Two photon exchange contribution in elastic e-p/e+p scattering.
Status of the Novosibirsk experiment.

Dmitri Toporkov
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Novosibirsk, Russia

Ferrara University,
26 August, 2008

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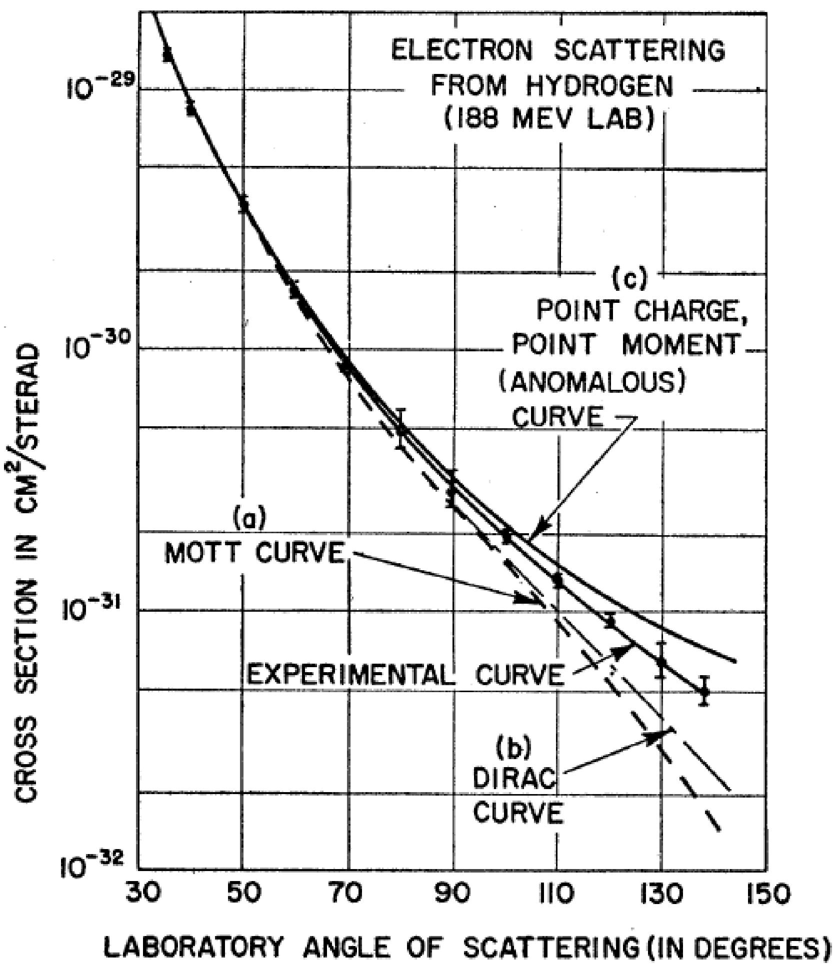
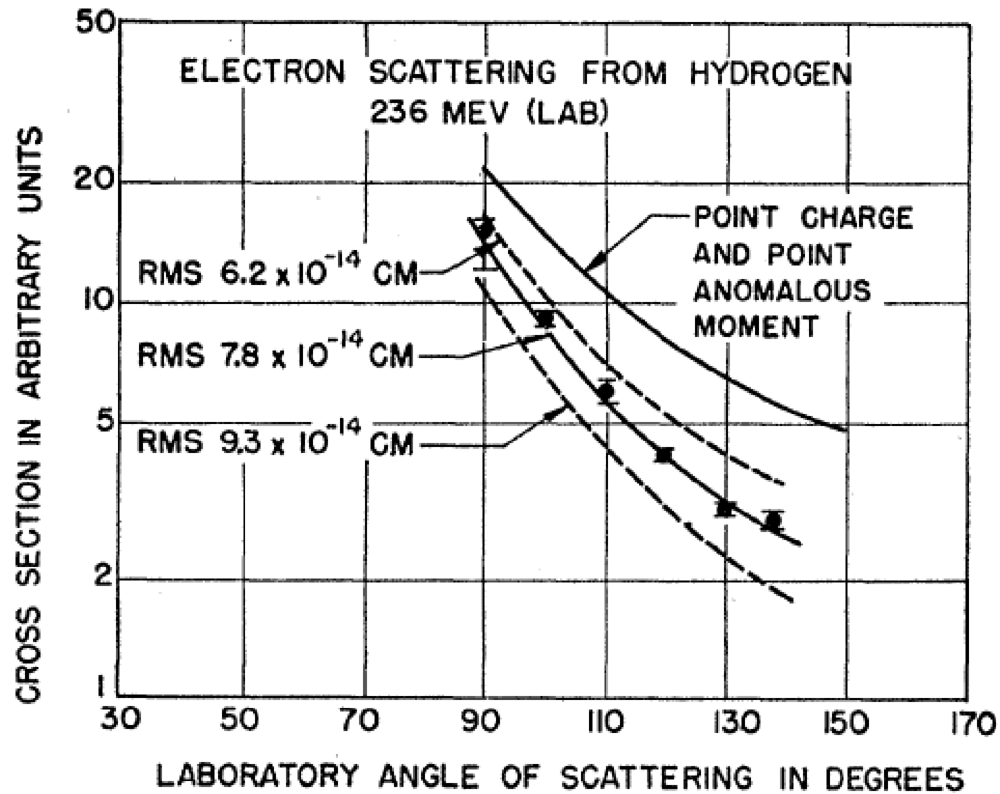
PHYSICAL REVIEW VOLUME 102, NUMBER 3 MAY 1, 1956

Elastic Scattering of 188-Mev Electrons from the Proton and the Alpha Particle*†‡§‖¶

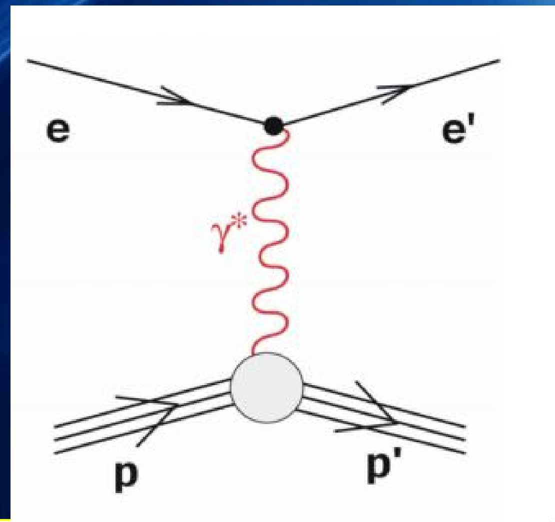
R. W. McAllister and R. Hofstadter
Department of Physics and High-Energy Physics Laboratory, Stanford University, Stanford, California
(Received January 25, 1956)





for his pioneering studies of electron scattering in atomic nuclei and for his thereby achieved discoveries concerning the structure of the nucleons. 1961.

Elastic e-p scattering



Dirac (non-spin-flip) F_1 and Pauli (spin-flip) F_2 Form Factors

$$\frac{d\sigma}{d\Omega}(E,\theta) = \frac{\alpha^2 E' \cos^2(\frac{\theta}{2})}{4E^3 \sin^4(\frac{\theta}{2})}\left[(F_1^2 + \kappa^2 \tau F_2^2) + 2\tau (F_1 + \kappa F_2)^2 \tan^2(\frac{\theta}{2})\right]$$

Rosenbluth separation of the form factors

Alternatively, Form Factors G_E and G_M can be used

$$F_1 = G_E + \tau G_M \qquad F_2 = \frac{G_M - G_E}{\kappa(1+\tau)} \qquad \tau = \frac{Q^2}{4M^2}$$

$$\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M \left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2\left(\frac{\theta}{2}\right)\right]$$

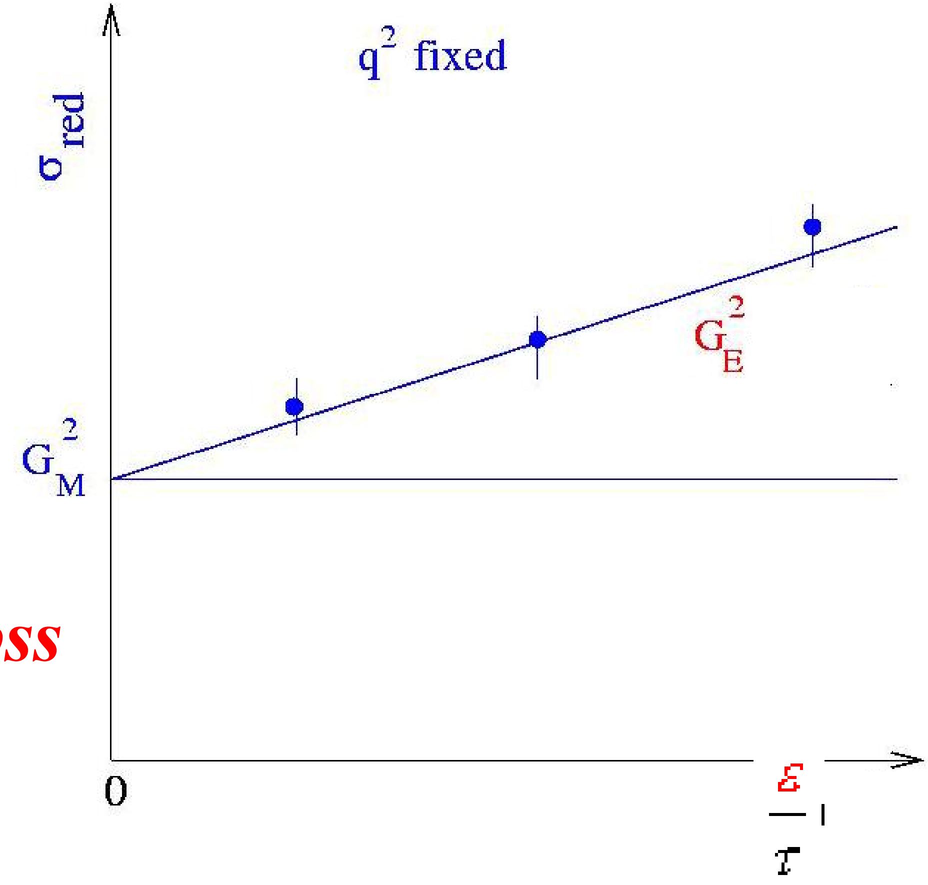
$$\sigma_R(Q^2,\varepsilon) = \varepsilon\left(1+\frac{1}{\tau}\right)\frac{E}{E'}\frac{\sigma(E,\theta)}{\sigma_{Mott}} = (G_M^p)^2(Q^2) + \frac{\varepsilon}{\tau}(G_E^p)^2(Q^2)$$

$$Q^2 = 4EE'\sin^2\left(\frac{\epsilon}{2}\right) \qquad \varepsilon = \frac{1}{1+2(1+\tau)\tan^2(\theta/2)}$$

Rosenbluth separation of the form factors

Alternatively, Form Factors G_E and G_M can be used

$$\sigma_{red} = \frac{\frac{d\sigma}{d\Omega_e}}{\frac{\alpha^2}{-q^2}\left(\frac{\epsilon_2}{\epsilon_1}\right)^2}$$



Linearity of the ***reduced cross section!***

Rosenbluth separation of the form factors

$$\sigma_R\left(Q^2,\varepsilon\right)=\varepsilon\left(1+\frac{1}{\tau}\right)\frac{E}{E'}\frac{\sigma(E,\theta)}{\sigma_{Mott}}=(G_M^p)^2\left(Q^2\right)+\frac{\varepsilon}{\tau}(G_E^p)^2\left(Q^2\right)$$

Due to the weighting $\frac{\varepsilon}{\tau}$ the contribution of G_E decreases as $1/Q^2$ and isolating the contribution of G_E becomes increasingly difficult as momentum increases.

Because of ε is correlated with beam energy, scattering angle and scattered electron energy for a fixed value of Q^2 and because Mott cross section varies rapidly with angle at fixed Q^2 there are several potential sources of ε dependent errors which might effect the extracted form factors.

Rosenbluth separation of the form factors

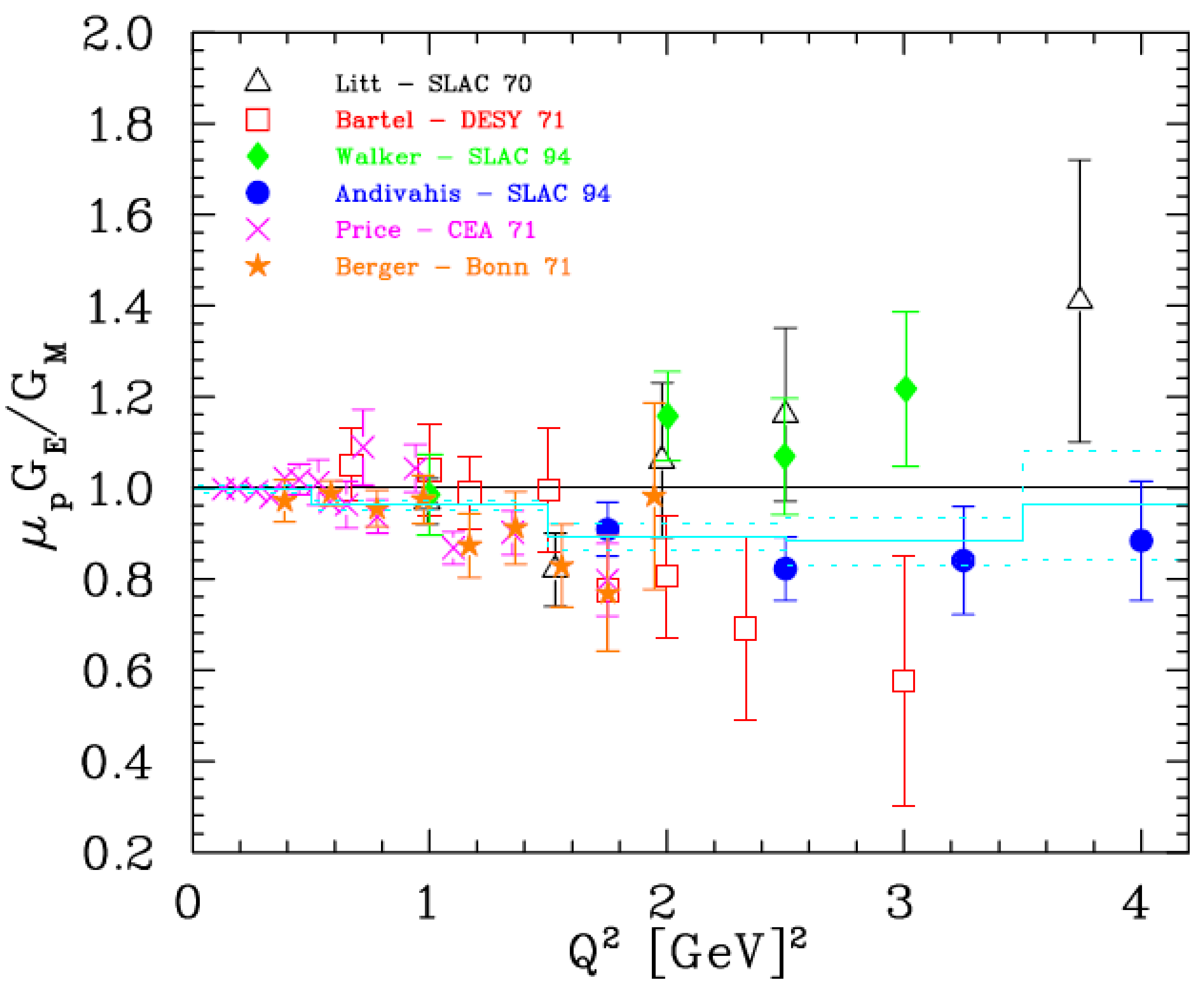
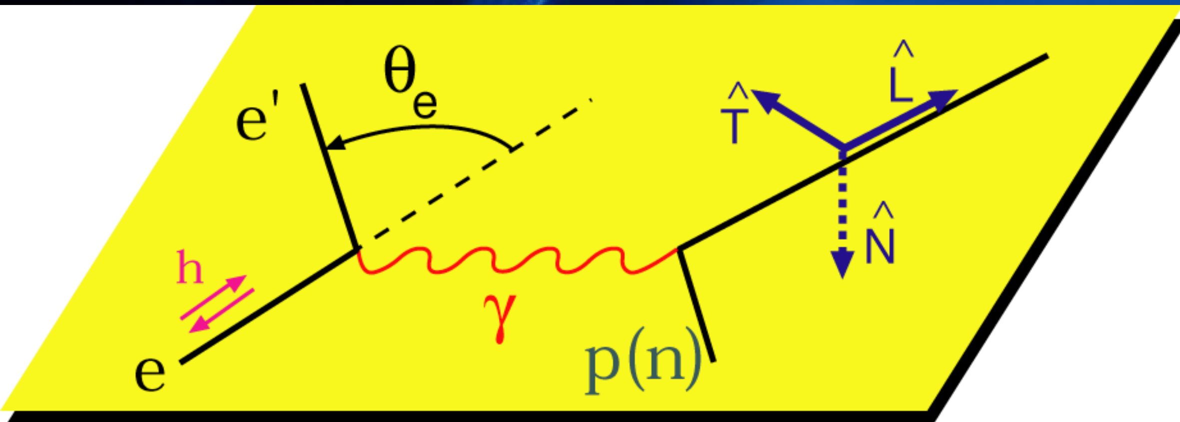


Fig. 2. $\mu_p G_E/G_M$ from individual Rosenbluth extractions.

Form factors measurements through polarization transfer experiments



A.I.Akhiezer et al., JETP v.33(1957)765, in Russian

Transferred polarization is:

(Akhiezer & Rekalo and Arnold, Carlson & Gross):

$$P_n = 0$$

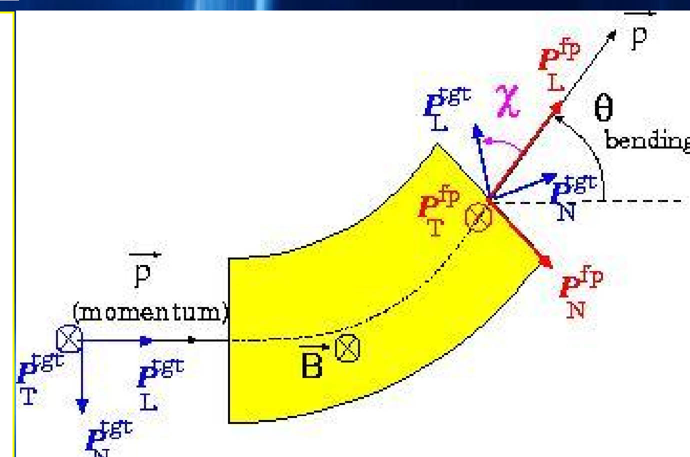
$$\pm h P_t = \mp h\, 2\sqrt{\tau(1+\tau)} G_E^p G_M^p \tan\left(\frac{\theta_e}{2}\right) / I_0$$

$$\pm h P_l = \pm h (E_e + E_{e'}) (G_M^p)^2 \sqrt{\tau(1+\tau)} \tan^2\left(\frac{\theta_e}{2}\right) / M / I_0$$

Where, $h = |h|$ is the beam helicity

$$I_0 = (G_E^p(Q^2))^2 + \frac{\tau}{\epsilon}(G_M^p(Q^2))^2$$

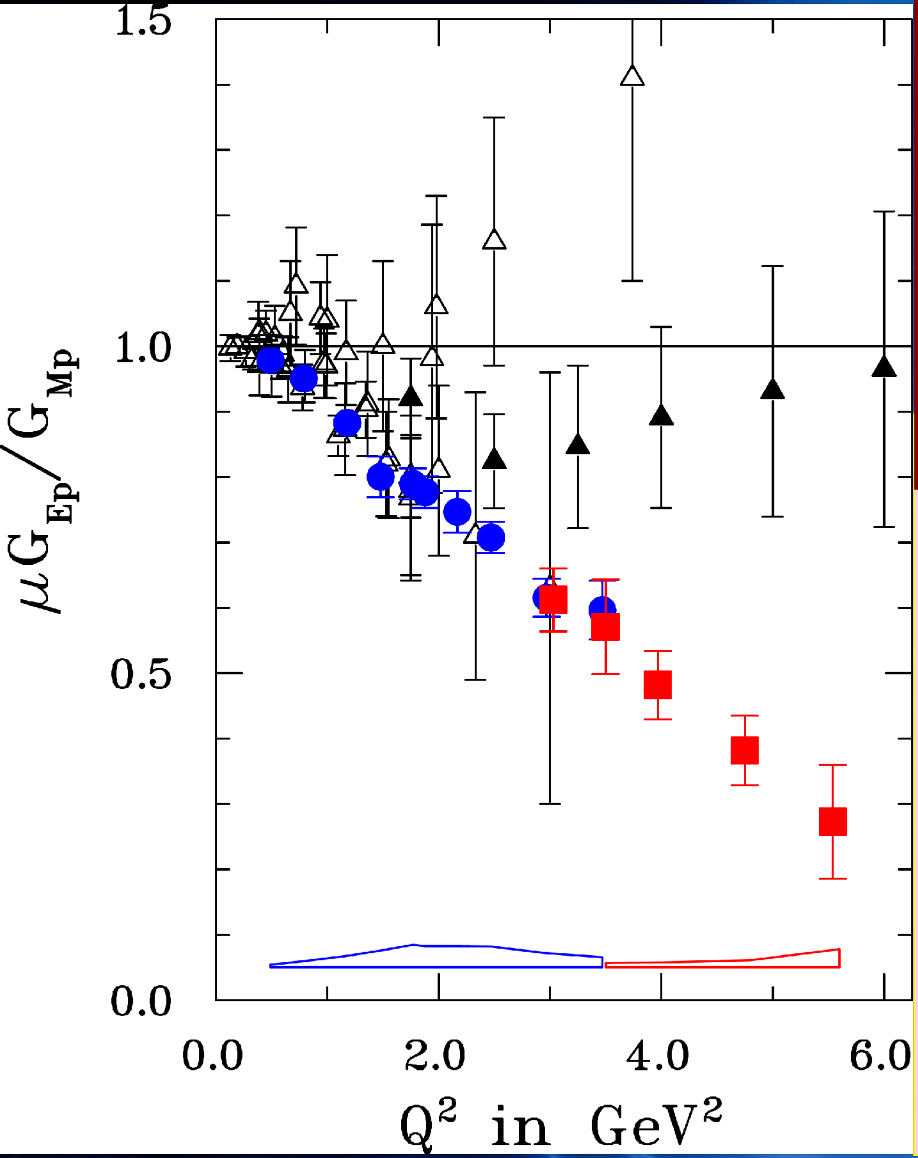
$$\Longrightarrow \frac{G_E^p}{G_M^p} = -\frac{P_t}{P_l}\frac{E_e + E_{e'}}{2M}\tan\left(\frac{\theta_e}{2}\right)$$



Advantages of form factors ratio measurements through polarization transfer experiments

- The ratio of the transverse to longitudinal component of the proton polarization is directly related to G_E/G_M.
- While this method is clearly superior at large Q^2 values, measuring a ratio of two polarization components means that uncertainties in the cross section, beam polarization and detector analyzing power all cancer out, significantly reducing the dominant sources of systematic uncertainty.
- The discrepancy between the Rosenbluth and recoil polarization measurements occur at Q^2 as low as ~ 1 GeV^2 where both techniques give precise measurement

Data and possible explanations for different results for values G_E/G_M



- E93-027 PRL 84, 1398 (2000)
  Used both HRS in Hall A with FPP
- E99-007 PRL 88, 092301 (2002)
  used Pb-glass calorimeter for electron detection to match proton HRS acceptance
- Reanalysis of E93-027 (Pentchev)
  Using corrected HRS properties

2. Rosenbluth experiments are wrong

2. The polarization transfer experiments are wrong (independent experiments are required)

8. There are some physical reasons why these two methods would give different results

(e.g. two photons exchange contributions,..)

Data and possible explanations for different results for values G_E/G_M

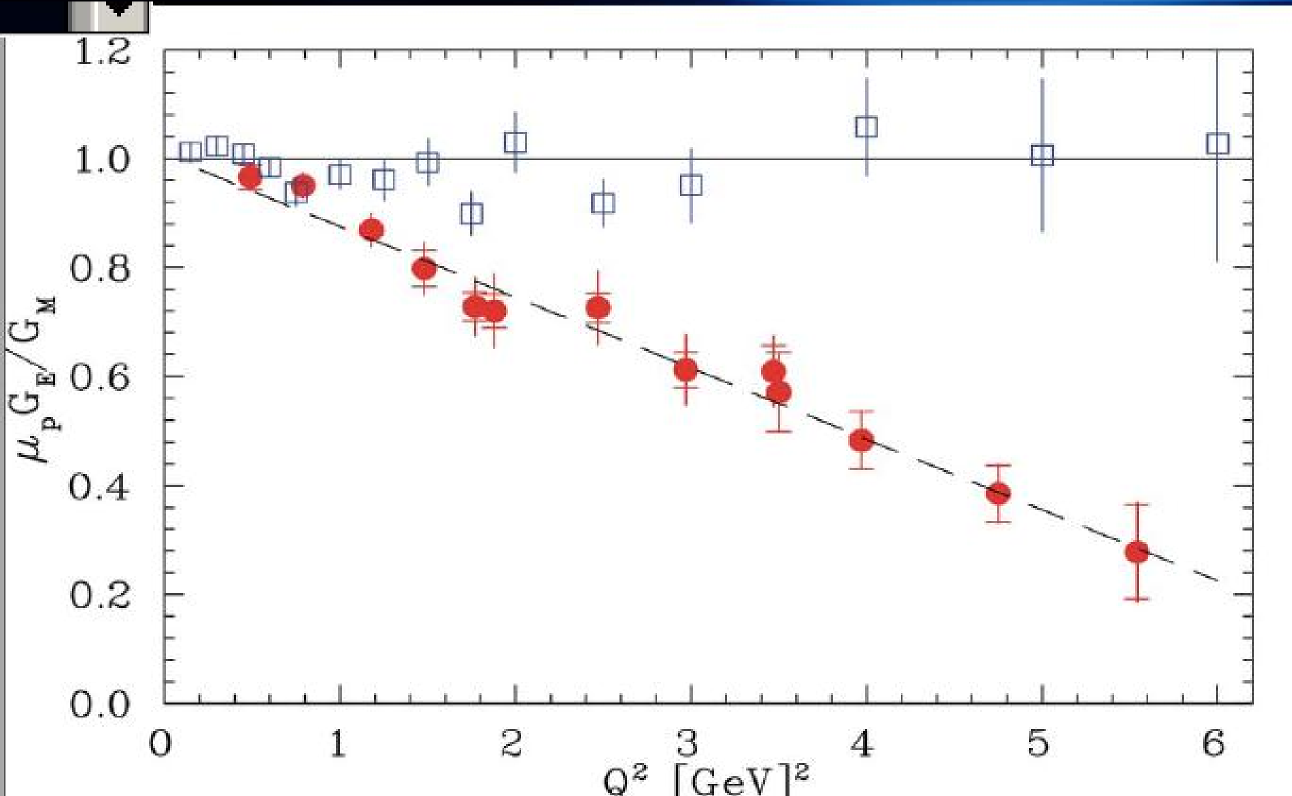


Figure: comparison of form factors ratio, obtained by Rosenbluth technique (hollow squares) with data of polarized measurements (full circles).

J.Arrington et al., Phys. Rev. C68 (2003); arXiv:nucl-ex/0305009

At present there are two physical reasons why these two methods would give different results:

- **radiative corrections;**
- **two photons exchange contributions.**

Yu.M.Bystritskiy et al., arXiv:hep-ph/0603132:"the results of numerical estimations show that the present calculation of radiative corrections can bring into agreement the conflicting experimental results on proton form factors and that the two photon contribution is very small".
The another group of theorists said that it's not a correct to use the one photon approximation in Rosenbluth technique and contribution of two photon exchange is considerable. (J.Arrington, Phys. Rev. C69(2004)032201;P.G.Blundend et al., Phys.Rev.Lett. 91(2003)142304;Y.Chen, arXiv:hep-ph/0403058)

Jefferson Lab Experiment E01-001

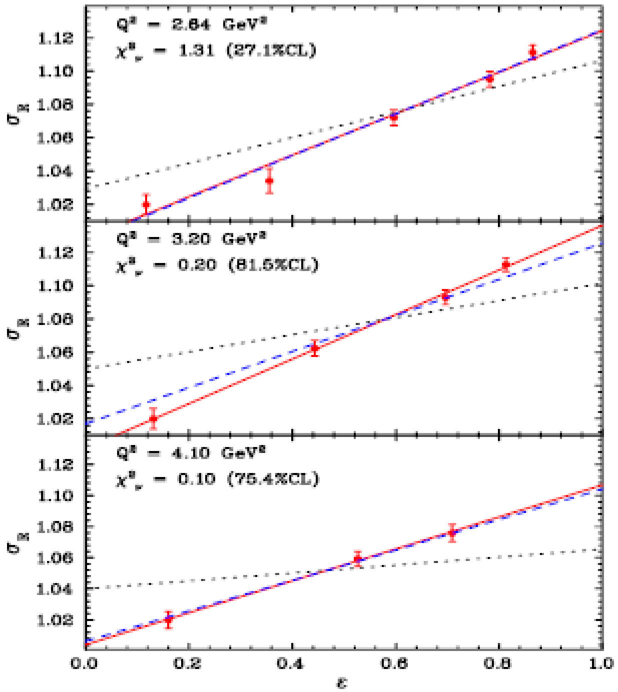


Figure 1:

The reduced cross section plotted as a function of ε. The solid line is the best linear fit to the data. The black dotted line indicates the expected slope as determined from polarization transfer experiments [2], while the blue dashed line is the best slope based of the global analysis of previous Rosenbluth measurements [5]. The new results confirm previous Rosenbluth extractions (within the uncertainties on the global analysis), and disagree with the polarization transfer results.

Data and possible explanations for different results for values G_E/G_M

$$e^{\pm} + p \rightarrow e^{\pm} + p$$

4 spin ½ fermions → 16 amplitudes in the general case.

- T-invariance of EM interaction,
- identity of initial and final states,
- helicity conservation,
- unitarity

1γ exchange	2γ exchange
• **Two EM form factors**	• **Three structure functions**
• **Real**	• **Complexe**
• **Functions of one variable *(t)***	• **Functions of TWO variables *(s,t)***
• **Describe e^+ and e^- scattering**	• **Different for e^+ and e^- scattering**

Data and possible explanations for different results for values G_E/G_M

Phenomenological analysis of two photon exchange effects in proton form factor measurements. D.Borisyuk and A.Kobushkin. ArcXiv:hep-ph/0703220v2

$$M = \frac{4\pi\alpha}{Q^2}\bar{u}'\gamma_\mu u \bar{U}'\left(\tilde{F}_1\gamma^\mu - \tilde{F}_2[\gamma^\mu,\gamma^\nu]\frac{q_\nu}{4M} + \tilde{F}_3 K_\nu \gamma^\nu \frac{P^\mu}{M^2}\right)U$$

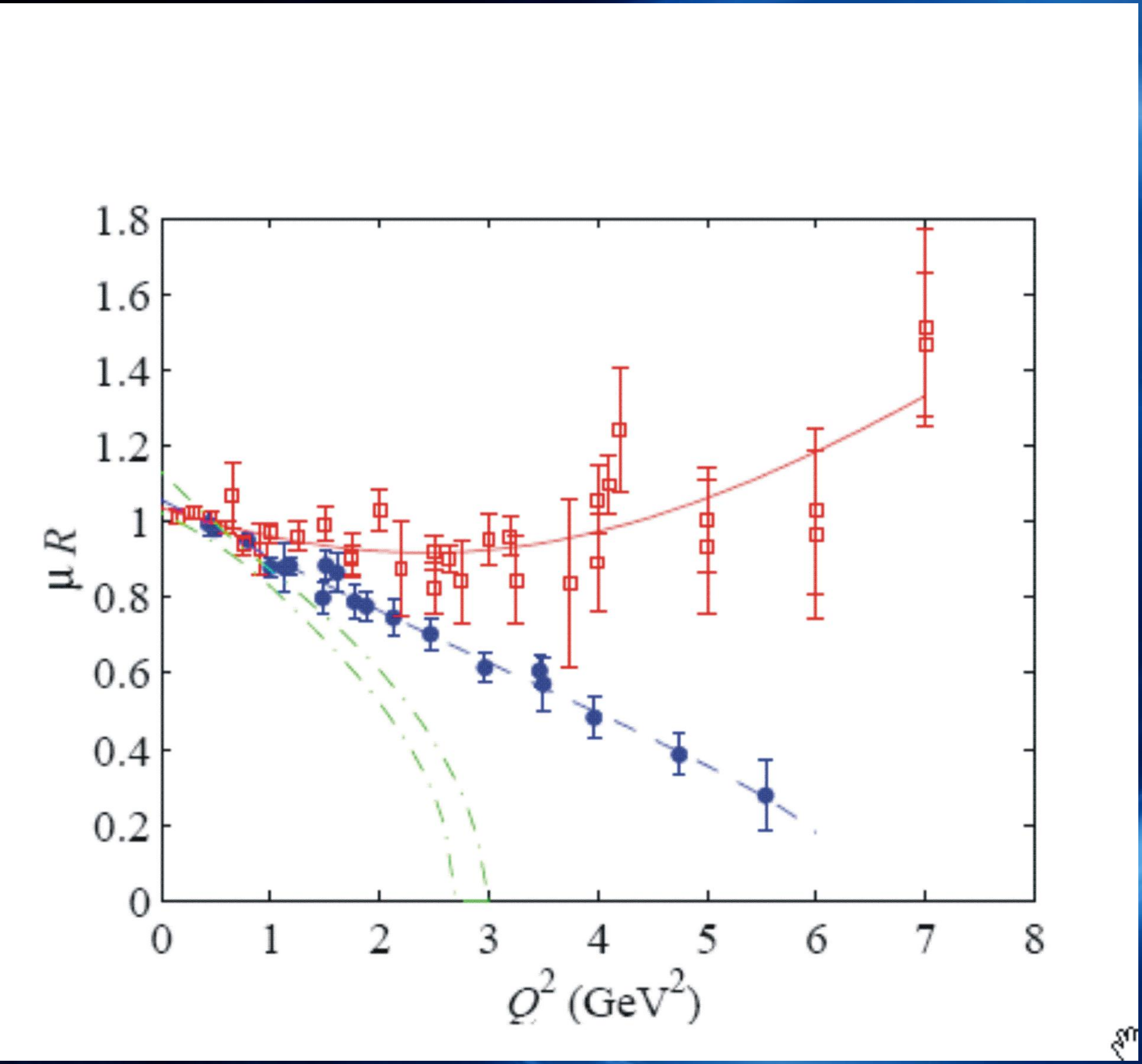
$$\left(\frac{G_E}{G_M}\right)^2_{LT} = \frac{G_E^2}{G_M^2} + 2\tau b$$

$$\left(\frac{G_E}{G_M}\right)_{PT} = \frac{\tilde{G}_E}{\tilde{G}_M}\left(1 - \frac{\varepsilon(1-\varepsilon)}{1+\varepsilon}\frac{\nu}{4M^2}\frac{\tilde{F}_3}{G_M}\right) + O(\alpha^2)$$

$$\left(\frac{G_E}{G_M}\right)_{PT} = \frac{G_E}{G_M}$$

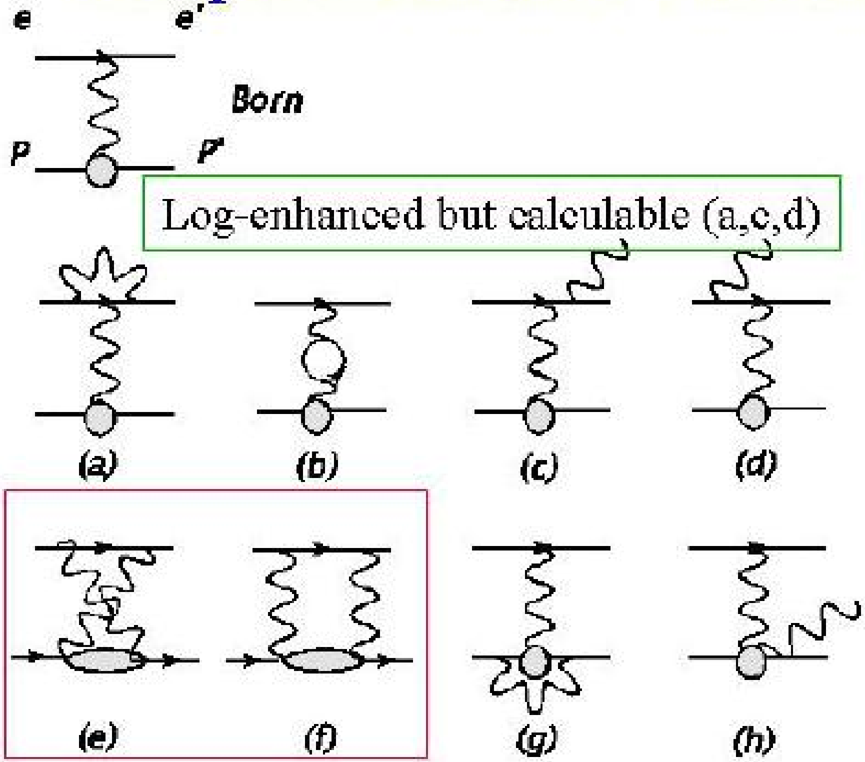
LT-longitudinal/transverse separation
PT-polarization transfer

Data and possible explanations for different results for values G_E/G_M



Phenomenological analysis of two photon exchange effects in proton form factor measurements. D.Borisyuk and A.Kobushkin ArcXiv:hep-ph/0703220v2

Complete radiative correction in $O(\alpha_{em})$



Radiative Corrections:

- Electron vertex correction (a)
- Vacuum polarization (b)
- Electron bremsstrahlung (c,d)
- Two-photon exchange (e,f)
- Proton vertex and VCS (g,h)
- Corrections (e-h) depend on the nucleon structure

•Meister&Yennie; Mo&Tsai

•Further work by Bardin&Shumeiko; Maximon&Tjon; AA, Akushevich, Merenkov;

•Guichon&Vanderhaeghen'03:
Can (e-f) account for the Rosenbluth vs. polarization experimental discrepancy? Look for ~3% ...

Main issue: Corrections dependent on nucleon structure

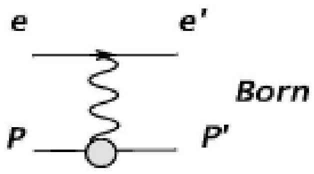
Model calculations:

•Blunden, Melnitchouk,Tjon, Phys.Rev.Lett.**91**:142304,2003

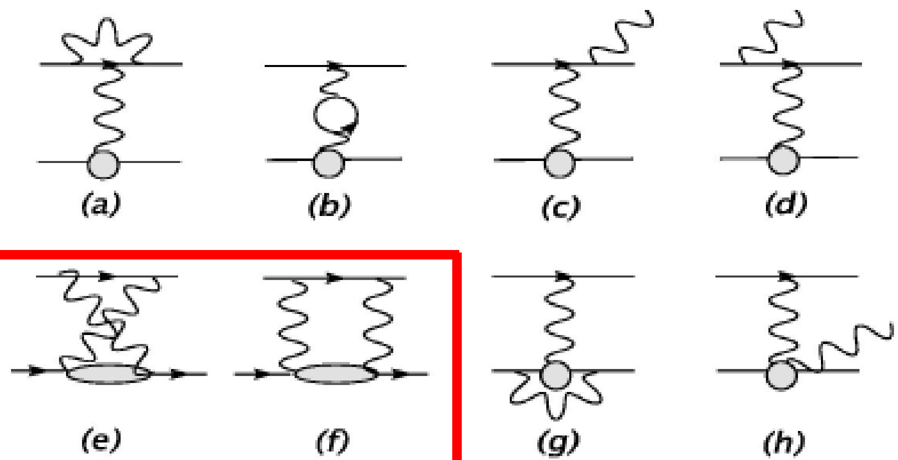
•Chen, AA, Brodsky, Carlson, Vanderhaeghen, Phys.Rev.Lett.**93**:122301,2004

Andrei Afanasev, Exclusive Reactions at High Momentum Transfer, 5/23/07

How to measure TPE



$A_{Born} \sim e^{\pm} = \pm 1$



$A_{2\gamma} \sim (e^{\pm})^2 = +1$

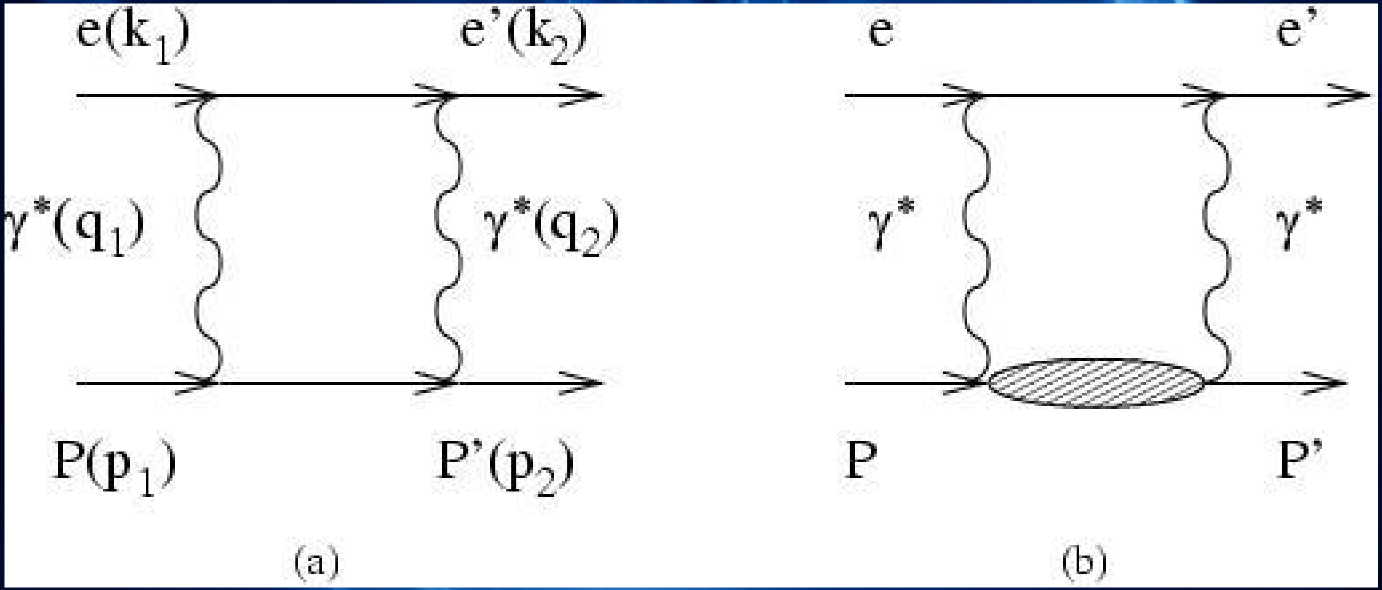
$$\sigma(e^{\pm}) \propto |A_{Born} + A_{2\gamma} + \ldots|^2$$
$$\sigma(e^{\pm}) \propto |A_{Born}|^2 \pm 2A_{Born} Re(A_{2\gamma})$$

$$R = \frac{\sigma(e^+)}{\sigma(e^-)} \approx 1 - \frac{4Re(A_{2\gamma})}{A_{Born}}$$

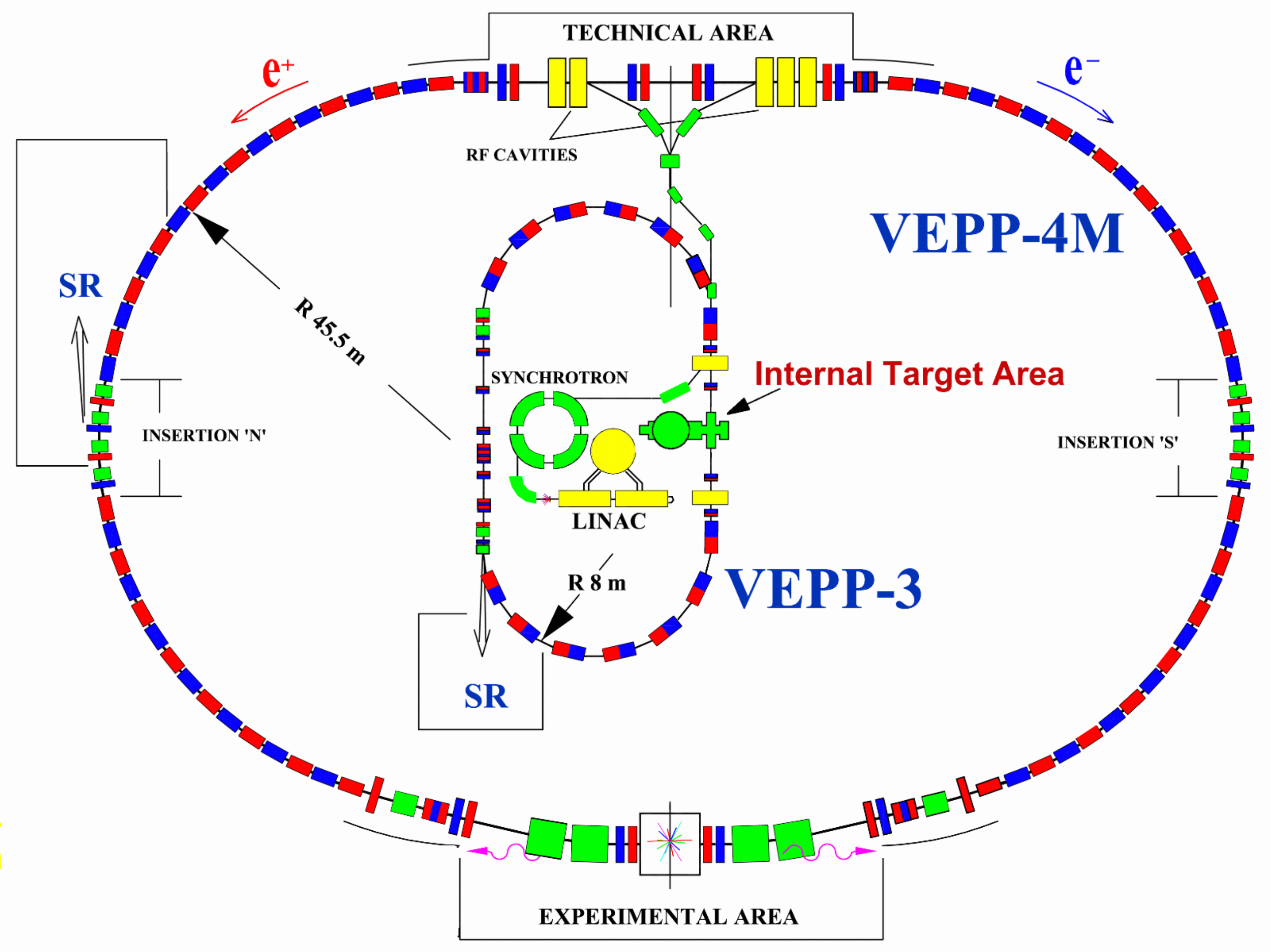
R measures the real part of the two-photon amplitude

Two photon exchange contribution in elastic e-p scattering

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
Proposal for a comparison of electron-proton and
positron-proton scattering at VEPP-3.
E-print: nucl-ex/0408020



Novosibirsk electron-positron facility



VEPP-3

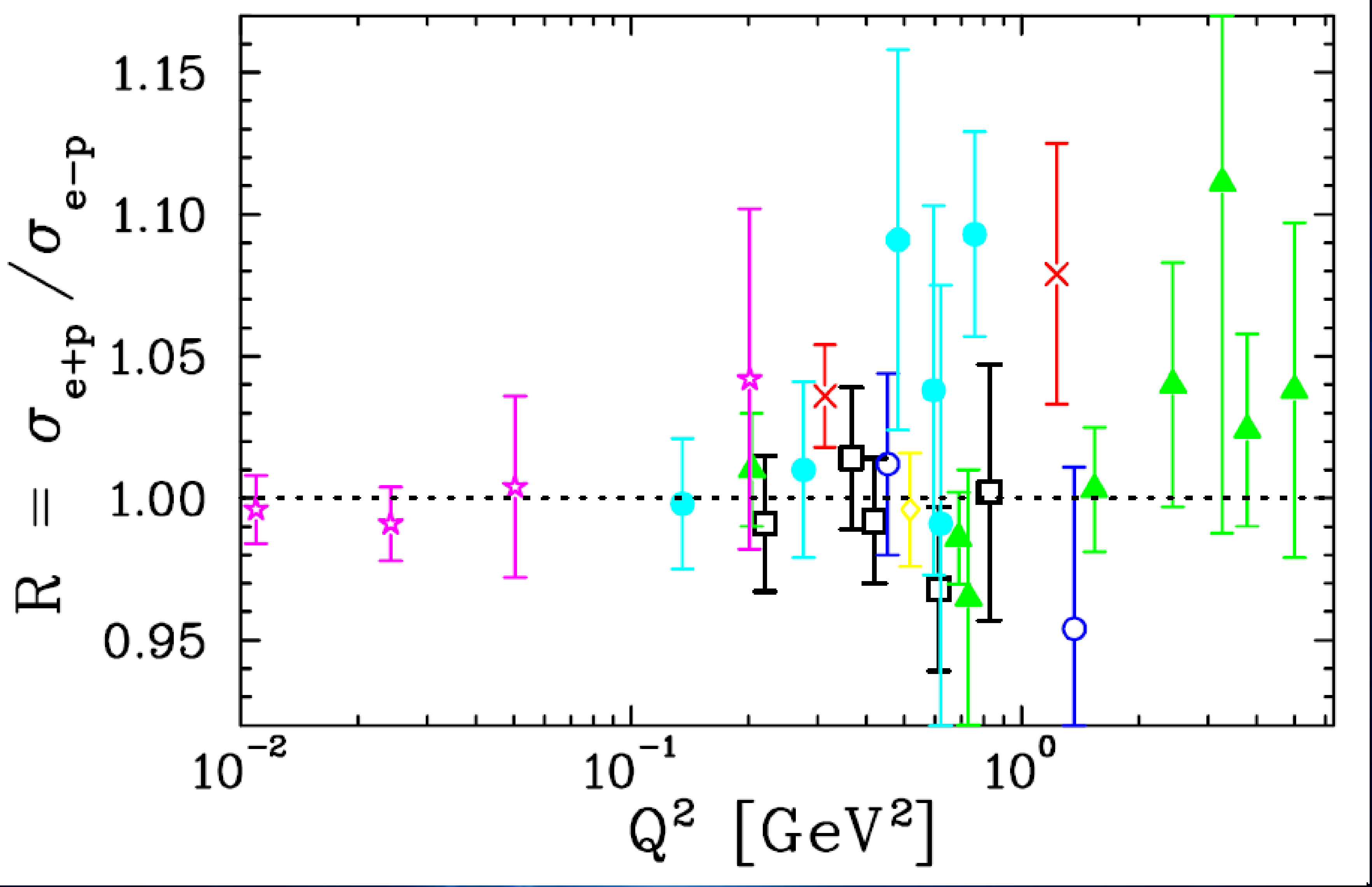
Energy : 2000 MeV

Lifetime : 20000 s

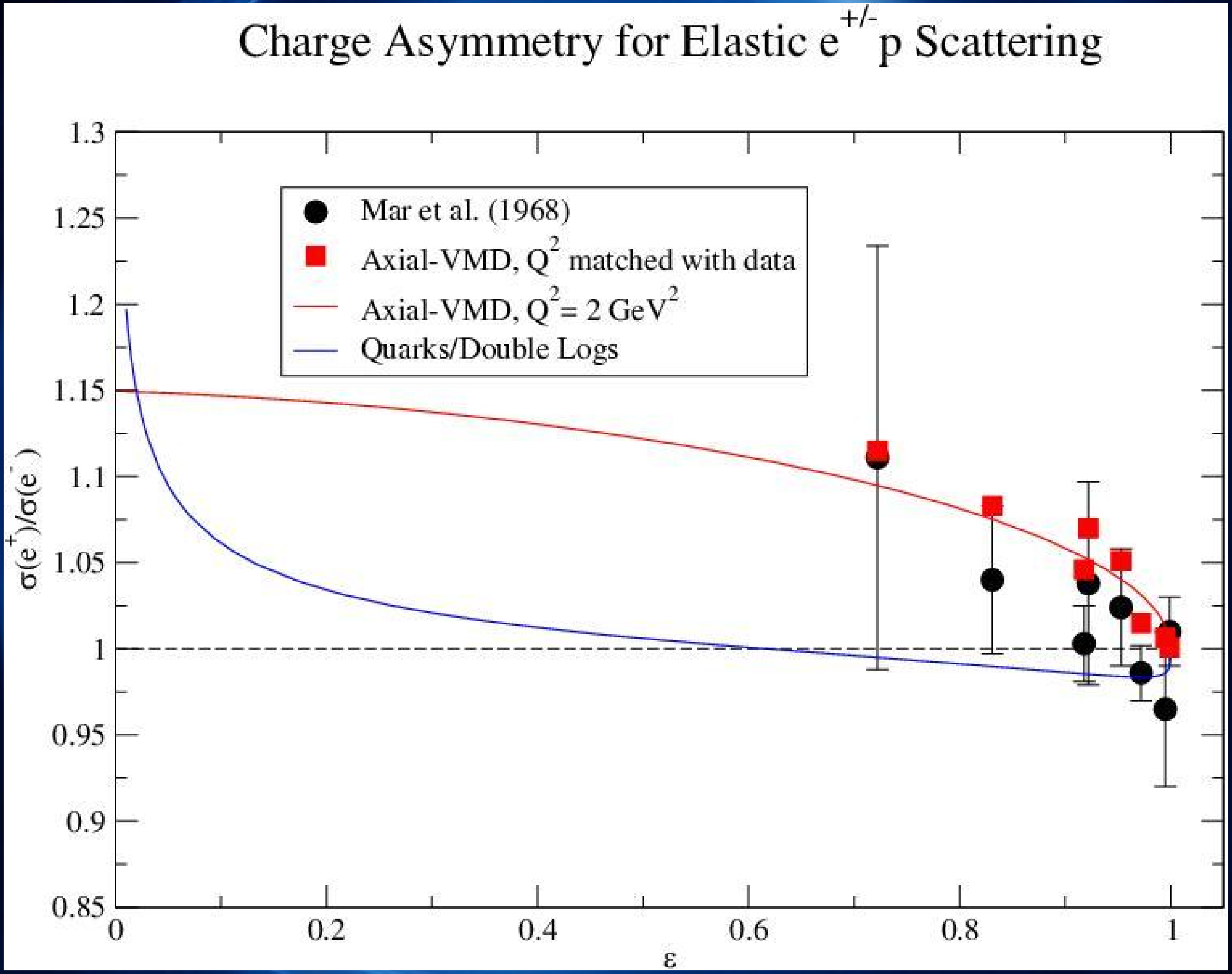
Av. curren : 100 mA

Bunch : 0.7x0.3 mm

Experimental data on R versus the momentum transfer



Existed data on e+- - p elastic scattering



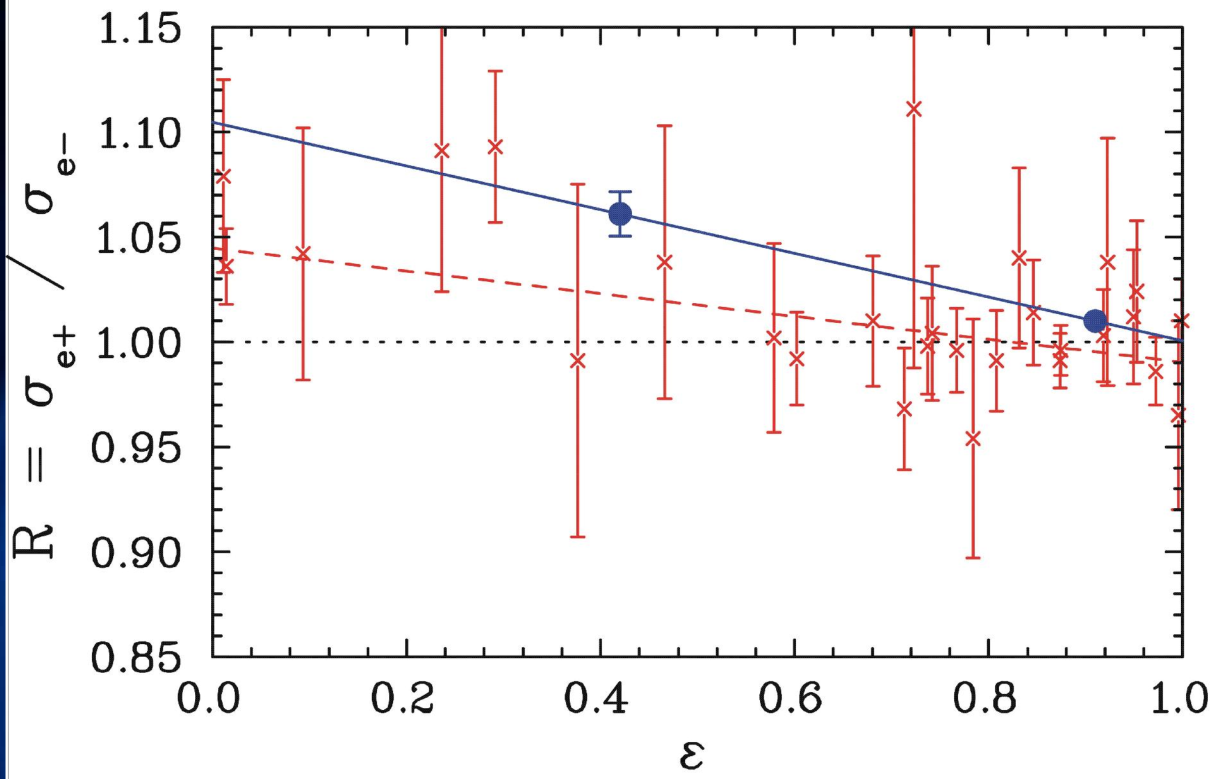
$R = \underline{\sigma}(e^+) / \underline{\sigma}(e^-)$, $N_- = 2 N_+$, E=1600 MeV

$\underline{\theta}_e$	$\underline{\varepsilon}$	$Q^2(GeV/c)^2$	N_+ events	$\underline{\Delta}$R/R %
10 –12	0.98	0.08–0.11	$8.7 \cdot 10^6$	----
19 – 27	0.91	0.26–0.47	$3.1 \cdot 10^6$	0.7
60 – 80	0.40	1.40–1.76	$1.5 \cdot 10^4$	1.00

Systematic errors

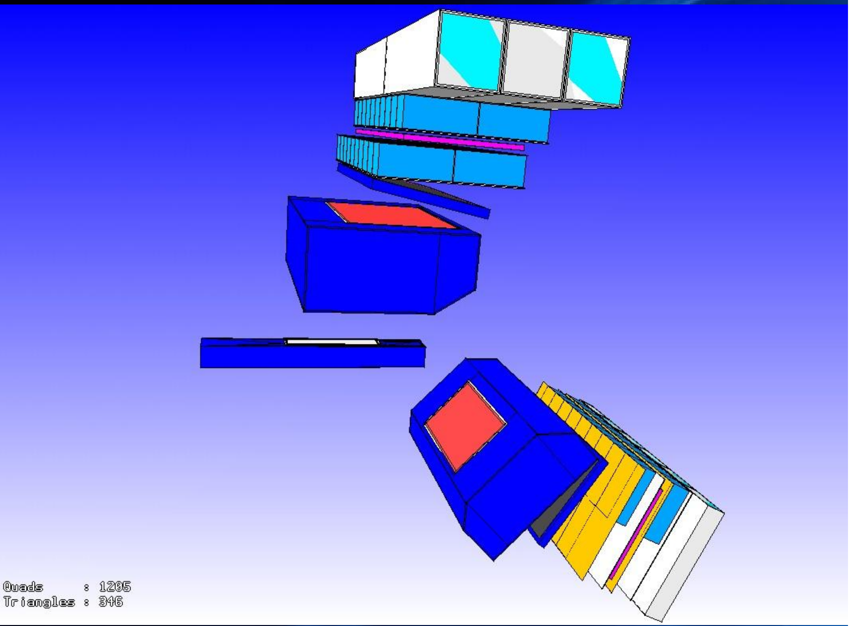
- **Different energy of e^+, e^- beams ($\underline{\Delta\sigma/\sigma}$ for three intervals 0.1, 0.2, 0.2 % / MeV)**
- **Different position of beams ($\underline{\Delta\sigma/\sigma}$ for three intervals 5.0, 1.4, 0.9 % / mm)**
- **Drift of the efficiency over the time of experiment**
- **Drift of the target thickness during the experiment**
- **Difference of the radiation corrections for electrons and positrons**

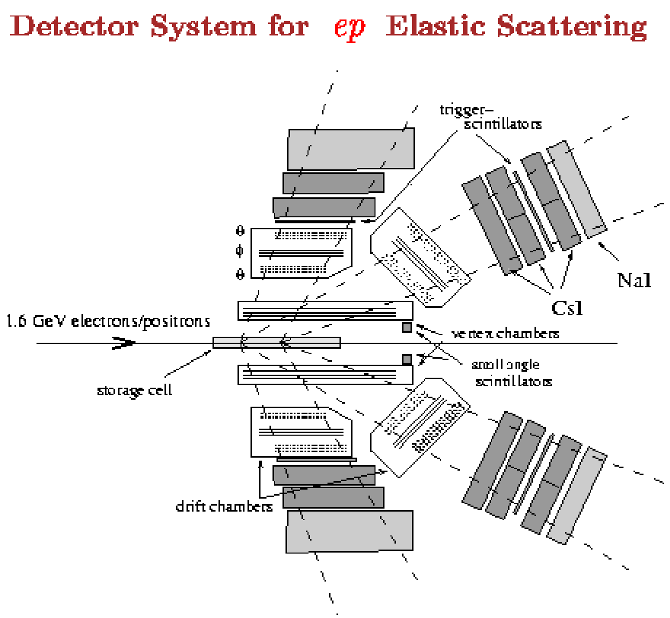
Expected results of the measurements



Projected uncertainty (combined statistical and systematic) for the proposed experiment (blue circles) compared to previous data (red x – J.Arrington Phys.Rev. C69 2004). Note the previous measurements have an average Q^2 range of approximately 0.5 GeV^2 for the data below $\varepsilon = .5$ and thus should have smaller TPE contribution than the proposed Experiment.

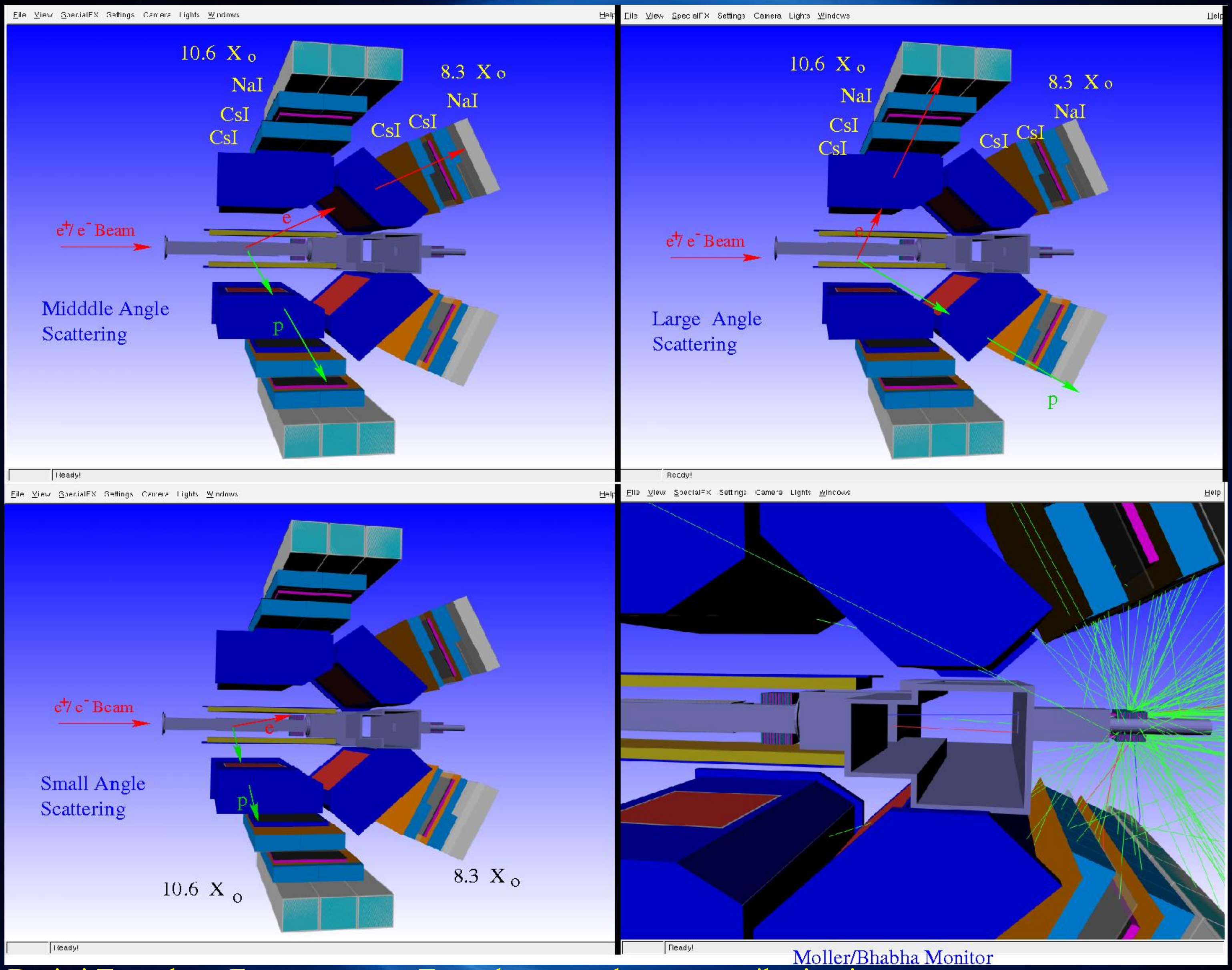
Side view of the detector for experiment

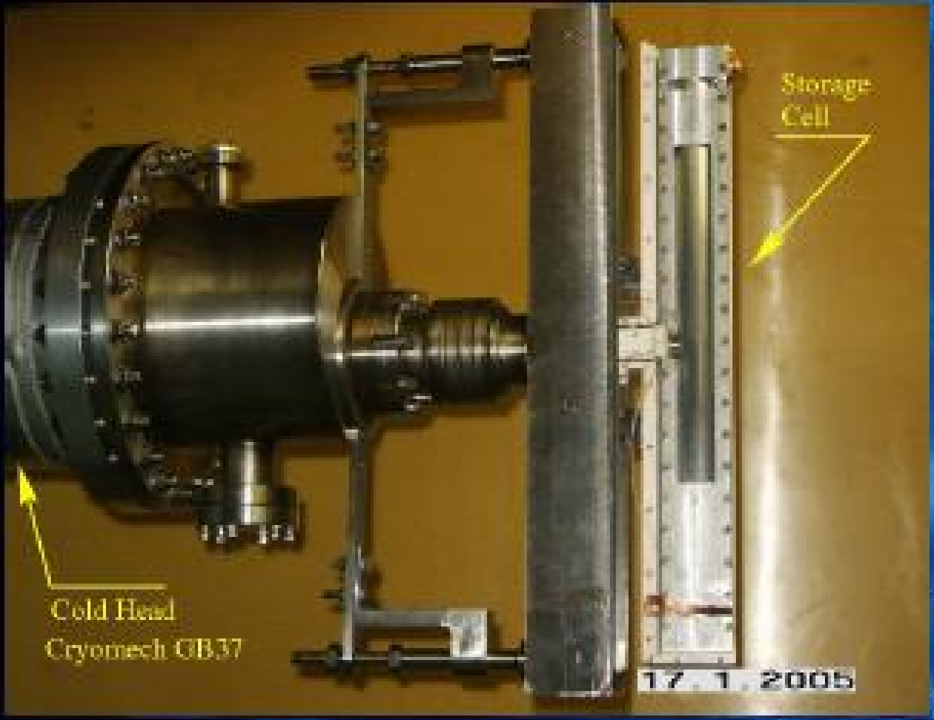


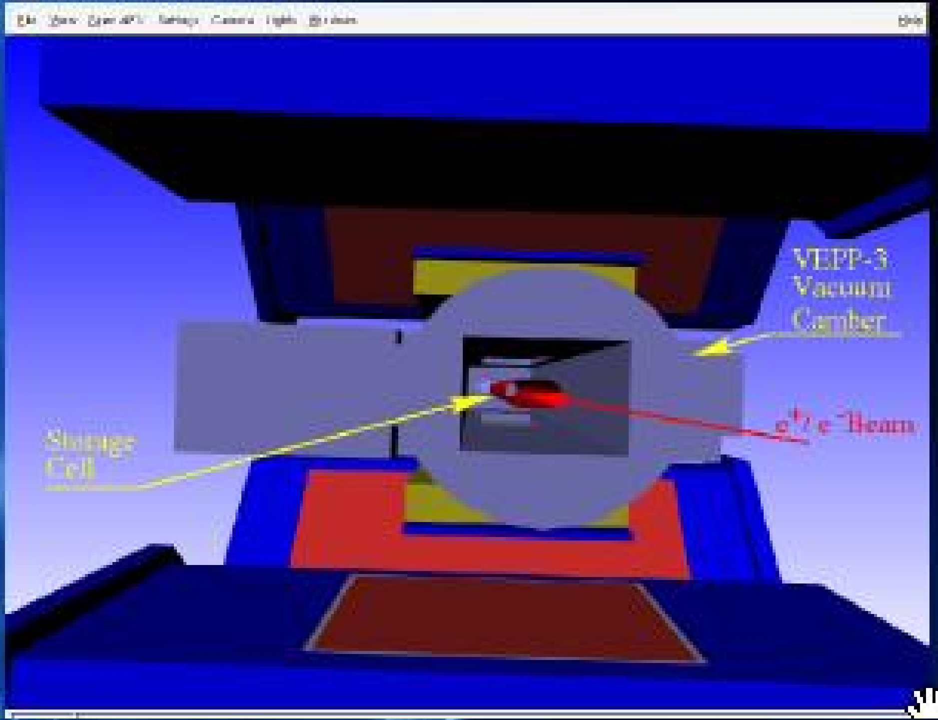


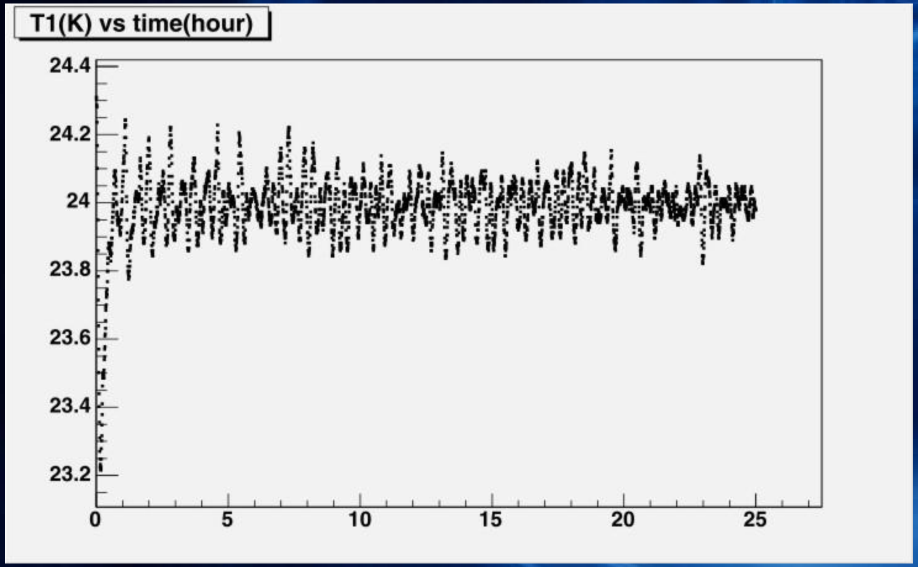
Unpolarized dense hydrogen target. The same storage cell for molecules at the temperature of about 20 K, Target thickness about 10^{15}at/cm^2

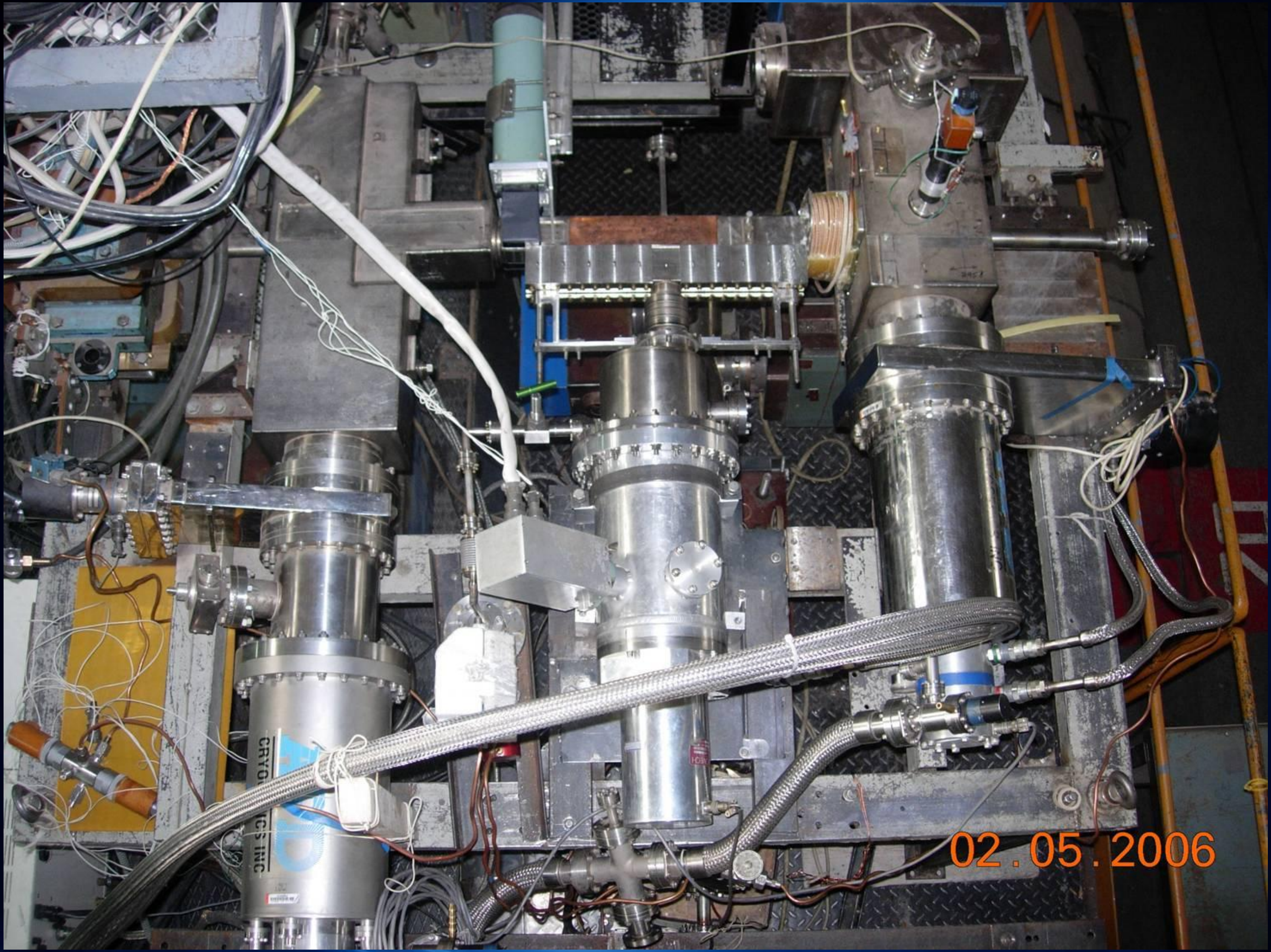
Detector used in experiment

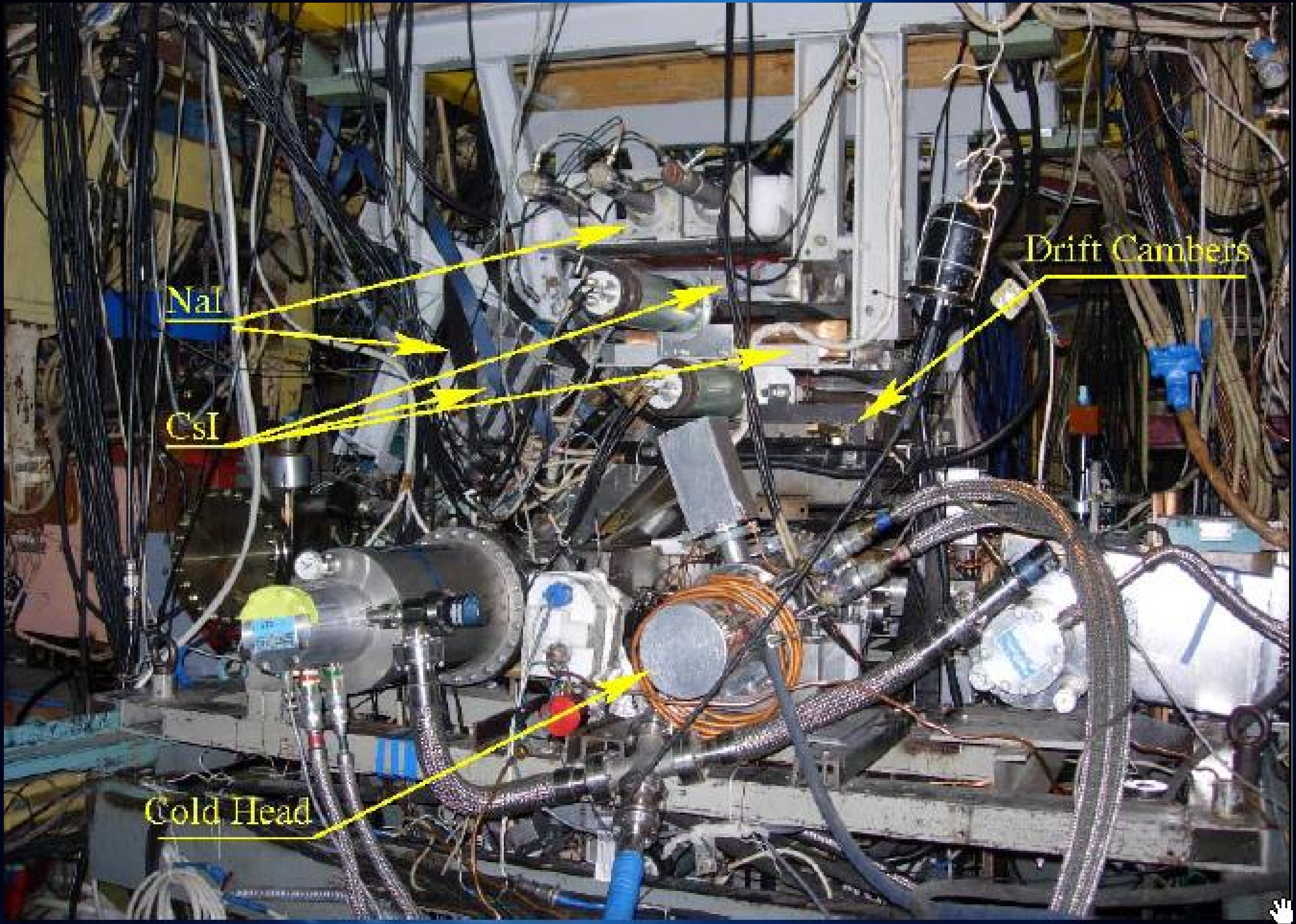



Storage Cell
Cold Head
Cryomech GB37
17.1.2005


VEPP-3
Vacuum
Camber
Storage
Cell
e+/e- Beam

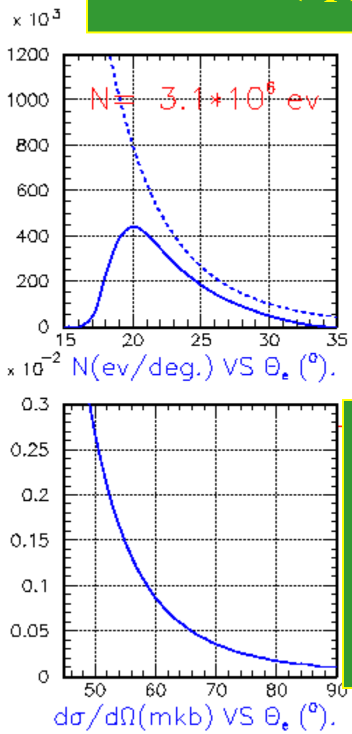

T1(K) vs time(hour)
24.4
24.2
24
23.8
23.6
23.4
23.2
0
5
10
15
20
25


02.05.2006


NaI
CsI
Drift Cambers
Cold Head

Cycle of the experiment

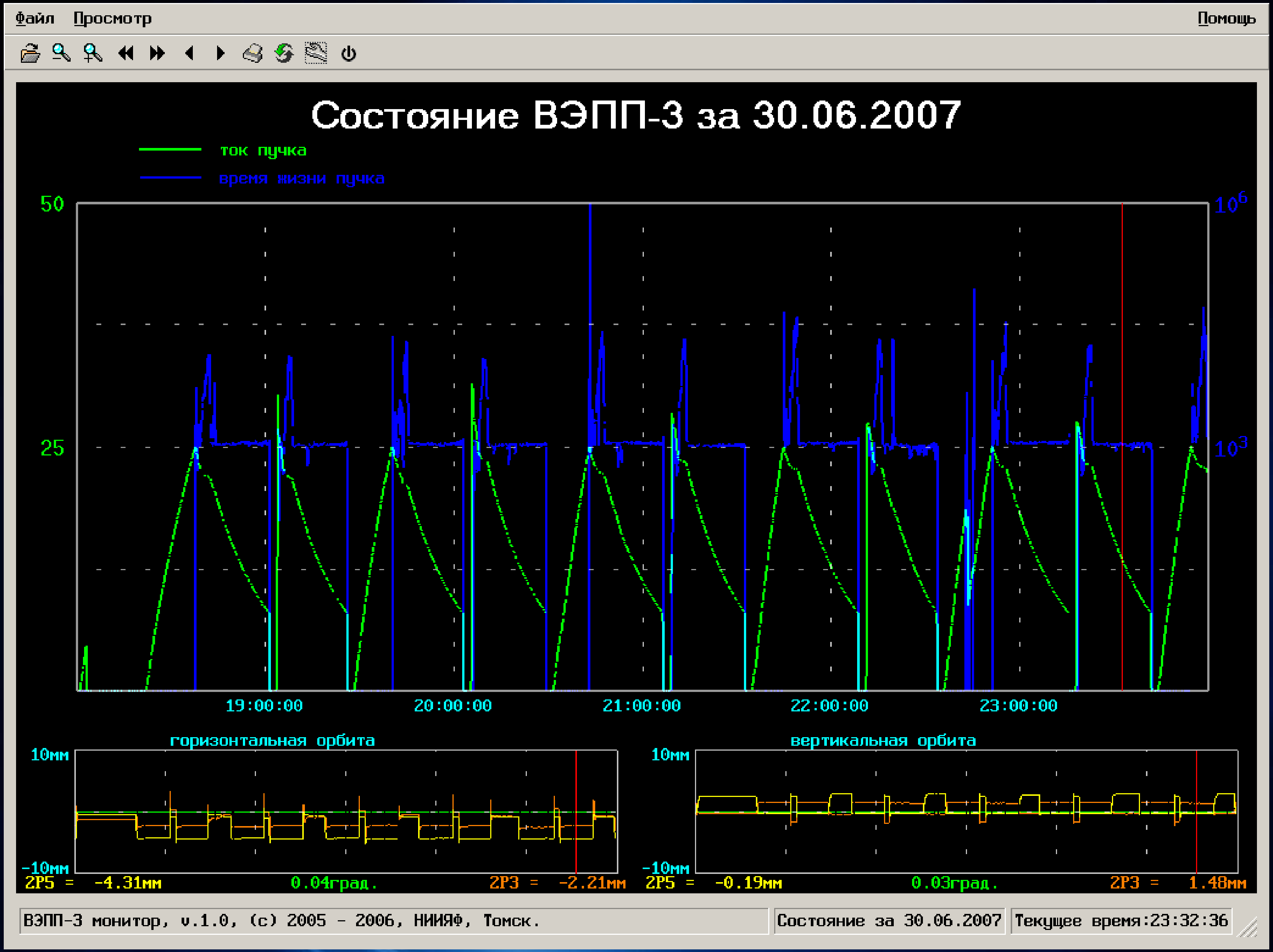
Elastic (ep)-scattering, E_e= 1600 MeV



Thickness of the target
10^{15}at/cm^2, $\Delta\phi$=120^0,
Total charge 12 kQ

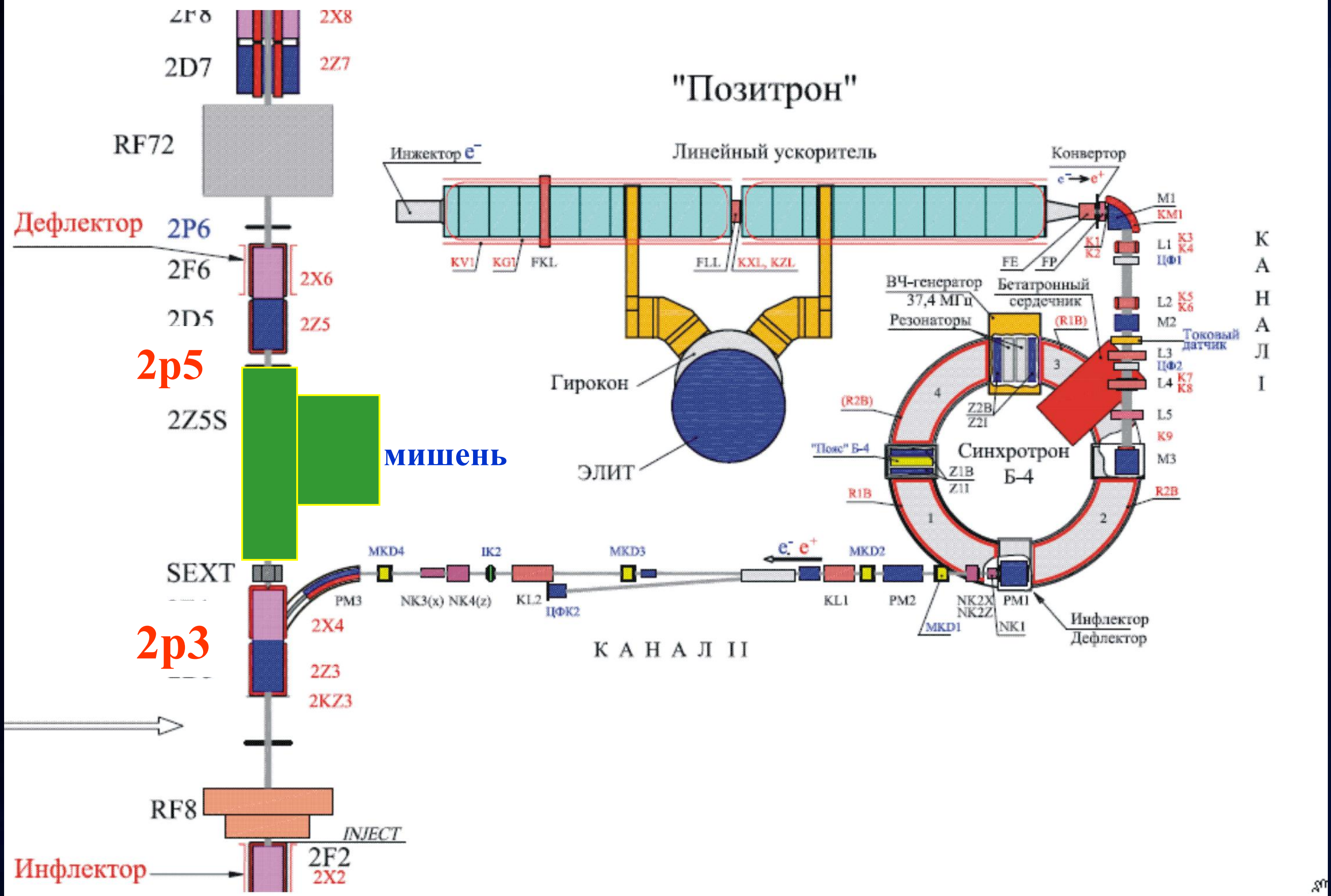
The cycle of experiment with positrons (electrons)– seconds

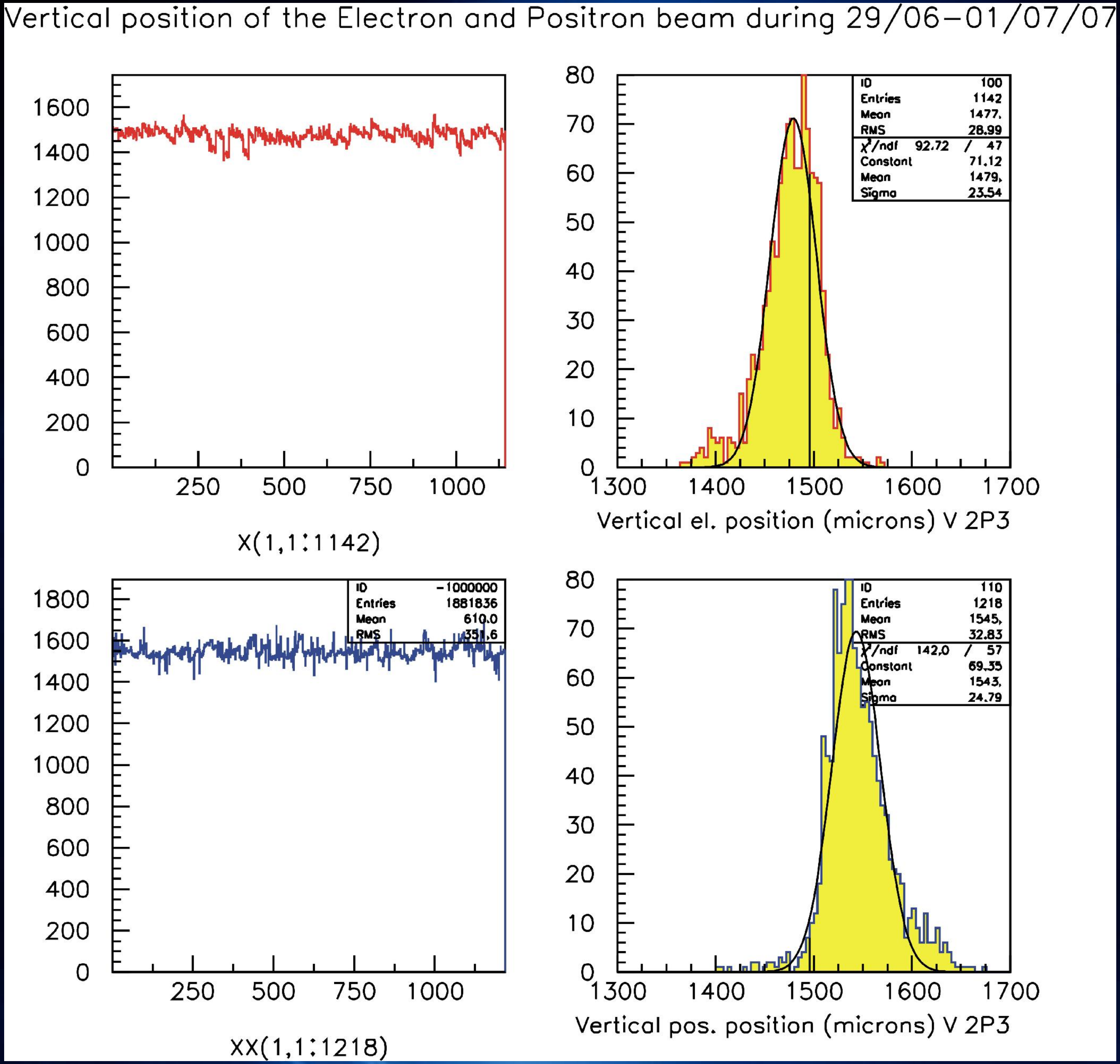
- **Fillings 1630 (10)**
- **Acceleration 300 (300)**
- **Experiment 1620 (1620)**
- **Magnetic field down 300 (300)**
- **Small cycle 4150 (2530)**
- **Full cycle (e^-)(e^+) (e^-) 9190**
- **300 cycles – 2.8x10^6sec – 32days**


Файл Просмотр
Помощь
Состояние ВЭПП-3 за 30.06.2007
ток пучка
время жизни пучка
50
25
10^6
10^3
19:00:00
20:00:00
21:00:00
22:00:00
23:00:00
горизонтальная орбита
10мм
-10мм
2Р5 = -4.31мм
0.04град.
2Р3 = -2.21мм
вертикальная орбита
10мм
-10мм
2Р5 = -0.19мм
0.03град.
2Р3 = 1.48мм
ВЭПП-3 монитор, v.1.0, (с) 2005 - 2006, НИИЯФ, Томск.
Состояние за 30.06.2007
Текущее время:23:32:36

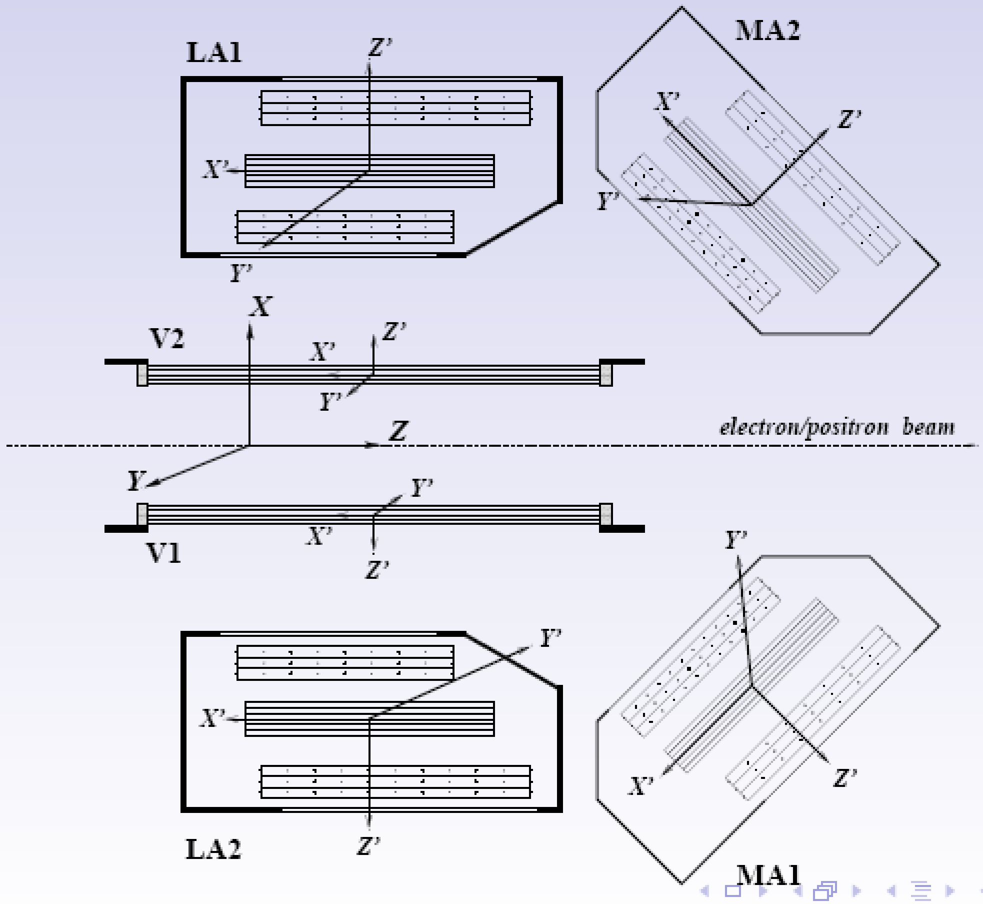
System of pick up electrodes at VEPP-3.

Positioning of pick up electrodes 2p3 and 2p5 at straight section of VEPP-3.

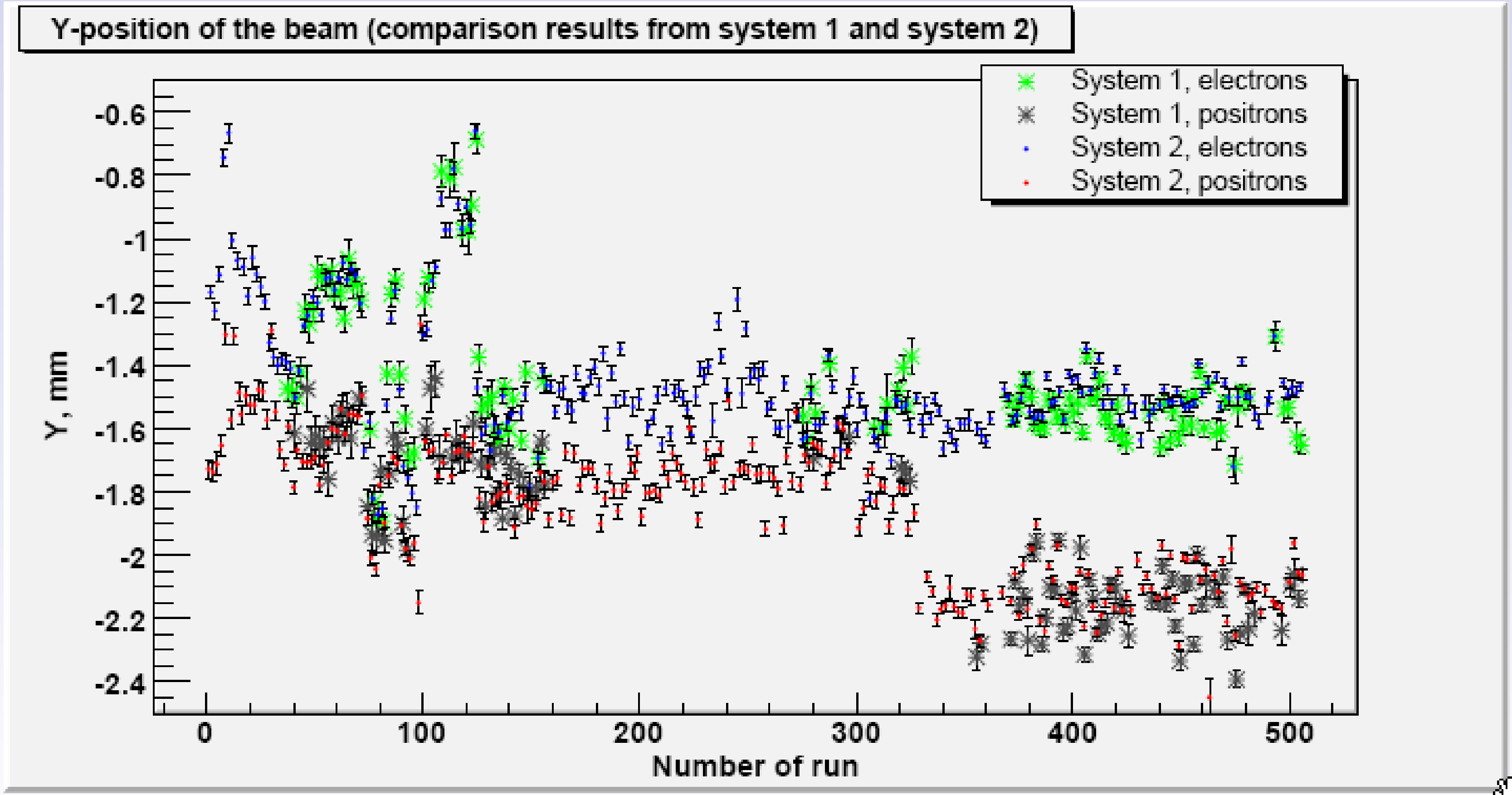



Vertical position of the Electron and Positron beam during 29/06-01/07/07
X(1,1:1142)
ID 100
Entries 1142
Mean 1477.
RMS 28.99
χ²/ndf 92.72 / 47
Constant 71.12
Mean 1479.
Sigma 23.54
Vertical el. position (microns) V 2P3
XX(1,1:1218)
ID -1000000
Entries 1881836
Mean 610.0
RMS 351.6
ID 110
Entries 1218
Mean 1545.
RMS 32.83
χ²/ndf 142.0 / 57
Constant 69.35
Mean 1543.
Sigma 24.79
Vertical pos. position (microns) V 2P3

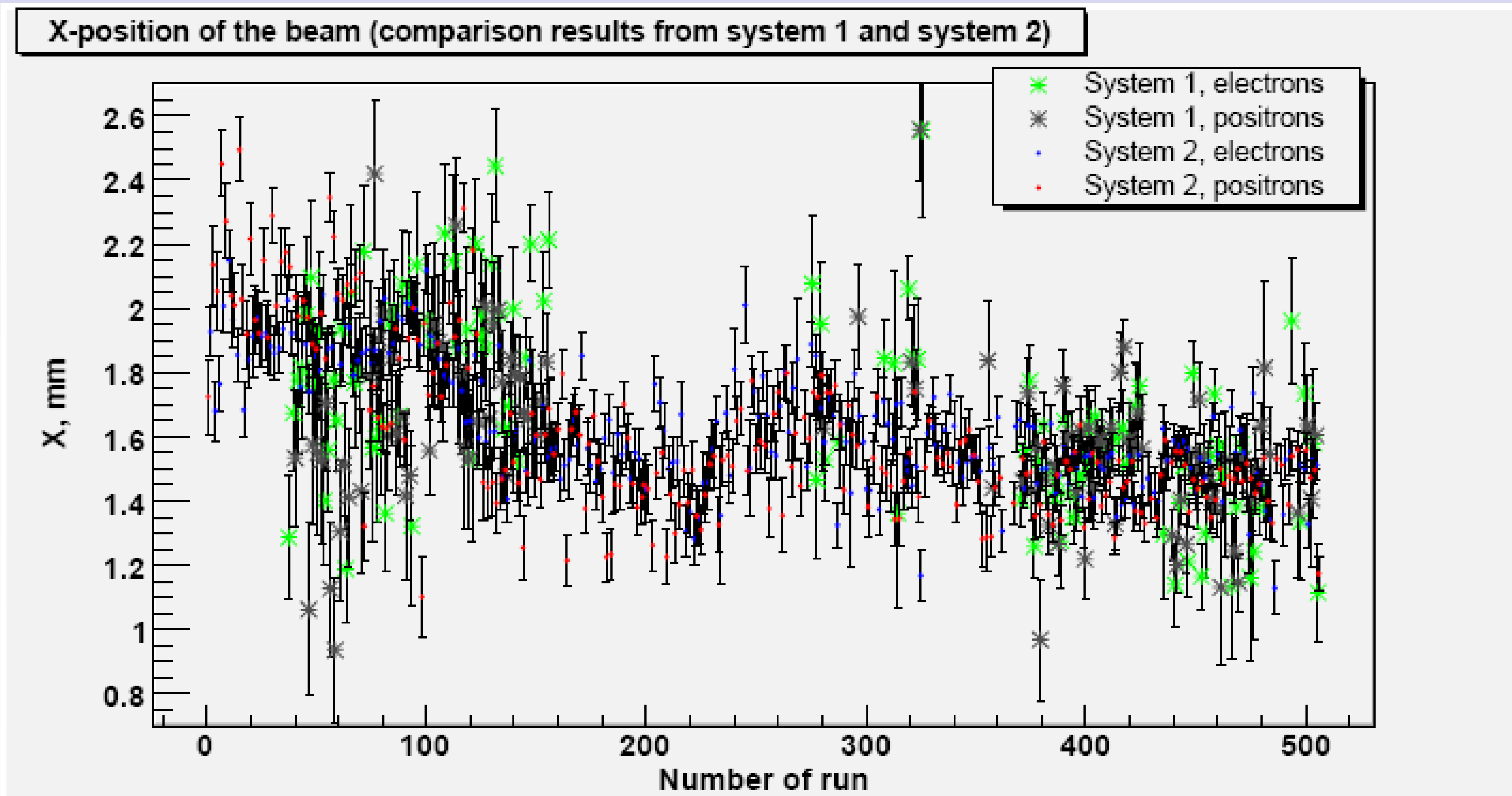
Tracking system of the detector



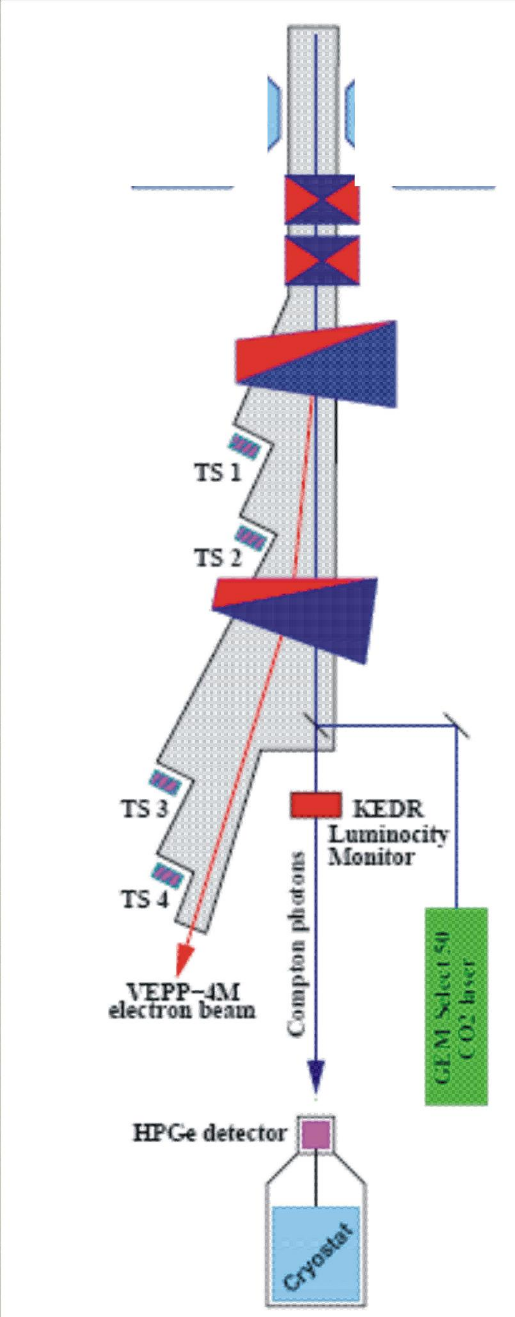
Horizontal beam position measured by system 1 and 2



Vertical beam position measured by system 1 and 2



Fast and precise beam energy monitor based on the Compton backscattering



$$\omega_{max} = \frac{\varepsilon^2}{(\varepsilon + m^2/4\omega_0)} .$$

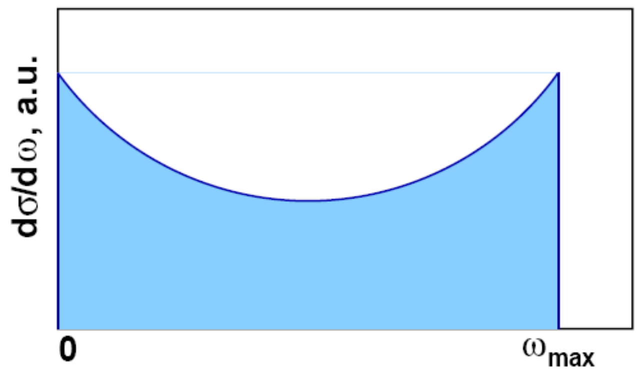


Figure 1: Energy spectrum of scattered photons

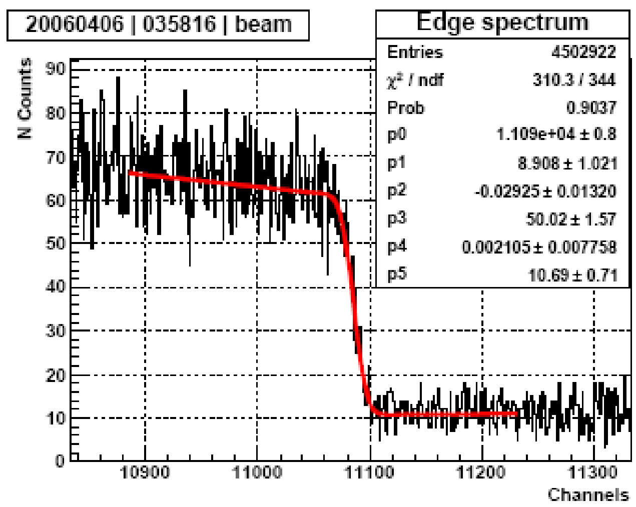
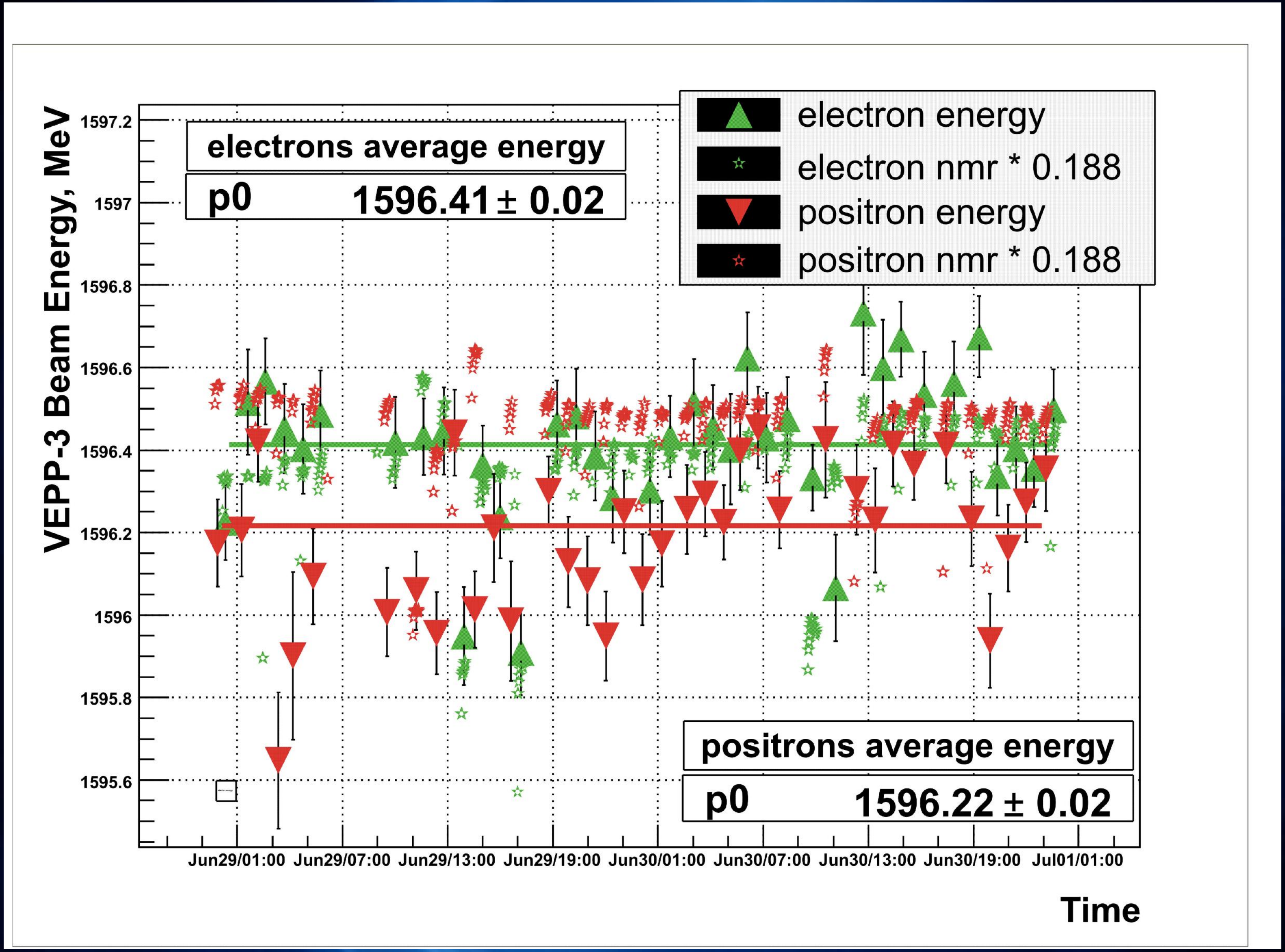


Figure 5: Spectrum fragment near ω_{max}

$$\varepsilon = \frac{\omega_{max}}{2}\left(1 + \sqrt{1 + \frac{m^2}{\omega_0\omega_{max}}}\right)$$

The energy comparison of the electron and positron beams at VEPP-3 storage ring using the method of backward Compton scattering



Selection of the elastic e-p scattering events

1. **Correlation between polar angles**

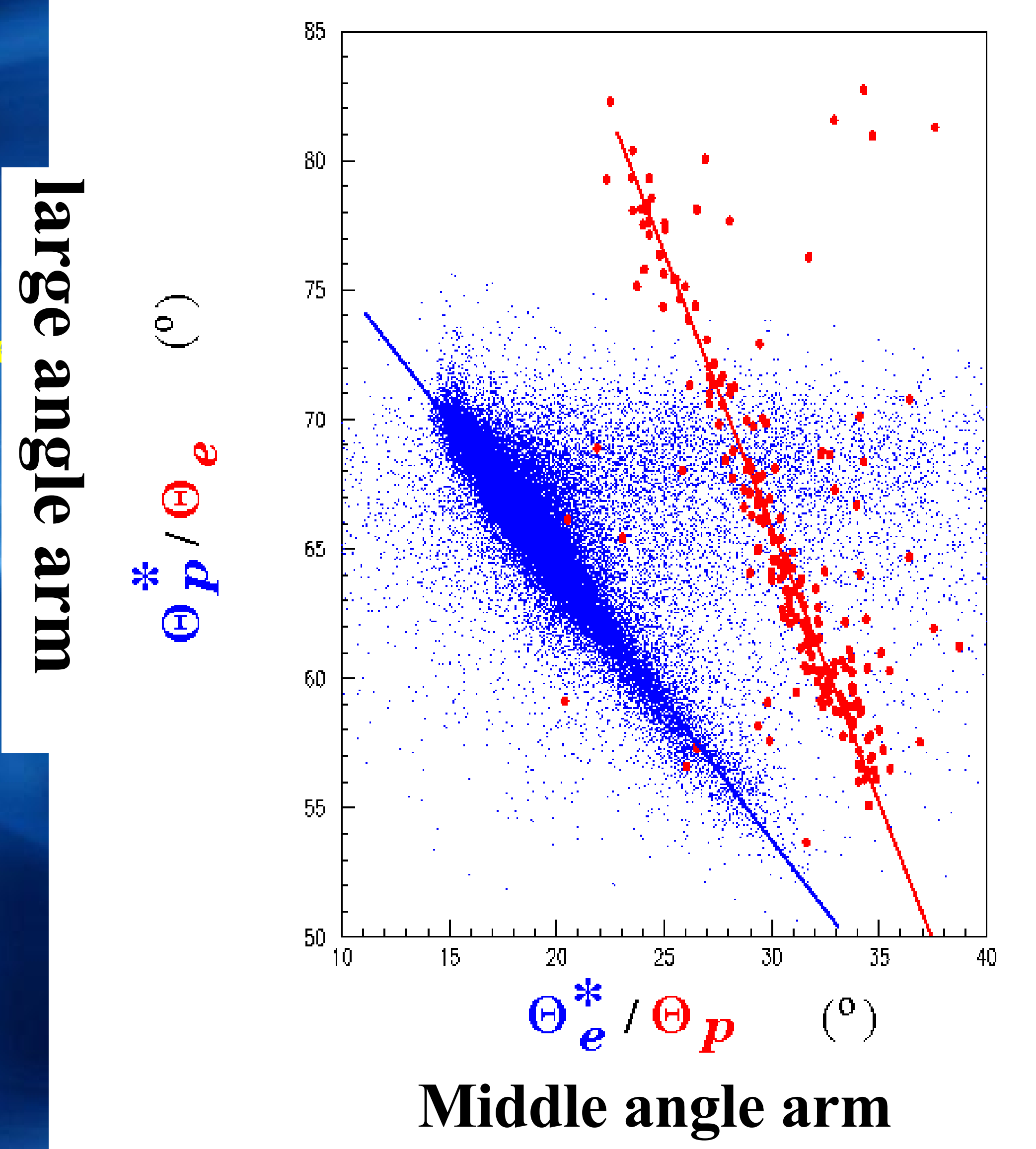
2. **Correlation between azimuthal angle**

3. **Correlation between electron scattering angle and proton energy**

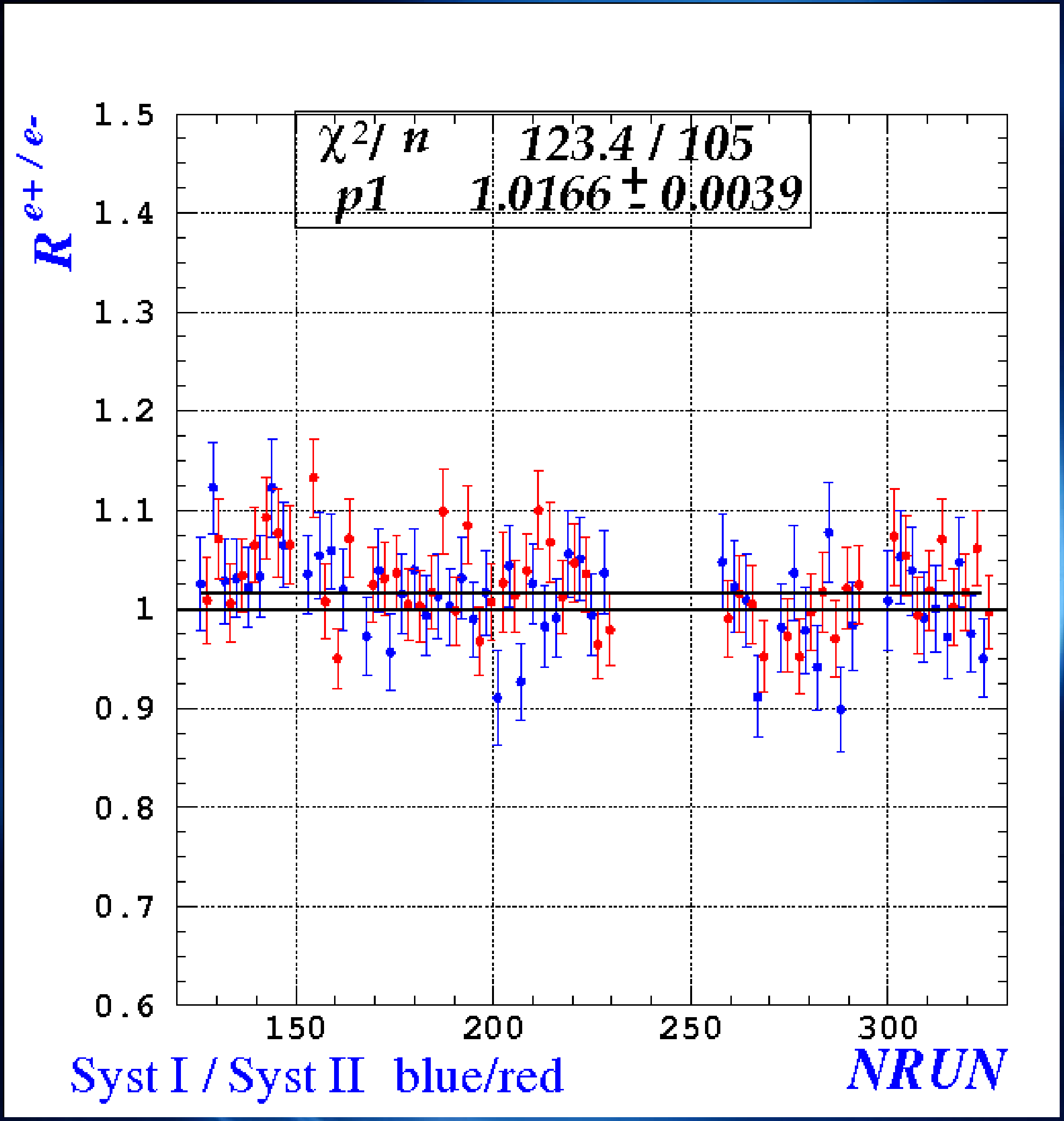
4. **Correlation between electron scattering angle and electron energy**

5. **ΔE – E analysis**

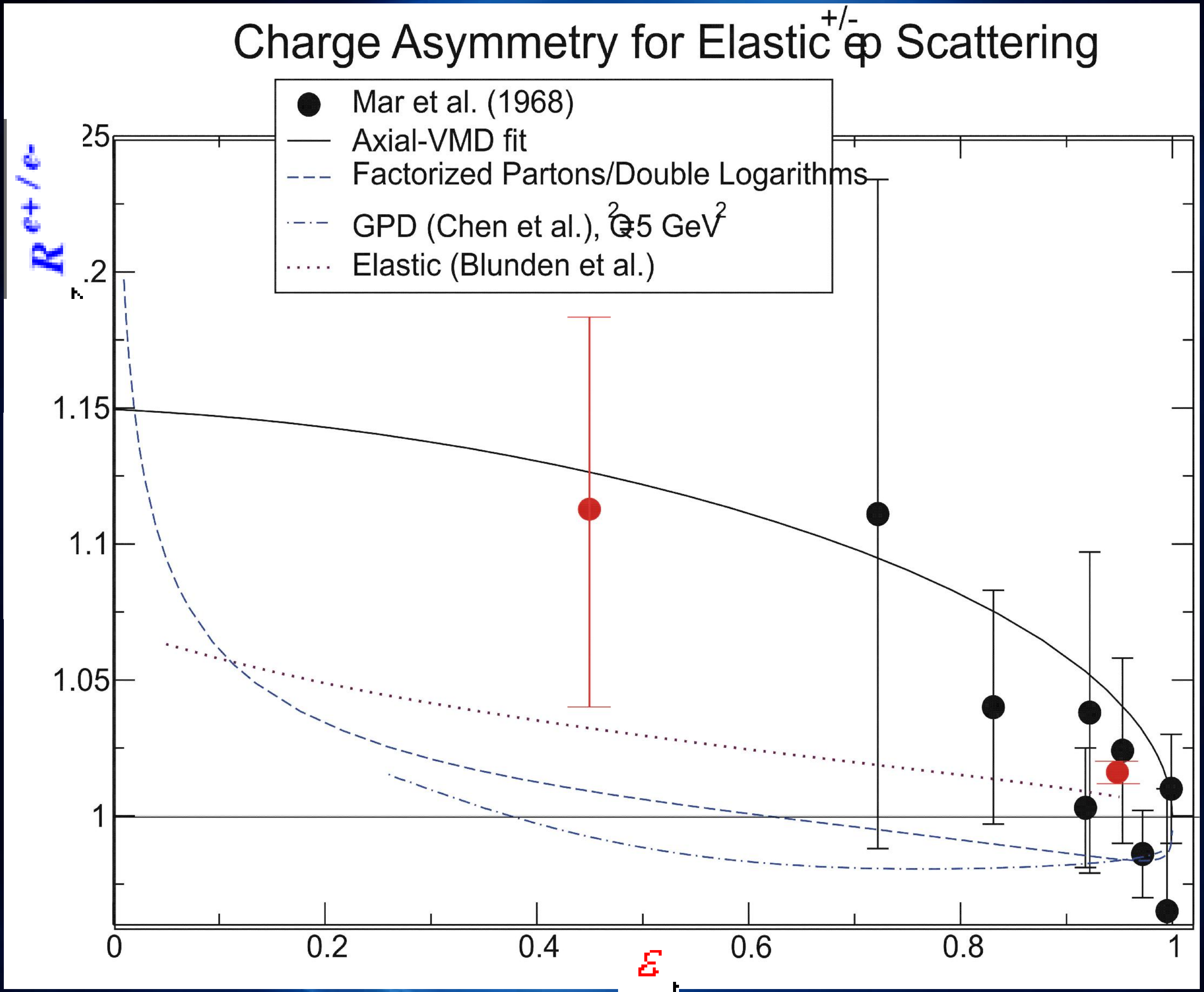
6. **Time of flight analysis for protons with low energy**



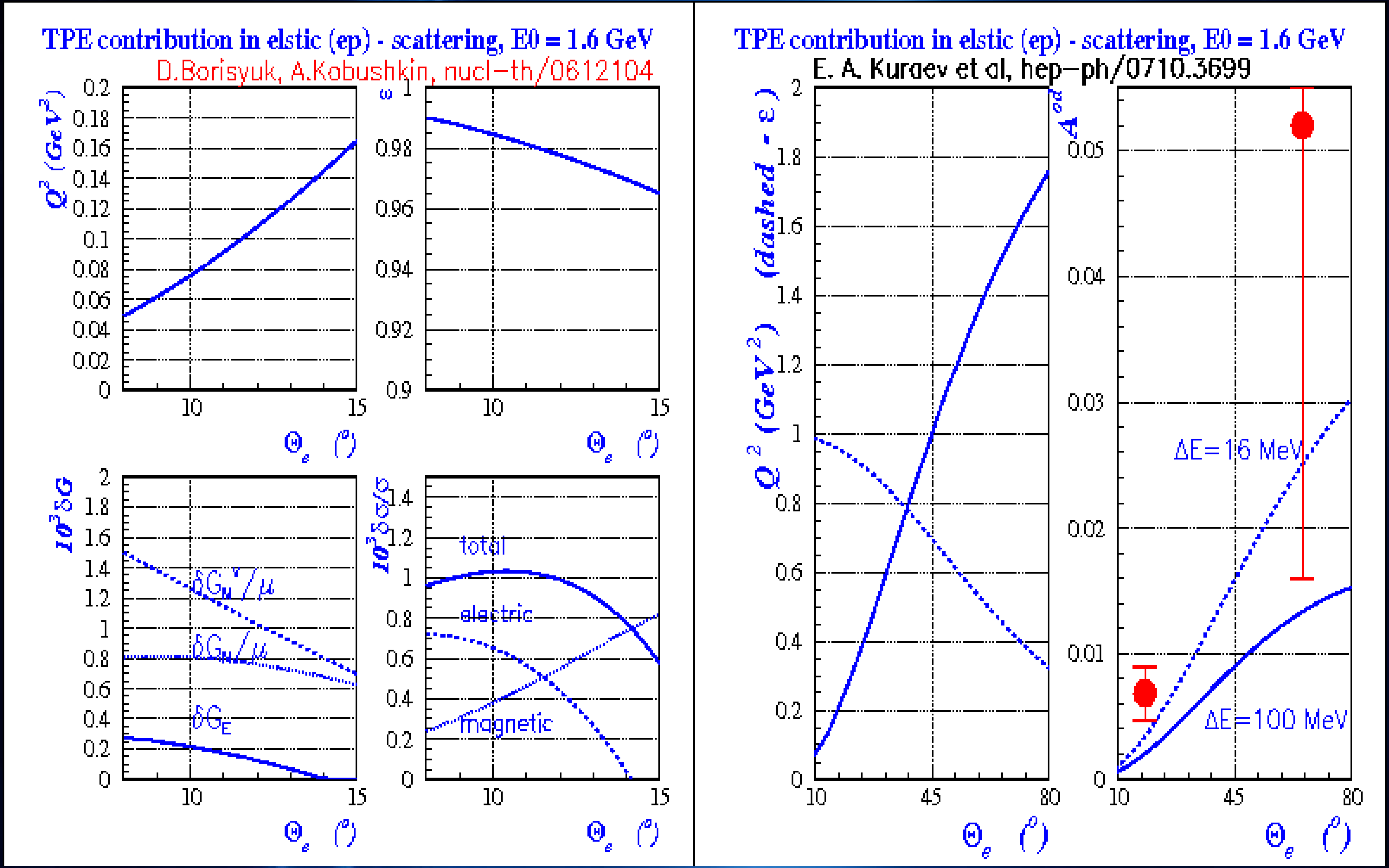
Cross section ratio for middle angles (normalized at small angle)



A ratio R for the middle and large angles of scattering (normalized to small angles)



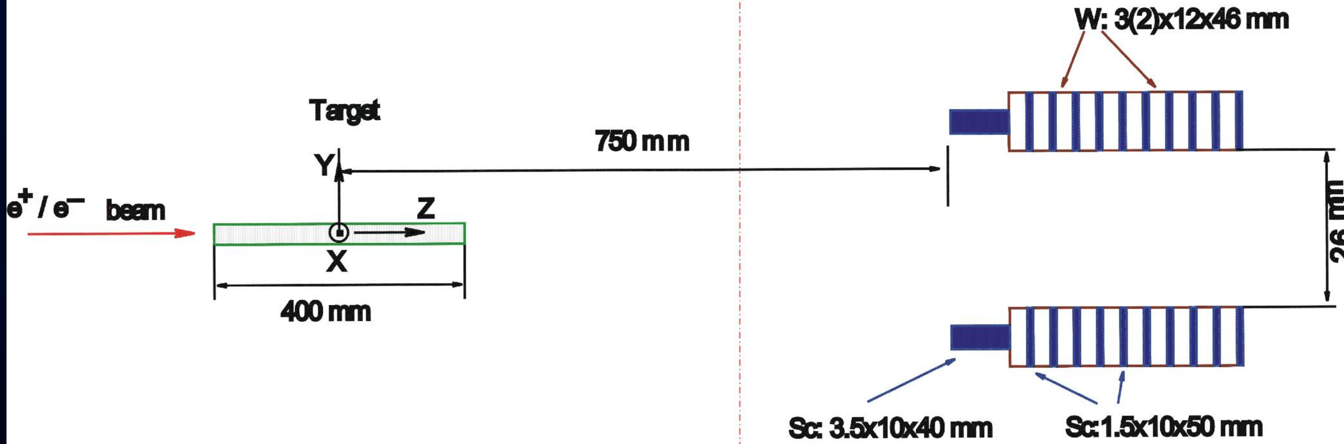
R for the middle and large scattering angles (normalized to small angle)



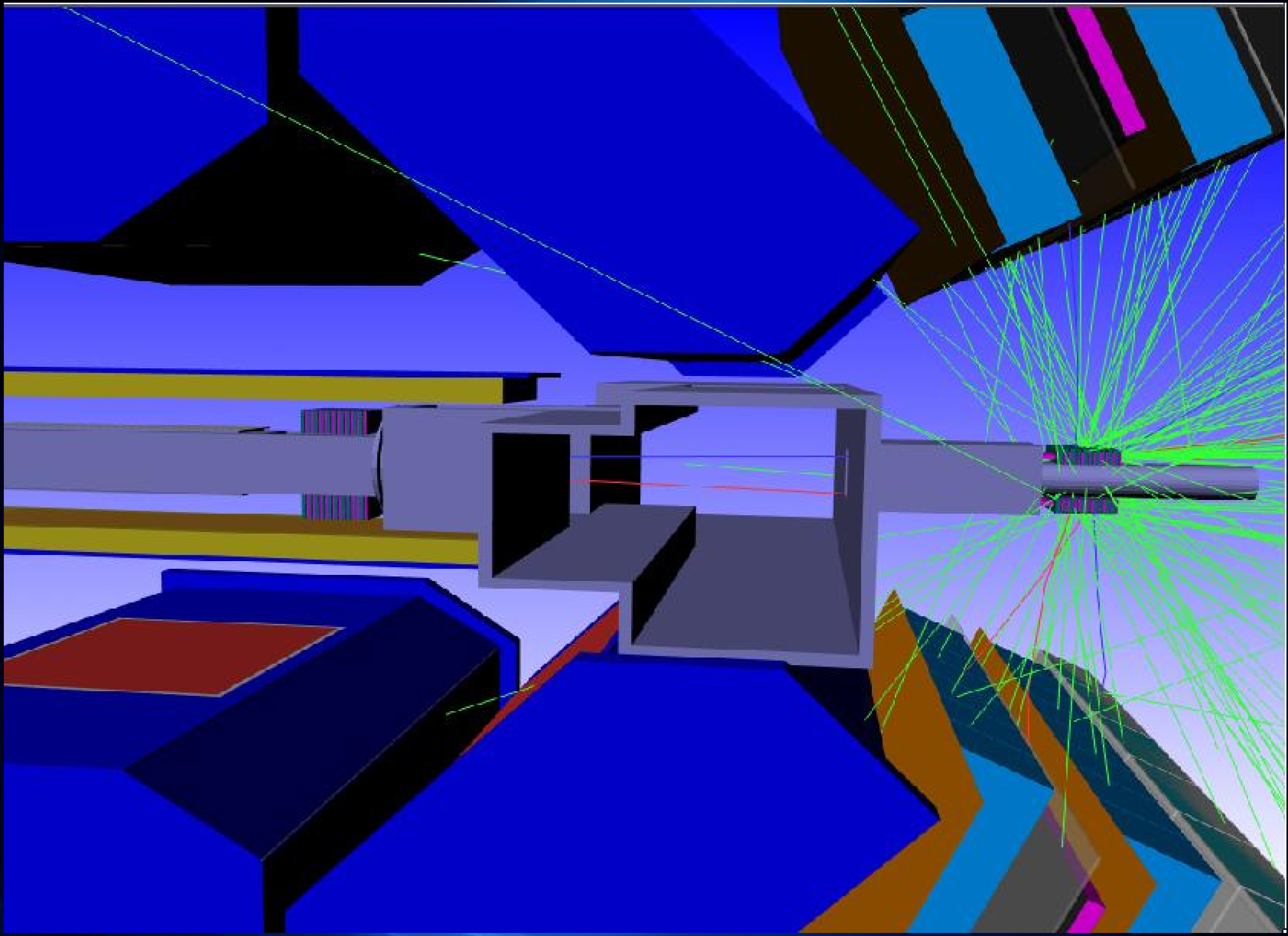
Luminosity monitor based on the measurement of the Moller/Bhabha scattering

$e^- e^- \longrightarrow e^- e^-$ or $e^+ e^- \longrightarrow e^+ e^-$

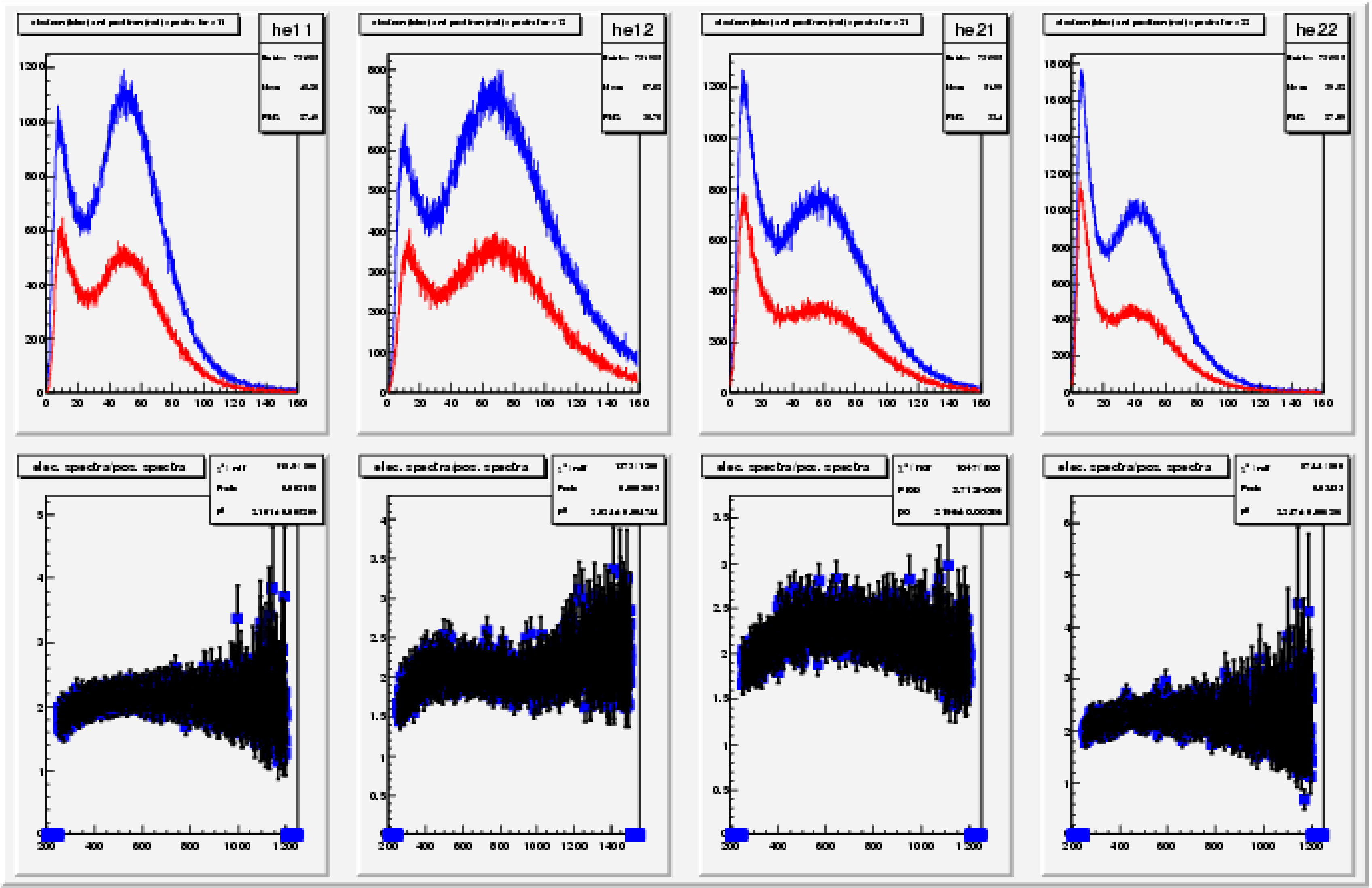
High counting rate of the coincidence events – about 100 Hz



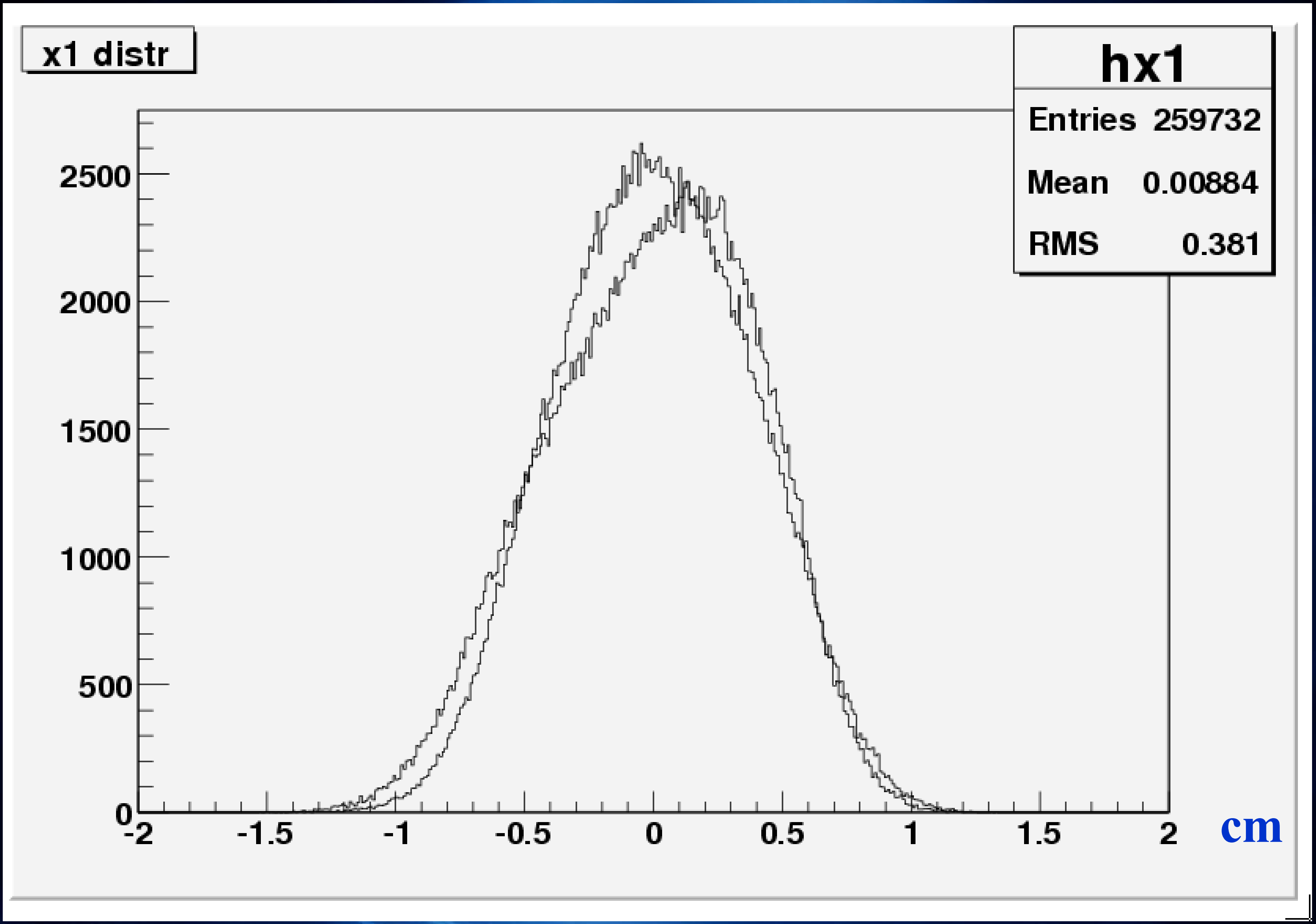
Moller/Bhabha MONITOR



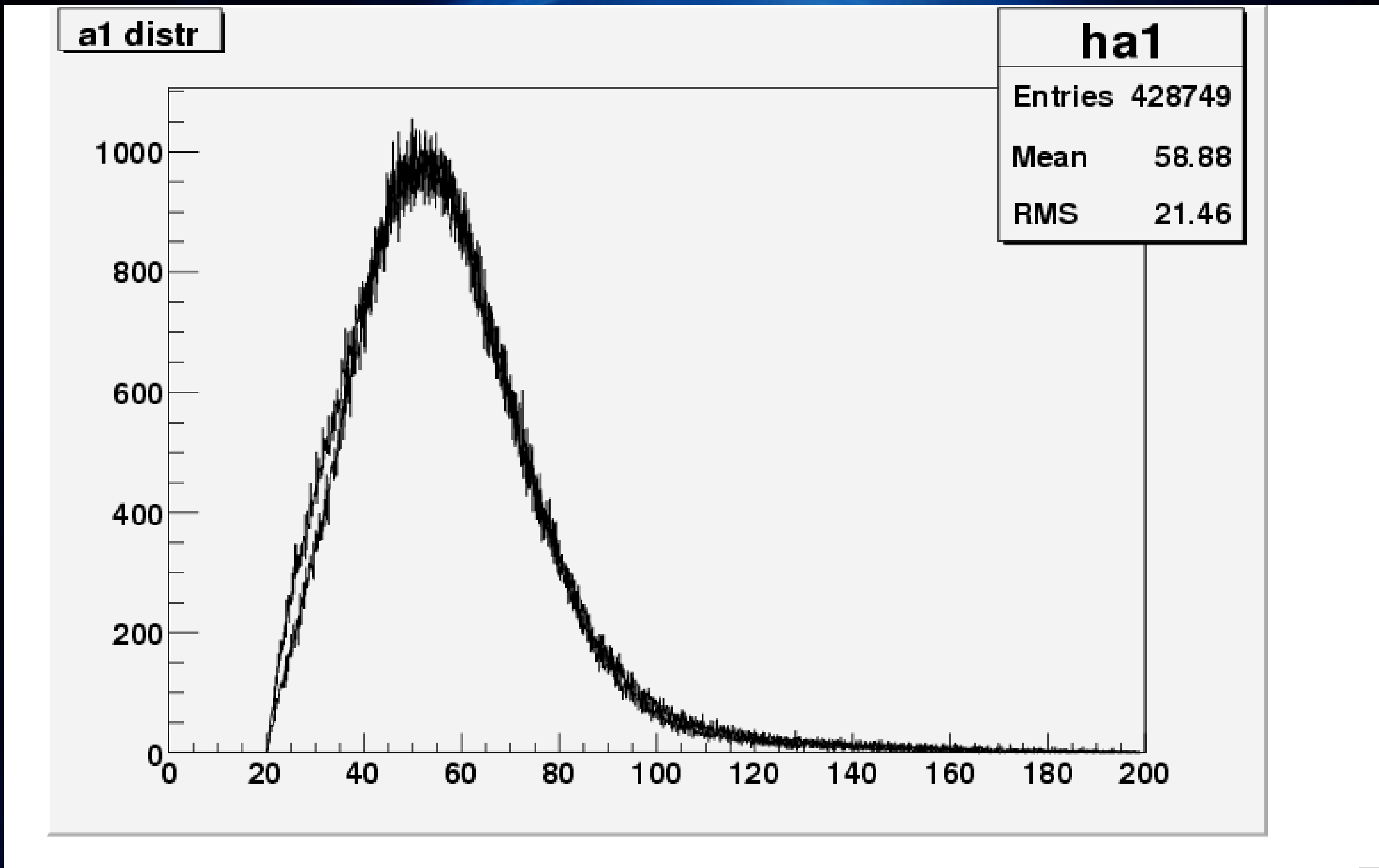
Energy spectrum of electrons and positrons in monitor detector



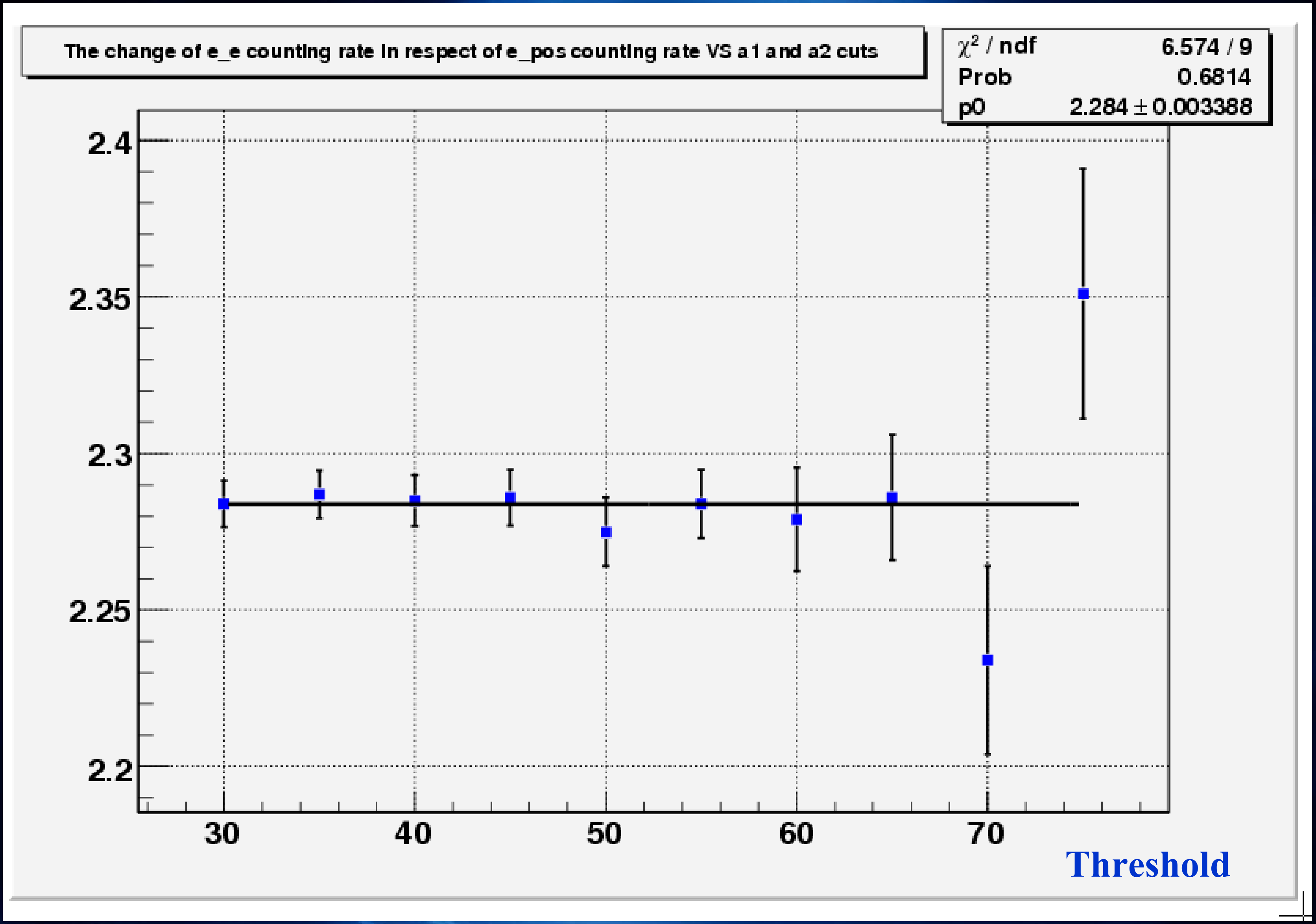
Space distribution of the events for up and down counter.



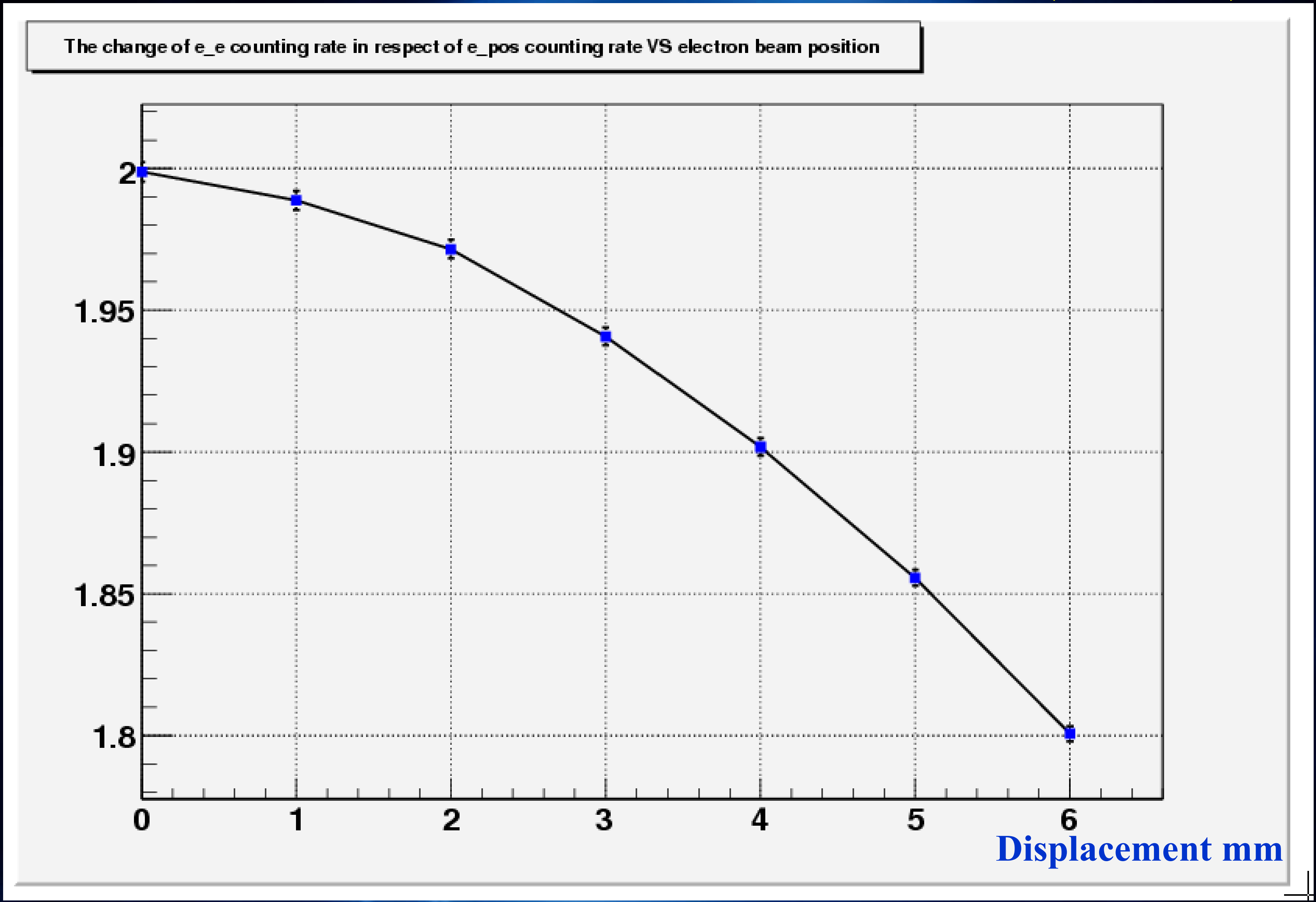
Energy distribution of electrons and positrons in the monitor detector



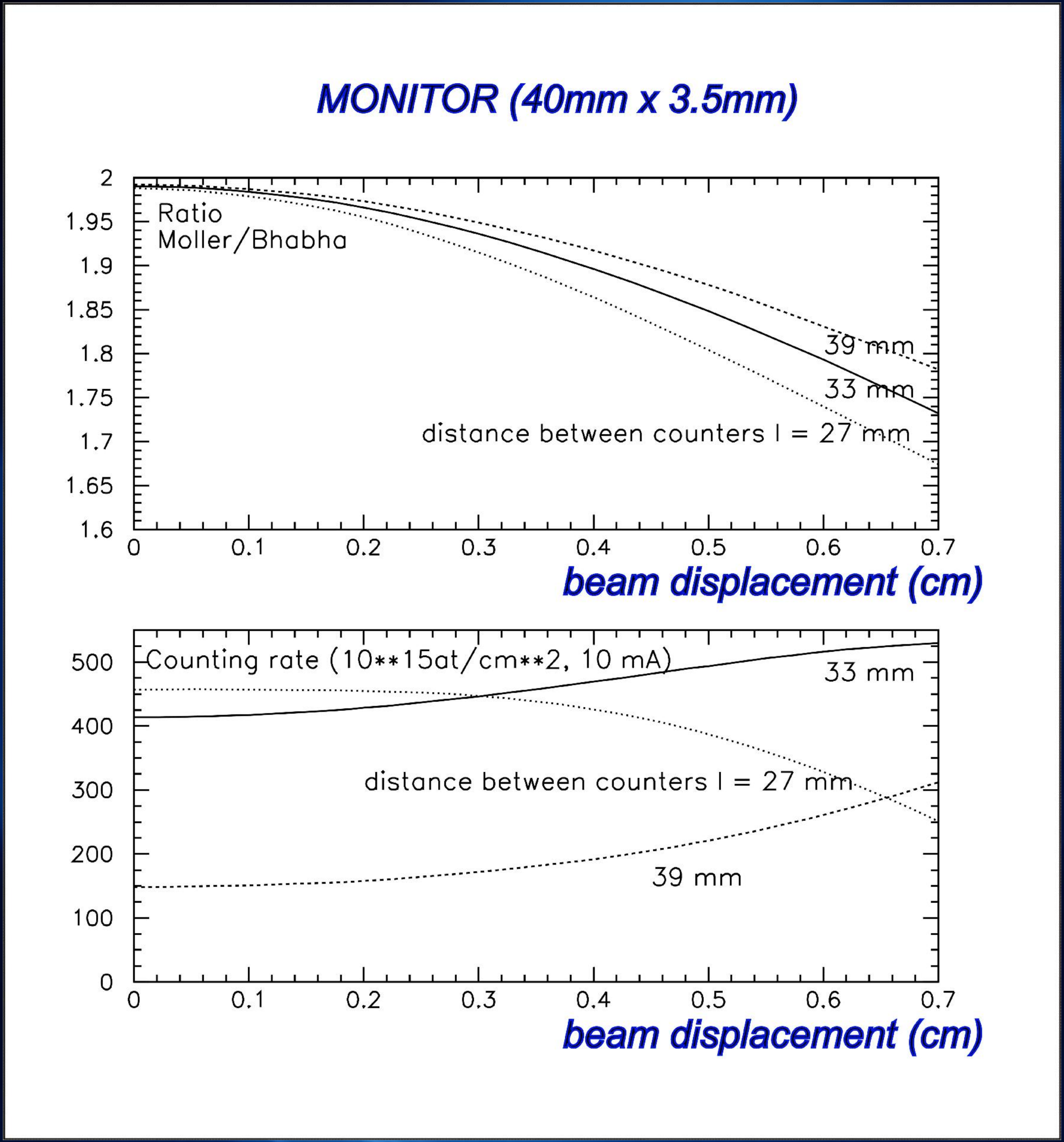
Sensitivity of the detector to the threshold of the energy



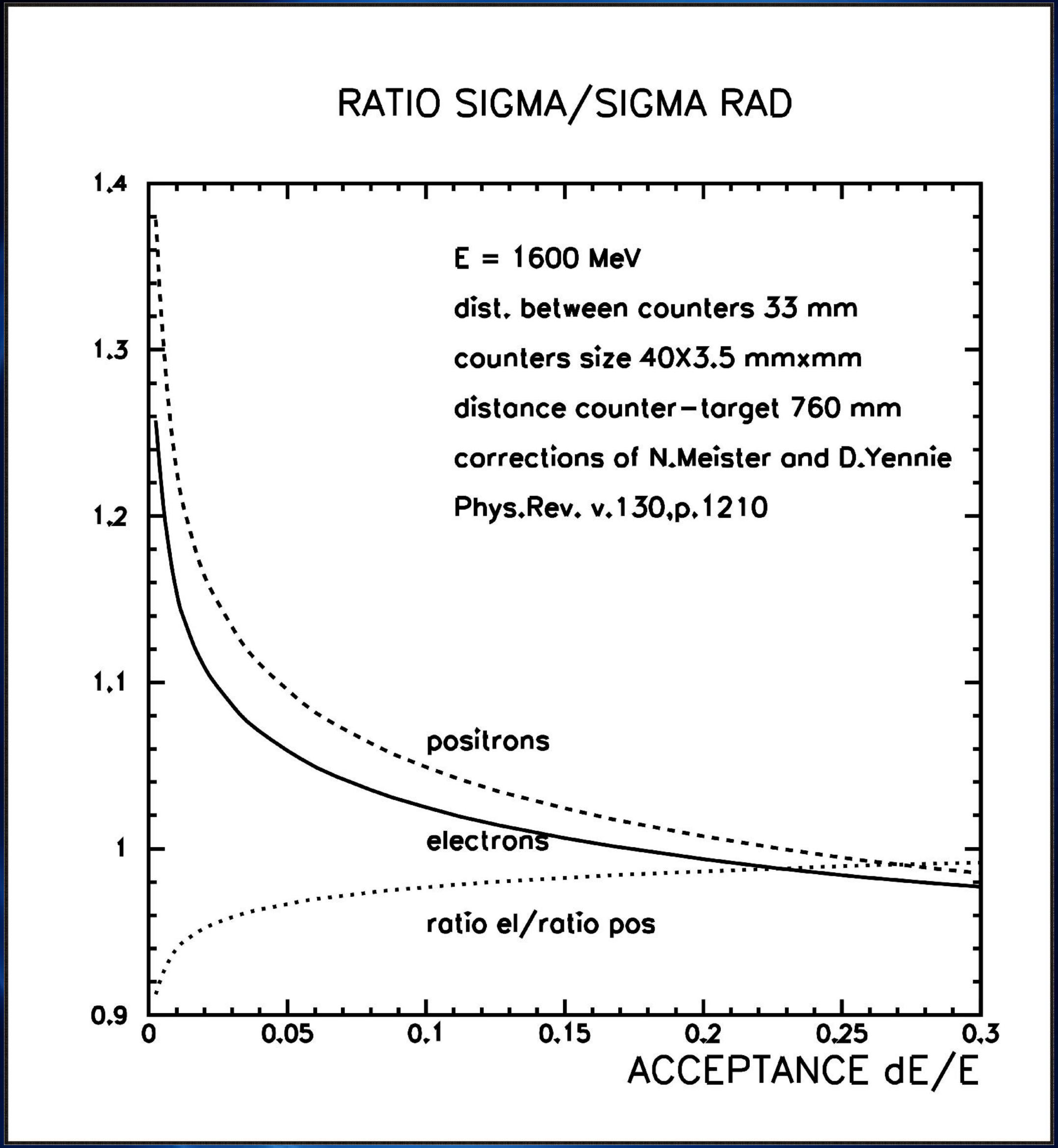
R dependence versus the e beam displacement
(calculation)



Dependence of the ratio of the cross sections versus the beam displacement



Radiation correction influence on the ratio of the cross section



CONCLUSIONS

- **Internal target and particles detector for R measurement were tested during the test run at VEPP-3 storage ring (April 16 – June 2 2007)**

- **Under the new optics of VEPP-3 and in the presence of a storage cell were found some regimes of VEPP-3 operation: storage of electrons/positrons, operation with the target at 1.6 GeV energy for R measurement, operation with synchrotron light beams, extraction of electron/positron beams into VEPP-4 storage ring**

- **Precise energy measurement of circulated electron/positron beam with the use of the backward Compton scattering has been performed**

- **A data taking run has been done. A sum integral for electrons/positrons charge collected during the run equals of 6 kC**
- **Run and analysis of the data supported the validity of decision on the target, detector and efforts directed to suppress systematic errors. A preliminary result on R for middle and large scattering electrons/positrons angles has been obtained. Some shortness of the electronics were found and now improved**

- **To be completed experiment requires two-three month of accelerator operation. A scheduled time for the beginning is February of 2009.**

Part of people, who did the experiment

Making Positrons in Hall B

1. Electron beam hits radiator foil, producing photon beam
2. Photon beam strikes converter foil. e-/e+ pairs are produced.
3. Magnetic chicane:
   a) separates lepton beams
   b) blocks photon beam
   c) recombines lepton beams

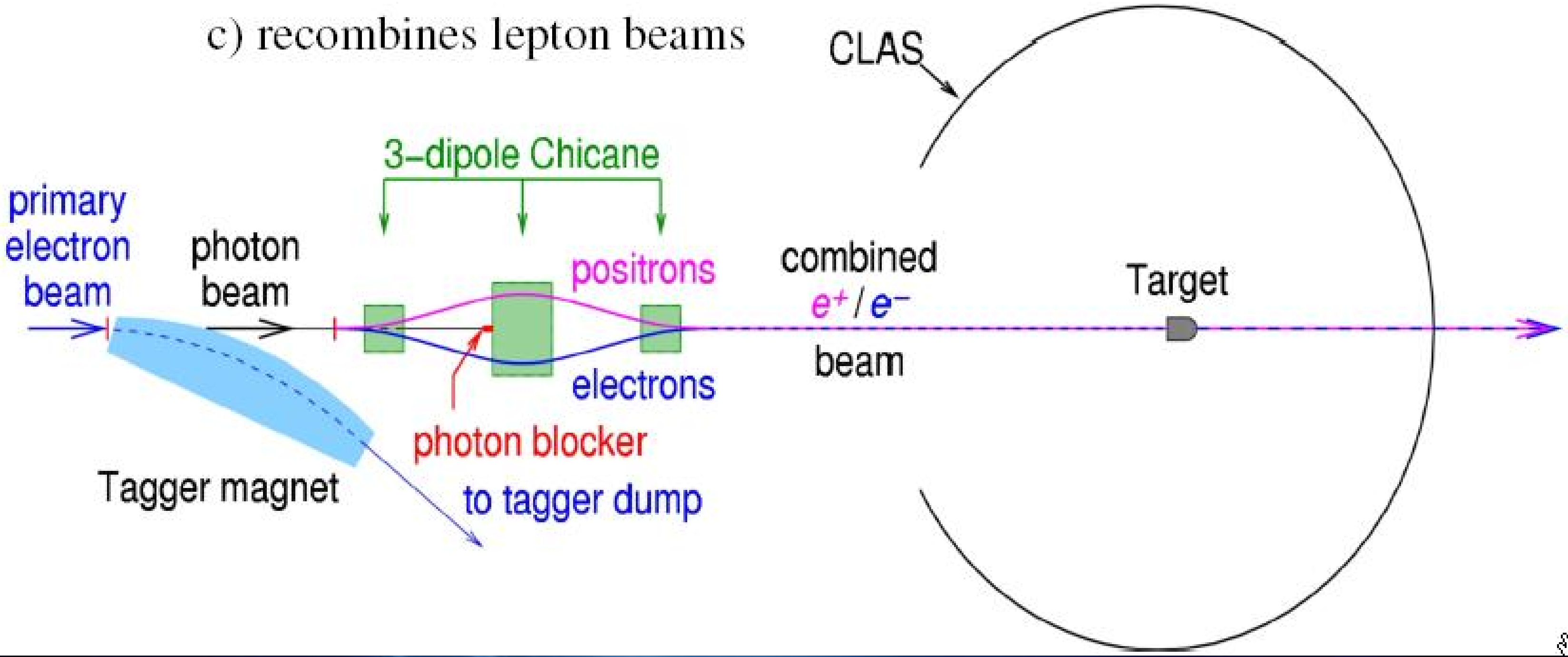
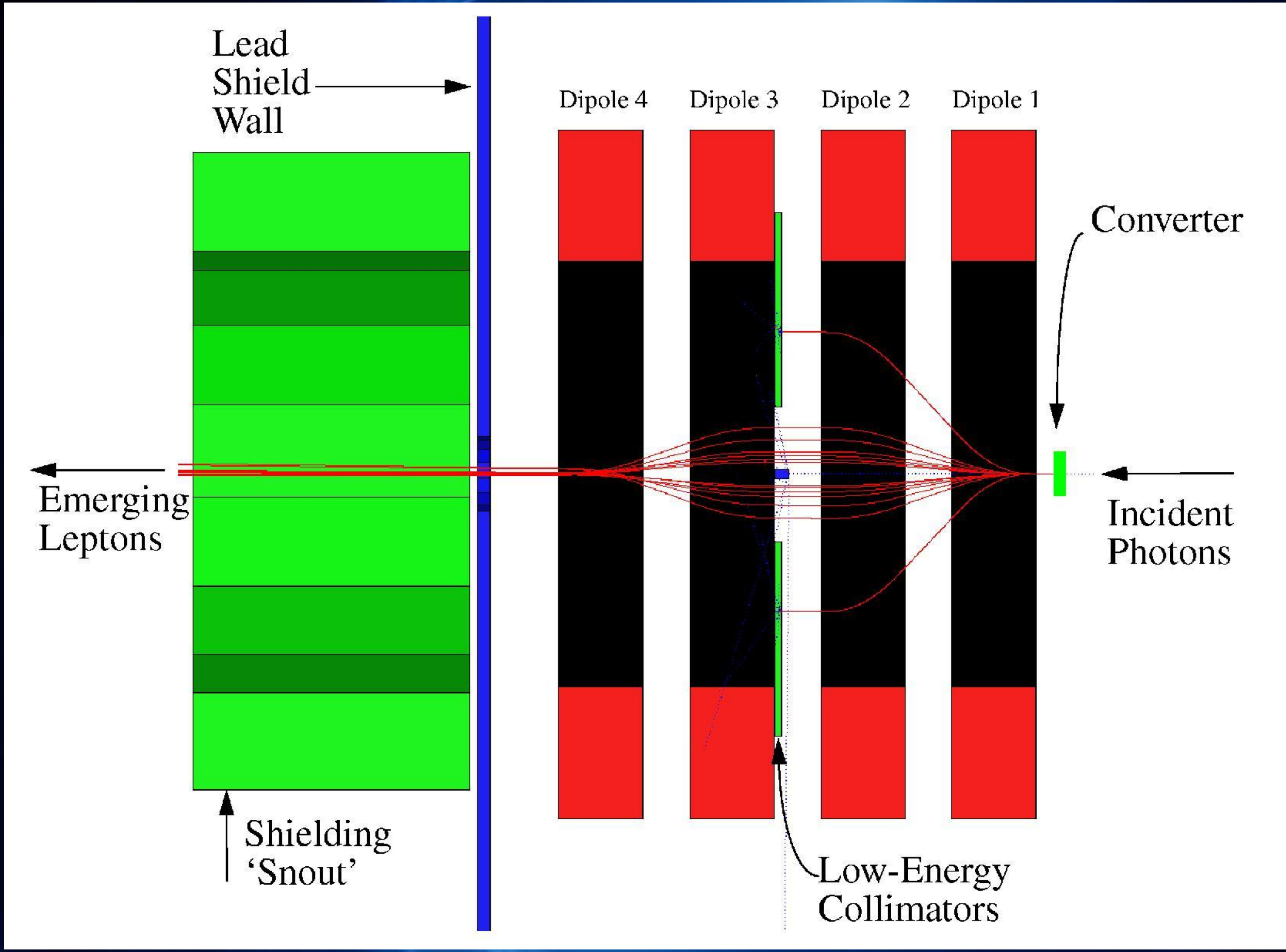
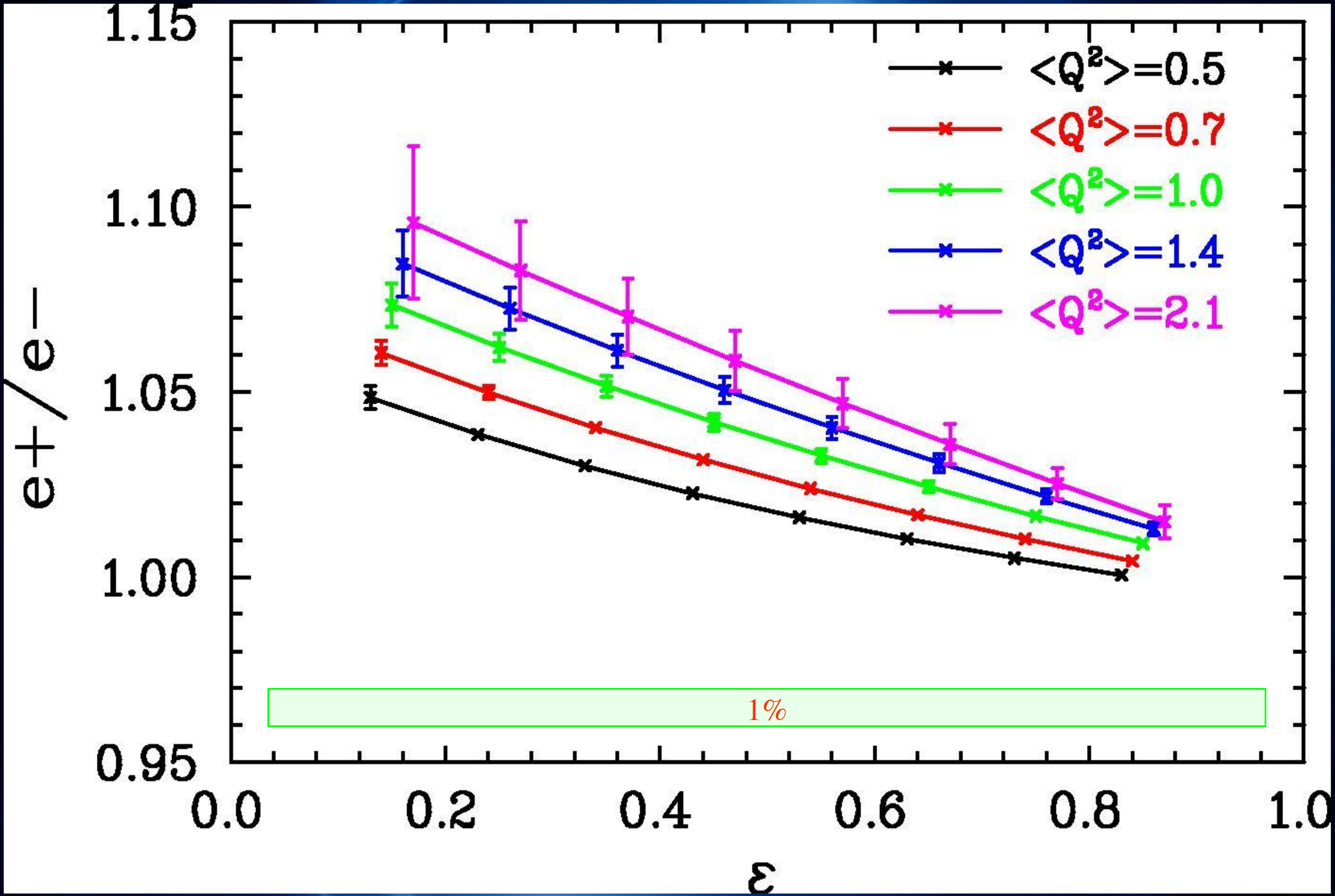


Схема эксперимента по измерению сечений *e+/e-* на протоне в JLab - США



Область переданных импульсов и ожидаемые в эксперименте ошибки в JLab_



Test Run Results: Luminosity

Maximum luminosity achieved:

- 80 nA 3.3 GeV electrons
- 0.5% radiator, 5% converter
- Lepton current at target: 20 pA (80nA*0.5%*5%)
  - Limited by non-track drift chamber (DC) occupancy
  - Region 1 DC occupancy 2.3% (3% is upper limit)
    - Dominated by beampipe and heat exchanger scattering
  - Region 3 DC occupancy 0.7%
    - Dominated by tagger
- Luminosity and backgrounds agree with simulations.
- Factor of ~20 improvement on previous test runs
- Need additional factor of ~25