Luminosity measurements @EIC – guided by experience from HERA

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Preamble

Precise luminosity measurements is a (very) arduous business…

In e^+e^- collisions, the integrated luminosity is generally measured from the rate of low-angle Bhabha interactions $e^+e^- \rightarrow e^+e^-$. In the published LEP results, the inferred theoretical uncertainty of $\pm 0.061\%$ on the predicted rate is significantly larger than the reported experimental uncertainties. We present an updated and more accurate prediction of the Bhabha cross section in this letter, which is found to reduce the Bhabha cross section by about 0.048%, and its uncertainty to $\pm 0.037\%$. When accounted for, these changes modify the number of light neutrino species (and its accuracy), as determined from the LEP measurement of the hadronic cross section at the Z peak, to $N_\nu = 2.9963 \pm 0.0074$. The 20-years-old 2σ tension with the Standard Model is gone.

https://doi.org/10.1016/j.physletb.2020.135319

EIC luminosity challenge

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 $\mathcal{L}$ measurements** with very high precision of $\lesssim 10^{-4}$

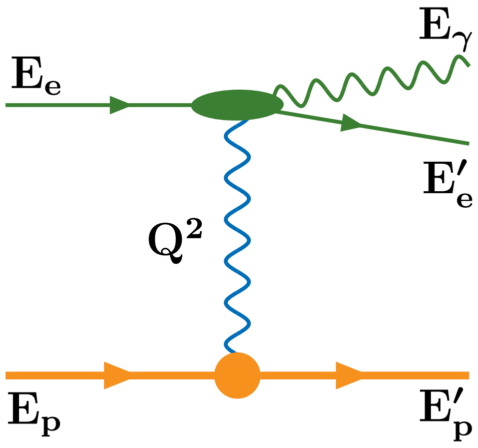
On top of that:

- Wide ranges of beam energies
- Many ion species: from *p* to *Au*
- (beam polarizations)

EIC luminosity challenge: electron-ion Bremsstrahlung

HERA recipe: use very precise measurements of bremsstrahlung rate R: $\mathcal{L} = R/\sigma$

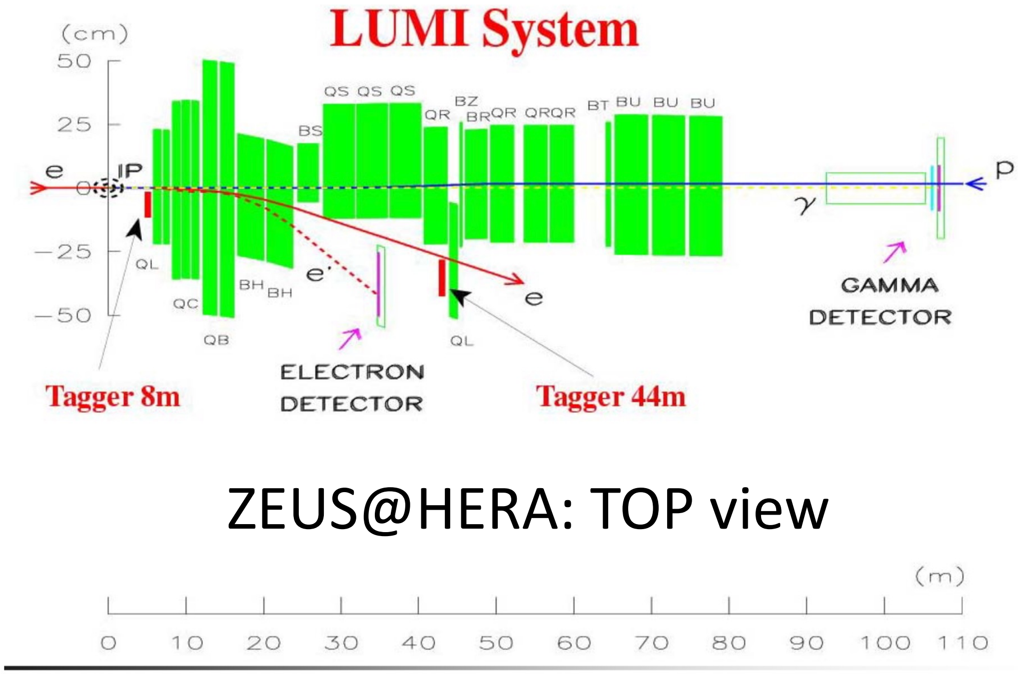
However: nominal EIC *ep* luminosity will be almost **1000 times bigger** than that at HERA I, and thanks to 10 times smaller bunch spacing event pileup will be only partially mitigated – for $E_\gamma/E_e > 1\%$, $\sigma_{BH} = 0.23$ b at $E_e = 10$ GeV; but **as event pileup scales roughly as Z²/2A** hence for *eAu* case, instead of **23** hard photons every 10 ns, more than **300** photons ($\sigma_{BH} = 1.4$ kb) will hit detectors, corresponding to **>30 GHz total event rate**!



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

- (very) large cross-sections (**∝ Z²**), with very small HO corrections
- unique signatures:
  $E_{e'} + E_\gamma = E_e$ to a very high accuracy, and BH is a truly "zero-angle process"

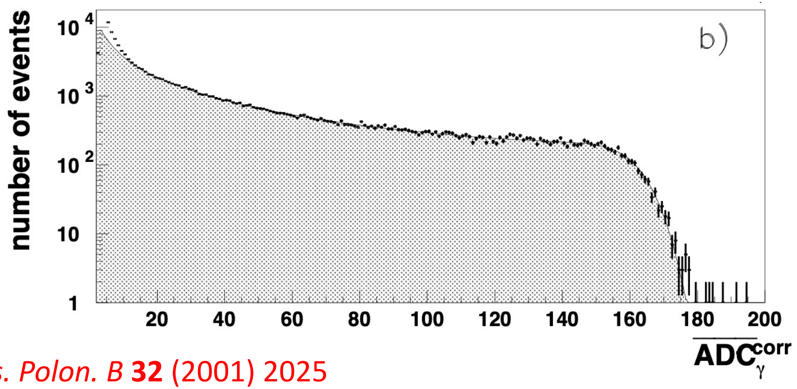
ep Bremsstrahlung: Luminosity measurements (w/ photons only) at HERA I



(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%

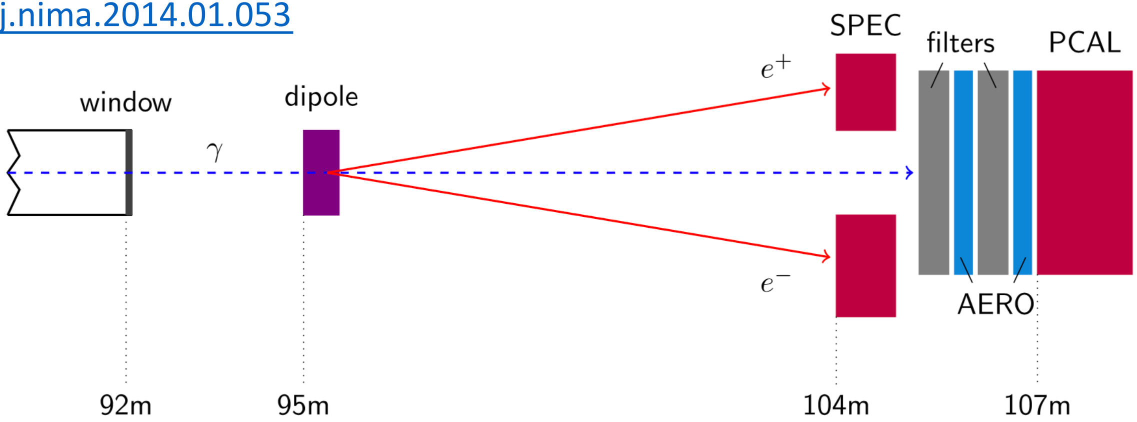


Acta Phys. Polon. B **32** (2001) 2025

ep Bremsstrahlung: Luminosity measurement at HERA II

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

ZEUS: SIDE view



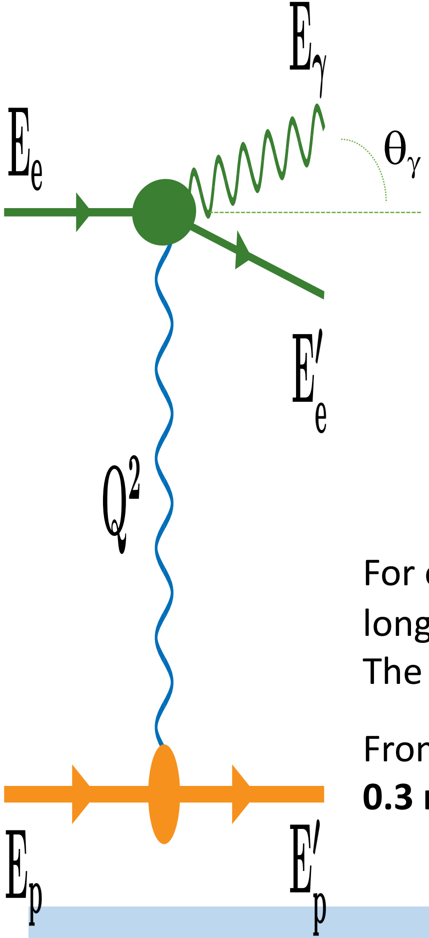
27.5 GeV *e*
×
920 GeV *p*

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 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%

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_γ = 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 ≈ $\hbar/\Delta p_z$ 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 **both** colliding 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:

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:

Event rate ≠ Luminosity × σ !

Bremsstrahlung at HERA: Observation of Beam-Size Effect

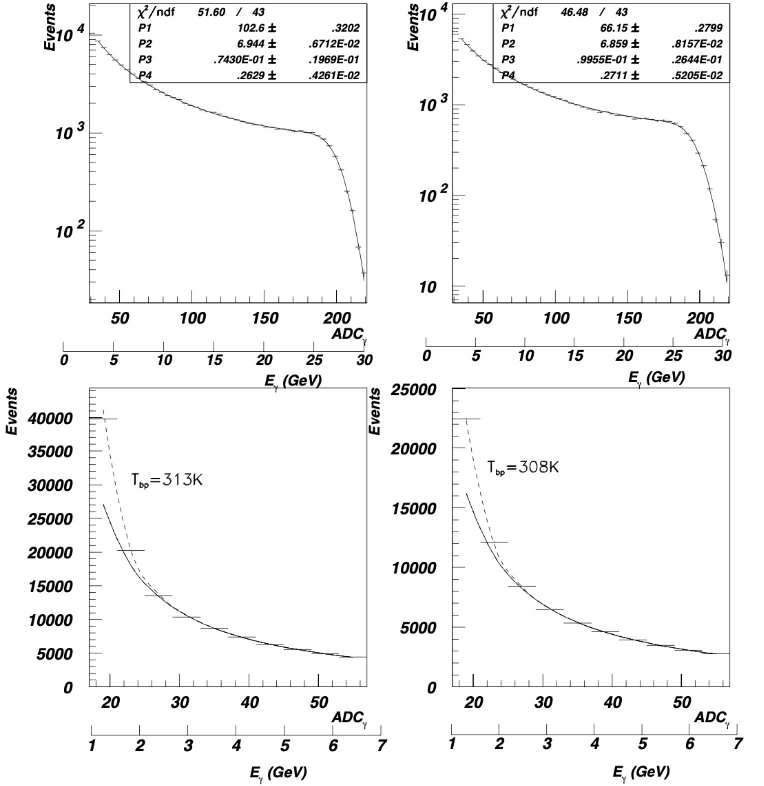
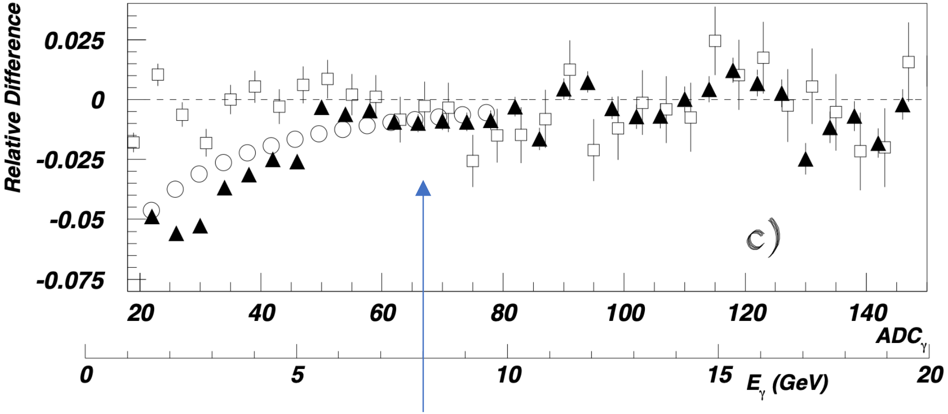


Figure 3: Two spectra of eN bremsstrahlung measured in the luminosity monitor using the electron pilot bunches. The histograms represent the data and the curves are results of fitting the function F (from Eq.1) for $E_\gamma > 3.5$ GeV; in the lower plots the low energy parts of the spectra are shown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



Measurements of Beam-Size Effects @ EIC

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

Letter   Open Access

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

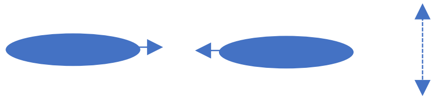
Krzysztof Piotrzkowski and Mariusz Przybycien
Phys. Rev. D **103**, L051901 – Published 5 March 2021

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

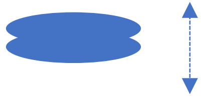
ABSTRACT

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

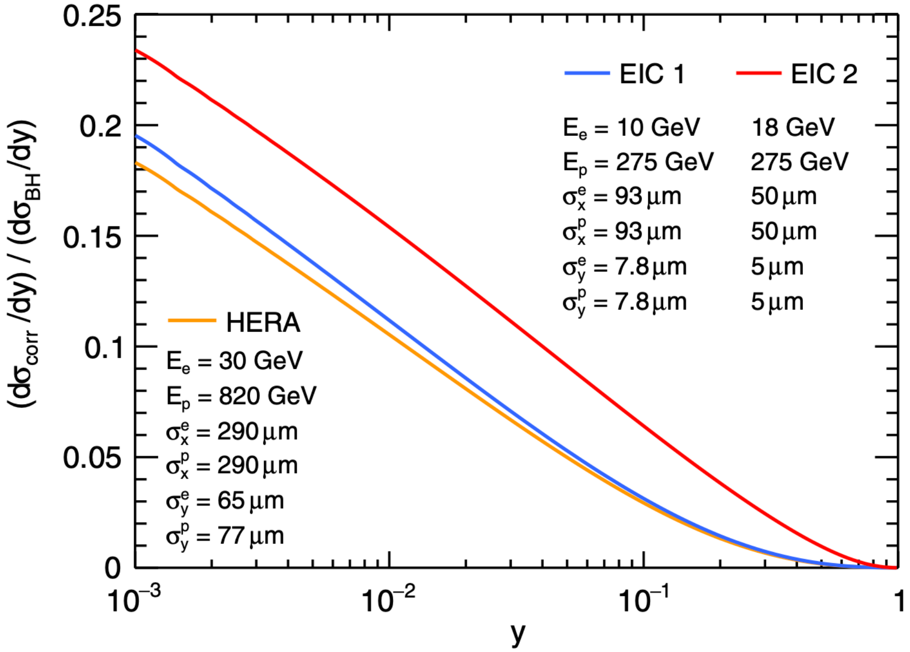


FIG. 2. Relative corrections to the standard Bethe-Heitler cross sections due to the beam-size effect. Relative suppression due to the beam-size effect $(d\sigma_{\rm corr}/dy)/(d\sigma_{\rm BH}/dy)$ is shown as a function of $y = E_\gamma/E_e$ for three cases of electron-proton bremsstrahlung.

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

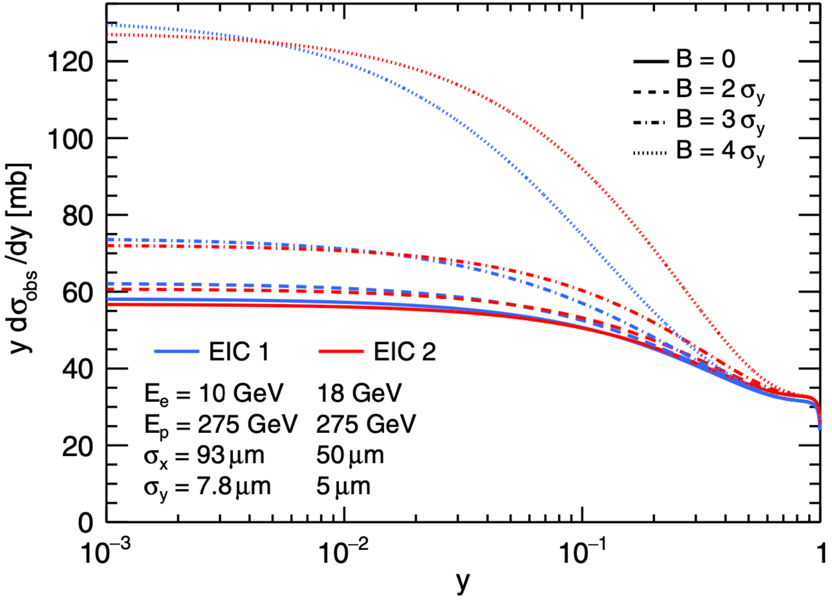


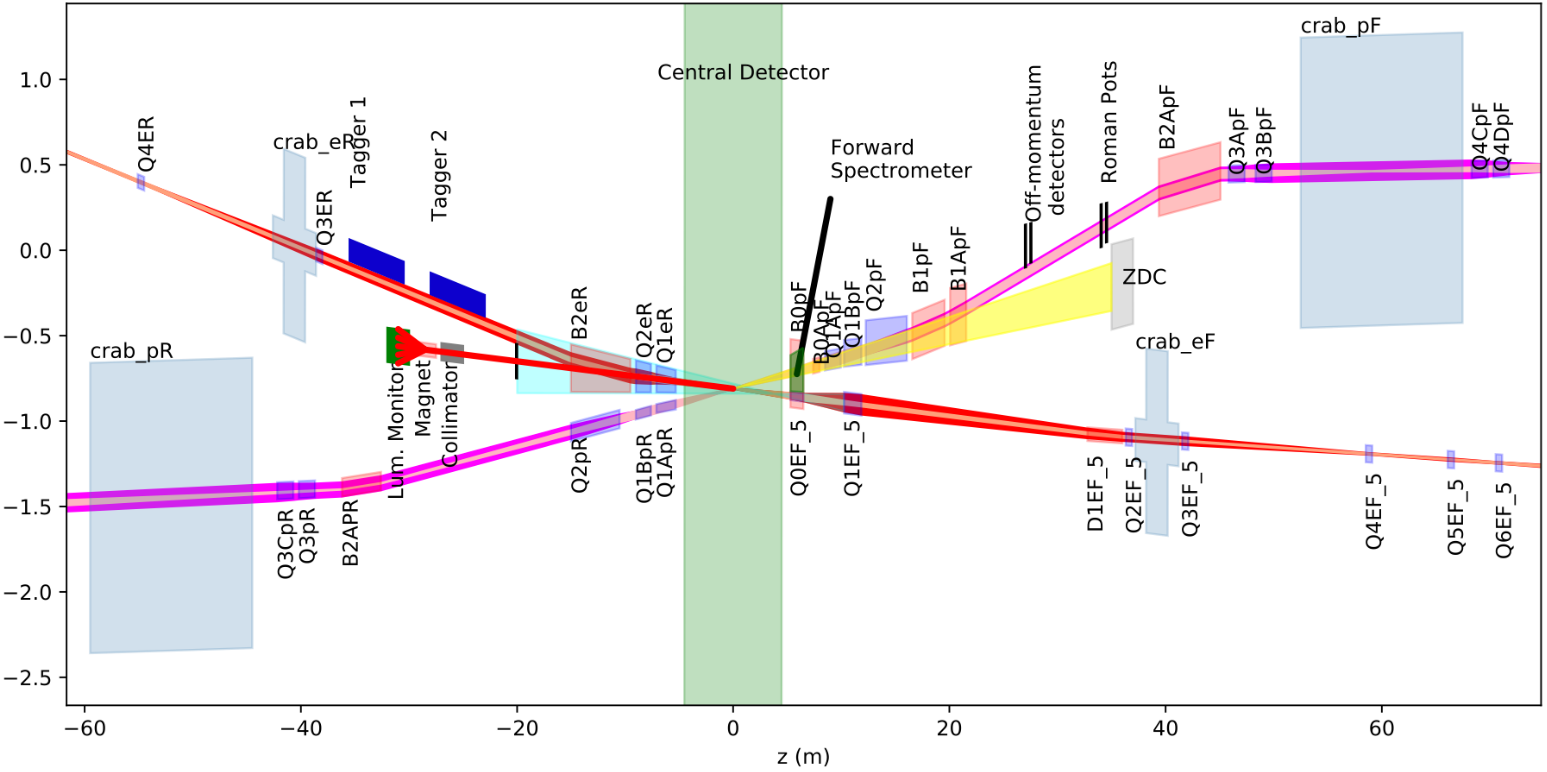
FIG. 4. The predicted spectra of $e\,p$ bremsstrahlung at the EIC for several vertical beam displacements. The standard Bethe-Heitler cross section $d\sigma_{\mathrm{BH}}/dy$ is modified due to the beam-size effect and beam displacements B. The effective cross sections (multiplied by y for better visibility)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

Original and powerful BSE tests are proposed by measuring bremsstrahlung spectra while performing vertical “Van der Meer scans” using hadron beams.

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!

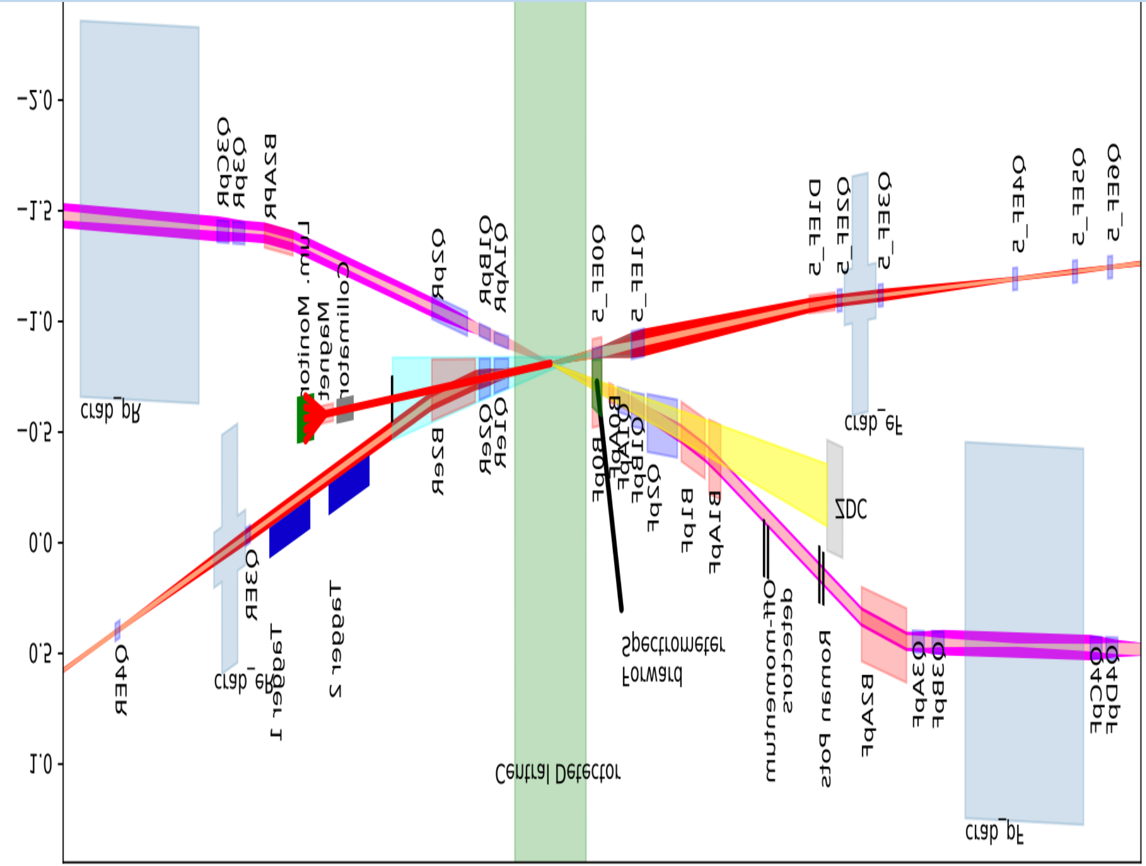
Interaction Region at the Electron-Ion Collider



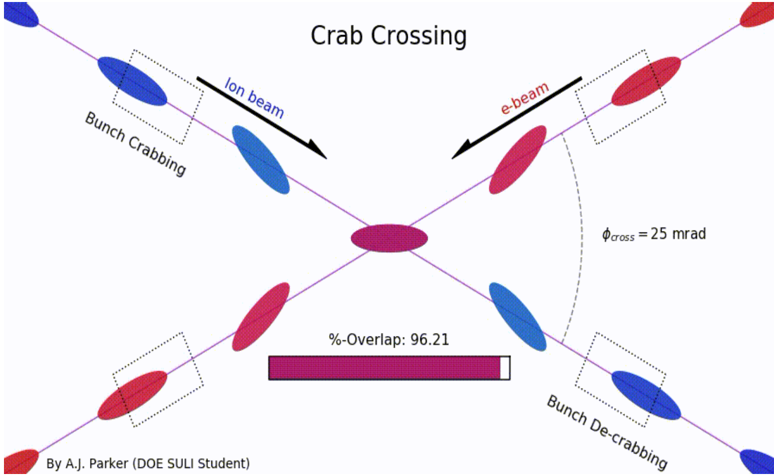
Provisions have been made in the EIC *Interaction Region* designs for the luminosity measurements using bremsstrahlung, as well as for very forward electron detectors (photoproduction taggers)

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

Interaction Region at the EIC

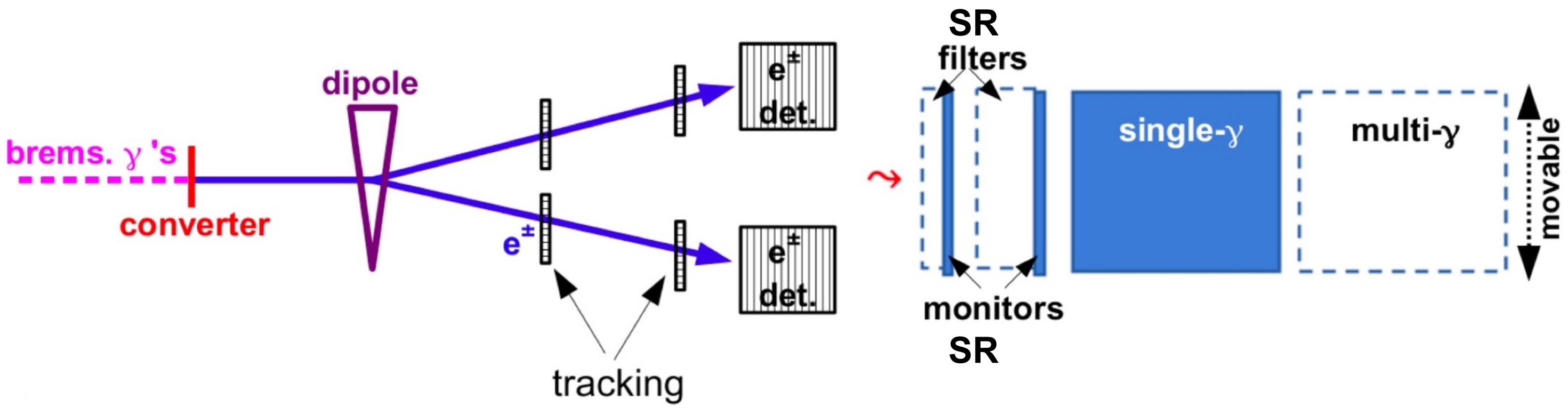


Vertex drift has negligible effect on γ–acceptance (in contrast to forward *p/e* tracking), as **all photons with polar angle < 1 mrad should be detected**



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

Luminosity detectors & photoproduction taggers

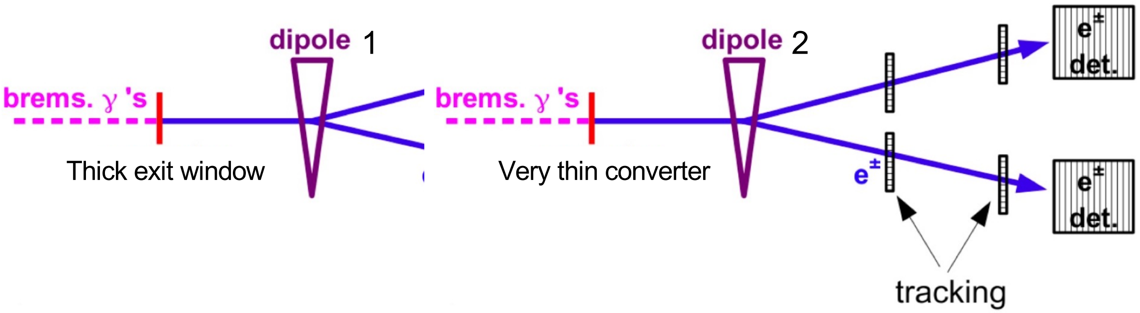


Profiting from (hard) lessons at HERA:

- Need to study BSE in depth – **dedicated calorimeter** is mandatory also for regular *calibration runs at low $\mathcal{L}$*
- Add simple tracking to Pair Spectrometer
- Monitor synchrotron radiation flux
- Use extensively **electron detectors** for various calibration checks – including geometrical acceptance and energy calibration ⇒ *fast hodoscopes* are mandatory for resolution/coping with high event pileup (→ HI beams!)

New Pair Spectrometer layout with **TWO** dipoles

K.P. – Aug'22



Problem with old layout of Pair Spectrometer (PS):

Photon converter serves as photon exit window which is **thick**, to properly separate from beam primary vacuum as well as to distribute SR heat load:

⇒ Such thick converter results in **significant event pileup** even in PS, in addition multiple scattering and bremsstrahlung at exit window seriously **limit the PS resolution**

Solution: **extra small dipole** magnet is introduced to sweep away all photon conversions at exit window and then *conversion foil(s)* can be **as thin as necessary**

Photon counting *vs.* Photon energy flow

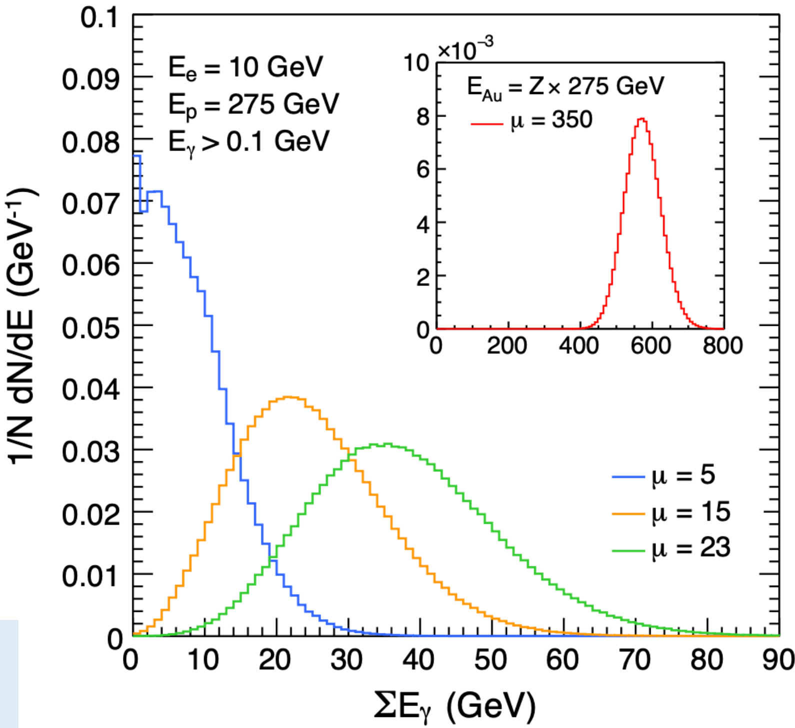
JINST **16** (2021) 09, P09023
https://doi.org/10.1088/1748-0221/16/09/P09023

For **direct photon measurement** bremsstrahlung pileup is huge at EIC and photon counting is not possible, instead, **total photon energy per bunch crossing** can be measured, ⇒⇒

which is directly proportional to $\mathcal{L}$

For nominal *eAu* collisions it is equivalent to measuring total photon energy ≈ 600 GeV !

In contrast to photon counting, such energy flow measurements are directly sensitive to photon energy scale – **calibration errors** need to be **≪ 1%**



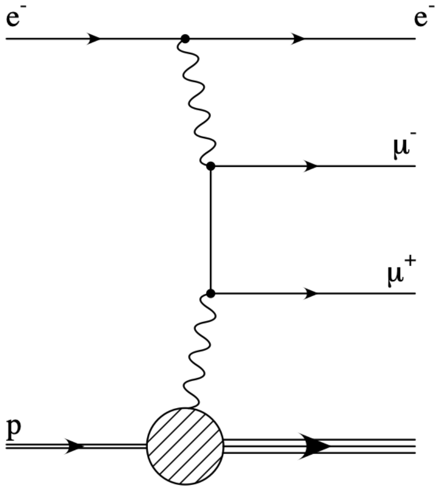
JINST **17** (2022) 10, P10019

e pilot bunches & exclusive lepton pairs

Non-colliding electron ***pilot bunches*** **will be necessary** not only to control *e-gas* backgrounds, but are essential for **precise data-driven** photon energy calibrations (using BH spectrum end-point) and for photon geometrical acceptance

In addition, 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 should give yet another **direct calibration of bremsstrahlung photon energy,** in the most relevant energy range!

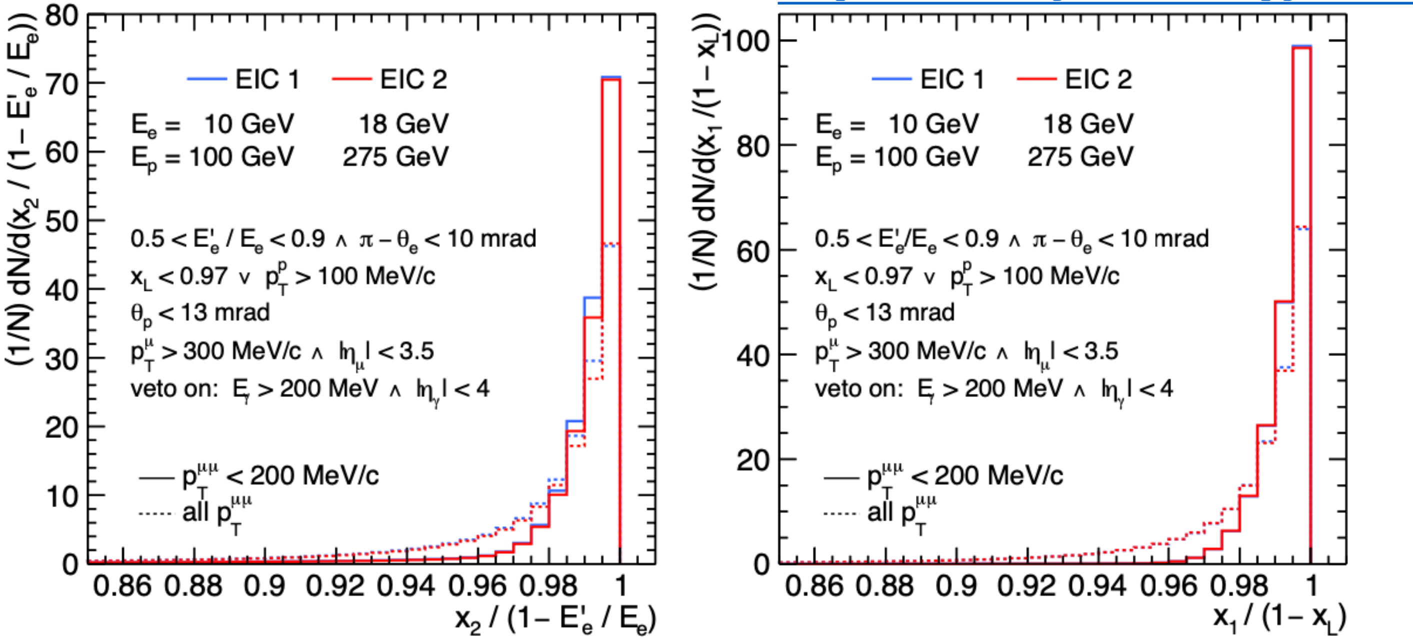


Energy calibration of far forward and far backward detectors

Use "DY formulae", assuming collinear photons: $x_{1,2} = \frac{M_{ll}}{\sqrt{s}} \sqrt{\frac{(E \pm p_z)}{(E \mp p_z)}} \exp(\mp Y^*)$, where

$Y^* = \mathrm{artanh}(\frac{P_{e,z}+P_{p,z}}{E_e+E_p})$

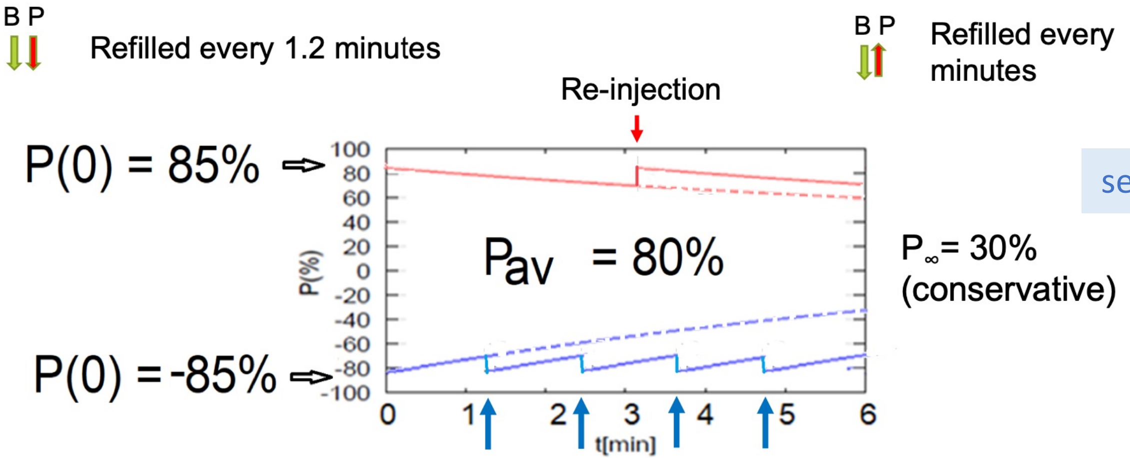
Eur. Phys. J. C **82** (2022) 9, 846
https://doi.org/10.1140/epjc/s10052-022-10820-0



Narrow "kinematic peaks" are clearly visible allowing for regular and precise data-driven calibrations of far detectors

Polarization Physics vs. Bunch-to-Bunch Luminosity

1160 (290) electron bunches at EIC – electron polarization can be flipped *bunch-to-bunch*



see Ch. Montag talk, on Tuesday

Double spin asymmetries are small hence the demand of very precise relative luminosities $\mathcal{L}_{+-}/\mathcal{L}_{++}$ with **at most 10^{-4}** uncertainty

Highly non-trivial problem – bremsstrahlung **photon counting** is the principal method here (statistics is there!)

Polarization Physics vs. Bunch-to-Bunch Luminosity II

Bremsstrahlung Cross Section with Polarized Beams for Luminosity Determination at the EIC

Dhevan Gangadharan*
University of Houston
(Dated: September 12, 2023)

The bremsstrahlung cross section is calculated at leading order for polarized beams of electrons and ions, which is needed for luminosity measurements at the upcoming Electron Ion Collider (EIC). Analytic expressions, differential in the emitted photon energy and polar angle, are derived. The component of the cross section which depends on the beam polarizations is found to be highly suppressed with respect to the unpolarized Bethe-Heitler component, owing to the low q^2 that characterizes the bremsstrahlung process.

https://arxiv.org/abs/2307.16245

Recent calculations confirmed that bremsstrahlung cross-section variations due to polarizations $\ll 10^{-4}$ $\Rightarrow$ **no need for special correction terms**

Summary

Precise luminosity determination is very challenging at the EIC – both in case of absolute measurements and of relative ones.

- **Two complementary methods** are mandatory – *Photon (Conversion) Counting vs. Photon Energy Flow*

- **New** instrumentation is needed to get good performance at nominal luminosity: **fast hodoscopes** in $e^{-}e^{+}$ spectrometer + synchrotron radiation monitors and a **dedicated photon calorimeter** which will allow for very precise reference luminosity measurements

- Will use a **sweeping magnet** and a **thin conversion foil** to minimize photon conversion errors

Finally, beam-size effects must be thoroughly studied at the EIC.

Thank you!

EIC *Conceptual Design Report* – February 2021

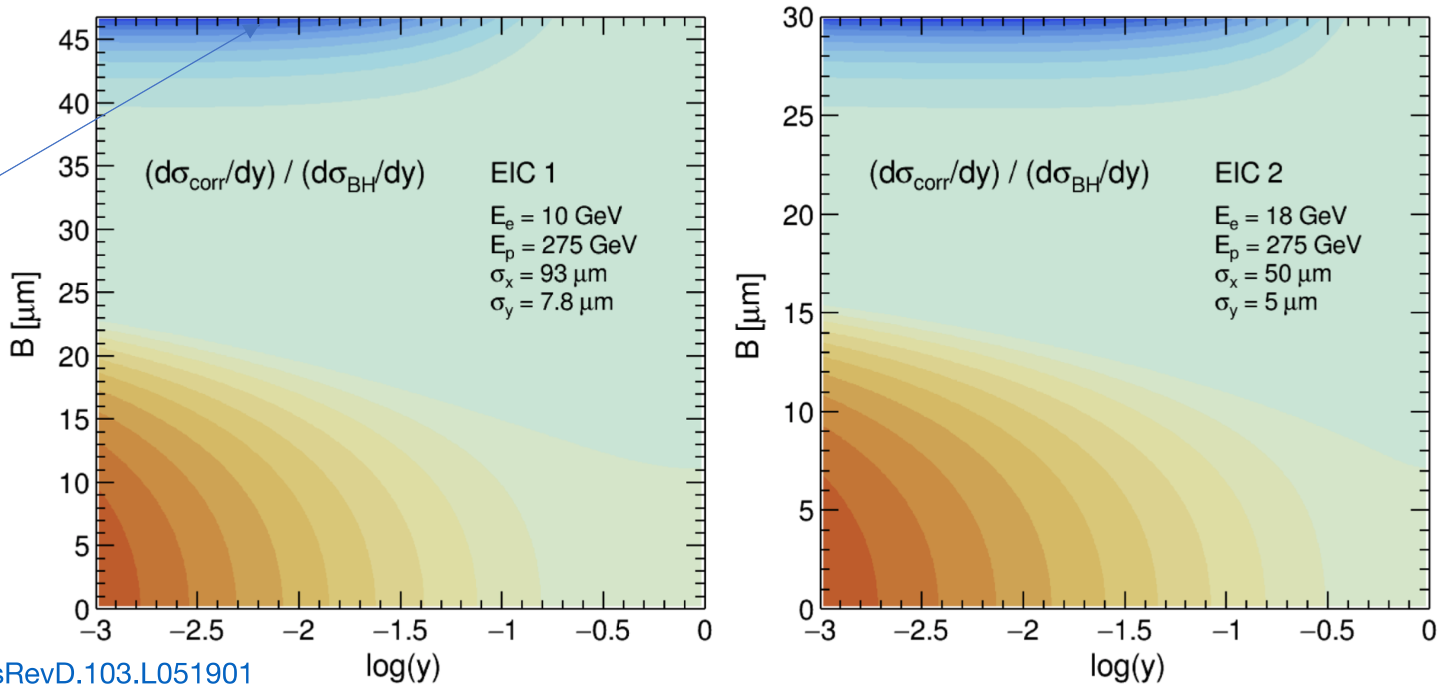
https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

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	

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.