Exclusive Lepton Pairs at the EIC

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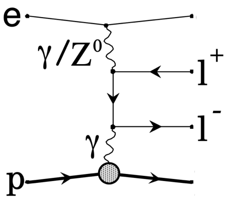

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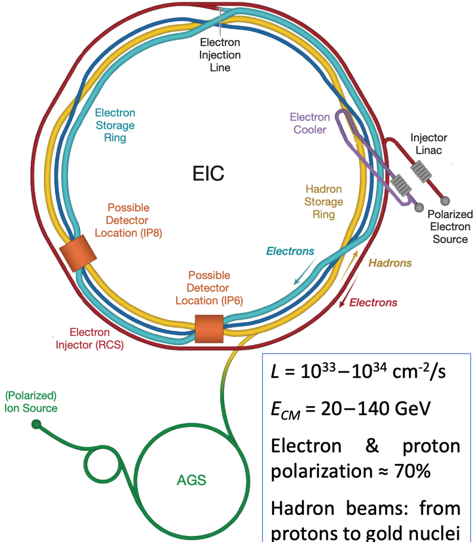
Motivation I

At HERA, two-photon exclusive ("Bethe-Heitler") production of lepton pairs in ep collisions was the main source of background in studies of the exclusive VM production



$L = 10^{33} - 10^{34}$ cm^{-2}/s

E_{CM} = 20−140 GeV

Electron & proton polarization ≈ 70%

Hadron beams: from protons to gold nuclei

- At the Electron Ion Collider (EIC), thanks to > 100 times bigger ep luminosity, very large 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 the use of DY pair kinematics for determination of Bjorken-x) – here we make first survey of scientific case for deep studies of $\gamma\gamma \to l^+ l^-$
- 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, the event pileup will be small (below 10%).
- The central tracking will provide high momentum resolution for leptons and thanks to the 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			$\pi/K/p$		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												Muons useful for background suppression and improved resolution
-3.5 to -3.0	Backward Detector		$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$	~5% or less	150-300			$1\%/E \oplus 2.5\%/\sqrt{E} \oplus 1\%$	π suppression up to $1:10^{-4}$	20 MeV	$\leq$ 10 GeV/c	$\geq 3\sigma$	$50\%/\sqrt{E} \oplus 10\%$	~500MeV	
-3.0 to -2.5															
-2.5 to -2.0			$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$												
-2.0 to -1.5						dca(xy) ~ $40/p_T$ µm $\oplus$ 10 µm	dca(z) ~ $100/p_T$ µm $\oplus$ 20 µm	$2\%/E \oplus (4\text{-}8)\%/\sqrt{E} \oplus 2\%$	π suppression up to $1:(10^{-3}\text{-}10^{-2})$	50 MeV					
-1.5 to -1.0															
-1.0 to -0.5	Barrel		$\sigma_p/p \sim 0.02\% \times p \oplus 5\%$		400	dca(xy) ~ $30/p_T$ µm $\oplus$ 5 µm	dca(z) ~ $30/p_T$ µm $\oplus$ 5 µm	$2\%/E \oplus (12\text{-}14)\%/\sqrt{E} \oplus (2\text{-}3)\%$	π suppression up to $1:10^{-2}$	100 MeV	$\leq$ 6 GeV/c		$100\%/\sqrt{E} \oplus 10\%$		
-0.5 to 0.0															
0.0 to 0.5															
0.5 to 1.0															
1.0 to 1.5	Forward Detectors		$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$		150-300	dca(xy) ~ $40/p_T$ µm $\oplus$ 10 µm	dca(z) ~ $100/p_T$ µm $\oplus$ 20 µm	$2\%/E \oplus (4^*\text{-}12)\%/\sqrt{E} \oplus 2\%$	3σ e/π up to 15 GeV/c	50 MeV	$\leq$ 50 GeV/c		$50\%/\sqrt{E} \oplus 10\%$		
1.5 to 2.0															
2.0 to 2.5															
2.5 to 3.0			$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$												
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

GRAPE event generator

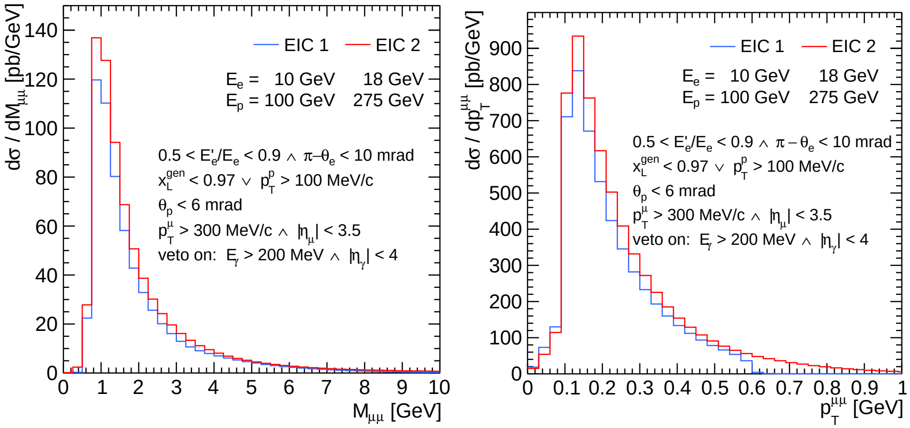
- GRAPE Monte Carlo generator by T. Abe (arXiv:hep-ph/0012029) is used for simulations of the lepton pair production in electron-proton interactions at the EIC – the pairs are produced via $\gamma\gamma$, γZ and ZZ exchanges, and by the internal photon conversions. Also, effects of the on-/off-shell Z production are included, as well as those of the ISR/FSR.
- Below only the exclusive ("elastic") case is studied where the proton-proton-photon vertex is calculated using the standard Sachs ("dipole") electromagnetic form factors as a function of the four-momentum transfer squared t, where μ_p is the proton magnetic moment:

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

- The detection acceptances are represented by the following kinematic cuts:
  $0.5 < E'_e/E_e < 0.9$ and $\pi - \theta < 10$ mrad for the scattered electrons,
  $x_L < 0.97$ or $p_T > 100$ MeV/c, and $\theta < 6$ mrad for for the scattered protons,
  $p_T > 300$ MeV/c and $|\eta| < 3.5$ for the produced leptons.

  In addition, the FSR veto can be applied by requesting no photons above 200 MeV within $|\eta| < 4$.

Muon pairs

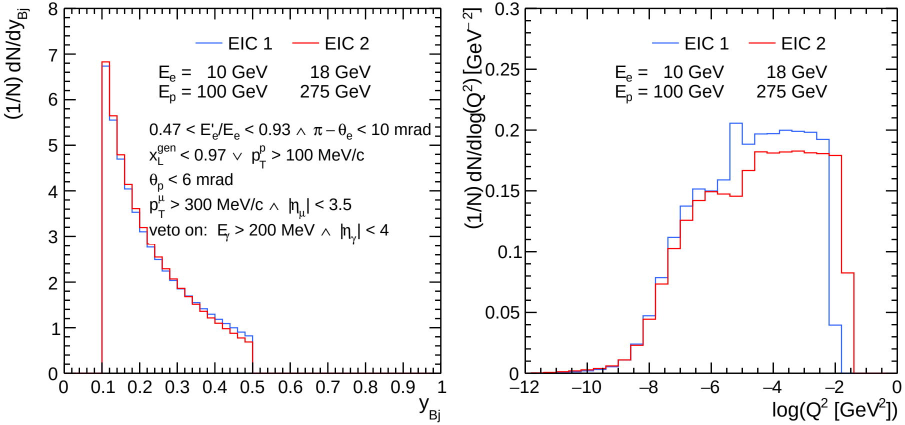


Total cross sections for the above selection of the muon exclusive pairs:

- EIC 1: $\sigma = 72.3$ pb
- EIC 2: $\sigma = 182.3$ pb

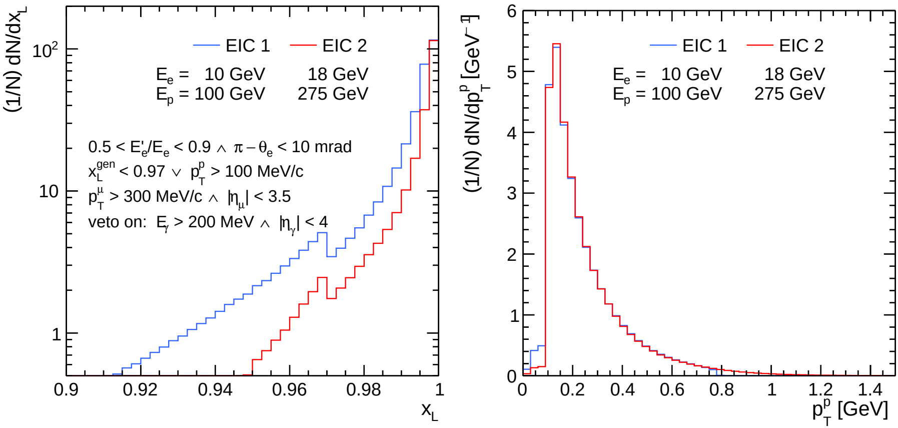
Note: Threshold effects are due to acceptances of the central tracker and far forward proton detectors, respectively

Acceptance windows: electrons



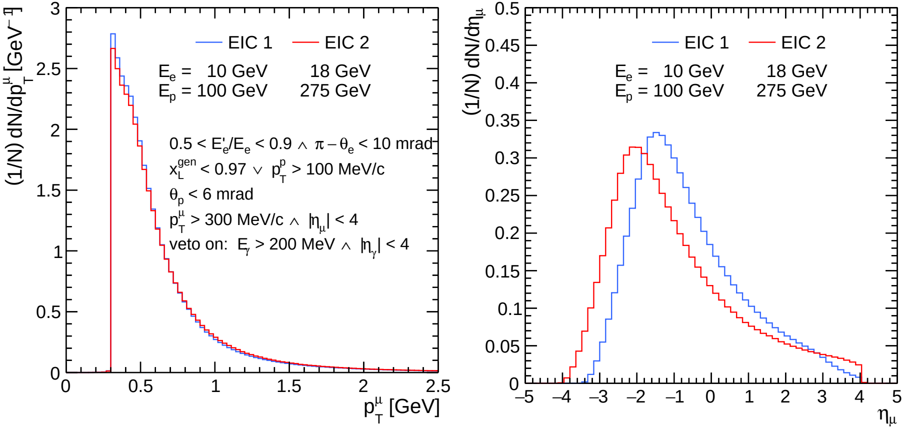
Kinematic ranges in y_{Bj} and the photon virtuality Q^2, at the electron vertex, are due to acceptances of the far backward electron detectors

Acceptance windows: protons



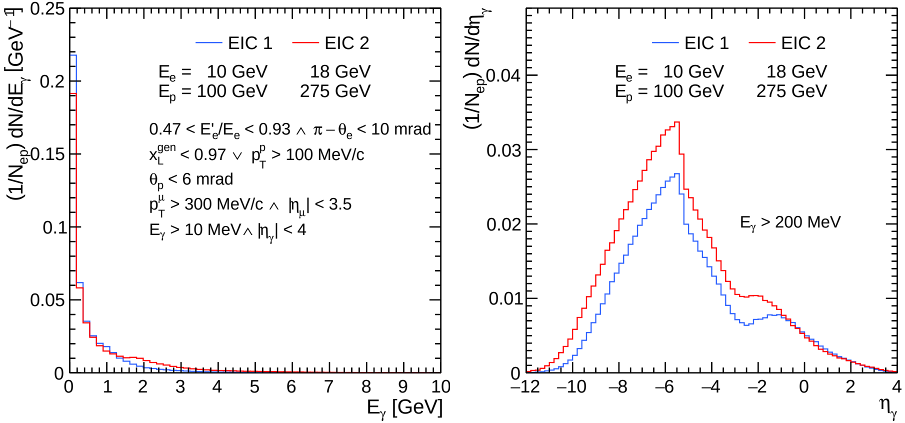
Kinematic ranges in x_L and p_T^p are due to acceptances of the far forward proton detectors

Acceptance windows: muons



Muon distributions within the acceptance of the central tracker

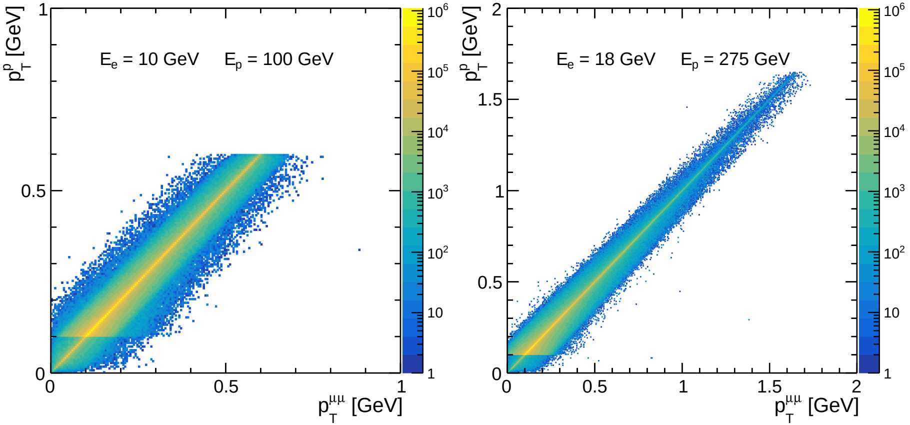
Photon veto



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

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

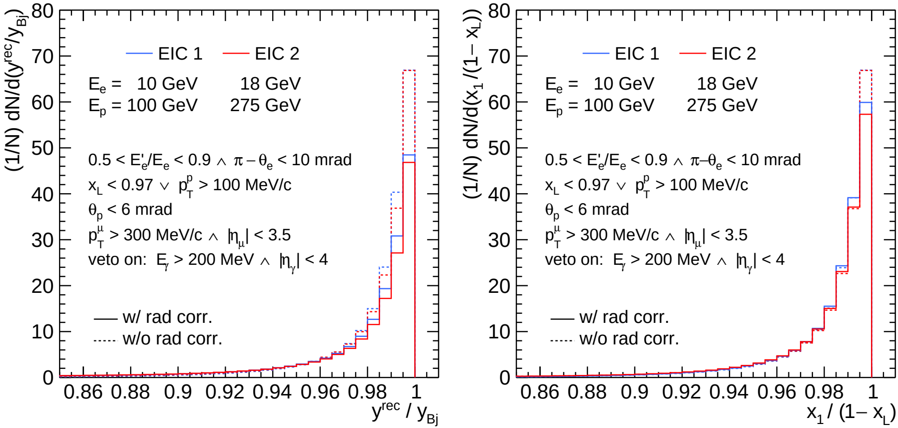
Correlations: proton p_T vs. pair p_T



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

Energy calibration of far forward and far backward detectors

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

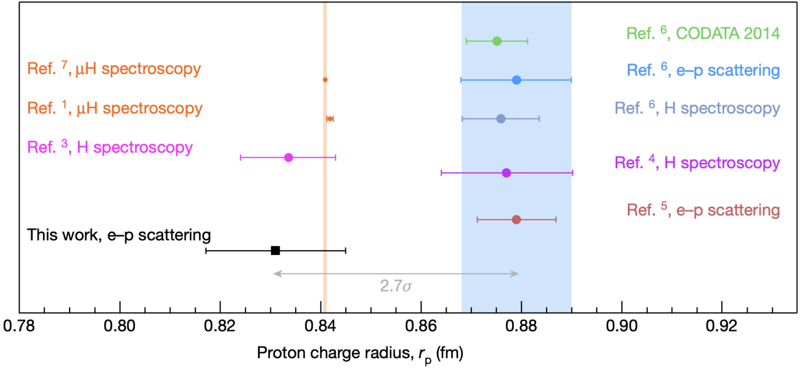


where $y^{rec} = x_2$.

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

Proton charge radius puzzle: Introduction

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



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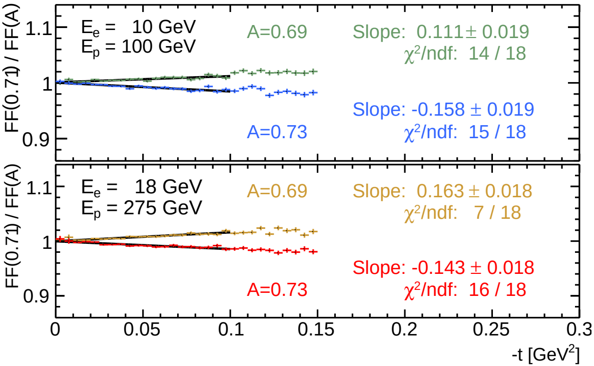
where the charge radius is determined from the elastic form-factor G_E at $t = 0$,

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

Proton charge radius: Sensitivity at the EIC

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

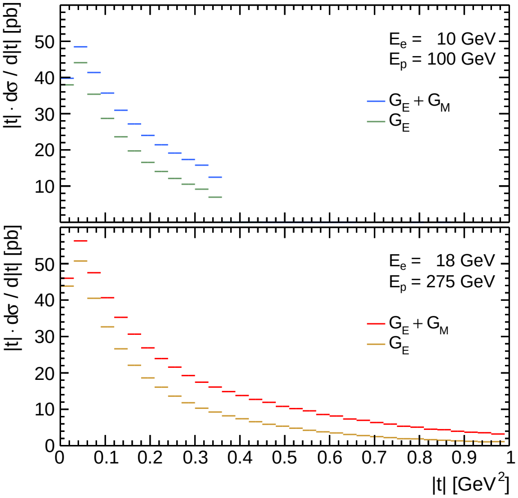


- t distributions of the selected events were made for three values of R_p
- ratios of these distributions were fitted next to $t = 0$ with straight lines
- fitted slopes are directly sensitive to the changes of R_p, as

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

Statistics of the GRAPE samples correspond to the integrated luminosities of about 70 fb^{-1}, what demonstrates that for the full EIC luminosity of 1 ab^{-1} one can expect statistical uncertainties, on the measured R_p, significantly below 1%

Separation of the form-factors G_E and G_M

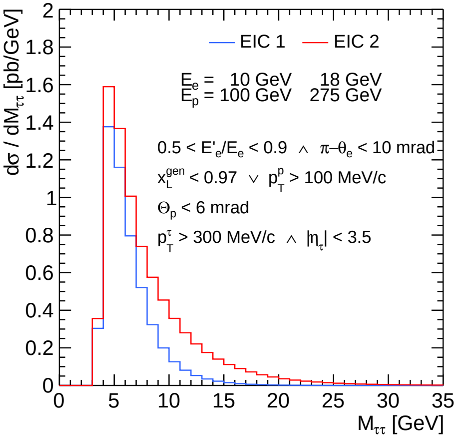


- Recently, there has been renewed interest in the proton electromagnetic form-factors in the region close to $-t = 1\ \mathrm{GeV}^2$ and beyond, in particular for testing the relation $G_M = \mu_p G_E$
- Here we show the "observed" cross-sections for fully exclusive production of muon pairs – only at high energy EIC 2 such a region can be studied
- Large cross-sections will allow for precise measurements of the G_E and G_M contributions

Note: High proton polarization and azimuthal $p - \mu\mu$ correlations will enhance the separation power for the G_E and G_M contributions

Tau lepton pairs

Two-photon production of pairs of τ leptons in the 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



- At the EIC, the detection of forward scattered protons and electrons will allow for a good event-by-event control of $\gamma\gamma$ kinematics
- Detection of the forward scattered protons will allow to build $p - \tau\tau$ azimuthal correlations, **amplified** by high polarization of incident protons
- Large "observed" cross-sections are expected at the EIC:
  - EIC 1: $\sigma = 10.9$ pb
  - EIC 2: $\sigma = 33.9$ pb

Excellent conditions will be available at the EIC for the 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 no 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,
- in addition, 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 understanding of acceptances and reconstructions.

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

- Precise studies of elastic production of muon and electron pairs will result in competitive measurements of the proton charge radius as well the elastic G_E and G_M form-factors;
- high statistics of exclusive τ pairs will provide unique access to the magnetic and electric moments of τ leptons.

Future studies will be yet extended to include the impact of beam polarizations as well as the electron-ion case, apart from introduction of various detector effects.