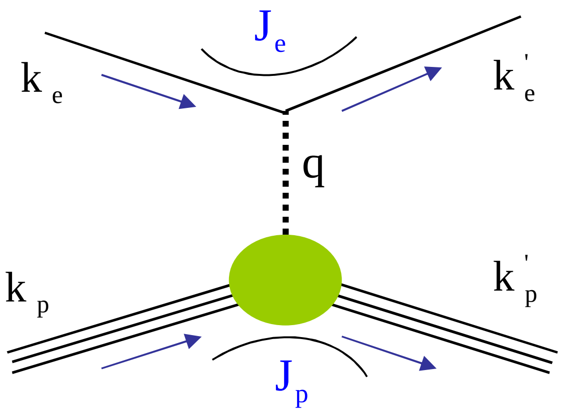
Эксперимент OLYMPUS и форм факторы протона

С.Белостоцкий

Юбилейная Сессия ОФВЭ декабрь 23-26, 2013

OVERVIEW



$$J_p^{\mu\nu} = e_p \bar{u}(k'_p)\left[F_1(Q^2)\gamma^\mu + \frac{1}{2M_p}F_2(Q^2)i\sigma^{\mu\nu}q_\nu\right]u(k_p)$$

Unpolarized experiments /Rosenbluth separation

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

$$\tau = \frac{Q^2}{4M_p^2} \quad \varepsilon = \frac{1}{1+2(1+\tau)\tan^2(\theta_e/2)} \quad 0<\varepsilon<1$$

Robert Hofstadter
Nobel prize 1961

ep-elastic
finite size of the proton
R_p ~ 0.8 fm

Nucleon elastic form factors …

- Fundamental quantities
- Defined in context of single-photon exchange

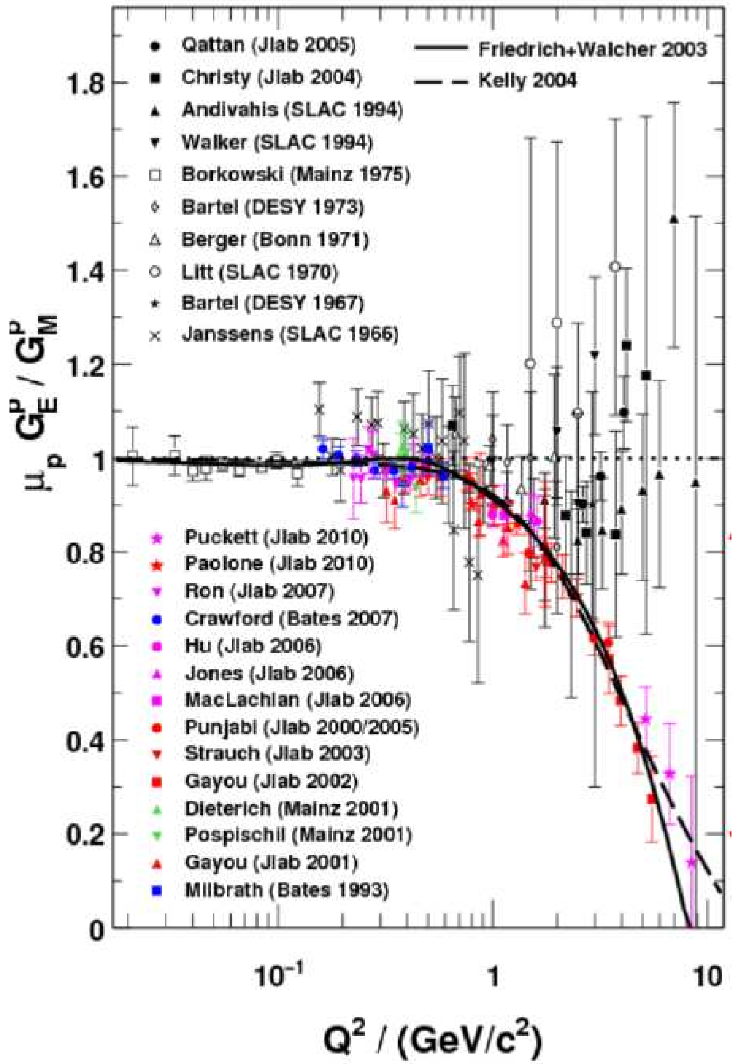
- Describe internal structure of the nucleons
- Related to spatial distribution of charge and magnetism

- Rigorous tests of nucleon models
- Determined by quark structure of the nucleon
- Role of orbital angular momentum and diquark correlation
- Ultimately calculable by Lattice-QCD
- Input to nuclear structure and parity violation experiments

50 years of ever increasing activity

- Tremendous progress in experiment and theory over last decade
- New techniques / polarization experiments
- Unexpected results

Drastic disagreement !!



World unpolarized experiments

Rosenbluth separation method suggests

$$\frac{\mu_p G_E(Q^2)}{G_M(Q^2)} \simeq 1$$

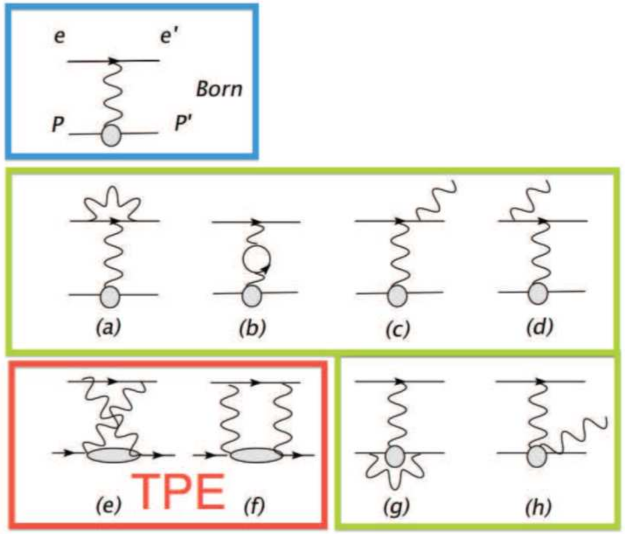
JLAB polarization experiments

Direct measurement of $\frac{\mu_p G_E(Q^2)}{G_M(Q^2)}$

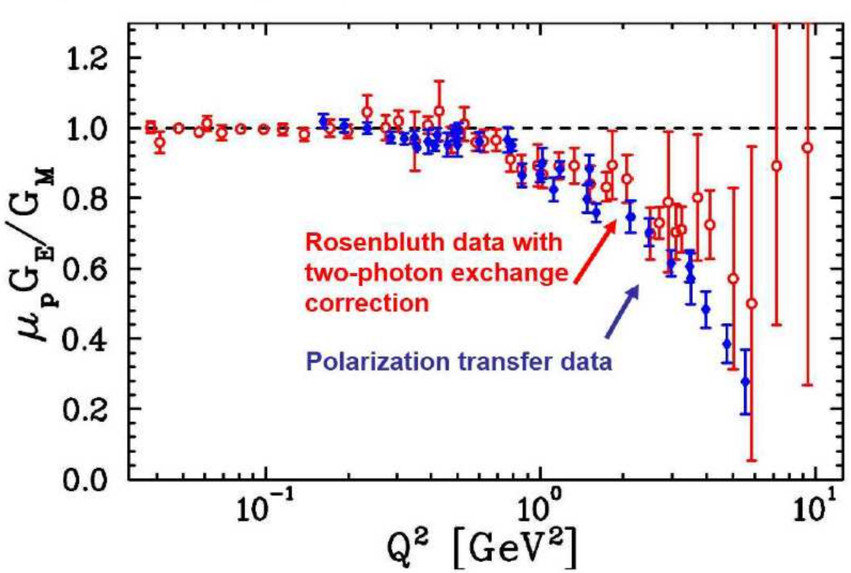
Spin transfer from polarized electron to recoil proton, $P_{\parallel}$ and $P_{\perp}$ components

$$\frac{\mu G_E(Q^2)}{G_M(Q^2)} = \mu \frac{P_{\perp}}{P_{\parallel}} \cdot \sqrt{\frac{\tau(1+\varepsilon)}{2\varepsilon}}$$

Possible explanation



TPE can explain form factor discrepancy
J. Arrington, W. Melnitchouk, J.A. Tjon,
Phys. Rev. C 76 (2007) 035205

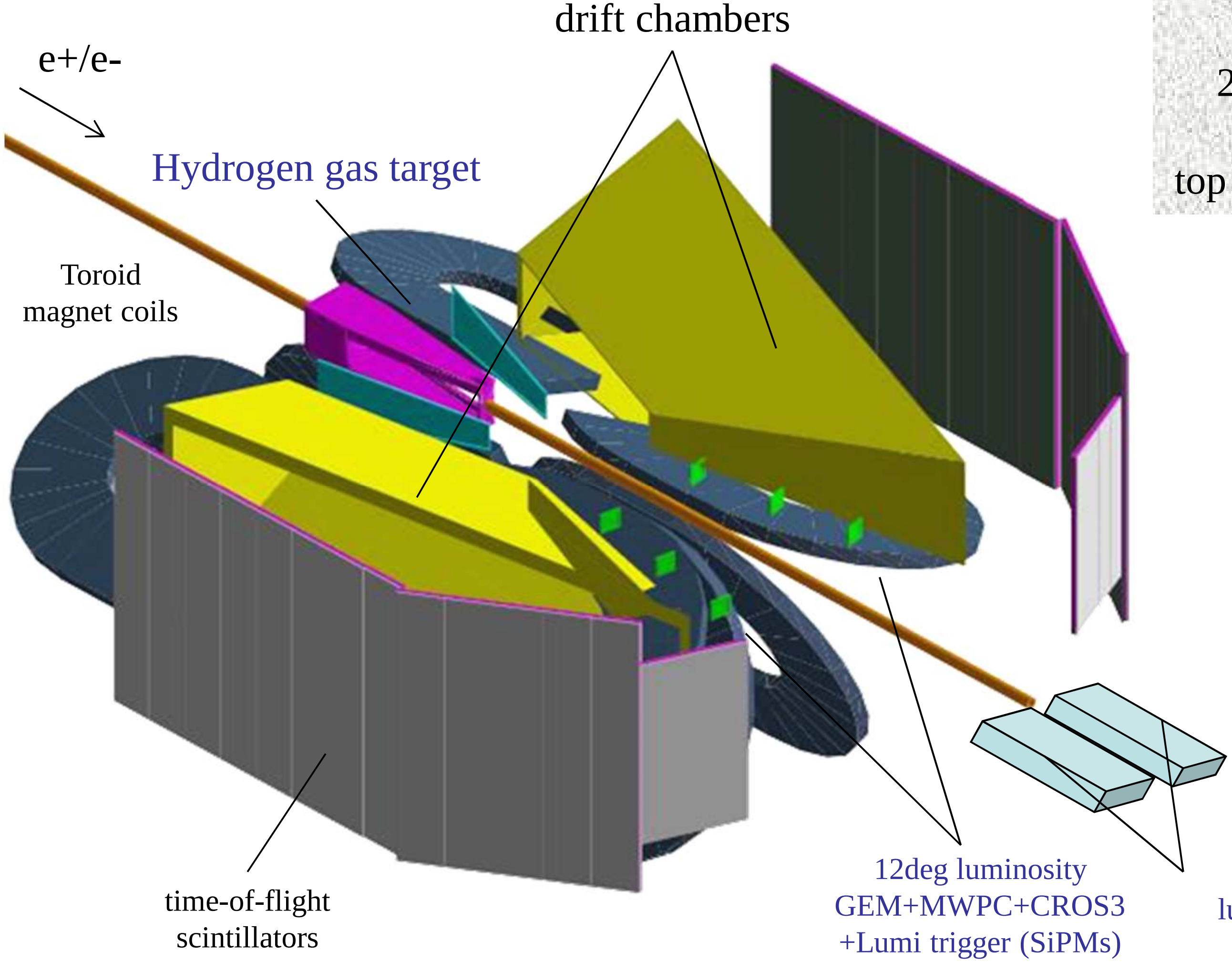


Sensitive to TPE is beam charge asymmetry:

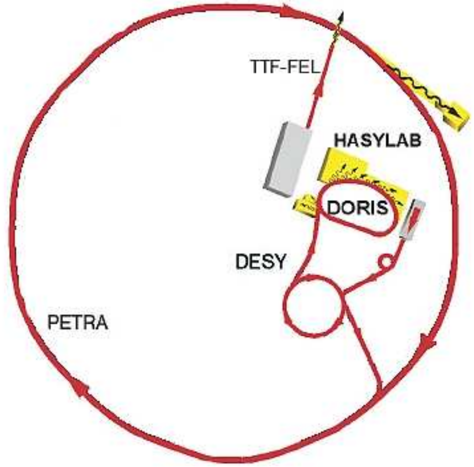
$$A^{\pm} = \frac{\sigma^{e^+p} - \sigma^{e^-p}}{\sigma^{e^+p} + \sigma^{e^-p}} = \frac{2\,\mathrm{Re}(M_{\mathrm{Born}} M^*_{\mathrm{TPE}}) + 2\,\mathrm{Re}(M_{e-\mathrm{bremstr}} M^*_{p-\mathrm{bremstr}})}{|M_{\mathrm{Born}}|^2 + \mathrm{QED}^{\mathrm{even}}_{\mathrm{rad.cor.}}} \simeq \frac{2\,\mathrm{Re}(M_{\mathrm{Born}} M^*_{\mathrm{TPE}})}{|M_{\mathrm{Born}}|^2}$$

$$\frac{\sigma^{e^+p}}{\sigma^{e^+p}} = \frac{1 - A^{\pm}}{1 + A^{\pm}}$$

Olympus experiment at Doris to measure e^+p / e^-p cross section ratio as function of Q^2



DORIS
2.01 GeV e+/e- beam 65 mA
switching every 8 hours
top up mode -> refill every 2 min



OLYMPUS collaboration

- Arizona State University, USA
- DESY, Hamburg, Germany
- Hampton University, USA
- INFN Bari, Ferrara, and Rome, Italy
- MIT and MIT-Bates, USA
- Petersburg Nuclear Physics Institute, Russia
- University of Bonn, Germany
- University of Glasgow, United Kingdom
- University of Mainz, Germany
- University of New Hampshire, USA
- Yerevan Physics Institute, Armenia

Российские участники

ПИЯФ

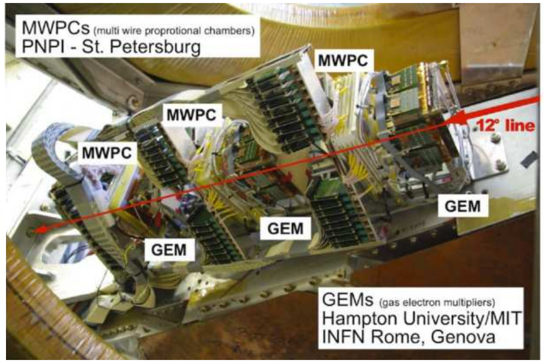
С.Белостоцкий Г.Гаврилов
Д.Веретенников А.Изотов
А.Киселев А.Крившич
О.Миклухо Ю.Нарышкин
К.Суворов

ПИЯФ hardware contribution

12deg. Luminosity monitor
MWPCs 6 UXV modules, 1mm
with CROS-3 readout electronics
+ trigger scintillation counters
readout with SiPMs

Olympus detector

Olympus detector in parking position



12deg. Luminosity monitor

Target cell and open vacuum chamber

Symmetric Møller / BhaBha monitor

Olympus timelines

2008 – 2012

- *Proposal* 09/ 2008
- *Experiment funded* 01/2010
- *Test experiment at Doris* 02/2011
- *Setup installed* 12/2011
- *Data taking Run I (1 month)* 02/2012
- *Tests, preparation to Run II, wire chambers upgrade* up to 10/2012
- *Data taking Run II (2.5 month)* up to mid 01/2013

Radiation corrections in ep elastic scattering workshops:

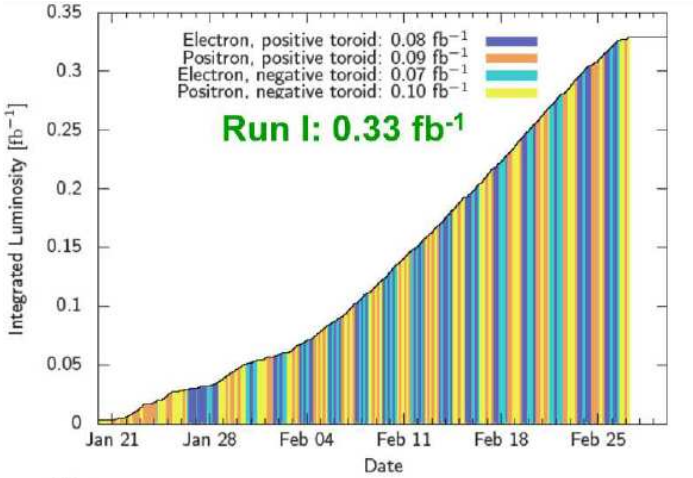
- **MIT July 2011**
- **PNPI July 2012**
- **Orsay September 2013**

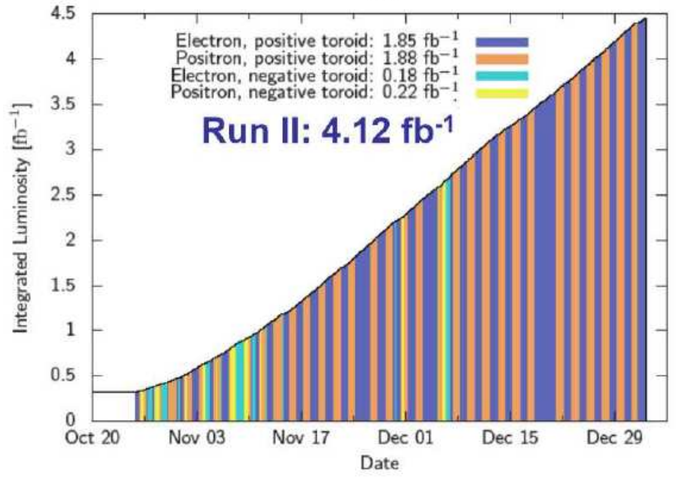
2013 – 2014

- *End of data taking* 01/ 2013
- *Doris shutdown* 02/2013
- *Toroid magnetic field measurements, data analysis started* 02/-03/2013
- *Setup survey and disassembly* 04/2013
- *100 runs (of 10^4 runs) tentatively analyzed* 09/2013
- *NIM paper submitted* 12/2013
- *Track reconstruction finished, all runs analyzed* 04/2014
- *Systematic studies, cross-checks* 09/2014
- *Paper submitted* 12/2014

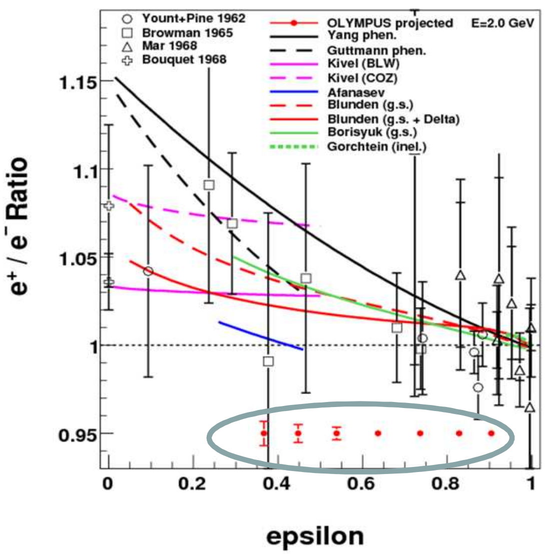
Total integrated luminosity 4.45 fb^{-1}

Collected in Run I+Run II for 2x500h data taking for each (e^+e^-) beam species





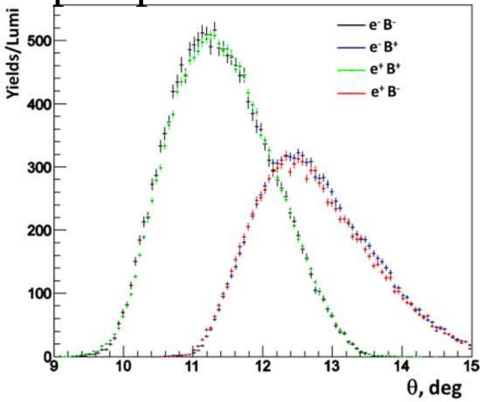
Projected statistical precision @ integrated luminosity of 3.6 fb^{-1}



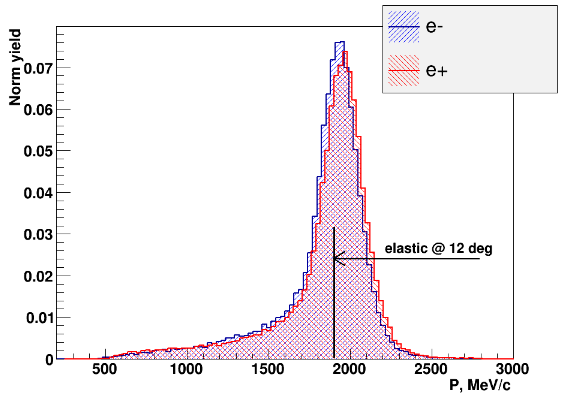
12 deg. monitor

e^+p or e^-p coincidences of 12 deg. trigger, GEM+MWPC tracking

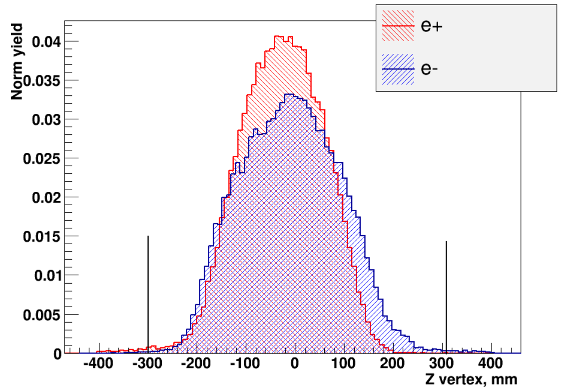
$e^+p/e^-p = 1.00672 \pm 0.00008$



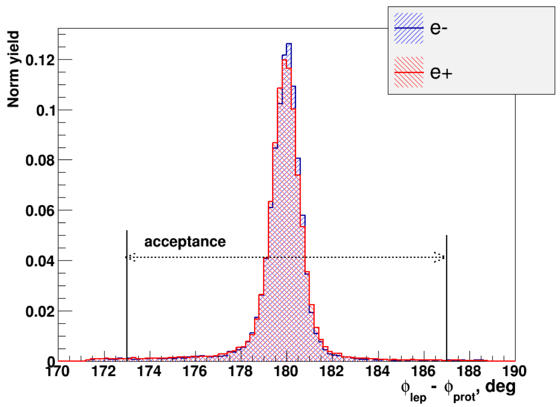
e^+p or e^-p at B^+ or B^-



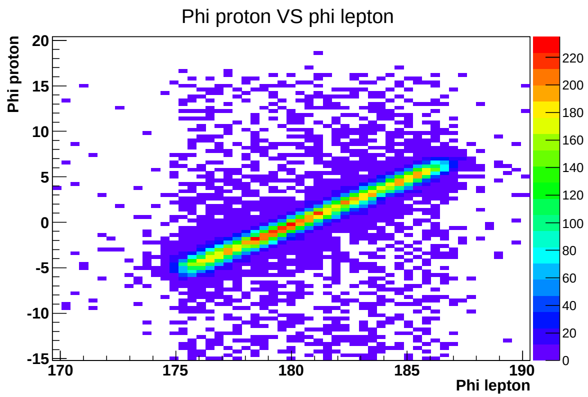
e^+ or e^- momentum distribution



e^+ or e^- vertex distribution (along the beam)

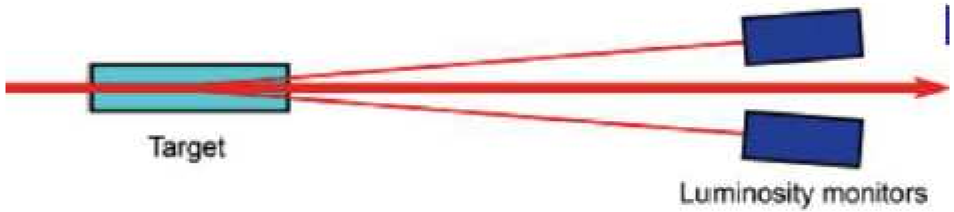


e^+p or e^-p co-planarity



e^+p or e^-p co-planarity

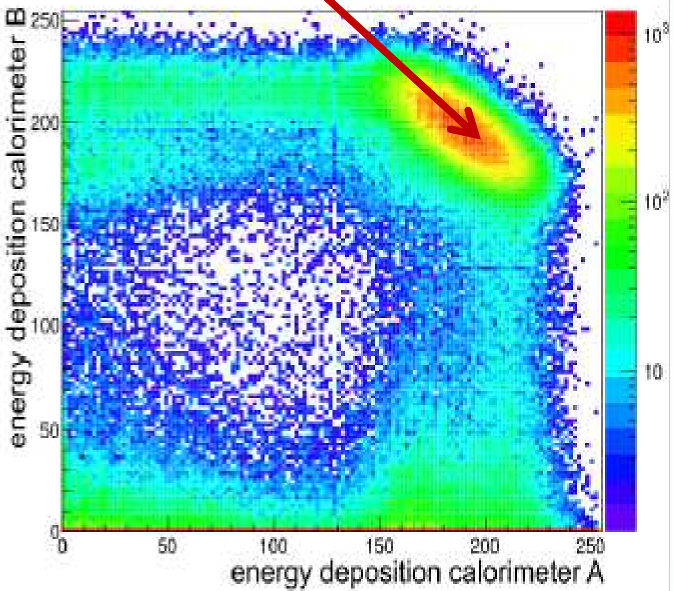
Symmetric Møller /Bhabha monitor

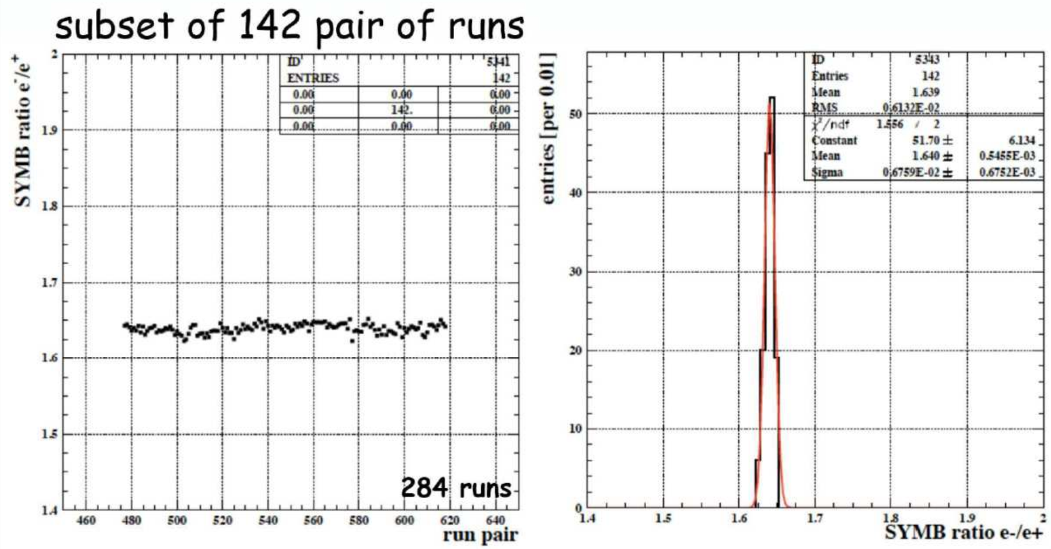


at 2 GeV $\theta_{symm.}(e^-e^-, e^+e^-) = 1.3 deg.$

e^-e^- Møller scattering
e^+e^- Bhabha scattering
e^-e^-/e^+e^- obtained 1.64
close to MC simulation

Coincidence peak



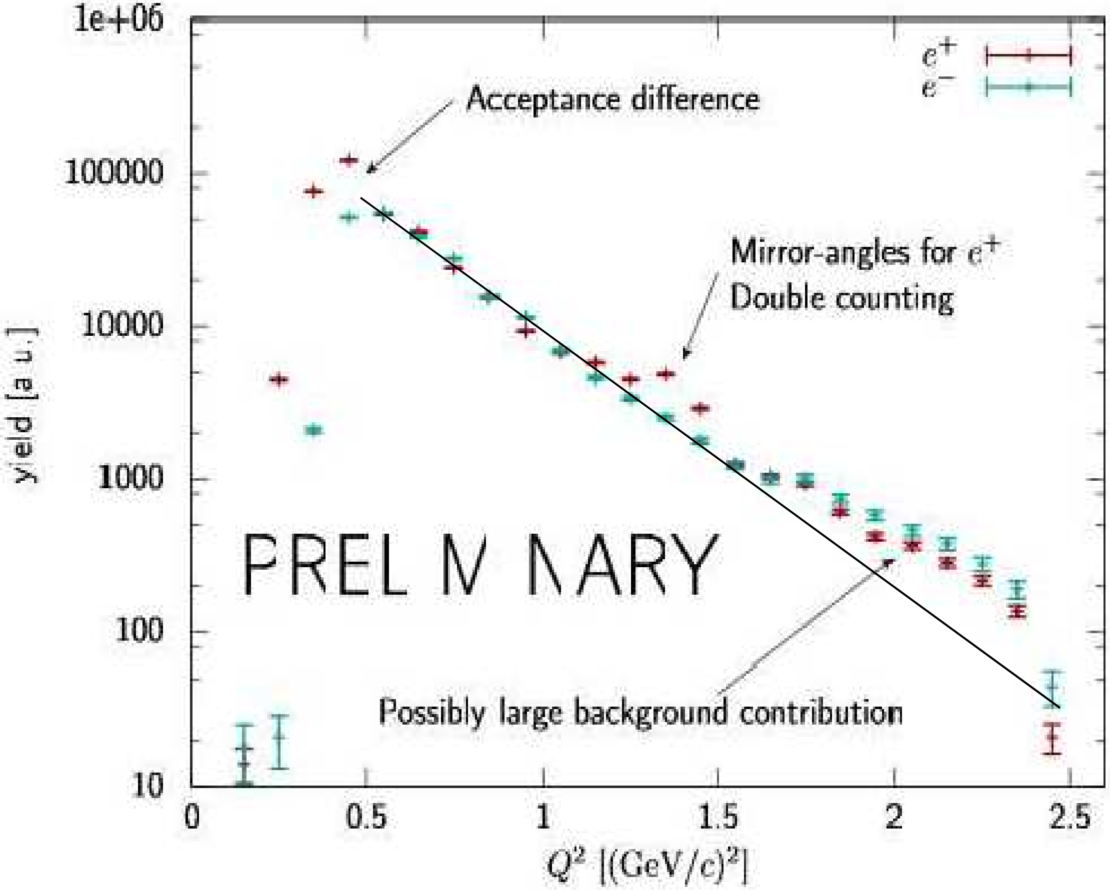


$\chi^2 = 1.556/2 = 0.778$

Mean $\pm$ RMS : 1.639 ± 0.006
Mean $\pm\ \sigma$: 1.640 ± 0.007

Raw yields of Q^2

- $\approx$ 2% of all data
- no acceptance correction
- relative normalization fixed at small Q^2
- Cuts on:
  - coplanarity
  - vertex z difference
  - momentum balance
  - proton missing momentum



Caveat: ***WC tracking is still not finished !!***

Outlooк: *PNPI in data analysis 2014*

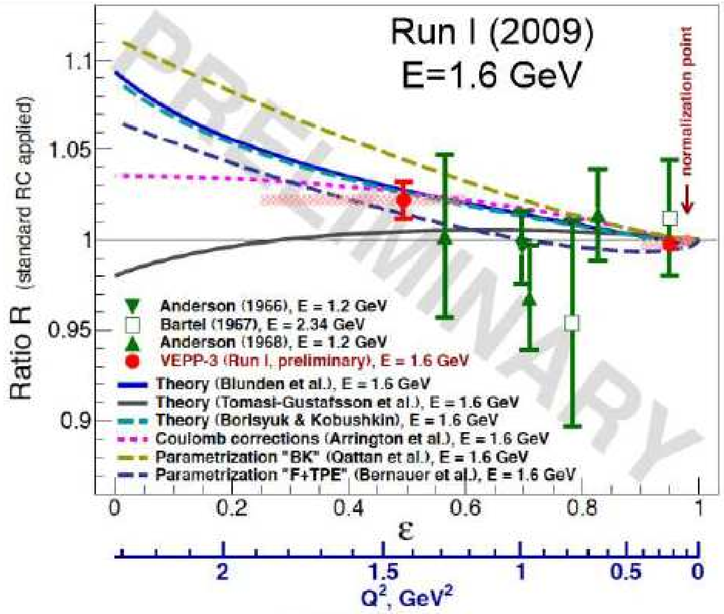
- MC simulation e^+ vs e^- systematics
  Ю.Нарышкин
- Extraction of experimental charge asymmetry
  Д.Веретенников
- 12deg. monitoring system data analysis
  Д.Веретенников
- MC generator for pion production
  К.Суворов
- DESY analysis group coordination
  С.Белостоцкий

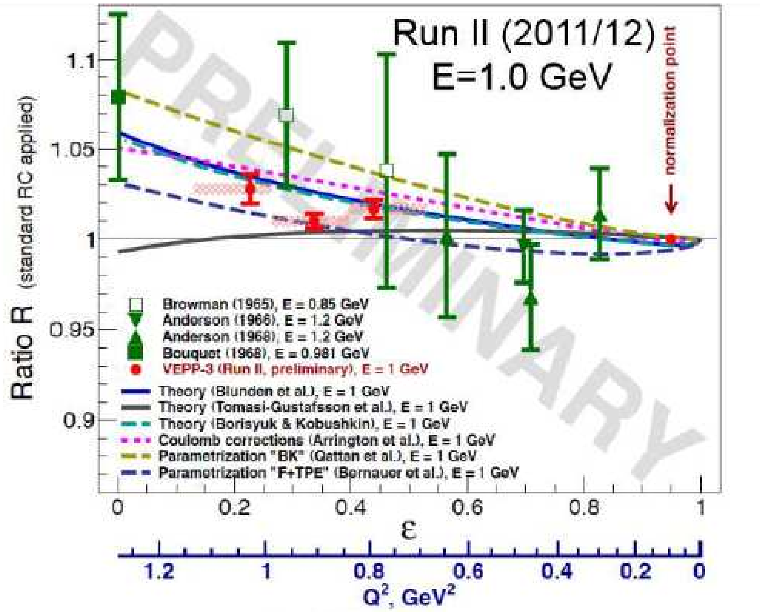
BACKUP SLIDES

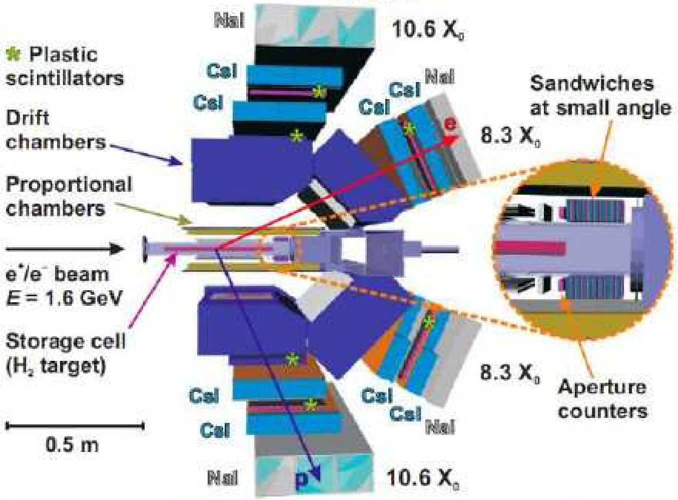
Comparison of beam charge asymmetry experiments

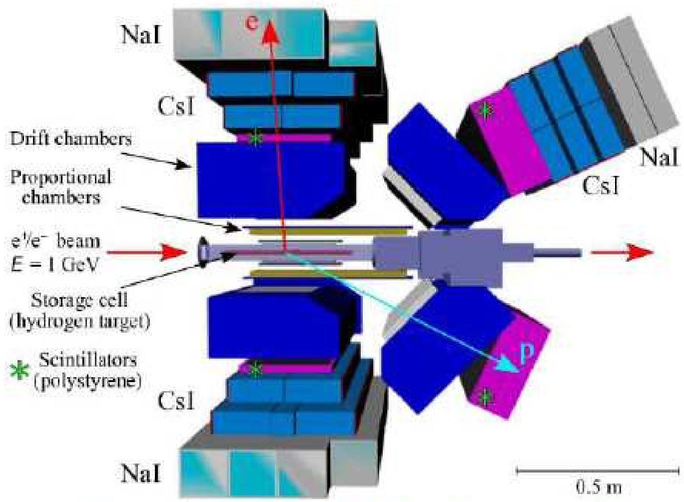
	VEPP–3 Novosibirsk	OLYMPUS DESY	EG5 CLAS JLab
beam energy	3 fixed	1 fixed	wide spectrum
equality of $e^{\pm}$ beam energy	measured	measured	reconstructed
e^+/e^- swapping frequency	half-hour	8 hours	simultaneously
e^+/e^- lumi monitor	elastic low-Q^2	elastic low-Q^2, Möller/Bhabha	from simulation
energy 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}
beam type	storage ring	storage ring	secondary beam
target type	internal H target	internal H target	liquid H target
data taken	2009, 2011-12	2012	2011
Publications	preliminary	data analysis	data analysis

VEPP-3 Novosibirsk experiment



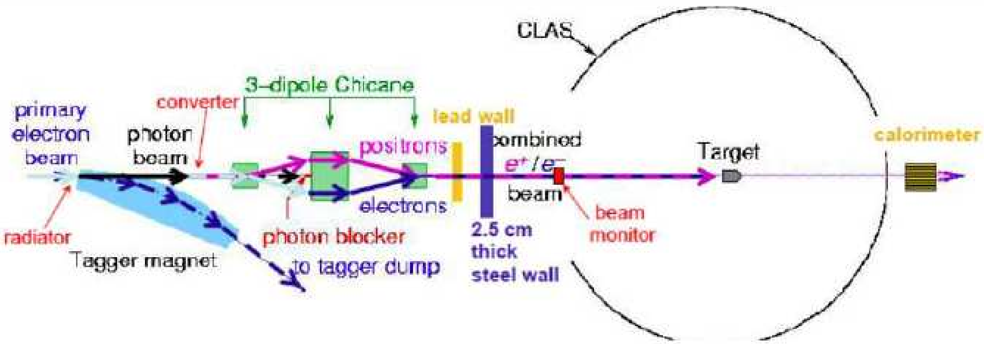


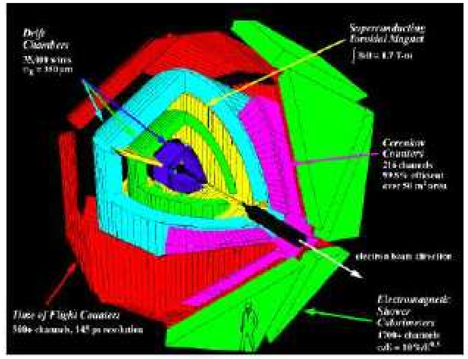


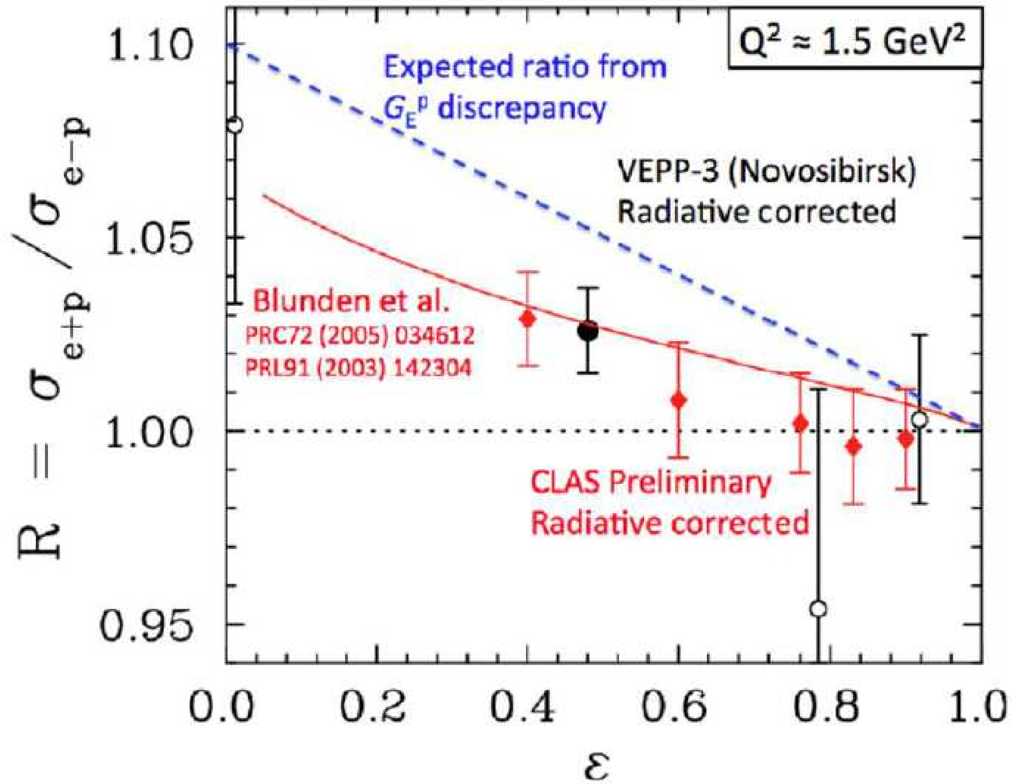


A. Gramolin, Workshop on Radiative Corrections in Annihilation and Scattering Experiments, Orsay, October 7-8, 2013

CLAS experiment at JLAB



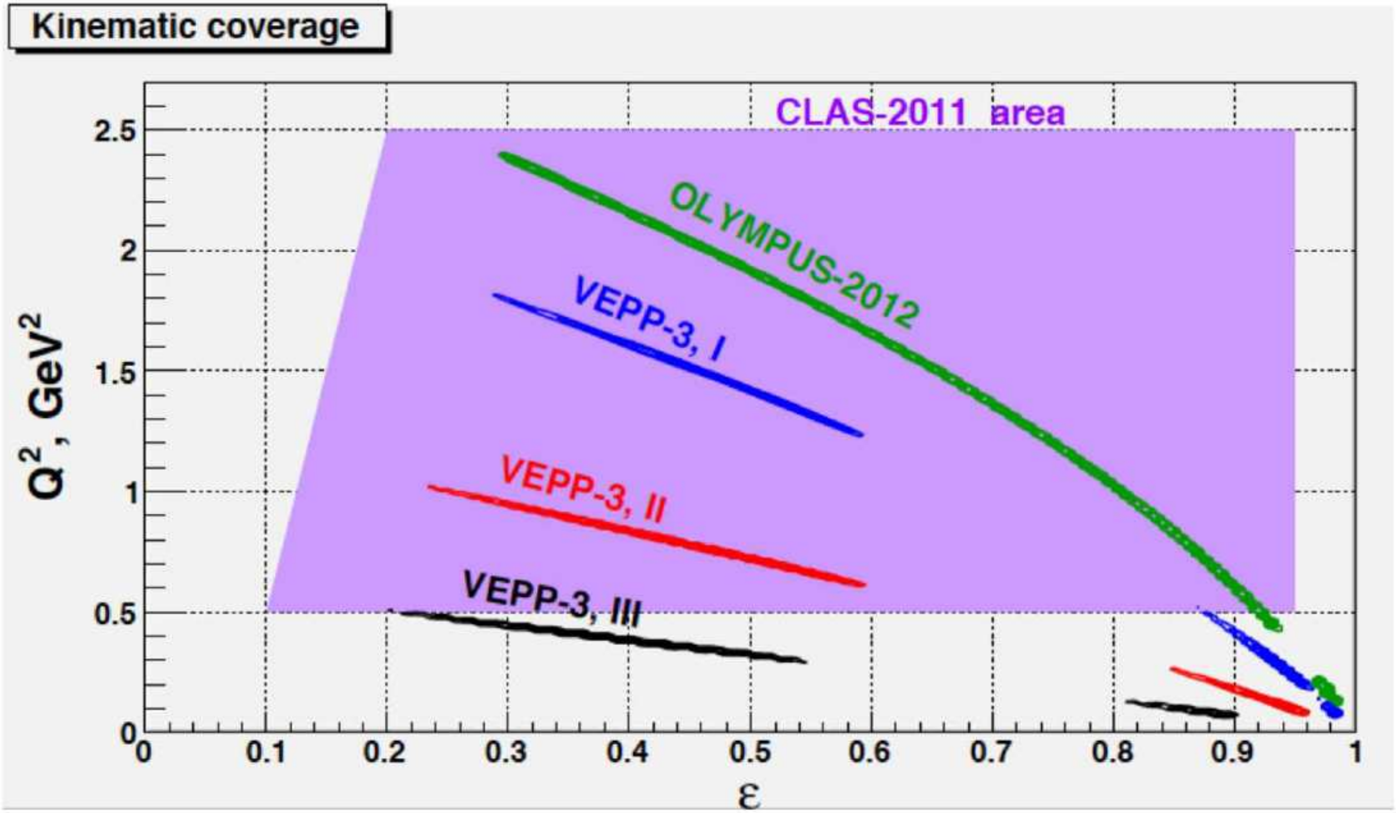




Dasuni Adikaram (ODU), DNP2013 DH.00005

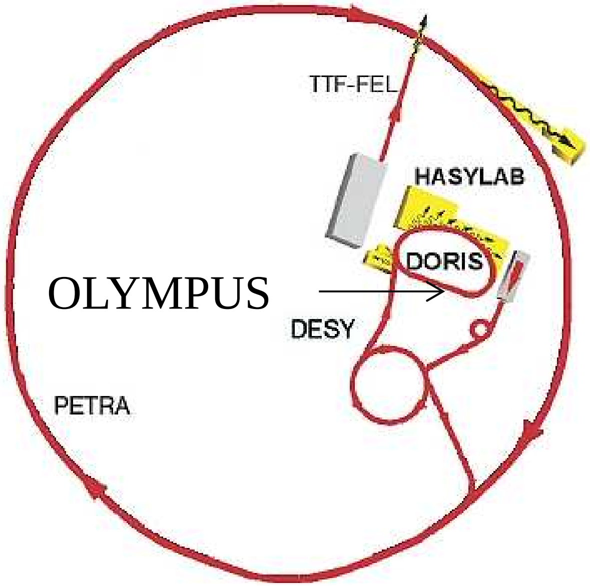
Dipak Rimal (FIU) DNP2013 DH.00006

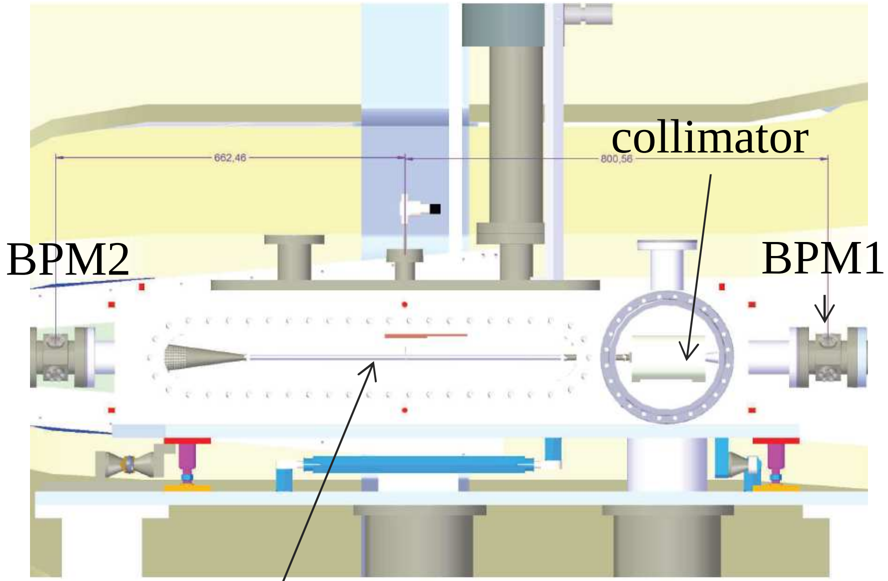
- Novosibirsk experiment ($E_{\text{beam}} = 1.6$, 1 and 0.6 GeV)
- CLAS @ JLab experiment ($E_{\text{beam}} = 0.5 \div 4$ GeV)
- OLYMPUS @ DESY experiment ($E_{\text{beam}} = 2$ GeV)



OLYMPUS at DORIS, DESY

Study of e^+p, e^-p elastic scattering in identical conditions @ 2 GeV





Hydrogen target region

Doris storage ring 2-4.5 GeV
2 GeV $\mathbf{e^+, e^-}$ beams, **100 mA**, change daily,
Beam energy stability **0.5 MeV**
Beam position **0.1mm**
quasi **continuous** beam ("topup" mode)

Target cell elliptical 9x16mm**2.
length 60mm, $\mathbf{8 \cdot 10^{15}\ atoms \cdot cm^{-2}}$
Beam sizes 0.6x0.1mm**2

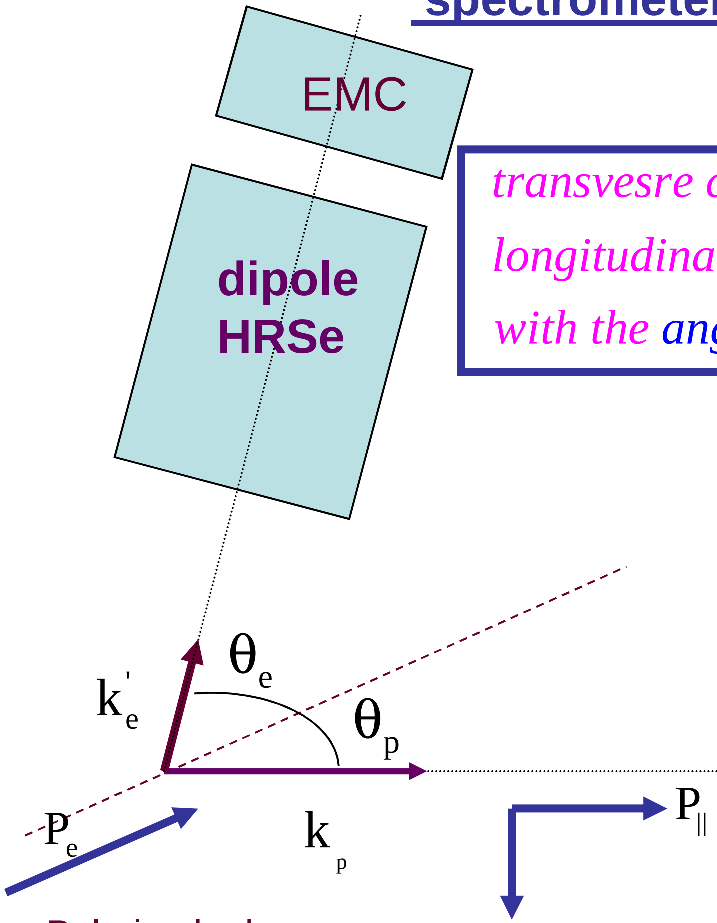
JLAB Polarization Transfer experiment

(V.Punjabi, C.F.Perdrisat, et al. Phys.Rev. C71, 2005)

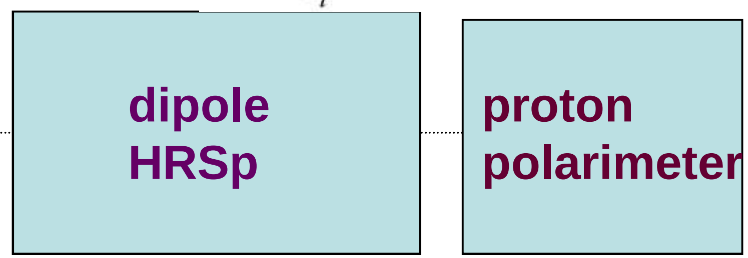
$$\frac{G_E^2(Q^2)}{G_M^2(Q^2)} = -\frac{P_\perp}{P_\parallel} \cdot \frac{E_e + E_e^{'}}{2M_p} \tan(\theta_e / 2)$$

JLAB Hall A two-arm spectrometer (top view)

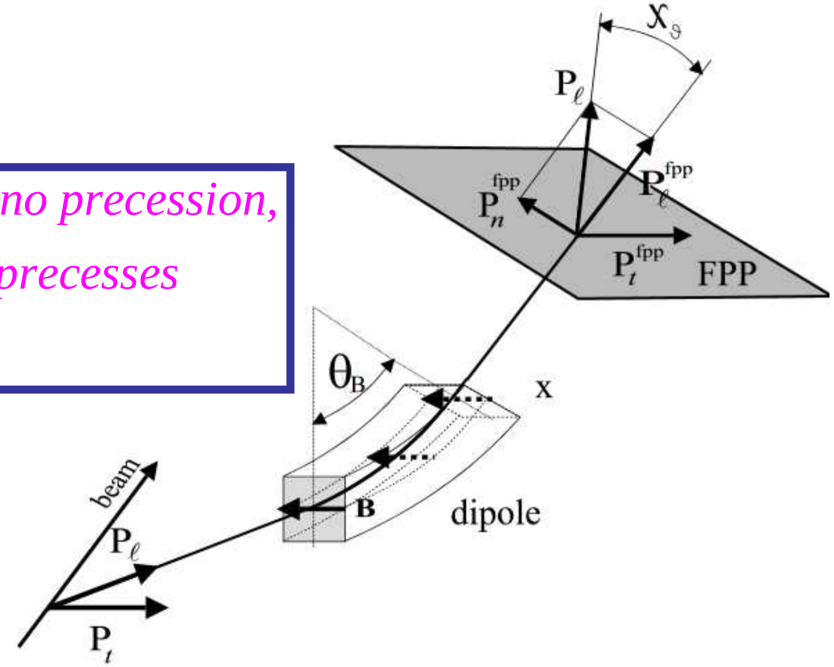
transvesre component $P_\perp$ *no precession,*
longitudinal component $P_\parallel$ *precesses*
with the angle $= \gamma(\mu_p - 1)\Theta_B$



Polarized e-beam
P_e ~0.4-0.6,
0.934-4.091 GeV,
5-15 μA.



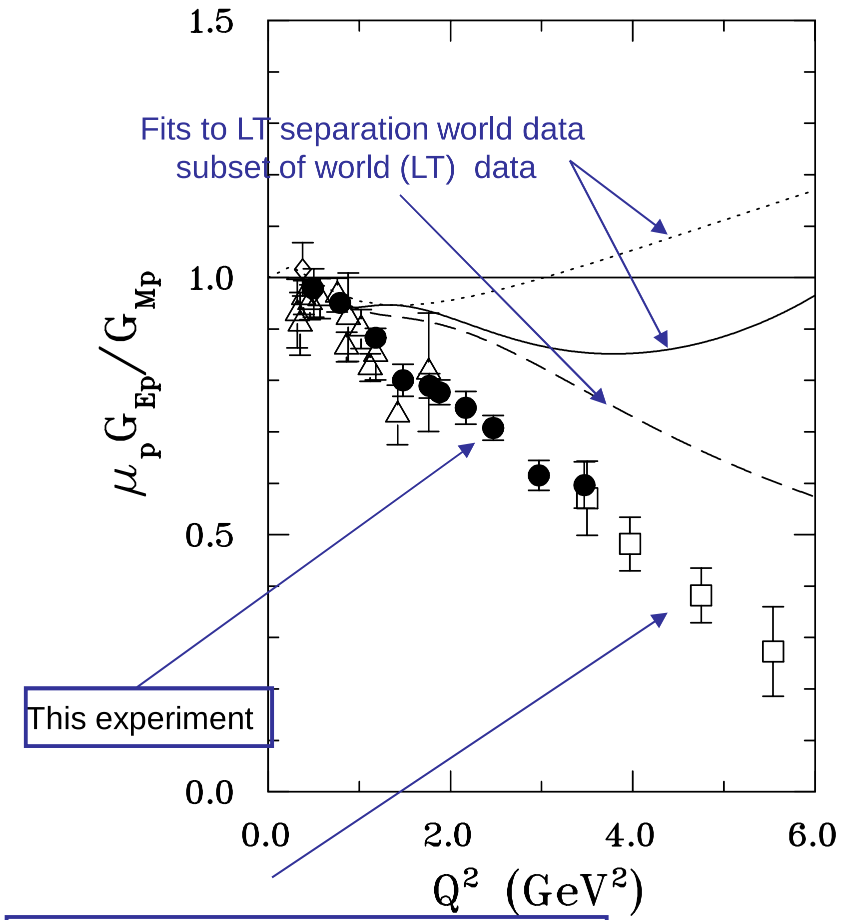
Vertical bending
Θ_B=45 deg.



JLAB Polarization Transfer Results

(V.Punjabi, C.F.Perdrisat, et al. Phys.Rev. C71, 2005)

disagreement with LT separation results



O.Gayou et al. phys.Rev.Lett. 88, 2002

TABLE VI: The ratio $\mu_p G_{Ep}/G_{Mp}\pm$ statistical uncertainty (1σ). Δ_{sys} is the systematic uncertainty from Table VII. $\overline{Q}^2$ and $\overline{\chi}_\theta$ are the weighted average four momentum transfer squared and spin precession angle, respectively. ΔQ^2 is half the Q^2 acceptance. The last column P_t/P_ℓ is the ratio of measured polarization components at the target, the relative uncertainty is the same as for $\mu_p G_{Ep}/G_{Mp}$.

$\overline{Q}^2 \pm \Delta Q^2$ (GeV^2)	$\overline{\chi}_\theta$ (deg)	$\mu_p G_{Ep}/G_{Mp}$ (± stat. uncert.)	Δ_{sys}	P_t/P_ℓ
0.49±.04	105	0.979 ± 0.016	0.006	-0.822
0.79±.02	118	0.951 ± 0.012	0.010	-0.527
1.18±.07	136	0.883 ± 0.013	0.018	-0.492
1.48±.11	150	0.798 ± 0.029	0.026	-0.422
1.77±.12	164	0.789 ± 0.024	0.035	-0.381
1.88±.13	168	0.777 ± 0.024	0.033	-0.368
2.13±.15	181	0.747 ± 0.032	0.034	-0.329
2.47±.17	196	0.703 ± 0.023	0.033	-0.284
2.97±.20	218	0.615 ± 0.029	0.021	-0.224
3.47±.20	239	0.606 ± 0.042	0.014	-0.198

Estimation of TPE effect on LT and polarization data

- ✓ *significant effect on LT separation results*
- ✓ *a few per cent effect on polarization data*

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

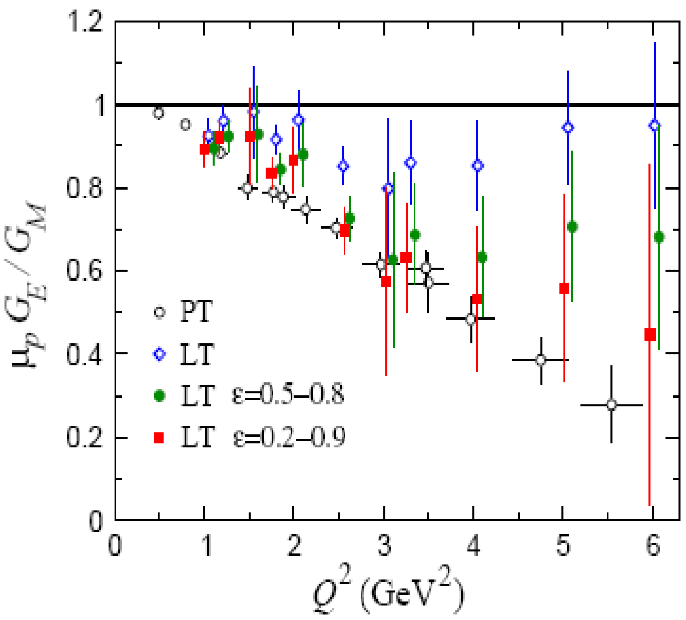


FIG. 5: The ratio of proton form factors $\mu_p G_E/G_M$ measured using LT separation (open diamonds) [2] and polarization transfer (PT) (open circles) [5]. The LT points corrected for 2γ exchange are shown assuming a linear slope for $\varepsilon = 0.2 - 0.9$ (filled squares) and $\varepsilon = 0.5 - 0.8$ (filled circles) (offset for clarity).

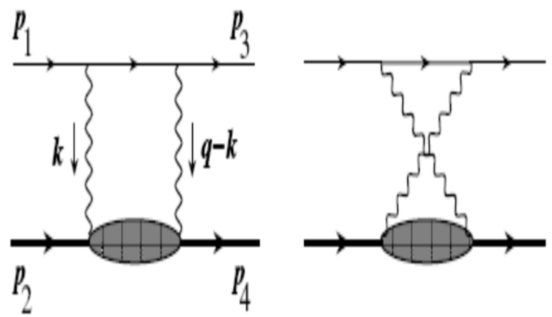


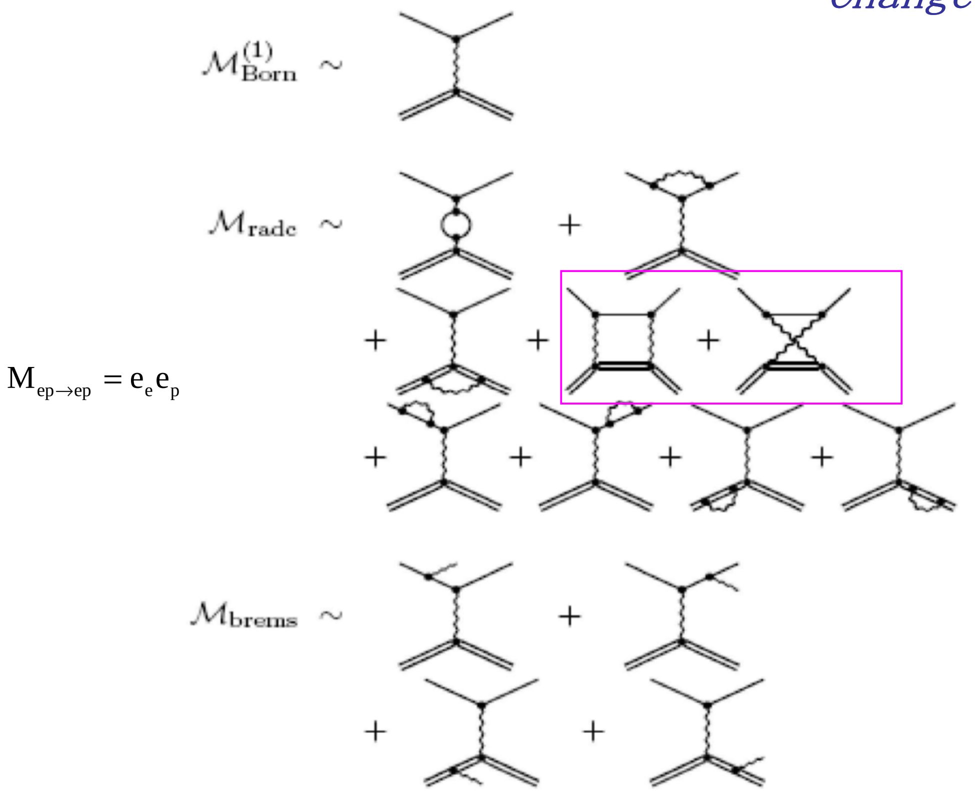
FIG. 1. Two-photon exchange box and crossed box diagrams for elastic electron-proton scattering.

Radiative Corrections & TPE graphs

Contribution from two photon exchange diagram not taken into account in traditional analysis may be an explanation

$$\left|M_{ep\to ep}\right|^2 = e_e^2 e_p^2\left[\left|M_{Born}\right|^2 + 2e_e e_p M_{Born}\,\mathrm{Re}\left(M^*_{2\gamma}\right) + 2e_e e_p\left(M_{e-bremm}\; M^*_{p-bremm}\right)\right]$$

Change sign



Calculable standard radiative correction

Projected OLYMPUS uncertainties

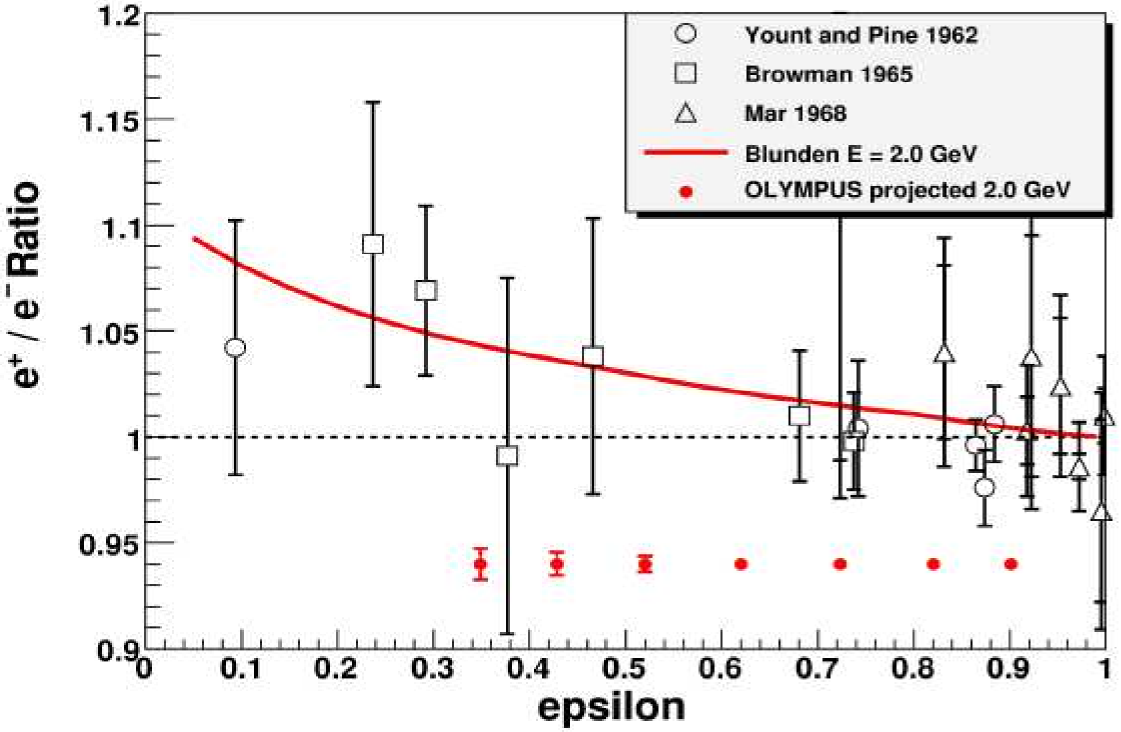


Figure 1.12: Projected uncertainties in the determination of the cross section ratio e^+p/e^-p for the BLAST detector for a beam energy of 2.0 GeV, as a function of ϵ. The assumed luminosity is $2 \cdot 10^{33}$ /(cm ^{2}s) $\times$ 500 hours each for running with electrons and positrons, respectively.

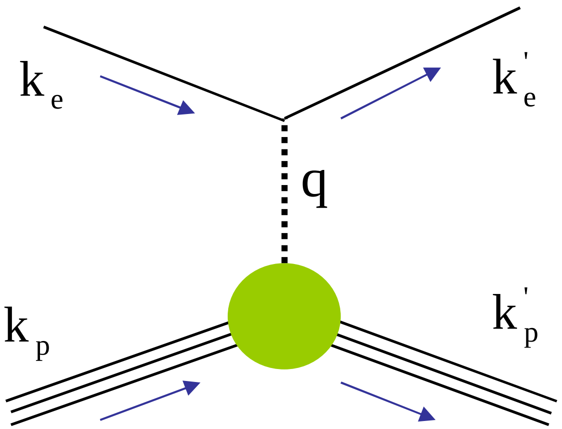
Conclusion & outlook

Experiments designed to measure charge asymmetry at per cent level

Experiment	E_{beam} GeV	Luminosity cm ^{2} sec^{-1}	ε_{min}	Q^{2} GeV	Planned for	Challenge
VEPP-3	1.6	10^{31}	0.4	0.1-1.76	2010-2012	Low lumi
JLAB	5.7	1.3×10^{33}	0.2	0.5-2.1	2012-….??	High bgr level
Olympus	2	$2. \times 10^{33}$	0.4	2-3	2011-2012	Continuation after 2012

FF DEFINITION.

FFs are defined in context of one photon exchange

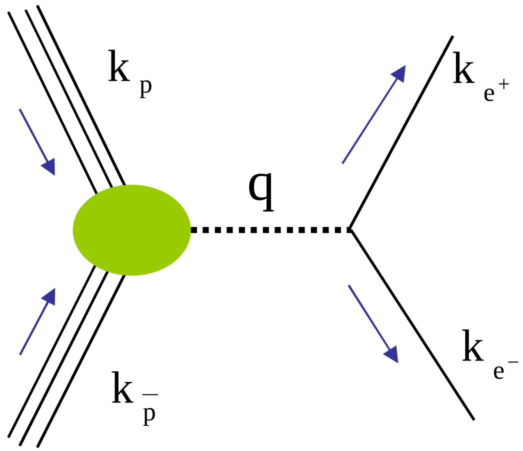


space-like photon $Q^2 > 0$

$$m_\gamma = q^2 = \left(k'_e - k_e\right)^2 = \left(k'_p - k_p\right)^2, \quad t = Q^2 = -q^2$$

$$q = q_0, \vec{q}$$

In CM frame $q_0 = 0,\ q^2 = q_0^2 - \vec{q}^{\,2} = -\left(\vec{p}\,' - \vec{p}\right)^2 = -4k^2 \sin^2\frac{\theta_{CM}}{2}$. *No energy transfer* $\rightarrow$ *equivalent to Breit frame*



time-like photon $Q^2 < 0$

$$m_\gamma = q^2 = \left(k_{e^+} + k_{e^-}\right)^2 = \left(k_p + k_{\bar{p}}\right)^2, \quad s = Q^2 = -q^2$$

$$q = q_0, \vec{q}$$

In CM frame $q_0 = 2k,\ \vec{q} = 0,\ q^2 = 4k^2$

poorly studied till now

$$q_0 = 0 \rightarrow \quad J_p^\mu = G_E(Q^2)\gamma^\mu + G_M(Q^2) i\sigma^{\mu\nu} q_\nu \quad \rightarrow \quad \rho_{E,M}\left(\vec{x}\right) = \int G_{E,M}\left(-q^2\right) e^{-i\vec{q}\vec{x}}\, d^3x$$

$$G_E^p(0) = 1 \quad G_E^n(0) = 0 \qquad G_M^p(0) = \mu_p \quad G_E^n(0) = \mu_n$$