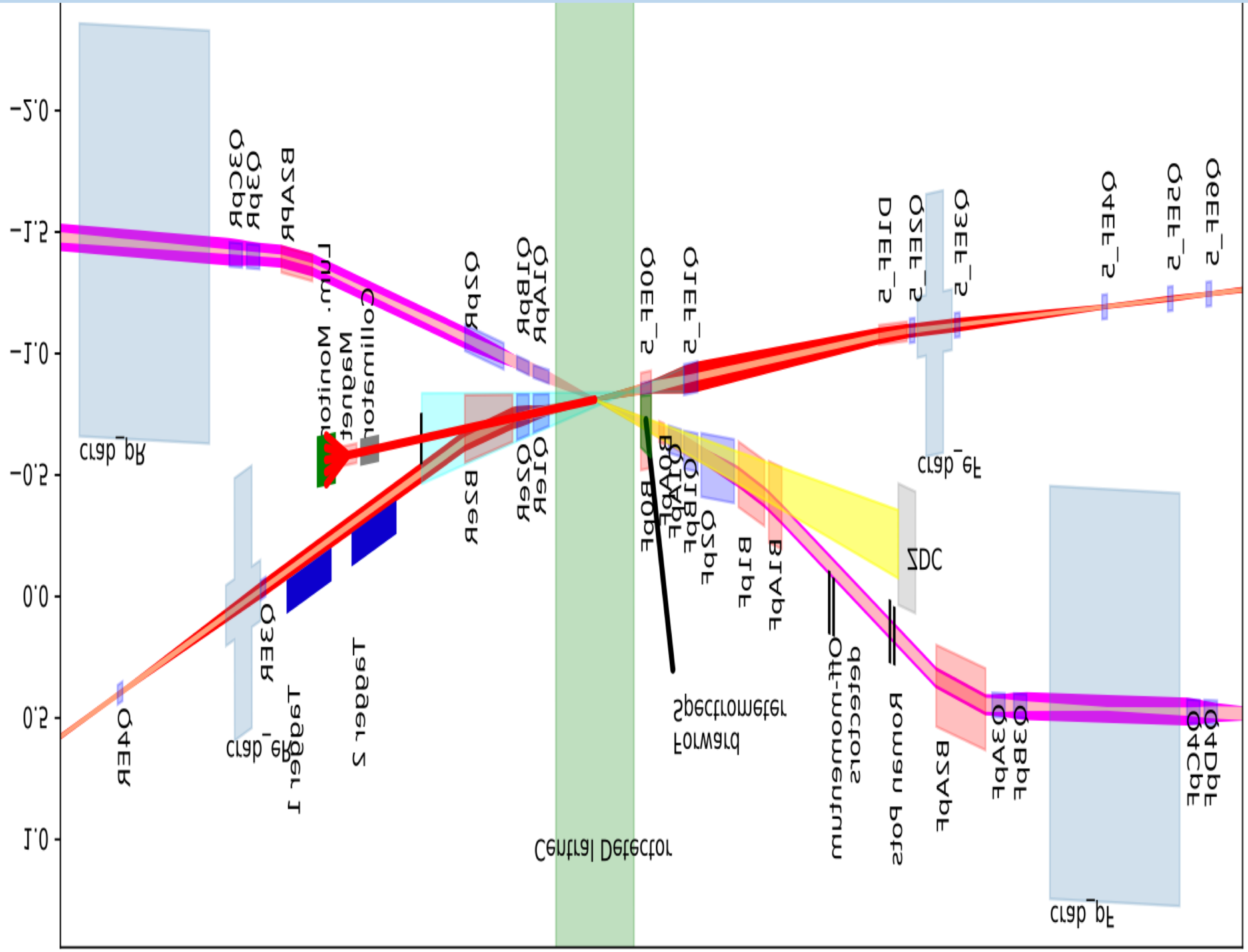
Interaction Region at the Electron-Ion Collider



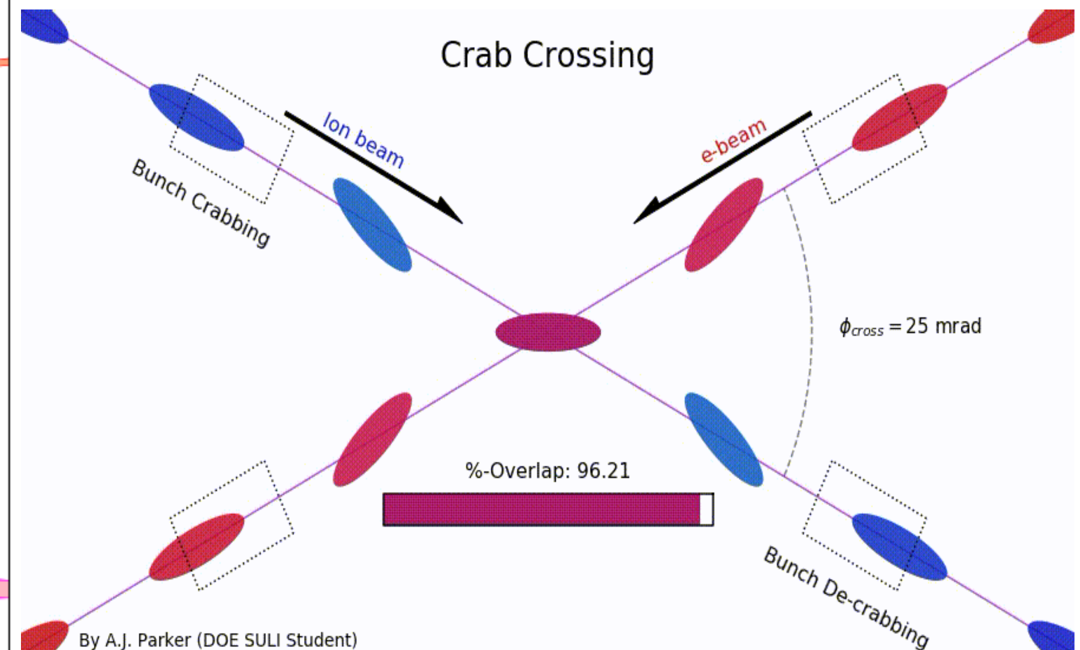
Provisions have been made in the EIC *Interaction Region* designs for the luminosity measurements using bremsstrahlung, as well as for very forward electron detectors (photoproduction taggers)

https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf
https://wiki.bnl.gov/eic/

Interaction Region at the EIC

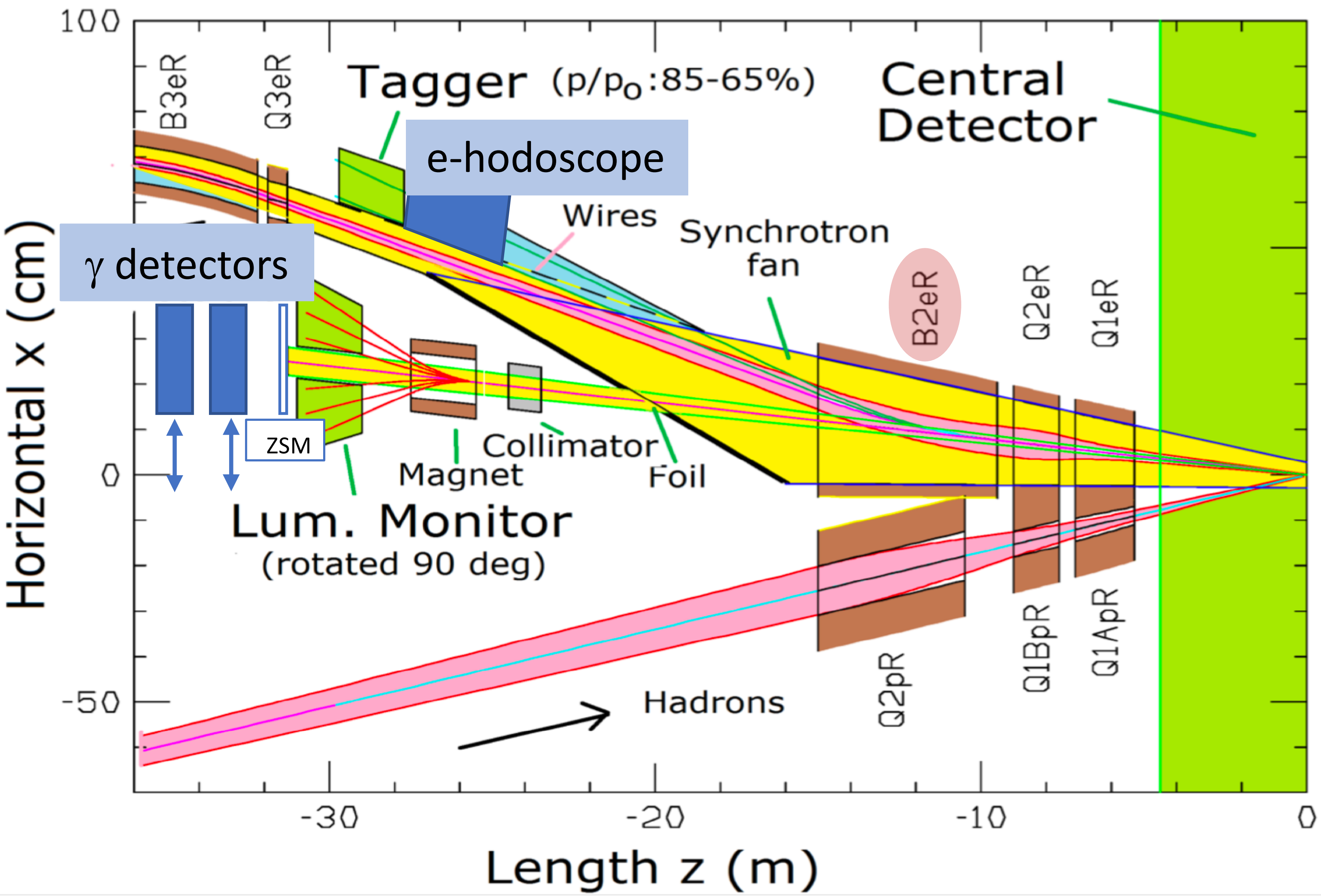


Vertex drift has negligible effect on γ–acceptance (in contrast to forward *p/e* tracking), as all photons with polar angle < 1 mrad should be detected



https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf
https://wiki.bnl.gov/eic/

Luminosity detectors & photoproduction taggers



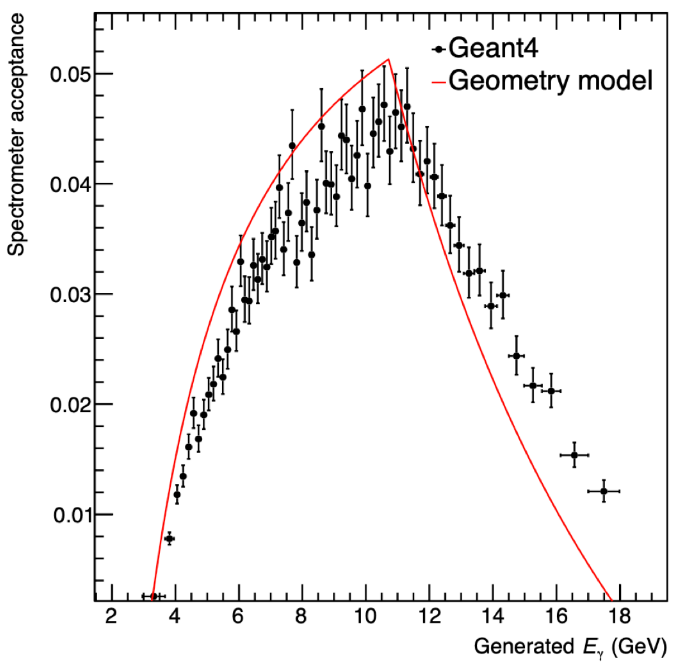
Profiting from (hard) lessons at HERA:

- Need to study the BSE in depth – a **dedicated calorimeter** is mandatory (for regular *calibration runs at low* $\mathcal{L}$)
- Need to **minimize** direct synchrotron radiation (huge @ 18 GeV) ⇒ better photon energy measurement/thin exit window – 9.5/12% X_0 at HERA I/II
- Monitor synchrotron radiation flux
- Use extensively **electron detectors** for various calibration checks – including γ–conversion factor and geometrical acceptance ⇒ *fast hodoscopes* are mandatory for precision and coping with high event pileup (→ HI beams!)

Direct Synchrotron Radiation (SR) – urgent challenge

***Direct* SR fan**, originating mostly in the *B2eR* dipole, poses two major experimental challenges:

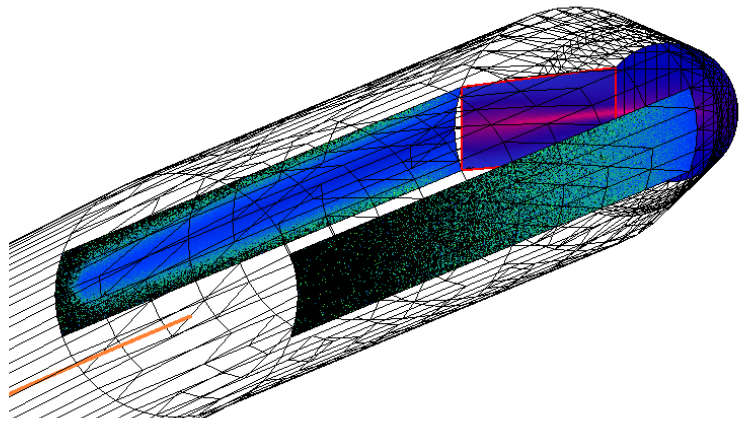
1. As it cannot be avoided, it requires strong SR filtering, which **compromises** BS photon energy measurements in calorimeters due to passive absorbers in front of them – it is mostly relevant at 18 GeV, where the BSE is maximal.
2. BS exit window has to withstand high SR power – for example, 10 mm thick *Al* window (equivalent to ≈ 11% X_0) ⇐ **significantly deteriorates** energy resolution of e^+e^- spectrometer + induce significant event pileup



Yellow Report 2021

Figure 11.114: Luminosity spectrometer acceptance as a function of the bremsstrahlung photon energy E_γ. The acceptance includes a photon to pair conversion probability of ~8%.

1[st] iteration for γ exit window design (*Ch. Hetzel*)



	10 GeV	18 GeV
Total Power [kW]	25.6	24.7
Window Power [kW]	10.2	9.91
Total Flux [ph/s]	$6.32\text{x}10^{19}$	$1.12\text{x}10^{19}$
Window Flux [ph/s]	$2.68\text{x}10^{19}$	$4.77\text{x}10^{18}$

Note, at 18 GeV the SR critical energy ≈ 6 times bigger!

Need for **optimization of *B2eR* magnet design** – split in two parts where *B2AeR* should be as weak as possible.

Aim at **6% X_0** window thickness (≈ 4% BS conversion)?

Predicted *Coherent BremsStrahlung* (CBS) at HERA

At HERA I, for $E_\gamma = 10$ keV, $\hbar/\Delta p_z \approx$ **11 cm** in LAB ⇒ the beam electron interacts with the **whole** proton bunch and the event rate becomes proportional to **number of protons squared**! Hence an extraordinary BS signal **amplification**.

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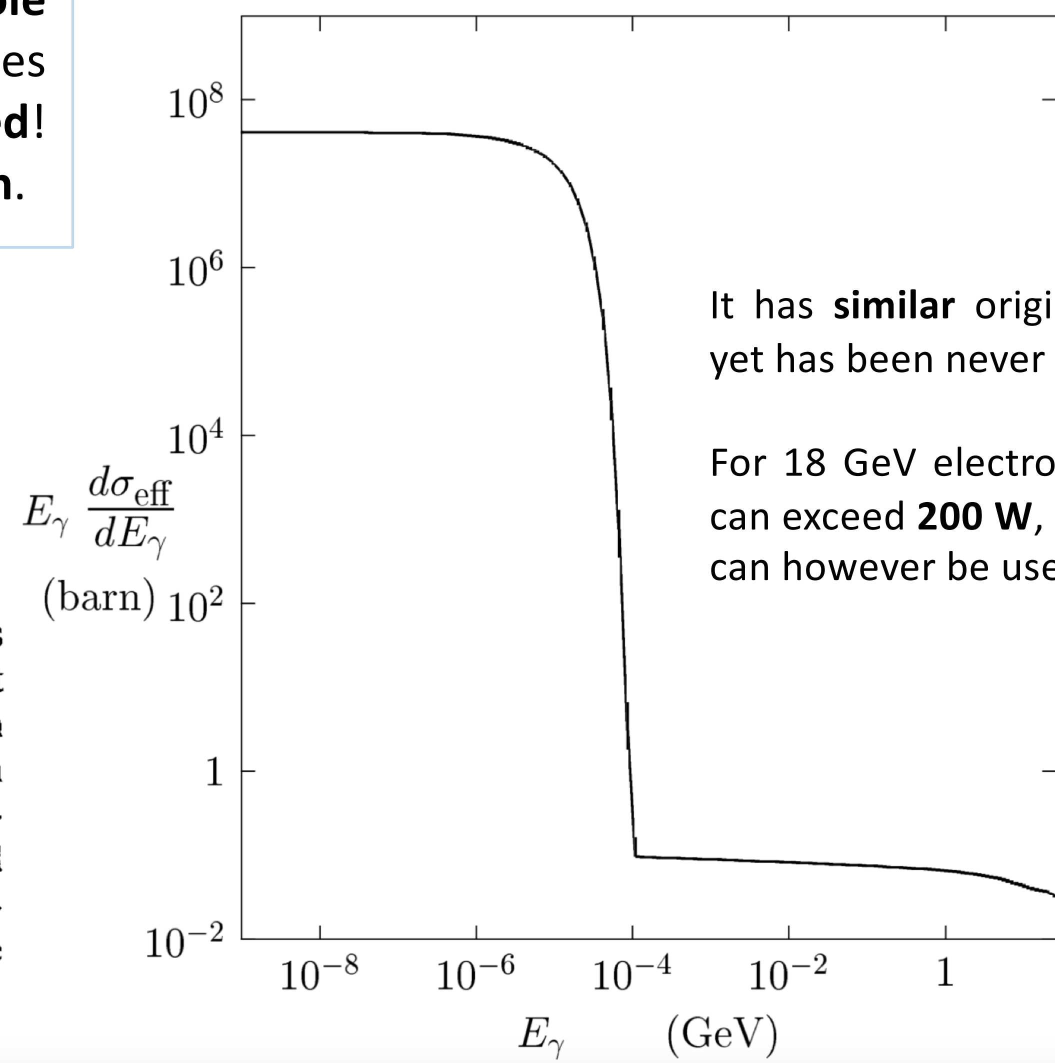
Received: 9 November 1995

Abstract. We consider coherent electromagnetic processes for colliders with short bunches, in particular the coherent bremsstrahlung (CBS). CBS is the radiation of one bunch particles in the collective field of the oncoming bunch. It can be a potential tool for optimizing collisions and for measuring beam parameters. A new simple and transparent method to calculate CBS is presented based on the equivalent photon approximation for this collective field. The results are



It has **similar** origin as famous *beamstrahlung*, yet has been never confirmed experimentally…

For 18 GeV electrons at the EIC the CBS power can exceed **200 W**, but still won't dominate SR, it can however be used for interesting diagnostics!

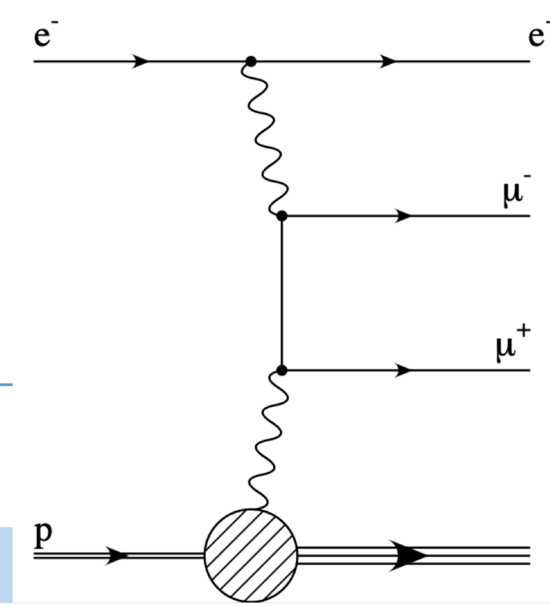
Bremsstrahlung electrons & exclusive lepton pairs

For 10 GeV beam electrons, at the nominal EIC *ep* luminosity, on average about **5 BS electrons** simultaneously hit taggers (for *eAu* collisions that number may exceed **70**…). Special, short calibrations runs, at low electron beam intensity, will be necessary to collect useful data for studies of various electron-photon correlations in bremsstrahlung.

In addition, non-colliding electron *pilot bunches* will be **necessary** to control *e-gas* backgrounds, what is essential for precise data-driven estimates of the photon geometrical acceptance, and possibly of the photon window conversion factor too.

Two-photon production of charged lepton pairs will provide excellent calibration tool for the electron detectors – possibly, also during normal (*ep*) data taking.

Effectively (via $E'_e + E_\gamma = E_e$), this may also give almost **direct calibration of bremsstrahlung photon energy scale,** in the most relevant energy range!



Summary

Precise luminosity determination is very challenging at the EIC – both the absolute measurement and the relative one.

- **Two complementary methods** are mandatory – *Photon Energy Flow* (PEF) vs. *Photon Conversion Counting* (PCC): **18 GeV** (PCC) vs. **5, 10 GeV beams** (PEF), or **p/light ions** (PCC) vs. **heavy ions** (PEF)
- **New** instrumentation is needed to get good performance at large event pileup: **fast hodoscopes** in photon spectrometer and taggers, synchrotron radiation monitors; a **dedicated photon calorimeter** will allow for very precise, data-driven detectors' inter-calibrations
- Need to **minimize the direct SR flux** and to use thin exit windows for photons and electrons

Precise measurements will require developing dedicated detector technologies and specialized fast electronics – 100 MHz sampling rate and, given >10 GHz event rates, near-detector signal (pre-) processing will be necessary

The beam-size effect must be thoroughly studied at the EIC and the proper calculations of HO/polarization corrections to the Bethe-Heitler cross-sections (and their uncertainties) are badly needed!

Thank you!

Basic research is what I am doing when I don’t know what I am doing.
-- *Wernher von Braun*

EIC *Conceptual Design Report* – February 2021

https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

https://wiki.bnl.gov/eic/

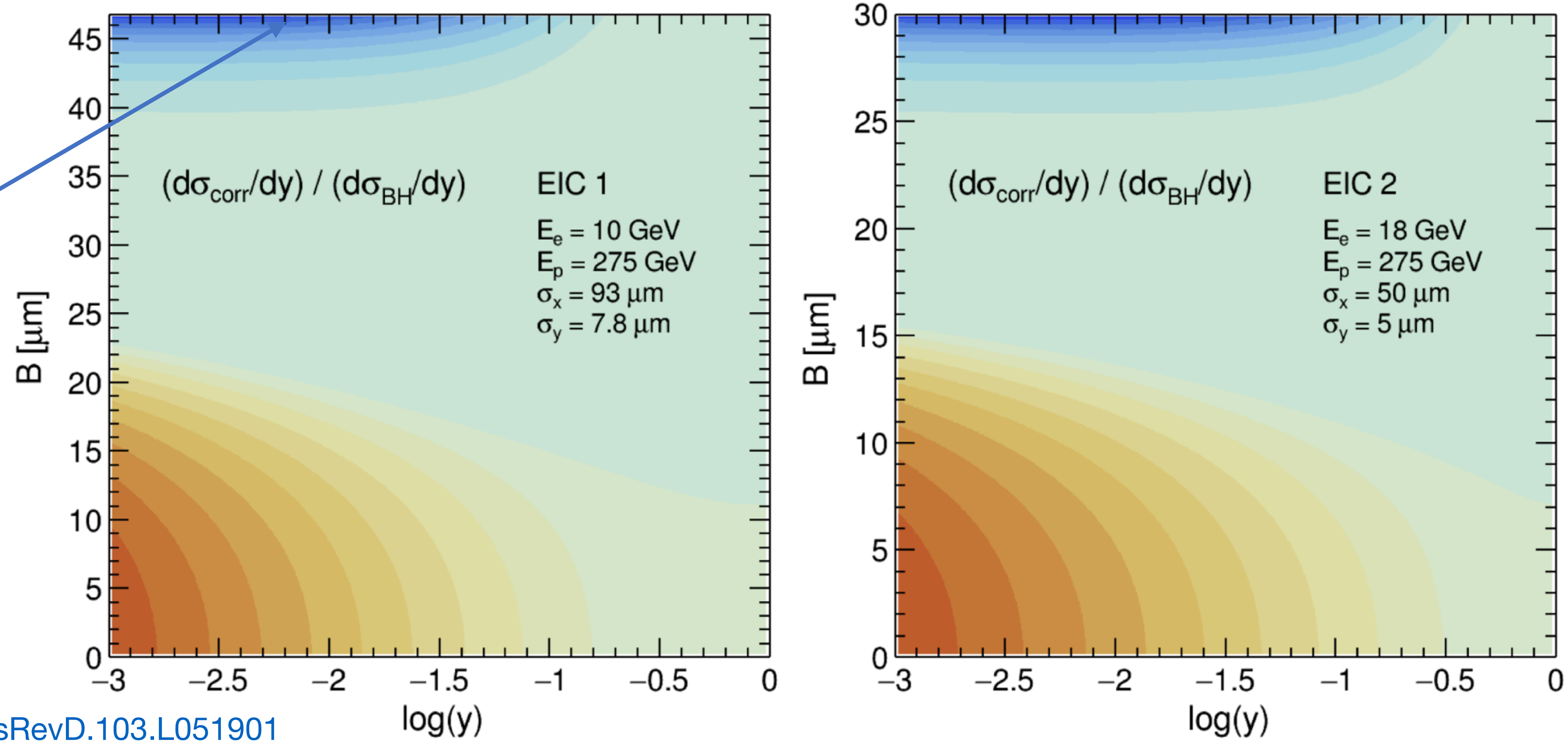
Species	proton	electron	proton	electron	proton	electron	proton	electron	proton	electron
Energy [GeV]	275	18	275	10	100	10	100	5	41	5
CM energy [GeV]	140.7		104.9		63.2		44.7		28.6	
Bunch intensity [10^{10}]	19.1	6.2	6.9	17.2	6.9	17.2	4.8	17.2	2.6	13.3
No. of bunches	290		1160		1160		1160		1160	
Beam current [A]	0.69	0.227	1	2.5	1	2.5	0.69	2.5	0.38	1.93
RMS norm. emit., h/v [μm]	5.2/0.47	845/71	3.3/0.3	391/26	3.2/0.29	391/26	2.7/0.25	196/18	1.9/0.45	196/34
RMS emittance, h/v [nm]	18/1.6	24/2.0	11.3/1.0	20/1.3	30/2.7	20/1.3	26/2.3	20/1.8	44/10	20/3.5
β^*, h/v [cm]]	80/7.1	59/5.7	80/7.2	45/5.6	63/5.7	96/12	61/5.5	78/7.1	90/7.1	196/21.0
IP RMS beam size, h/v [μm]	119/11		95/8.5		138/12		125/11		198/27	
K_x	11.1		11.1		11.1		11.1		7.3	
RMS $\Delta\theta$, h/v [μrad]	150/150	202/187	119/119	211/152	220/220	145/105	206/206	160/160	220/380	101/129
BB parameter, h/v [10^{-3}]	3/3	93/100	12/12	72/100	12/12	72/100	14/14	100/100	15/9	53/42
RMS long. emittance [10^{-3}, eV·s]	36		36		21		21		11	
RMS bunch length [cm]	6	0.9	6	0.7	7	0.7	7	0.7	7.5	0.7
RMS $\Delta p/p$ [10^{-4}]	6.8	10.9	6.8	5.8	9.7	5.8	9.7	6.8	10.3	6.8
Max. space charge	0.007	neglig.	0.004	neglig.	0.026	neglig.	0.021	neglig.	0.05	neglig.
Piwinski angle [rad]	6.3	2.1	7.9	2.4	6.3	1.8	7.0	2.0	4.2	1.1
Long. IBS time [h]	2.0		2.9		2.5		3.1		3.8	
Transv. IBS time [h]	2.0		2		2.0/4.0		2.0/4.0		3.4/2.1	
Hourglass factor H	0.91		0.94		0.90		0.88		0.93	
Luminosity [10^{33}cm^{-2}s^{-1}]	1.54		10.00		4.48		3.68		0.44	

Beam angular divergence at the I.P. of about **200 μrad** provides the ultimate limit of p_T resolutions

This is for *ep* collisions, and in case of heavy ions, as *eAu* collisions, both CM energy and luminosity **per nucleon** is about 40% of *ep* one

BSE @ EIC

!! σ × 80



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 $(d\sigma_{\mathrm{corr}}/dy)/(d\sigma_{\mathrm{BH}}/dy)$ 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 spans approximately from −80.5 to +0.24.

High energy bremsstrahlung – coherence loss

This long-range character of bremsstrahlung has spectacular consequences:

$\Delta p_z \rightarrow$ *Landau-Pomeranchuk-Migdal effect** and dielectric/*Ter-Mikaelian effect*** & other "environmental" effects as strong magnetic fields – all that due to extremely small **longitudinal** momentum transfers.

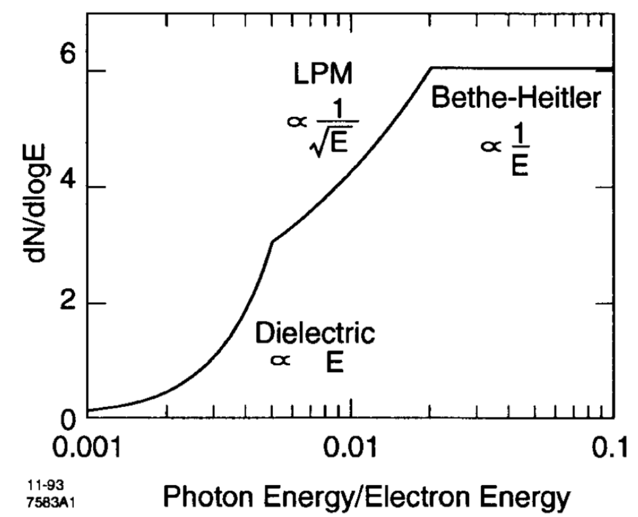
The notion of a coherence length (often called the *formation length* in this context) is introduced – bremsstrahlung is **suppressed**, when the electrons/photons are "perturbated during interaction", leading to *coherence loss.* In dense media bremsstrahlung is not a "binary" process anymore.

Investigation of an Electromagnetic Cascade of Very High Energy in the First Stage of its Development.

M. Mięsowicz, O. Stanisz and W. Wolter

Institute of Nuclear Physics, Department of Cosmic Rays - Krakow

(ricevuto il 17 Settembre 1956)



*) L.D. Landau & I. Pomeranchuk (1953) "Limits of applicability of the theory of bremsstrahlung electrons and pair production at high-energies", *Dokl. Akad. Nauk S. F.* **92**; A.B. Migdal (1956) "Bremsstrahlung and pair production in condensed media at high-energies", *Phys. Rev.* **103**: 1811.
) M.L. Ter-Mikaelian (1954), *Dokl. Akad. Nauk Ser. Fiz.* **94: 1033.

LPM effect and formation length for UHECR

LPM effect for bremsstrahlung was studied at SLAC only in 1990s, but LPM also affects VERY high-energy photon pair production:

Ultra-High-Energy Cosmic Ray is a cosmic ray with an energy greater than 1 EeV = 10^{18} eV, for such photon energies its interactions in medium are extremely distorted ⇒

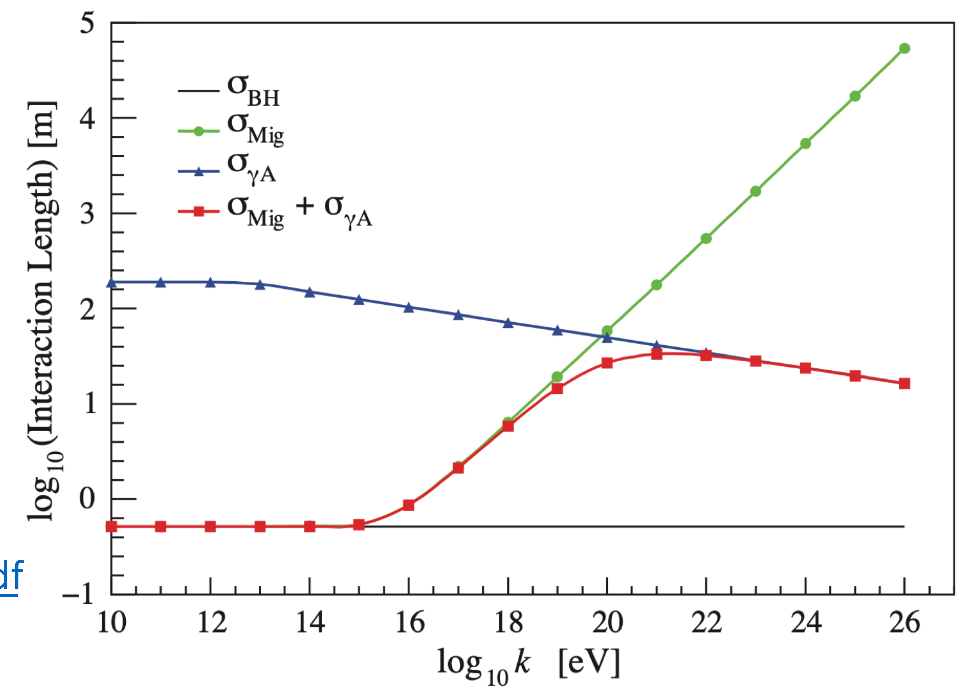


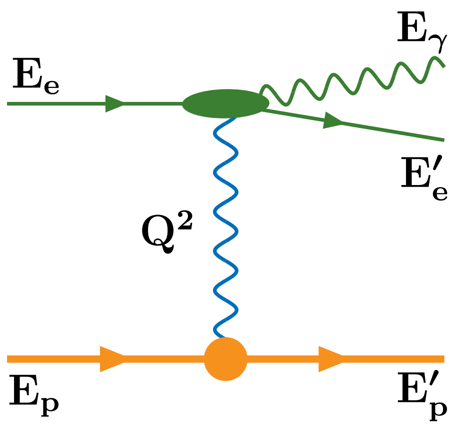
Figure 34.19: Interaction length for a photon in ice as a function of photon energy for the Bethe-Heitler (BH), LPM (Mig) and photonuclear (γA) cross sections [57]. The Bethe-Heitler interaction length is $9X_0/7$, and X_0 is 0.393 m in ice.

https://pdg.lbl.gov/2020/reviews/rpp2020-rev-passage-particles-matter.pdf
https://doi.org/10.1103/PhysRevD.82.074017

Formation length l_f for the electron bremsstrahlung $= 2\hbar c \gamma_e^2/E_\gamma = 2\hbar c \gamma_e / m_e r_\gamma$ where γ_e is the electron Lorentz factor.

For example, if $E_e = 50$ EeV and $r_\gamma = E_\gamma/E_e = 1$ (0,001) % one gets **l_f = 4 (4000) km!**

Bremsstrahlung: *Bethe-Heitler process*



Bremsstrahlung process was first studied already in 1934 by Hans Bethe and Walter Heitler – hence the *Bethe-Heitler* reference still used today – however, its "macroscopically" long-range nature has been elusive ever since…

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