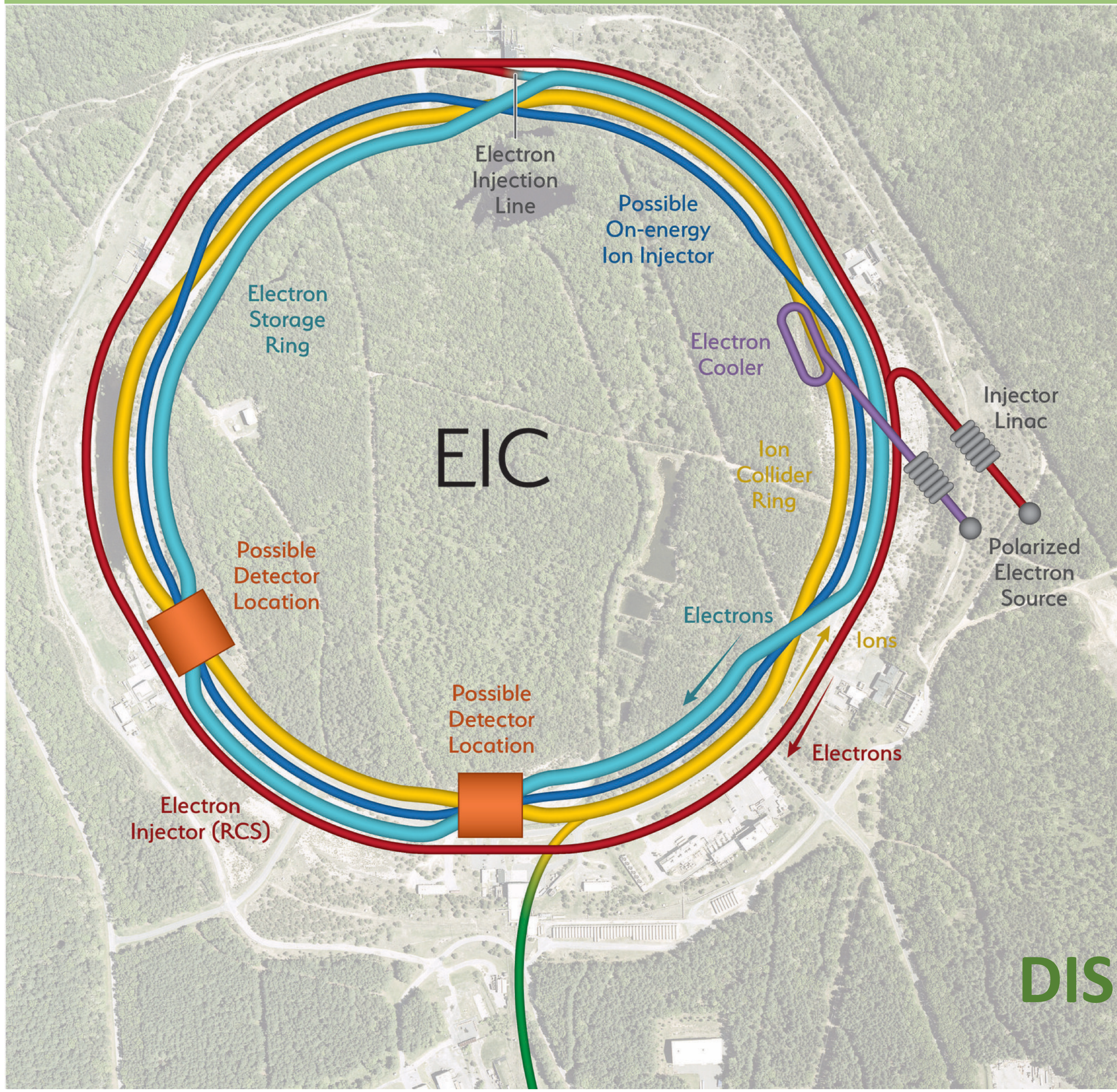
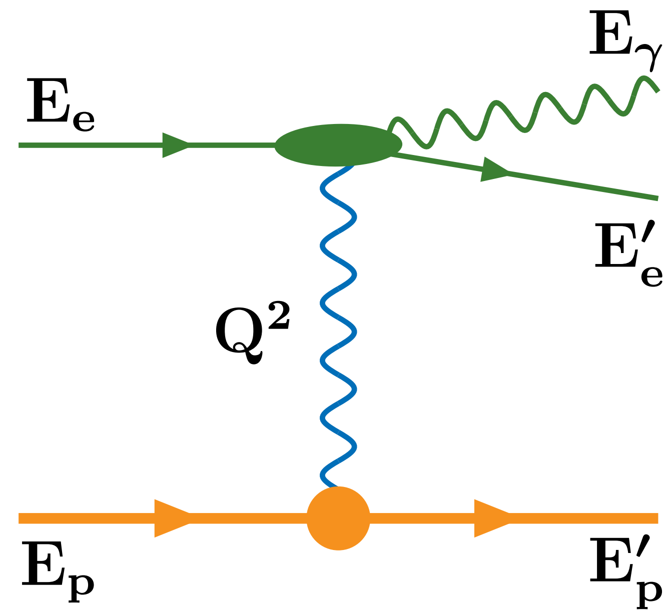
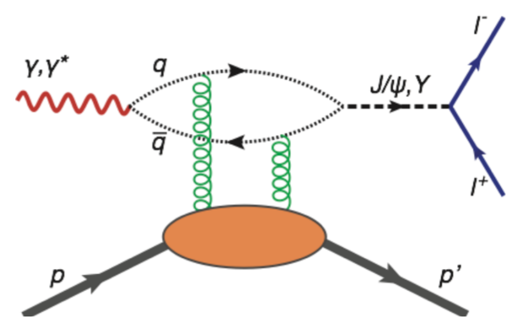
Extreme Photon Interactions – precise luminosity measurement & photoproduction tagging at the EIC

Krzysztof PIOTRZKOWSKI – CP[3] Center, *UCLouvain*

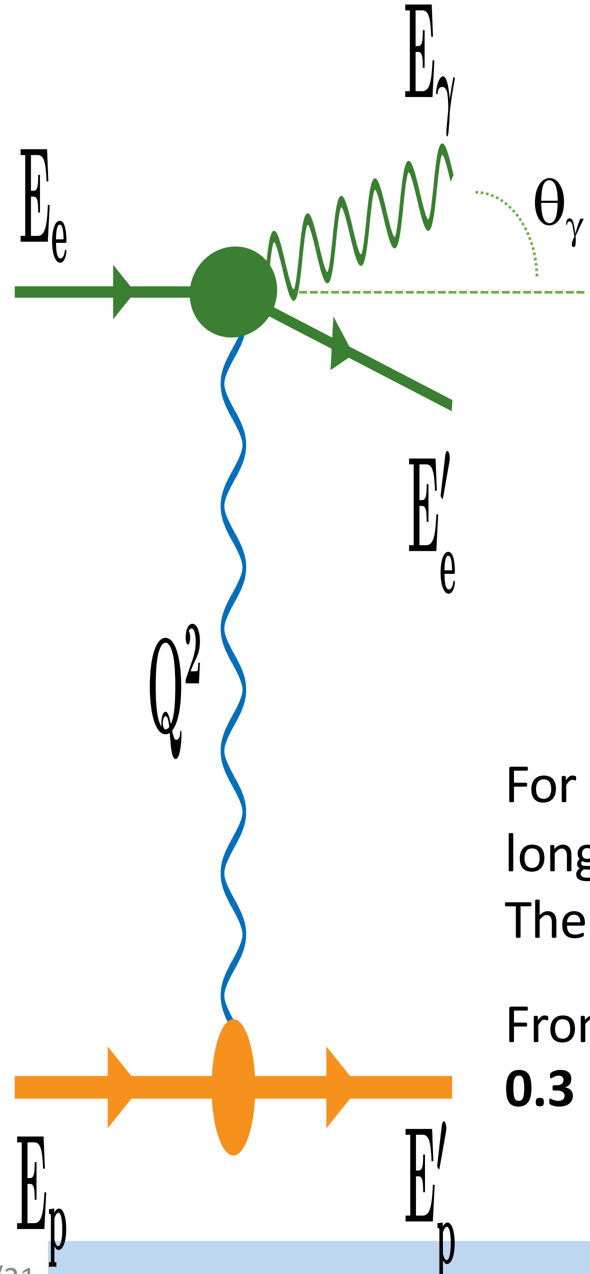




DIS 2021



ep Bremsstrahlung at High Energy



electron-proton bremsstrahlung $\boldsymbol{e + p \rightarrow e' + \gamma + p'}$ 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,

$p_T = 0$ → infinite impact parameter,

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

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

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

BSE effectively comes from ("textbook") **definition** of a cross-section:

Event rate = Luminosity × σ

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

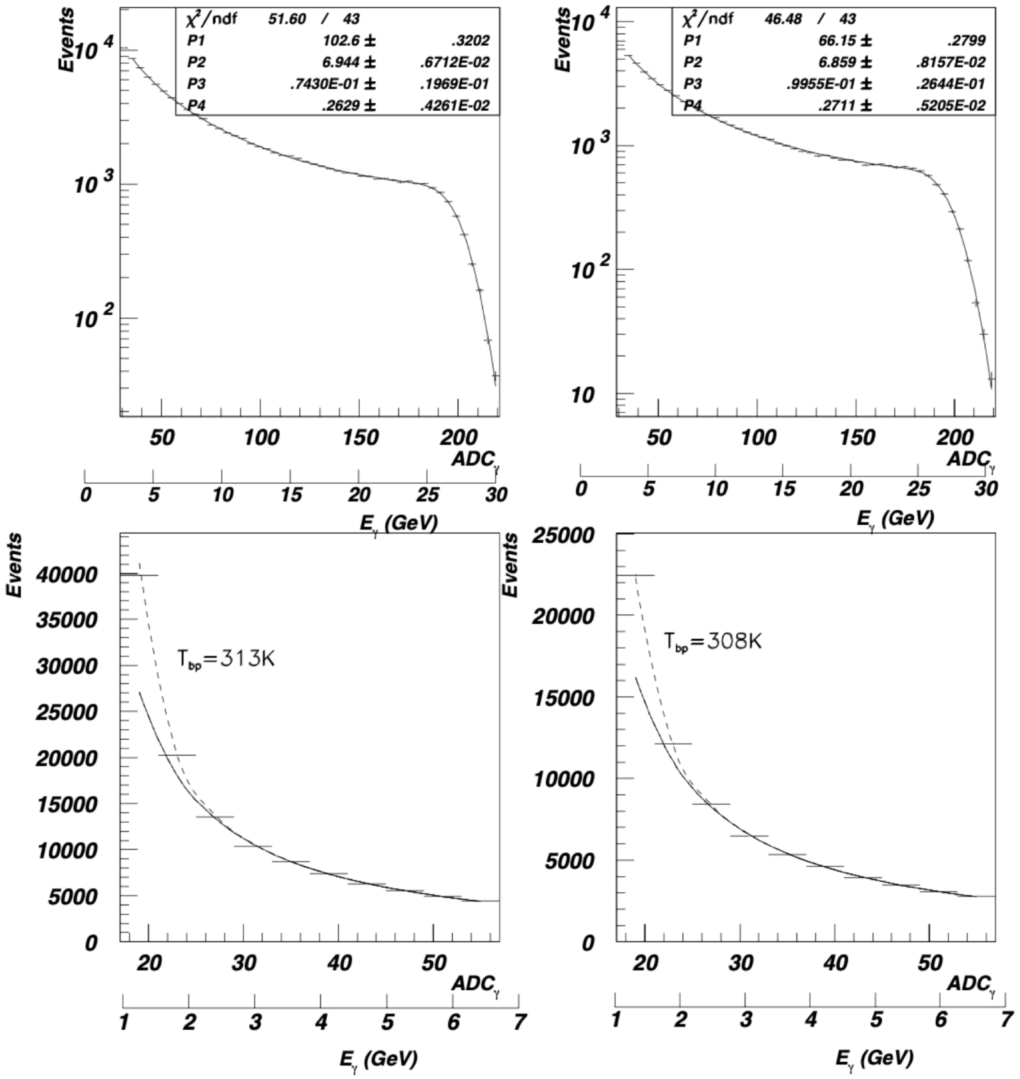
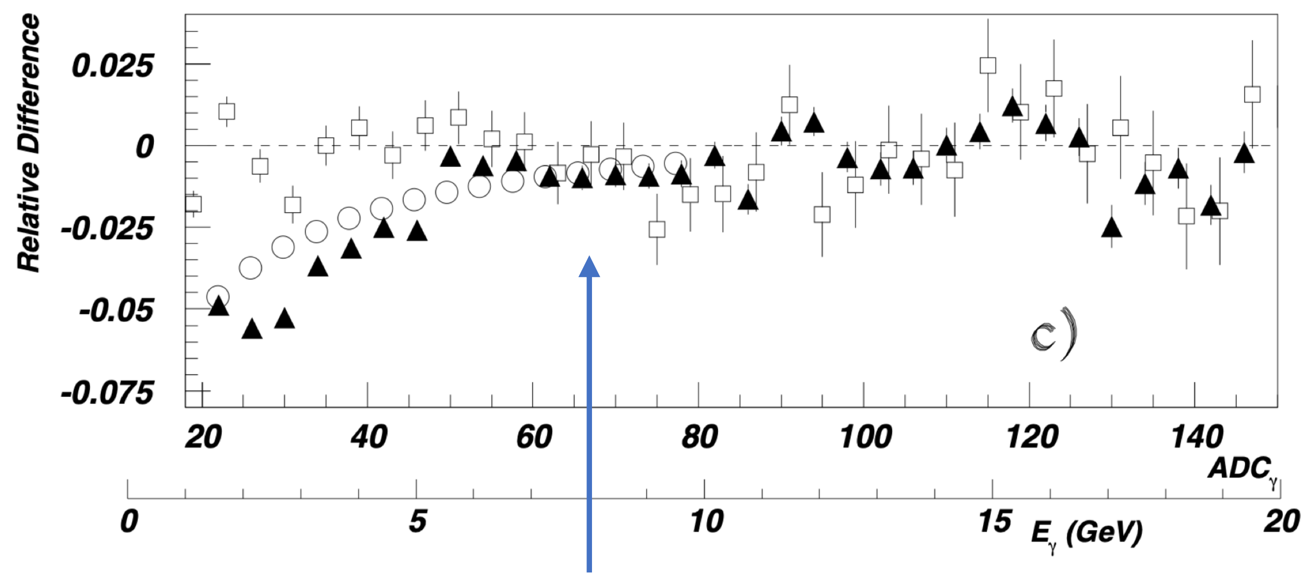


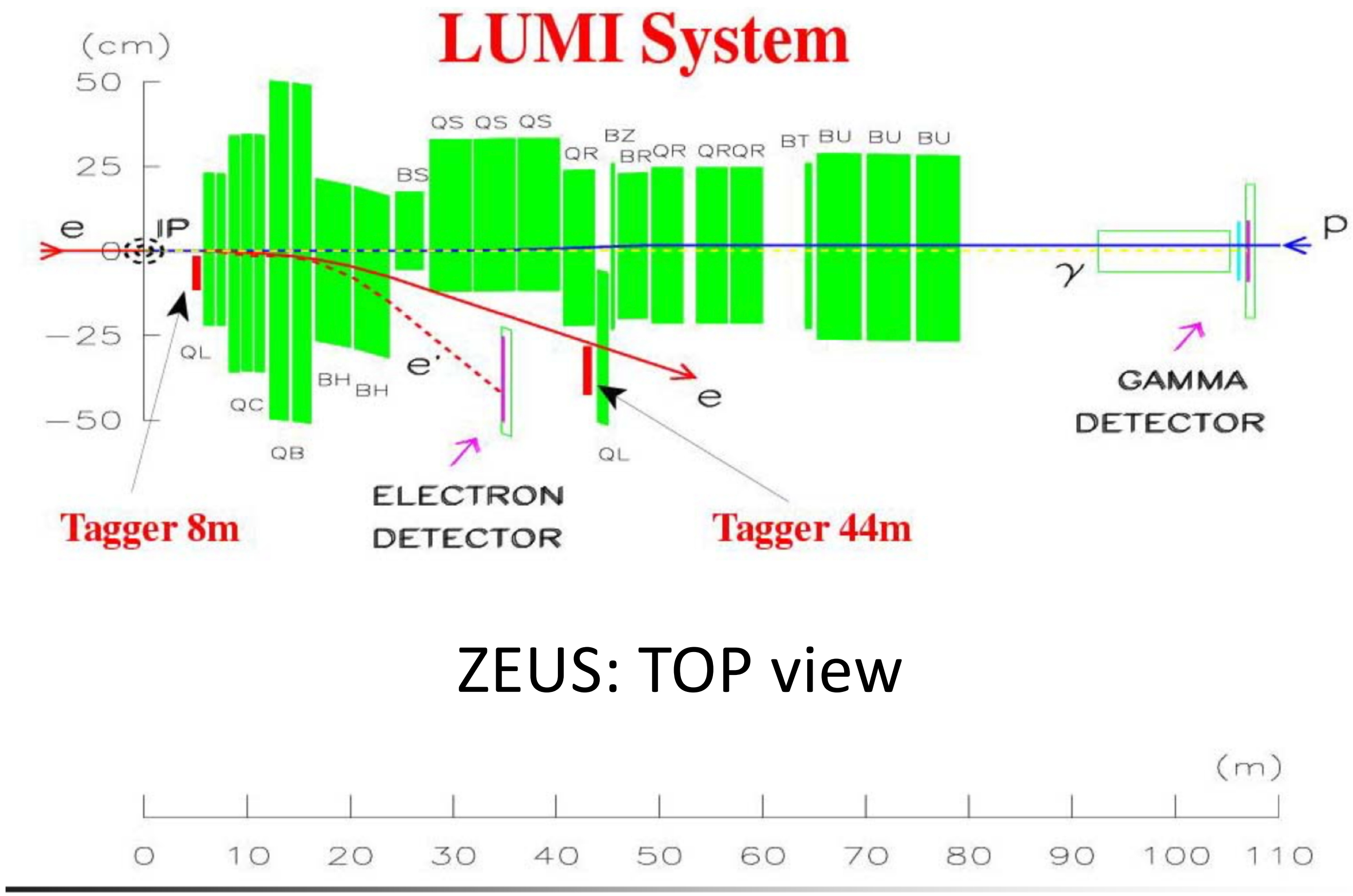
Figure 3: Two spectra of eN bremsstrahlung measured in the luminosity monitor using the electron pilot bunches. The histograms represent the data and the curves are results of fitting the function F (from Eq.1) for $E_\gamma > 3.5$ GeV; in the lower plots the low energy parts of the spectra are shown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

K. Piotrzkowski, 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 (photon) measurement at HERA I

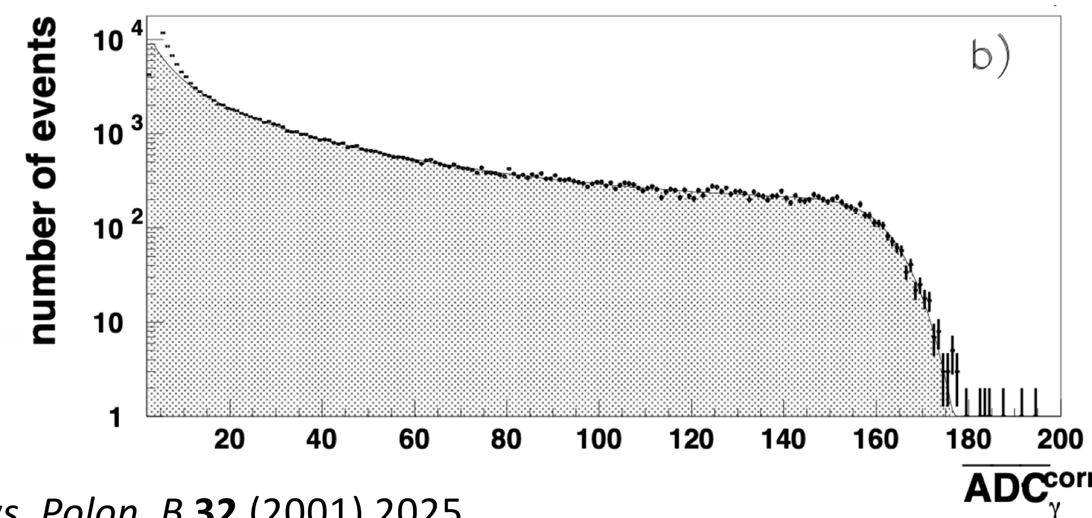


ZEUS: TOP view

(H1 used similar photon detectors)

27.5 GeV $e \times$ 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%

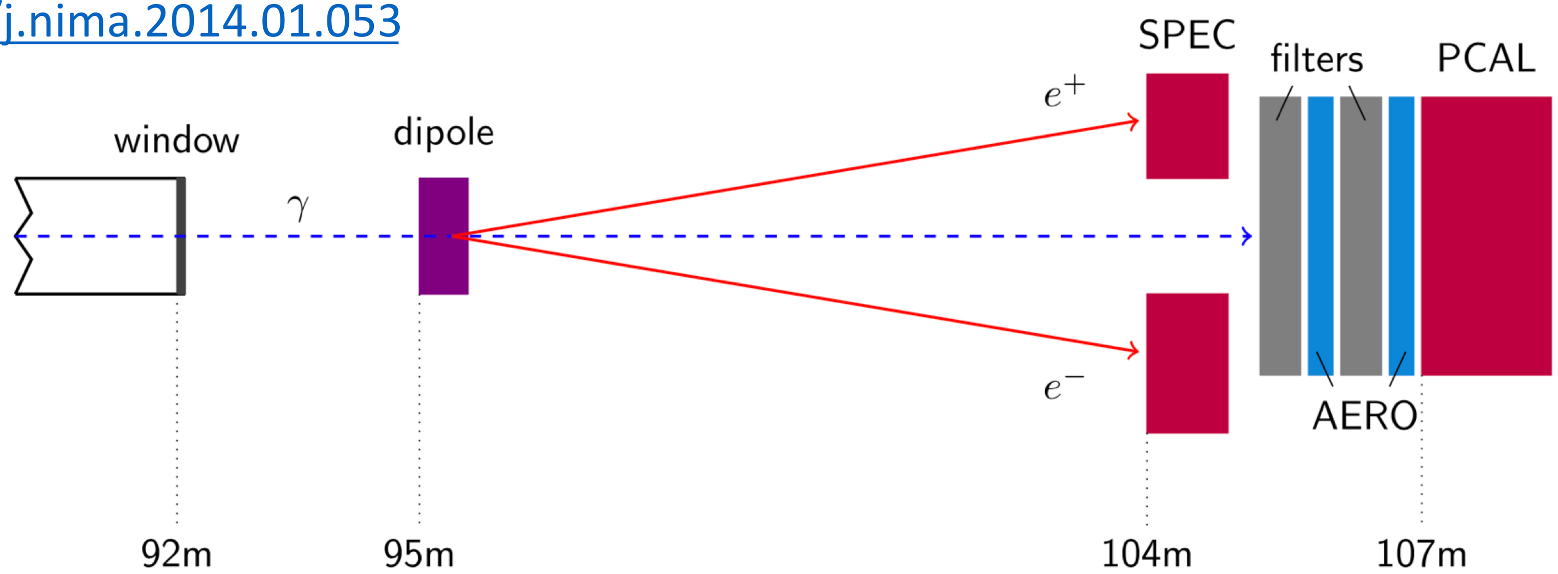


Acta Phys. Polon. B **32** (2001) 2025

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 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 EIC luminosity measurement:

- Absolute $\mathcal{L}$ precision better than 1%
- Bunch-to-bunch relative measurements with very high precision of $\delta\mathcal{L}/\mathcal{L} \approx 10^{-4}$

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

However: the EIC *ep* luminosity will be almost **1000 times bigger** than that at HERA I, and thanks to almost 10 times smaller bunch spacing the event pileup will be partially mitigated but still will be large even for *ep* collisions; **the event pileup scales roughly as Z^2/A** hence for the *eAu* case instead of 10 hard photons every 10 ns more than 100 will hit detectors, what corresponds to **> 10 GHz total event rate**!

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

- (very) large cross-sections (**$\propto Z^2$**), with very small HO corrections
- σ_{BH} is *insensitive* to the beam polarizations
- 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

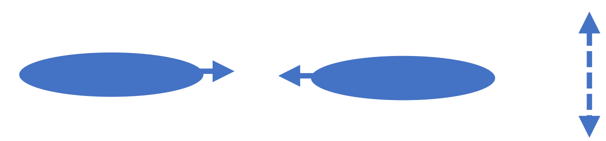
Krzysztof Piotrzkowski and Mariusz Przybycien
Phys. Rev. D **103**, L051901 – Published 5 March 2021

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

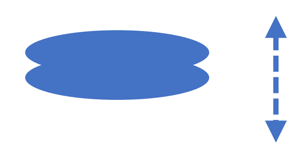
ABSTRACT

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

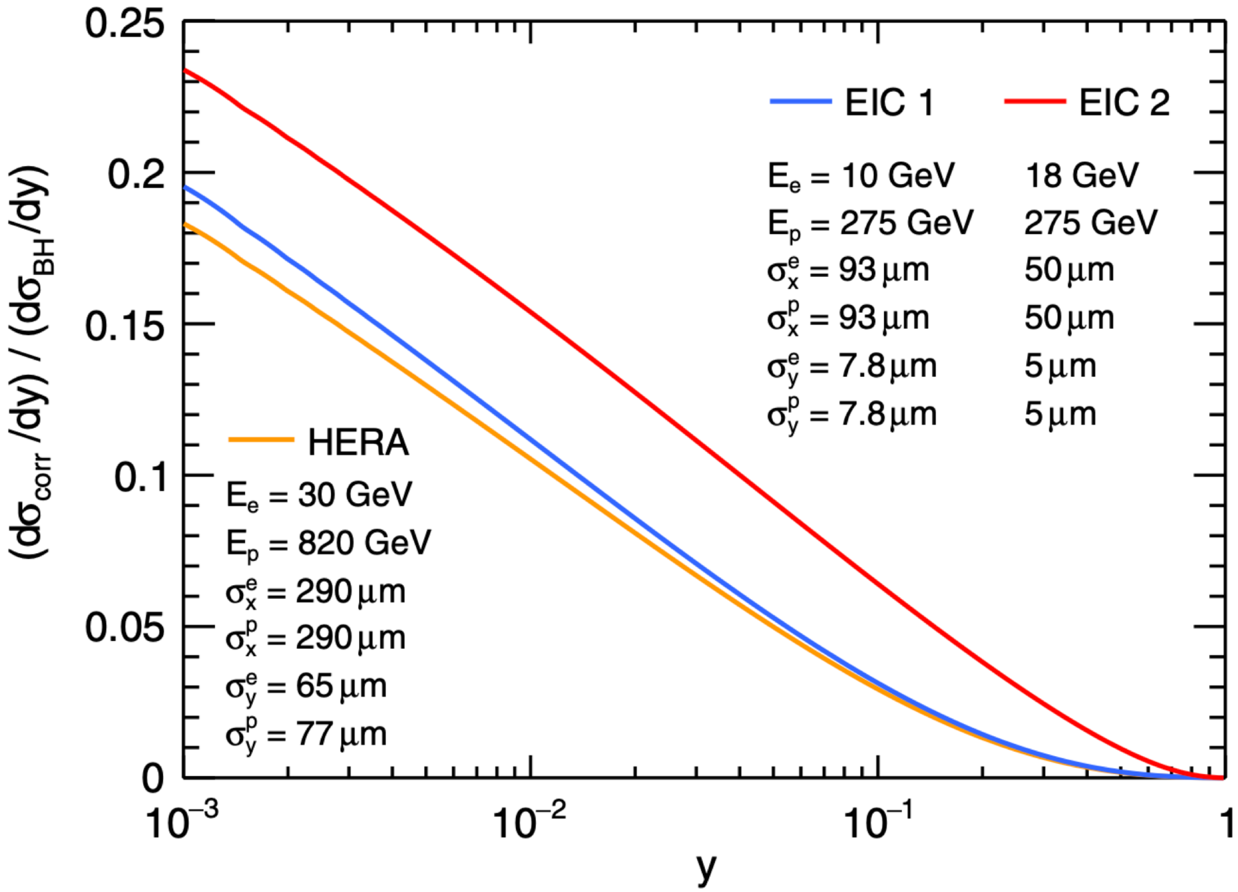


FIG. 2. Relative corrections to the standard Bethe-Heitler cross sections due to the beam-size effect. Relative suppression due to the beam-size effect $(d\sigma_{\text{corr}}/dy)/(d\sigma_{\text{BH}}/dy)$ is shown as a function of $y = E_\gamma/E_e$ for three cases of electron-proton bremsstrahlung.

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

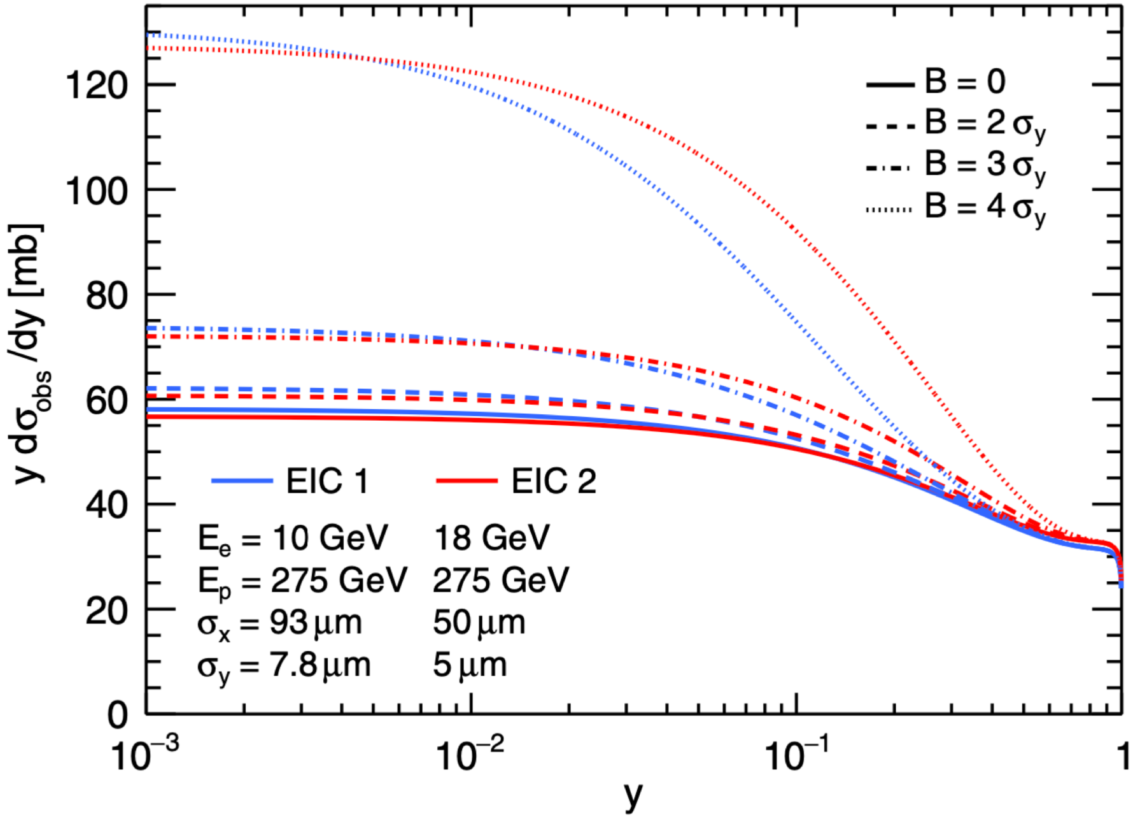


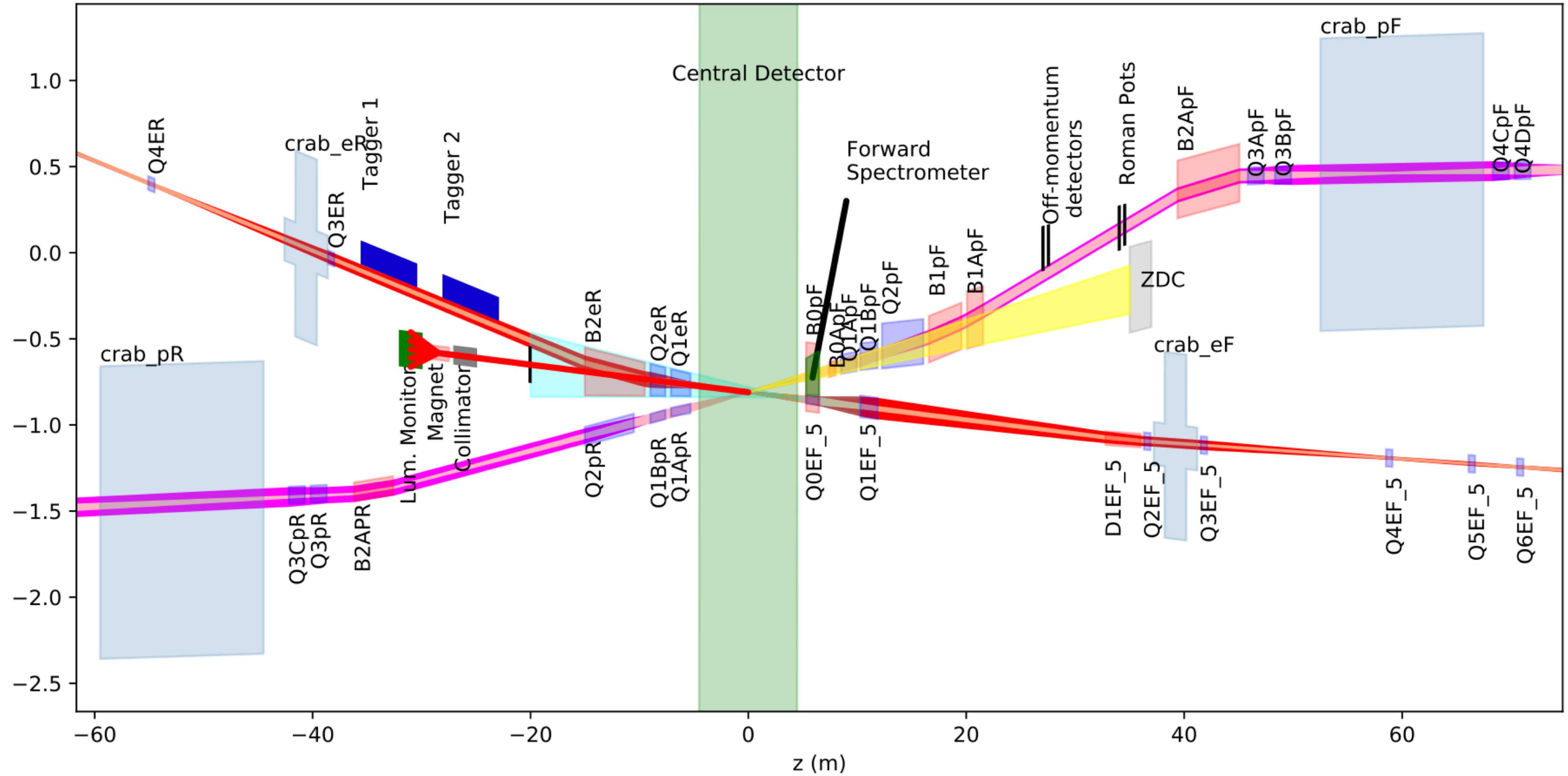
FIG. 4. The predicted spectra of ep bremsstrahlung at the EIC for several vertical beam displacements. The standard Bethe-Heitler cross section $d\sigma_{\mathrm{BH}}/dy$ is modified due to the beam-size effect and beam displacements B. The effective cross sections (multiplied by y for better visibility)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

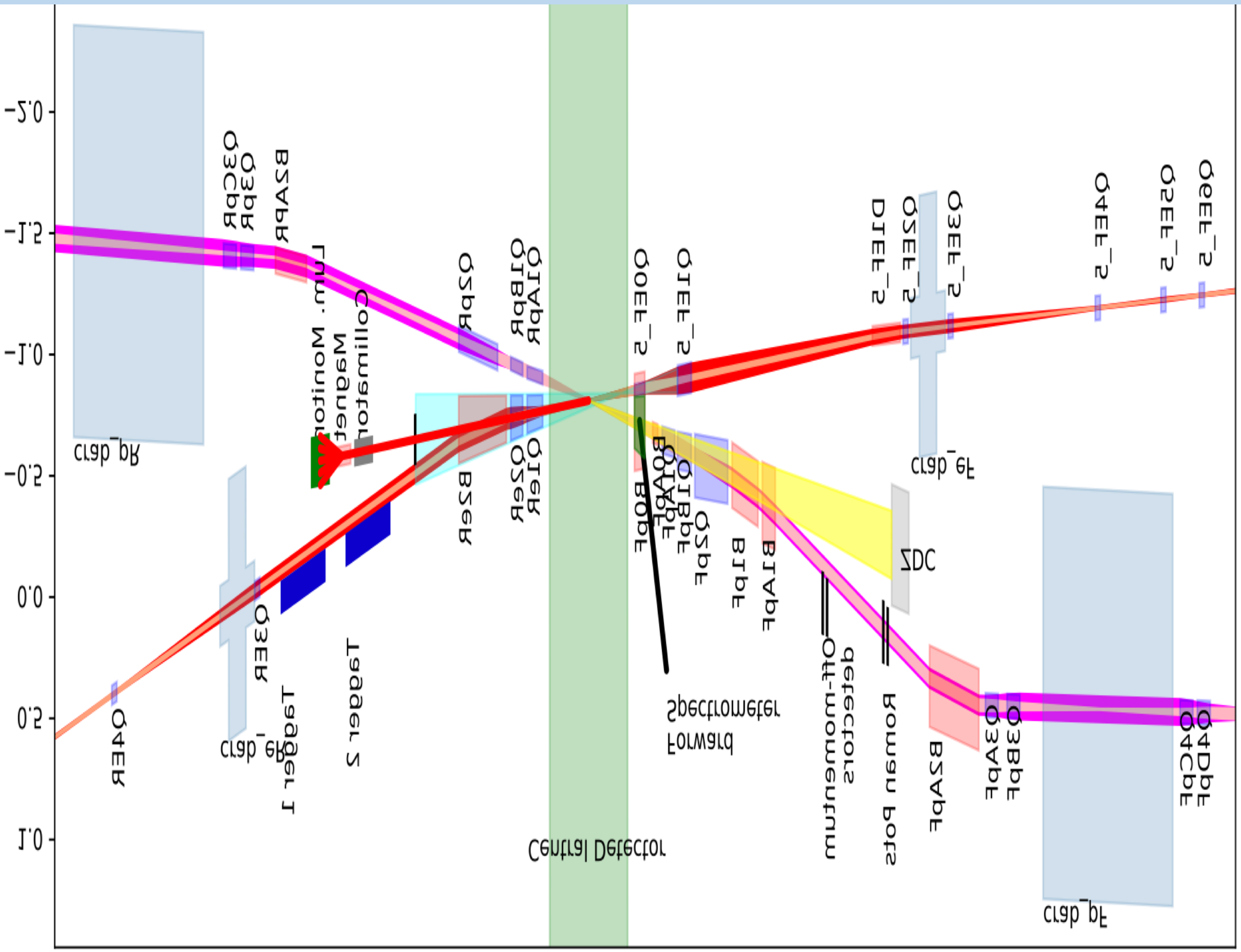
Interaction Region at the Electron-Ion Collider



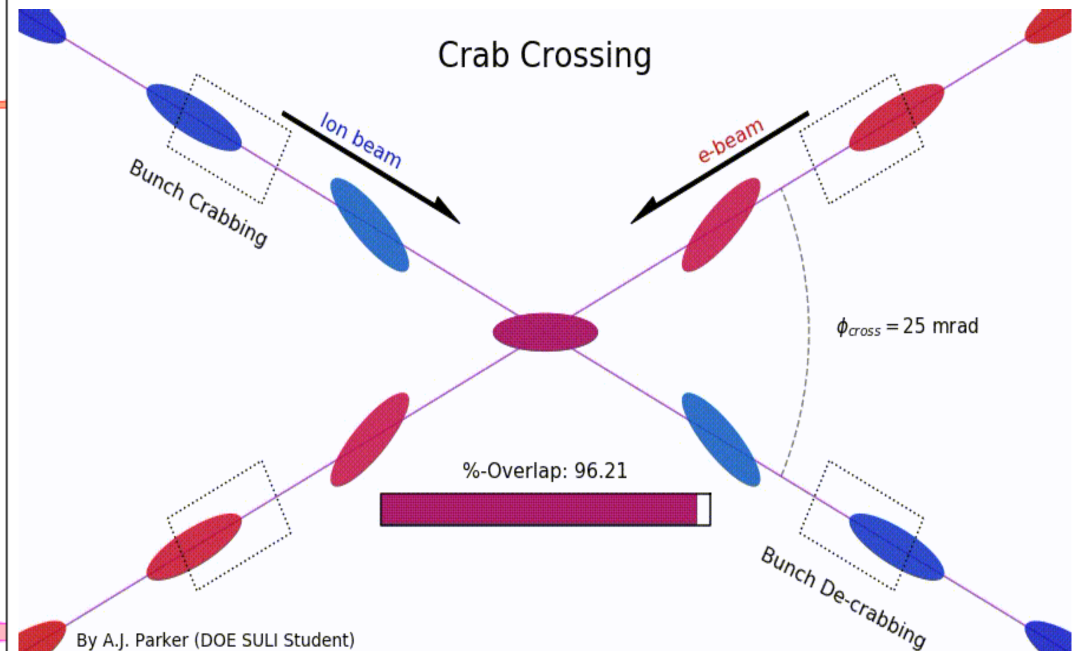
Provisions have been made in the EIC *Interaction Region* designs for the luminosity measurements using bremsstrahlung, as well as for very forward electron detectors (photoproduction taggers)

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

Interaction Region at the EIC

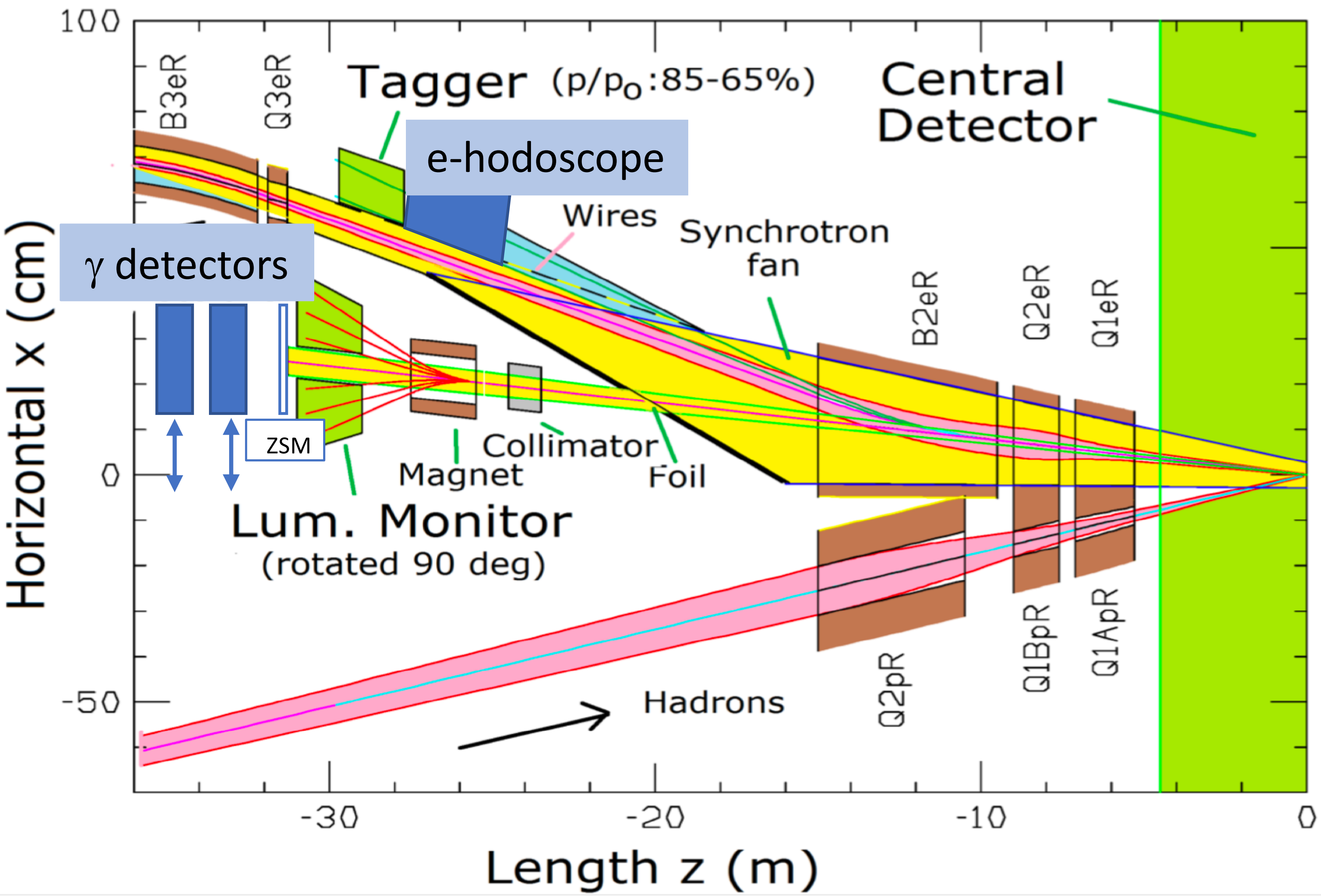


Vertex drift has negligible effect on γ–acceptance, as all photons with polar angle < 1 mrad should be detected



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

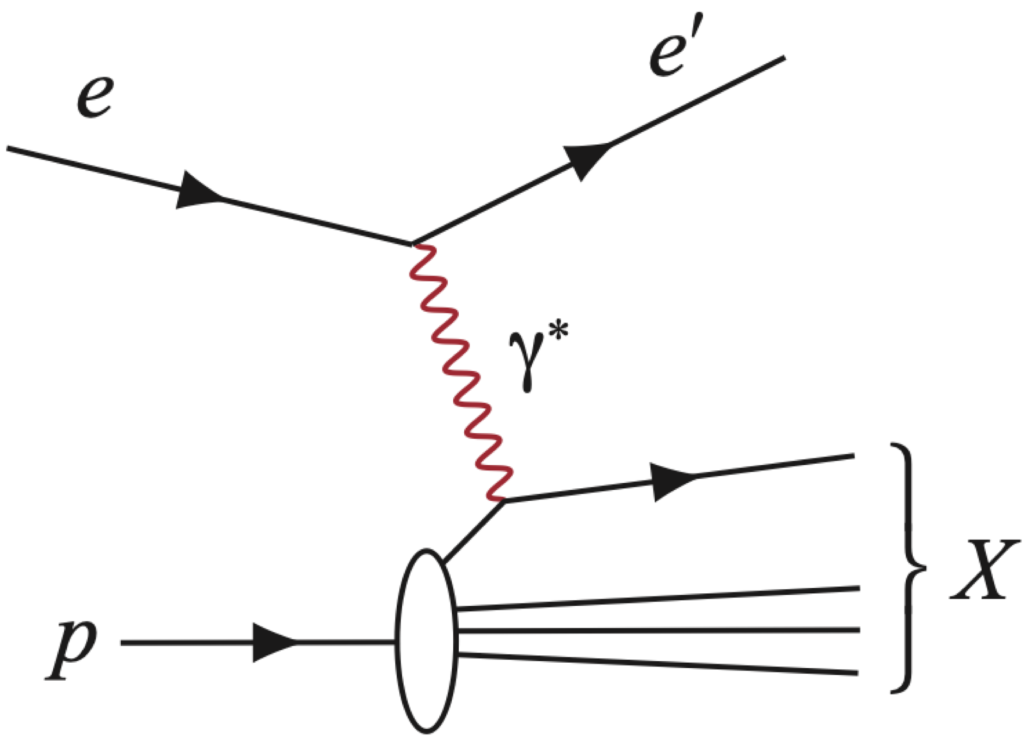
Luminosity detectors & photoproduction taggers



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 – should aim at < 5% (is 2% possible?)
- 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!)

Converting EIC to PIC: *Photon-Ion Collider*



For very forward scattered electrons the exchanged photons are *quasi-real:*

$$Q^2 \simeq Q^2_{min} + E_e E'_e \theta_e^2 = Q^2_{min} + p_T^2/(1-y)$$

where familiar $Q^2_{min} \simeq m_e^2 y^2/(1-y)$ and $1-y = E'_e/E_e$.

If we **tag photoproduction**, that is, we catch such scattered electrons for $0.6 < y < 0.9$ and $\theta_e < 3$ mrad then $Q^2_{min} \approx 10^{-7}$ GeV^2 and $Q^2_{max} \approx 2.10^{-3}$ GeV^2 for 18 GeV beam energy.

From above discussions – the corresponding **impact parameters are much larger than the proton size**, as $m_p/m_e \gg 1$.

Why one needs photoproduction tagging – why not enough that we just do not see the scattered electron?

For better kinematical reconstruction, as in DIS – essential for non-exclusive events, as for the untagged samples we know only that $Q^2_{max} \lesssim 1$ GeV^2, **and for ion beams!** Reminder: the scattered electron p_T has *intrinsic resolution limit* of about 5 MeV/c due to the electron beam divergence.

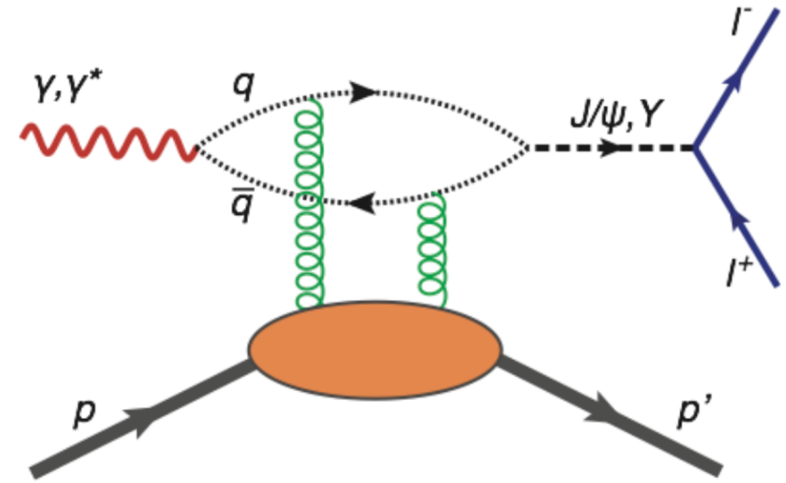
For cleaner selection, if one efficiently kills accidental coincidences (bremsstrahlung!), using timing information.

Converting EIC to MIC*: *Meson-Ion Collider*

*) In *Vector Dominance Model*, photons interact hadronically by fluctuating into neutral vector mesons ($V = \rho, \phi, J/\psi, \Upsilon$...) prior to such interactions.

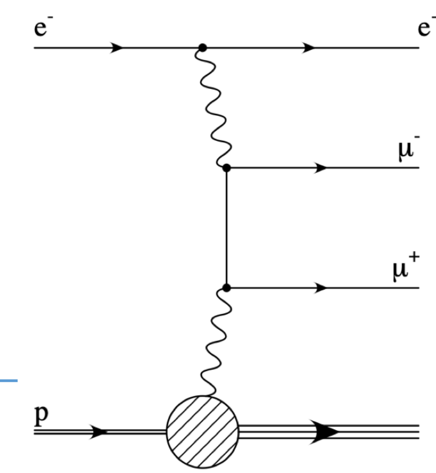
Particularly interesting is exclusive, *quasi-elastic* scattering, like: $\gamma p \to V p$, or in general $\gamma A \to V A$.

Nota bene: For exclusive events full event kinematics might be reconstructed using only very forward proton detectors.



Semi-elastic reactions, $\gamma p \to V X$, **require photoproduction tagging**, as in high-p_T meson scattering – note that M_X might be evaluated from electron-meson kinematics.

Finally, two photon production of charged (lepton) pairs will be studied, in particular, for the Z^2 enhanced electron-ion case. Photoproduction tagging will be important there for good control of the semi-elastic contributions.



Summary

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

- Two complementary methods are mandatory – *Photon Energy Flow* (PEF) and *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 high resolutions at large event pileup: **fast hodoscopes** in photon spectrometer and taggers, synchrotron radiation **monitors** and electron **ps-timing** (see below); dedicated calorimeter will allow for very precise, data-driven detectors' inter-calibrations
- Need to minimize SR flux and use very thin exit windows for photons and electrons

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- Need to minimize SR flux and use very thin exit windows for photons and electrons

Still some issues to address apart from pure detector aspects: For example, is an ultimate 0.5% absolute luminosity precision enough? What are theoretical uncertainties of the HO/polarization corrections?

Efficient detection of very forward scattered electrons is a very powerful tool, effectively turning the EIC into a high energy photon-ion collider – and it is **especially important for ion beams** when very forward hadron detectors have limited acceptance: to cope with high electron pileup fast hodoscopes seem mandatory

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

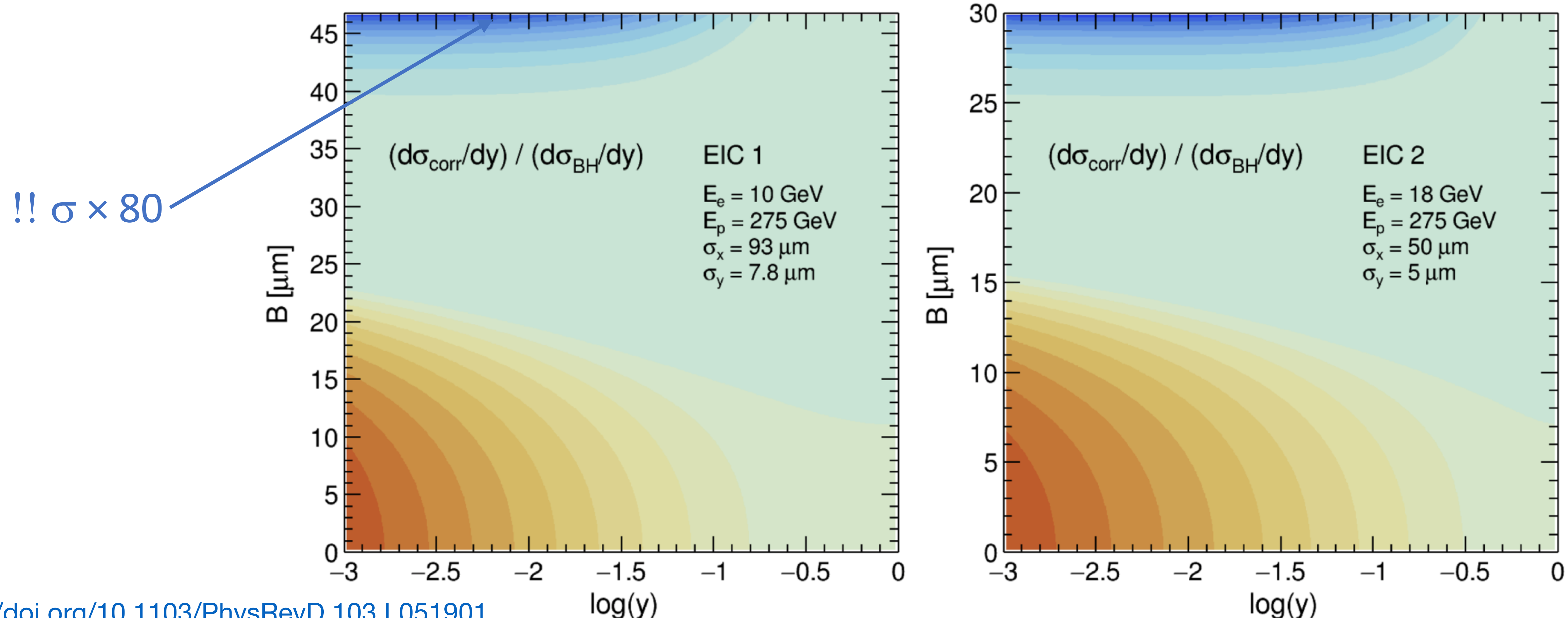
https://wiki.bnl.gov/eic/

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



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 spans approximately from -80.5 to $+0.24$.

Predicted coherent bremsstrahlung (CBS) at HERA

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

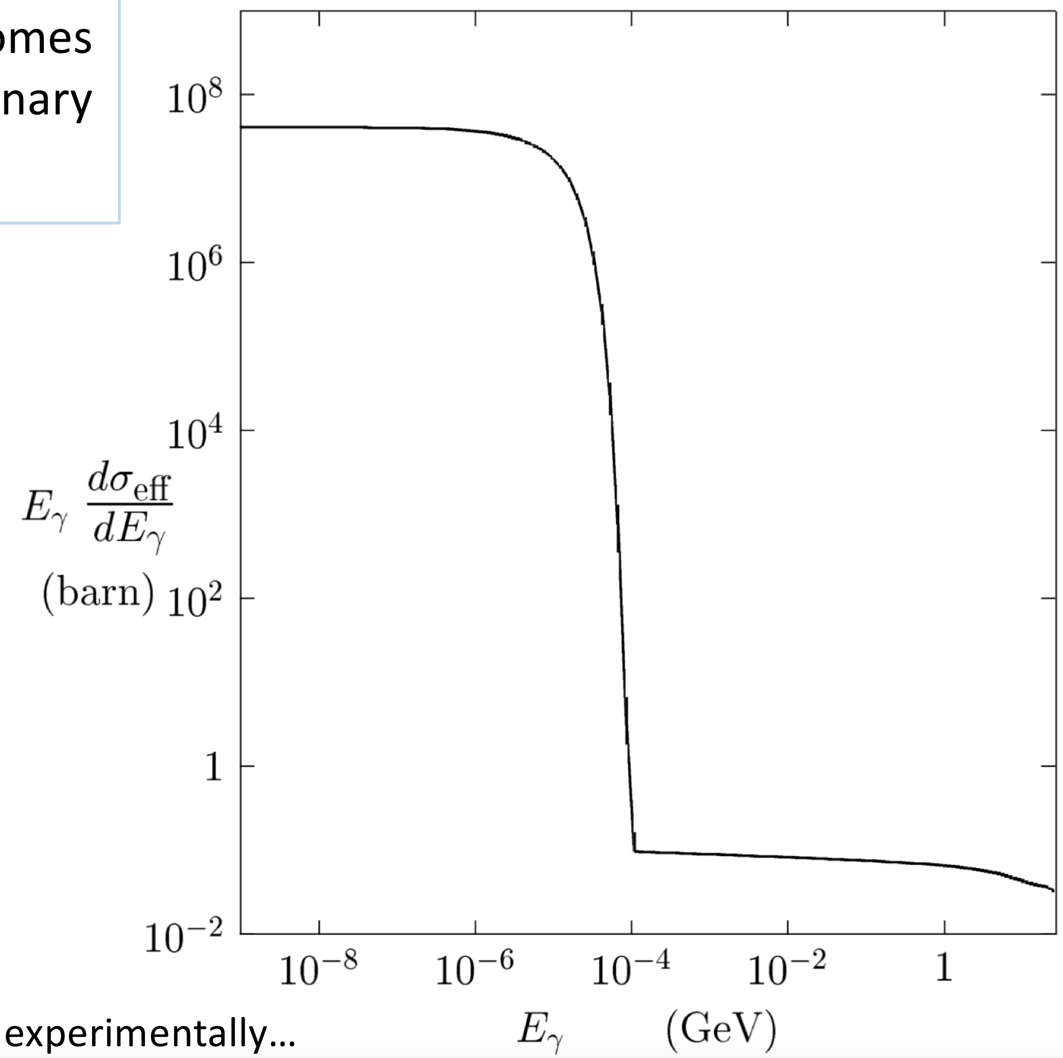
The equivalent photon approximation for coherent processes at colliders

R. Engel, A. Schiller & V. G. Serbo

Zeitschrift für Physik C Particles and Fields **71**, Article number: 651 (1996) | Cite this article

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



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