# Exclusive lepton pair production at the Electron-Ion Collider - a powerful research tool

Mariusz Przybycień

AGH University of Science and Technology

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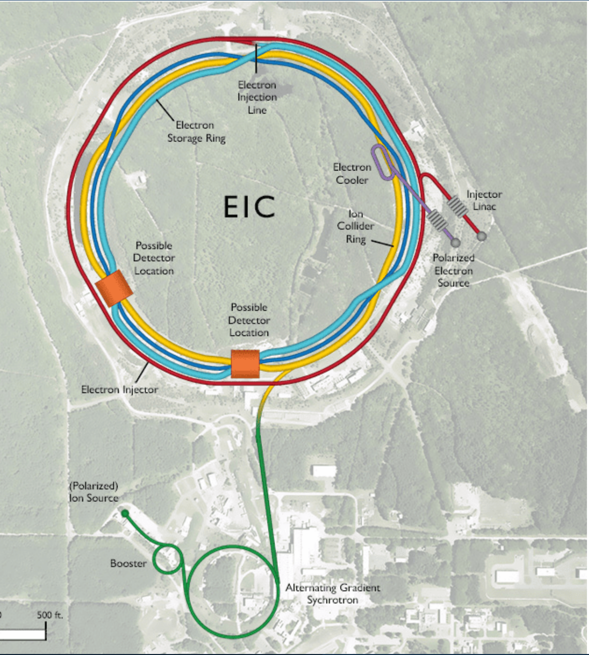
# Introduction

- The future EIC machine and experiment(s) will provide perfect conditions for studying exclusive processes:
  - a very high luminosity will ensure high statistics data even for rare processes,
  - the data streaming will result in no trigger losses and in a lack of the efficiency corrections,
  - negligible event pileup ($\mu \ll 1$), excellent particle momentum resolutions and the particle identification (at low and medium transverse momenta) will strongly enhance full final state reconstruction.
- The two-photon exclusive production of lepton pairs at the EIC will open interesting research directions:
  - unique measurements of the proton electromagnetic form-factors,
  - a possibility of studying the anomalous electromagnetic dipole moments of $\tau$ leptons.
  - In addition, high resolution detectors of protons in Far-Forward (FF) and electrons in Far-Backward (FB) directions, will enable the over-constrained event kinematics reconstruction, resulting in a possibility of precise data-driven inter-calibrations and tests of the understanding of acceptances and reconstructions.
- This presentation is based on:

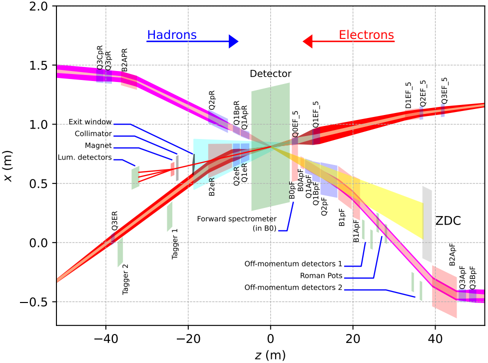
  J. Chwastowski, K. Piotrzkowski, M.P., EPJC (2022), arXiv:2206.02466 [hep-ph]

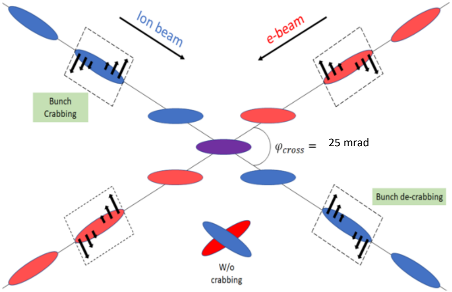
# EIC accelerator main parameters

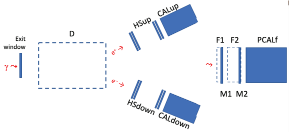


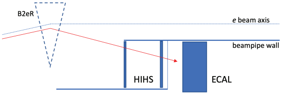

- Make use of existing RHIC infrastructure: ion sources, pre-accelerator chain, ion storage ring (circum. 3.83 km).
- New: electron source, electron accelerator, storage ring.
- Beam energies:
  $E_e = 2.5 - 18$ GeV
  $E_p = 40 - 275$ GeV
  $E_\mathrm{A} = (Z/A)E_p$
- $\sqrt{s_{ep}} = 20 - 141$ GeV
- # of bunches per beam: 1320; collision every $\sim 10$ ns
- Luminosity: $\sim 10^{34}$ cm$^{-2}$s$^{-1}$
- Beams polarization: $> 70\%$ $e, p$, and light ions: $d$, $^3\mathrm{He}$ (longitudinal and transverse)
- Ion species: $p$ - Uranium
- # of interaction regions: $1 - 2$

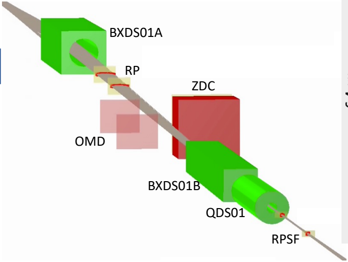
# Interaction Region and FF and FB detection systems

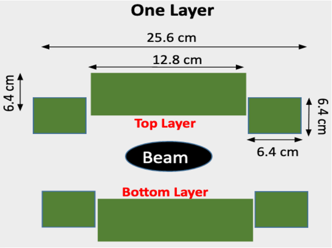


# Exclusive lepton pair production in $ep$ scattering

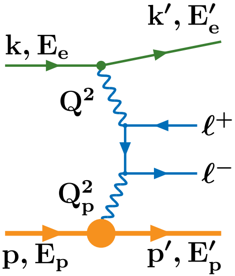
- Kinematical variables:

$$Q^2 \equiv -q^2 = -(k-k')^2 \approx 2E_eE'_e(1-\cos\theta_e)$$

$$y = \frac{E_e - E'_e}{E_e}$$

$$Q_p^2 \equiv -t = -(p-p')^2 \qquad x_L = \frac{p_z^{p'}}{p_b^p}$$

$$M_{\ell\ell}^2 = (l^+ + l^-)^2$$




- Selection cuts corresponding to geometrical acceptances of the EIC detectors:
  - scattered electron: $0.5 < E'_e/E_e < 0.9 \;\wedge\; \pi - \theta_e < 10$ mrad
  - scattered proton: $(x_L < 0.97 \;\vee\; p_T^{p'} > 100$ MeV$/c) \;\wedge\; \theta_p < 13$ mrad
  - central leptons: $p_T^{\ell} > 300$ MeV $\wedge\; |\eta_\ell| < 3.5$
  - photon veto: no photons with $E_\gamma > 200$ MeV $\wedge\; |\eta_\gamma| < 4$
- Two collision beams configuration will be considered in the following:

EIC 1: $E_e = 10$ GeV, $E_p = 100$ GeV

EIC 2: $E_e = 18$ GeV, $E_p = 275$ GeV

# GRAPE–Dilepton Monte Carlo

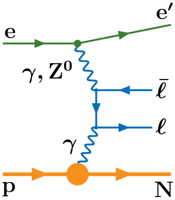
- Cross sections calculated based on exact MEs in EW theory at the tree level.
- Feynman diagrams included in the quasi-elastic $ep$ scattering: Bethe-Heitler, QED Compton, $Z^0$ on/off-shell production.
- Radiative corrections: ISR (only collinear from lepton line), FSR (both from scattered electron and from produced leptons).
- All fermion masses are kept non-zero both in MEs and in the kinematics - these allow for using the program with arbitrary small scattering angles of $e^{\pm}$ and/or small invariant masses of dilepton down to the kinematical limits.
- For the elastic $ep$ scattering the $pp\gamma$ vertex can be written as:

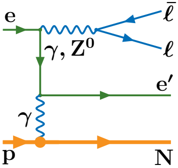
$$\Gamma^{\mu}_{pp\gamma} = e_p \left( F_1(Q_p^2)\gamma^{\mu} + \frac{\kappa_p}{2M_p} F_2(Q_p^2) i\sigma^{\mu\nu} q_{\nu} \right)$$

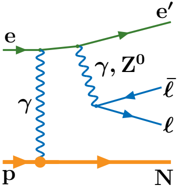
where $\kappa_p$ is the anomalous magnetic moment and $q^2 = -Q_p^2$.

The electric and magnetic form-factors are defined as:

$$\begin{aligned} G_E(Q_p^2) &= F_1(Q_p^2) - \frac{\kappa_p Q_p^2}{4M_p^2} F_2(Q_p^2) \\ G_M(Q_p^2) &= F_1(Q_p^2) + \kappa_p F_2(Q_p^2) \end{aligned}$$



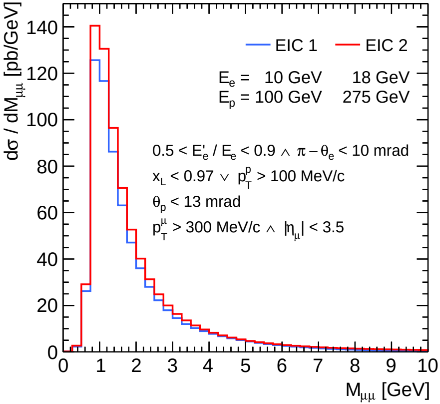



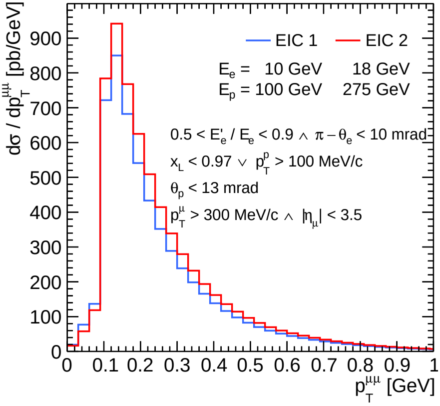
# Cross sections for exclusive muon pair production

- Total visible cross sections for exclusive muon pair production passing selection cuts without/with photon veto:

  EIC 1: $\sigma_{\text{vis}} = 169/163$ pb  EIC 2: $\sigma_{\text{vis}} = 192/185$ pb

- Threshold effects are due to the requirements on final state muons and scattered proton.



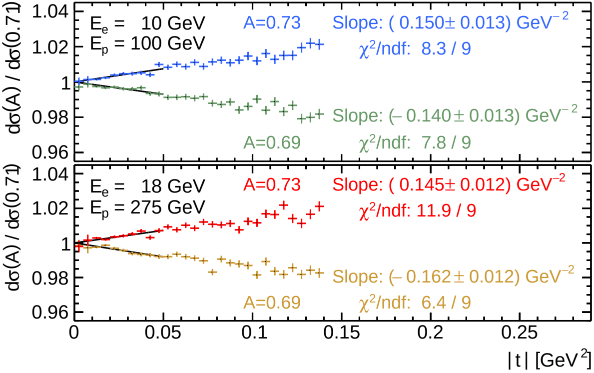
# Determination of the proton charge radius at the EIC

- The mean proton charge radius $R_p$ can be obtained from the proton $G_E$:

$$G_E(t) = \left(1 - \frac{t}{A_0}\right)^{-2} \quad \Rightarrow \left\{ A_0 = \frac{12}{R_p^2} \right\} \Rightarrow \quad R_p^2 = 6\, \frac{dG_E(t)}{dt}\bigg|_{t=0}$$

For the "standard" dipol: $A_0 = 0.71\,\mathrm{GeV}^2 \;\Rightarrow\; R_p \approx 0.811$ fm

- Slope of the cross sections ratio: $$\frac{d}{dt}\left(\frac{d\sigma(A_1)/dt}{d\sigma(A_2)/dt}\right)\bigg|_{t=0} = \frac{1}{3}\left(R_1^2 - R_2^2\right)$$




- Expected values of the slope for $A_2 = A_0$ and $|t|$:

| $A_1$ [GeV$^2$] | slope [GeV$^{-2}$] |
|---|---|
| 0.73 | 0.154 |
| 0.69 | −0.163 |

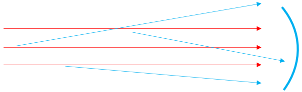
- No scattered electron required to increase $\sigma_{\text{vis}}$ and to avoid sensitivity to bremsstrahlung overlays.
- Stat. errors correspond to $\mathcal{L}_{\text{int}} \approx 100$ fb$^{-1}$.

# Determination of the proton charge radius at the EIC

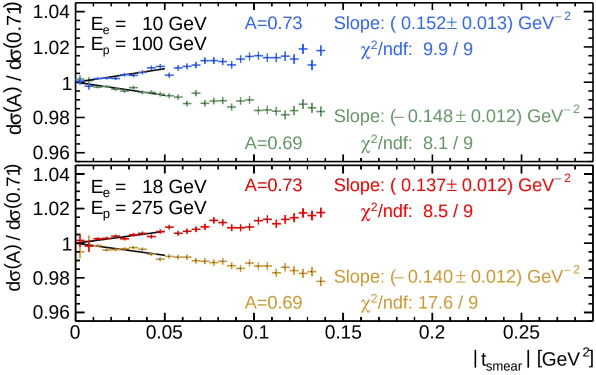
- Proton beam angular divergence and its energy dispersion give some small initial transverse momentum to the protons:

EIC 1: $\sigma_{\theta_x} = \sigma_{\theta_y} = 220$ µrad $\quad \Delta p/p = 9.7 \cdot 10^{-4}$

EIC 2: $\sigma_{\theta_x} = \sigma_{\theta_y} = 150$ µrad $\quad \Delta p/p = 6.8 \cdot 10^{-4}$



- This introduces smearing in the momentum reconstruction in RP detectors.
- Fits to smeared $t$-distributions result in slopes only weakly changed.




- Exclusive lepton pairs at the EIC will enable unique determination of the proton charge radius with competitive precision.
- The proposed technique can be applied to perform novel measurements of the elastic form-factors and charge radii of light ions.
- Data to be taken at different energies and polarizations.

# Proton form-factors

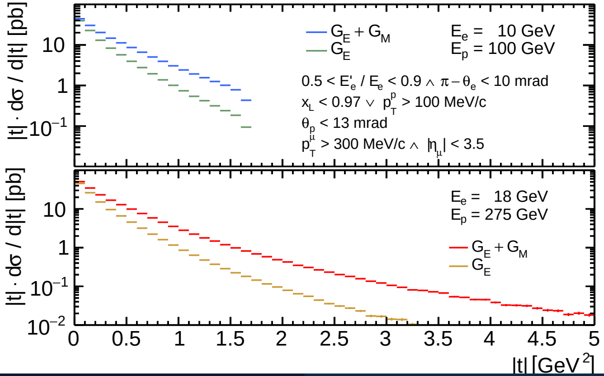
- Using the Gordon decomposition and the scaling law of the form-factors:

$$G_E(Q_p^2) = G_M(Q_p^2)/|\mu_p| \quad \text{where} \quad \mu_p = (1+\kappa_p)\mu_B$$

one gets a general formula for the $pp\gamma$ vertex expressed in terms of $G_E(Q_p^2)$:

$$\Gamma^\mu_{pp\gamma} = e_p \left( \mu_p G_E(Q_p^2)\gamma^\mu - \frac{p^\mu + p'^\mu}{2M_p} \frac{\kappa_p}{1+Q_p^2/(2M_p)^2} G_E(Q_p^2) \right)$$

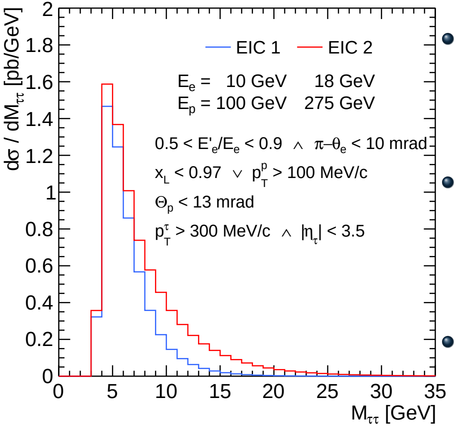
- Setting $G_M(Q_p^2) \equiv 0$, the formula shortens: $\Gamma^\mu_{pp\gamma} = \frac{p^\mu + p'^\mu}{2M_p} \frac{e_p G_E(Q_p^2)}{1+Q_p^2/(2M_p)^2}$




- Significant cross sections at the EIC also for larger $|t| \gtrsim 1$ GeV$^2$.
- At high $|t|$, the $G_M$ contribution dominates, but the $G_E$ one is still significant allowing their separation by combining data at different energies.
- Will provide additional constraints on GPD.

# Exclusive production of tau lepton pairs

- Exclusive production of $\tau^+\tau^-$ pairs via two-photon fusion in UPC has recently become a very active field of research, as $\gamma\gamma \to \tau^+\tau^-$ is particularly sensitive to the anomalous electromagnetic moments of $\tau$ leptons.

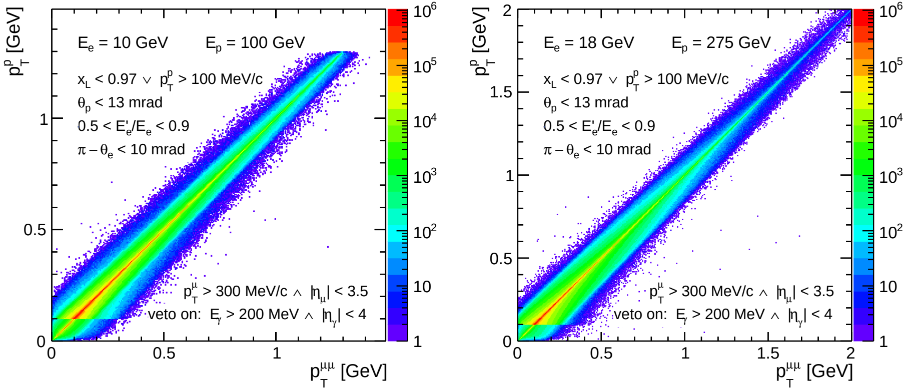



- At the EIC, the detection of forward scattered protons and electrons will allow for a good event-by-event control of $\gamma\gamma$ kinematics.
- Total visible cross sections for exclusive $\tau^+\tau^-$ pair production passing selection cuts without photon veto are quite large:

  EIC 1: $\sigma_{\text{vis}} = 5.5$ pb  EIC 2: $\sigma_{\text{vis}} = 7.8$ pb
- The expected $\tau^+\tau^-$ event samples at the EIC will be factor 100 bigger than those expected to be collected at the HL-LHC.

- Detection of the forward scattered protons will allow to build $p - \tau\tau$ azimuthal correlations, amplified by high polarisation of incident protons.

- Exclusive muon (and electron) pairs can be used as a powerful tool for energy calibration the FF and FB detectors.
- Correlation between muon pair $p_T^{\mu\mu}$ and the proton $p_T^p$ can be amplified by the requirement of the scattered electron within acceptance of the FB detectors (this ensures a very small $p_T$ transfer at the electron vertex, i.e. a very low $Q^2$) and applying a veto on FSR photons within the acceptance of the experiment ($E_\gamma > 200$ MeV and $|\eta_\gamma| < 4$).

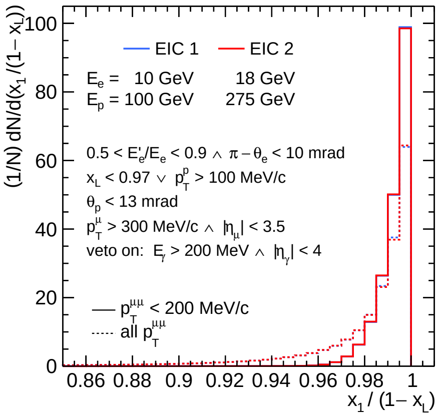


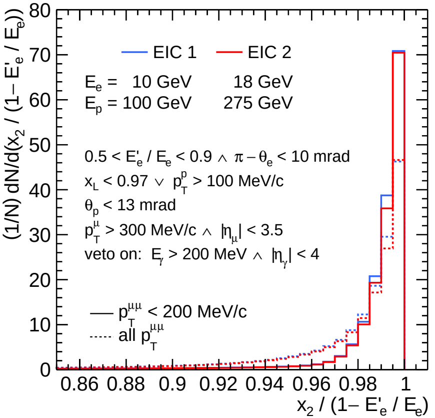
# Energy callibration of far forward and far backward detectors

- Longitudinal momenta of the scattered electron and proton can be calibrated following the Drell-Yan technique used for determination of fractional momenta of collinear partons from the invariant mass and rapidity of lepton pairs:

$$x_{1,2} = \frac{M_{\ell\ell}}{\sqrt{s}} \sqrt{\frac{E^{\ell\ell} \pm p_z^{\ell\ell}}{E^{\ell\ell} \mp p_z^{\ell\ell}}} \exp\left(\mp Y^\star\right) \quad \text{where} \quad Y^\star = \operatorname{arctanh} \frac{P_{e,z} + P_{p,z}}{E_e + E_p}$$

- Observed narrow ratios allow for precise data-driven calibrations of the detectors.



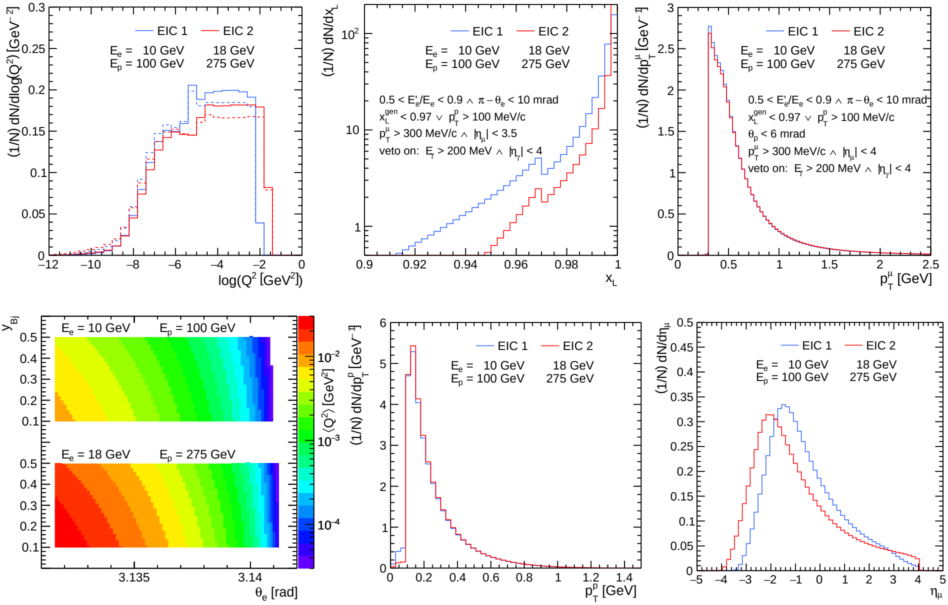



# Summary

- EIC will provide perfect conditions for studying exclusive processes.
- Precise studies of elastic production of muon and/or electron pairs will result in competitive measurements of the proton charge radius as well as the elastic $G_E$ and $G_M$ form-factors.
- The above studies could be extended to light nuclei and to polarized both target and projectile.
- Large statistics expected for the exclusive production of tau pairs will enable further studies of the anomalous electromagnetic dipole moments of the tau lepton.
- Exclusive production of muon pairs will enable data-driven calibrations of FF and FB detectors.

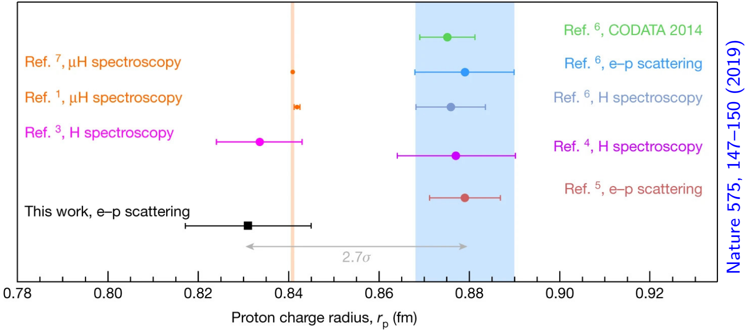
Thank you for your attention!

# Backup slides


EIC 1
EIC 2
E_e = 10 GeV 18 GeV
E_p = 100 GeV 275 GeV
(1/N) dN/dlog(Q^2) [GeV^-2]
log(Q^2 [GeV^2])
(1/N) dN/dx_L
x_L
0.5 < E'_e/E_e < 0.9 ∧ π − θ_e < 10 mrad
x_L^gen < 0.97 ∨ p_T^p > 100 MeV/c
p_T^μ > 300 MeV/c ∧ |η_μ| < 3.5
veto on: E_γ > 200 MeV ∧ |η_γ| < 4
(1/N) dN/dp_T^μ [GeV^-1]
p_T^μ [GeV]
θ_p < 6 mrad
p_T^μ > 300 MeV/c ∧ |η_μ| < 4
y_Bj
E_e = 10 GeV E_p = 100 GeV
E_e = 18 GeV E_p = 275 GeV
θ_e [rad]
⟨Q^2⟩ [GeV^2]
(1/N) dN/dp_T^p [GeV^-1]
p_T^p [GeV]
(1/N) dN/dη_μ
η_μ

# Proton charge radius puzzle

- There are ongoing discrepancies among measurements of the proton charge radius from scattering and spectroscopic (hydrogen and muonic hydrogen) experiments, but also between the scattering experiments themselves.




- In the $ep$ elastic scattering experiments, the proton charge radius is determined from the elastic form-factor $G_E$ at $t = 0$:

$$R_p^2 = 6\,\frac{dG_E}{dt}\bigg|_{t=0} \quad \Rightarrow \quad R_p = \sqrt{12/0.71}\ \text{GeV}^{-1} \approx 0.811\ \text{fm}$$

for the standard dipol form-factor $G_E(t) = (1 - t/0.71)^{-2}$