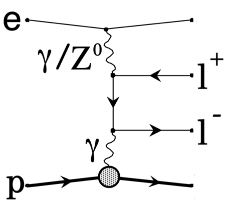
Exclusive Lepton Pair Production at the Electron-Ion Collider

K. Piotrzkowski (AGH University of Science and Technology, Kraków)

In collaboration with

J. Chwastowski (IFJ PAN, Kraków) and M. Przybycień (AGH UST, Kraków)

Eur. Phys. J. C 82 (2022) 9, 846

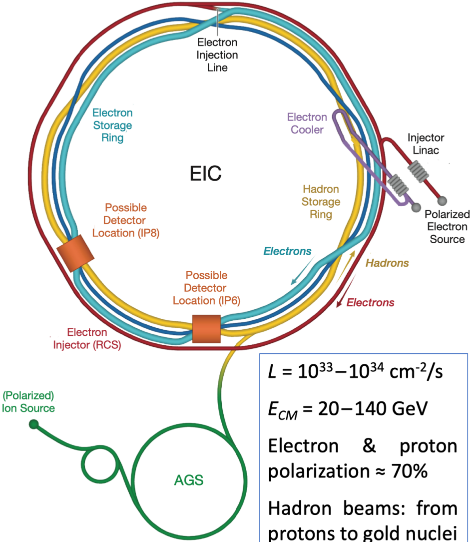


25^{th} International Symposium on Spin Physics

SPIN 2023, September 24–29 at Duke University

Motivation I

Two-photon exclusive ("Bethe-Heitler") production of lepton pairs in ep collisions is usually studied as the main source of background in TCS or DDVCS, however...



L = 10^{33}–10^{34} cm^{-2}/s

E_{CM} = 20–140 GeV

Electron & proton polarization ≈ 70%

Hadron beams: from protons to gold nuclei

- Thanks to huge ep luminosity at the Electron Ion Collider (EIC) a very large exclusive lepton pair event statistics can be acquired
- This will allow to carry out original and very interesting research as well as to perform important energy calibrations of very forward detectors (in analogy to DY pair kinematics in pp used for determination of Bjorken-x) – here we make first survey of scientific case for deep studies of $\gamma\gamma \to l^+l^-$ at the EIC
- In addition, such studies will profit from high polarizations of both electron and proton beams as well as from electron-ion collisions for investigating nuclear effects

Motivation II

- Experimental conditions at the EIC will be very favorable for studies of exclusive processes – in spite of very high luminosity, event pileup will be small, below 10%
- Central tracking will provide high momentum resolution for leptons and thanks to data streaming in DAQ, a very high efficiency of selecting the (semi-)exclusive events is expected – "two opposite-charge tracks within $|\eta| < 3.5$, and nothing else"
- Far forward and far backward detectors will measure hadrons and electrons, respectively, scattered at very small angles – and will allow for selection of pure samples of fully exclusive events

η	Nomenclature	Tracking						Electrons and Photons			π/K/p		HCAL		Muons
		Resolution	Relative Momentun	Allowed X/X_0	Minimum-p_T (MeV/c)	Transverse Pointing Res.	Longitudinal Pointing Res.	Resolution σ_E/E	PID	Min E Photon	p-Range	Separation	Resolution σ_E/E	Energy	
< -4.6	Low-Q2 tagger														
-4.6 to -4.0		Not Accessible													
-4.0 to -3.5			Reduced Performance												
-3.5 to -3.0	Backward Detector		σ_p/p ~ 0.1%×p⊕2%	~5% or less	150-300			1%/E ⊕ 2.5%/√E ⊕ 1%	π suppression up to 1:10^{-4}	20 MeV	≤ 10 GeV/c	≥ 3σ	50%/√E ⊕ 10%	~500MeV	Muons useful for background suppression and improved resolution
-3.0 to -2.5															
-2.5 to -2.0			σ_p/p ~ 0.02% × p ⊕ 1%												
-2.0 to -1.5						dca(xy) ~ 40/p_T µm ⊕ 10 µm	dca(z) ~ 100/p_T µm ⊕ 20 µm	2%/E ⊕ (4-8)%/√E ⊕ 2%	π suppression up to 1:(10^{-3}-10^{-2})	50 MeV					
-1.5 to -1.0															
-1.0 to -0.5	Barrel		σ_p/p ~ 0.02% × p ⊕ 5%		400	dca(xy) ~ 30/p_T µm ⊕ 5 µm	dca(z) ~ 30/p_T µm ⊕ 5 µm	2%/E ⊕ (12-14)%/√E ⊕ (2-3)%	π suppression up to 1:10^{-2}	100 MeV	≤ 6 GeV/c		100%/√E ⊕ 10%		
-0.5 to 0.0															
0.0 to 0.5															
0.5 to 1.0															
1.0 to 1.5	Forward Detectors		σ_p/p ~ 0.02% × p ⊕ 1%		150-300	dca(xy) ~ 40/p_T µm ⊕ 10 µm	dca(z) ~ 100/p_T µm ⊕ 20 µm	2%/E ⊕ (4*-12)%/√E ⊕ 2%	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		50%/√E ⊕ 10%		
1.5 to 2.0															
2.0 to 2.5															
2.5 to 3.0			σ_p/p ~ 0.1%×p⊕2%												
3.0 to 3.5															
3.5 to 4.0	Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5		Not Accessible													
> 4.6	Proton Spectrometer Zero Degree Neutral Detection														

From the EIC Yellow Report

Event generation with GRAPE

- GRAPE Monte Carlo generator by T. Abe (arXiv:hep-ph/0012029) is used for simulations of lepton pair production in electron-proton collisions at the EIC – such pairs are produced via $\gamma\gamma$, γZ and ZZ exchanges, and by internal photon conversions. Also, effects of on-/off-shell Z production are included, as well as those of ISR/FSR.

- Below only exclusive ("elastic") case is studied where proton-proton-photon vertex is calculated using standard Sachs ("dipole") electromagnetic form factors as a function of four-momentum transfer squared t, where μ_p is proton magnetic moment:

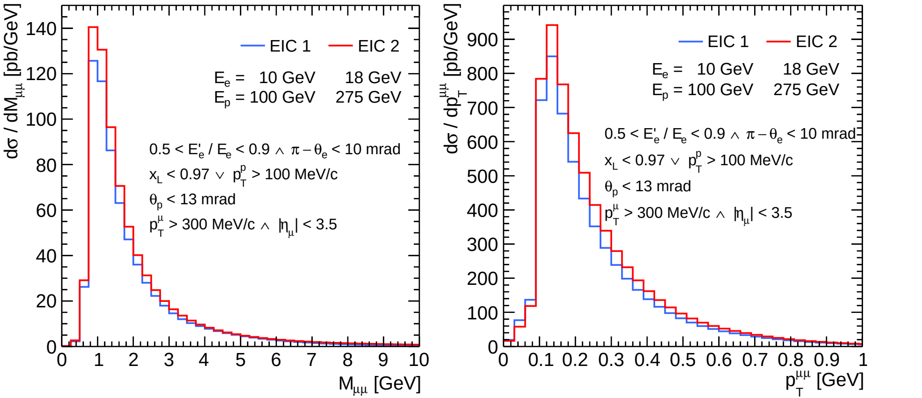
$$G_E(t) = (1 - t/0.71\ \mathrm{GeV}^2)^{-2},\ G_M(t) = \mu_p G_E(t)$$

- **Detection acceptances** are represented by following kinematic cuts:

  $0.5 < E'_e/E_e < 0.9$ and $\pi - \theta < 10$ mrad for scattered electrons,
  $x_L < 0.97$ or $p_T > 100$ MeV/c, and $\theta < 13$ mrad for scattered protons,
  $p_T > 300$ MeV/c and $|\eta| < 3.5$ for produced leptons.

  In addition, FSR veto might be applied by requesting no photons within $|\eta| < 4$ above (for example) 200 MeV.

Muon pairs within acceptances

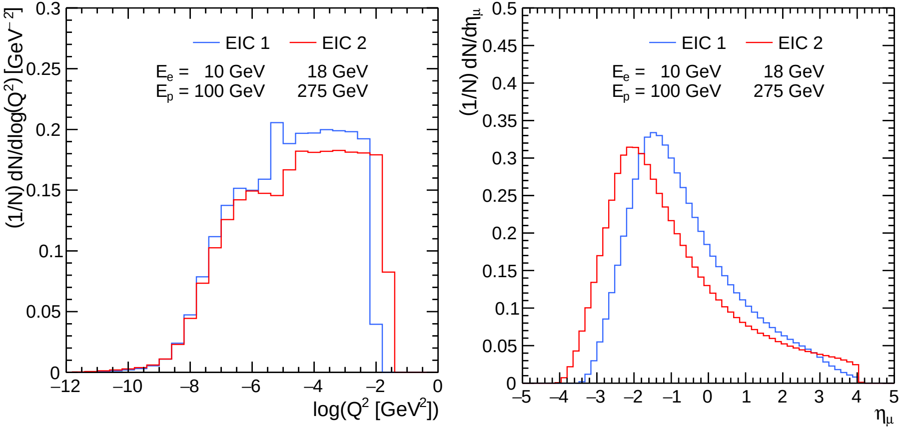


Total cross sections for the above selection of the muon exclusive pairs (w/ photon veto):

- EIC 1: $\sigma = 169\ (163)$ pb
- EIC 2: $\sigma = 192\ (185)$ pb

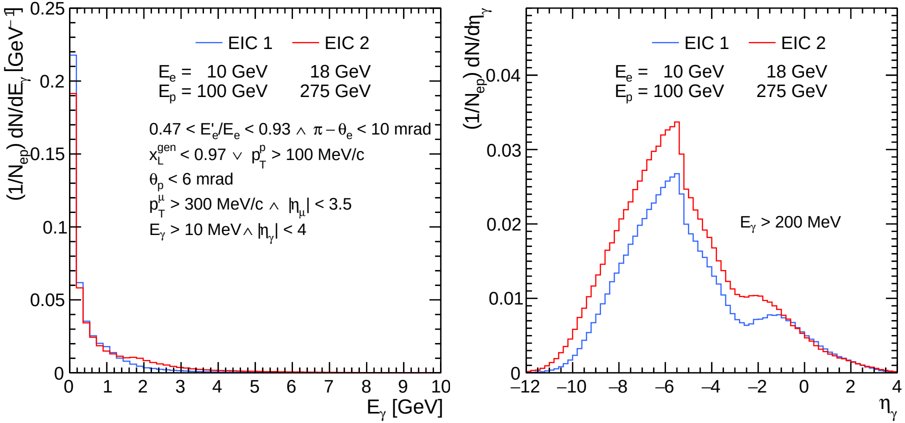
Note: Threshold effects are due to acceptances of the central tracker and far forward proton detectors, respectively.

Distributions of accepted events



Distributions of the photon virtuality Q^2, at the electron vertex, and muon pseudo-rapidity for the accepted events (with a $|\eta_\mu| < 4$ cut).

Photon veto

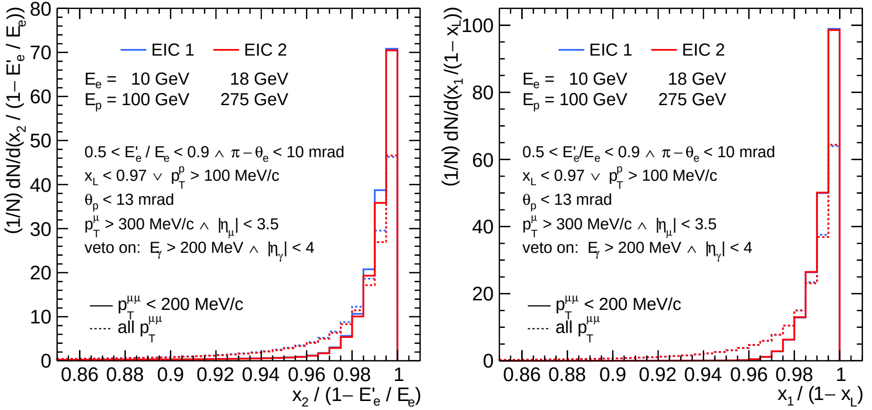


There is a significant amount of Final State Radiation (FSR), which can affect the reconstruction of event kinematic

Note: ISR can only be detected at low luminosity running of the EIC

Energy calibration of far forward and far backward detectors

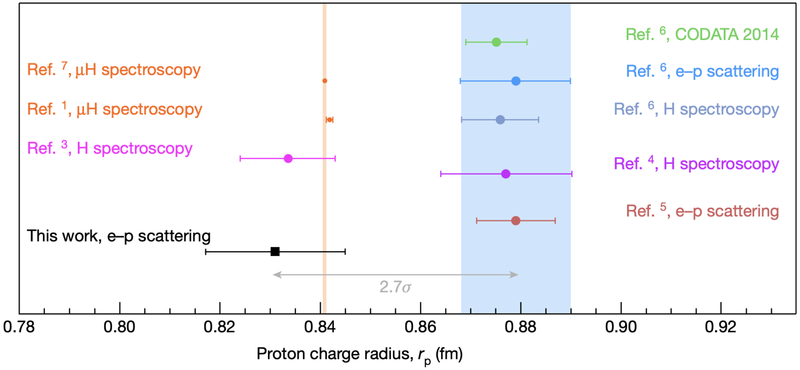
Use "DY formulae", assuming collinear photons: $x_{1,2} = \frac{M_{ll}}{\sqrt{s}} \sqrt{\frac{(E \pm p_z)}{(E \mp p_z)}} \exp(\mp Y^*)$, where $Y^* = \mathrm{artanh}(\frac{P_{e,z}+P_{p,z}}{E_e+E_p})$



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

Proton charge radius puzzle: Reminder

There are continuing discrepancies among measurements of the proton charge radius, in particular among "classic" measurements using electron-proton *elastic* scattering:



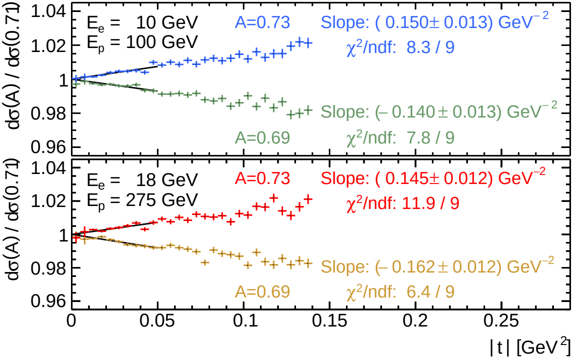
From Nature 575, 147–150 (2019)

where the average charge radius is determined from the elastic form-factor G_E at $t = 0$,

$$R_p^2 = 6\frac{\mathrm{d}G_E}{\mathrm{d}t}(0)/G_E(0), \text{hence } R_p^2 = 12/0.71\ \mathrm{GeV}^2 \text{ for the standard } G_E$$

Proton charge radius: Sensitivity at the EIC

We estimated an "ultimate" sensitivity to R_p at the EIC using the "elastic" muon pairs, true kinematic variables and statistical errors only:

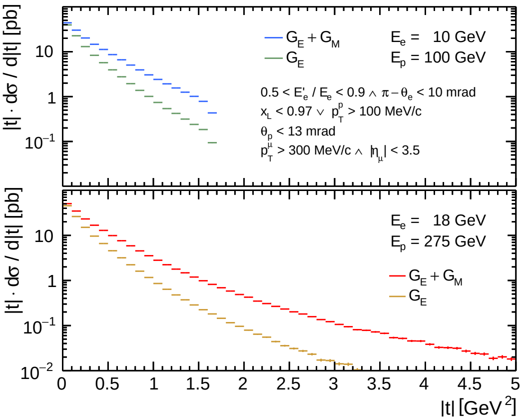


- t distributions of selected events were made for three values of R_p
- ratios of these distributions were fitted next to $t = 0$ with straight lines
- fitted slopes are directly sensitive to changes of R_p

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{d\sigma_1}{dt} / \frac{d\sigma_2}{dt}\right)\Big|_{t=0} = 3\Delta(R_p^2)$$

Statistics of above GRAPE (untagged) samples correspond to integrated luminosities of about 100 fb^{-1}, and **obtained statistical uncertainties on R_p are of about 0.1%**

Separation of form-factors G_E and G_M

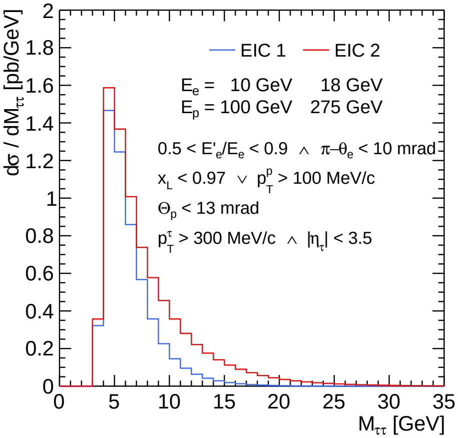


- Separation of proton electromagnetic form-factors at about $-t = 1\ \mathrm{GeV}^2$ and beyond, is particularly interesting
- As we show, the "observed" cross-section for fully exclusive production of muon pairs is only accessible at EIC 2 in such a region
- Unique feature of two-photon exclusive pair production is its variable and very well controlled γp center-of-mass energy ($\rightarrow$ Rosenbluth-like separation)

Note: High proton polarization might enhance the $G_E - G_M$ separation power

Exclusive tau lepton pairs

Two-photon production of pairs of τ leptons in UPC became recently a very active field of research as $\gamma\gamma \to \tau^+\tau^-$ is particularly sensitive to the τ lepton anomalous magnetic dipole moment a_τ, and its electric dipole moment d_τ



- Large "observed" cross-sections are expected at the EIC:
  - EIC 1: $\sigma = 5.5$ pb
  - EIC 2: $\sigma = 7.8$ pb
- At the EIC, detection of very forward (backward) scattered protons (electrons) will allow for good event-by-event control of $\gamma\gamma$ kinematics
- It should also allow to build various angular correlations to increase sensitivities thanks to high beam polarizations

Excellent conditions will be available at the EIC for τ lepton studies, with very high $\tau\tau$ event statistics – about two orders of magnitude larger than at the HL-LHC

Summary and Outlook

EIC will provide perfect conditions for studying exclusive processes:

- very high luminosity will ensure high statistics even for relatively rare processes;
- data streaming will result in low trigger losses and in lack of efficiency corrections;
- negligible event pileup and excellent particle momentum resolutions/PID (at low and medium p_T) will strongly enhance full final state reconstruction;
- far forward and far backward high resolution detectors of protons and electrons, respectively, might even provide "over-constrained reconstruction" allowing for precise data-driven inter-calibrations and testing acceptances and reconstructions.

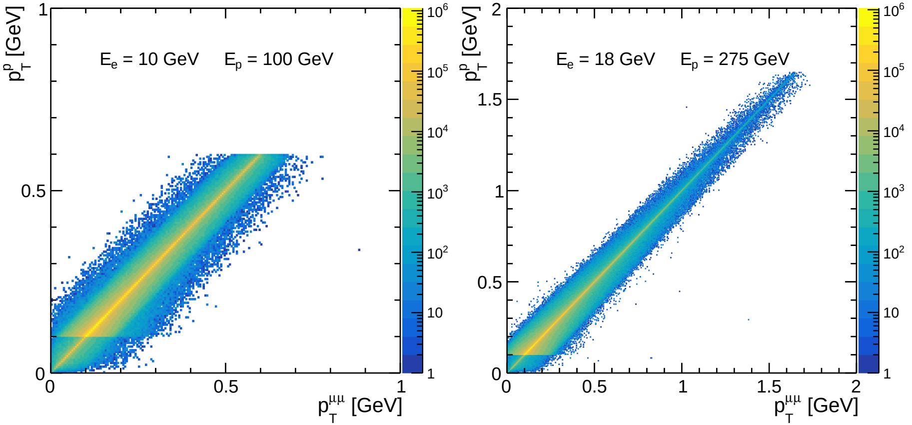
First exploratory studies show that two-photon exclusive production of lepton pairs can be used at the EIC for original tests of Standard Model:

- precise measurements of elastic production of muon (and electron) pairs may result in competitive determinations of the average proton charge radius as well the elastic G_E and G_M form-factors;
- very high statistics of exclusive τ pairs should provide unique access to the magnetic and electric moments of τ leptons.

Future studies will include the electron-ion cases as well as impacts of TCS/DDVCS and of beam polarizations, apart from introducing further detector effects.

Backup Slides

Correlations: proton p_T vs. pair p_T



Muon (and electron) pair p_T will provide an excellent calibration tool for the direct proton p_T measurement; possibly, also the proton acceptance can be well calibrated using the exclusive muon pairs