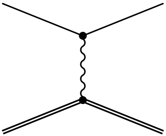
Status of the Novosibirsk two-photon exchange experiment

J. Arrington,[2] L. M. Barkov,[1] V. F. Dmitriev,[1] V. V. Gauzshtein,[3] R. A Golovin,[1] A. V. Gramolin,[1] R. J. Holt,[2] V. V. Kaminsky,[1] B. A. Lazarenko,[1] S. I. Mishnev,[1] N. Yu. Muchnoi,[1] V. V. Neufeld,[1] D. M. Nikolenko,[1] I. A. Rachek,[1] R. Sh. Sadykov,[1] Yu. V. Shestakov,[1] V. N. Stibunov,[3] D. K. Toporkov,[1] H. de Vries,[4] S. A. Zevakov,[1] and V. N. Zhilich[1]

[1]Budker Institute of Nuclear Physics, Novosibirsk, Russia
[2]Argonne National Laboratory, Argonne, USA
[3]Nuclear Physics Institute at Tomsk Polytechnical University, Tomsk, Russia
[4]NIKHEF, Amsterdam, The Netherlands

Symposium "Experimental and theoretical aspects of the proton form factors"

Differential cross section for elastic ep-scattering is given by the Rosenbluth formula:



$$\frac{d\sigma_{\text{Ros}}}{d\Omega_\ell} = \left[\frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\,\mathrm{tg}^2\frac{\theta_\ell}{2}\right]\frac{d\sigma_{\text{Mott}}}{d\Omega_\ell},$$

$$\frac{d\sigma_{\text{Mott}}}{d\Omega_\ell} = \frac{\alpha^2}{4E_\ell^2}\,\frac{\cos^2(\theta_\ell/2)}{\sin^4\theta_\ell/2}\,\frac{E'_\ell}{E_\ell},$$

where $\tau = Q^2/(4M^2)$, $Q^2 = 2M(E_\ell - E'_\ell)$, $d\sigma_{\text{Mott}}/d\Omega_\ell$ — Mott cross section, $G_E(Q^2)$ and $G_M(Q^2)$ — electric and magnetic form factors of the proton.

G_E and G_M are functions of the 4-momentum transfer squared (Q^2) only and describe the distributions of charge and magnetic moment inside the proton.

Introducing the variable ε (virtual photon polarization)

$$\varepsilon = \left[1 + 2(1+\tau)\,\mathrm{tg}^2\frac{\theta_\ell}{2}\right]^{-1},$$

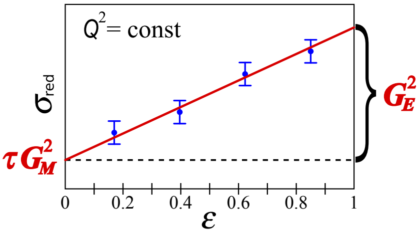
the Rosenbluth formula can be written as follows:

$$\frac{d\sigma_{\text{Ros}}}{d\Omega_\ell} = \frac{1}{\varepsilon(1+\tau)}\left[\varepsilon G_E^2(Q^2) + \tau G_M^2(Q^2)\right] = \frac{\sigma_{\text{red}}}{\varepsilon(1+\tau)},$$

where σ_{red} (reduced cross section) is a linear function of ε if $Q^2 = \text{const}$.

The proton's form factors, two methods of measuring

$$\sigma_{\mathrm{red}} = \varepsilon(1+\tau)\frac{d\sigma}{d\Omega_\ell} = \varepsilon G_E^2 + \tau G_M^2$$



Rosenbluth method

It consists in measuring of $d\sigma/d\Omega_\ell$ for fixed Q^2, but with different E_ℓ, θ_ℓ. $\Rightarrow$ Dipole formula for G_E and G_M:

$$G_E(Q^2) \approx \left(1 + \frac{Q^2}{0.71\ \mathrm{GeV}^2}\right)^{-2},$$

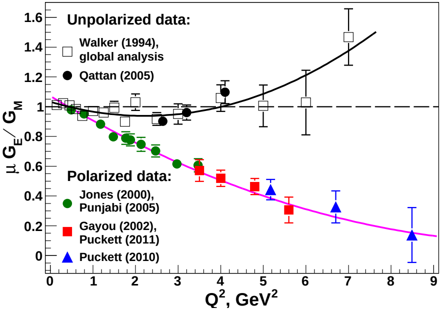
$$G_M(Q^2) \approx \mu G_E(Q^2).$$

Polarization transfer method

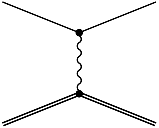
(Akhiezer and Rekalo, 1968)

The ratio G_E/G_M is proportional to the ratio of transverse P_T and longitudinal P_L polarization components of the recoil proton in reaction $\vec{e}p \to e'\vec{p}'$:

$$\frac{G_E}{G_M} = -\frac{P_T}{P_L}\,\frac{E_\ell + E'_\ell}{2M}\,\mathrm{tg}\,\frac{\theta}{2}.$$

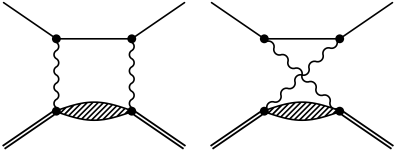


Two-photon exchange contribution?



This discrepancy has been explained as the effect of two-photon exchange (TPE) beyond the usual one-photon exchange approximation in the calculation of the elastic electron-proton scattering cross section.

Complications arising in the calculation of the TPE corrections are connected with difficulties in accounting for proton excitations in the intermediate state.



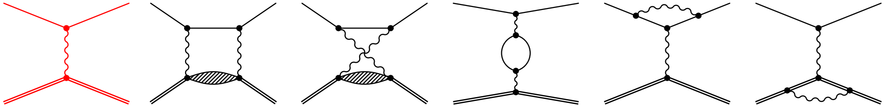
Fortunately, the contribution of two-photon exchange can be measured directly. This is possible due to the fact that the TPE corrections have opposite signs for e^+p and e^-p scattering cross sections, producing a measurable charge asymmetry

$$R = \frac{\sigma(e^+p)}{\sigma(e^-p)} \approx 1 + 4\frac{\mathrm{Re}\left(\mathcal{M}^\dagger_{\mathrm{Born}}\mathcal{M}_{2\gamma}\right)}{|\mathcal{M}_{\mathrm{Born}}|^2},$$

where $\sigma(e^+)$ and $\sigma(e^-)$ denote elastic cross sections of positron-proton and electron-proton scattering, respectively.

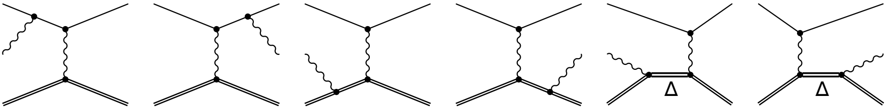
It should be taken into account the radiative corrections

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



$\mathcal{M}_{\text{Born}}$ $\mathcal{M}_{2\gamma}$ $\mathcal{M}_{\text{vac}}$ $\mathcal{M}^{\ell}_{\text{vert}}$ $\mathcal{M}^{p}_{\text{vert}}$

Bremsstrahlung ($e^\pm p \to e^\pm p\,\gamma$):



$\mathcal{M}^{\ell}_{\text{brem}}$ $\mathcal{M}^{p}_{\text{brem}}$ $\mathcal{M}_{\Delta}$

$$\sigma(e^\pm p) = |\mathcal{M}_{\text{Born}}|^2 \pm 2\,\mathrm{Re}\left(\mathcal{M}^\dagger_{\text{Born}}\mathcal{M}_{2\gamma}\right) +$$

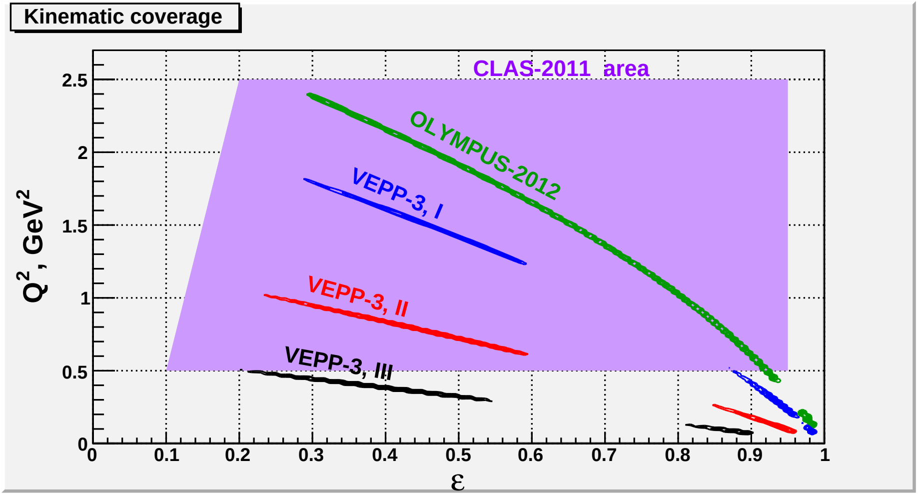
$$+\,2\,\mathrm{Re}\left(\mathcal{M}^\dagger_{\text{Born}}\mathcal{M}_{\text{vac}}\right) + 2\,\mathrm{Re}\left(\mathcal{M}^\dagger_{\text{Born}}\mathcal{M}^{\ell}_{\text{vert}}\right) + 2\,\mathrm{Re}\left(\mathcal{M}^\dagger_{\text{Born}}\mathcal{M}^{p}_{\text{vert}}\right) +$$

$$+\,|\mathcal{M}^{\ell}_{\text{brem}}|^2 + |\mathcal{M}^{p}_{\text{brem}}|^2 \pm 2\,\mathrm{Re}\left(\mathcal{M}^{\ell\dagger}_{\text{brem}}\mathcal{M}^{p}_{\text{brem}}\right) \pm 2\,\mathrm{Re}\left(\mathcal{M}^{\ell\dagger}_{\text{brem}}\mathcal{M}_{\Delta}\right) + \ldots$$

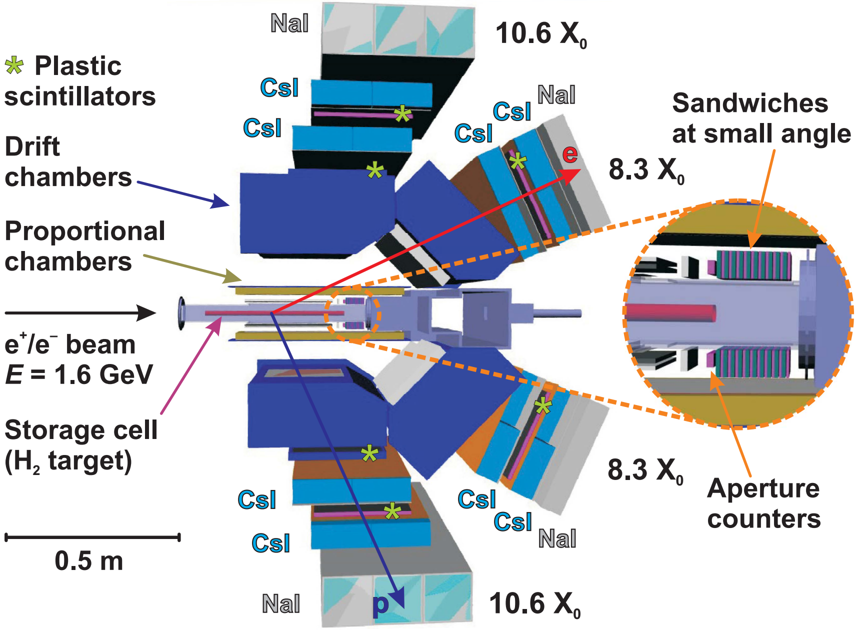
Details: in tomorrow's talks of Victor Fadin and Alexander Gramolin

Three experiments aimed at measuring the ratio R

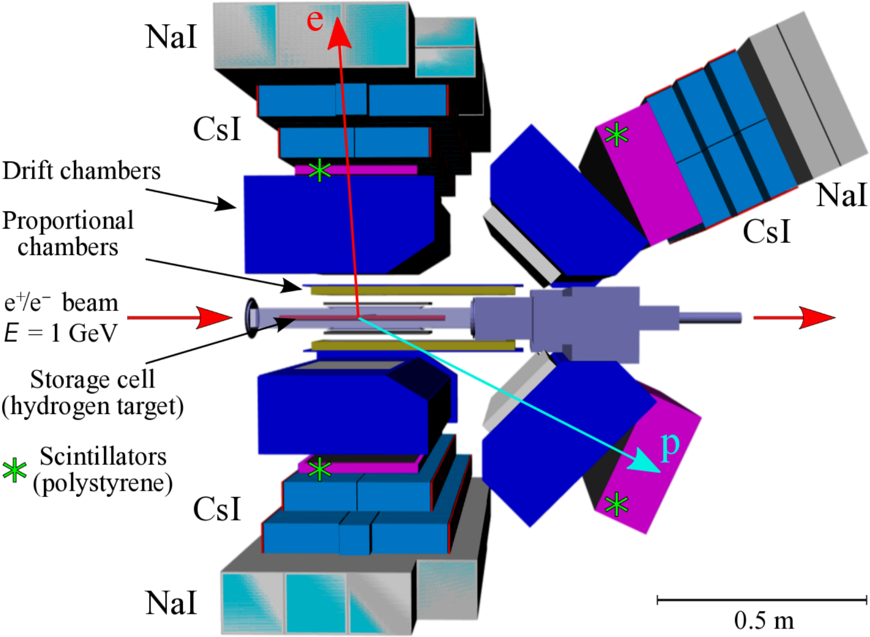
- Novosibirsk experiment ($E_{\mathrm{beam}} = 1.6$, 1 and 0.6 GeV)
- CLAS @ JLab experiment ($E_{\mathrm{beam}} = 0.5 \div 4$ GeV)
- OLYMPUS @ DESY experiment ($E_{\mathrm{beam}} = 2$ GeV)



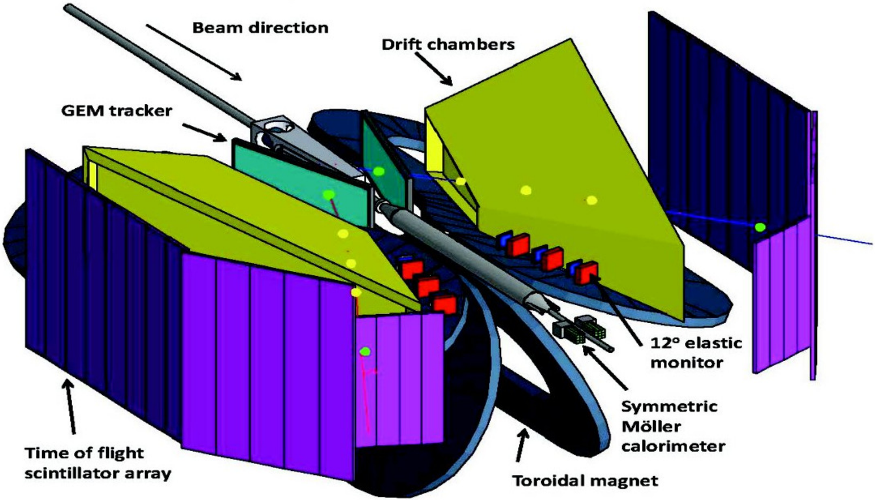
Novosibirsk TPE experiment (run I)



Novosibirsk TPE experiment (runs II, III)

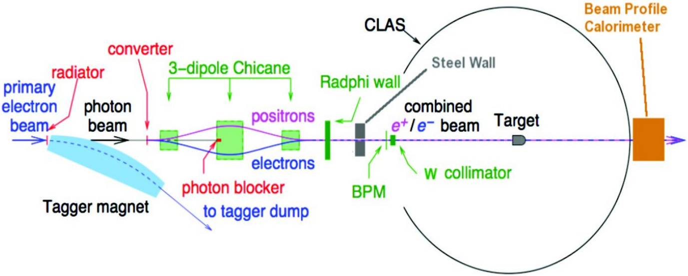


OLYMPUS experiment @ DESY



Details: in the next talk (Rebecca Russell)

CLAS TPE experiment @ JLab



- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 1% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 10% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
- Remaining photons are stopped at the photon blocker
- e^+ ande^- beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)

Details: in the EVO-talk of Robert Bennett

Comparison of the three experiments

	VEPP–3 Novosibirsk	OLYMPUS DESY	EG5 CLAS JLab
beam energy	3 fixed	1(+1?) fixed	wide spectrum
equality of $e^{\pm}$ beam energy	measured	assumed	reconstructed
e^+/e^- swapping frequency	half-hour	8 hours	simultaneously
e^+/e^- lumi monitor	elastic low-Q^2	elastic low-Q^2, Möller/Bhabha	from simulation
energy of scattered $e^{\pm}$	EM-calorimeter	mag. analysis	mag. analysis
proton PID	$\Delta E/E$, TOF	mag. analysis, TOF	mag. analysis, TOF
e^+/e^- detector acceptance	identical	big difference	big difference
luminosity	1.0×10^{32}	2.0×10^{33}	2.5×10^{32}

- Novosibirsk experiment is inferior to the other two in experimental luminosity and in quality of particle ID.
- However, the detector performance is sufficient for reliable identification of elastic scattering events.
- Non-magnetic detector, measurement of beams energy, frequent swapping of e^+/e^- beams allow us to obtain lowest systematic error.

Novosibirsk experiment at the VEPP–3 storage ring

A precision measurement of the ratio $R = \sigma(e^+p)/\sigma(e^-p)$ has been performed recently at the VEPP–3 storage ring at the energy of electron/positron beams of 1.6 GeV (run I), 1.0 GeV (run II) and 0.6 GeV (run III). The smallest angle regions were used for luminosity monitoring only.

Kinematic parameters of the experiment are shown in the table:

Parameter	Run I			Run II		Run III	
	LA	MA	SA	LA	MA	LA	MA
E_{beam}, GeV	1.6			1.0		0.6	
$\int I_{\mathrm{beam}} dt$, kC	54			100		3	
θ_ℓ, $^\circ$	55÷75	15÷25	8÷15	65÷105	15÷25	75÷110	25÷35
Q^2, GeV^2	1.26÷ ÷1.68	0.16÷ ÷0.41	0.05÷ ÷0.16	0.71÷ ÷1.08	0.07÷ ÷0.17	0.36÷ ÷0.52	0.06÷ ÷0.12
ε	0.37÷ ÷0.58	0.90÷ ÷0.97	0.97÷ ÷0.99	0.18÷ ÷0.51	0.91÷ ÷0.97	0.18÷ ÷0.44	0.83÷ ÷0.91
$\Delta R/R$, stat.	1.1%	0.1%	—	0.3%	—	0.8%	—

Milestones of the Novosibirsk experiment

- The proposal was published (Aug 2004): nucl-ex/0408020

Two-photon exchange and elastic scattering of electrons/positrons on the proton. (Proposal for an experiment at VEPP-3).
J. Arrington, V.F. Dmitriev, R.J. Holt, D.M. Nikolenko, I.A. Rachek, Yu.V. Shestakov, V.N. Stibunov, D.K. Toporkov, H. de Vries. Aug 2004. 13 pp.
e-Print: **nucl-ex/0408020 [nucl-ex]** PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 45 records

- Data taking:

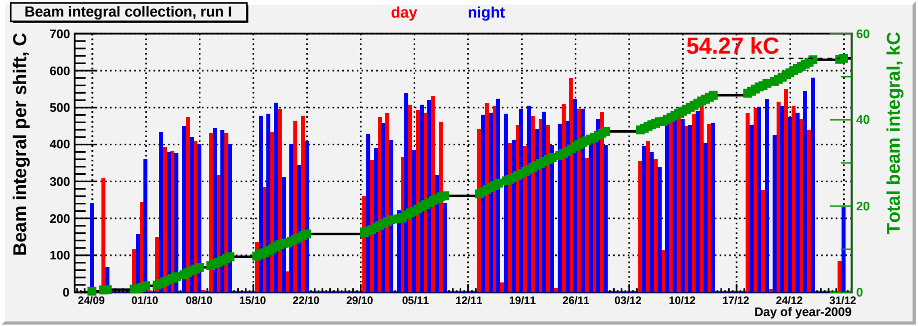
Run	Duration	E_{beam}, GeV	Number of $e^+ + e^-$ cycles	$\int$ luminosity, pb^{-1}
Engineering run	May–Jul 2007	1.6	90	12
Run I	Sep–Dec 2009	1.6	1100	324
Run II	Sep 2011 – Mar 2012	1.0	2350	600
Run III	Apr 2012	0.6	220	18

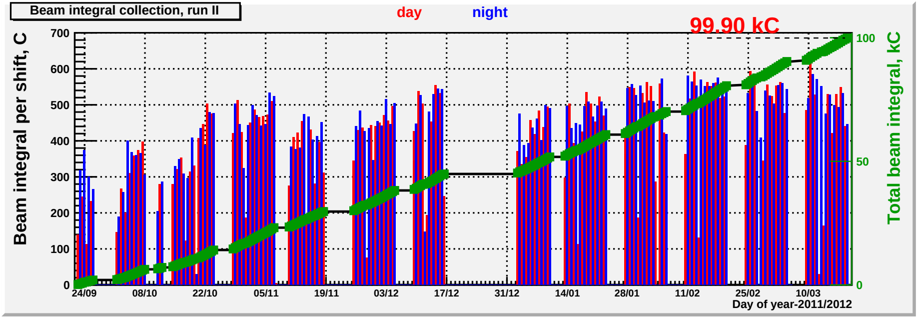
- Some preliminary results were published (Dec 2011): arXiv:1112.5369

Measurement of the two-photon exchange contribution in elastic ep scattering at VEPP-3.
A.V. Gramolin (Novosibirsk, IYF), J. Arrington (Argonne), L.M. Barkov (Novosibirsk, IYF), V.F. Dmitriev (Novosibirsk, IYF & Novosibirsk State U.), V.V. Gauzshtein (Tomsk Polytechnic U.), R.A. Golovin (Novosibirsk, IYF), R.J. Holt (Argonne), V.V. Kaminsky, B.A. Lazarenko, S.I. Mishnev (Novosibirsk, IYF) *et al.*. Dec 2011. 5 pp.
Published in **Nucl.Phys.Proc.Suppl. 225-227 (2012) 216**
To appear in the proceedings of Conference: C11-09-19
e-Print: **arXiv:1112.5369 [nucl-ex]** PDF
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
Detailed record - Cited by 1 record

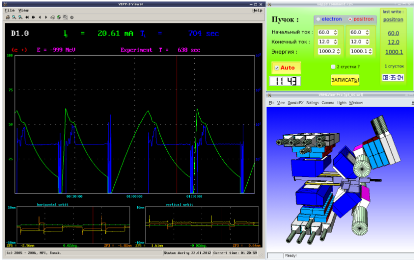
- Final results of the experiment: expected in 2013

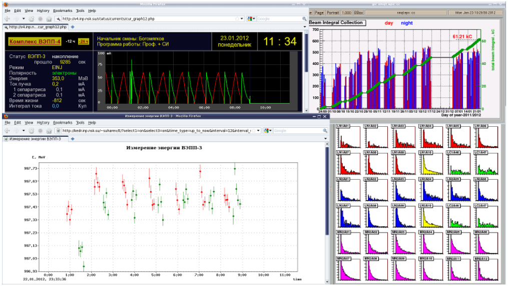
Beam integral collection during run I and run II

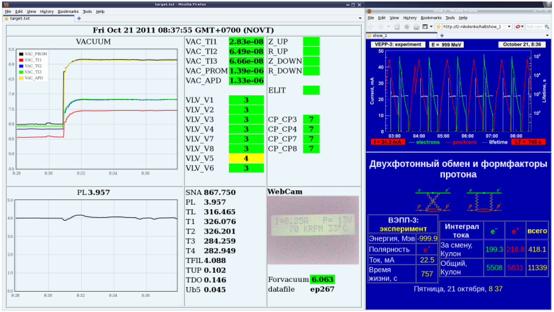


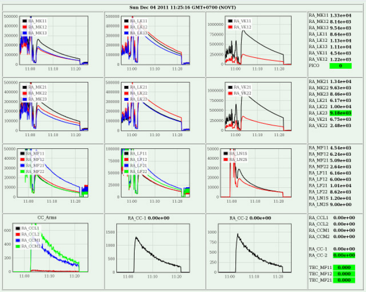


Slow control system of the experiment









Slow control system of the experiment

...and the shift leader during a 12-hour shift:

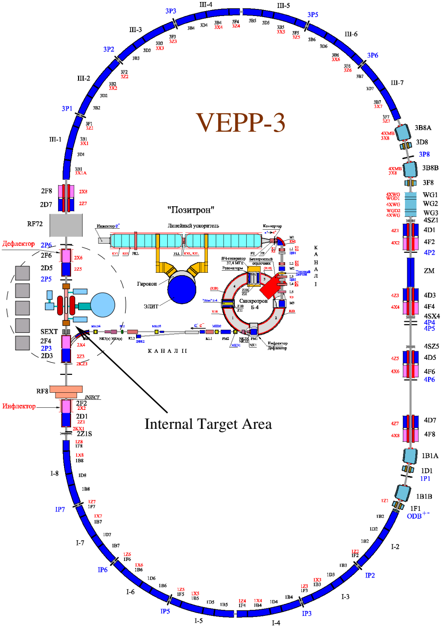
VEPP–3 is a booster for the VEPP–4M electron-positron collider.

VEPP–3 parameters for e^- beam:

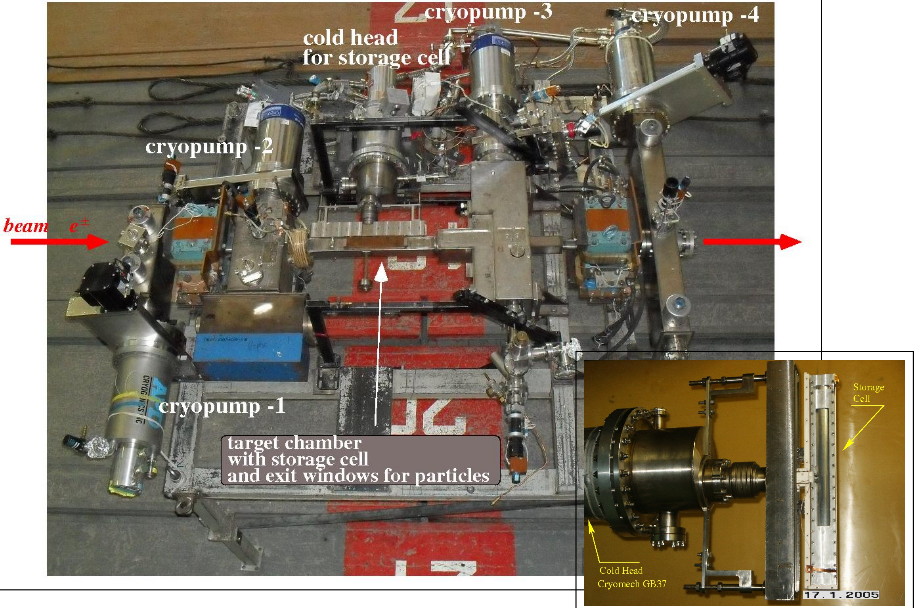
Electron energy	E_0	2 GeV
Mean beam current	I_0	150 mA
Energy spread	$\Delta E/E$	0.05%
RF HV magnitude	U_{72}	0.8 MV
revolution period	T	248.14 ns
bunch length	σ_L	15 cm
vertical beam size*	σ_z	0.5 mm
horizontal beam size*	σ_x	2.0 mm
vert. β-function*	β_z	2 m
horiz. β-function*	β_x	6 m
Injection beam 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*

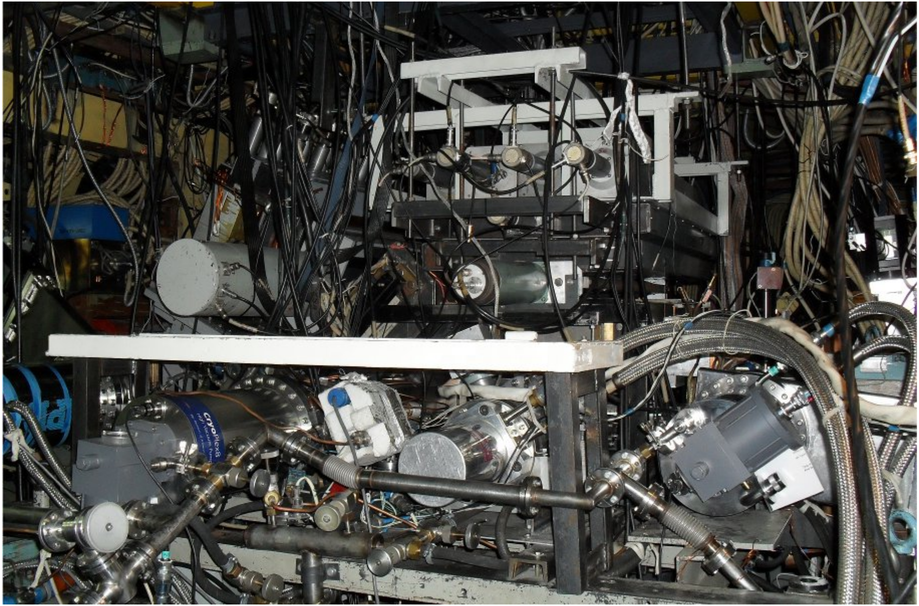
Maximal e^+ current: 60 mA



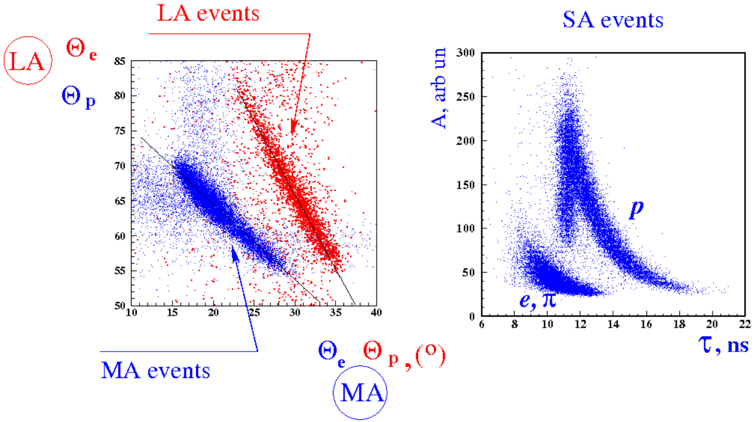
VEPP–3 internal target section



Detector and target at VEPP–3



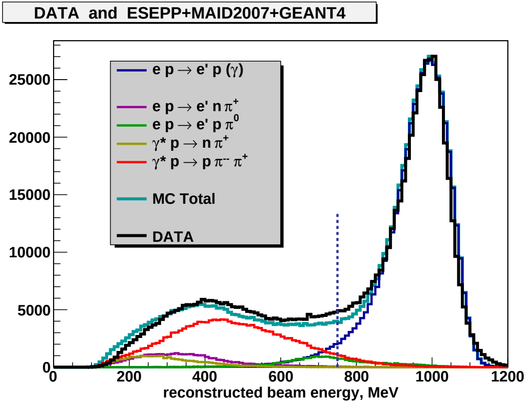
- Correlation between polar angles (θ_ℓ vs. θ_p)
- Correlation between azimuthal angles (ϕ_ℓ vs. ϕ_p)
- Correlation between lepton scattering angle and proton energy (θ_ℓ vs. E_p)
- Correlation between lepton scattering angle and electron energy (θ_ℓ vs. E_ℓ)
- ΔE–E analysis
- Time-of-flight analysis for low-energy protons

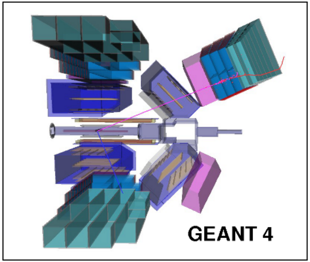


MC simulation of the background processes

- Geant4 detector model
- MAID2007 and 2-PION-MAID based event generator for single- and double-pion electro-production
- ESEPP event generator for elastic *ep* scattering with bremsstrahlung

Result for the reconstructed beam energy spectrum (run II, LA-kinematics), after just loose $(\Delta\phi, \Delta\theta)$–cuts applied:

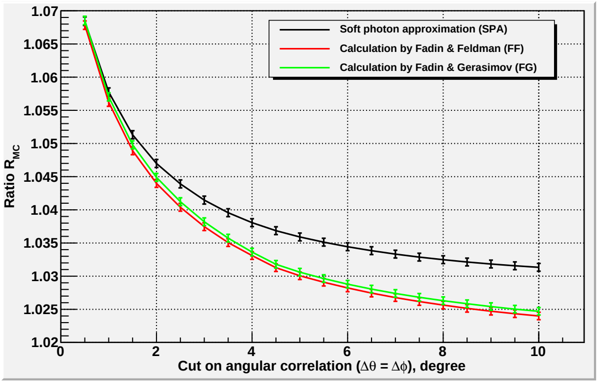




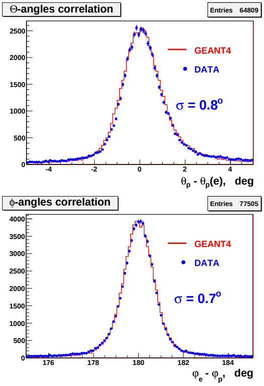
when all cuts applied:

$N_{background} / N_{elastic} < 1\%$

- The first-order bremsstrahlung: calculation by Fadin & Feldman instead of the simplified soft-photon one.
- Calculation by Fadin & Gerasimov to account for bremstrahlung with Δ-isobar excitation.
- New event generator ESEPP is applied to the Monte-Carlo detector simulation using the Geant4 software package.

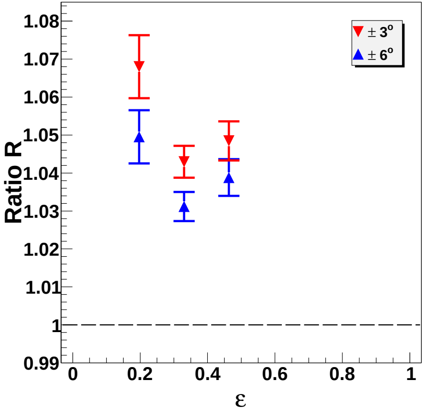


Angular correlations

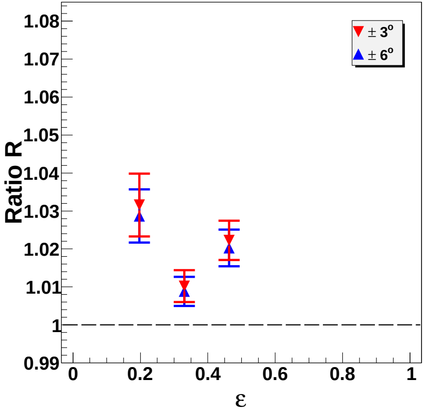


Ratio R and RC depend both on the kinematic cuts used

Raw data for the ratio R:



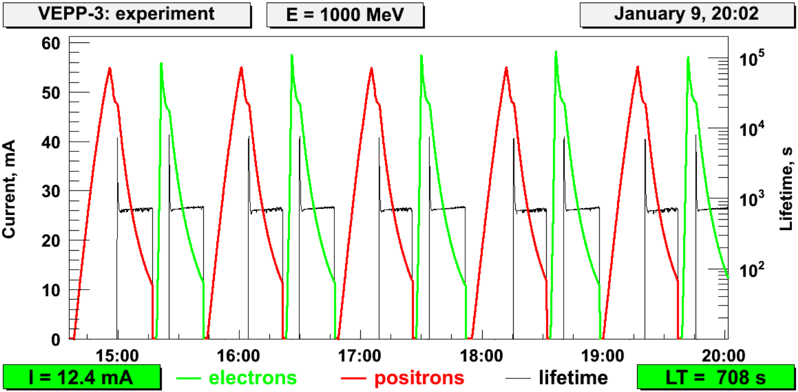
Radiatively corrected ratio R:



Experimentally measured ratio R is shown before (left figure) and after (right figure) taking into account the radiative corrections (FF model). Red markers correspond to the cut $\Delta\theta = \Delta\phi = 3^\circ$ on the angular correlations, blue markers correspond to the cut $\Delta\theta = \Delta\phi = 6^\circ$ (data for LA range of the run II).

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

- Data collection with e^- and e^+ beams was alternated regularly. This allows us to suppres effects of slow drift in time of the target thickness, detection efficiency and some other parameters.
- One cycle (e^+ and e^- beams) per 1 hour approximately.
- Starting and ending values of beam currents and beam lifetime for e^- and e^+ beams in each cycle were kept as close as possible.

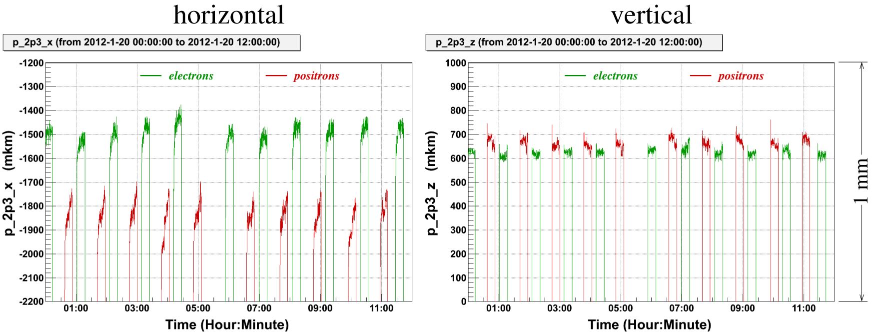


Contribution to the systematic error: $< 0.2\%$

Suppression of the systematics: beam position

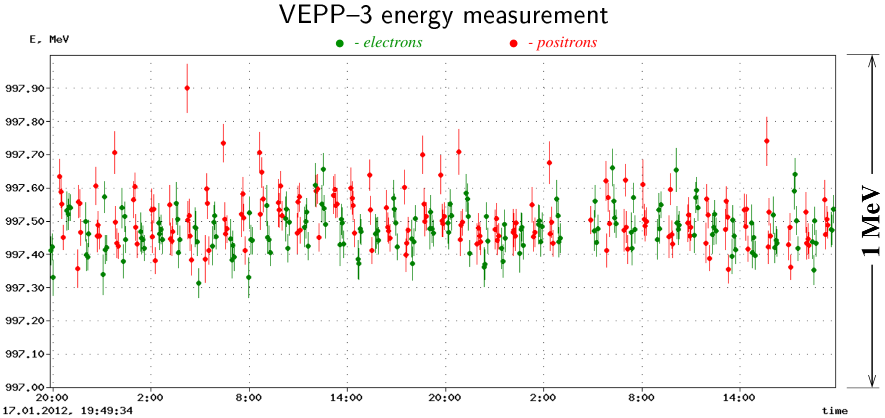
- Using the VEPP–3 beam orbit stabilisation system.
- Continuous measurement of the beam position at the entrance and exit of the experimental section by pick-up electrodes.
- Periodical "absolute" beam position measurements using moveable shutters.
- Determination of beam position in the target from data analysis.

Measurement of beam position by the **2P3** pick-up electrode:



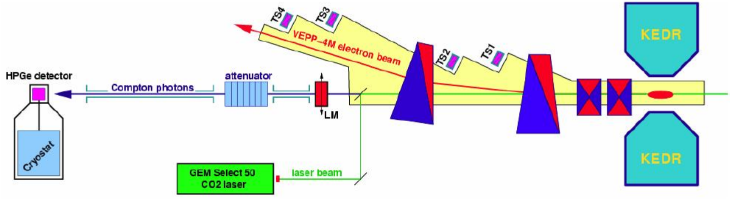
Contribution to the systematic error: $< 0.1\%$

- Method of measuring the energy of the laser photons back-scattered by the VEPP–3 beam is used.
- This allows us to tune the VEPP–3 operation regimes and to monitor the beams energy during the experiment.

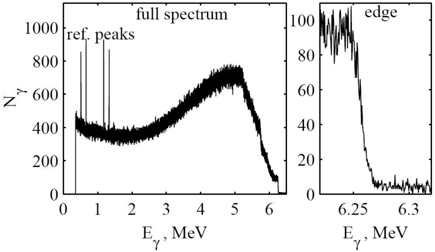


Contribution to the systematic error: $< 0.1\%$

Already existing system created earlier for the VEPP–4M collider has been used.



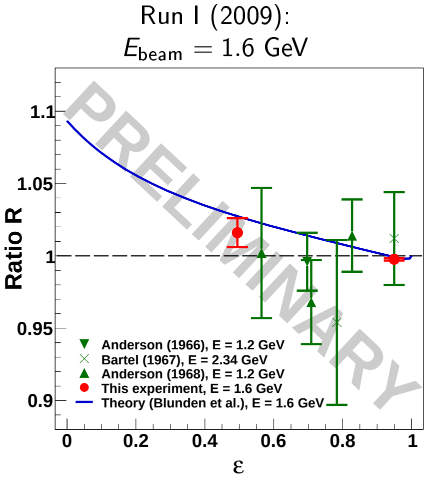
Photons from a CO_2 laser are scattered in a head-on collision with the stored beam. From the spectrum of the backscattered photons that are detected by an energy-calibrated high purity Ge detector the beam energy can be determined:

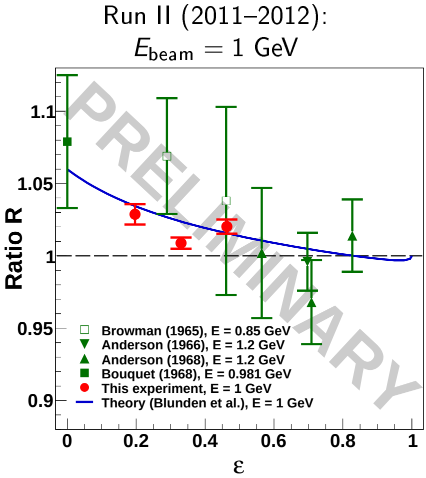


$$E = \frac{\omega_{\max}}{2}\left(1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{\max}}}\right),$$

where $\omega_{\max}$ — maximal energy of backscattering photons (the edge of spectrum), ω_0 — energy of laser photons, m_e — electron mass.

Preliminary results of the Novosibirsk experiment





Theory: *P. G. Blunden, et al.*, Phys. Rev. C **72** (2005) 034612

Only statistical errors are shown. Systematic errors for both the runs: $\leqslant 0.3\%$

Note that the radiative corrections have been taken into account. Some minor corrections have not yet been made (for example, corrections related to the variation in time of beam energy and position).

Conclusion

✓ The first precision measurement of the ratio $R = \sigma(e^+p)/\sigma(e^-p)$ has been performed. Data taking has been completed and analysis is still ongoing.

✓ Systematic errors of the measurement have been discussed. Here we have some advantages in comparison with OLYMPUS and CLAS.

✓ It is very important to carefully consider the radiative corrections due to bremsstrahlung in this experiment. Procedure of account of RC has been developed (ESEPP event generator + Geant4 simulation).

✓ Some preliminary results have been presented. They are consistent with the theoretical predictions by Blunden et al.

✓ Final results of the experiment are expected in the next year.

Thank you for your attention!

My participation in the Symposium was supported in part by
Russian Foundation for Basic Research under the grant 12–02–16065_mob_z_ros.

Conclusion

✓ The first precision measurement of the ratio $R = \sigma(e^+p)/\sigma(e^-p)$ has been performed. Data taking has been completed and analysis is still ongoing.

✓ Systematic errors of the measurement have been discussed. Here we have some advantages in comparison with OLYMPUS and CLAS.

✓ It is very important to carefully consider the radiative corrections due to bremsstrahlung in this experiment. Procedure of account of RC has been developed (ESEPP event generator + Geant4 simulation).

✓ Some preliminary results have been presented. They are consistent with the theoretical predictions by Blunden et al.

✓ Final results of the experiment are expected in the next year.

Thank you for your attention!

My participation in the Symposium was supported in part by
Russian Foundation for Basic Research under the grant 12–02–16065_mob_z_ros.