Measurement of the two-photon exchange contribution in elastic $e^{\pm}p$ scattering at the VEPP–3 storage ring

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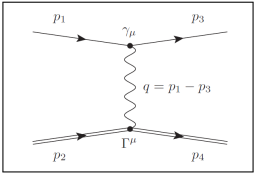
Workshop "Scattering and annihilation electromagnetic processes"

Proton electromagnetic form factors

The EM form factors are essential ingredients of our knowlegde 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
  $G_E(Q^2) = F_1(Q^2) - \frac{Q^2}{4M} F_2(Q^2)$
- 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

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

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

- Polarized beams and targets and recoil polarimeters

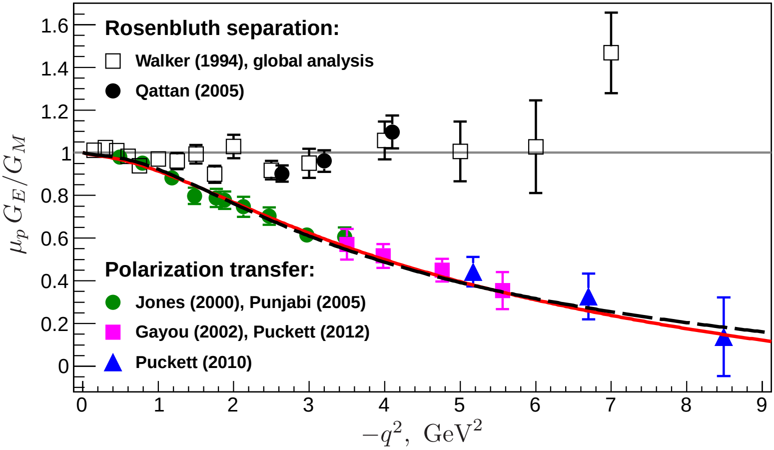
Form factor ratio from polarization transfer

Akhiezer & Rekalo, 1968

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

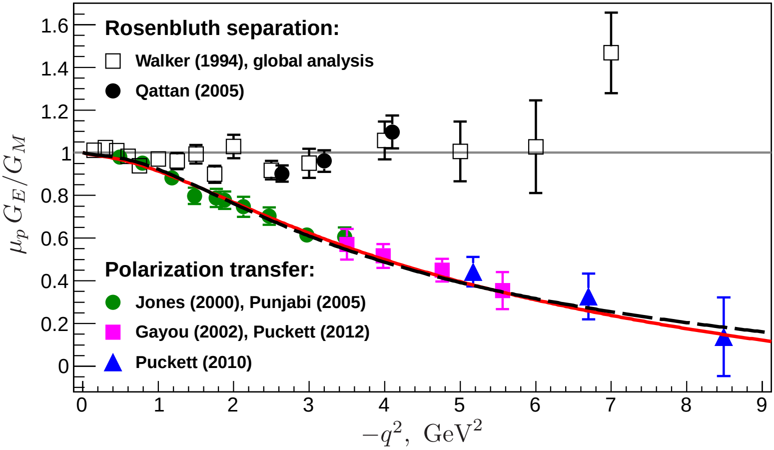
where P_T and P_L – transverse and longitudinal polarization components of proton,
$K = -\sqrt{\tau(1+\epsilon)/2\epsilon}$ – kinematic factor

Inconsistency?



Clear discrepancy between the two experimental data sets is observed.

Inconsistency?



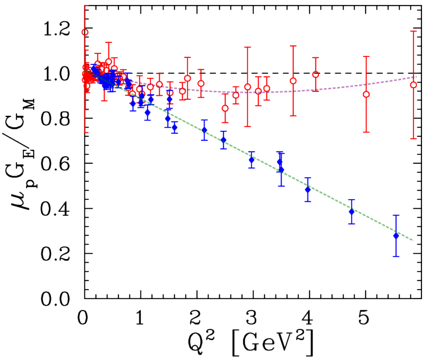
Clear discrepancy between the two experimental data sets is observed.

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

Example of calculation of the TPE contribution

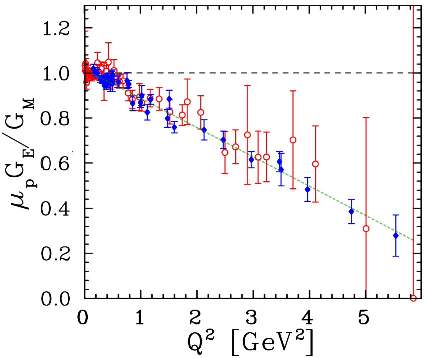
P. G. Blunden, W. Melnitchouk and J. A. Tjon, Phys. Rev. C 72 (2005) 034612

without TPE contribution



$\Rightarrow$

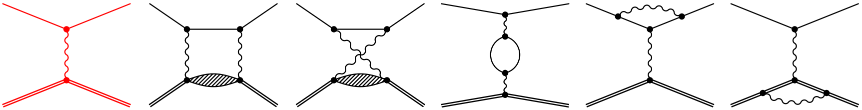
with TPE contribution



If this model is correct, the contradiction in the measurements of G_E^p/G_M^p will be eliminated!

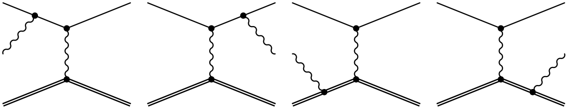
Radiative corrections to elastic ep scattering

"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 ($e^{\pm}p \to e^{\pm}p\,\gamma$):



$\mathcal{M}^{\ell}_{\text{brems}}$ $\mathcal{M}^{p}_{\text{brems}}$

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

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

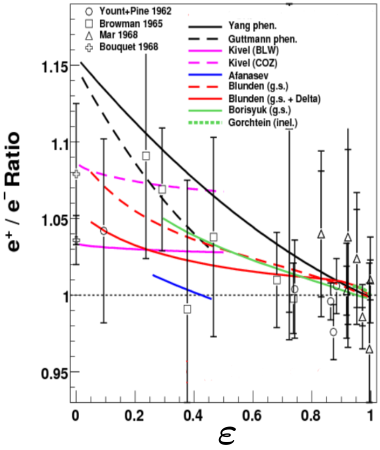
✓ Some of the terms are of different signs ("±") for $e^{+}p$ and $e^{-}p$ scattering

Direct measurement of TPE

Method of direct measurement of TPE :

Measure the ratio of positron-proton to electron-proton elastic scattering cross-section
$\Rightarrow$ interference term is extracted:

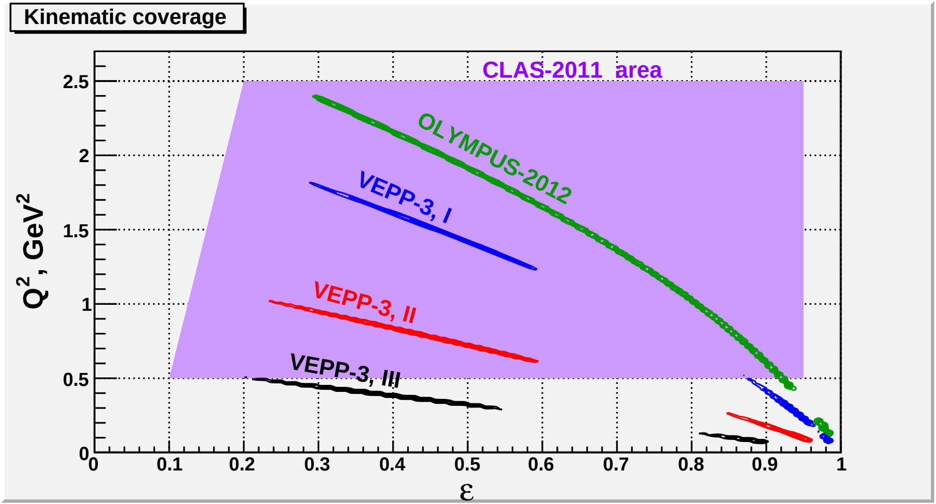
$$R = \frac{\sigma(e^+p)}{\sigma(e^-p)} \approx 1 + 4\frac{\mathcal{R}e\left(\mathcal{M}^{\dagger}_{\text{Born}}\mathcal{M}_{2\gamma}\right)}{|\mathcal{M}_{\text{Born}}|^2}$$



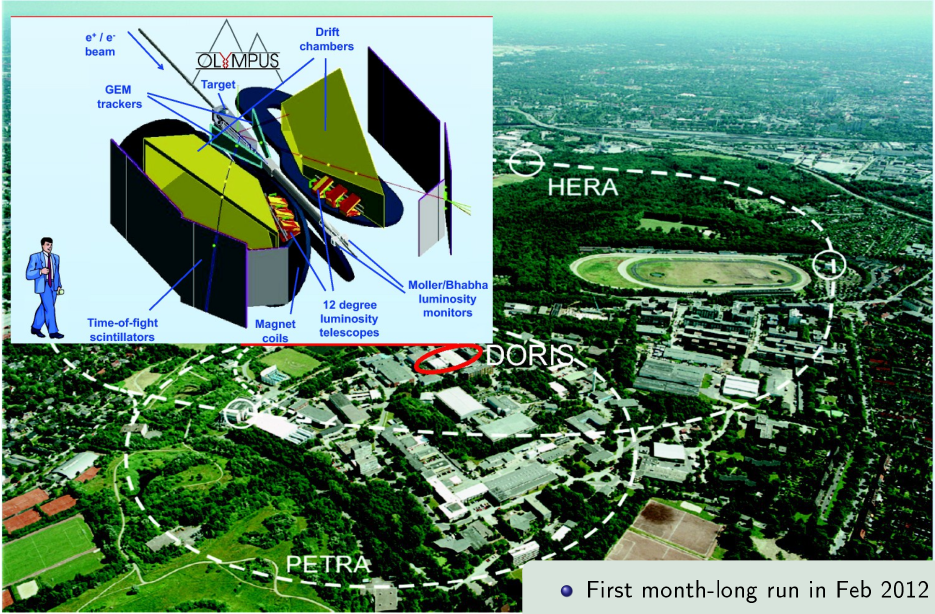
- Experimental data – from 1960-th
- Many theoretical/phenomenological approaches, producing clearly different results
- new precise data, especially for $\varepsilon \leq 0.5$ are required to verify the models

Three experiments aimed at measuring the ratio R

- Novosibirsk experiment ($E_{\text{beam}} = 1.6$, 1.0 and 0.6 GeV)
- CLAS @ JLab experiment ($E_{\text{beam}} = 0.5 \div 4$ GeV)
- OLYMPUS @ DESY experiment ($E_{\text{beam}} = 2$ GeV)

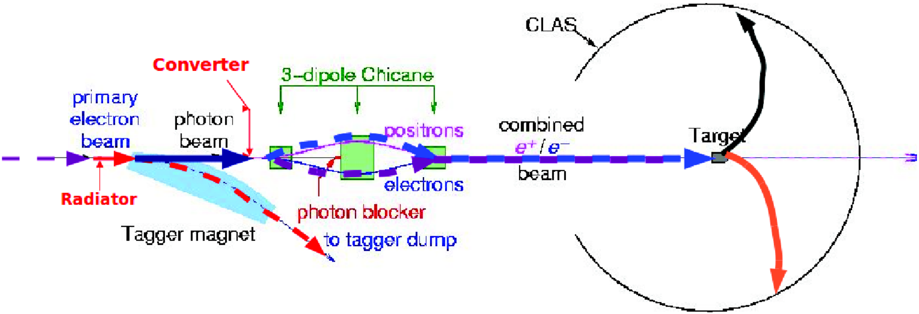


OLYMPUS experiment at DESY



- First month-long run in Feb 2012
- Another run: Oct – Dec 2012

TPE experiment at CLAS (JLab Hall B)



- Primary electron beam: 5.5 GeV and 100 nA
- Radiator: 0.9% of primary electrons radiate high energy photons
- Tagger magnet: Transport electrons tagger dump
- Converter: 9% of photons are converted to electron/positron pairs
- Chicane: separate the lepton beams
  – Remaining photons are stopped at the photon blocker
  – e^+ and e^- beams are then recombined and continue to the target
- Target: liquid hydrogen: length = 18cm (30 cm) & diameter = 6cm (6 cm)
- Detector: CLAS (DC, TOF)

- Data taking completed in Feb-2011
- Very preliminary results reported

Comparison of three TPE experiments

	VEPP-3 Novosibirsk	OLYMPUS DESY	EG5 CLAS JLab
Beam energy	3 fixed	1 fixed	wide spectrum
equality of $e^{\pm}$ beam energy	measured precisely	assumed (measured?)	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}
systematic error	$< 0.3\%$	1%	1%

- 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 lowest systematic error;
- Novosibirsk is the first to provide results on precise measurement of $R(e^{\pm}p)$ ratio.

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 data analysis are expected in 2013

Novosibirsk experiment at the VEPP–3 storage ring

A precision measurement of the ratio $R = \sigma(e^+p)/\sigma(e^-p)$ 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).

Kinematic parameters of three runs

Parameter	Run I			Run II		Run III	
	LA	MA	SA	LA	MA	LA	MA
E_{beam}, GeV	1.6			1.0		0.6	
$\int I_{\text{beam}} dt$, kC	54			100		3	
θ_ℓ, °	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%	—

The smallest angle regions were used for luminosity monitoring only.

VEPP–3 electron-positron storage ring

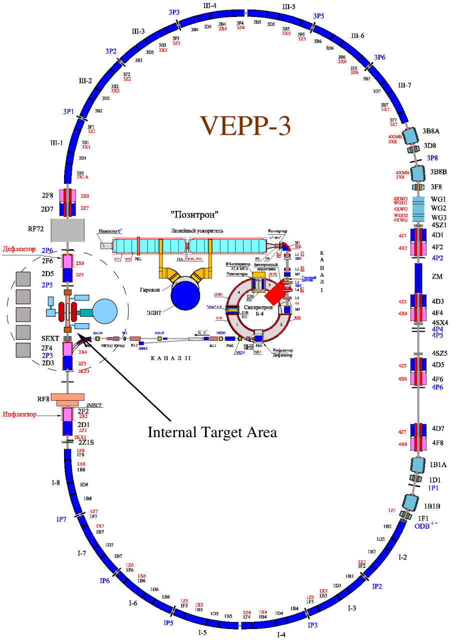
VEPP–3 is a booster for the VEPP–4M electron-positron collider.

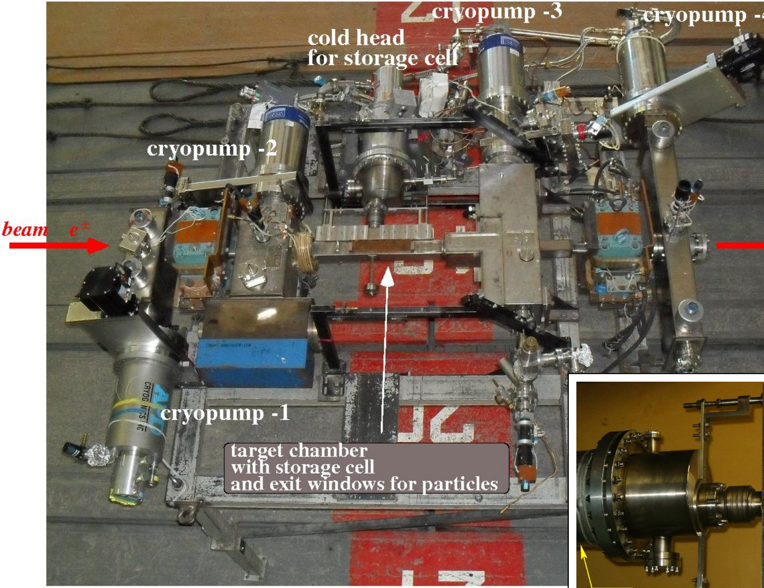
VEPP–3 parameters for e^- beam:

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	$\dot{I}_{inj}$	$1.5 \cdot 10^9$ s^{-1}

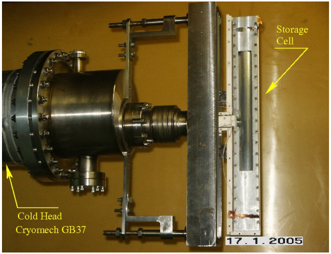
* ***parameters in the center of 2nd straight section (in Internal Target Area)***

Largest e^+ current: 60 mA

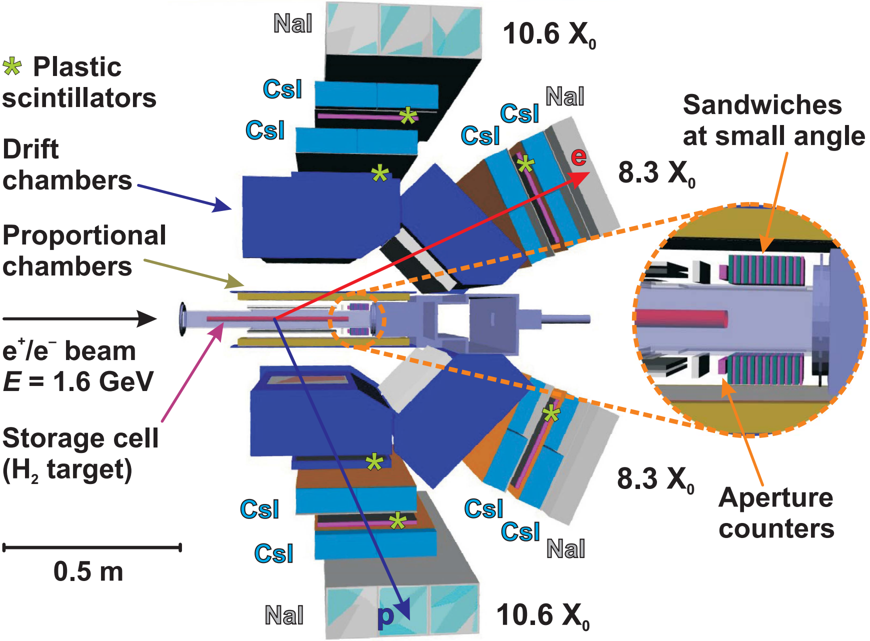




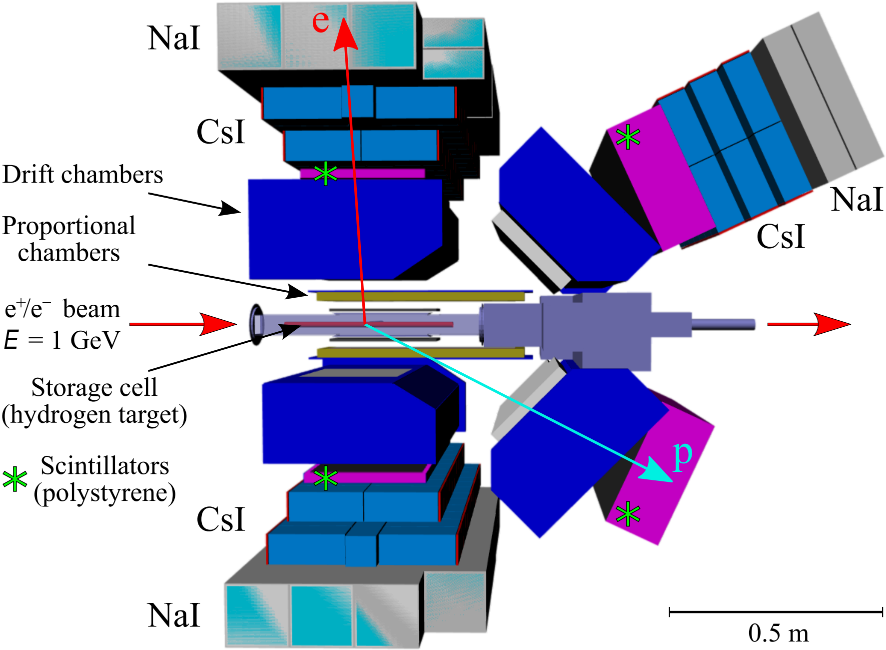
target thickness $= 1 \div 2 \cdot 10^{15}$ at/cm^2



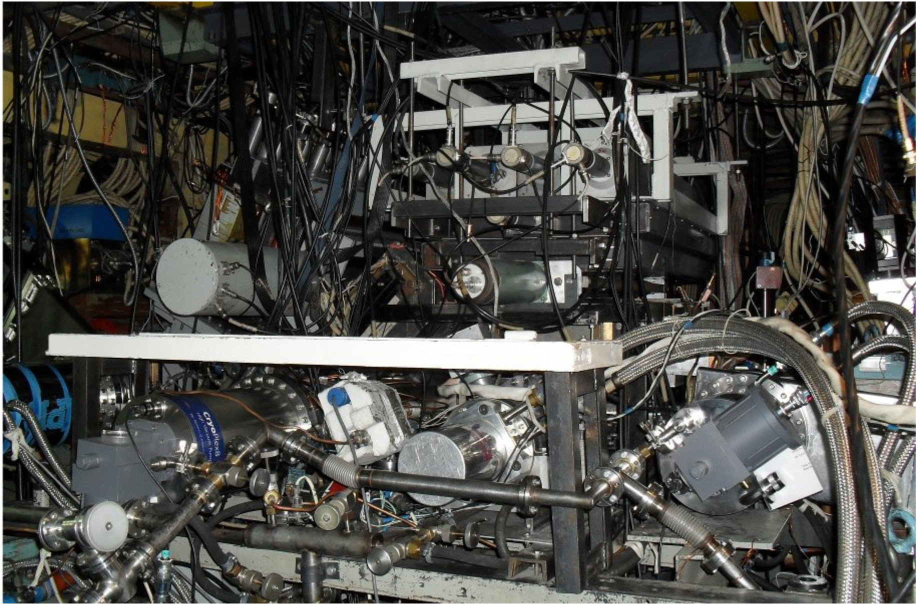
Detector package for the run I



Detector package for the runs II, III

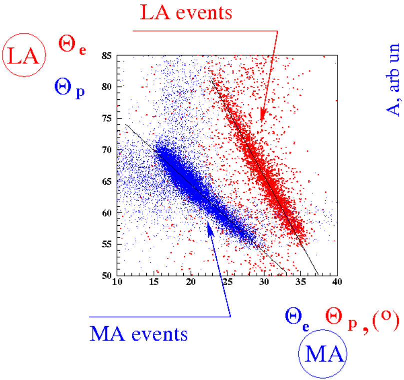


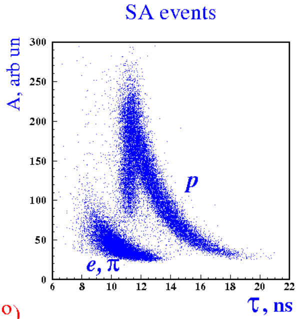
Detector and target at VEPP–3



Selection of the elastic scattering events

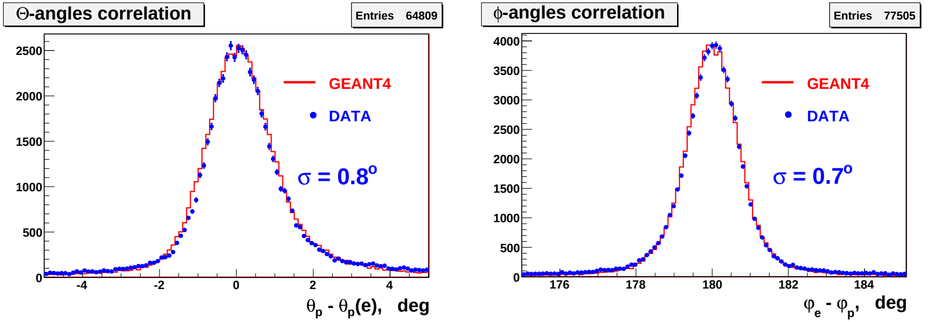
- Correlations characteristic for two-body final state:
  - Correlation between polar angles ($\theta_{e^\pm}$ vs. θ_p)
  - Correlation between azimuthal angles ($\phi_{e^\pm}$ vs. ϕ_p)
  - Correlation between lepton scattering angle and proton energy ($\theta_{e^\pm}$ vs. E_p)
  - Correlation between lepton scattering angle and electron energy ($\theta_{e^\pm}$ vs. $E_{e^\pm}$)
- Particle ID:
  - Time-Of-Flight analysis for low-energy protons
  - ΔE–E analysis for middle-energy protons
  - Energy deposition in EM-calorimeter for electrons/positrons





- Standard prescription with soft-photon/peaking approximation is not applicable. Detailed Monte Carlo simulation with a dedicated event generator is mandatory.
- The first-order bremsstrahlung: accurate QED calculation by V. S. Fadin, A. L. Feldman & R. E. Gerasimov instead of the simplified soft-photon one.
- New event generator ESEPP is applied to the Monte-Carlo detector simulation using the Geant4 software package.

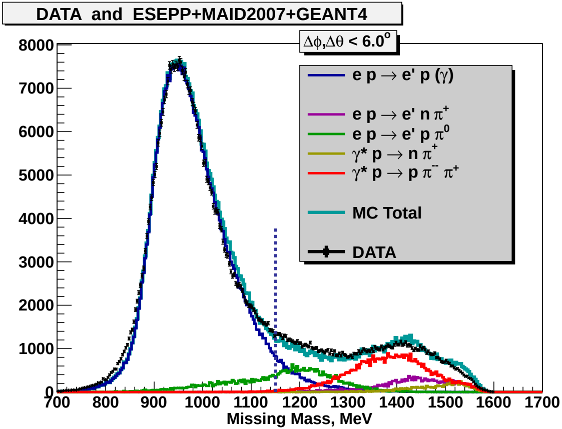
Angular correlations:

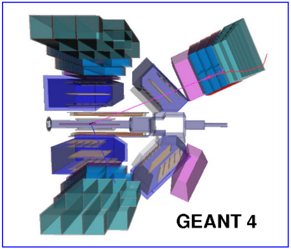


MC simulation of background processes

- **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

Spectrum of missed mass, reconstructed from energy and direction of electron (for $E_{e^\pm} = 1$ GeV), after cuts on $(\Delta\phi, \Delta\theta)$ applied:





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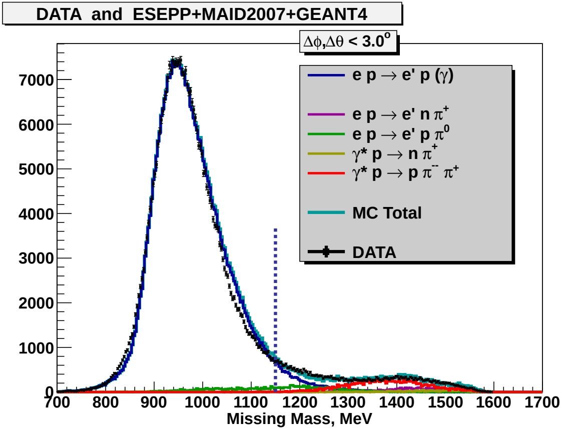
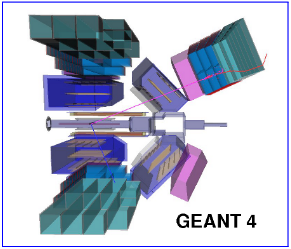


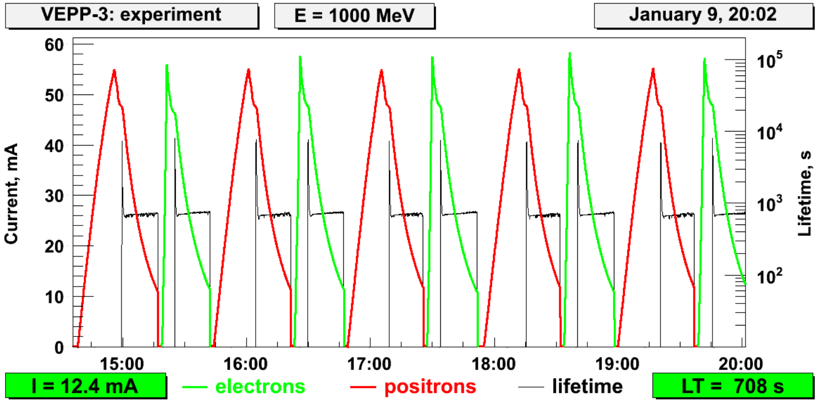


when all cuts applied:

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

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

- Data collection with e^- and e^+ beams was alternated regularly. This allows us to suppress 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.



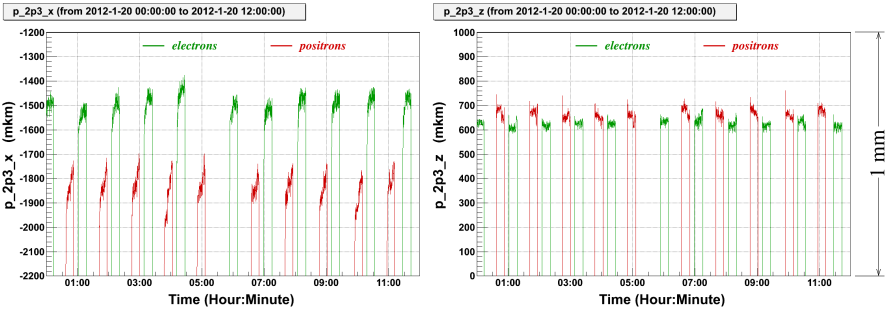
Contribution to the systematic error: $< 0.2\%$

Suppression of the systematics: beam position

- Using the VEPP–3 beam orbit 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.

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

horizontal vertical



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

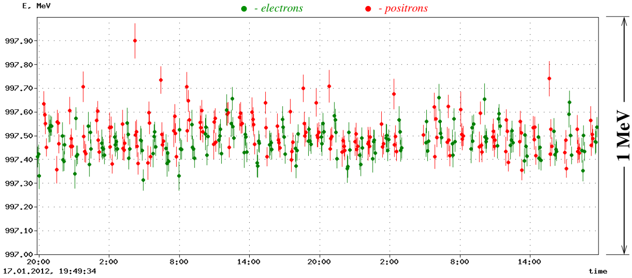
Suppression of the systematics: beam energy

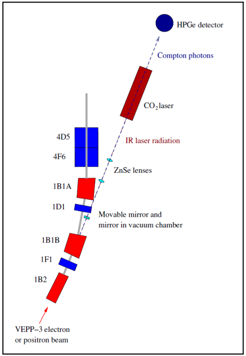
- Reconstruction of beam energy from the energy spectrum of laser photons backscattered on beam particles.

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

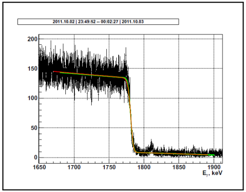
- This allows us to tune the VEPP–3 operation regimes and to monitor the beams energy during the experiment.

VEPP–3 energy measurement





photon spectrum



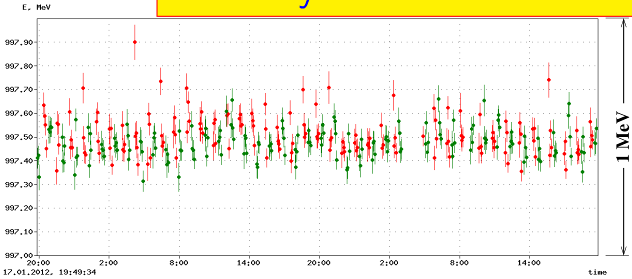
Contribution to the systematic error: $< 0.1\%$

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

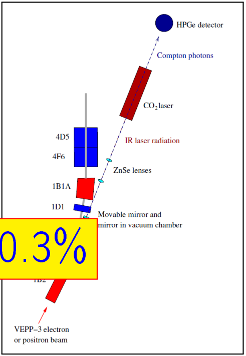
$$E_{\text{beam}} = 0.5 \cdot \omega_{max} \cdot \left(1 + \sqrt{1 + m_e^2/\omega_0\omega_{max}}\right)$$

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

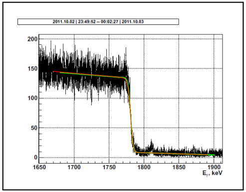
Total systematic error is $< 0.3\%$



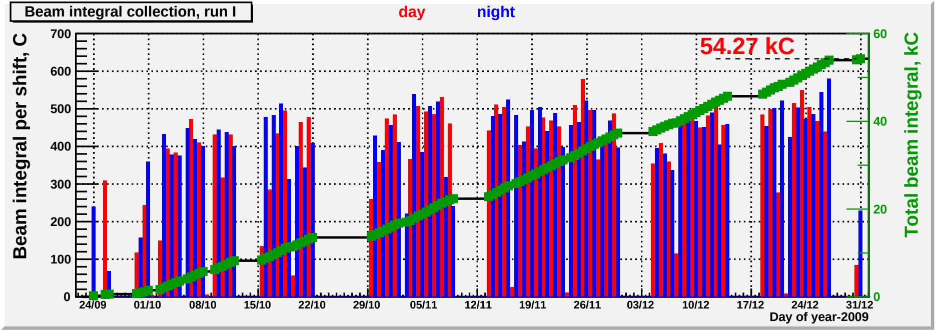
Contribution to the systematic error: $< 0.1\%$

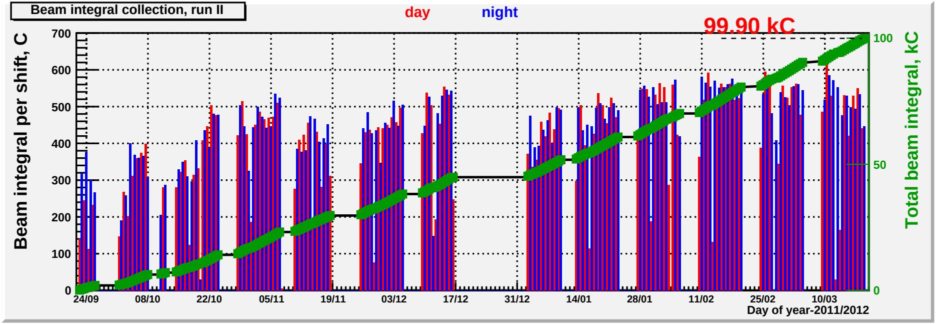


photon spectrum

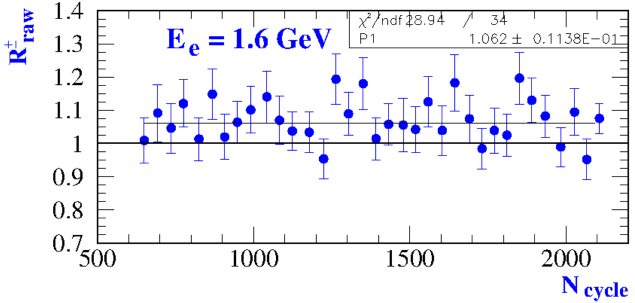


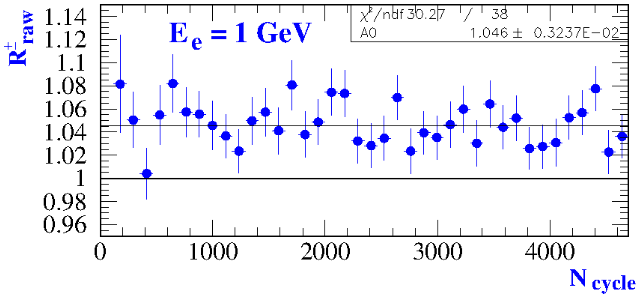
Beam integral collection during run I and run II





Raw ratio R during the run I and run II

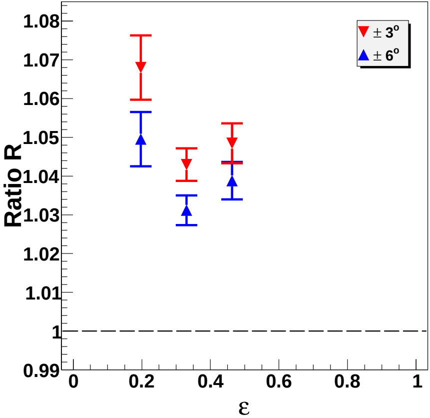




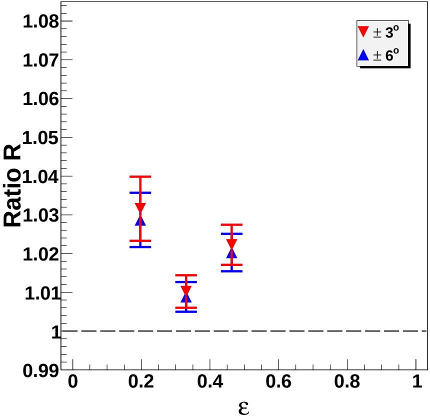
Ratio R as a function of kinematic cuts

RUN II

Raw data for the ratio R:



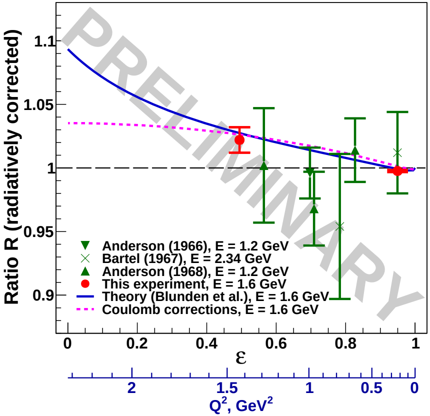
Radiatively corrected ratio R:



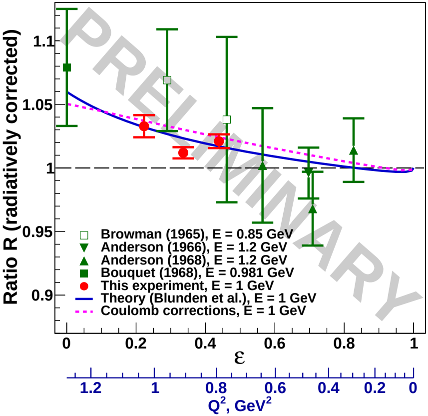
The experimentally measured ratio R before (left figure) and after (right figure) taking into account the radiative corrections (FF model). Red markers correspond to the cut $\Delta\theta = \Delta\phi = 3^\circ$ on the angular correlations, blue markers correspond to the cut $\Delta\theta = \Delta\phi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

Preliminary results of the Novosibirsk TPE experiment

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



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



Theory: *J. Arrington and I. Sick,* Phys. Rev. **C70** (2004) 028203
P. G. Blunden, et al., Phys. Rev. **C72** (2005) 034612

- *Only statistical errors are shown.*
- *The radiative corrections are taken into account.*
- *Some minor corrections have not yet been made.*

Conclusion

- The first precision measurement of the ratio $R = \sigma(e^+p)/\sigma(e^-p)$ has been performed. Data taking has been completed, analysis is in progress.
- Systematic errors in VEPP-3 experiment is 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 results are presented. They are pretty consistent with the theoretical predictions by Blunden et al.
- Final results of the experiment will be published this year.

Support

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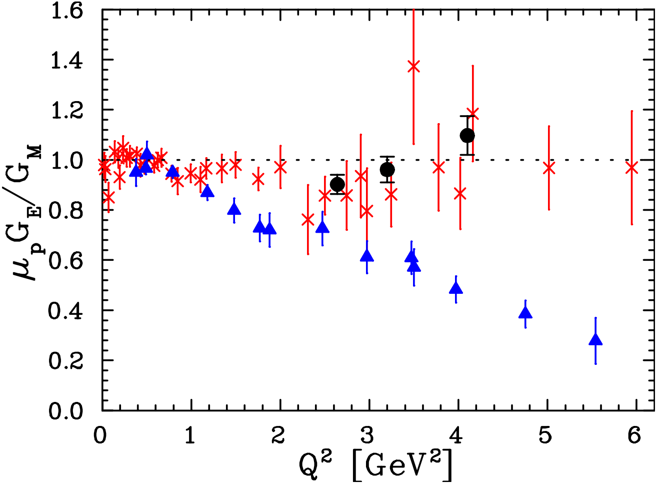
Thank you for your attention!

Backup slides

I. A. Qattan et al., Phys. Rev. Lett. **94** (2005) 142301

Uses modified Rosenbluth separation technique, detecting proton: *black points*



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

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

How are they related?

$$A = \frac{R-1}{R+1} \approx \frac{R-1}{2}$$

$$R = \frac{1+A}{1-A} \approx 1 + 2A$$

After taking into account the radiative corrections:

$$A \approx 2\frac{\mathcal{R}\mathrm{e}\left(\mathcal{M}^{\dagger}_{\mathrm{Born}}\mathcal{M}_{2\gamma}\right)}{|\mathcal{M}_{\mathrm{Born}}|^2}$$

$$R \approx 1 + 4\frac{\mathcal{R}\mathrm{e}\left(\mathcal{M}^{\dagger}_{\mathrm{Born}}\mathcal{M}_{2\gamma}\right)}{|\mathcal{M}_{\mathrm{Born}}|^2}$$

How to take into account the radiative corrections?

$$A = A_{\mathrm{exp}} - A_{\mathrm{MC}}$$

(exp = experimental,

MC = Monte Carlo)

$$R = \frac{R_{\mathrm{exp}}R_{\mathrm{MC}} + 3R_{\mathrm{exp}} - R_{\mathrm{MC}} + 1}{R_{\mathrm{exp}}R_{\mathrm{MC}} - R_{\mathrm{exp}} + 3R_{\mathrm{MC}} + 1}$$

$$R \approx R_{\mathrm{exp}} - R_{\mathrm{MC}} + 1$$

The asymmetry is more natural, but the ratio is used more often.