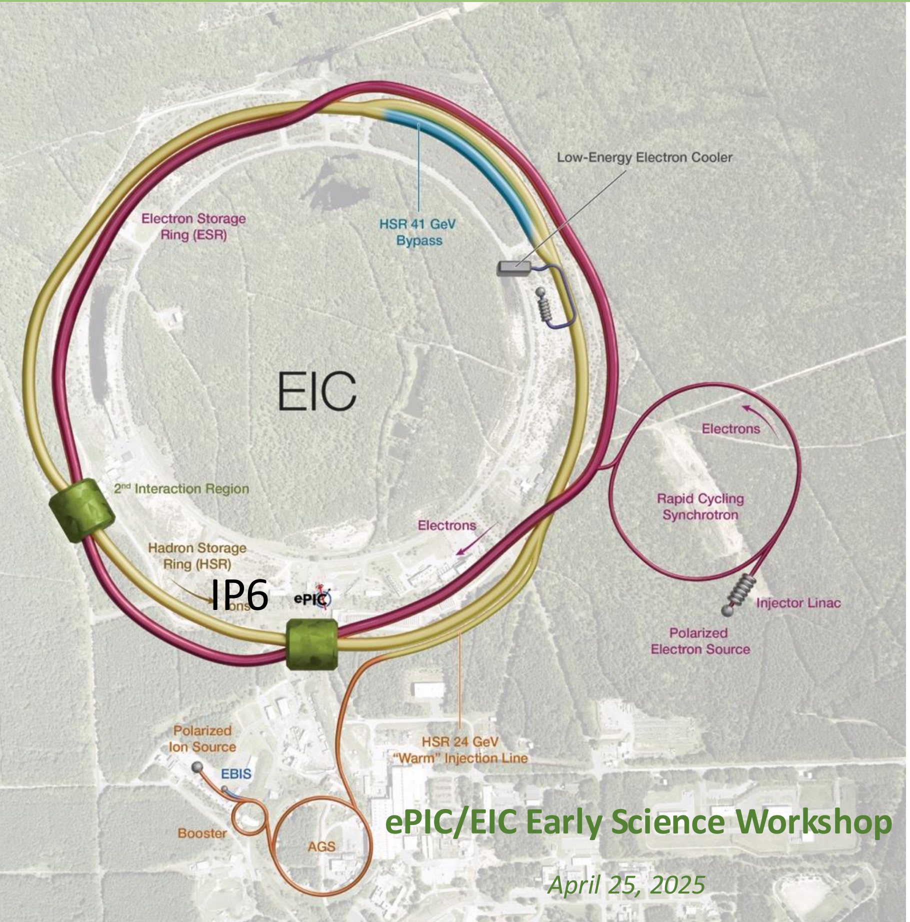
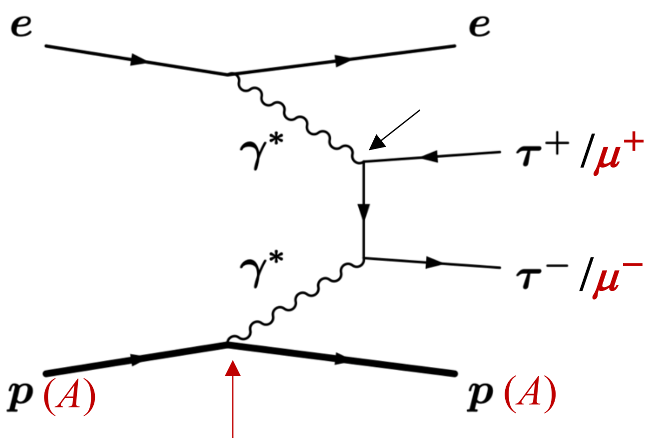
Exclusive Lepton Pairs at EIC/ePIC



ePIC/EIC Early Science Workshop

April 25, 2025

Krzysztof PIOTRZKOWSKI (AGH University)



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

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Exclusive lepton pair production at the electron–ion collider

Janusz J. Chwastowski[1,a], Krzysztof Piotrzkowski[2,b], Mariusz Przybycien[2,c]

[1] Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, 31-342 Kraków, Poland
[2] AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Al. Mickiewicza 30, 30-055 Kraków

Proposal for EIC Science Program in the First Years

Year - 1

Start with Phase 1 EIC

New Capability:
Commission electron polarization in parallel

Run:
10 GeV electrons on 115 GeV/u heavy ion beams (Ru or Cu)

Physics:
Saturation & Structure of Nuclei (nuclear PDF & nFF)

Year - 2

Phase 1 EIC
+ electron polarization

New Capability:
Commission proton polarization in parallel

Run:
10 GeV polarized electrons on 130 GeV/u Deuterium

Physics:
free vs. bound proton structure

Run:
Last weeks 10 GeV electrons on 130 GeV transversely polarized protons

Physics:
spatial and dynamical structure of QCD

Year - 3

Phase 1 EIC
+ electron polarization
+ proton polarization

New Capability:
Commission running with hadron spin rotators

Run:
10 GeV polarized electrons on 130 GeV transverse polarized protons

Physics:
spatial and dynamical structure of QCD

Run:
Last weeks switch to longitudinal proton polarization

Physics:
Spin structure of the proton

Year - 4

Phase 1 EIC
+ electron polarization
+ proton polarization
+ operation of hadron spin rotators

New Capability:
Commission hadron accelerator to operate with not centered orbits

Run:
10 GeV polarized electrons on 100 GeV Au

Physics:
Saturation & Structure of Nuclei (nuclear PDF & nFF)

Run:
10 GeV electrons on 250 GeV transverse and longitudinal polarized protons

Physics:
spatial and dynamical structure of QCD
Spin structure of the proton

Year - 5

Phase 1 EIC
+ electron polarization
+ proton polarization
+ operation of hadron spin rotators
+ operation of hadron beams with not centered orbits

Run:
10 GeV polarized electrons on 100 GeV Au

Physics:
Saturation & Structure of Nuclei (nPDF & nFF)

Run:
10 GeV electrons on 166 GeV transverse and longitudinal polarized He-3

New Capability:
Commission running with polarized He-3

Physics:
flavor dependent spatial and dynamical structure of QCD
flavor dependent spin structure of the nucleon

2034?

-- EA,RE (Jan'25)

Time to install additional ESR RF and HSR PS to reach design Current and max. Energies

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:

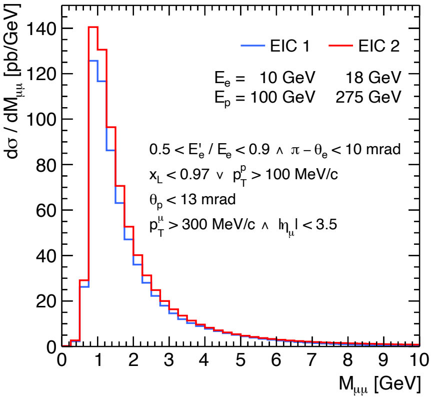
$$G_E(t) = (1 - t/0.71\ \mathrm{GeV}^2)^{-2},\ G_M(t) = \mu_p G_E(t)$$

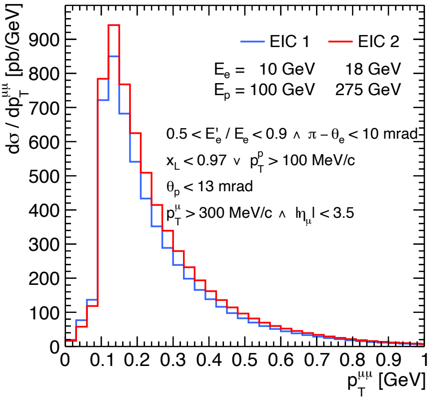
- **Detection acceptances** are represented by following kinematic cuts:

  $0.5 < E'_e/E_e < 0.9$ 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



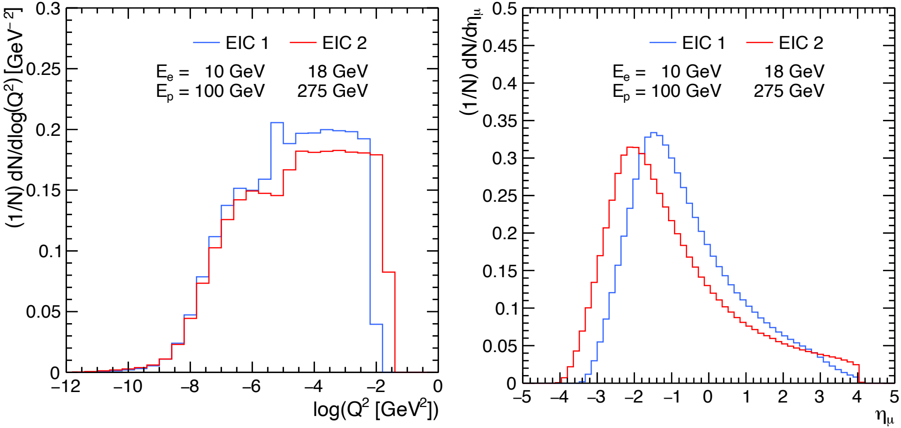


Total cross sections for the above selection of the muon exclusive pairs (w/ photon veto):

- 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.

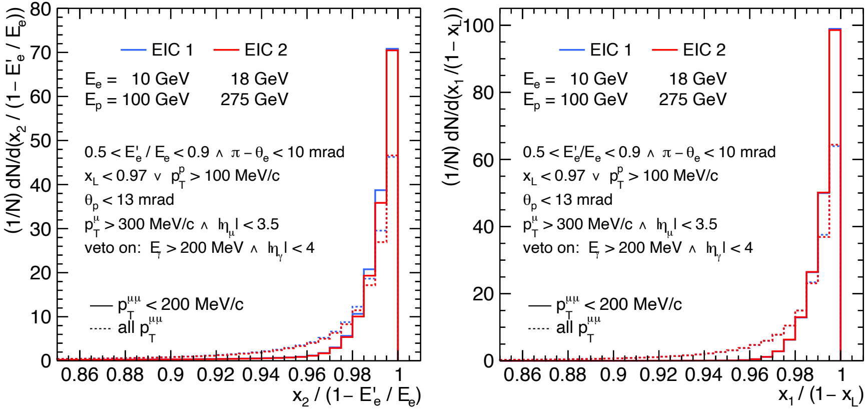
Distributions of accepted events



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

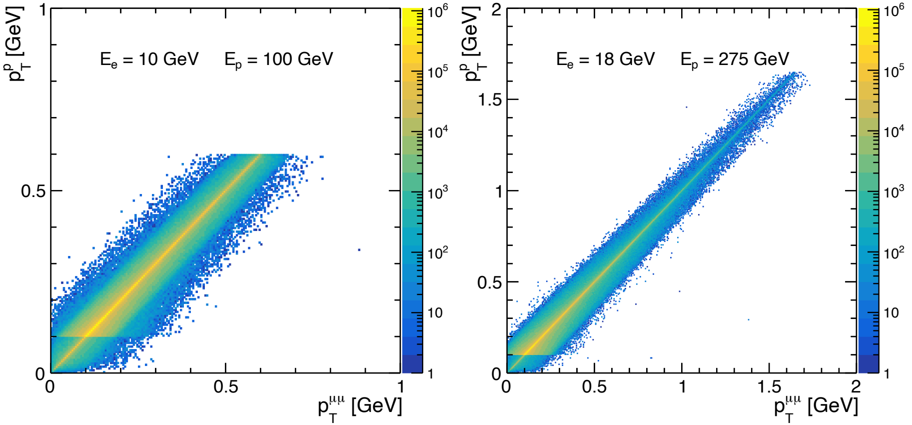
Energy calibration of far forward and far backward detectors

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

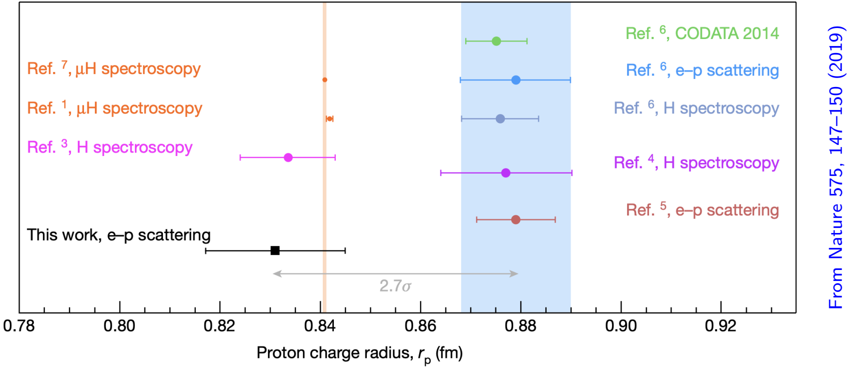
Correlations: proton p_T vs. pair p_T



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

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:

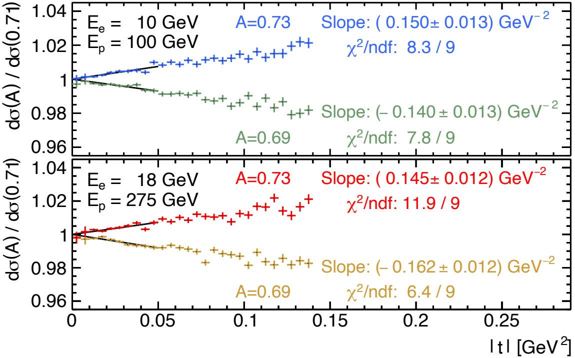


where the average charge radius is determined from the elastic form-factor G_E at $t = 0$,

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

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:

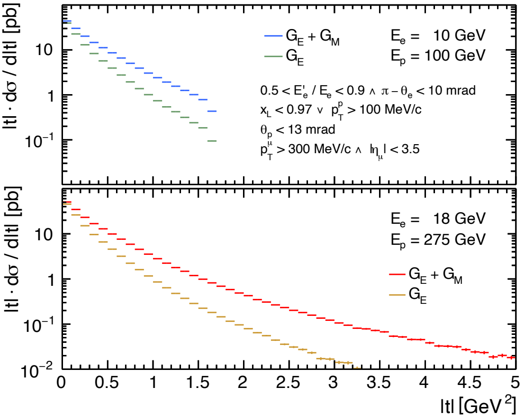


- t distributions of selected events were made for three values of R_p
- ratios of these distributions were fitted next to $t = 0$ with straight lines
- fitted slopes are directly sensitive to changes of R_p

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

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

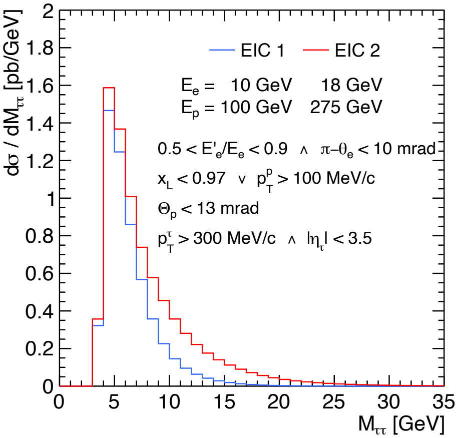


- Separation of proton electro-magnetic form-factors at about $|t| = 1\ \mathrm{GeV}^2$ and beyond, is of significant interest
- Data at high proton energy particularly interesting
- NB: Electron detection not mandatory
- Unique feature of two-photon exclusive pair production is its variable and very 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 for UPC at the HL-LHC

Exclusive Dileptons for Early Science

	Species	Energy (GeV)	Luminosity/year (fb-1)	Electron polarization	p/A polarization
YEAR 1	e+Ru or e+Cu	10 x 115	0.9	NO (Commissioning)	N/A
YEAR 2	e+D e+p	10 x 130	11.4 4.95 - 5.33	LONG	NO TRANS
YEAR 3	e+p	10 x 130	4.95 - 5.33	LONG	TRANS and/or LONG
YEAR 4	e+Au e+p	10 x 100 10 x 250	0.84 6.19 - 9.18	LONG	N/A TRANS and/or LONG
YEAR 5	e+Au e+3He	10 x 100 10 x 166	0.84 8.65	LONG	N/A TRANS and/or LONG

Note: the eA luminosity is per nucleon

- Exciting science from year-1 ⇒ $\sigma_{Ru}(\gamma\gamma \to \mu\mu)$ per nucleon = $\mathcal{O}$(10 nb) ⇒ 10^7 events!
  - Note: σ_{Au} per nucleon = $\mathcal{O}$(20 nb)
- Similar statistics for p, D and ^{3}He with polarizations and very forward hadrons

Dimuon challenges/next steps

- So far only (high energy) two-photon BH production was assumed – need to consider contributions due to (interference with) TCS/DDVCS

NB: this is already pursued for low energy experiments ⇒

Physics Letters B
Volume 858, November 2024, 139023

Letter

The proton charge radius from dimuon photoproduction off the proton

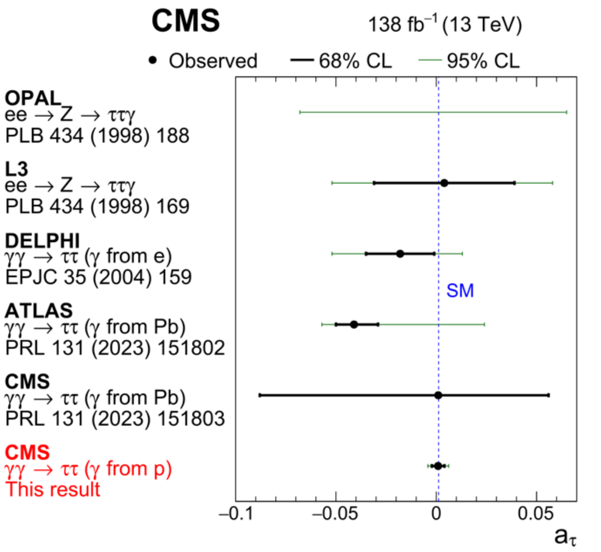
Yong-Hui Lin [a], Feng-Kun Guo [b c d], Ulf-G. Meißner [a e f]

- In addition, effects of beam polarizations will be included/employed (using EpIC)
- … and nuclear effects (with polarization for d and ^{3}He)
- Finally, high statistics ePIC event full simulations are a must

Exclusive tau pairs – open questions

- Need to use polarization effects
- … and all kinematics, including properties of decays

Can it be competitive with CMS?



https://iopscience.iop.org/article/10.1088/1361-6633/ad6fcb

Summary

- As it stands, each year planned for Early Science gives excellent prospects for studies with $\gamma\gamma \to \mu^+\mu^-/e^+e^-$ and tau pairs:
  - Year-1: nuclear EM FF for HI + 1st tau measurements
  - Year-2: nuclear EM FF for LI + proton EM FF + τ cont'd
  - Year-3: precision proton EM FF + τ cont'd
  - Year-4: large-$|t|$ proton FF + precision EM FF and τ cont'd
  - Year-5: precision nuclear EM FF + "final" τ
  - All years: provide unique calibration tool for far forward/backward detectors
- To make further progress/evaluation one needs large samples of ePIC full simulations with exclusive dileptons – at least 10^6 (very light) events

Thank you!

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