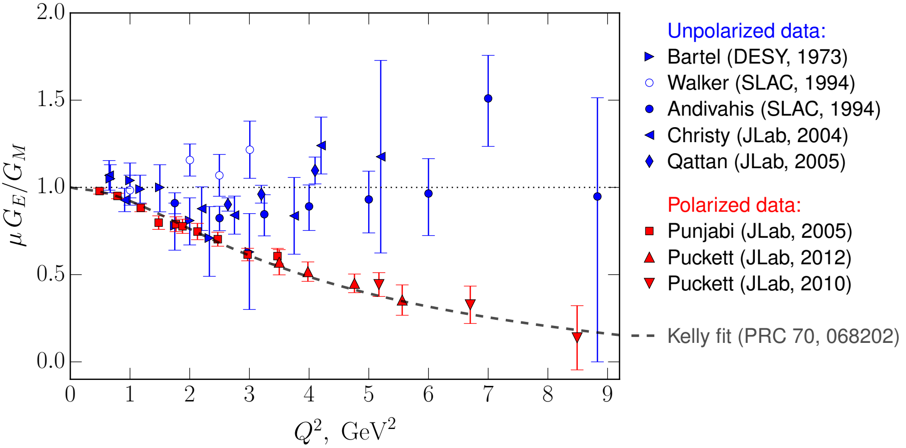
The two-photon exchange experiment at VEPP-3

Alexander Gramolin
(Budker Institute of Nuclear Physics, Novosibirsk, Russia)

On behalf of the Novosibirsk TPE Collaboration

7th Workshop of the APS Topical Group on Hadronic Physics
February 1–3, 2017
Washington, DC

Proton form factor puzzle



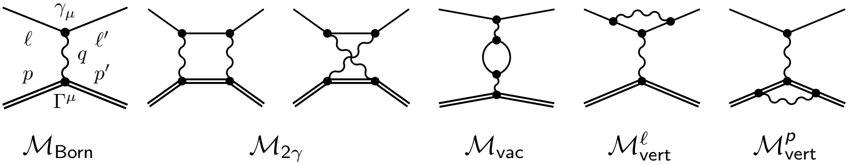
The most likely origin of the discrepancy:

Radiative corrections?

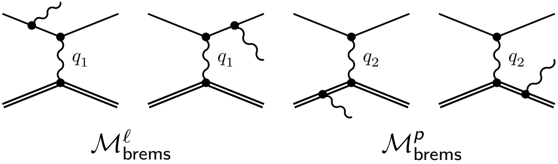
Specifically, two-photon exchange?

First-order radiative corrections to elastic *ep* scattering

"Elastic" scattering ($e^{\pm}p \to e^{\pm}p$):



First-order bremsstrahlung ($e^{\pm}p \to e^{\pm}p\,\gamma$):

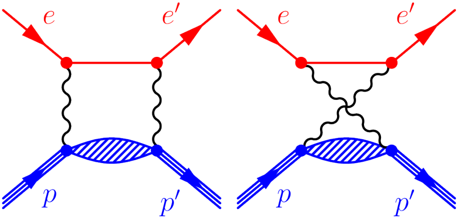


$$\sigma(e^{\pm}p) \propto |\mathcal{M}_{\text{Born}}|^2 \pm 2\,\text{Re}\left(\mathcal{M}^{\dagger}_{\text{Born}}\mathcal{M}_{2\gamma}\right)$$
$$+\,2\,\text{Re}\left(\mathcal{M}^{\dagger}_{\text{Born}}\mathcal{M}_{\text{vac}}\right) + 2\,\text{Re}\left(\mathcal{M}^{\dagger}_{\text{Born}}\mathcal{M}^{\ell}_{\text{vert}}\right) + 2\,\text{Re}\left(\mathcal{M}^{\dagger}_{\text{Born}}\mathcal{M}^{p}_{\text{vert}}\right)$$
$$+\,|\mathcal{M}^{\ell}_{\text{brems}}|^2 + |\mathcal{M}^{p}_{\text{brems}}|^2 \pm 2\,\text{Re}\left(\mathcal{M}^{\ell\dagger}_{\text{brems}}\mathcal{M}^{p}_{\text{brems}}\right) + \mathcal{O}(\alpha^4)$$

✓ Cancellation of infrared divergences (corresponding terms are marked in color)

✓ Some of the terms are of different signs ("±") for $e^{+}p$ and $e^{-}p$ scattering

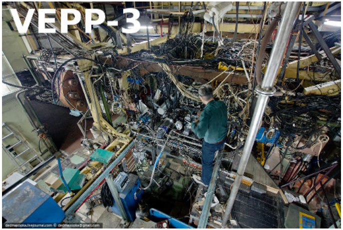
Three contemporary experiments

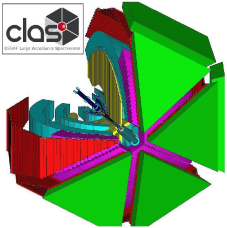


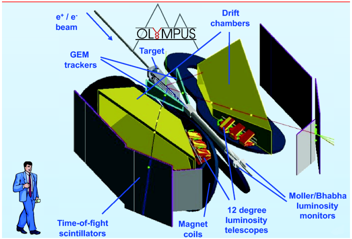
$$\delta_{2\gamma} = \frac{2\mathrm{Re}\left(\mathcal{M}_{1\gamma}^{\dagger}\mathcal{M}_{2\gamma}^{\mathrm{hard}}\right)}{|\mathcal{M}_{1\gamma}|^2},$$

$$R_{2\gamma} = \frac{1-\delta_{2\gamma}}{1+\delta_{2\gamma}} \approx 1 - 2\delta_{2\gamma}$$

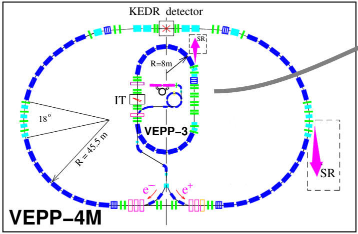
1. Novosibirsk: VEPP-3
   $E_{\mathrm{beam}} = 1.6$ and 1.0 GeV
   PRL 114, 062005 (2015)
2. JLab: CLAS in Hall B
   $E_{\mathrm{beam}} = 0.9$–3.5 GeV
   PRL 114, 062003 (2015)
   arXiv:1603.00315 (2016)
3. DESY: OLYMPUS at DORIS
   $E_{\mathrm{beam}} = 2$ GeV
   arXiv:1611.04685 (2016)

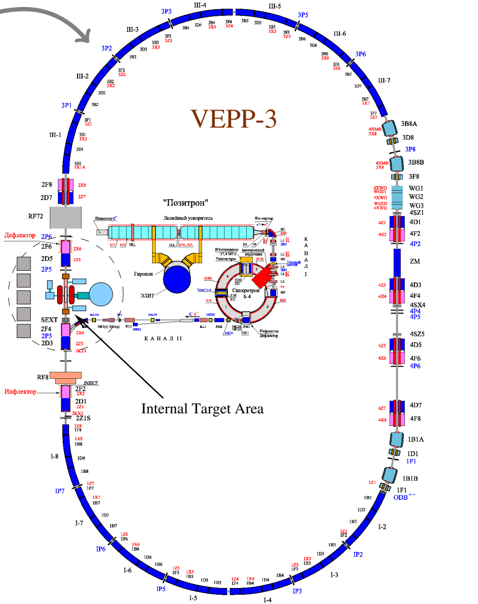






The VEPP-3 electron-positron storage ring





VEPP-3 is a booster for the VEPP-4M electron-positron collider

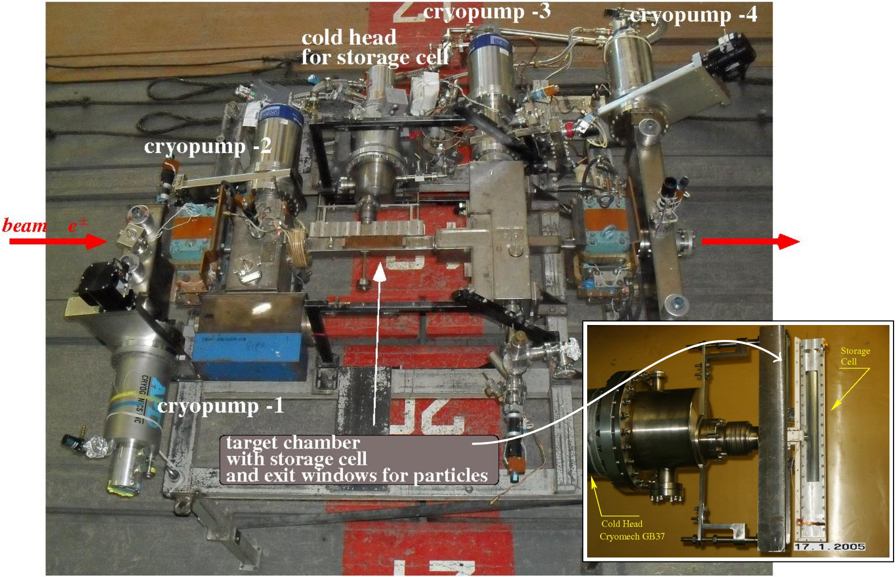
VEPP-3 parameters for e^- beam:

Electron energy	E_0	2 GeV
Mean beam current	I_0	150 mA
Energy spread	σ_E/E	0.05%
Revolution period	T	248.14 ns
Bunch length	σ_L	15 cm
Vertical beam size*	σ_z	0.5 mm
Horizontal beam size*	σ_x	2.0 mm
Injection beam energy	E_{inj}	350 MeV
Injection rate	$\dot{I}_{inj}$	$1.5 \cdot 10^9$ s^{-1}

* *parameters in the center of 2nd straight section (in the Internal Target Area)*

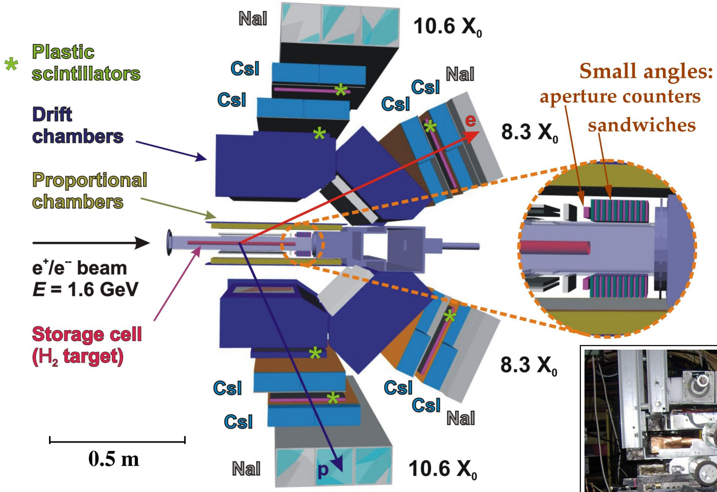
Max e^+ current: 60 mA

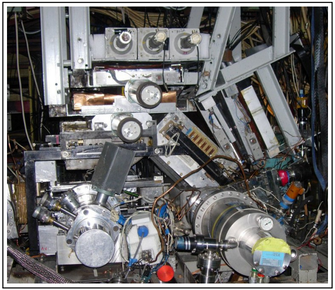
The internal-target section of VEPP-3



target thickness $\approx 10^{15}$ atom/cm^2, luminosity $\approx 10^{32}$ cm^{-2}s^{-1}

The detector configuration for run I ($E_{beam} = 1.6$ GeV)

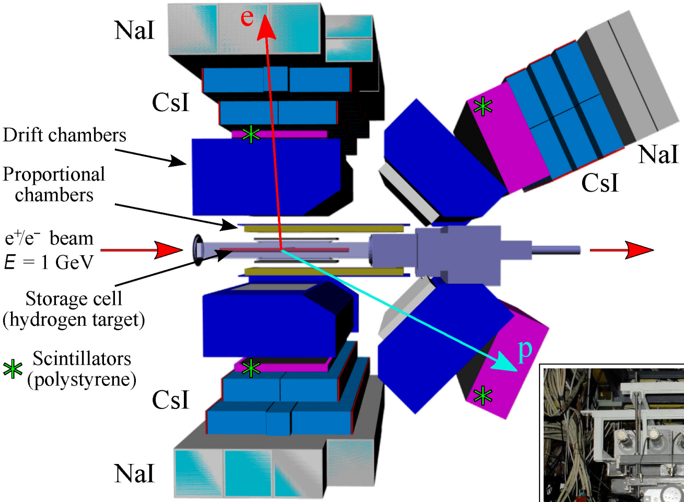




Wide-aperture non-magnetic detector

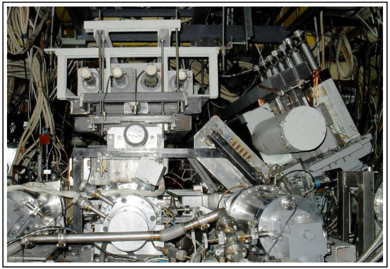
θ_e acceptance:	$7^\circ - 16^\circ$, $15^\circ - 28^\circ$, and $55^\circ - 83^\circ$
ϕ_e acceptance:	$2 \times 60^\circ$

The detector configuration for run II ($E_{\text{beam}} = 1.0$ GeV)



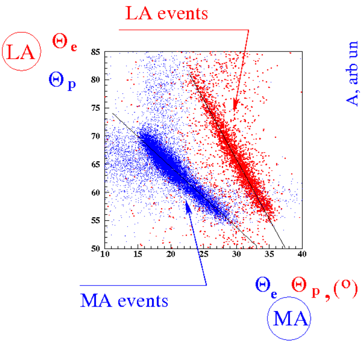
θ_e acceptance: $15^\circ - 30^\circ$ and $65^\circ - 105^\circ$

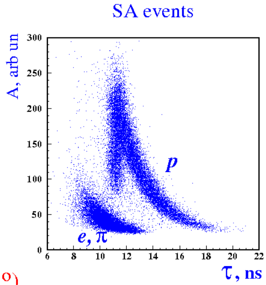
ϕ_e acceptance: $2 \times 60^\circ$



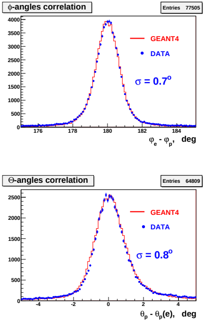
Event selection

- Correlations characteristic for two-body final state:
  - Correlation between azimuthal angles ($\phi_{e^\pm}$ vs. ϕ_p) → *coplanarity*
  - Correlation between polar angles ($\theta_{e^\pm}$ vs. θ_p) → *collinearity in CM*
  - Correlation between scattering angle and proton energy ($\theta_{e^\pm}$ vs. E_p)
  - Correlation between scattering angle and electron energy ($\theta_{e^\pm}$ vs. $E_{e^\pm}$)
- Particle identification:
  - Time-Of-Flight analysis for low-energy protons
  - dE/dx analysis for middle-energy protons
  - Energy deposition in layers of the EM-calorimeter for electrons/positrons





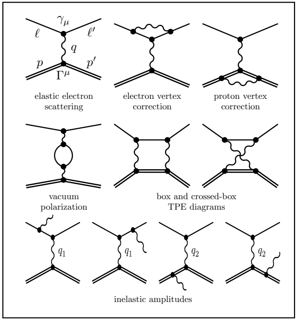
angular correlations



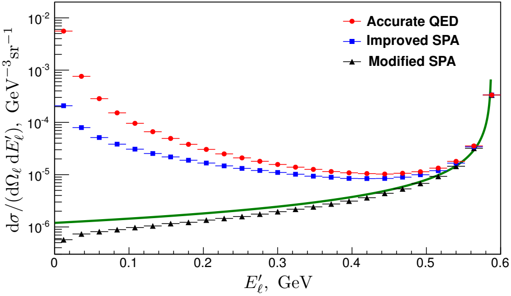
Radiative corrections: the ESEPP event generator

Elastic Scatterring of Electrons and Positrons on Proton – J. Phys. G **41**, 115001 (2014)

- More accurate calculation of first-order bremsstrahlung instead of the usual soft-photon approximation
- Various options, including different parametrizations of the proton form factors
- The generator was used to perform a GEANT4-based simulation of the detector response



Radiative tail for various ESEPP options
$E_e = 1$ GeV, $\theta_e = 70^\circ \Rightarrow E'_e$(elastic)$= 0.588$ GeV



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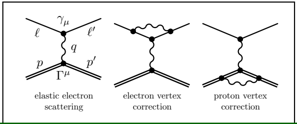
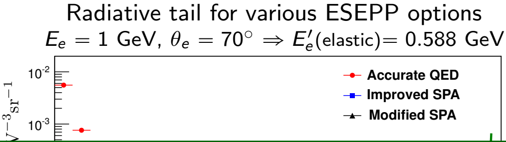


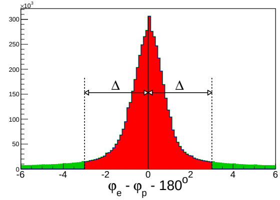


The following options of ESEPP were chosen:

- The dipole parametrization for the proton form factors
- An accurate QED calculation beyond the soft-photon approximation for first-order bremsstrahlung
- The vacuum polarization correction that includes the hadronic contribution
- The soft two-photon exchange terms according to the Mo and Tsai prescription

Radiative corrections: dependence of R on kinematic cuts

- Bremsstrahlung gives a significant contribution to the measured cross section ratio
- Magnitude of the bremsstrahlung contribution depends on kinematic cuts
- When the standard radiative corrections are applied, only $R_{2\gamma}$ remains, which is independent on kinematic cuts



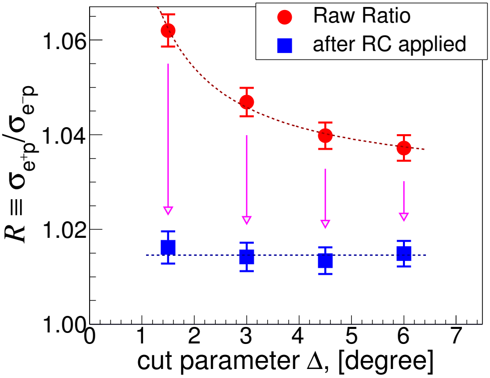
Event selection cuts:

$$\left| |\varphi_e - \varphi_p| - 180^\circ \right| < \Delta\phi$$

$$\left| \theta_p - \theta_p^* \right| < \Delta\theta$$

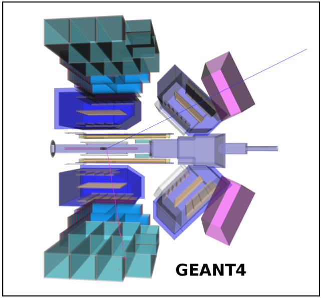
θ_p^* is calculated from θ_e assuming elastic kinematics

Run II, single combined point:

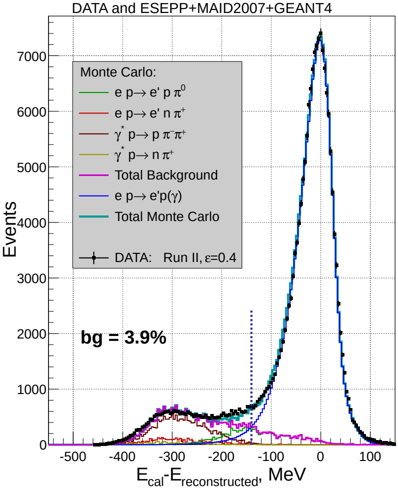


Monte Carlo simulation of background processes

- GEANT4 model of the detector
- A dedicated event generator of pion production processes based on the MAID2007 and 2-PION-MAID models
- The ESEPP event generator for elastic scattering and first-order bremsstrahlung
- According to the simulation, the fraction of background events does not exceed 4%

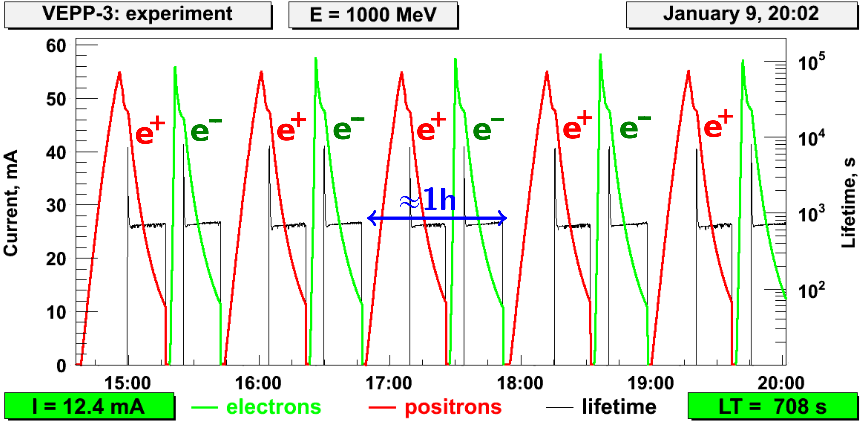


Difference between the electron energies measured by the calorimeter and reconstructed from the scattering angle:



Suppression of the systematics: alternation of e^+ and e^-

- During the data collection, e^+ and e^- beams were alternated regularly to suppress the effect of slow variation in time of the detection efficiency
- One cycle (e^+ and e^- beams) per $\approx$ 1 hour, about 3000 cycles in total
- Beam currents and lifetimes were kept identical for e^+ and e^- beams

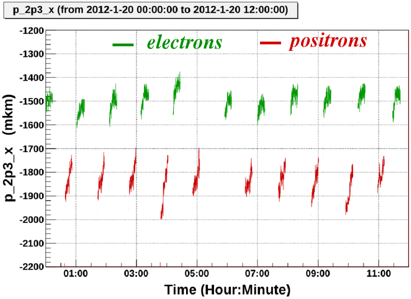


Suppression of the systematics: beam position

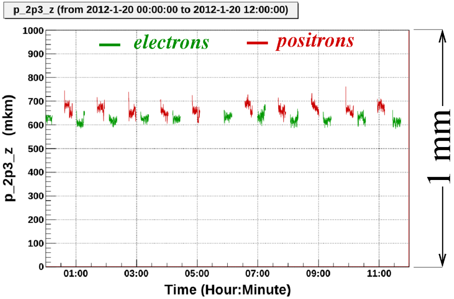
- Beam orbit stabilization system at VEPP-3
- Continuous measurement of the beam position by pick-up electrodes
- Periodical "absolute" beam position measurements using movable beam scrapers
- Determination of the beam position in the target area from data analysis
- Two symmetrical sets of detector arms: the sum is insensitive to vertical shifts of beams

Measurements of the beam position by a pick-up electrode:

horizontal



vertical

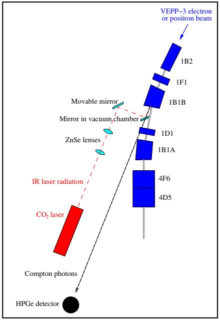


Suppression of the systematics: beam energy

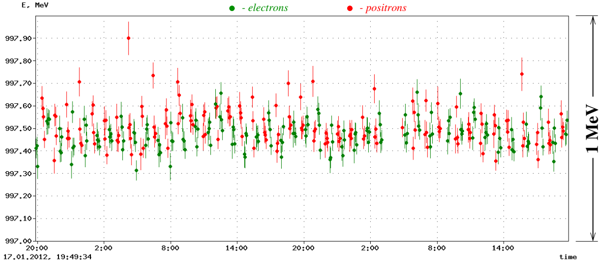
- Reconstruction of the beam energy from an energy spectrum of laser photons backscattered on beam particles:

$$E_{\text{beam}} = \frac{\omega_{max}}{2}\left(1 + \sqrt{1 + m_e^2/(\omega_0\omega_{max})}\right)$$

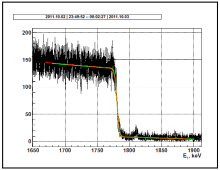
- Achieved accuracy is $\Delta E/E \approx 4 \times 10^{-5}$
- This allowed us to adjust the VEPP-3 operation regimes, to monitor the beam energy, and to apply corrections during the data analysis



VEPP-3 energy measurements:



Photon spectrum:

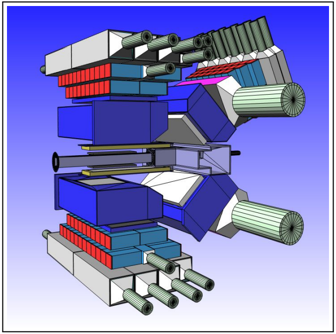


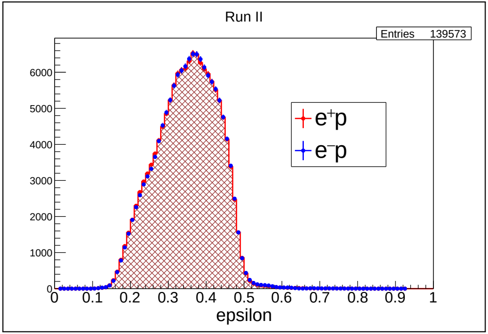
More details: JINST **9**, T06006 (2014)

Suppression of the systematics: no magnetic field

- Non-magnetic detectors
- No magnetic field near the target

$\Longrightarrow$ *Identical acceptances for electrons and positrons*





Systematic uncertainties: $\leqslant 0.32\%$

Results of the Novosibirsk TPE experiment

	Run I			Run II		
	No. 1	No. 2	LNP	No. 3	No. 4	LNP
Kinematic parameters of the data points:						
E_{beam}, GeV	1.594	1.594	1.594	0.998	0.998	0.998
$\langle \varepsilon \rangle$	0.452	0.932	0.980	0.272	0.404	0.931
$\langle Q^2 \rangle$, GeV^2	1.51	0.298	0.097	0.976	0.830	0.128
$\langle \theta_e \rangle$	66.2°	20.8°	11.4°	91.3°	75.4°	21.4°
Main kinematic cuts:						
$\Delta\phi$, $\Delta\theta$	3.0°	5.0°	—	3.0°	3.0°	—
$\Delta E/E_\theta$	0.25	0.45	—	0.29	0.29	—
Raw ratio and radiative corrections:						
R	1.0705	1.0037	—	1.0555	1.0447	—
$(1+\delta^+_{RC})$	1.0347	1.0600	—	1.0501	1.0206	—
$(1+\delta^-_{RC})$	0.9981	1.0563	—	1.0117	0.9898	—
Final results:						
$R_{2\gamma}$	1.0332	1.0002	1	1.0174	1.0133	1
$\Delta R^{\text{stat}}_{2\gamma}$	± 0.0112	± 0.0012	—	± 0.0049	± 0.0037	—
$\Delta R^{\text{syst}}_{2\gamma}$	± 0.0032	± 0.0020	—	± 0.0016	± 0.0008	—

LNP $\equiv$ Luminosity Normalization Point

Phys. Rev. Lett. **114**, 062005

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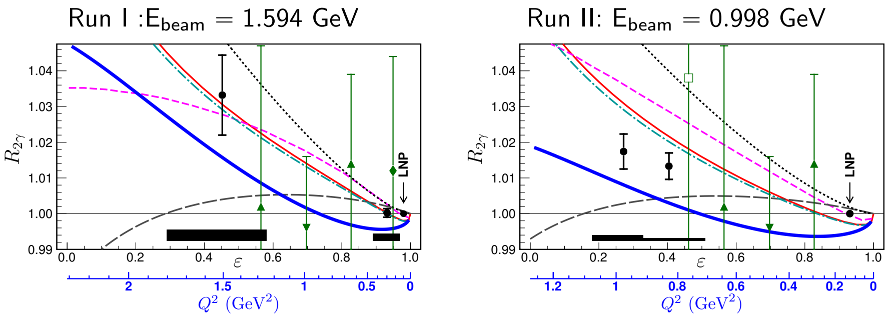


Curves:

(red solid line)	*P. G. Blunden, et al.,*	Phys. Rev. **C72** (2005) 034612	:hadronic TPE calculation
(dash-dotted line)	*D. Borisyuk and A. Kobushkin,*	Phys. Rev. **C78** (2008) 025208	:dispersion relations
(grey dashed line)	*E. Tomasi-Gustafsson, et al.,*	Phys. Atom. Nucl. 76 (2013) 937	:"analytical model"
(magenta dashed line)	*J. Arrington and I. Sick,*	Phys. Rev. **C70** (2004) 028203	:Coulomb corrections
(dotted line)	*I. A. Qattan, et al.,*	Phys. Rev. **C84** (2011) 054317	:Parametrisation
(thick blue line)	*J. Bernauer, et al.,*	Phys. Rev. **C90** (2014) 015206	:Global *ep*-data fit

Data: □ SLAC, 1965; ▾ Cornell, 1966; ♦ DESY, 1967; ▲ Cornell, 1968; ● VEPP-3, 2015

- LNP (Luminosity Normalization Point) is set to $R_{2\gamma} = 1$
- Error bars are statistical errors, shaded bands show ε-bin width and systematic uncertainties
- Radiative corrections are applied according to J. Phys. G **41**, 115001 (2014)

Our results vs predictions

	$R_{2\gamma}^{\text{LNP}}$	$\frac{\chi^2}{n_{\text{d.f.}}}$	$R_{2\gamma}^{\text{LNP}}$ Run I	$R_{2\gamma}^{\text{LNP}}$ Run II	$\frac{\chi^2}{n_{\text{d.f.}}}$
Borisyuk and Kobushkin	1	2.14	0.998	0.997	3.80
Blunden, et al.	1	2.94	0.998	0.997	4.75
Bernauer, et al.	1	4.19	0.997	0.995	1.00
Tomasi-Gustafsson, et al.	1	5.09	1.001	1.001	5.97
Arrington and Sick	1	7.72	1.000	1.001	8.18
Qattan, et al.	1	25.0	1.000	1.002	22.0
No hard TPE ($R_{2\gamma} \equiv 1$)	1	7.97	1	1	7.97

The "no hard TPE" hypothesis is excluded (p-value is 2×10^{-6})

VEPP-3, CLAS, and OLYMPUS results in one plot?

- Following [J. C. Bernauer *et al.*, PRC **90**, 015206], assume that TPE can be parametrized as

$$\delta_{2\gamma}(Q^2,\, \varepsilon) = \delta_F - (1-\varepsilon)\, \widetilde{\delta}_{2\gamma}(Q^2),$$

  where

$$\delta_F = \alpha\pi \, \frac{\sin(\theta_e/2)}{1+\sin(\theta_e/2)} = \alpha\pi \, \frac{\sqrt{1-\varepsilon}}{\sqrt{1-\varepsilon}+\sqrt{1+\varepsilon+2\varepsilon\tau}}$$

  is the Feshbach correction having the correct asymptotics when $Q^2 \to 0$.
- Since $R_{2\gamma} \approx 1 - 2\delta_{2\gamma}$,

$$R_{2\gamma}(Q^2,\, \varepsilon) \approx 1 - 2\delta_F + 2(1-\varepsilon)\, \widetilde{\delta}_{2\gamma}(Q^2).$$

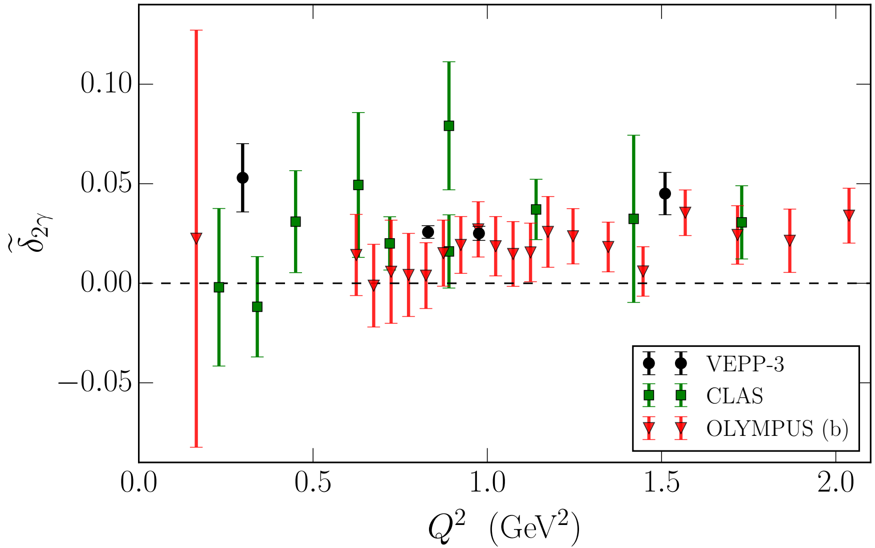
- Now, we can introduce the quantity

$$\widetilde{\delta}_{2\gamma}(Q^2) = \frac{R_{2\gamma} - 1 + 2\delta_F}{2(1-\varepsilon)}$$

  with the corresponding uncertainty

$$\Delta\widetilde{\delta}_{2\gamma} = \frac{\Delta R_{2\gamma}}{2(1-\varepsilon)}.$$

VEPP-3, CLAS, and OLYMPUS results in one plot?



Conclusion

- A high-precision comparison of the elastic e^+p and e^-p scattering cross sections has been performed at the VEPP-3 storage ring.
- This allowed us to determine the hard TPE contribution to elastic electron-proton scattering.
- The results obtained at VEPP-3 show evidence of a significant hard TPE effect.
- Therefore, our data support the suggestion that the proton form factor puzzle is due to the neglected hard TPE contribution.
- Nevertheless, the puzzle is far from being solved, and new comparisons at higher Q^2 values are very desirable.
- There is a qualitative agreement between the results obtained by VEPP-3, CLASS, and OLYMPUS.

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Thank you for your attention!