

Status of the Novosibirsk two-photon exchange experiment

J. Arrington,¹ V.F. Dmitriev,^{2,3} V.V. Gauzshtein,⁴ R.A. Golovin,²
A.V. Gramolin,² R.J. Holt,¹ V.V. Kaminsky,² B.A. Lazarenko,² S.I. Mishnev,²
N.Yu. Muchnoi,^{2,3} V.V. Neufeld,² D.M. Nikolenko,² I.A. Rachek,²
R.Sh. Sadykov,² Yu.V. Shestakov,^{2,3} V.N. Stibunov,⁴ D.K. Toporkov,^{2,3}
H. de Vries,⁵ S.A. Zevakov,² and V.N. Zhilich²

¹Argonne National Laboratory, Argonne, USA

²Budker Institute of Nuclear Physics, Novosibirsk, Russia

³Novosibirsk State University, Novosibirsk, Russia

⁴Nuclear Physics Institute at Tomsk Polytechnical University, Tomsk, Russia

⁵NIKHEF, Amsterdam, The Netherlands

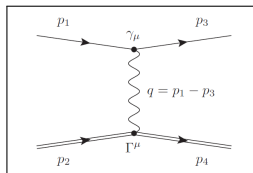
**Radiative Corrections in Annihilation and Scattering Experiments
(IPN Orsay, France; October 7–8, 2013)**



Proton electromagnetic form factors

The EM form factors are essential ingredients of our knowledge of the nucleon structure and this justifies the efforts devoted to their experimental determination.

In the one-photon (Born) approximation:



Nucleon current operator $\Gamma^\mu(q)$

$$\Gamma^\mu(q) = \gamma^\mu F_1(q^2) + \frac{i\sigma^{\mu\nu}q_\nu}{2M} F_2(q^2)$$

$F_1(q^2)$ – non-spin-flip Dirac form factor

$F_2(q^2)$ – spin-flip Pauli form factor

Sachs form factors

- Electric form factor
 $G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M^2} F_2(Q^2)$

- Magnetic form factor
 $G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$

$$G_E \approx G_M/\mu_p \approx G_D \equiv (1 + Q^2/0.71)^{-2}$$

*In non-relativistic limit G_E and G_M describe **charge** and **magnetization** distribution in nucleon.*

Measurements of the proton form factors

- Study with elastic ep scattering
- The **Rosenbluth separation** method at constant Q^2

Rosenbluth Formula

Rosenbluth, 1950

$$\frac{d\sigma}{d\Omega} = \frac{1}{\varepsilon(1+\tau)} [\varepsilon G_E^2 + \tau G_M^2] \frac{d\sigma_{\text{Mott}}}{d\Omega},$$

where $\tau = Q^2/4M^2$ and $\varepsilon = [1 + 2(1 + \tau)\tan^2(\theta/2)]^{-1}$

- **Polarized** beams and targets or recoil polarimeters

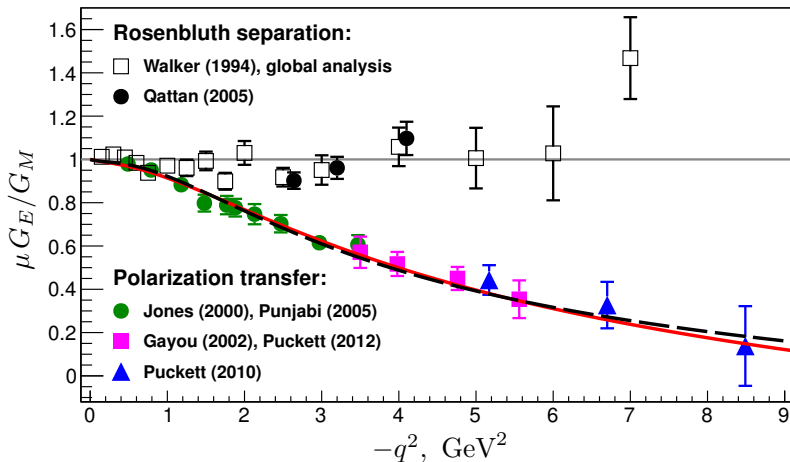
Form factor ratio from polarization transfer

Akhiezer & Rekalo, 1968

$$\frac{G_E}{G_M} = \frac{P_T}{P_L} \times K,$$

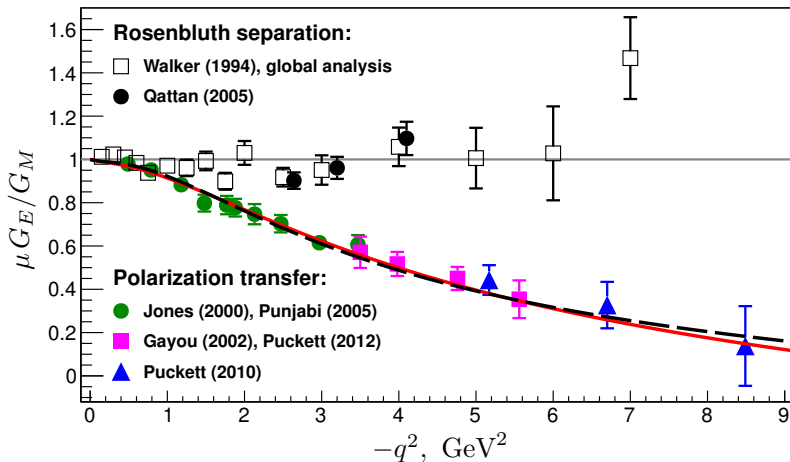
where P_T and P_L – transverse and longitudinal polarization components of proton,
 $K = -\sqrt{\tau(1+\varepsilon)}/2\varepsilon$ – kinematic factor

Inconsistency?



Clear discrepancy between the two experimental data sets is observed.

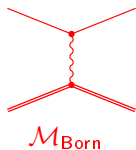
Inconsistency?



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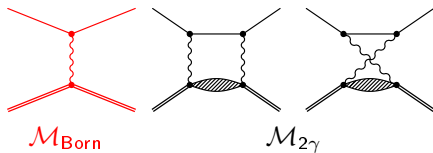
Radiative corrections, in particular, a hard Two-Photon Exchange (TPE) is a likely origin of the discrepancy.

The first-order radiative corrections to elastic ep scattering



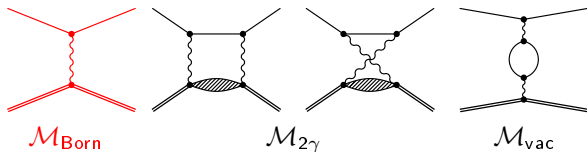
$$\sigma(e^\pm p) = |\mathcal{M}_{\text{Born}}|^2$$

The first-order radiative corrections to elastic ep scattering



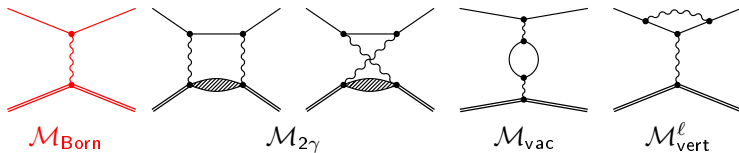
$$\sigma(e^\pm p) = |\mathcal{M}_{\text{Born}}|^2 \pm 2 \operatorname{Re} \left(\mathcal{M}_{\text{Born}}^\dagger \mathcal{M}_{2\gamma} \right)$$

The first-order radiative corrections to elastic ep scattering



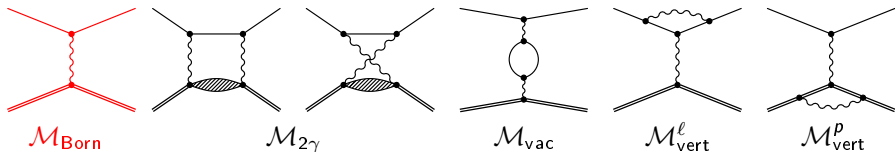
$$\sigma(e^\pm p) = |\mathcal{M}_{\text{Born}}|^2 \pm 2 \operatorname{Re} \left(\mathcal{M}_{\text{Born}}^\dagger \mathcal{M}_{2\gamma} \right) + \\ + 2 \operatorname{Re} \left(\mathcal{M}_{\text{Born}}^\dagger \mathcal{M}_{\text{vac}} \right)$$

The first-order radiative corrections to elastic ep scattering



$$\sigma(e^{\pm}p) = |\mathcal{M}_{\text{Born}}|^2 \pm 2 \operatorname{Re} \left(\mathcal{M}_{\text{Born}}^{\dagger} \mathcal{M}_{2\gamma} \right) + \\ + 2 \operatorname{Re} \left(\mathcal{M}_{\text{Born}}^{\dagger} \mathcal{M}_{\text{vac}} \right) + 2 \operatorname{Re} \left(\mathcal{M}_{\text{Born}}^{\dagger} \mathcal{M}_{\text{vert}}^{\ell} \right)$$

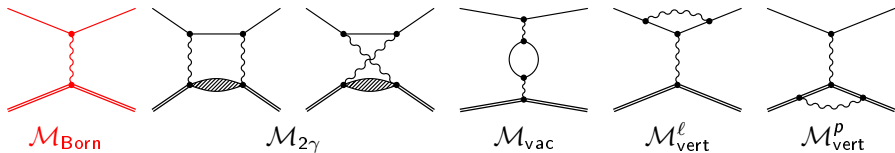
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The first-order radiative corrections to elastic ep scattering

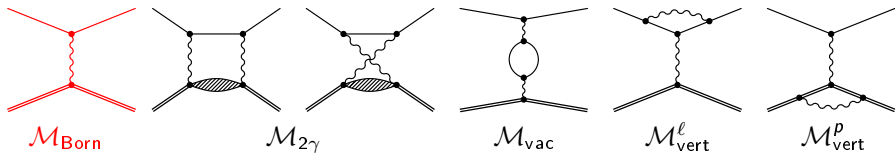
“Elastic” scattering ($e^\pm p \rightarrow e^\pm p$):



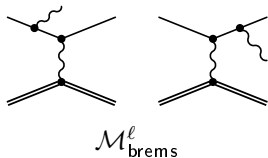
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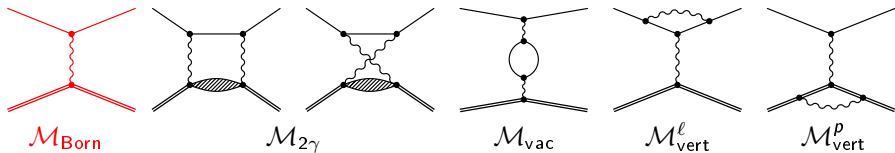
The first-order bremsstrahlung ($e^\pm p \rightarrow e^\pm p \gamma$):



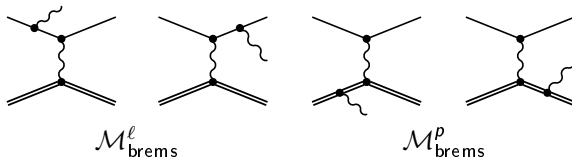
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The first-order radiative corrections to elastic ep scattering

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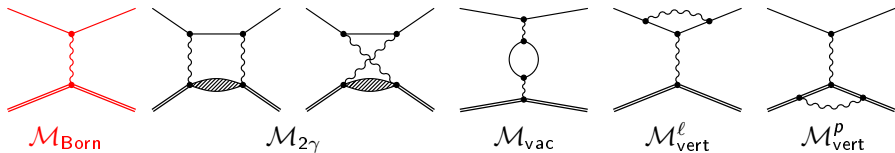
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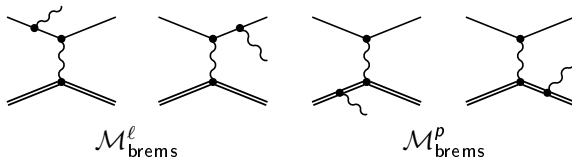
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The first-order radiative corrections to elastic ep scattering

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The first-order bremsstrahlung ($e^\pm p \rightarrow e^\pm p \gamma$):



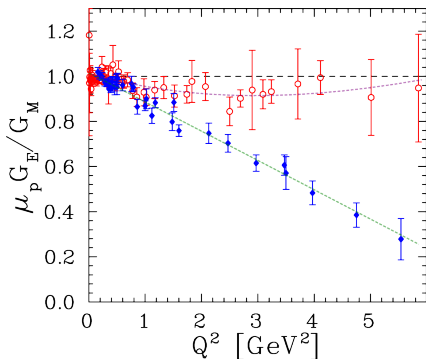
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- ✓ Cancellation of infrared divergences (corresponding terms are marked in color)
- ✓ Some of the terms are of different signs (“ \pm ”) for e^+p and e^-p scattering

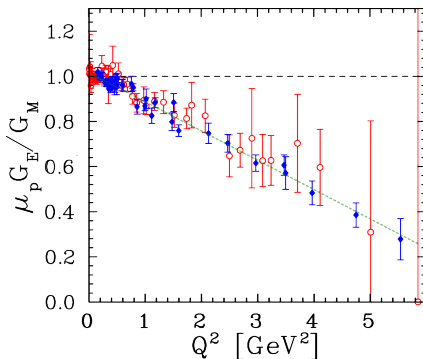
Example of calculation of the TPE contribution

P. G. Blunden, W. Melnitchouk, and J. A. Tjon, Phys. Rev. C **72** (2005) 034612

without TPE contribution



with TPE contribution



If this model is correct, the contradiction in the measurements of G_E/G_M is probably resolved.

Ratio $R = \sigma(e^+p)/\sigma(e^-p)$ of elastic cross sections

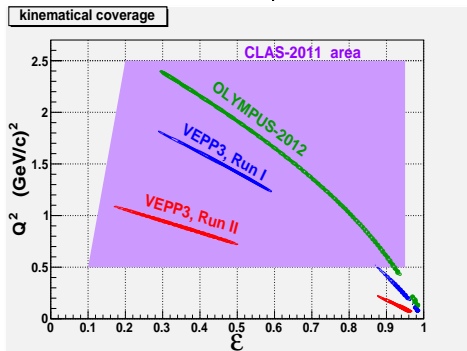
Direct method to measure a contribution of 2γ -process:

To measure a cross section ratio for elastic scattering of electrons and positrons on the proton \Rightarrow interference term can be extracted (after applying the standard radiative corrections):

$$\sigma \sim |\alpha(1\gamma) + \alpha^2(2\gamma) + \dots|^2 = \alpha^2(1\gamma) + \alpha^3 \text{Re}[(1\gamma)(2\gamma)] + \dots$$

$$R \equiv \frac{\sigma(e^+p)}{\sigma(e^-p)} \approx 1 + 2\alpha \cdot \frac{(2\gamma)}{(1\gamma)}$$

Three experiments to measure $R = \sigma(e^+p)/\sigma(e^-p)$:



$$\epsilon \equiv \frac{1}{1 + 2(1 + Q^2/4M^2) \tan^2 \theta/2}$$

- 1 **VEPP-3 at BINP**: 2 runs
 $E_{\text{beam}} = 1.6$ GeV (2009)
and $E_{\text{beam}} = 1.0$ GeV (2011/12)
- 2 **CLAS at JLab**: run is completed in
February-2011, $E_{\text{beam}} = 0.5 \div 4$ GeV
- 3 **OLYMPUS at DESY**: run is completed
in December-2012, $E_{\text{beam}} = 2$ GeV

Comparison of the three TPE experiments

	VEPP-3 Novosibirsk	OLYMPUS DESY	CLAS JLab
beam energy	2 fixed	1 fixed	wide spectrum
equality of e^\pm beam energies	measured precisely	assumed (measured?)	reconstructed
e^+/e^- alternation frequency	half-hour	8 hours	simultaneously
e^+/e^- luminosity 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}
systematic error	< 0.3%	1%	1%

- The Novosibirsk experiment is inferior to the other two in experimental luminosity and in quality of particle identification (PID);
- However, the detector performance is sufficient for reliable identification of elastic scattering events;
- Non-magnetic detector, measurement of beam energies, frequent alternation of e^+/e^- beams allow lowest systematic error.

Experiment at the VEPP-3 storage ring

A precise measurement of the ratio $R = \sigma(e^+p)/\sigma(e^-p)$ at the VEPP-3 storage ring (Novosibirsk) at the energy of electron/positron beams of 1.6 GeV (run I) and 1.0 GeV (run II).

Kinematic parameters of two runs

Parameter	Run I			Run II	
	LA	MA	SA	LA	MA
$E_{\text{beam}}, \text{ GeV}$	1.6			1.0	
$\int I_{\text{beam}} dt, \text{ kC}$	54			100	
$\int L dt, \text{ pb}^{-1}$	320			600	
$\theta_{e\pm}$	$55^\circ-75^\circ$	$15^\circ-25^\circ$	$8^\circ-15^\circ$	$65^\circ-105^\circ$	$15^\circ-25^\circ$
$Q^2, \text{ GeV}^2$	1.26–1.68	0.16–0.41	0.05–0.16	0.71–1.08	0.07–0.17
\mathcal{E}	0.37–0.58	0.90–0.97	0.97–0.99	0.18–0.51	0.91–0.97
$\Delta R/R, \text{ stat.}$	1.1%	0.1%	—	0.3%	—

The smallest angle regions were used for luminosity monitoring only.

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](#) | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#)

[Detailed record](#) - Cited by 52 records [50+](#)

- Data taking runs:

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

- 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)** 216-220

DOI: [10.1016/j.nuclphysbps.2012.02.045](#)

To appear in the proceedings of Conference: [C11-09-19 Proceedings](#)

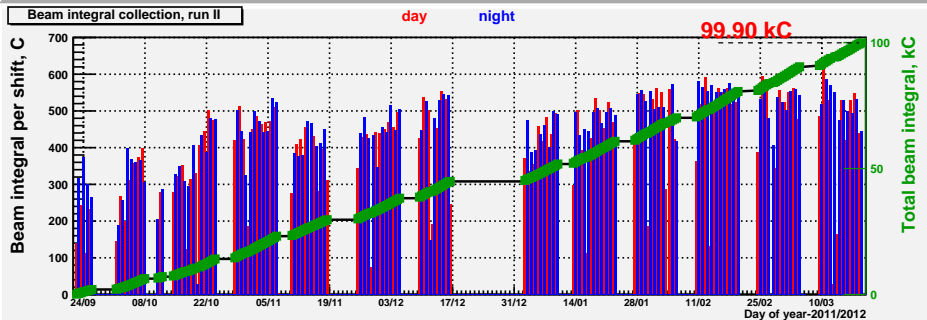
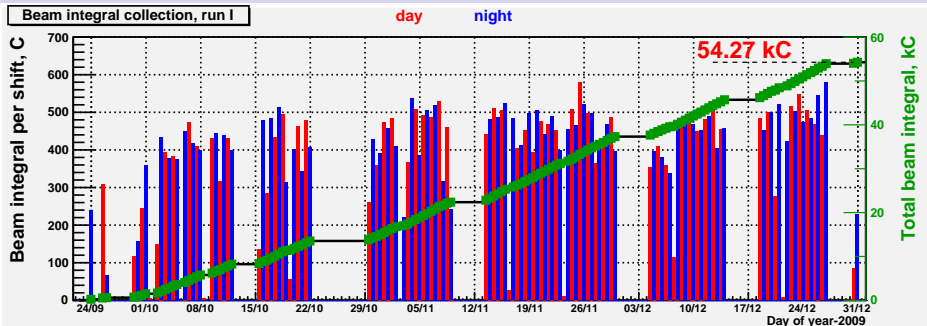
e-Print: [arXiv:1112.5369](#) [[nucl-ex](#)] | [PDF](#)

[References](#) | [BibTeX](#) | [LaTeX\(US\)](#) | [LaTeX\(EU\)](#) | [Harvmac](#) | [EndNote](#)

[ADS Abstract Service](#)

[Detailed record](#) - Cited by 7 records

Beam integral collection during the Run I and Run II



VEPP-3 electron-positron storage ring

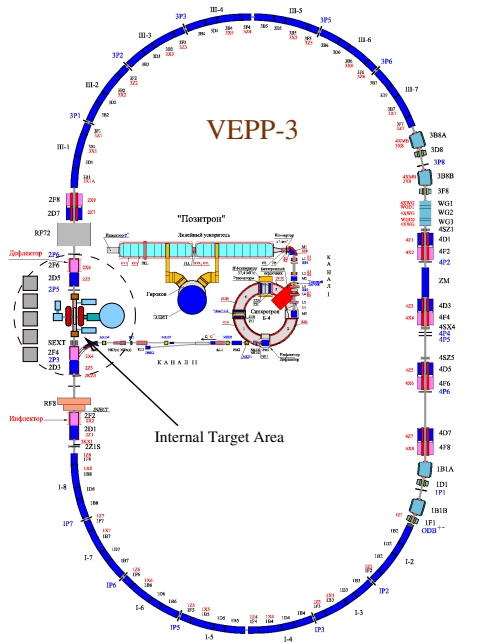
VEPP-3 is a booster for the
VEPP-4M electron-positron collider.

VEPP-3 parameters for e^- beam:

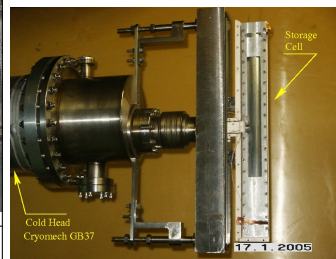
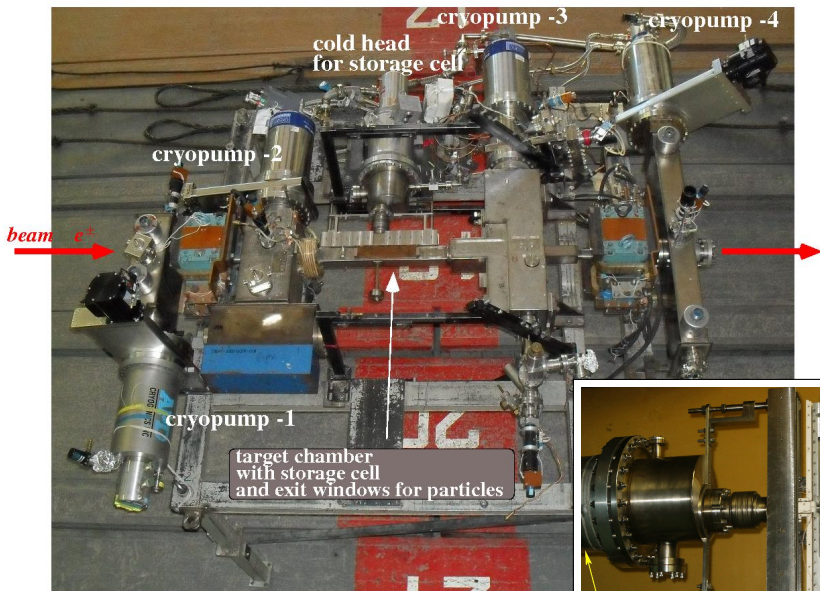
Electron energy	E_0	2 GeV
Mean beam current	I_0	150 mA
Energy spread	$\Delta E/E$	0.05%
RF HV magnitude	U_{72}	0.8 MV
revolution period	T	248.14 ns
bunch length	σ_L	15 cm
vertical beam size*	σ_z	0.5 mm
horizontal beam size*	σ_x	2.0 mm
vert. β -function*	β_z	2 m
horiz. β -function*	β_x	6 m
Injection beam energy	E_{inj}	350 MeV
Injection rate	i_{inj}	$1.5 \cdot 10^9 \text{ s}^{-1}$

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

Largest e^+ current: 60 mA

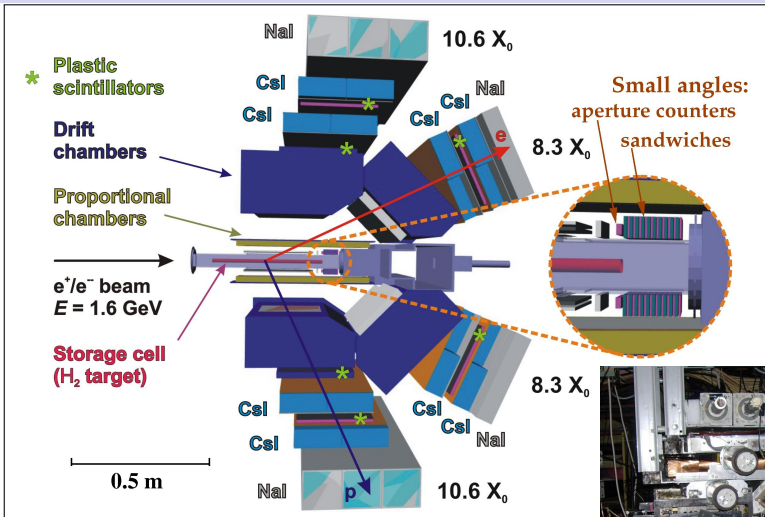


Internal target section at VEPP-3



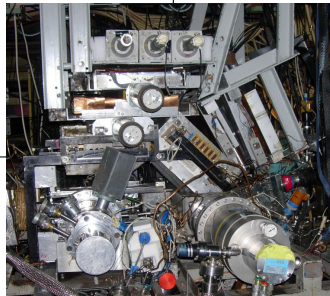
target thickness = $1-2 \times 10^{15}$ at./cm²

Detector package for the Run I



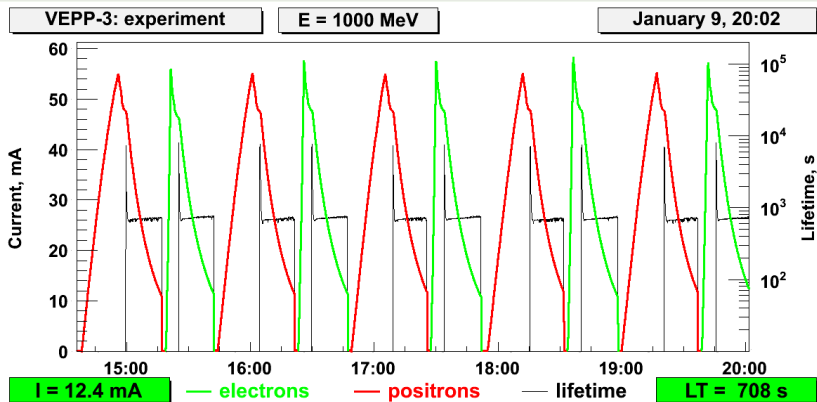
Wide-aperture non-magnetic detector

θ_e -acceptance: $8^\circ - 13^\circ$, $15^\circ - 25^\circ$ and $55^\circ - 75^\circ$
 ϕ_e -acceptance: $2 \times 60^\circ$



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

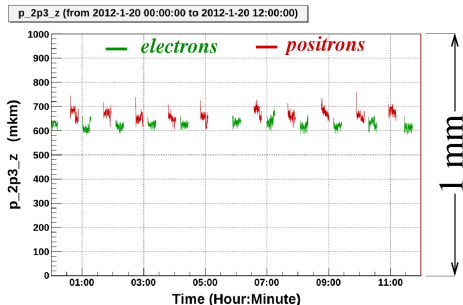
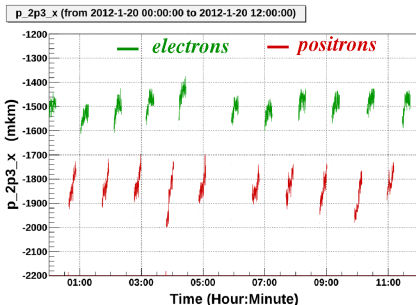
- During data collection, e^- and e^+ beams were alternated regularly. This allows us to suppress effects of slow drift in time of the target thickness, detection efficiency, etc.
- One cycle (e^+ and e^- beams) per 1 hour approximately.
1100 cycles in Run I, 2350 cycles in Run II
- Starting and ending values of beam currents and beam lifetime for e^- and e^+ beams in each cycle were kept as close as possible.



Suppression of the systematics: beam position

- Using the VEPP-3 beam orbit stabilization 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 movable shutters.
- Determination of beam position in the target from data analysis.
- Two symmetrical sets of detector arms: the sum is insensitive to vertical shifts of (e^+/e^-)-beams.

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



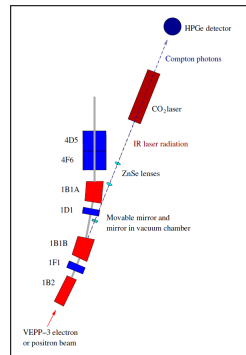
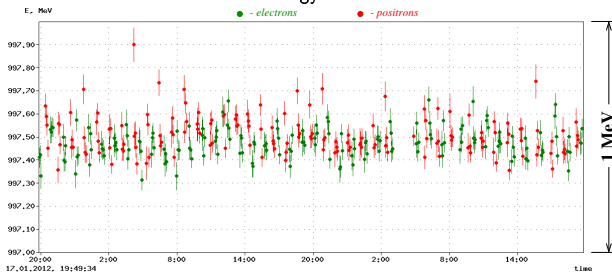
Suppression of the systematics: beam energy

- Reconstruction of beam energy (at ~ 0.1 MeV accuracy) from an energy spectrum of laser photons backscattered on beam particles.

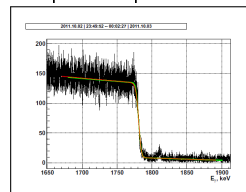
$$E_{\text{beam}} = 0.5 \cdot \omega_{\text{max}} \cdot \left(1 + \sqrt{1 + m_e^2 / \omega_0 \omega_{\text{max}}} \right)$$

- This allows us to tune the VEPP-3 operation regimes and to monitor the beams energy during the experiment.

VEPP-3 energy measurement



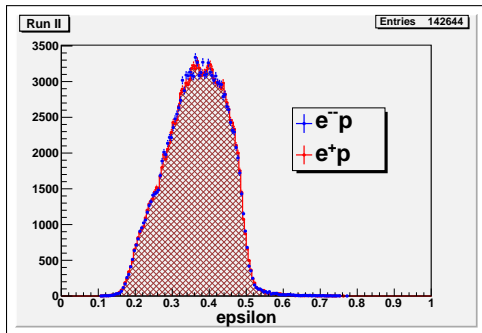
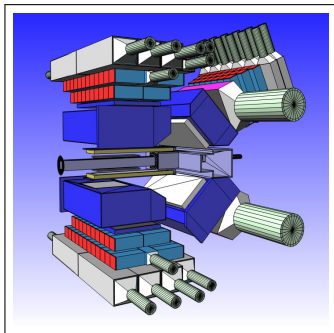
photon spectrum



Suppression of the systematics: no magnetic field!

- Non-magnetic detectors
- Magnetic-field-free target area

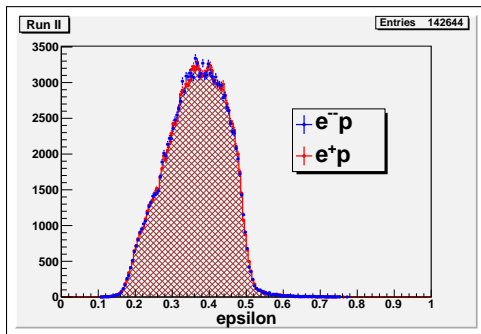
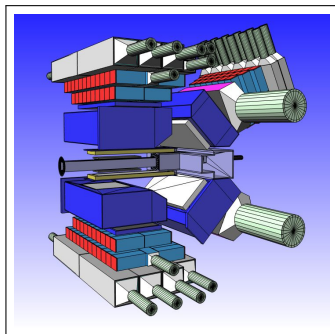
⇒ *Exactly identical acceptance for electrons and positrons*



Suppression of the systematics: no magnetic field!

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⇒ *Exactly identical acceptance for electrons and positrons*



Total systematic error estimated: $< 0.3\%$

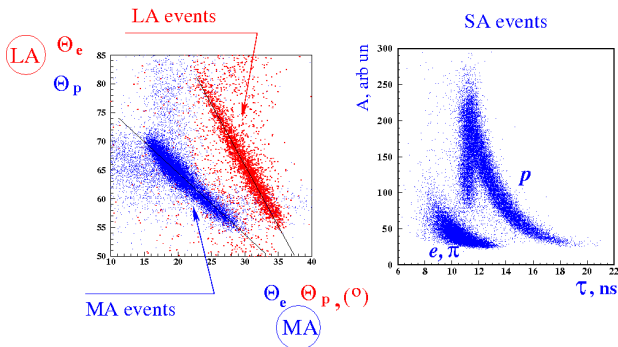
Selection of the elastic scattering events

- Correlations characteristic for two-body final state:

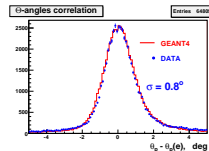
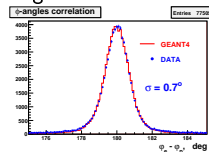
- Correlation between azimuthal angles ($\phi_{e\pm}$ vs. ϕ_p) \rightarrow coplanarity
- Correlation between polar angles ($\theta_{e\pm}$ vs. θ_p) \rightarrow collinearity in CM
- Correlation between lepton scattering angle and proton energy ($\theta_{e\pm}$ vs. E_p)
- Correlation between lepton scattering angle and electron energy ($\theta_{e\pm}$ vs. $E_{e\pm}$)

- Particle ID:

- Time-of-flight analysis for low-energy protons
- $\Delta E-E$ analysis for middle-energy protons
- Energy deposition in EM-calorimeter for electrons/positrons



angular correlations



Radiative corrections: a new event generator

The radiative corrections due to bremsstrahlung depend on the type of detector used (magnetic or not), the detector acceptance, its spatial and energy/momentum resolutions and the kinematic cuts applied to select elastic events. For this reason, careful account of the radiative corrections requires a realistic Monte Carlo simulation of the detector response, for example, using the Geant4 toolkit. We developed a new multi-purpose event generator ($\ell p \rightarrow \ell' p'$ and $\ell p \rightarrow \ell' p' \gamma$), called ESEPP (Elastic Scattering of Electrons and Positrons on Protons).

See <http://gramolin.com/esepp/> and a dedicated talk tomorrow.

The main advantages of ESEPP:

- ✓ Four types of incident particles are possible: e^- , e^+ , μ^- , μ^+ ;
- ✓ All the kinematic parameters of the final particles are known \Rightarrow ESEPP is a multi-purpose generator;
- ✓ We use an accurate calculation for the first-order bremsstrahlung instead of the usual soft-photon approximation;
- ✓ Not only the lepton bremsstrahlung is considered, but also the proton bremsstrahlung and the interference term.

The main disadvantage:

- ✓ Only the first-order bremsstrahlung is taken into account.

Is it enough to consider only the first-order bremsstrahlung?

- In the case of single-arm experiments (when only the scattered lepton is detected):

$$\frac{d\sigma_{\text{meas}}}{d\Omega_\ell} = [1 + \delta_{\text{virt}} + \delta_{\text{brems}}(\Delta E)] \frac{d\sigma_{\text{Born}}}{d\Omega_\ell}.$$

- Schwinger was the first who calculated the lowest-order QED radiative corrections for an electron scattering in a Coulomb potential (ignoring the proton recoil and radiation):

$$\delta_{\text{virt}}^{\text{Schw}} = -\frac{2\alpha}{\pi} \left(\frac{14}{9} - \frac{13}{12} \ln \frac{-q^2}{m^2} \right),$$
$$\delta_{\text{brems}}^{\text{Schw}}(\Delta E) = -\frac{2\alpha}{\pi} \left(\ln \frac{-q^2}{m^2} - 1 \right) \ln \frac{E}{\Delta E},$$

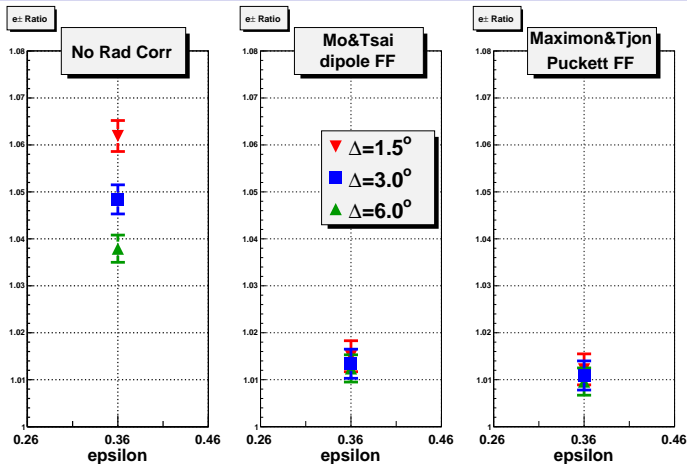
where E is the energy of incident or scattered electron (both energies are the same in the case of potential scattering).

- It was originally proposed by Yennie, Frautschi and Suura that the emission of soft bremsstrahlung photons can be summed up to all orders in α via **exponentiation**:

$$\frac{d\sigma_{\text{meas}}}{d\Omega_\ell} = (1 + \delta_{\text{virt}}) \exp [\delta_{\text{brems}}(\Delta E)] \frac{d\sigma_{\text{Born}}}{d\Omega_\ell}.$$

Taking the values of $-q^2 = 1 \text{ GeV}^2$ and $E/\Delta E = 10$, which approximately correspond to the parameters of the Novosibirsk TPE experiment, we obtain that $\delta_{\text{virt}}^{\text{Schw}} = 0.0691$ and $\delta_{\text{brems}}^{\text{Schw}} = -0.1515$. Hence, it is easy to calculate that neglecting the exponentiation procedure will lead to an **error only about 0.1%** for the cross section $d\sigma_{\text{Born}}/d\Omega_\ell$.

Radiative corrections for R as a function of kinematic cuts



RUN II: single point with various event selecting angular correlation cuts

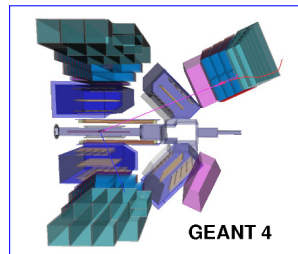
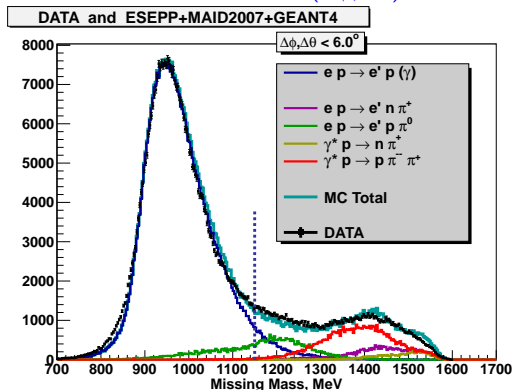
- Left panel – before any RC applied – **big difference!**
- Middle panel – TPE amplitudes according to Mo&Tsai, proton FF in the dipole form
- Right panel – TPE amplitudes by Maximon&Tjon, proton FF – parametrization by Puckett

MC simulation of 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**

Missing mass spectrum, reconstructed from energy and direction of particle detected in LA arm, assuming this is *elastic scattered* e^- (for $E_{e^\pm} = 1$ GeV)

soft cut on $(\Delta\phi, \Delta\theta)$

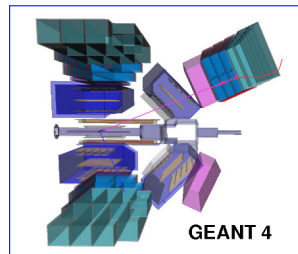
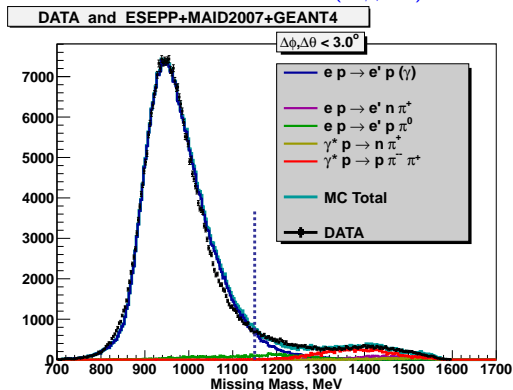


MC simulation of background processes

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Missing mass spectrum, reconstructed from energy and direction of particle detected in LA arm, assuming this is *elastic scattered* e^- (for $E_{e\pm} = 1$ GeV)

standard cut on $(\Delta\phi, \Delta\theta)$

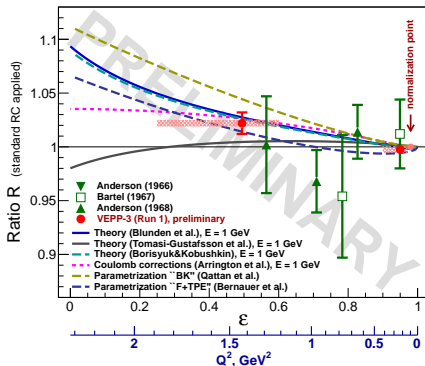


when all cuts applied:

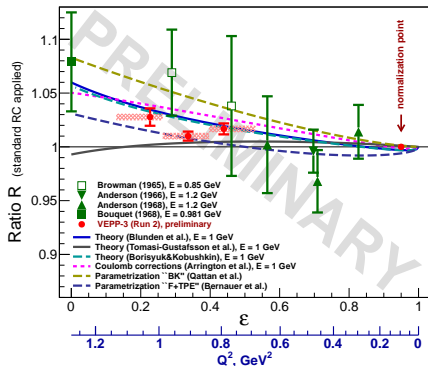
$$N_{\text{background}} / N_{\text{elastic}} < 1.5\%$$

Preliminary results of the Novosibirsk TPE experiment

Run I (2009):
 $E_{\text{beam}} = 1.6 \text{ GeV}$



Run II (2011–2012):
 $E_{\text{beam}} = 1 \text{ GeV}$

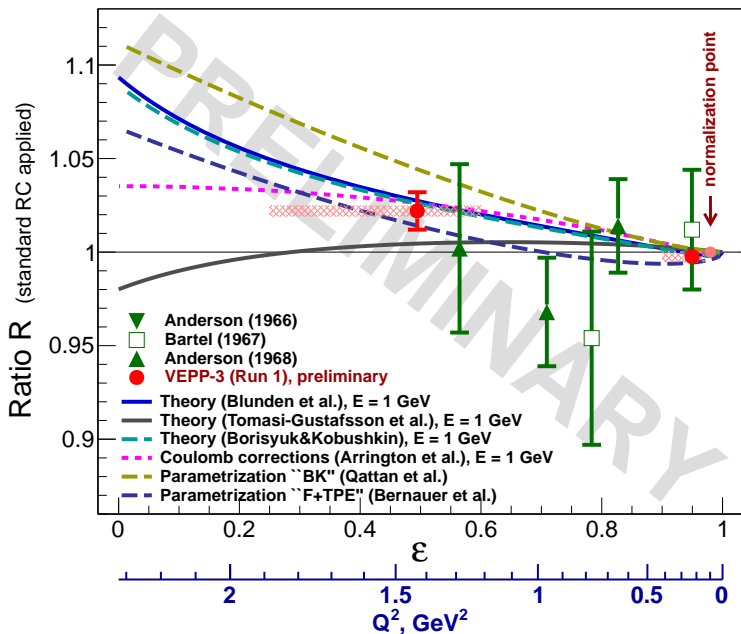


Curves:

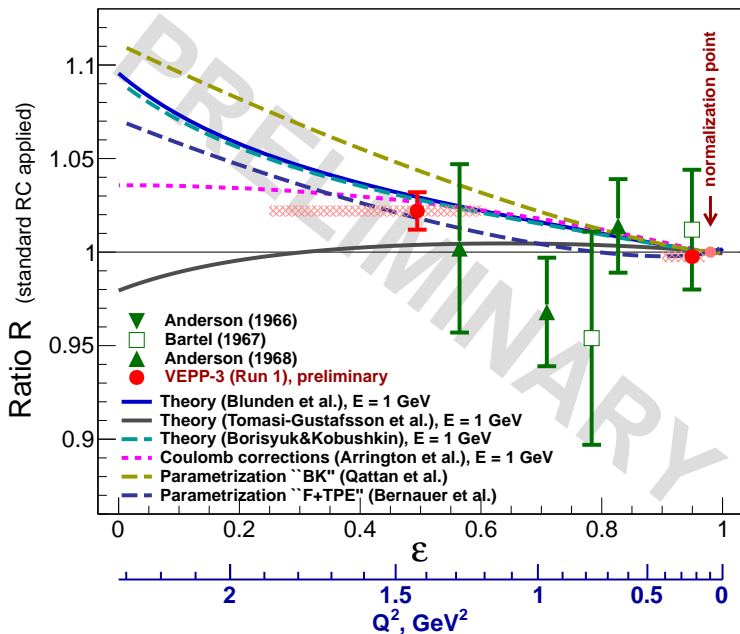
<i>P. G. Blunden, et al.,</i>	Phys. Rev. C 72 (2005) 034612	:hadronic TPE calculation
<i>E. Tomasi-Gustafsson, et al.,</i>	arXiv:0909.4736	:“analytical model”
<i>D. Borisyuk and A. Kobushkin,</i>	Phys. Rev. C 78 (2008) 025208	:dispersion relations
<i>J. Arrington and I. Sick,</i>	Phys. Rev. C 70 (2004) 028203	:Coulomb corrections
<i>I. A. Qattan, et al.,</i>	Phys. Rev. C 84 (2011) 054317	:phenomenology
<i>J. C. Bernauer, et al.,</i>	arXiv:1307.6227	:phenomenology

- error bars are statistical errors, hashed areas show ϵ -range and systematic uncertainties;
- the standard radiative corrections are taken into account.

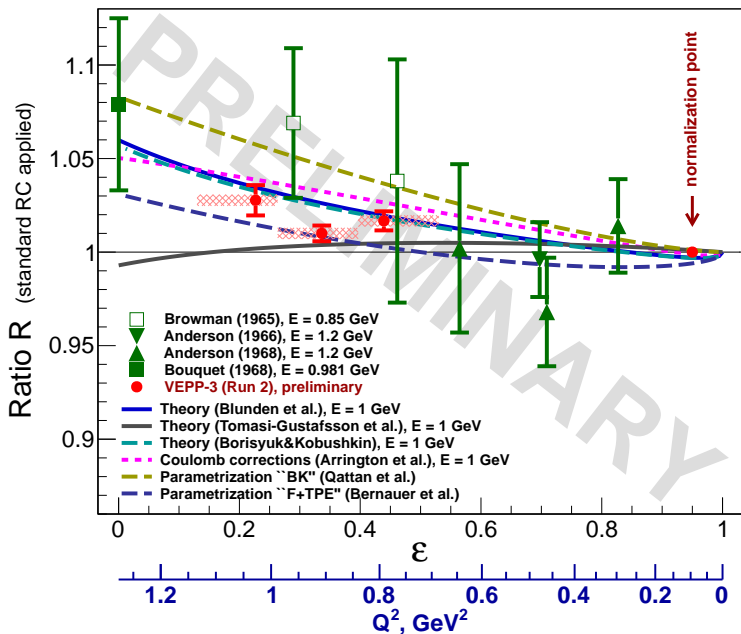
Preliminary results: Run I, without normalization



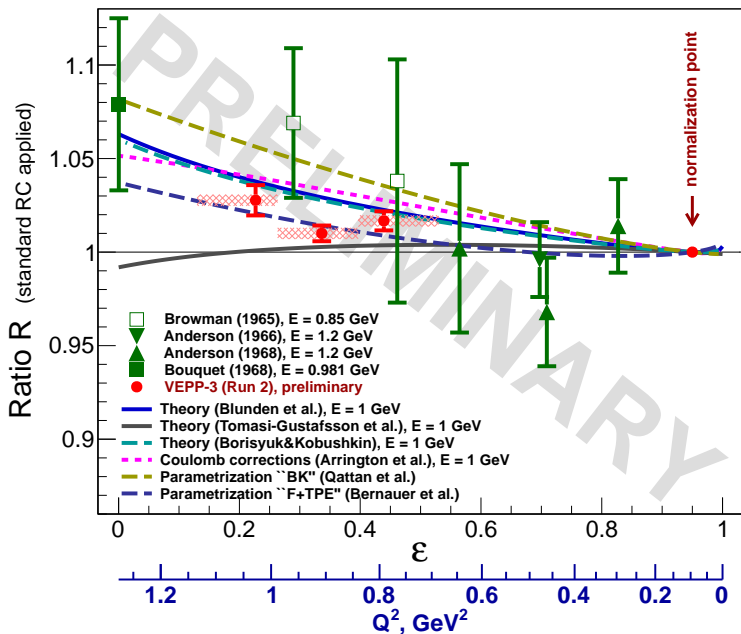
Preliminary results: Run I, with normalization



Preliminary results: Run II, without normalization

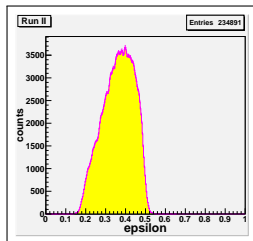
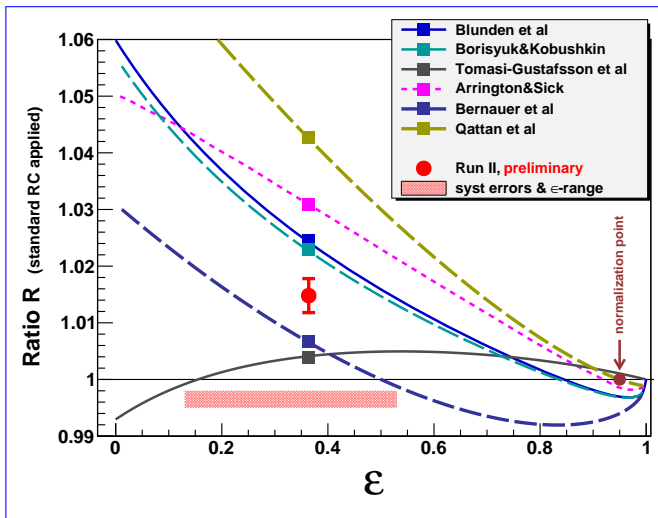


Preliminary results: Run II, with normalization



Run II data versus theoretical predictions

Run-II data at large scattering angle in a single point:

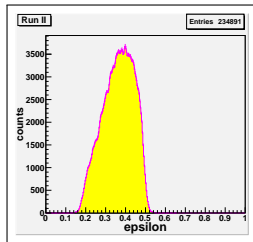
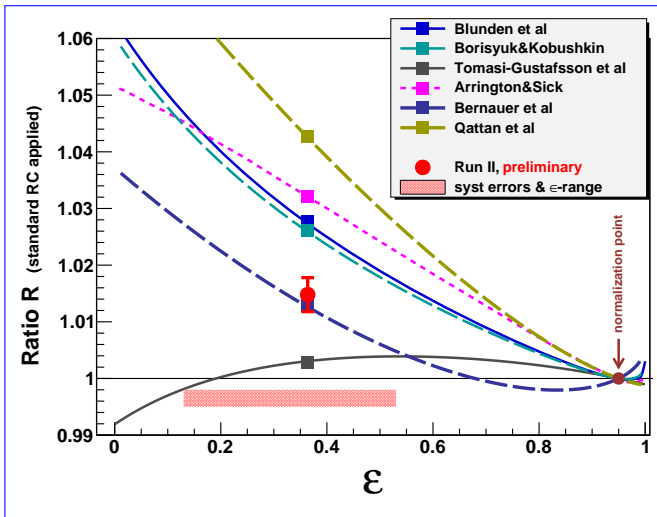


points on theoretical curves are **weighted means**, obtained with experimental *epsilon*-distribution.

Without normalization

Run II data versus theoretical predictions

Run-II data at large scattering angle in a single point:



points on theoretical curves are **weighted means**, obtained with experimental *epsilon*-distribution.

With normalization

Conclusion

- A precise measurement of the ratio $R = \sigma(e^+p)/\sigma(e^-p)$ has been performed. Data taking has been completed, analysis is in the final stage.
- Systematic errors in VEPP-3 experiment are expected to be lower than those at OLYMPUS and CLAS TPE experiments.
- It is very important to carefully consider the standard radiative corrections. Procedure of account for RC has been developed (ESEPP event generator + Geant4 detector simulation).
- Preliminary (nearly final) results have been presented. Comparison with several theoretical predictions has been made.

Support

This work was supported by the Ministry of Education and Science of the Russian Federation (project No. 14.B37.21.1181); by the Russian Foundation for Basic Research (grants 08-02-00624-a, 08-02-01155-a, and 12-02-33140); by US DOE grant DE-AC02-06CH11357; by US NSF grant PHY-03-54871.



Thank you for your attention!

How to apply radiative corrections to the ratio R

- There are two natural combinations of $\sigma(e^-p)$ and $\sigma(e^+p)$ to characterize quantitatively the difference between these cross sections, namely the cross section ratio

$$R = \frac{\sigma(e^+p)}{\sigma(e^-p)}$$

and cross section asymmetry

$$A = \frac{\sigma(e^-p) - \sigma(e^+p)}{\sigma(e^-p) + \sigma(e^+p)}.$$

For historical reasons, the ratio R is usually considered, although the asymmetry A is more convenient for analysis (because it contains only charge-odd terms in the numerator and only charge-even terms in the denominator).

- The ultimate goal of the TPE experiments is to measure the TPE contribution

$$\delta_{2\gamma} = \frac{2 \operatorname{Re}(\mathcal{M}_{\text{Born}}^\dagger \mathcal{M}_{2\gamma})}{|\mathcal{M}_{\text{Born}}|^2}.$$

- Measured and simulated asymmetries in the case of the first-order radiative corrections:

$$A_{\text{meas}} = \frac{N_{\text{meas}}^- - N_{\text{meas}}^+}{N_{\text{meas}}^- + N_{\text{meas}}^+} = \frac{2 \operatorname{Re}(\mathcal{M}_{\text{Born}}^\dagger \mathcal{M}_{2\gamma}) + 2 \operatorname{Re}(\mathcal{M}_{\text{brems}}^{\ell\dagger} \mathcal{M}_{\text{brems}}^p)}{|\mathcal{M}_{\text{Born}}|^2 + 2 \operatorname{Re}(\mathcal{M}_{\text{Born}}^\dagger \mathcal{M}_{\text{virt}}) + |\mathcal{M}_{\text{brems}}^\ell|^2 + |\mathcal{M}_{\text{brems}}^p|^2},$$
$$A_{\text{sim}} = \frac{N_{\text{sim}}^- - N_{\text{sim}}^+}{N_{\text{sim}}^- + N_{\text{sim}}^+} = \frac{2 \operatorname{Re}(\mathcal{M}_{\text{brems}}^{\ell\dagger} \mathcal{M}_{\text{brems}}^p)}{|\mathcal{M}_{\text{Born}}|^2 + 2 \operatorname{Re}(\mathcal{M}_{\text{Born}}^\dagger \mathcal{M}_{\text{virt}}) + |\mathcal{M}_{\text{brems}}^\ell|^2 + |\mathcal{M}_{\text{brems}}^p|^2}.$$

How to apply radiative corrections to the ratio R

- If we take the difference ($A_{\text{meas}} - A_{\text{sim}}$), then we will reduce in the numerator the interference term due to bremsstrahlung, while the denominator remains the same.
- Now it is easy to understand that the desired quantity $\delta_{2\gamma}$ can be expressed as

$$\delta_{2\gamma} = \left(\frac{N_{\text{meas}}^- - N_{\text{meas}}^+}{N_{\text{meas}}^- + N_{\text{meas}}^+} - \frac{N_{\text{sim}}^- - N_{\text{sim}}^+}{N_{\text{sim}}^- + N_{\text{sim}}^+} \right) \frac{N_{\text{sim}}^- + N_{\text{sim}}^+}{2N_{\text{sim}}^0},$$

where N_{sim}^0 is the number of events corresponding to the value $|\mathcal{M}_{\text{Born}}|^2$. This number can be obtained in a Monte Carlo simulation using the elastic events generated in accordance with the Rosenbluth formula. It is assumed that the numbers of generated events of the three different types correspond to the same value of integrated luminosity. Let us also note that the factor $(N_{\text{sim}}^- + N_{\text{sim}}^+)/2N_{\text{sim}}^0$ can be neglected in many practical cases.

- The cross section ratio $R_{2\gamma}$ after taking into account the standard radiative corrections can be expressed as

$$R_{2\gamma} = \frac{1 - \delta_{2\gamma}}{1 + \delta_{2\gamma}} = \frac{R_{\text{meas}}(N_{\text{sim}}^0 + N_{\text{sim}}^-) + N_{\text{sim}}^0 - N_{\text{sim}}^+}{R_{\text{meas}}(N_{\text{sim}}^0 - N_{\text{sim}}^-) + N_{\text{sim}}^0 + N_{\text{sim}}^+}.$$

- The remarkable fact is that $A_{2\gamma} \equiv \delta_{2\gamma}$ for our choice of notation, where $A_{2\gamma}$ is the cross section asymmetry due to the TPE effect only.