Results and implications of OLYMPUS

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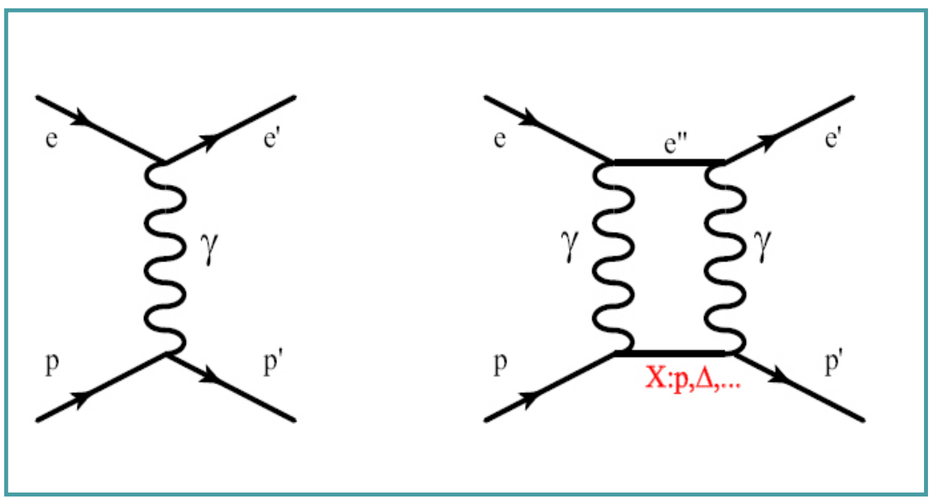
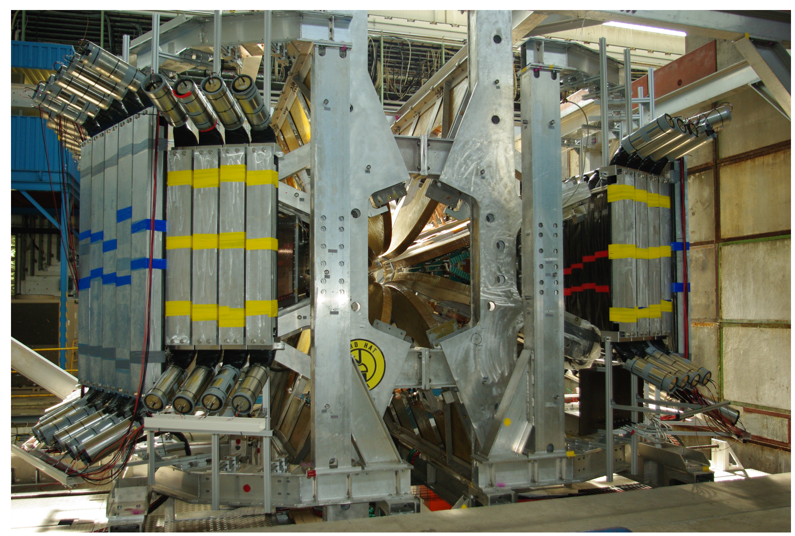
Outline

- **Proton form factors in the context of one-photon exchange (OPE)**
- **The limit of OPE or:**
  - **What is G_E^p ?**
  - **What is the nature of lepton scattering?**
- **Two-photon exchange (TPE): New observables**
- **Current and future experiments to probe TPE**
  ➔ OLYMPUS & more
- **Latest Review:**
  A. Afanasev, P.G. Blunden, D. Hasell, and B.A. Raue, PPNP 95, 245 (2017)





OLYMPUS @ DESY

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

60+ years of ever increasing activity

- Considerable progress in experiment and theory over last two decades
- New techniques / polarization experiments
- Unexpected results

G. Miller,
PRC68, 022201 (2003)

Recent proton FF, TPE, and PR experiments

Recoil polarization and polarized target (Jlab)

E04-108 – high-Q^2 recoil polarization (GEp-III) – published (2010+2017)
E04-019 – ε dependence of recoil pol. (2-Gamma) – published (2011+2017)
E08-007 – part I: low-Q^2 recoil polarization – published (2011)
E08-007 – part II: low-Q^2 polarized target – analysis in progress
E07-003 – high-Q^2 polarized target (SANE) – to be published
E12-07-109 – high Q^2 recoil pol. (GEp-V/SBS) – in preparation

Unpolarized cross sections (Jlab)

E05-017 – high-Q^2 Rosenbluth (Super-Rosen) – first results, to be published
E12-07-108 – high-Q^2 unpolarized (GMp) – first results, to be published

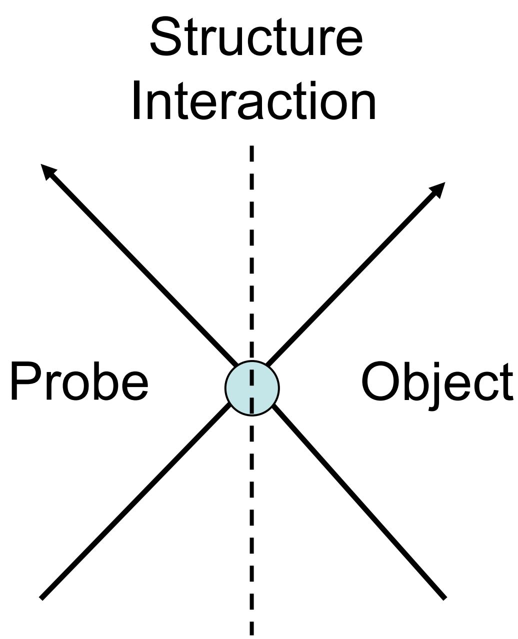
Positron-electron comparisons

Novosibirsk/VEPP-3 – published (2015)
CLAS/JLab – published (2015+2017)
OLYMPUS/DESY – published (2017)

Proton radius measurements

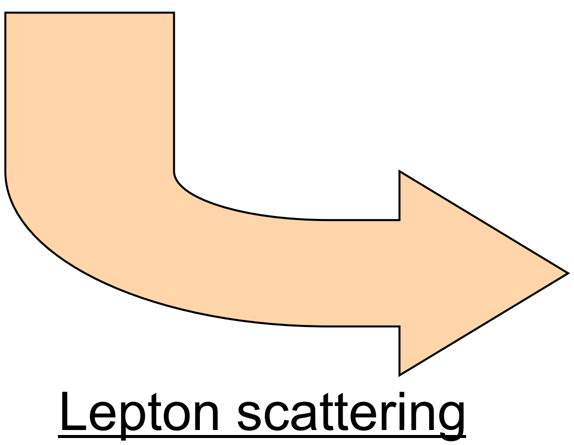
MAMI / A1 (e-scattering) – published (2010+2014)
MAMI / A1 (ISR) – published (2017), t.b. cont'd
MAMI / A2 (TPC); MESA / MAGIX – in preparation
Jlab / PRad @ CEBAF (e-scattering) – analysis in progress
Orsay / ProRad @ PRAE; Sendai (Tohoku U.) – in preparation
PSI / MUSE @ piM1 ($e^{\pm}$, $\mu^{\pm}$ scattering) – in preparation
CERN / COMPASS @ SPS ($\mu^{\pm}$ scattering) – in preparation

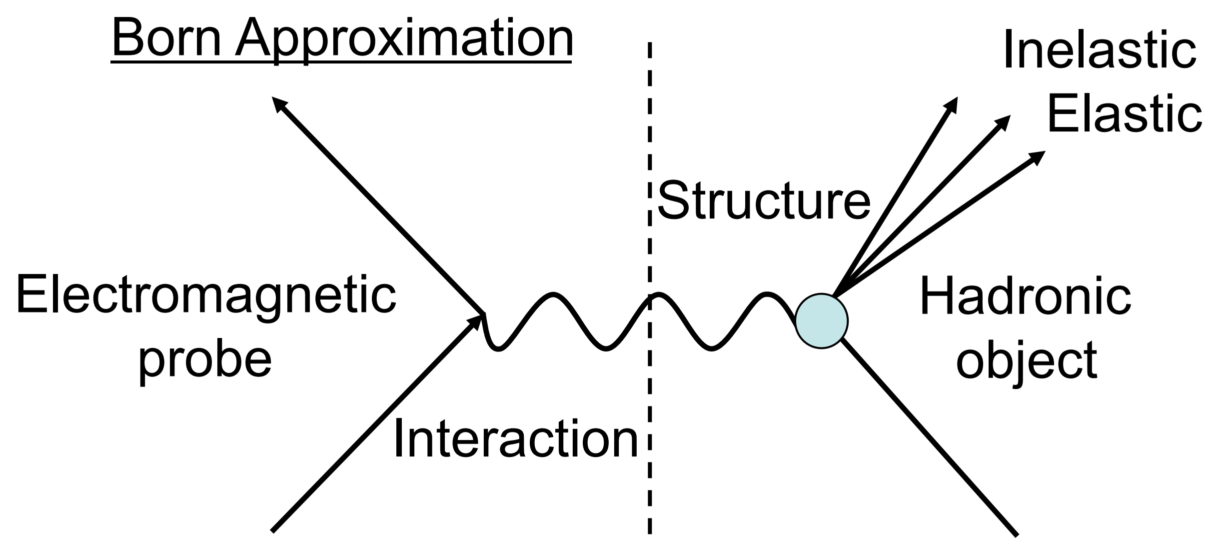
Hadronic structure and EM interaction



Factorization!

$$|\text{Form factor}|^2 = \frac{\sigma(\text{structured object})}{\sigma(\text{pointlike object})}$$





One-Photon Exchange Approximation

The beginnings

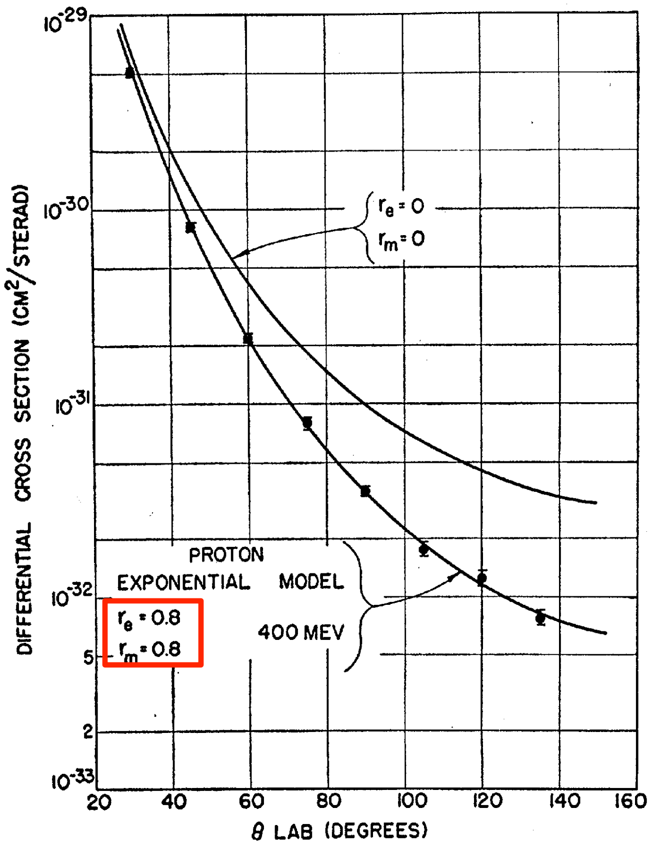


FIG. 26. Typical angular distribution for elastic scattering of 400-Mev electrons against protons. The solid line is a theoretical curve for a proton of finite extent. The model providing the theoretical curve is an exponential with rms radii $=0.80\times10^{-13}$ cm.

R. Hofstadter, Rev. Mod. Phys. 56 (1956) 214

ep-elastic
finite size of the proton
$R_p \sim 0.8$ fm

Robert Hofstadter
Nobel prize 1961

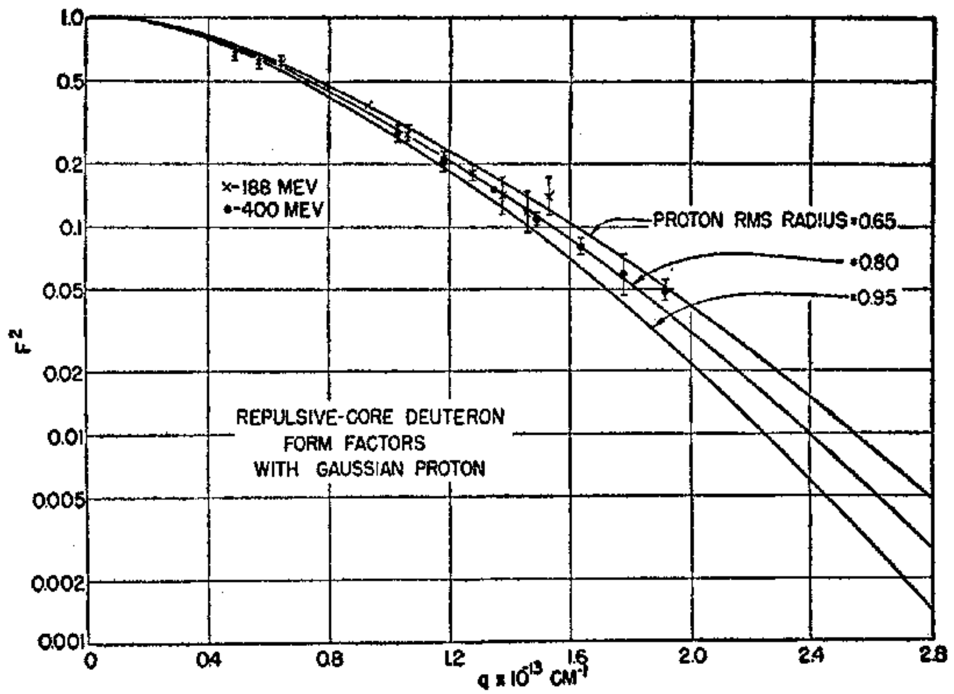
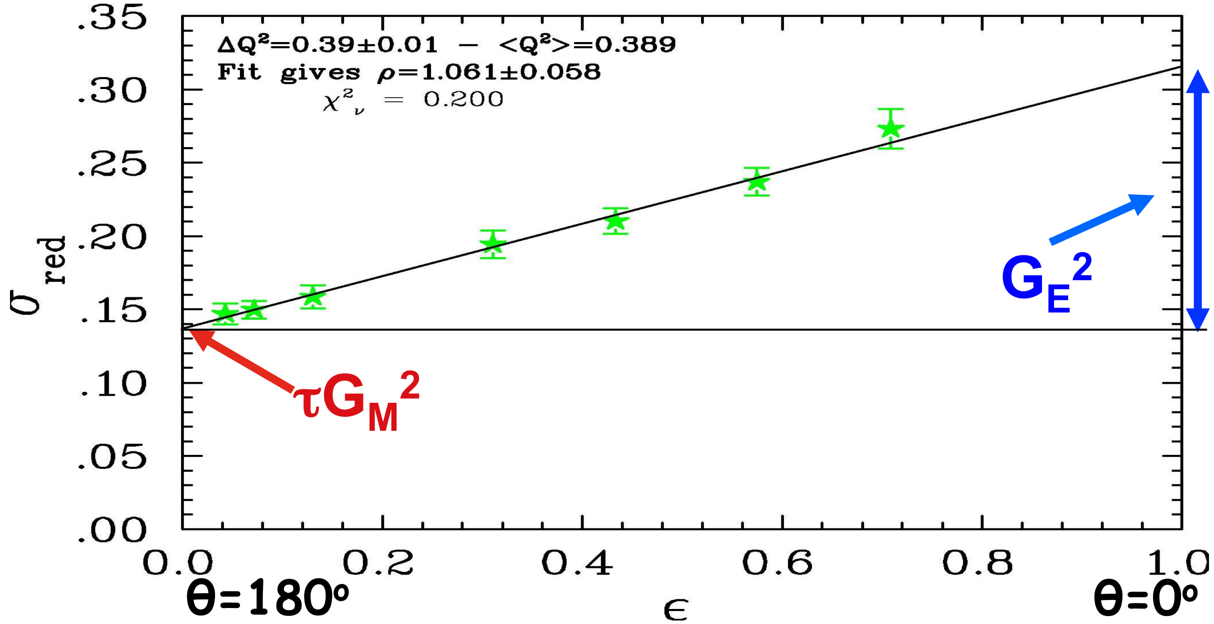


FIG. 31. Introduction of a finite proton core allows the experimental data to be fitted with conventional form factors (McIntyre).

ed-elastic
Finite size + nuclear structure

Form factors from Rosenbluth method



$\sigma_{red} = \varepsilon G_E^2 + \tau G_M^2$

➔**Determine**

$|G_E|$, $|G_M|$, $|G_E/G_M|$

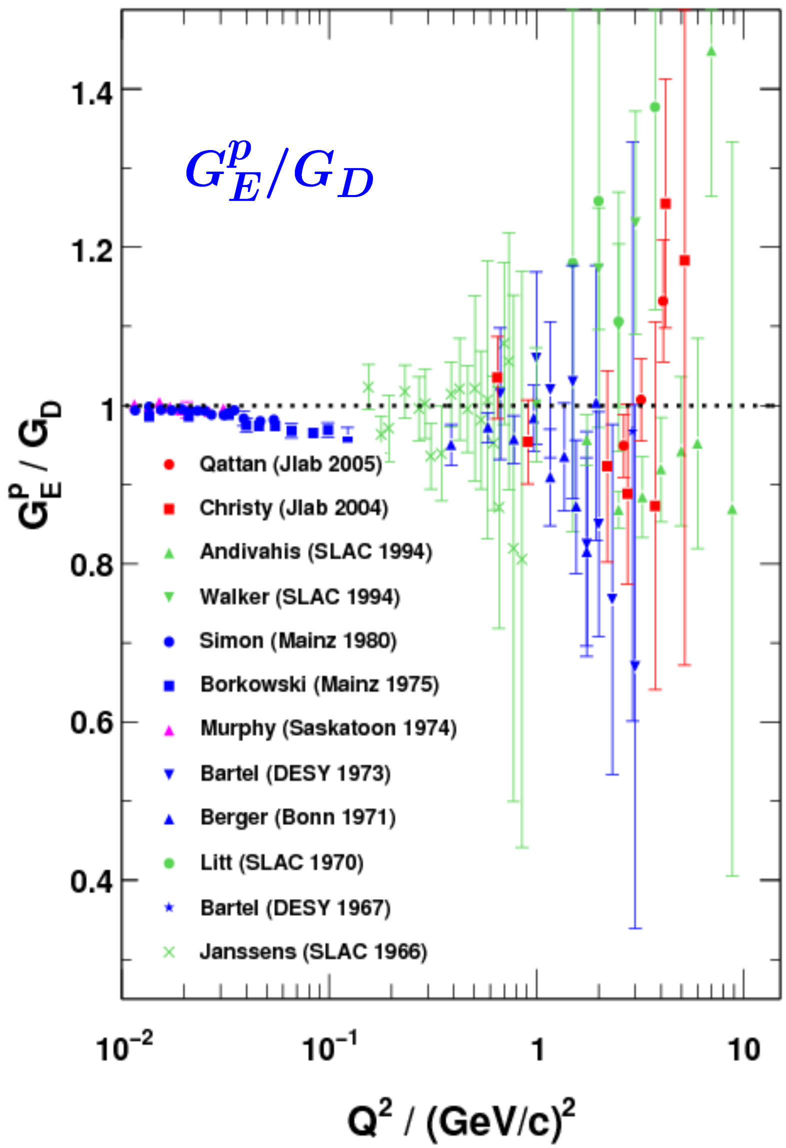
- **In One-photon exchange, form factors are related to radiatively corrected elastic electron-proton scattering cross section**

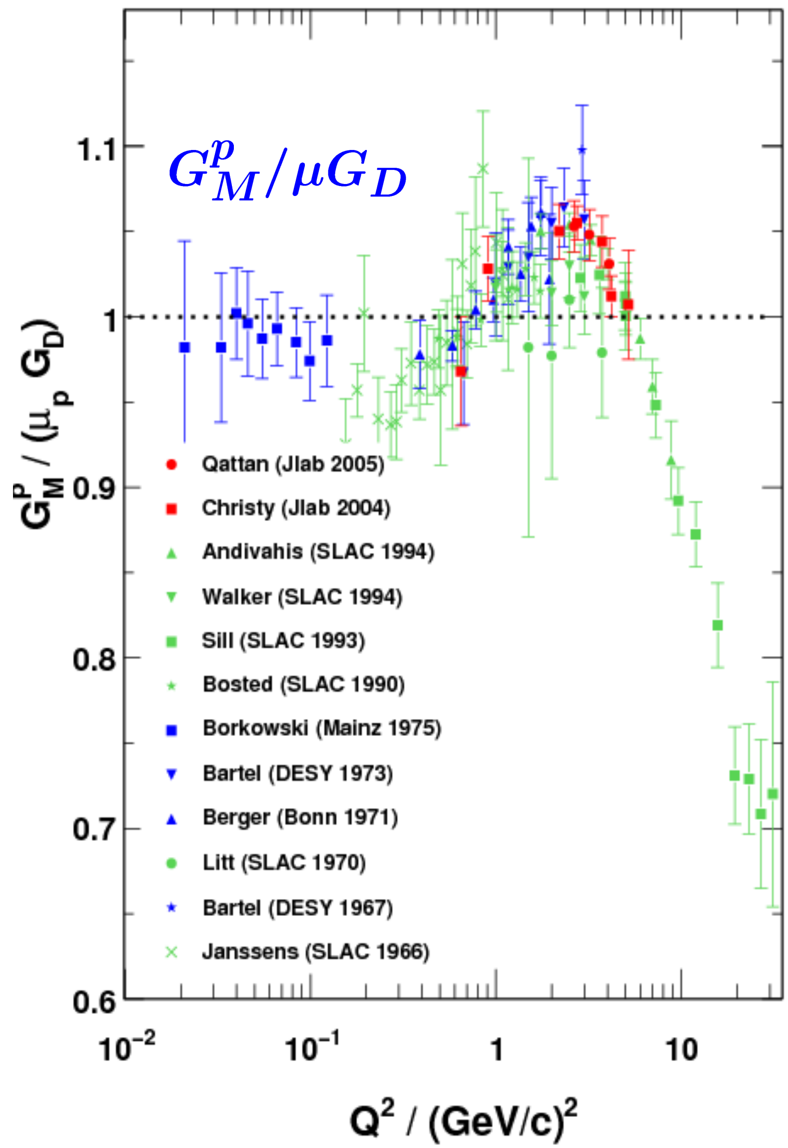
$$\frac{d\sigma/d\Omega}{(d\sigma/d\Omega)_{Mott}} = S_0 = A(Q^2) + B(Q^2)\tan^2\frac{\theta}{2}$$

$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

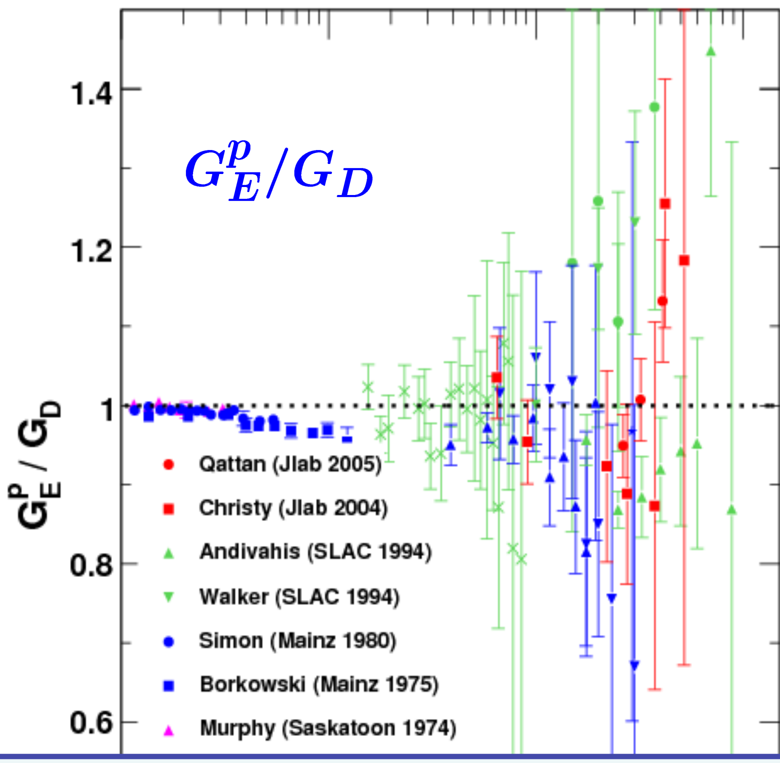
$$= \frac{\epsilon G_E^2 + \tau G_M^2}{\epsilon(1+\tau)}, \qquad \epsilon = \left[1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right]^{-1}$$

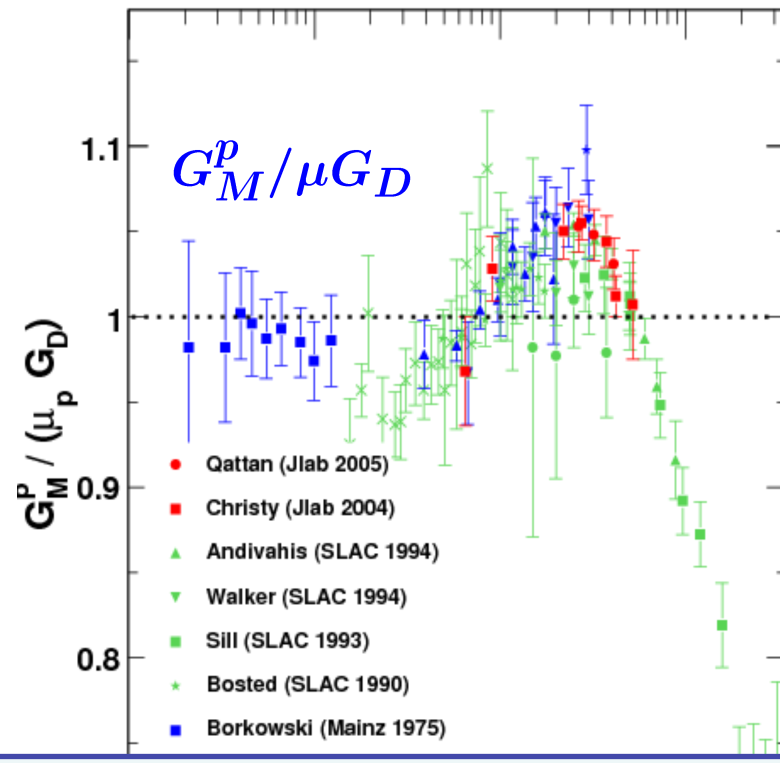
G^p_E and G^p_M from unpolarized data





G^p_E and G^p_M from unpolarized data



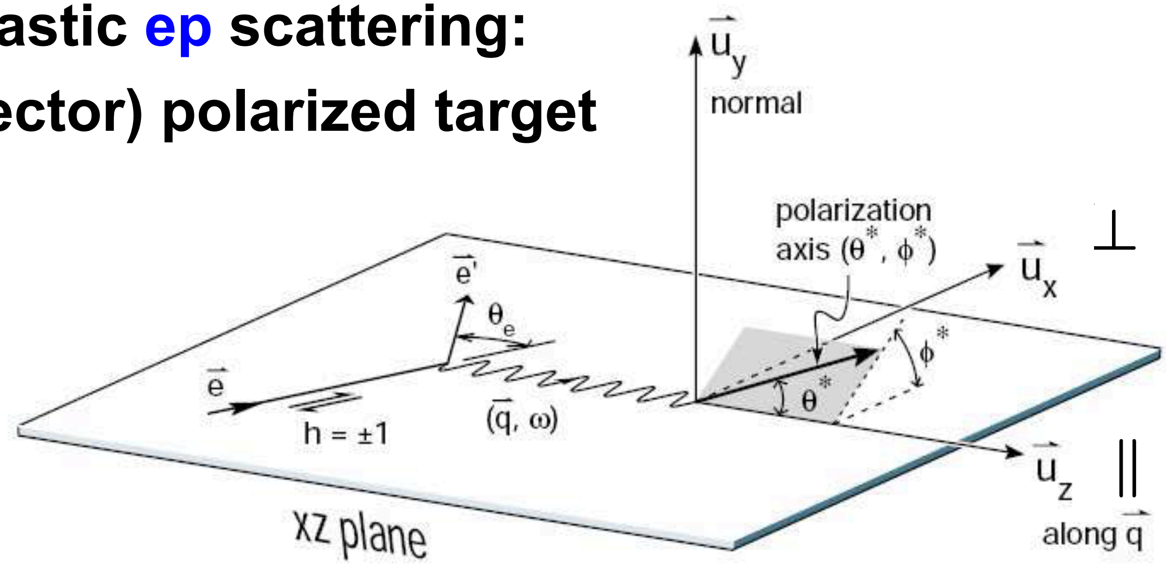


- $G(Q^2) \overset{\text{Fourier}}{\longleftrightarrow} \rho(r)$ **charge and magnetization density (Breit fr.)**
- **Dipole form factor** $G_D = \frac{1}{\left(1+\frac{Q^2}{0.71}\right)^2} \longleftrightarrow \rho_D(r) = \rho_0\, e^{-\sqrt{0.71}r}$
- $G^p_E \approx G^p_M/\mu_p \approx G^n_M/\mu_n \approx G_D$ **within 10% for Q^2 < 10 $(GeV/c)^2$**

Nucleon form factors and polarization

- **Double polarization in elastic ep scattering:**
  Recoil polarization or (vector) polarized target

  $^1H(\vec{e},e'\vec{p})$, $^1\vec{H}(\vec{e},e'p)$



- **Polarized cross section**

$$\sigma = \sigma_0 \left(1 + P_e \, \vec{P}_p \cdot \vec{A}\right)$$

- **Double polarization observable = spin correlation**

$$-\sigma_0 \, \vec{P}_p \cdot \vec{A} = \sqrt{2\tau\epsilon(1-\epsilon)} G_E G_M \sin\theta^* \cos\phi^* + \tau\sqrt{1-\epsilon^2} {G_M}^2 \cos\theta^*$$

- **Asymmetry ratio ("Super ratio")**

$$\frac{P_\perp}{P_{||}} = \frac{A_\perp}{A_{||}} \propto \frac{G_E}{G_M}$$

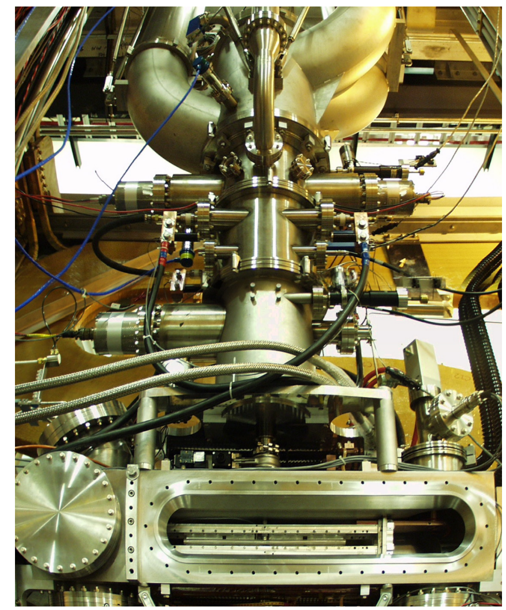
independent of
polarization or analyzing power

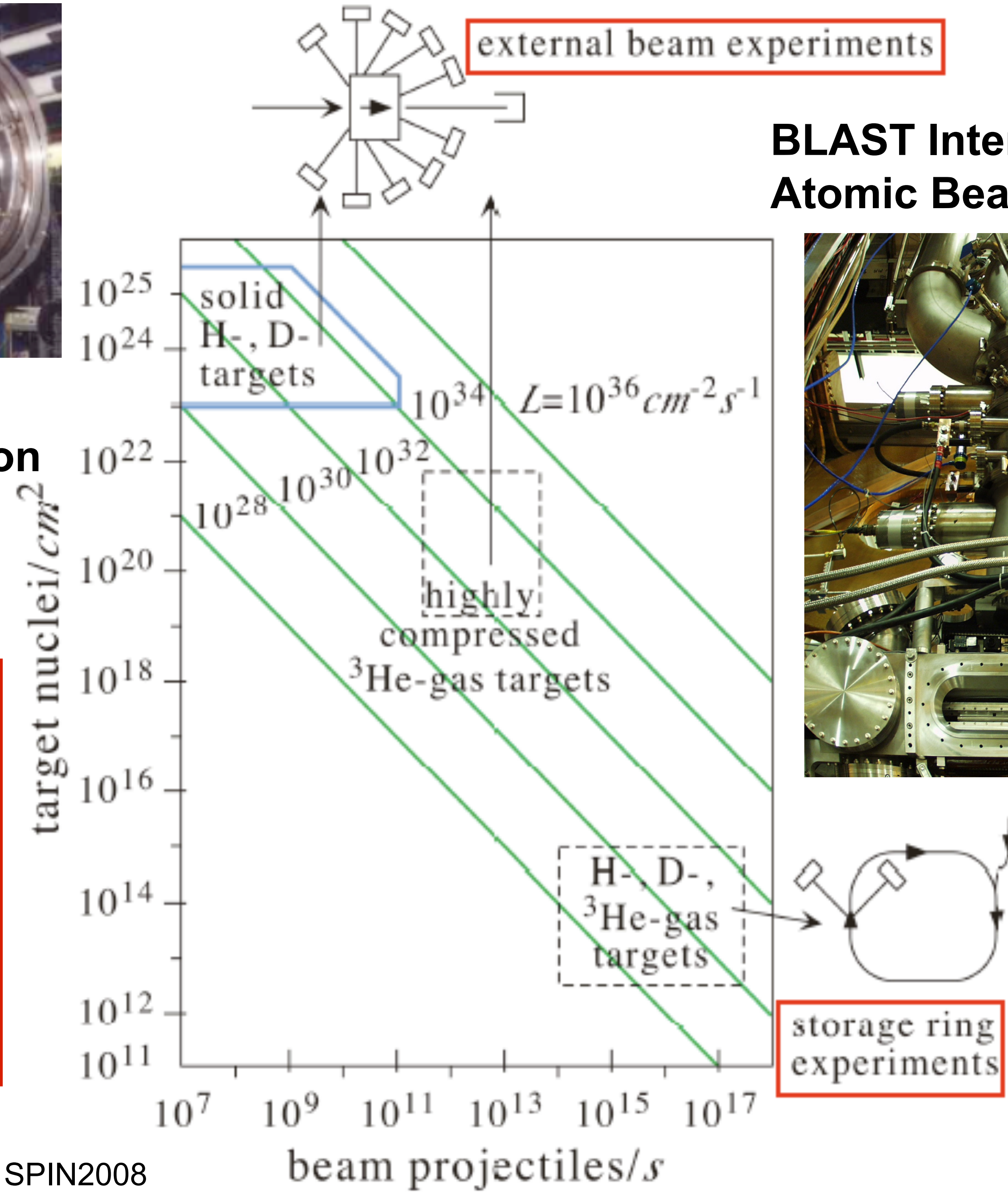
Dombey (1969)
Donnelly and Raskin (1986)

Polarized targets

UVA / "SLAC"-Target: Dynamic Nuclear Polarization

BLAST Internal Target: Atomic Beam Source



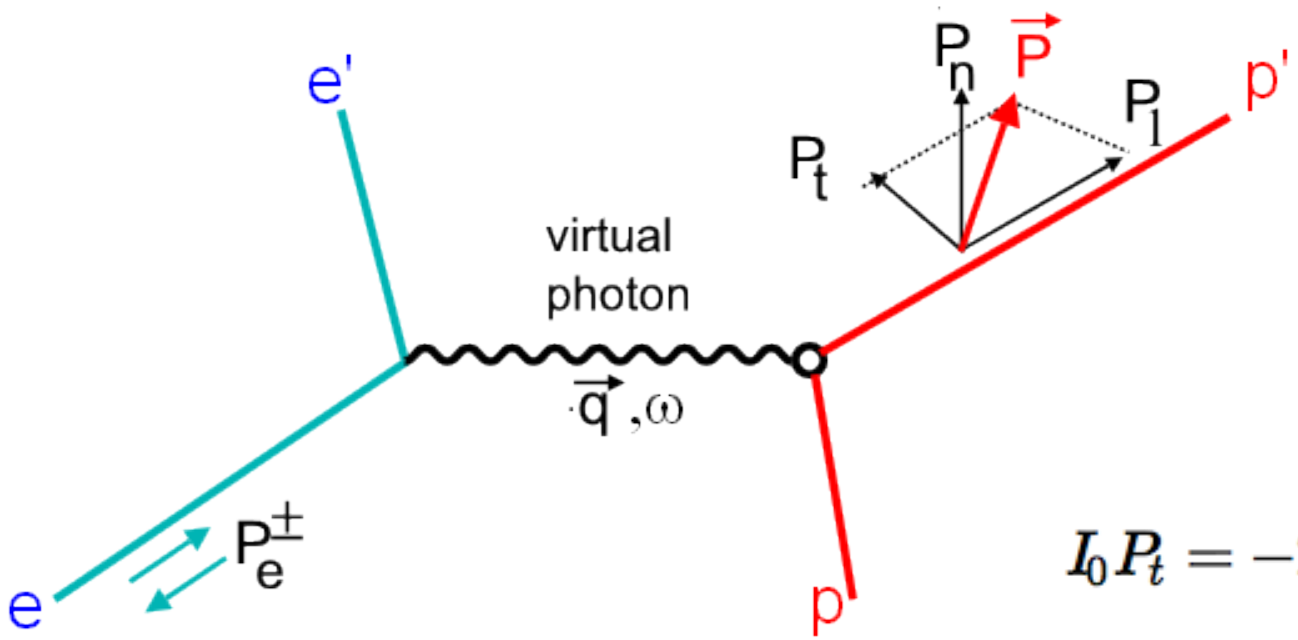


from W. Meyer, SPIN2008

Limited luminosity for polarized hydrogen/ deuterium targets

Very precise at low to moderately high Q^2

Recoil polarization technique



$$I_0 P_t = -2\sqrt{\tau(1+\tau)} G_E G_M \tan\frac{\theta_e}{2}$$

$$I_0 P_\ell = \frac{1}{M}(E_e + E_e')\sqrt{\tau(1+\tau)} G_M^2 \tan^2\frac{\theta_e}{2}$$

$$\frac{G_E}{G_M} = -\frac{P_t}{P_\ell}\frac{(E_e + E_e')}{2M_p}\tan\left(\frac{\theta_e}{2}\right)$$

$$I_0 \propto G_E^2 + \frac{\tau}{\epsilon} G_M^2$$

<u>Applicable to protons and neutrons</u>

Akhiezer and Rekalo (1968+1974)
Arnold, Carlson and Gross (1981)

Recoil polarization technique

- Pioneered at MIT-Bates
- Pursued in Halls A and C, and MAMI A1
- In preparation for Jlab @ 12 GeV

V. Punjabi *et al.*,
Phys. Rev. C 71, 05520 (2005)

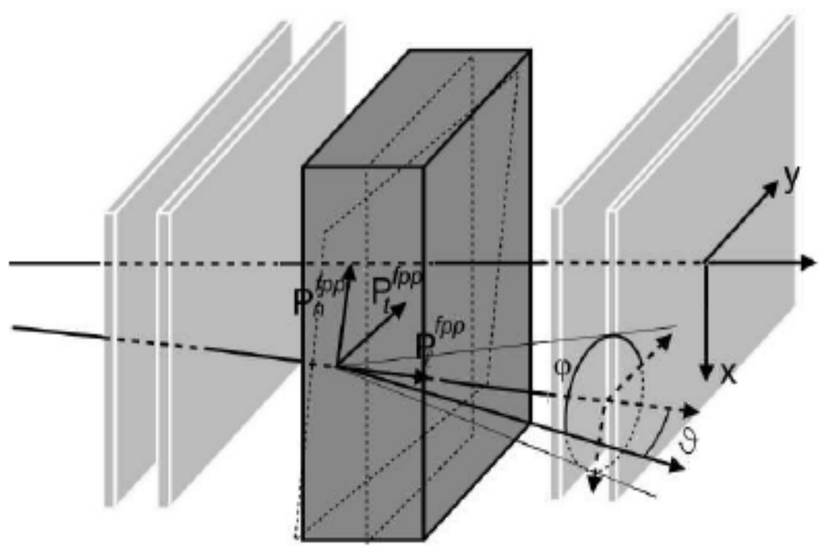


FIG. 9: Schematic of the polarimeter chambers and analyzer, showing a non-central trajectory; ϑ is the polar angle, and φ is the azimuthal angle from the y-direction counterclockwise.

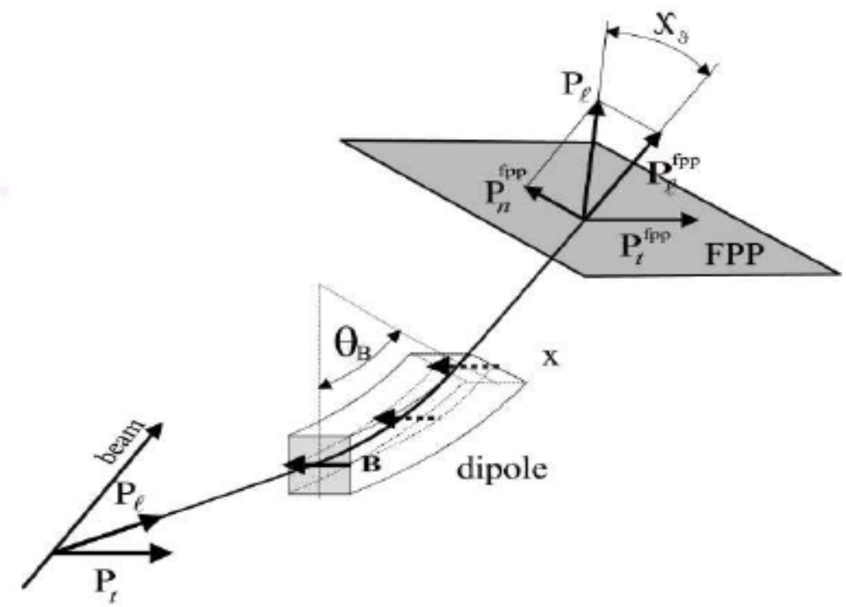
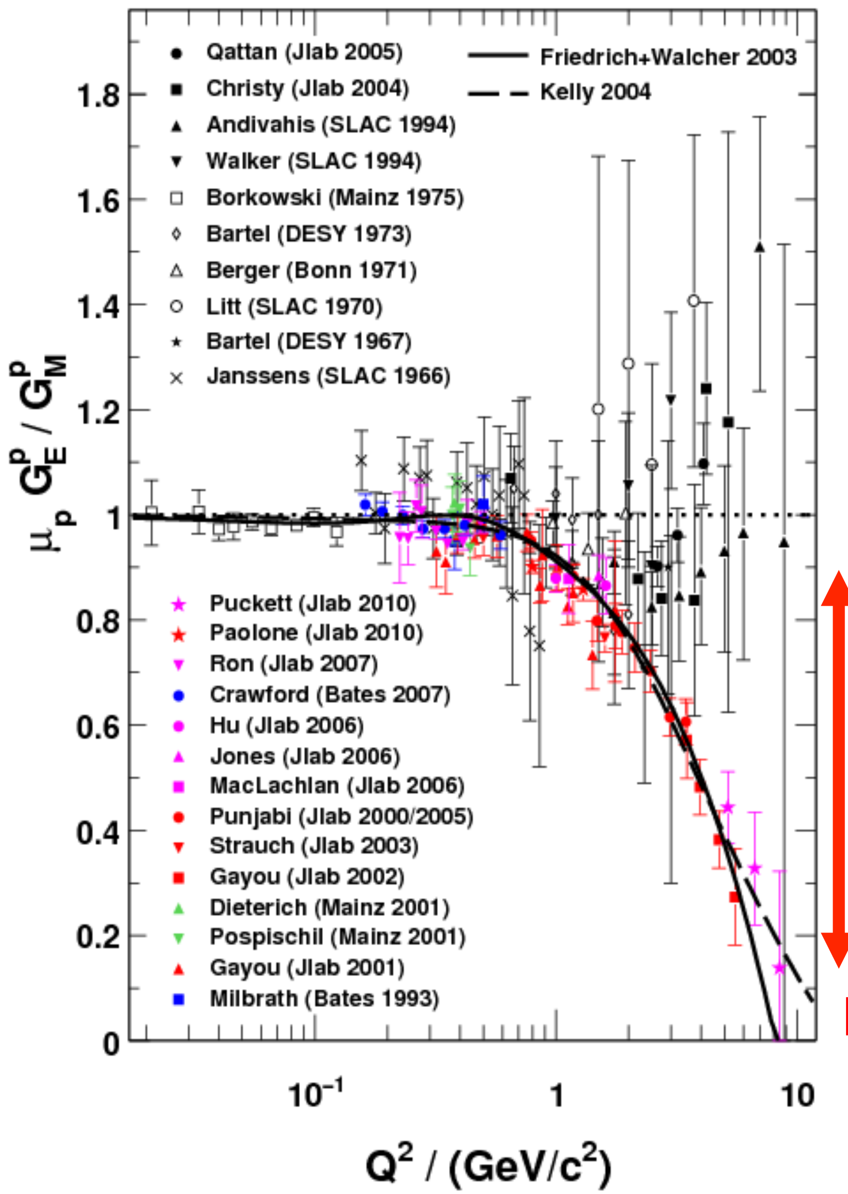


FIG. 15: Schematic drawing showing the precession by angle χ_θ of the P_ℓ component of the polarization in the dipole of the HRS.

Focal-plane polarimeter
Secondary scattering of polarized proton from unpolarized analyzer requiring polarization in transverse plane

Spin transfer formalism to account for spin precession through spectrometer required to measure longitudinal polariz.

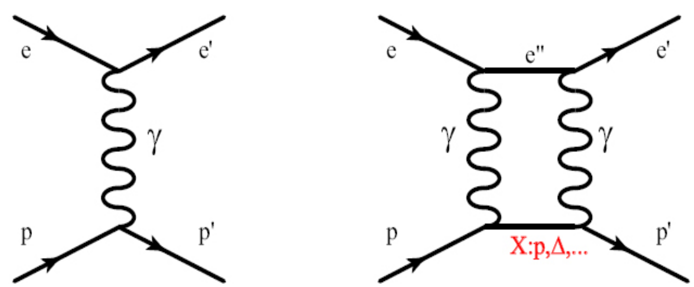
Proton form factor ratio



Dramatic discrepancy!

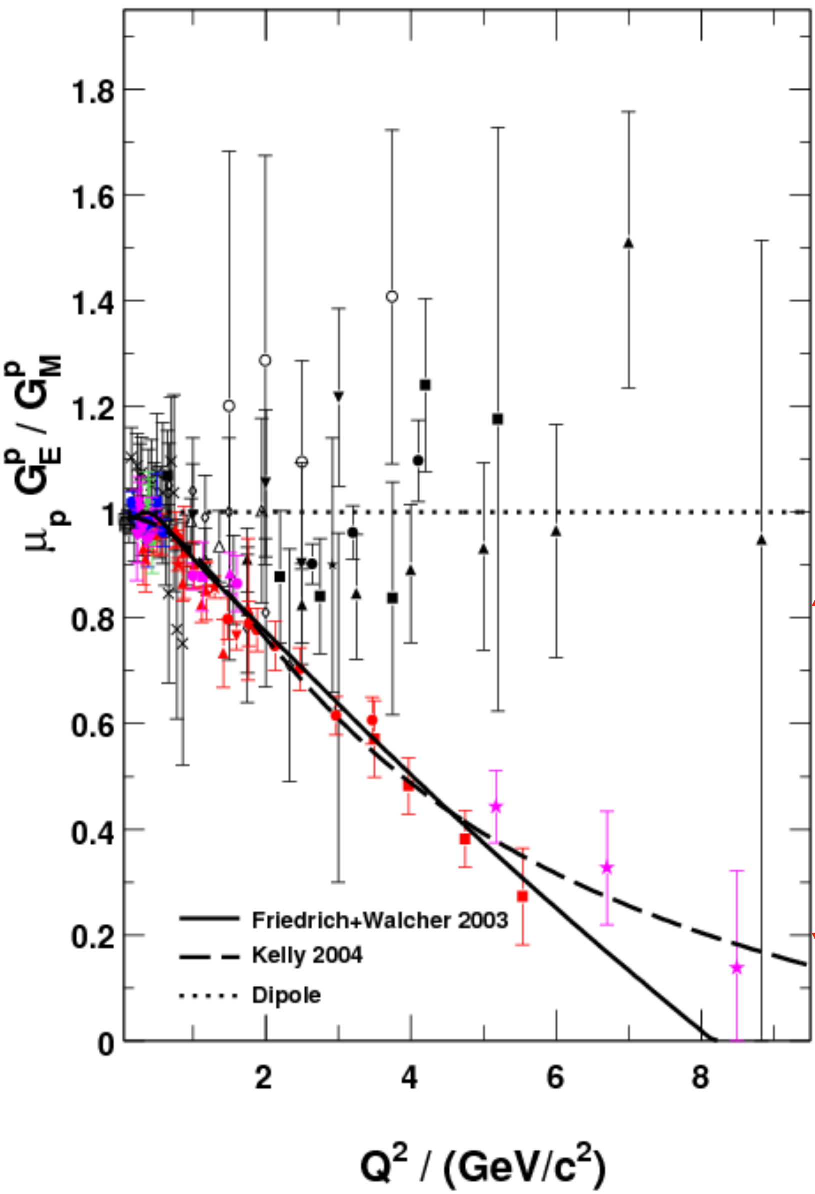
Jefferson Lab 2000–

- All Rosenbluth data from SLAC and Jlab in agreement
- Dramatic discrepancy between Rosenbluth and recoil polarization technique
- Multi-photon exchange considered best candidate



>800 citations

Proton form factor ratio



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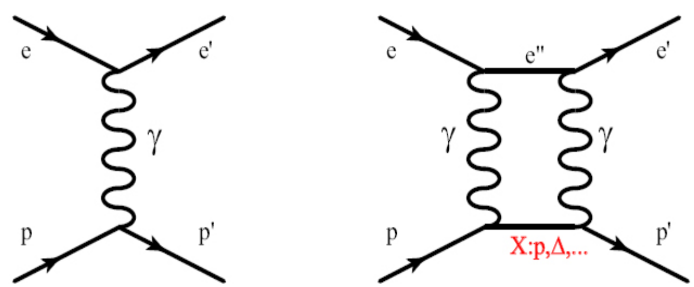
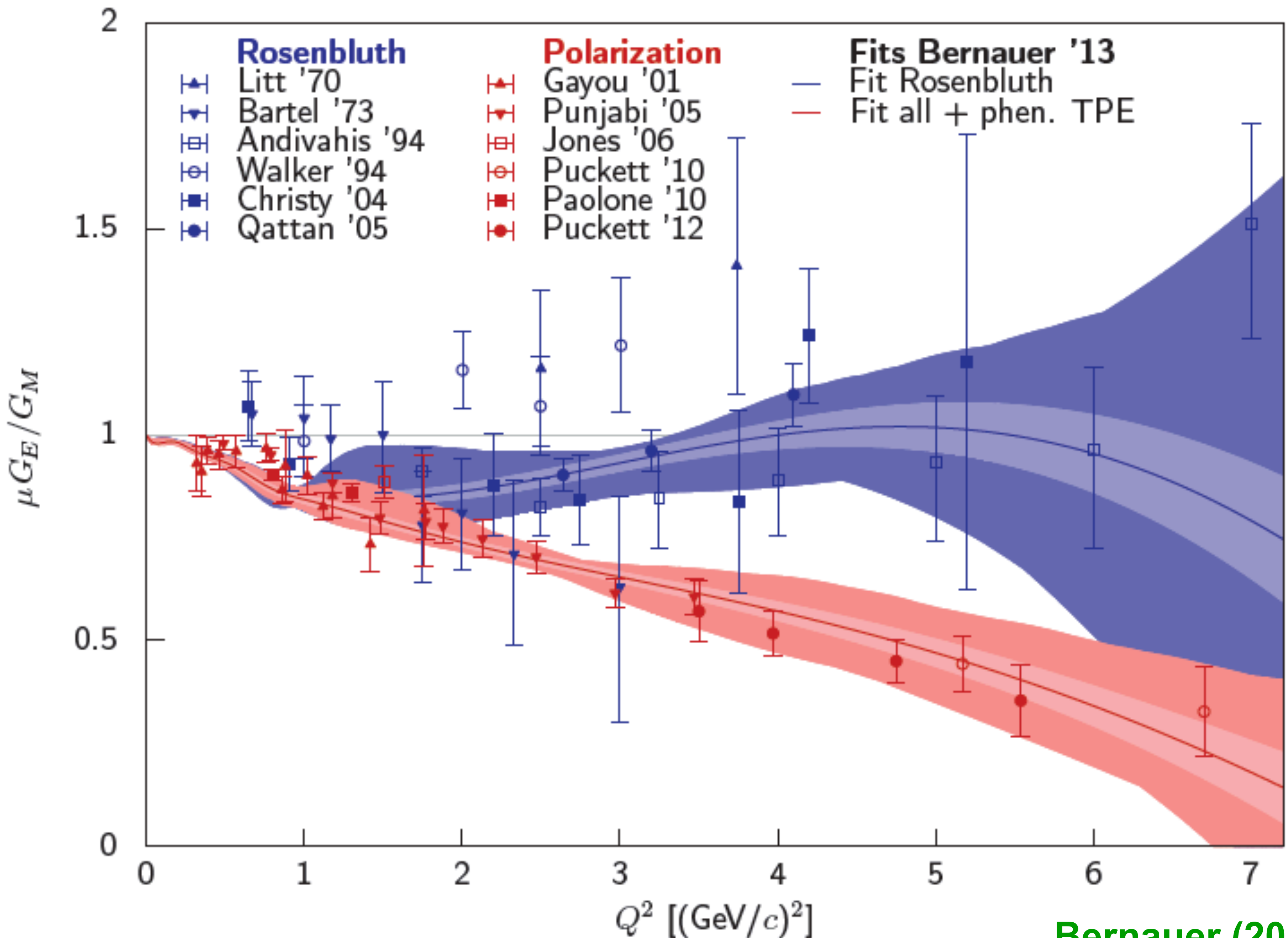


Dramatic discrepancy!

>800 citations

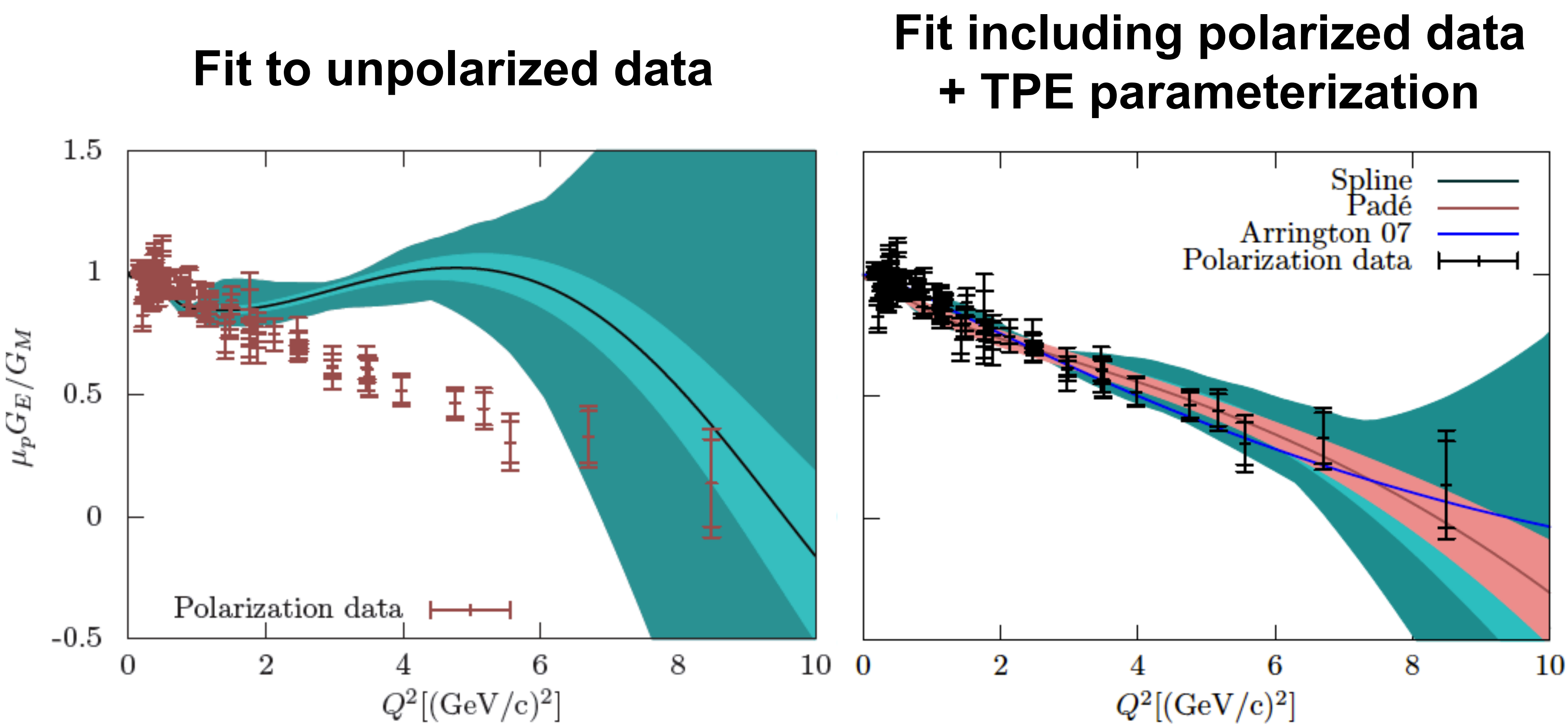
Another look



Bernauer (2014)

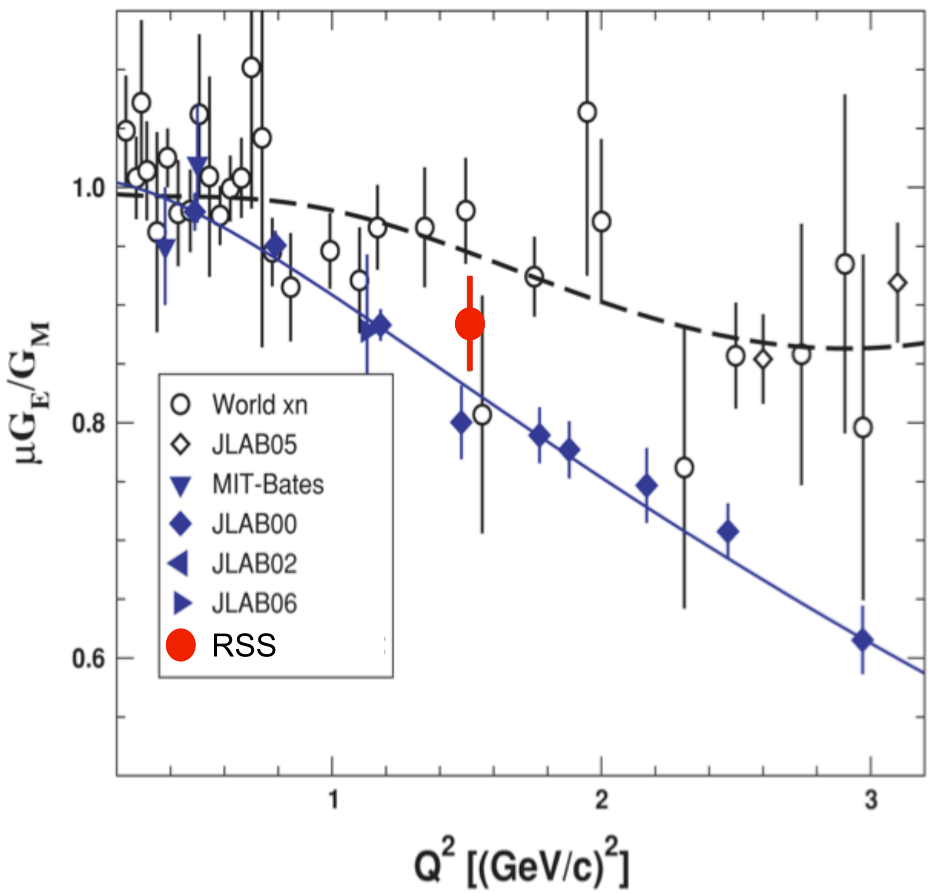
No discrepancy below $Q^2 < 2$ (GeV/c)^2 ?

Global analysis



J.C. Bernauer *et al.*, PRC 90, 015206 (2014) [arXiv:1307.6227v2]

Polarized target data at high Q^2



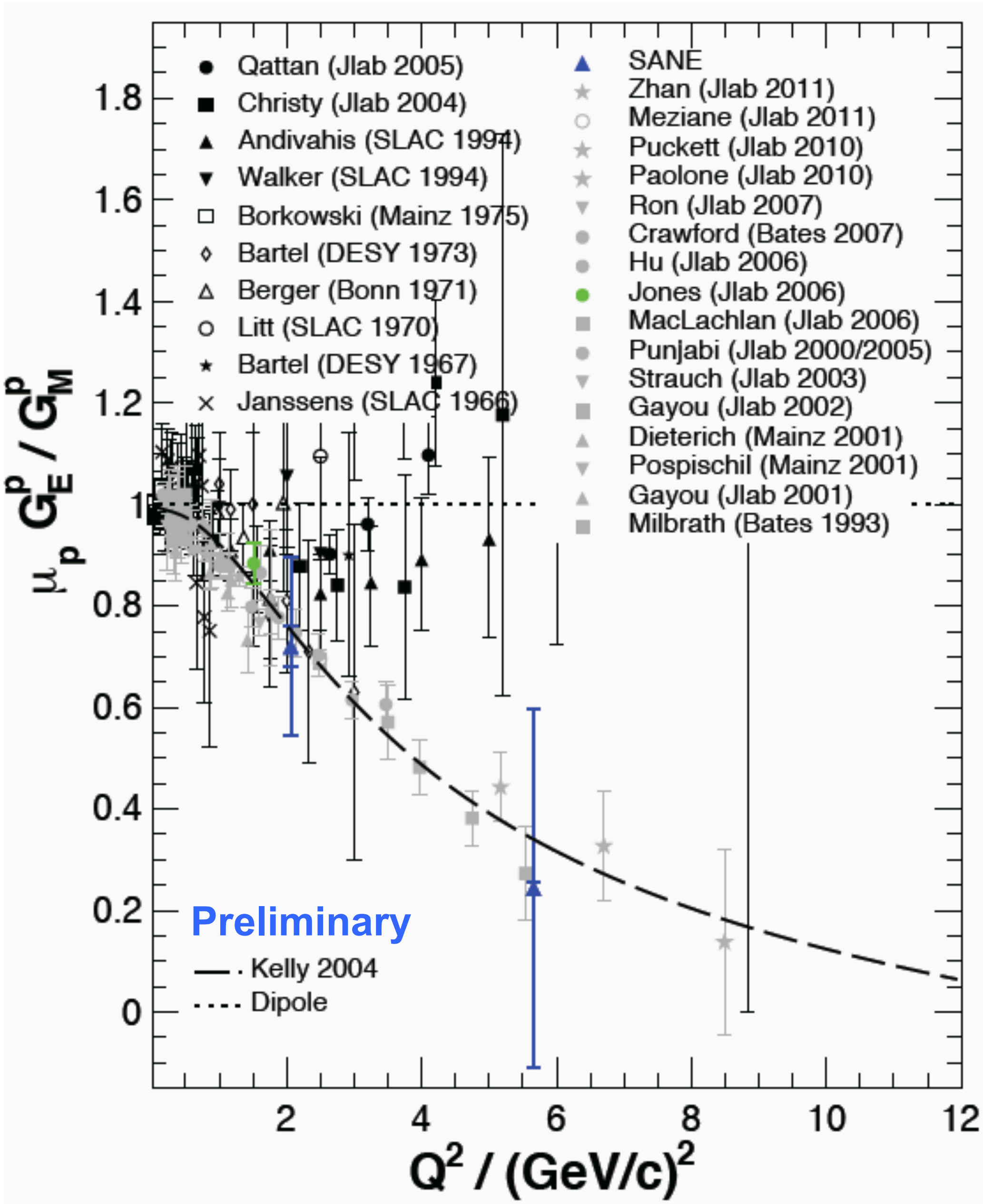
Polarized Target:
Independent verification of recoil polarization result is crucial

Polarized internal target / low Q^2: **BLAST**
Q^2<0.65 (GeV/c)^2 not high enough to see deviation from scaling

RSS /Hall C: $Q^2 \approx 1.5$ (GeV/c)^2

M.K. Jones *et al.*, PRC74, 035201 (2006)

Polarized target data at high Q^2



A. Liyanage, M.K. *et al.*, to be published

Polarized Target:
Independent verification of recoil polarization result is crucial

Polarized internal target / low Q^2: **BLAST**
$Q^2<0.65$ (GeV/c)^2 not high enough to see deviation from scaling

RSS /Hall C: $Q^2 \approx 1.5$ (GeV/c)^2

SANE/Hall C: completed March 2009
BigCal electron detector
Recoil protons in HMS parasitically
G_E/G_M at $Q^2 \approx 2.1$ and 5.7 (GeV/c)^2

Decline of G_E/G_M has been confirmed!

Future precision measurements at high Q^2 are feasible

New unpolarized data at high Q^2

- **GMp (E12-07-108):**

  Magnetic form factor of the proton at high Q^2 (cross section)

  Scattered electron detection (single-arm)

  Data taking completed in 2016

  Preliminary results available

  Final results by fall 2018

- **Super-Rosen (E05-017):**

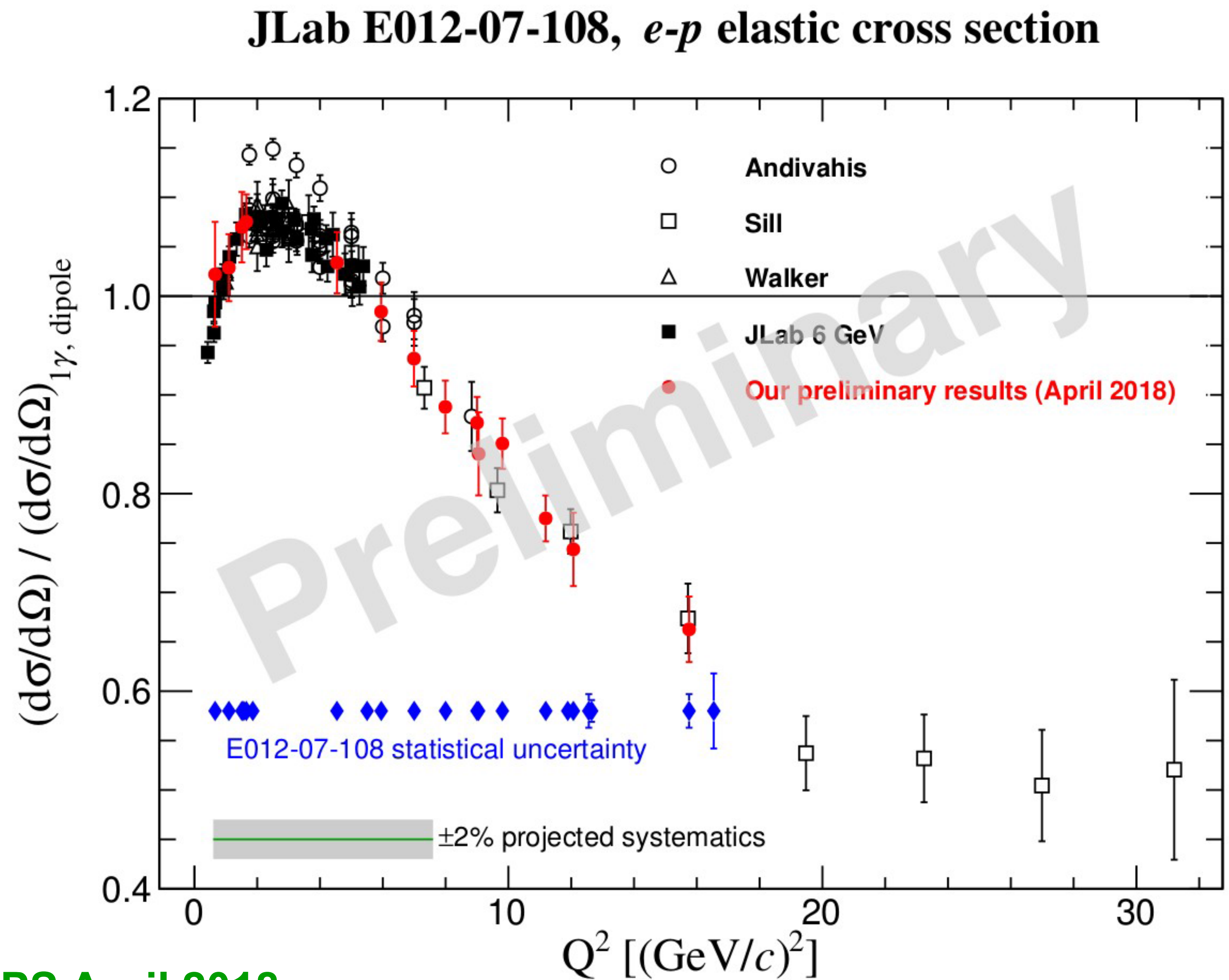
  High-Q^2 Rosenbluth separation up to $Q^2 < 5.7$ (GeV/c)^2

  Recoil proton detection (single-arm)

  Preliminary results available

GMp (E12-07-108) at high Q^2

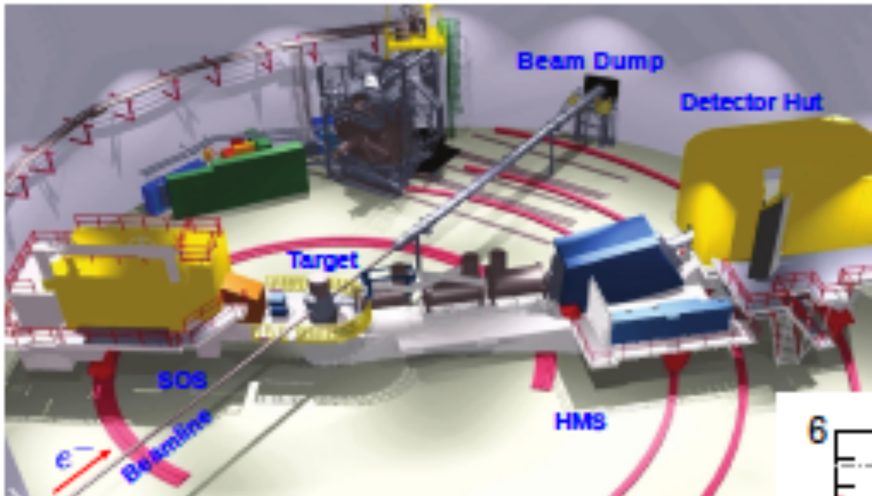
- Preliminary cross-section results are presented below with 5% total uncertainty
- Final results will be available by fall 2018 with <2% systematic uncertainty



T. Gautam,
E. Christy

APS April 2018

E05-017 HALL C, JLAB



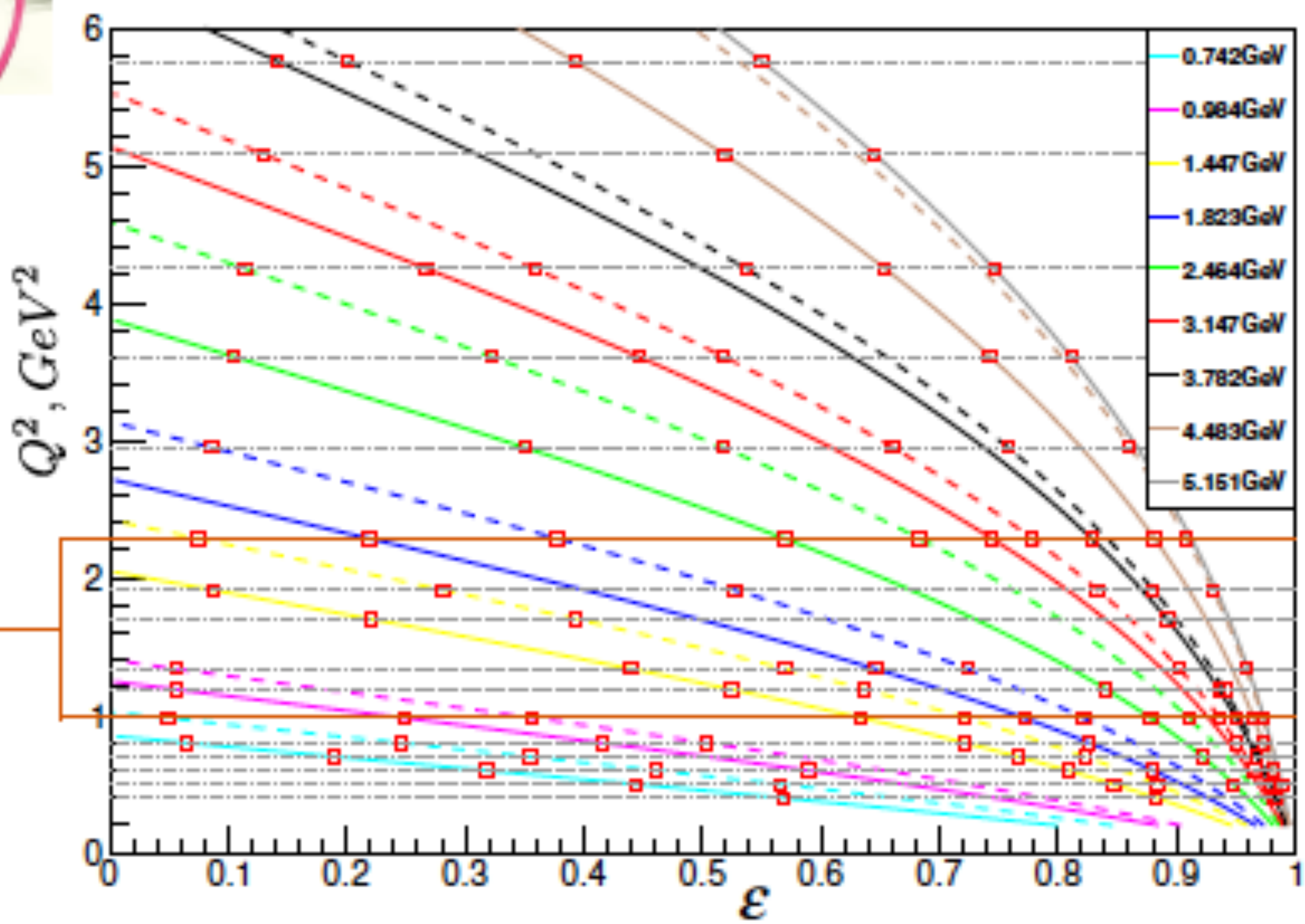
Experimental Hall C Layout

- 4 cm LH2 and dummy targets
- recoil proton detected in HMS
- 17 settings of beam energy

102 Kinematics points

10 points at $Q^2 = 2.284$

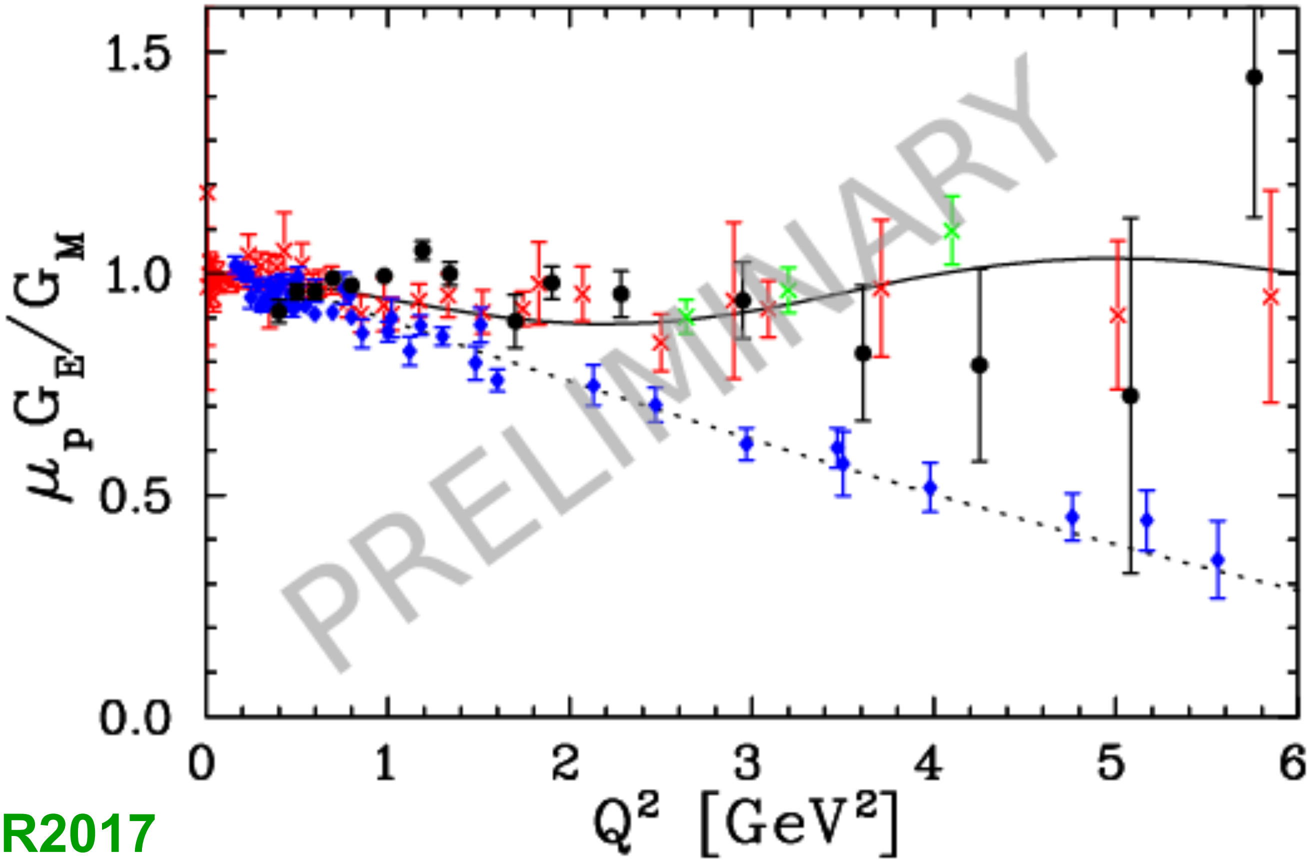
13 points at $Q^2 = 0.983$



NSTAR2017

PRELIMINARY RESULTS

- $\mu_p G_E/G_M$ **extraction:**
  - from analysis that focused on low Q^2 settings
- **expected uncertainty reduction:**
  - slope by factor of 2 everywhere
  - point-to-point by factor 1.3 at $Q^2 < 2$ and by 1.5 above

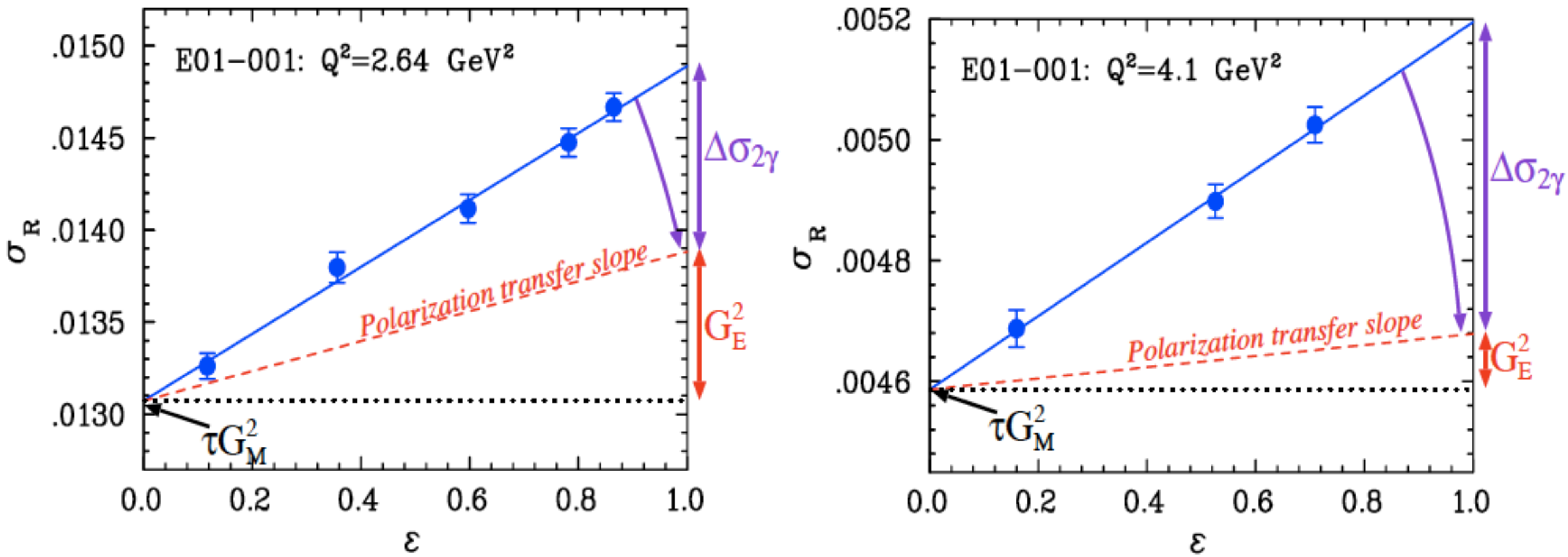


- this E05-017
- proton LT
- global LT
- PT
- solid: fit to LT
- dashed: fit to PT

NSTAR2017

Effect of two-photon exchange

J. Arrington, P. Blunden, W. Melnitchouk, Prog. Part. Nucl. Phys. 66, 782 (2011)

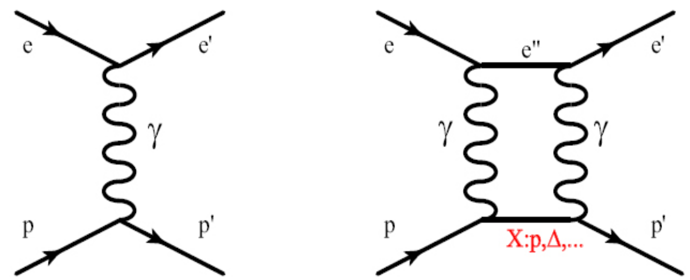


By construction, theorists sought mechanism that affects the "slope" in the Rosenbluth plot (ε-dependence)

At high Q^2 , the contribution of G_E to the cross section is of similar order as the TPE effect (few %)

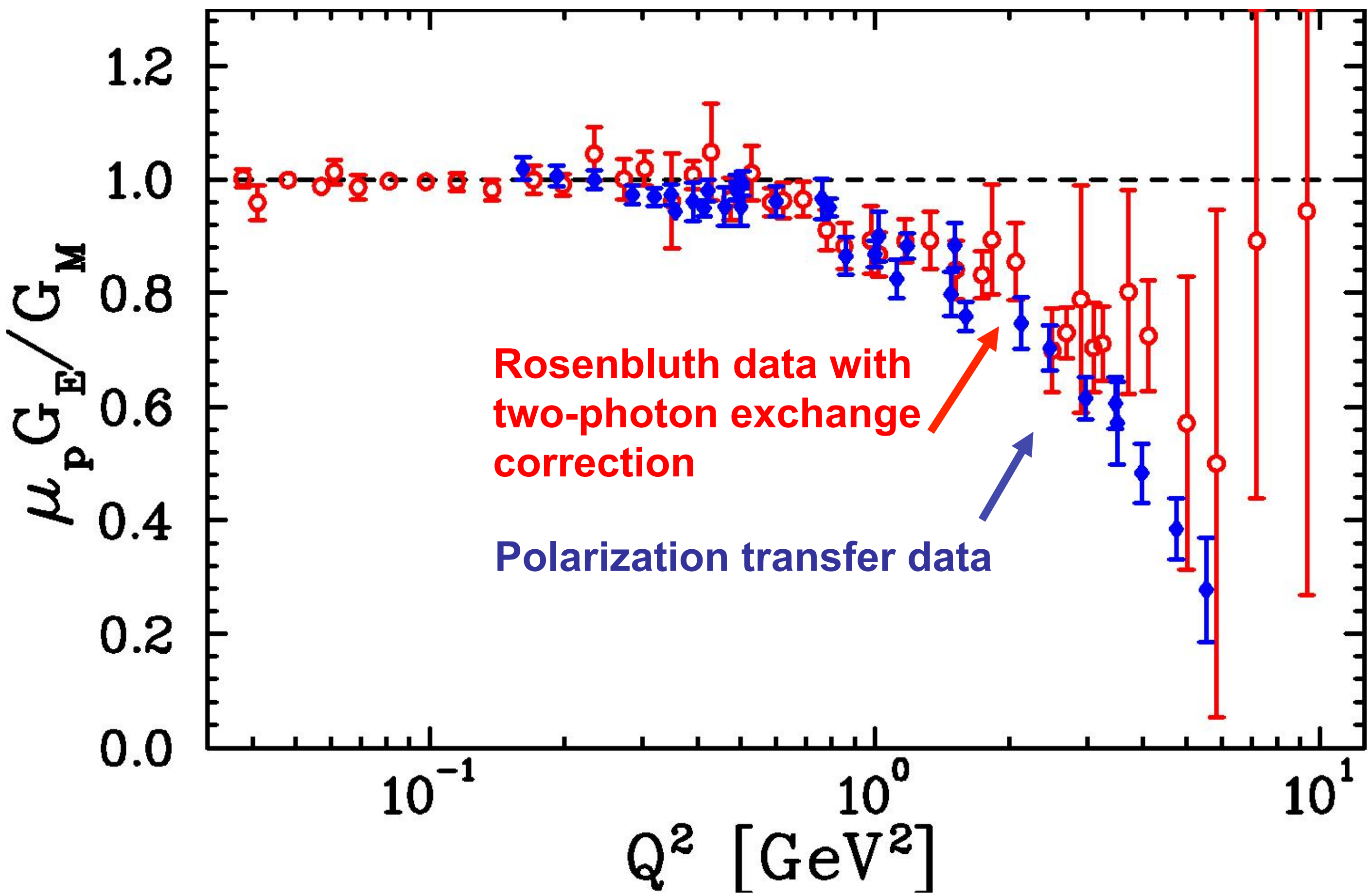
Two-photon exchange: exp. evidence

Two-photon exchange theoretically suggested

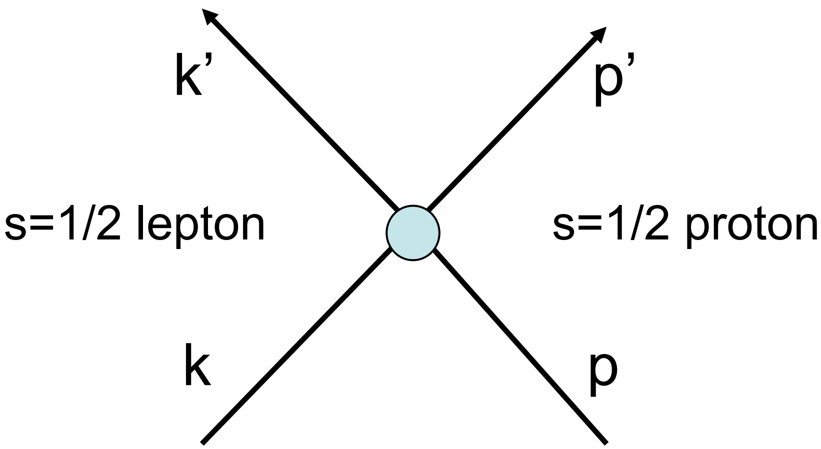


TPE can explain form factor discrepancy

J. Arrington, W. Melnitchouk, J.A. Tjon, Phys. Rev. C 76, 035205 (2007)



Elastic ep scattering beyond OPE



$$P \equiv \frac{p+p'}{2}, \qquad K \equiv \frac{k+k'}{2}$$

Kinematical invariants :

$$\begin{aligned} Q^2 &= -(p-p')^2 \\ \nu &= K \cdot P = (s-u)/4 \end{aligned}$$

Next-to Born approximation:

$$\begin{aligned} T^{non-flip}_{h'\lambda'_N, h\lambda_N} &= \frac{e^2}{Q^2} \bar{u}(k',h') \gamma_\mu u(k,h) \\ &\times \; \bar{u}(p',\lambda'_N) \left(\tilde{G}_M \, \gamma^\mu - \tilde{F}_2 \frac{P^\mu}{M} + \tilde{F}_3 \frac{\gamma.K P^\mu}{M^2} \right) u(p,\lambda_N) \end{aligned}$$

($m_e = 0$)

The T-matrix still factorizes, however a new response term F_3 is generated by TPE

Born-amplitudes are modified in presence of TPE; modifications ~α^3

$$\begin{aligned} \tilde{G}_M(\nu,Q^2) &= G_M(Q^2) + \delta\tilde{G}_M \\ \tilde{F}_2(\nu,Q^2) &= F_2(Q^2) + \delta\tilde{F}_2 \\ \tilde{F}_3(\nu,Q^2) &= 0 + \delta\tilde{F}_3 \end{aligned}$$

$$\tilde{G}_E \equiv \tilde{G}_M - (1+\tau)\,\tilde{F}_2$$

$$\tilde{G}_E(\nu,Q^2) = G_E(Q^2) + \delta\tilde{G}_E$$

New amplitudes are complex!

Inherited from M. Vanderhaeghen

Observables involving real part of TPE

$$P_t = -\sqrt{\frac{2\varepsilon(1-\varepsilon)}{\tau}}\,\frac{G_M^2}{d\sigma_{red}}\left\{R + R\frac{\Re\left(\delta\tilde{G}_M\right)}{G_M} + \frac{\Re\left(\delta\tilde{G}_E\right)}{G_M} + Y_{2\gamma}\right\}$$

$$P_l = \sqrt{(1+\varepsilon)(1-\varepsilon)}\,\frac{G_M^2}{d\sigma_{red}}\left\{1 + 2\frac{\Re(\delta\tilde{G}_M)}{G_M} + \frac{2}{1+\varepsilon}\varepsilon Y_{2\gamma}\right\}$$

$$\frac{P_t}{P_l} = -\sqrt{\frac{2\varepsilon}{(1+\varepsilon)\tau}}\left\{R - R\frac{\Re\left(\delta\tilde{G}_M\right)}{G_M} + \frac{\Re\left(\delta\tilde{G}_E\right)}{G_M} + 2\left(1 - R\frac{2\varepsilon}{1+\varepsilon}\right)Y_{2\gamma}\right\}$$

E04-019
(Two-gamma)

$$d\sigma_{red} / G_M^2 = 1 + \frac{\varepsilon R^2}{\tau} + 2\frac{\Re(\delta\tilde{G}_M)}{G_M} + 2R\frac{\varepsilon\Re(\delta\tilde{G}_E)}{\tau G_M} + 2\left(1 + \frac{R}{\tau}\right)\varepsilon Y_{2\gamma}$$

e^+/e^- x-section ratio
CLAS,VEPP3,OLYMPUS

Rosenbluth non-linearity
E05-017

$$\Re(\tilde{G}_E) = G_E(Q^2) + \Re(\delta\tilde{G}_E(Q^2,\varepsilon))$$

$$\Re(\tilde{G}_M) = G_M(Q^2) + \Re(\delta\tilde{G}_M(Q^2,\varepsilon))$$

$$R = G_E / G_M \qquad Y_{2\gamma} = 0 + \sqrt{\frac{\tau(1+\tau)(1+\varepsilon)}{1-\varepsilon}}\,\frac{\Re(\tilde{F}_3(Q^2,\varepsilon))}{G_M}$$

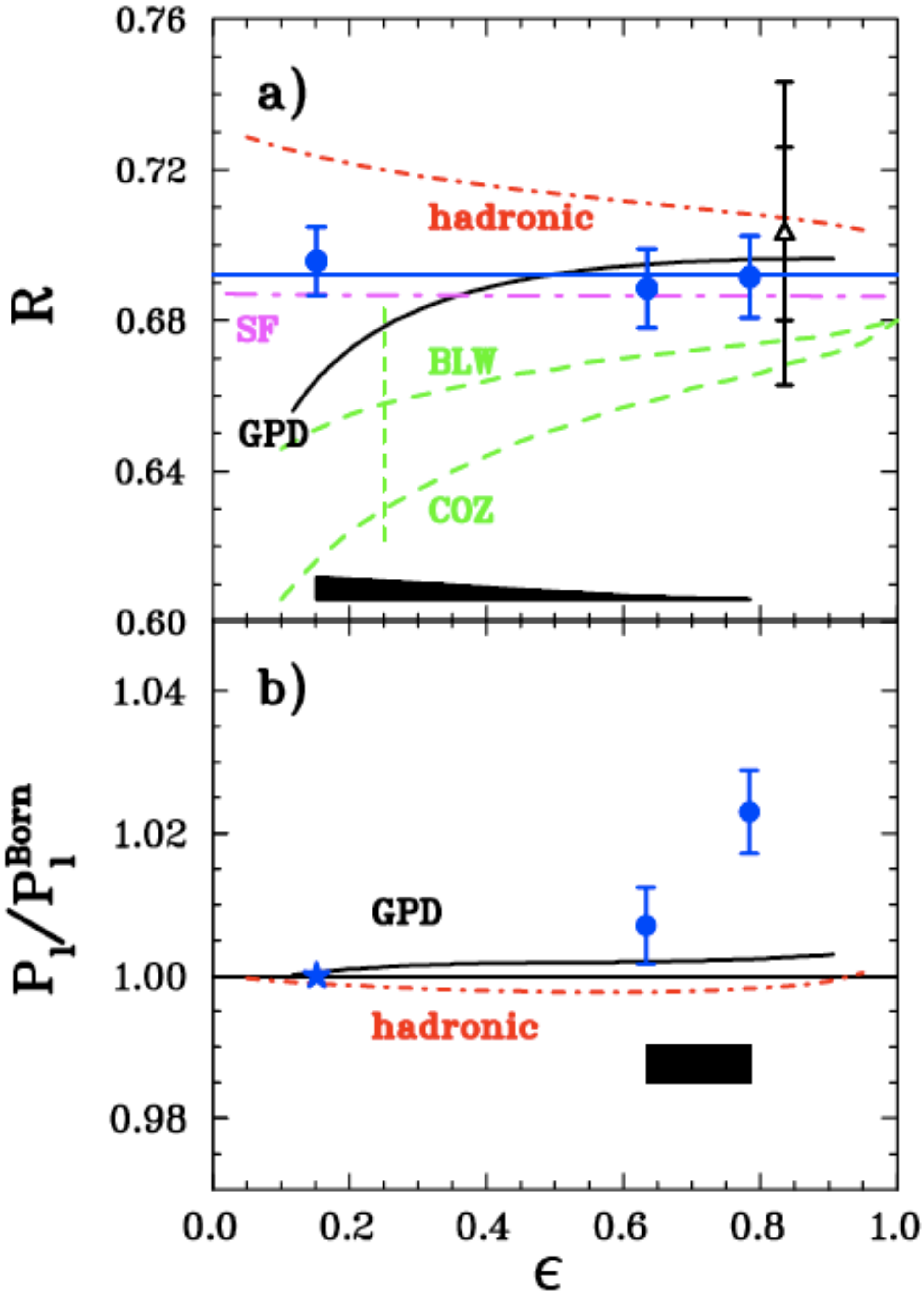
Born Approximation | **Beyond Born Approximation**

P.A.M. Guichon and M.Vanderhaeghen, Phys.Rev.Lett. 91, 142303 (2003)

M.P. Rekalo and E. Tomasi-Gustafsson, E.P.J. A 22, 331 (2004)

Slide idea:
L. Pentchev

Jefferson Lab E04-019 (Two-gamma)



Jlab – Hall C
Q^2 = 2.5 (GeV/c)^2

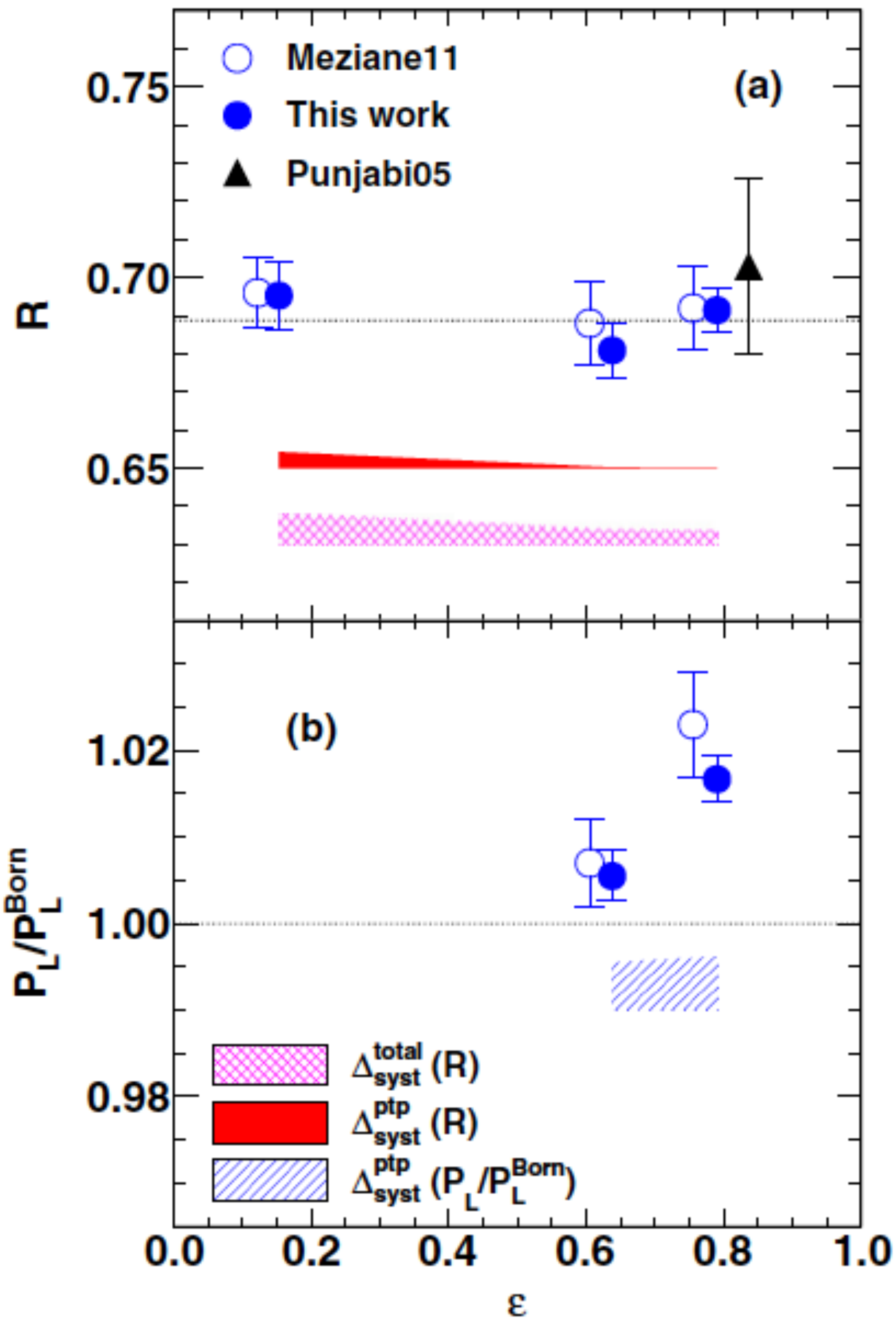
G_E/G_M from P_t/P_l constant vs. ε

➔ **no effect in P_t/P_l**
➔ **some effect in P_l**

Expect larger effect in e+/e-!

M. Meziane *et al.*, hep-ph/1012.0339v2
Phys. Rev. Lett. 106, 132501 (2011)

Jefferson Lab E04-019 (Two-gamma)



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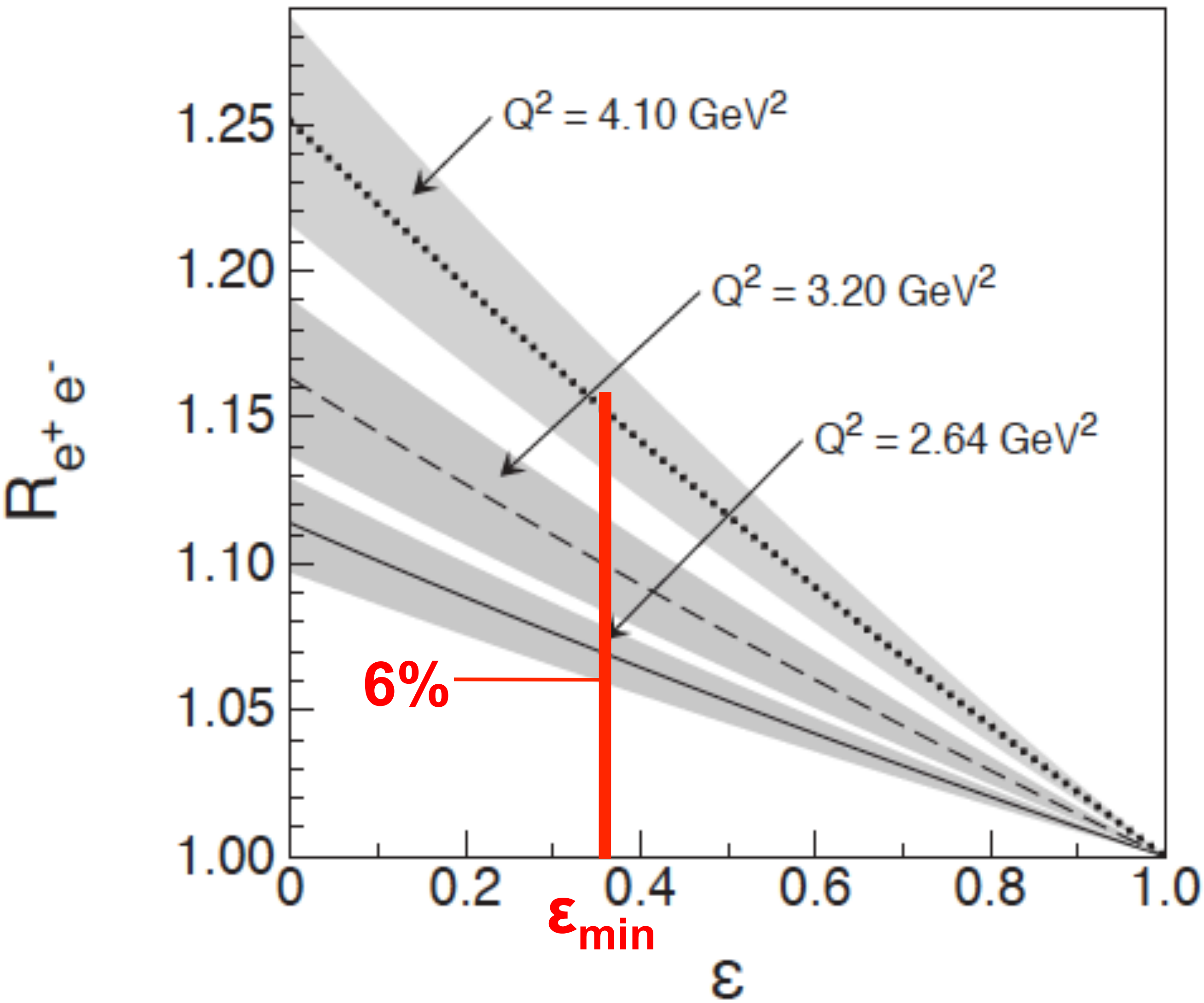
M. Meziane *et al.*, hep-ph/1012.0339v2
Phys. Rev. Lett. 106, 132501 (2011)

A. Puckett *et al.*, nucl-ex/1707.08587v2
Phys. Rev. C 96, 055203 (2017)

Empirical extraction of TPE amplitudes

J. Guttmann, N. Kivel, M. Meziane, and M. Vanderhaeghen, EPJA 47, 77 (2011)

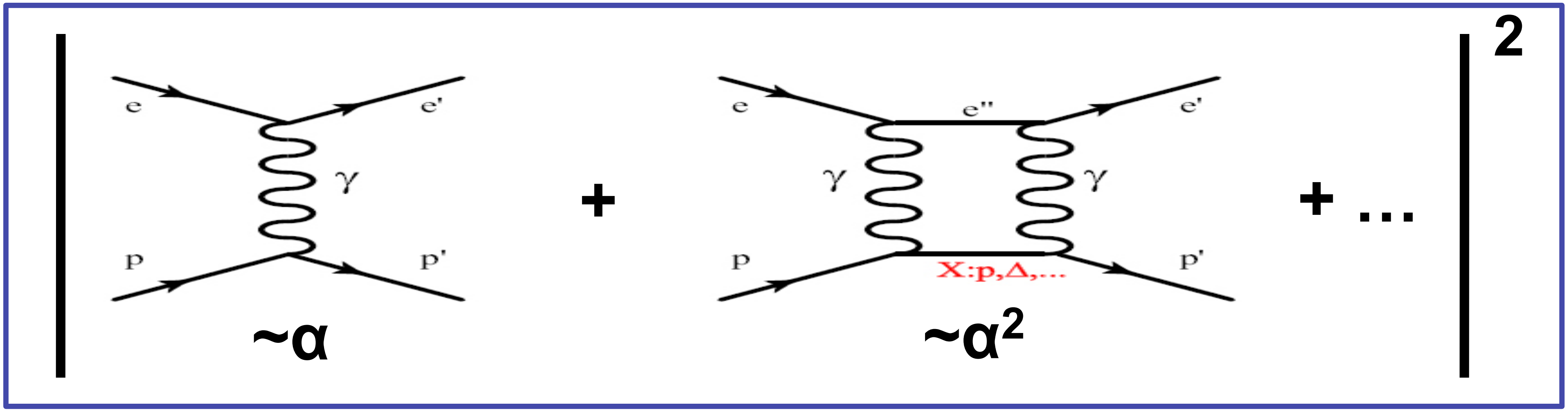


grows with Q^2!

Expect ~6% effect for OLYMPUS@2.0GeV

ε_{min}>0.35, Q^2<2.2 (GeV/c)^2

Lepton-proton elastic scattering



- **Interference term depends on lepton charge sign (C-odd)**

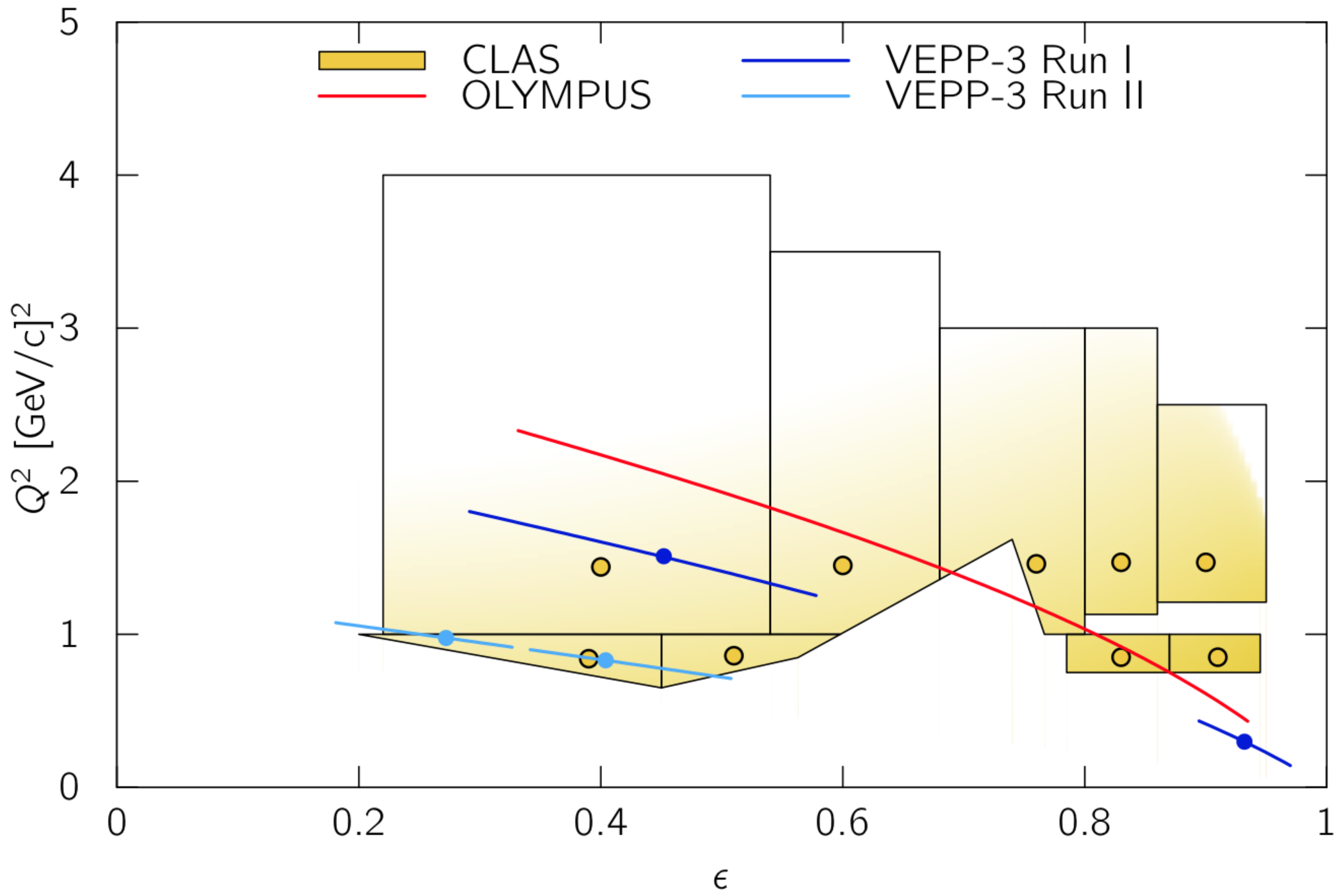
$$\sigma_{e^\pm p} = |\mathcal{M}_{1\gamma}|^2 \pm 2\Re\{\mathcal{M}^\dagger_{1\gamma}\mathcal{M}_{2\gamma}\} + \cdots$$

- **e^+/e^- ratio deviates from unity by two-photon contribution**

$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + 4\frac{\Re\{\mathcal{M}^\dagger_{1\gamma}\mathcal{M}_{2\gamma}\}}{|\mathcal{M}_{1\gamma}|^2}$$

Comparison of e^+/e^- experiments

- VEPP-3 @ Novosibirsk: E_{beam} = 1.6, 1.0 (and 0.6) GeV
- CLAS @ JLAB : E_{beam} = 0.5 – 4.0 GeV continuous
- OLYMPUS @ DESY: E_{beam} = 2.0 GeV

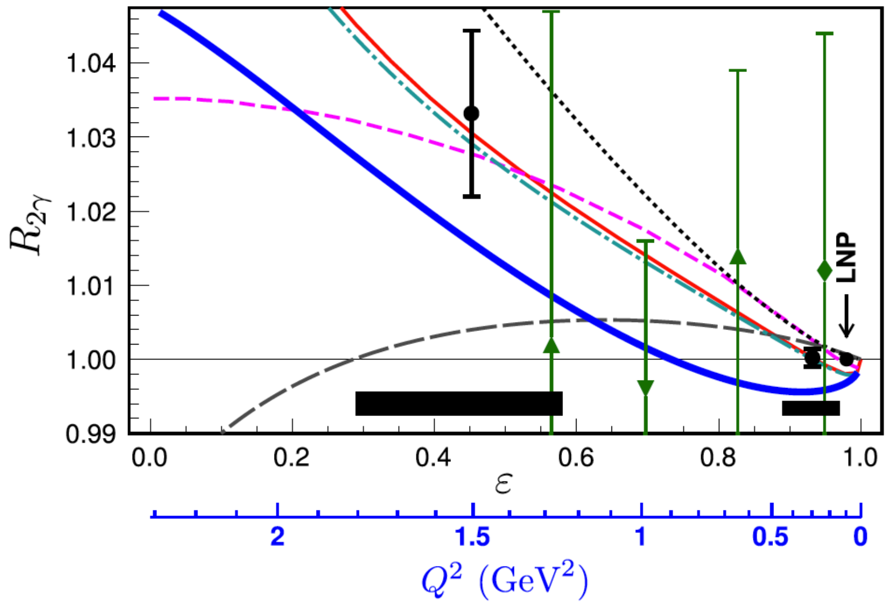


Comparison of e^+/e^- experiments

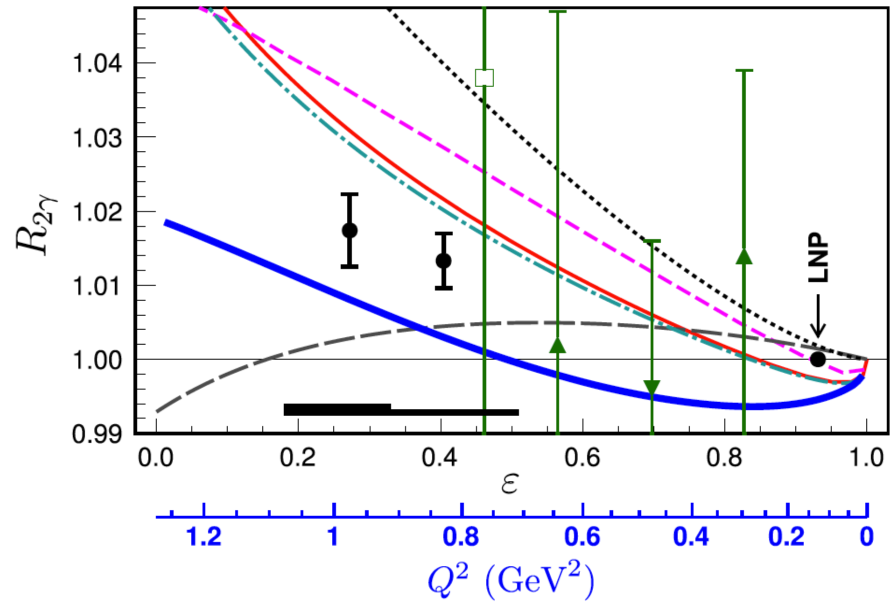
	VEPP–3 Novosibirsk	OLYMPUS DESY	EG5 CLAS JLab
beam energy	3 fixed	1 fixed	wide spectrum
equality of $e^\pm$ beam energy	measured	measured	reconstructed
e^+/e^- swapping frequency	half-hour	24 hours	simultaneously
e^+/e^- lumi monitor	elastic low-Q^2	elastic low-Q^2, Möller/Bhabha	from simulation
energy 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
published	2015	2017	2015

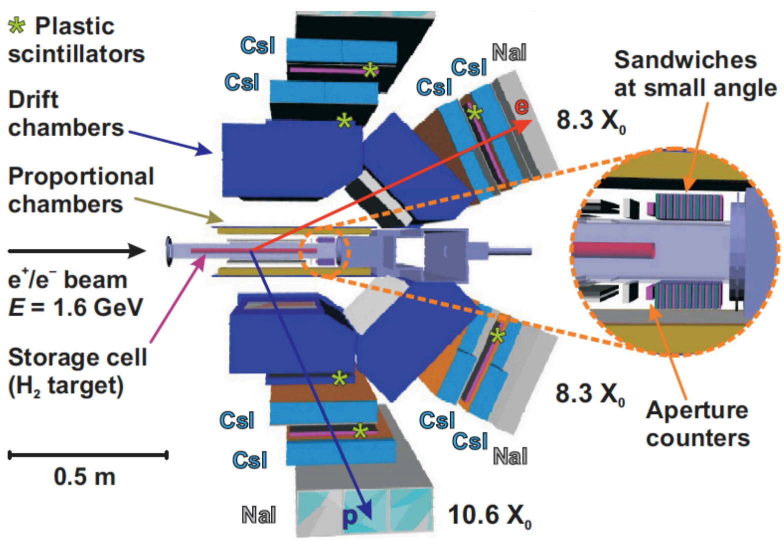
TPE experiments: Novosibirsk/VEPP-3

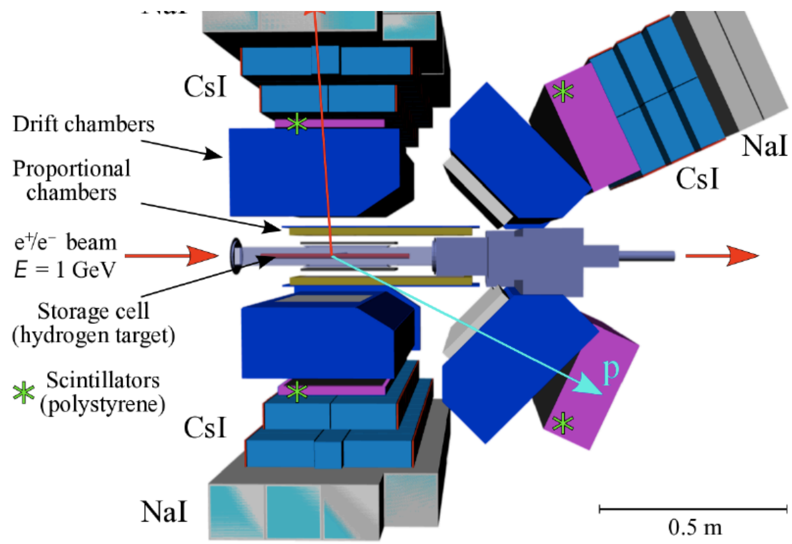
Run I (2009)
E=1.6 GeV



Run II (2011/12)
E=1.0 GeV

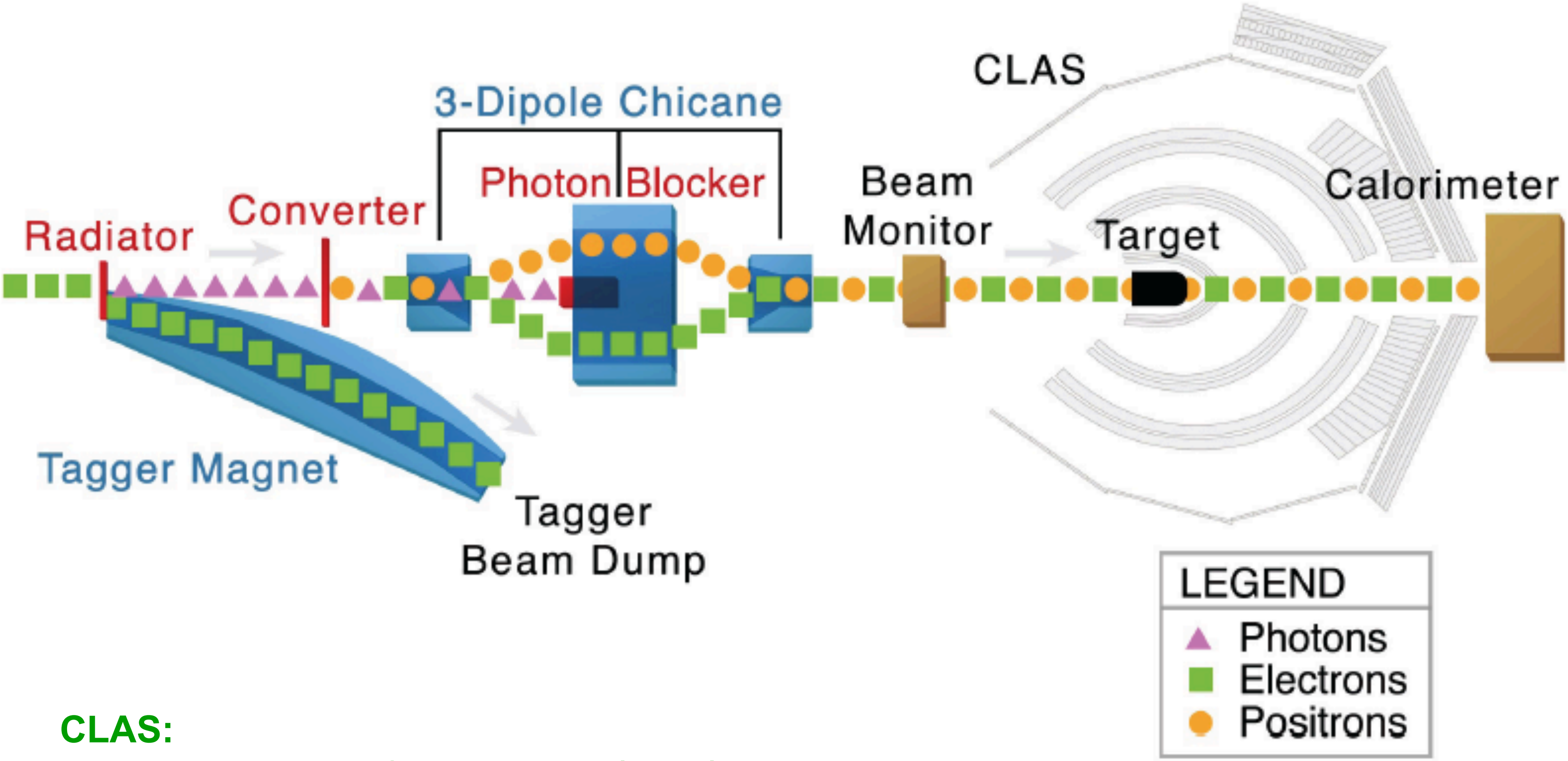






I.A. Rachek *et al.*, PRL 114, 062005 (2015)

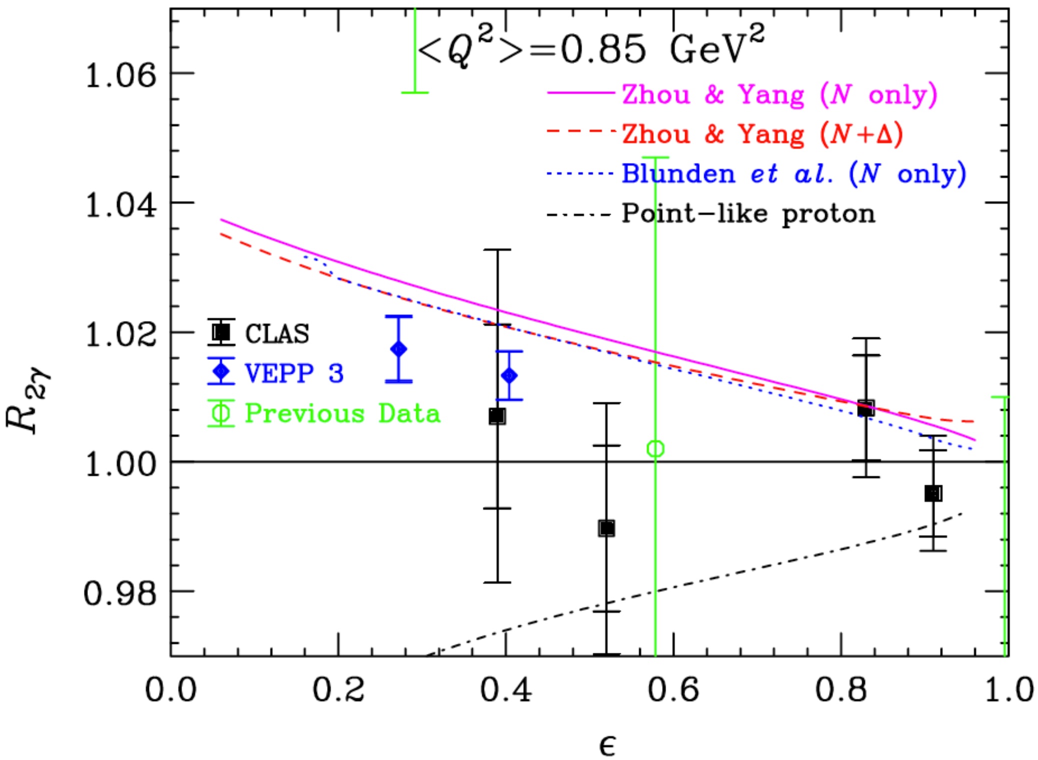
TPE experiments: CLAS (E04-116)

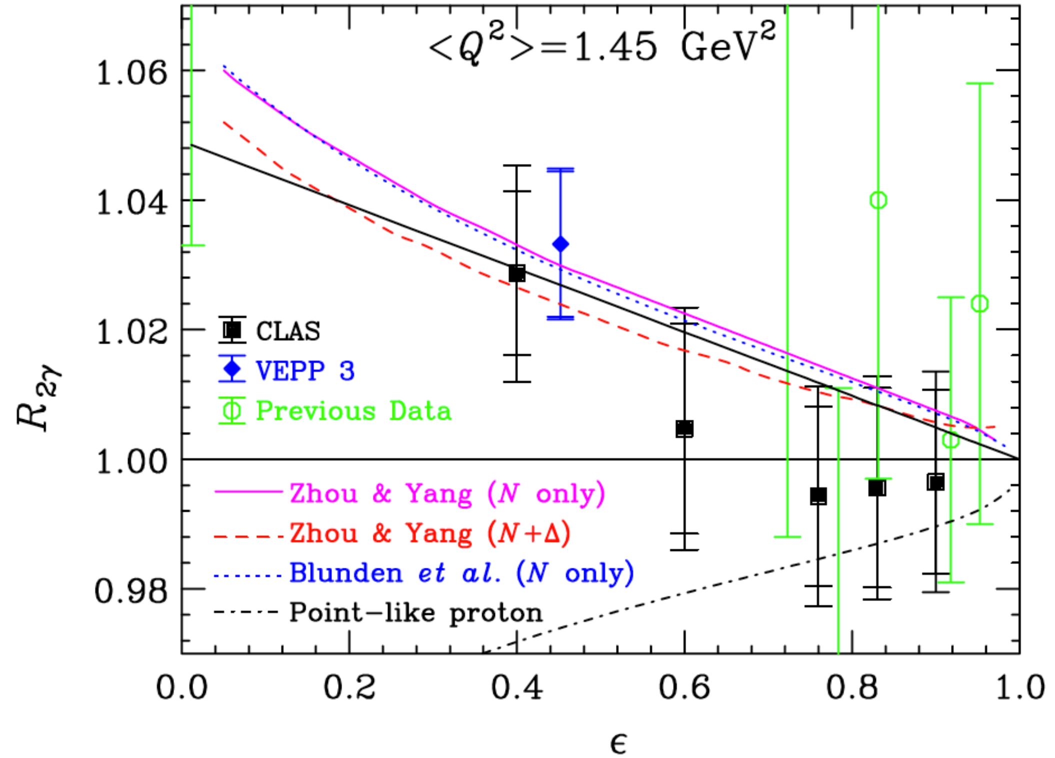


CLAS:
D. Rimal *et al.*, PRC 95, 065201 (2017)
D. Adikaram *et al.,* PRL 114, 062003 (2015)

TPE experiments: CLAS (E04-116)

ε dependence





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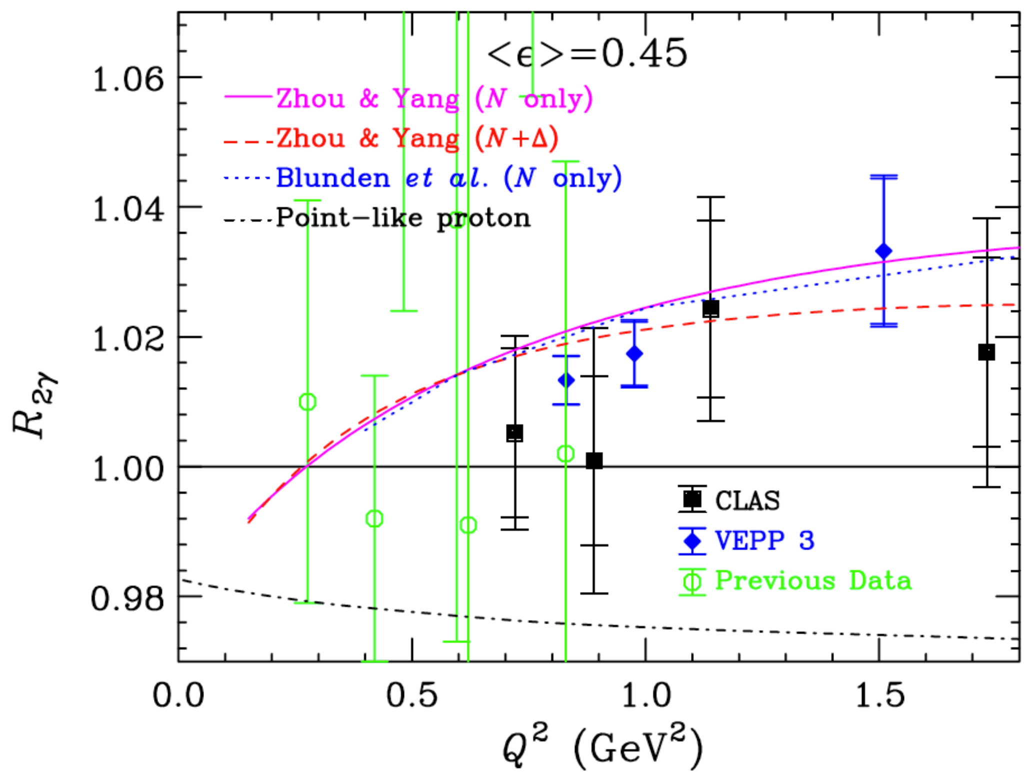
D. Rimal *et al.*, PRC 95, 065201 (2017)
D. Adikaram *et al.*, PRL 114, 062003 (2015)

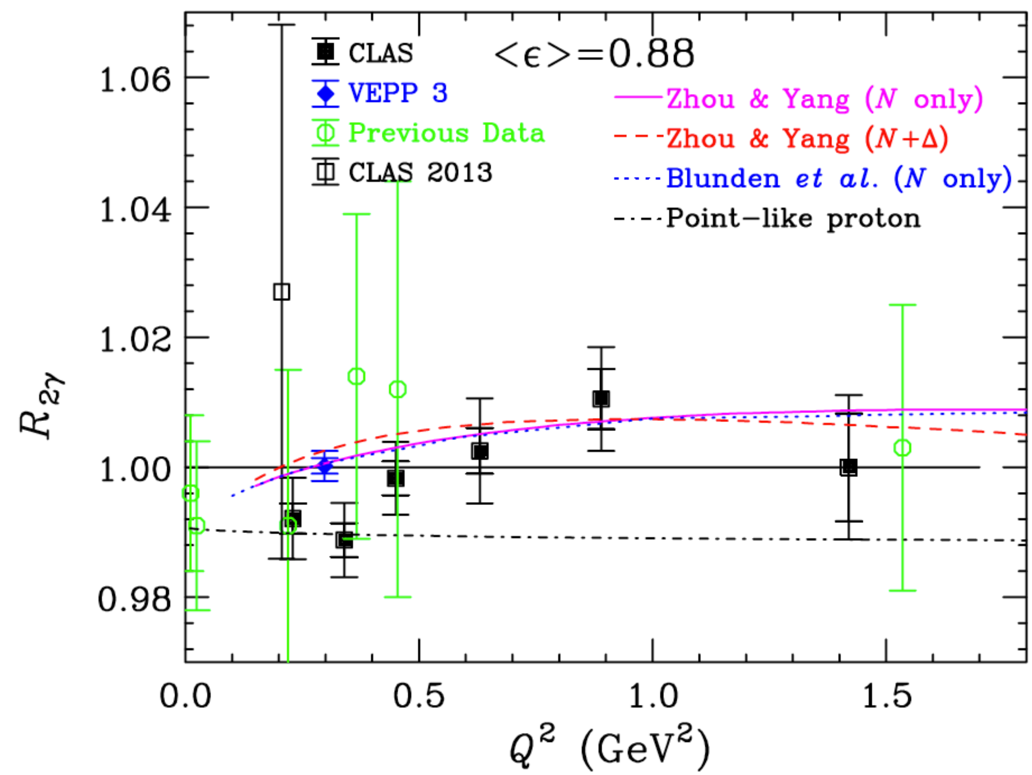
VEPP-3:
I.A. Rachek *et al.*, PRL 114, 062005 (2015)

CLAS result consistent with “standard” TPE prescription
… however, limited precision

TPE experiments: CLAS (E04-116)

Q² dependence





CLAS:
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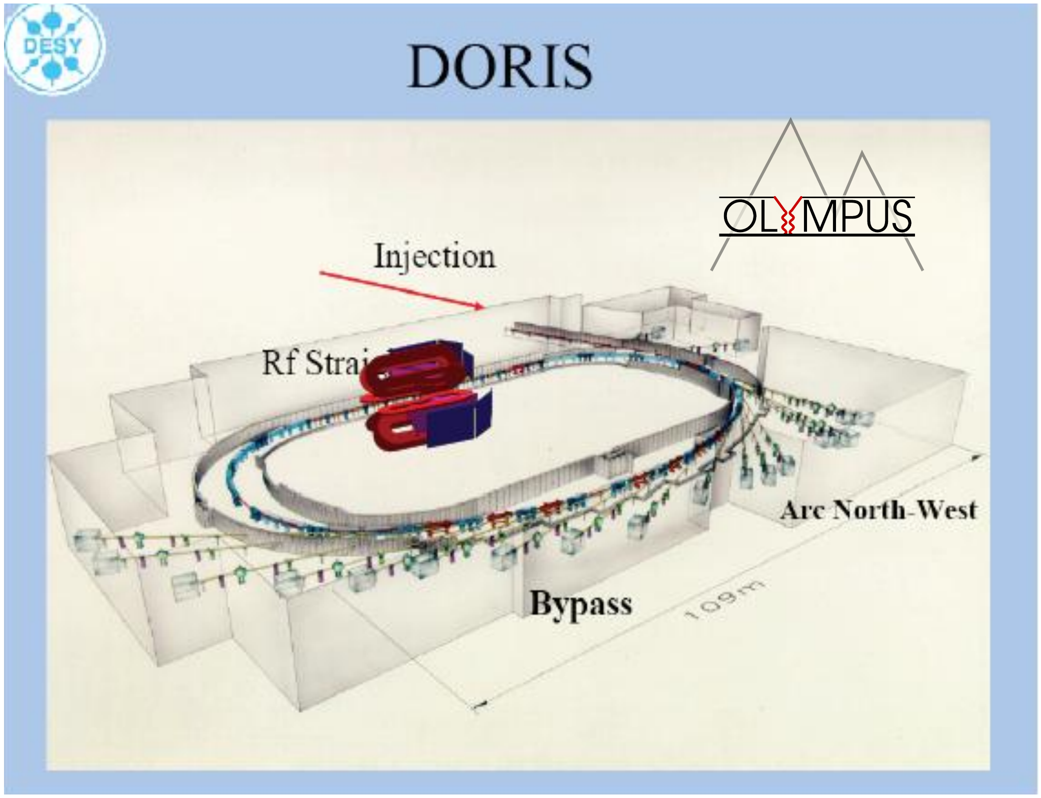
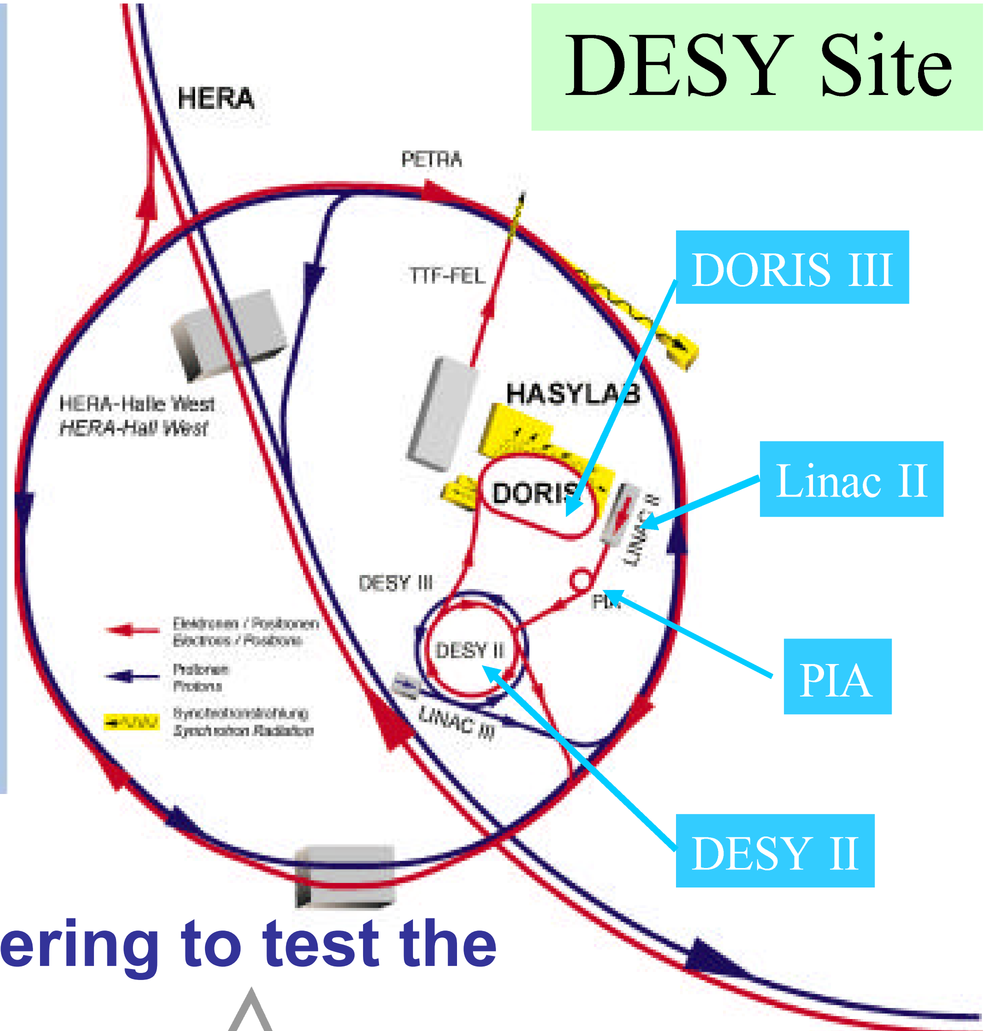
VEPP-3:
I.A. Rachek *et al.*, PRL 114, 062005 (2015)

CLAS result consistent with "standard" TPE prescription
… however, limited precision

OLYMPUS @ DORIS/DESY





p**O**sitron-proton and
e**L**ectron-proton elastic scattering to test the
h**Y**pothesis of
Multi-
Photon exchange
Using
Dori**S**

OLYMPUS collaboration

~50 physicists from 13 institutions in 6 countries

Elected spokesmen / deputy:	**R. Milner / R. Beck**	**(2009–2011)**
	M.K. / A. Winnebeck	**(2011–2013)**
	D. Hasell / U. Schneekloth	**(2013–)**

PhDs: O. Ates, A. Schmidt, R. Russell, B. Henderson, L. Ice, C. O'Connor, D. Khaneft

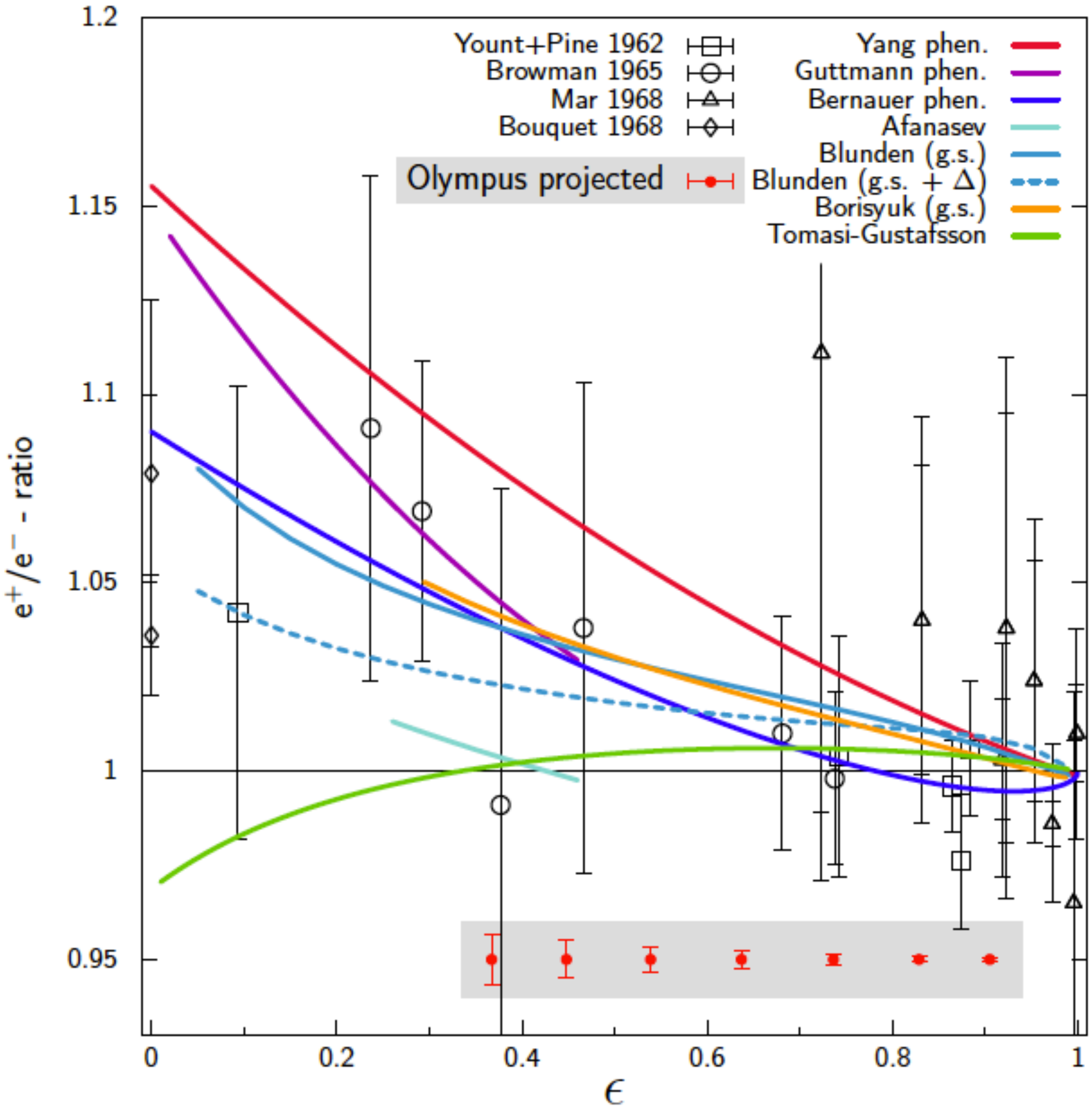
- **Arizona State University:** TOF support, particle identification, magnetic shielding
- **DESY:** Modifications to DORIS accelerator and beamline, toroid support, infrastructure, installation
- **Hampton University:** GEM luminosity monitor
- **INFN Bari:** GEM electronics
- **INFN Ferrara:** Target
- **INFN Rome:** GEM electronics
- **MIT:** BLAST spectrometer, wire chambers, tracking upgrade, target and vacuum system, transportation to DESY, simulations, slow control, analysis framework
- **Petersburg Nuclear Physics Institute:** MWPC luminosity monitor
- **University of Bonn:** Trigger, data acquisition, and online monitor
- **University of Mainz:** Trigger, DAQ, Symmetric Moller monitor
- **University of Glasgow**: TOF scintillators
- **University of New Hampshire:** TOF scintillators
- **A. Alikhanyan National Laboratory (AANL), Yerevan:** TOF scintillators

The OLYMPUS experiment

- **Electrons/positrons (100mA) in 2.0–4.5 GeV storage ring**
  DORIS at DESY, Hamburg, Germany
- **Unpolarized internal hydrogen target (buffer system)**
  3×10^{15} at/cm^2 @ 100 mA $\rightarrow$ L = 2×10^{33} / (cm^{2}s)
- **Large acceptance detector for e-p in coincidence**
  BLAST detector from MIT-Bates available
- **Redundant monitoring of luminosity**
  Pressure, temperature, flow, current measurements
  Small-angle elastic scattering at high epsilon / low Q^2
  Symmetric Moller/Bhabha scattering

- **Measure ratio of positron-proton to electron-proton unpolarized elastic scattering to 1% stat.+sys.**

Projected results for OLYMPUS



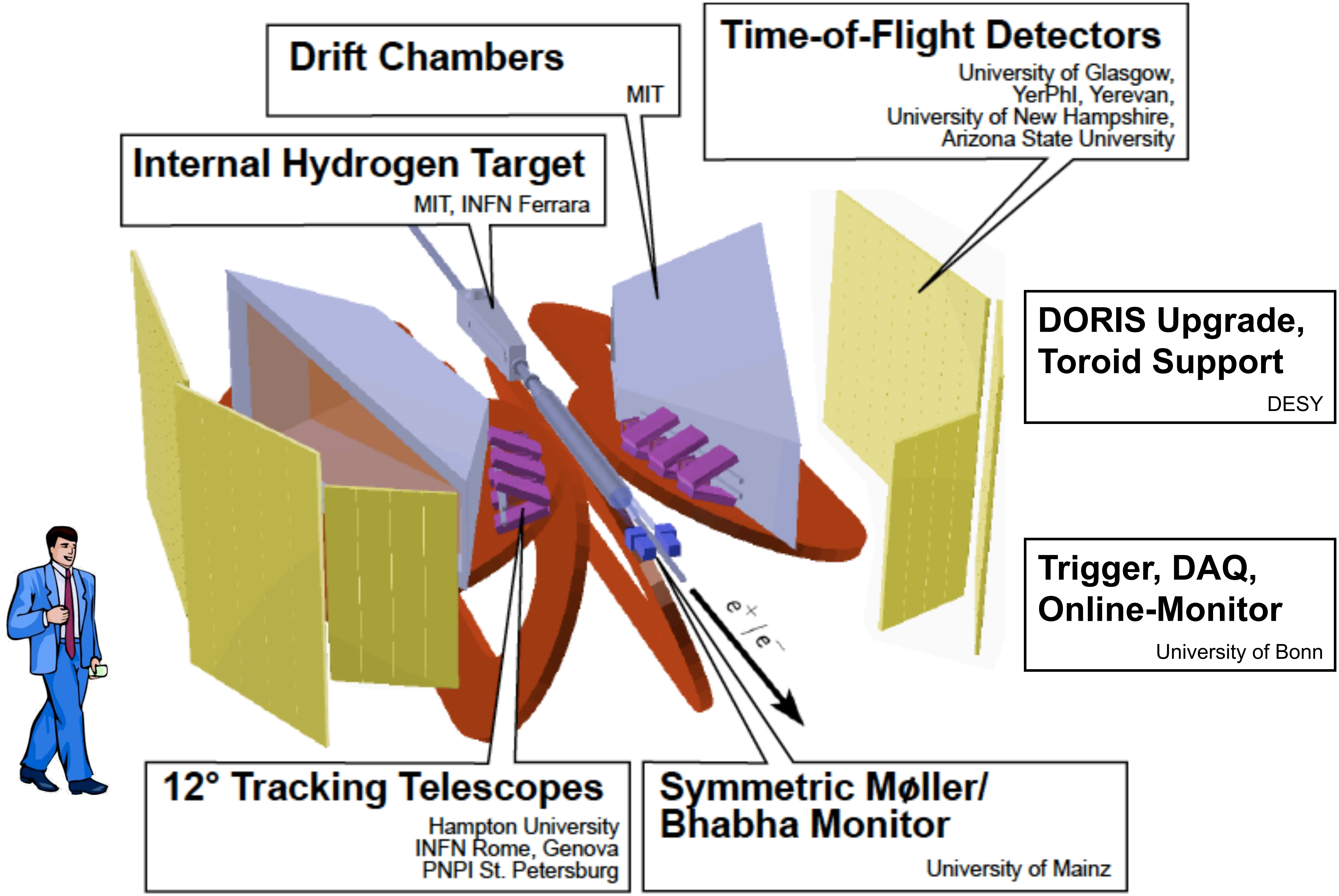
Data from 1960's

Many theoretical predictions with little constraint

OLYMPUS:
- **E= 2.0 GeV**
- **$0.4 < Q^2/(GeV/c)^2 < 2.2$**
- **Acquire 3.6 fb^{-1} for <1% projected uncertainties**

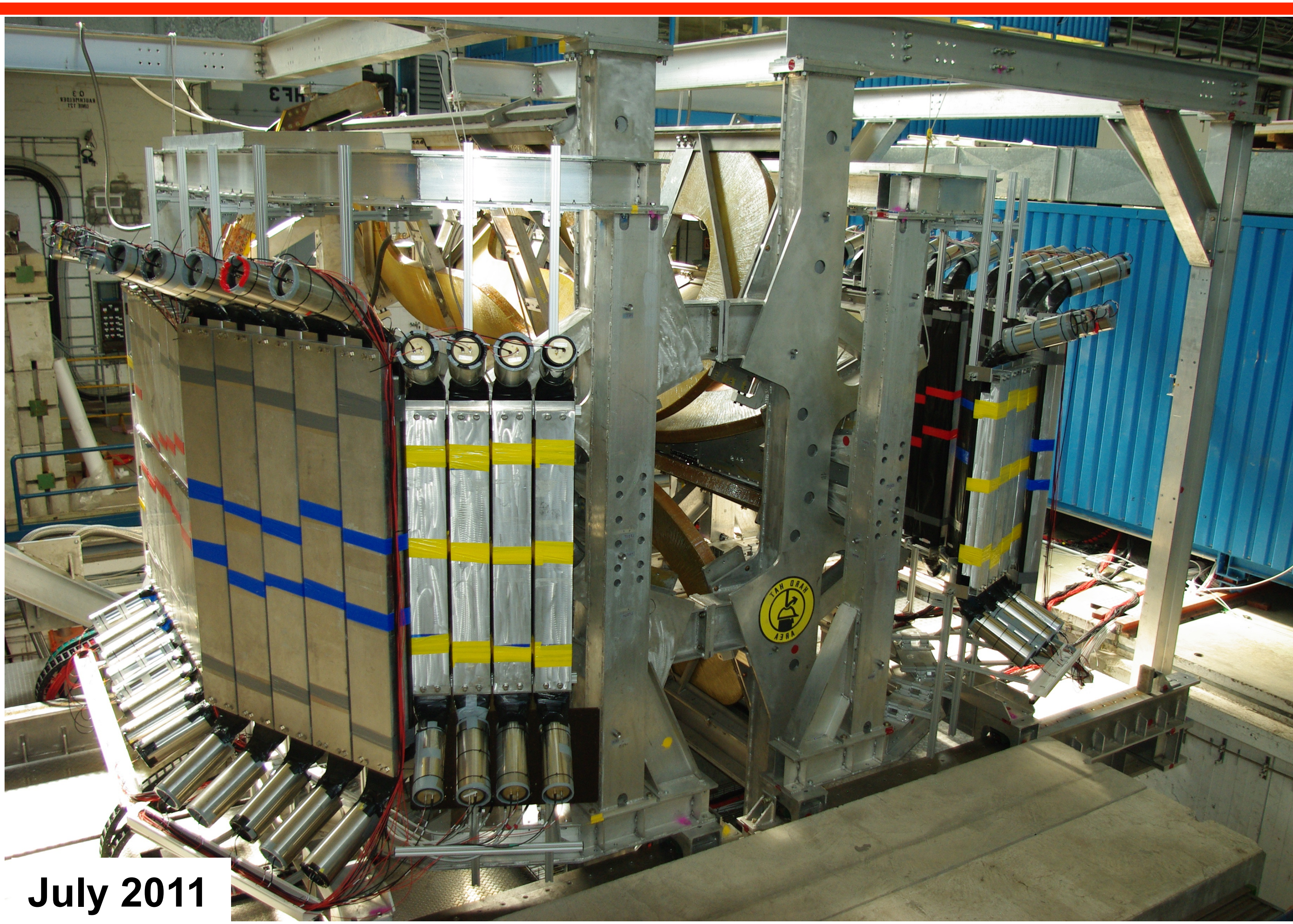
Data taking completed in 2012

The designed OLYMPUS detector



based on a figure by R. Russell

The realized OLYMPUS detector



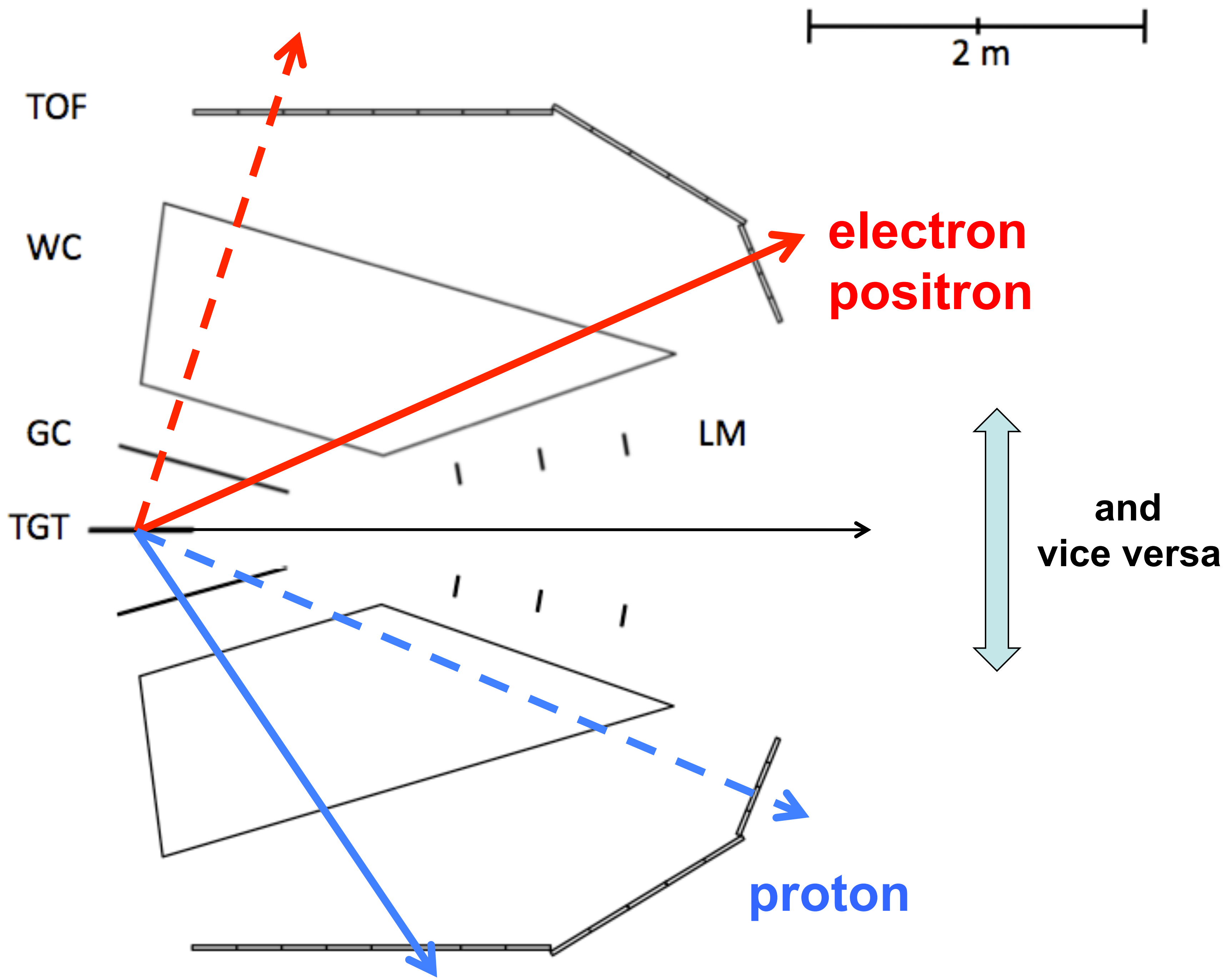
July 2011

Apparatus: ***"The OLYMPUS Experiment"*****, R. Milner *et al.*, NIMA 741, 1 (2014)**

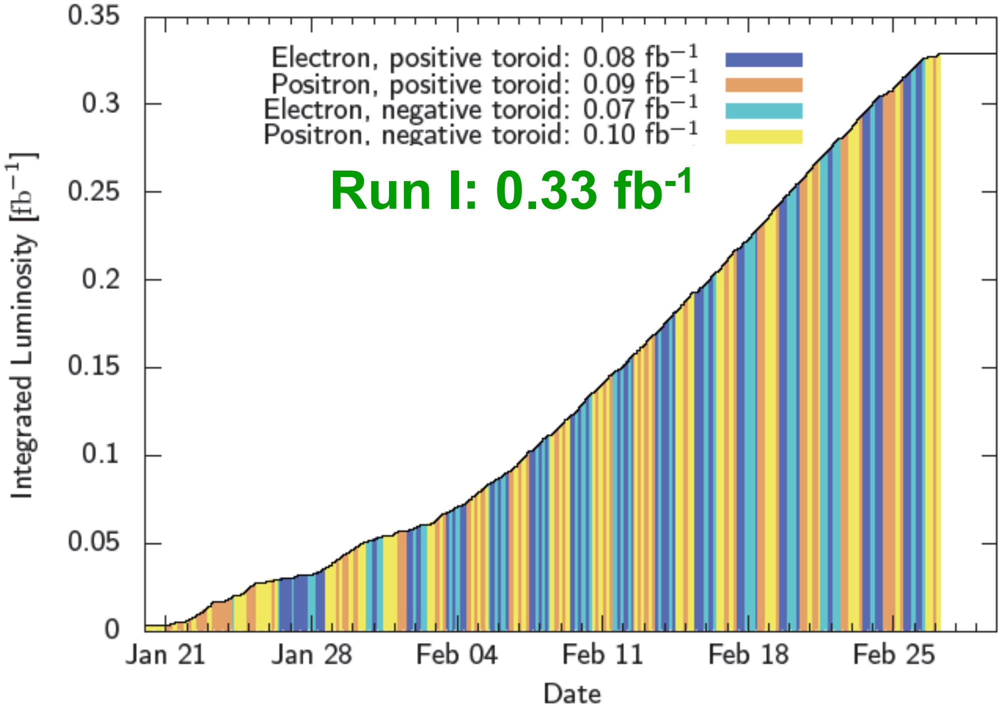
Target: ***"The OLYMPUS internal hydrogen target"*****, J.C. Bernauer, NIMA 755, 20 (2014)**

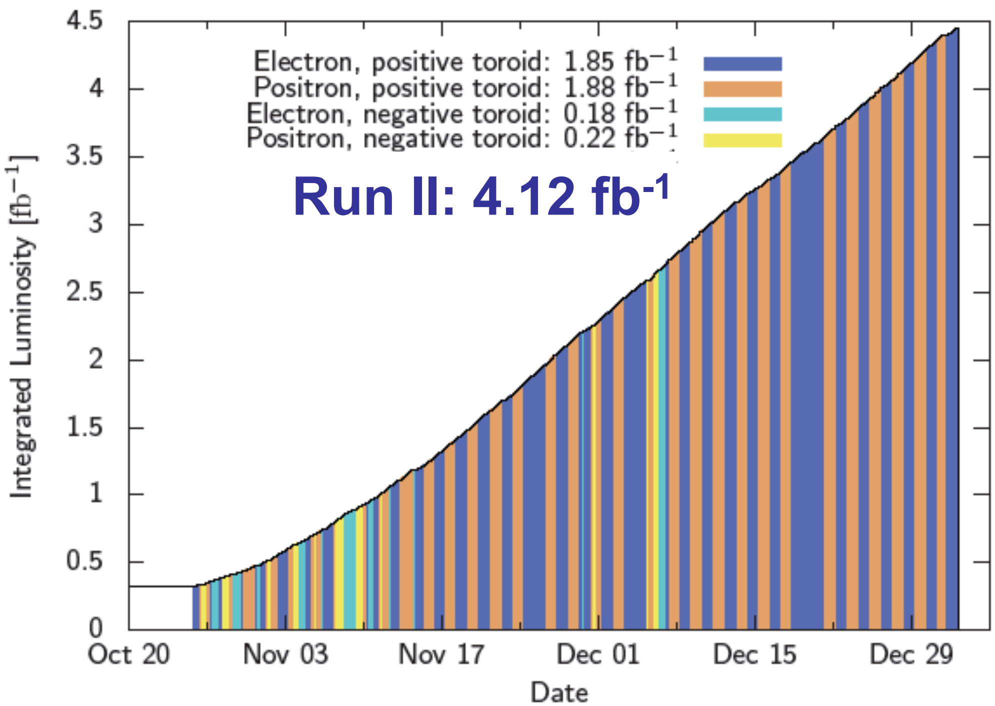
Magnet: ***"Measurement and tricubic interpolation of the magnetic field for the OLYMPUS experiment"*****, J.C. Bernauer *et al.*, NIMA 823, 9 (2016)**

OLYMPUS kinematics at 2.0 GeV



Timeline of OLYMPUS





- 2007 Letter of Intent
- 2008 Proposal
- 2009 Technical review
- 2010 Approval and funding
- Summer 2010 BLAST transfer
- Spring 2011 Target test run
- Summer 2011 Detector installed
- Fall 2011 Commissioning

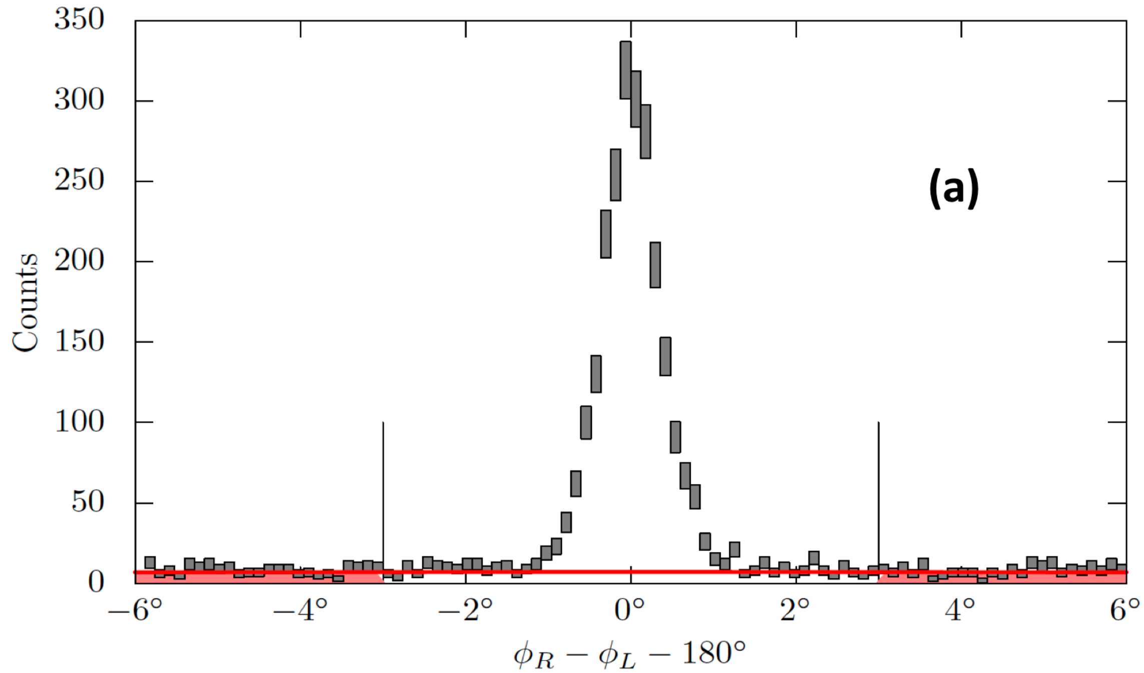
First run Jan 30 – Feb 27, 2012
… acquired < 0.3 fb^{-1}

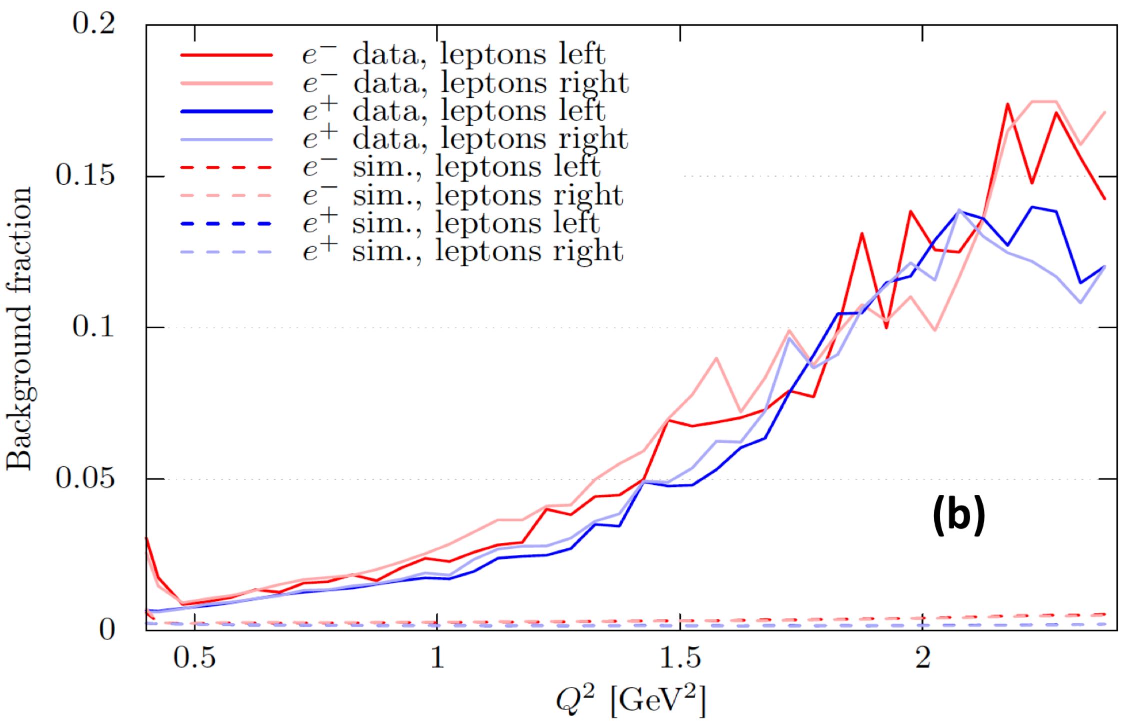
- Summer 2012 Repairs and upgrades

Second run Oct 24, 2012 – Jan 2, 2013
… acquired > 4.0 fb^{-1}

- Smooth performance of machine, target, detector
- Spring 2013 Survey & field mapping
- Analysis progressing – framework, calibrations, tracking, simulations
- **Results released in November 2016**

Backgrounds

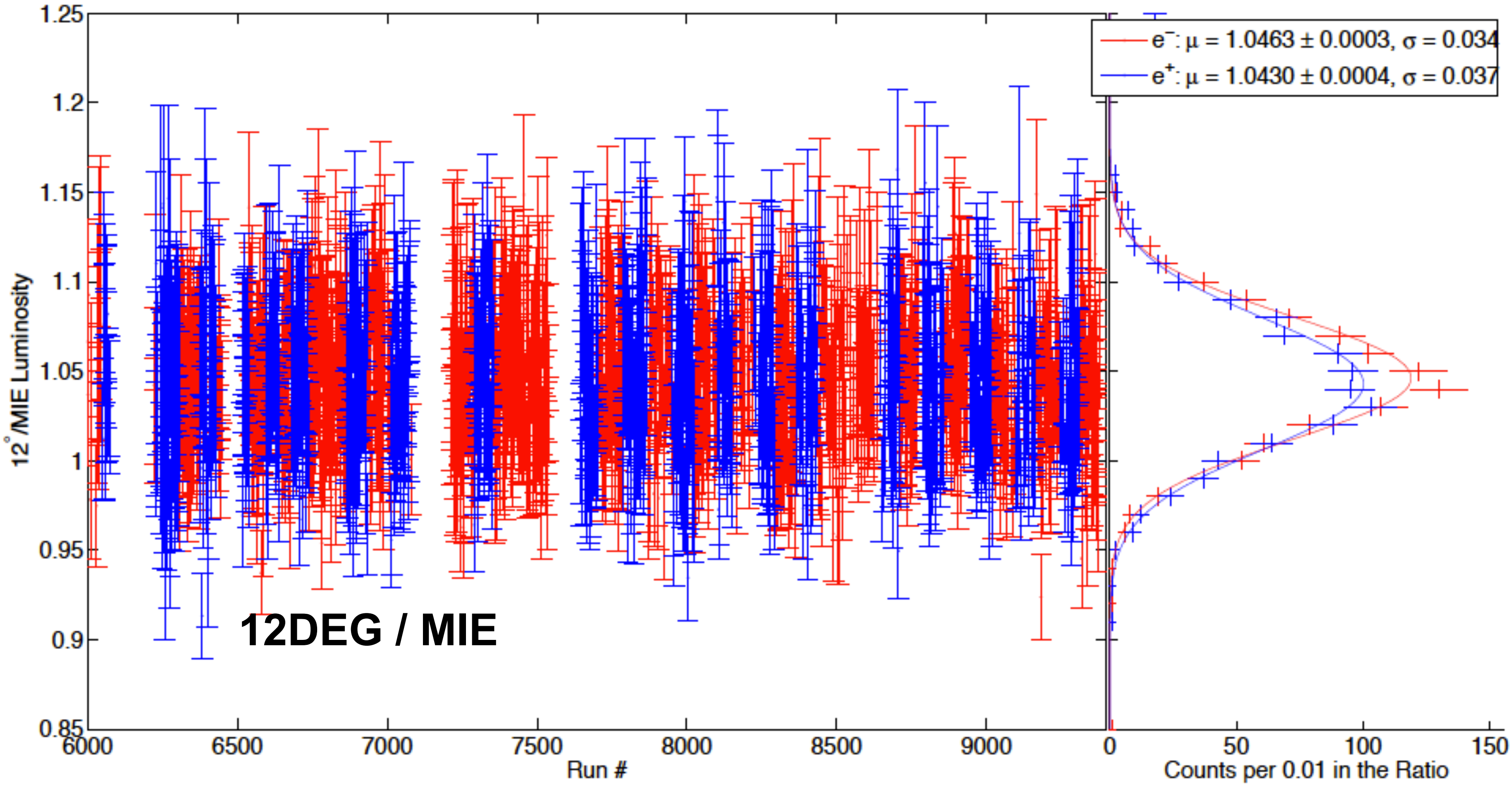




- **Coplanarity peak for background estimation**
- **Backgrounds range from negligible at forward angles to 15-20% at large angles**
- **Mostly independent of species**

Luminosity monitoring

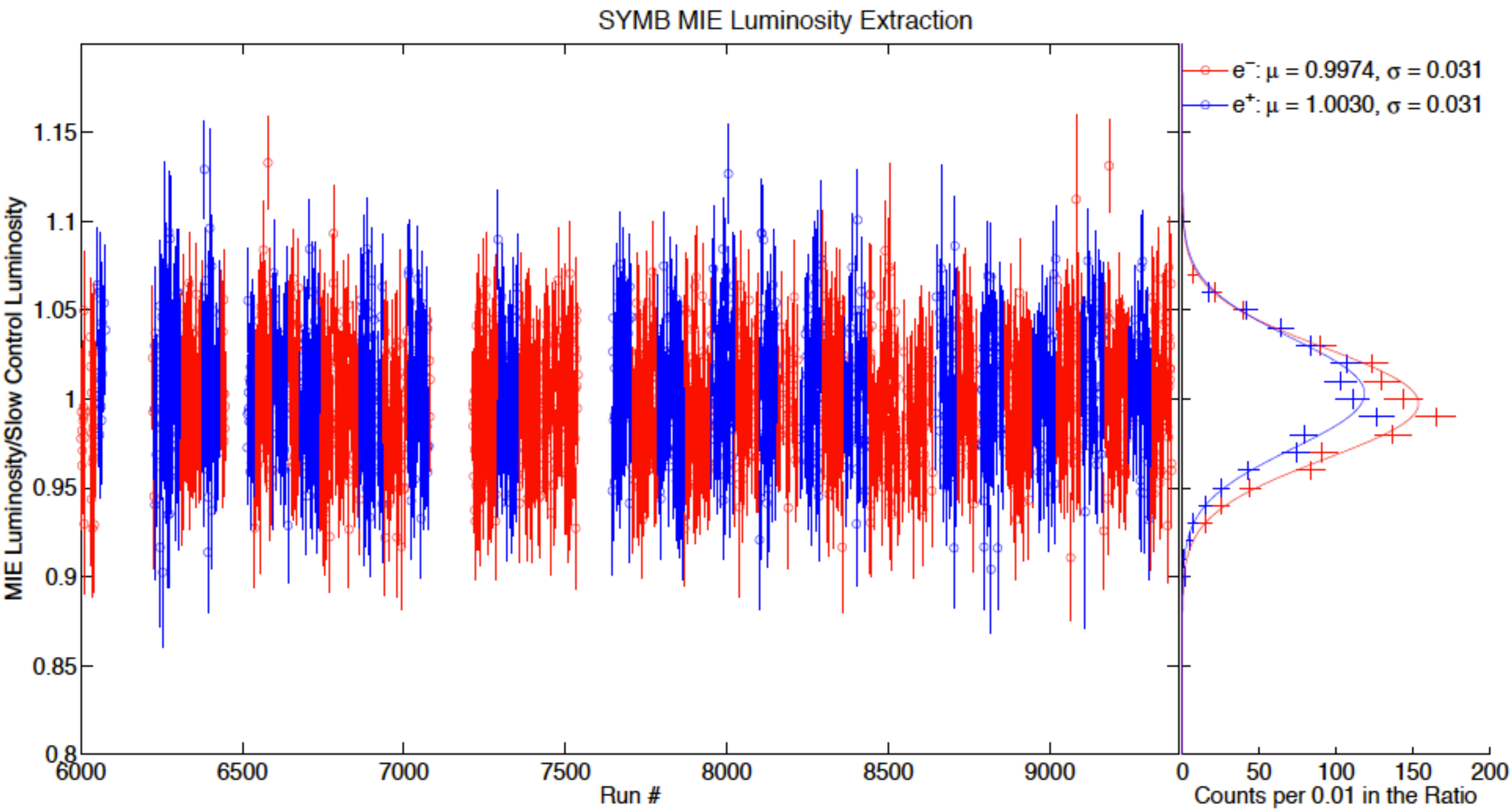
- Five redundant systems: Slow Control, SYMB, MIE, 12DEG-L,R
- Absolute luminosity from each rate to a few %
- Ratio of e^+/e^- luminosities for $R_{2\gamma}$ to sub %
- Time variation, mean and variance, systematics from comparisons
- Excellent agreement between SC, MIE, and 12DEG-L,R
- Final luminosity ratio from MIE, using 12DEG for high-ε data point



A. Schmidt, B. Henderson (MIT)

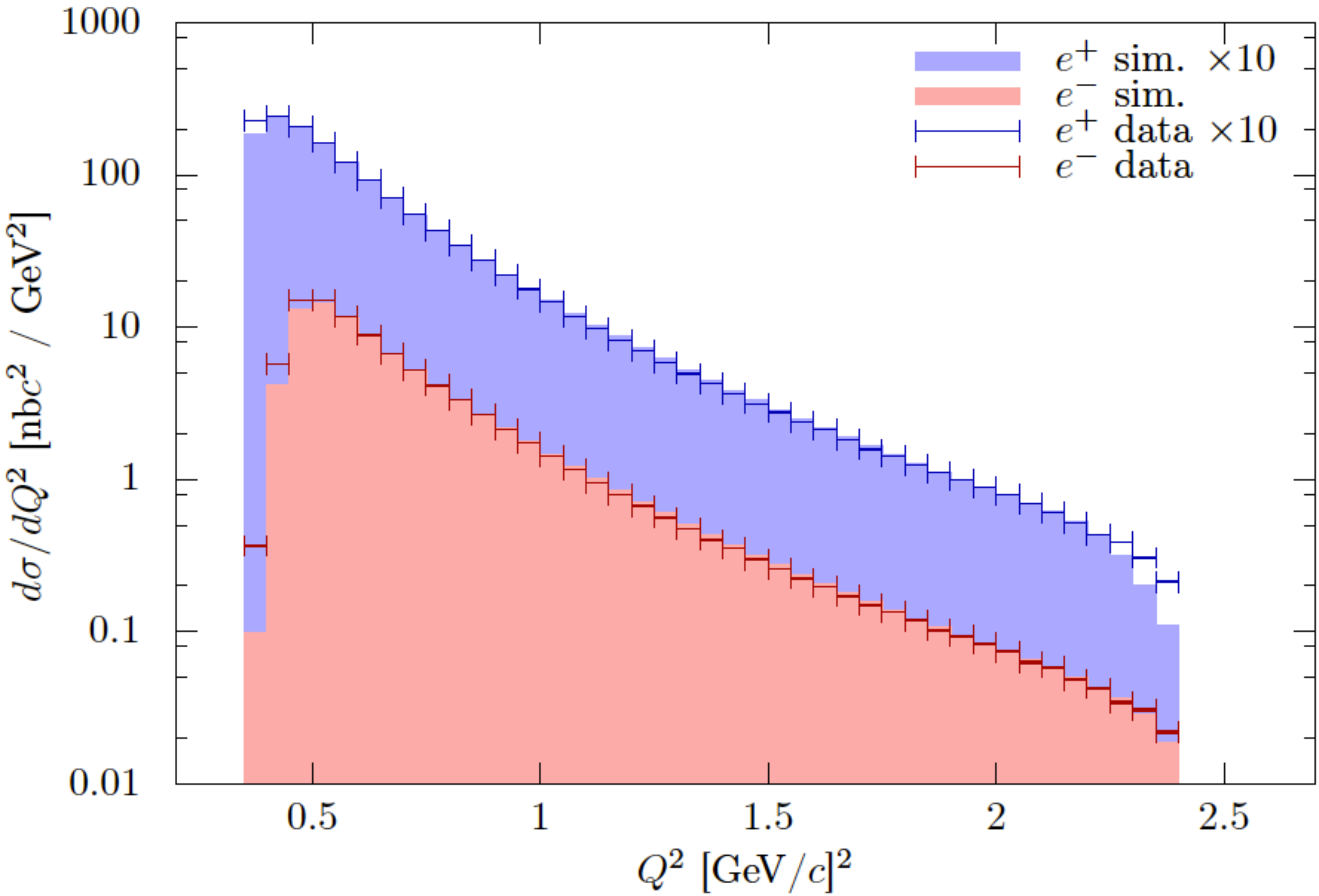
Luminosity monitoring

MIE / SC



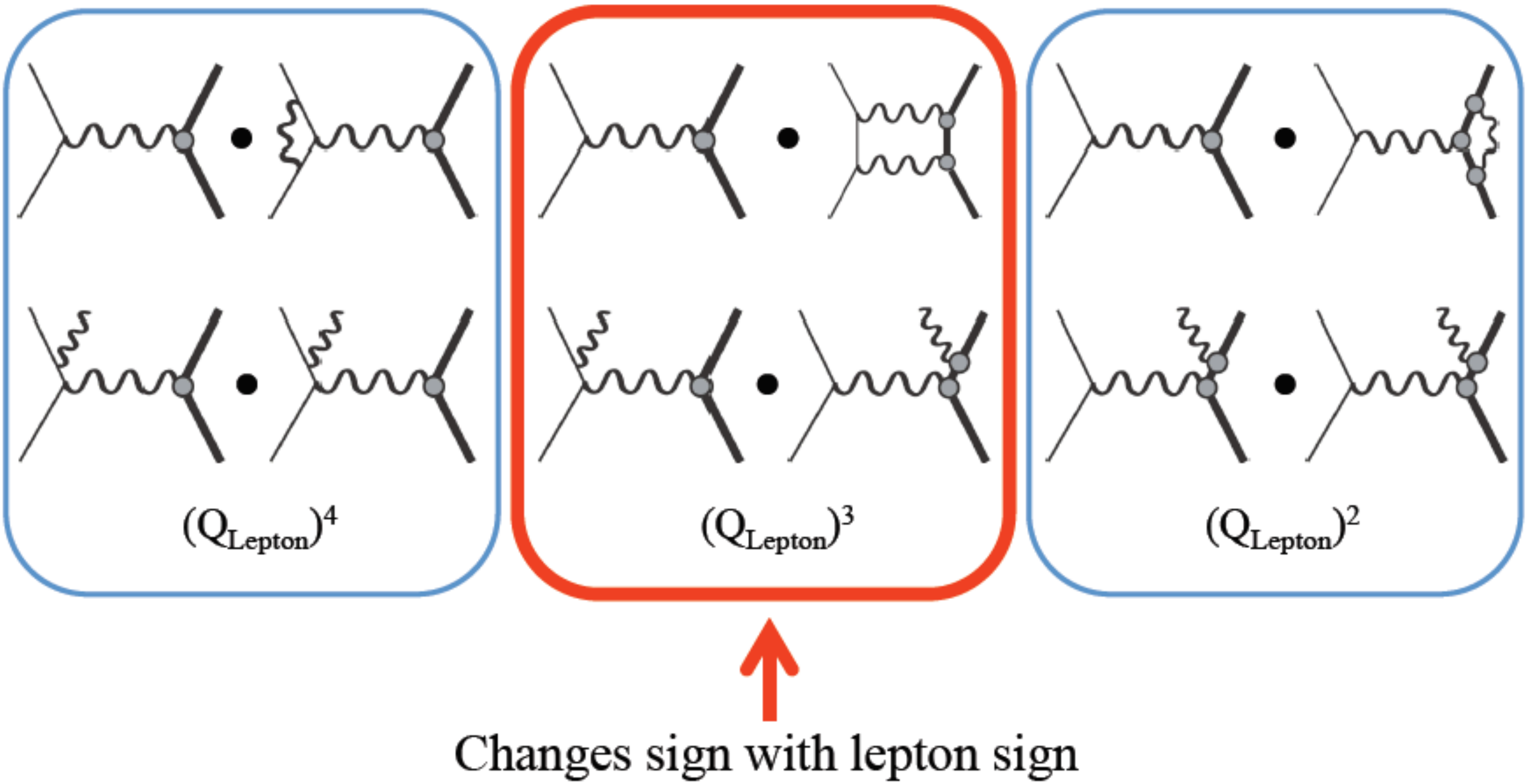
A. Schmidt, B. Henderson (MIT)

Yields


1000
100
10
1
0.1
0.01
0.5
1
1.5
2
2.5
$d\sigma/dQ^2$ [nbc^2 / GeV^2]
Q^2 [GeV$/c$]^2
e^+ sim. ×10
e^- sim.
e^+ data ×10
e^- data

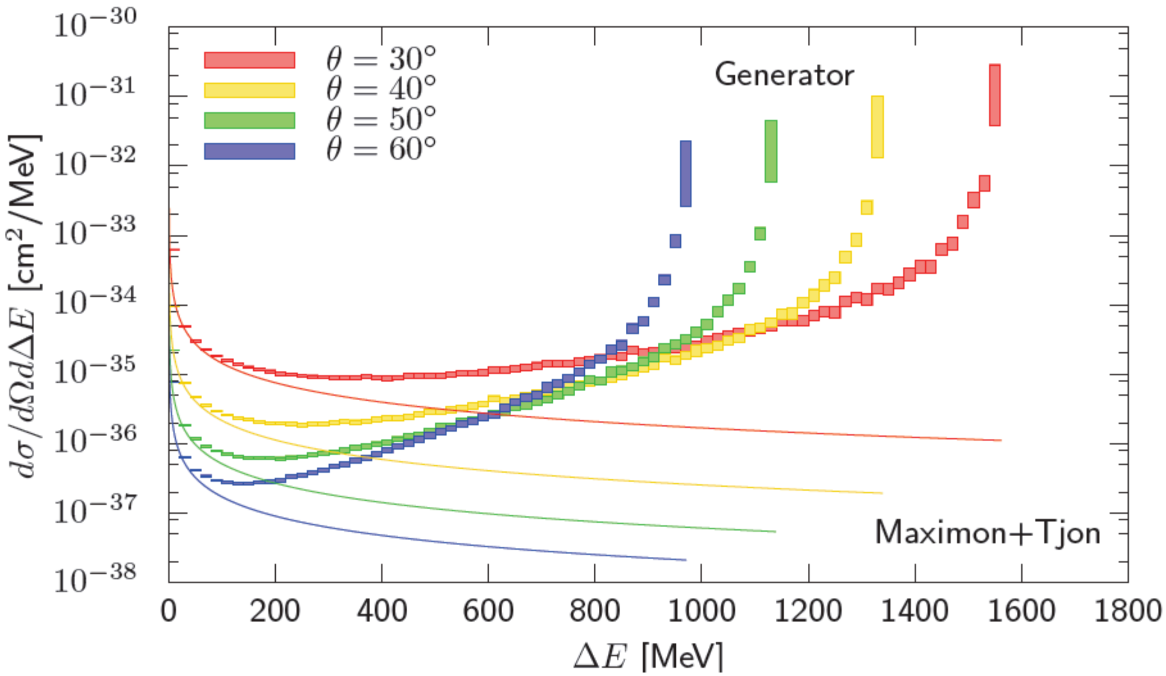
Radiative corrections of order α^3

- **Use MC framework to accurately implement all 'standard' RC and to extract effect from hard TPE**
- **Ensure consistency between different experiments**

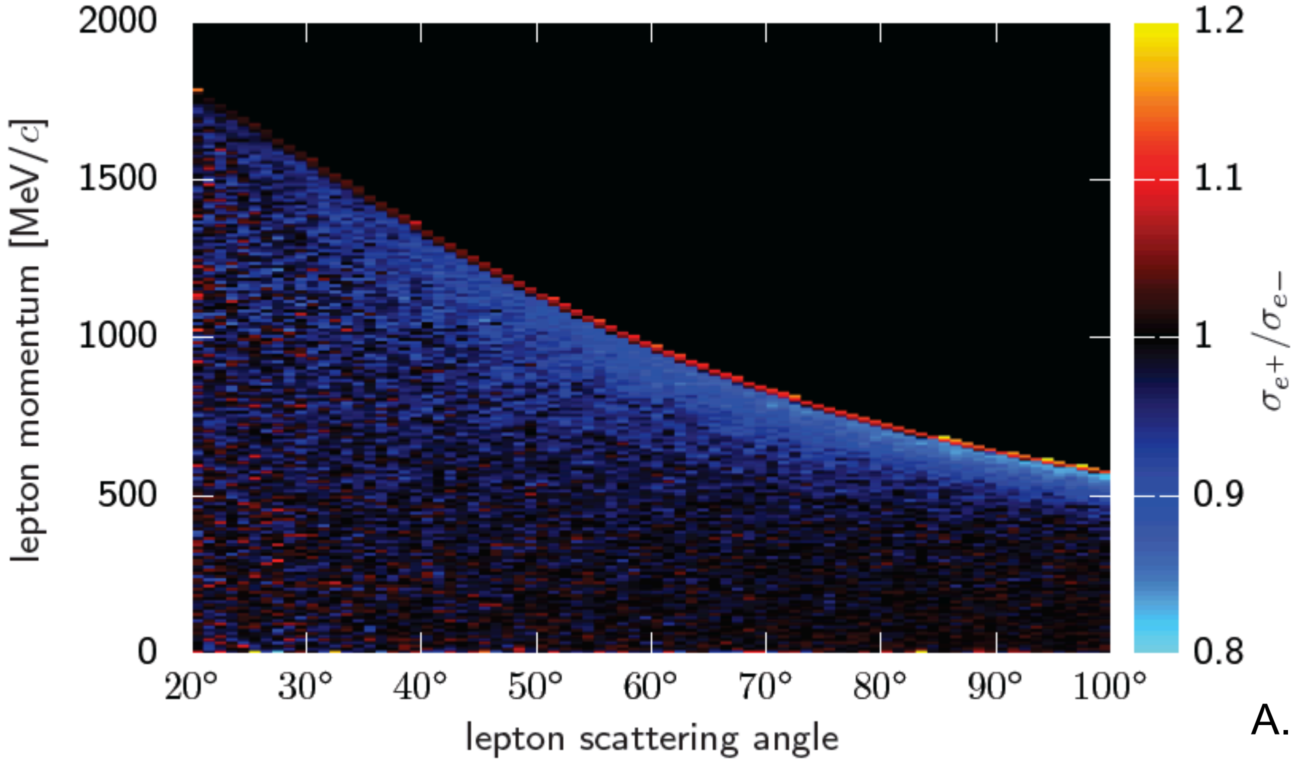


A. Schmidt, R. Russell, J. Bernauer (MIT)

MIT radiative generator



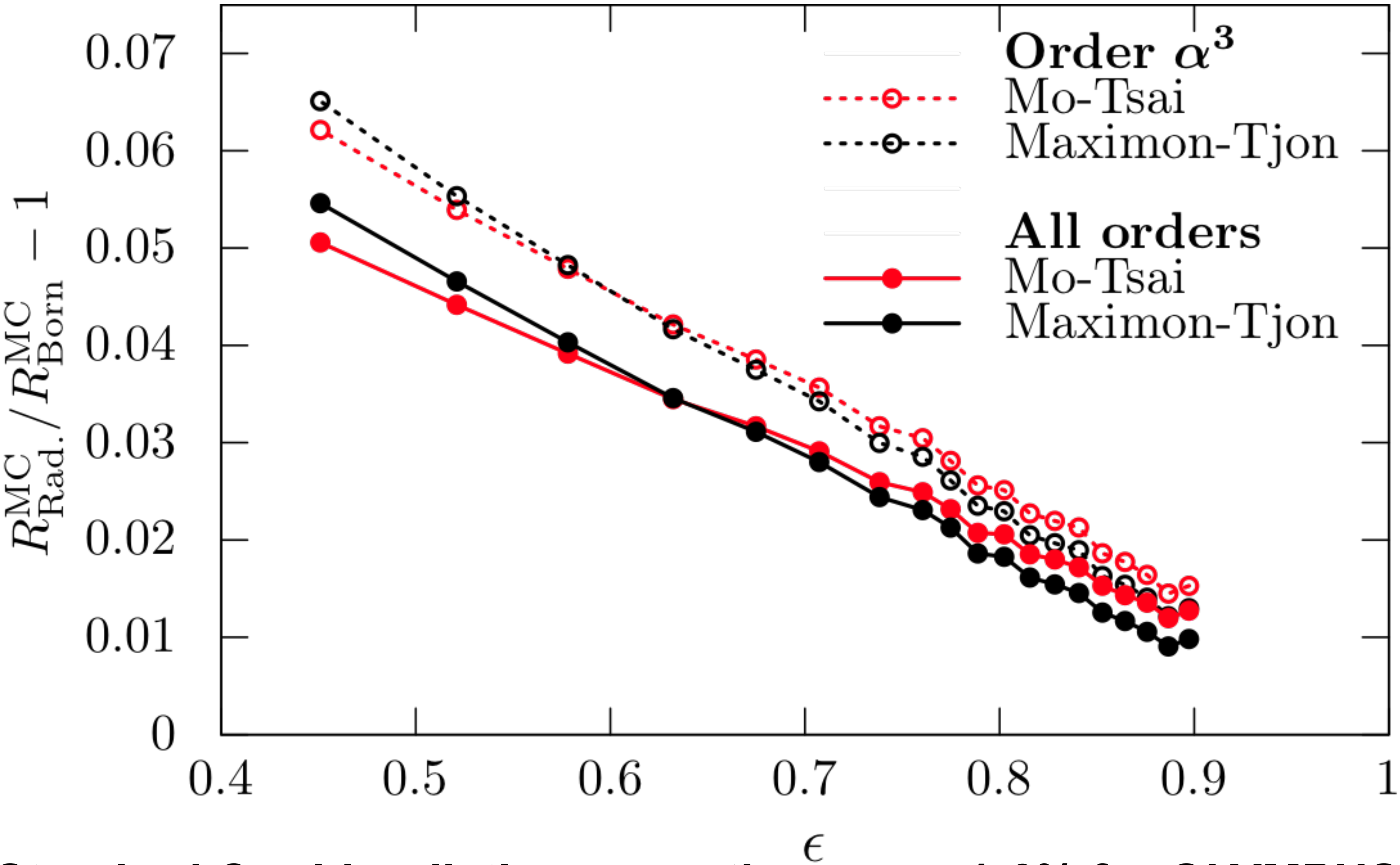
- Avoids approximations
- Agreement with Maximon&Tjon (soft photons) at low ΔE
- Excellent agreement with VEPP-3 generator at $O(\alpha^3)$



Effect on σ_{e+}/σ_{e-}

A. Schmidt, R. Russell, J. Bernauer (MIT)

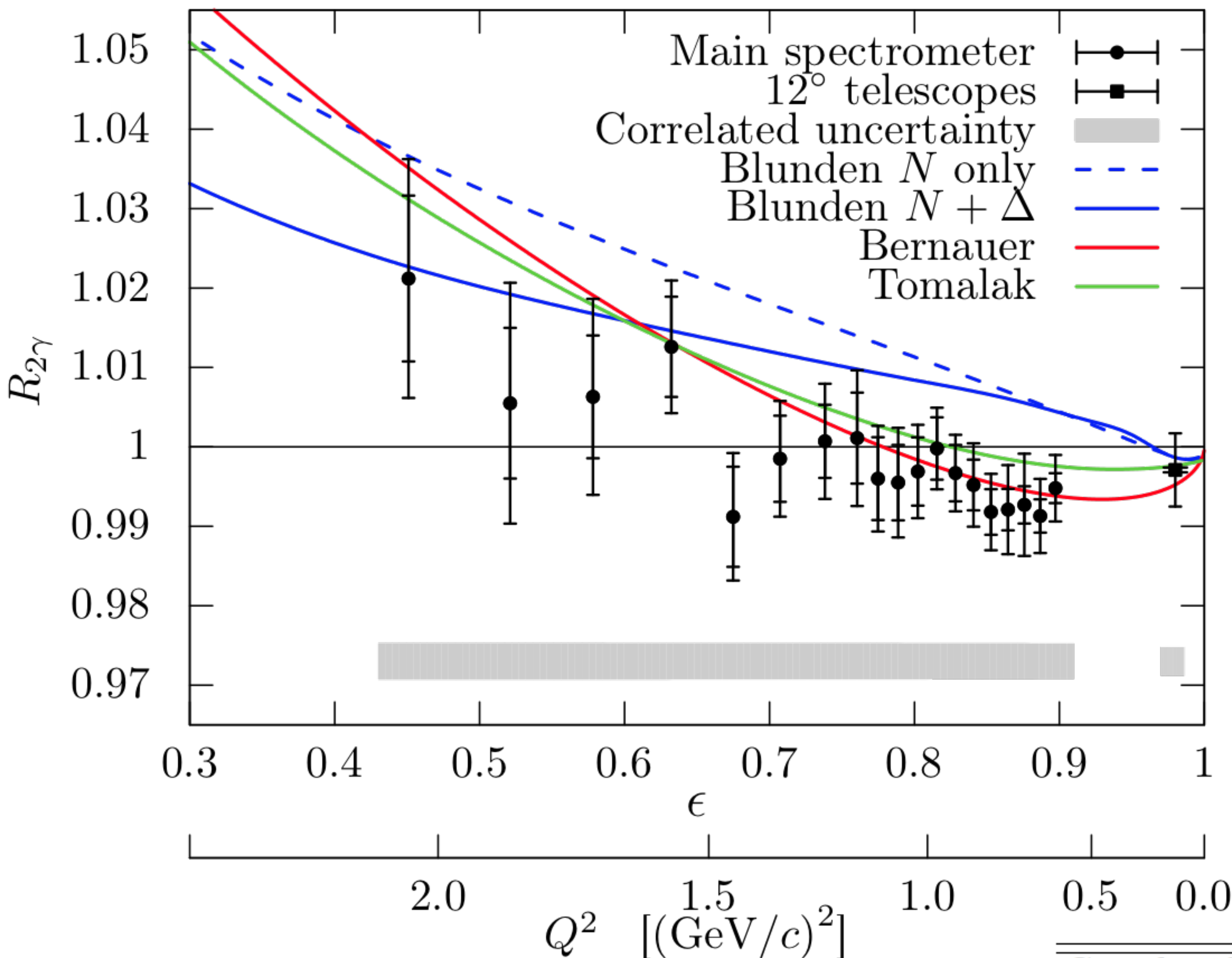
MIT radiative generator



- **Standard C-odd radiative corrections are ~1-6% for OLYMPUS**
- **Variation due to higher orders at ~1% level**

B.S. Henderson *et al.*, PRL 118, 092501 (2017) [arXiv:1611.04685v2]

Result for hard two-photon exchange



- **Mo-Tsai to all orders**
- **Results based on 3.1 fb^{-1}, statistics 0.2 – 1%**

Hard TPE is small !

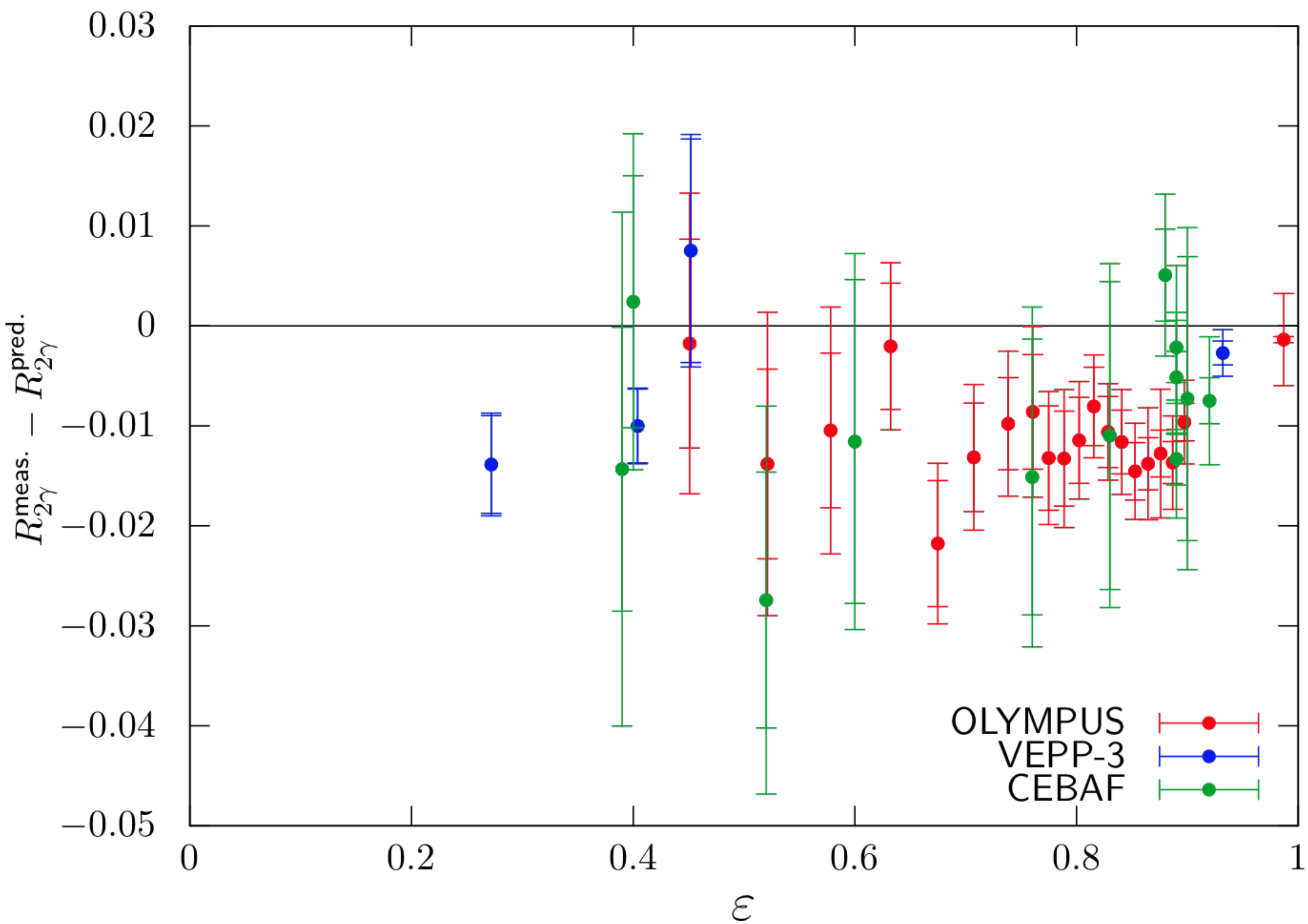
- **Below Hadronic Model by Blunden at low Q^2**
- **Good agreement with phenomenology**

Correlated contributions	Uncertainty in $R_{2\gamma}$
Beam energy	0.04–0.13%
MIE luminosity	0.36%
Beam and detector geometry	0.25%
Uncorrelated contributions	
Tracking efficiency	0.20%
Elastic selection and background subtraction	0.25–1.17%

Data needed at higher $Q^2 > 2.5$ (GeV/c)^2 where TPE effects are expected to be larger

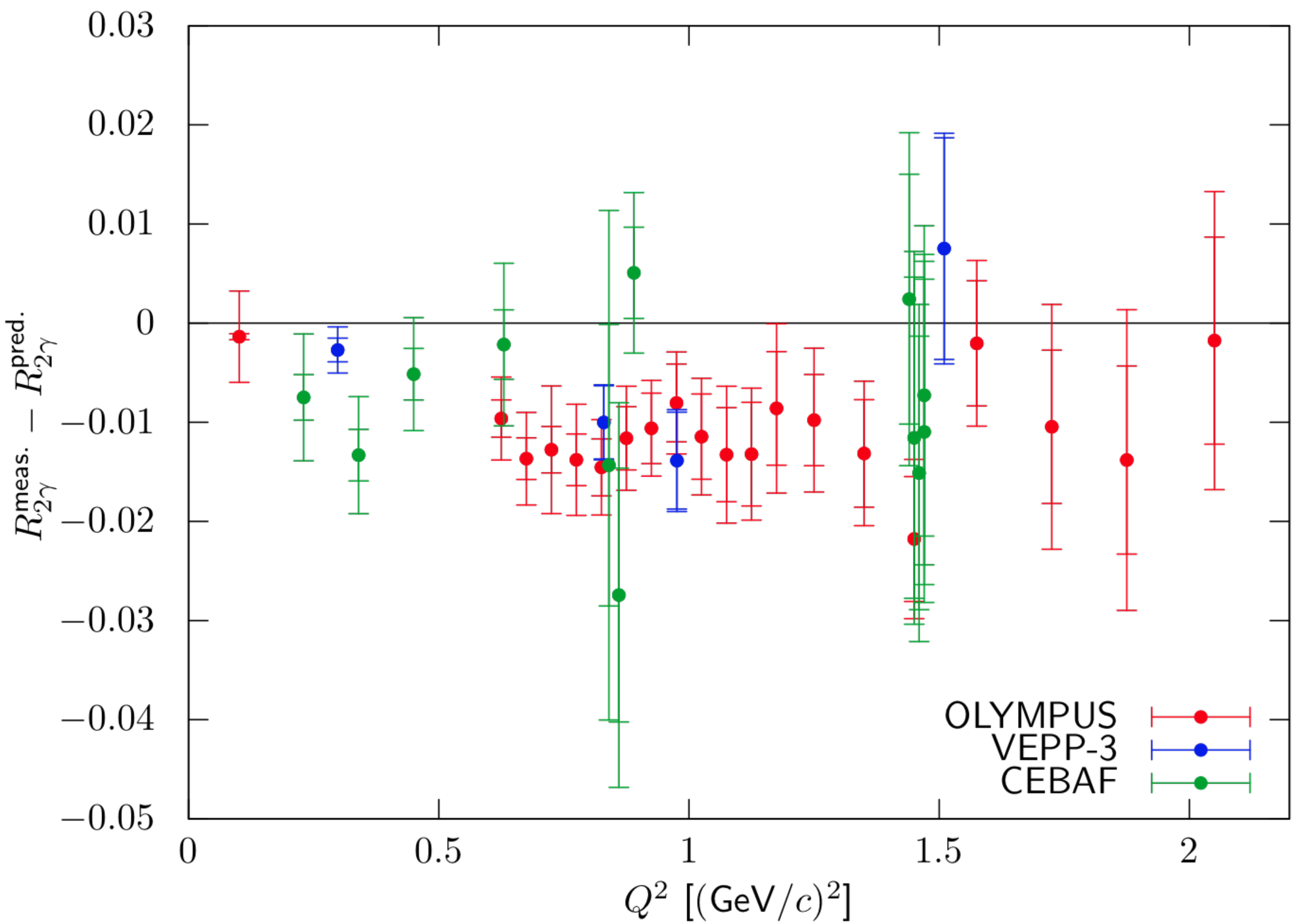
B.S. Henderson *et al.*, PRL 118, 092501 (2017)

Comparison with VEPP-3 and CLAS



- **OLYMPUS, VEPP-3 and CLAS (limited precision) all in agreement**
- **Hard TPE observed is small, below Blunden**
- **Need data at higher Q^2 > 2.5 $(GeV/c)^2$ for validation where TPE *could be* sizable**

Comparison with VEPP-3 and CLAS



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- **Hard TPE observed is small, below Blunden**
- **Need data at higher Q^2 > 2.5 (GeV/c)^2 for validation where TPE *could be* sizable**

Implications

Dedicated workshops and conference sessions:

- **NSTAR2017, Columbia, SC, August 20-23, 2017**
  http://nstar2017.physics.sc.edu/
- **Hadronic Physics with Lepton and Hadron Beams, Jlab, Sep. 5-8, 2017**
  https://www.jlab.org/conferences/hadrons2017/index.html
- **JPOS2017, JLab, Sep. 12-15, 2017**
  https://www.jlab.org/conferences/JPos2017/
- **EW Box, Amherst, MA, Sep. 28-30, 2017**
  http://www.physics.umass.edu/acfi/seminars-and-workshops/the-electroweak-box
- **EINN2017, Paphos, Cyprus, Oct. 29 – Nov. 4, 2017**
  http://einnconference.org/2017/
- **This workshop (668. WE-Heraeus-Seminar), Bad Honnef, Germany, Apr. 23-27, 2018**
  https://indico.him.uni-mainz.de/event/14/

More data!

Possible future high-Q^2 measurement of $R_{2\gamma}$:

Need 3 GeV e^+ and e^- beams to reach $Q^2 = 4.5$ (GeV/c)^2

Jefferson Lab

Add positron source to CEBAF?

Jefferson Lab Positron Working Group https://wiki.jlab.org/pwgwiki

E. Voutier, J. Grames

TPE measurements in Halls A (spectrometers), Hall B (CLAS12)

JLAB has detectors and equipment but no positrons

OLYMPUS-II (or "Above-OLYMPUS") at DESY

D. Hasell, R. Milner, U. Schneekloth

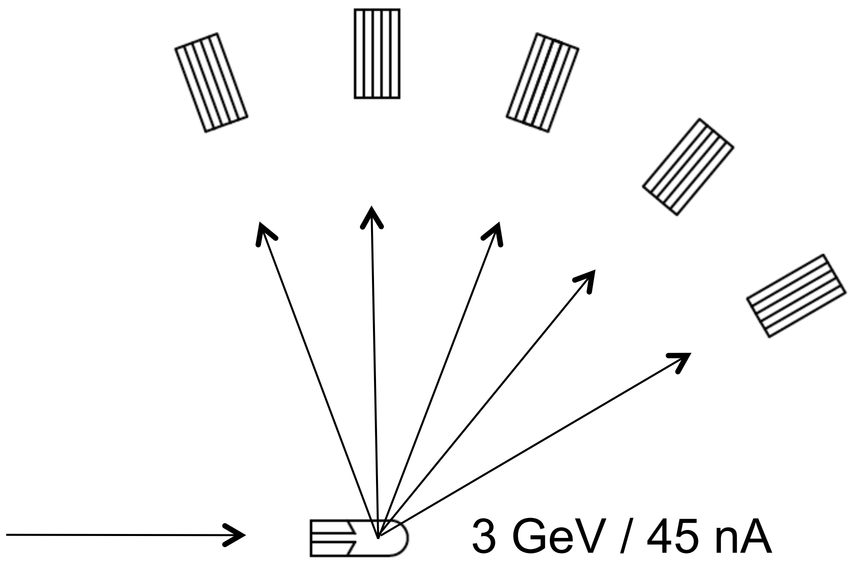
DESY has positrons but no detectors and equipment

DESY

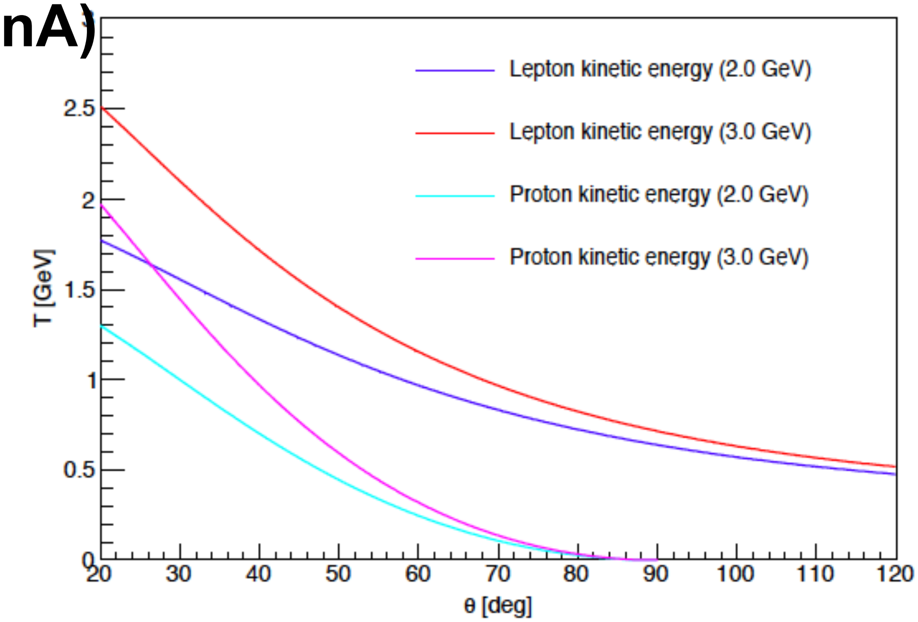
Above OLYMPUS

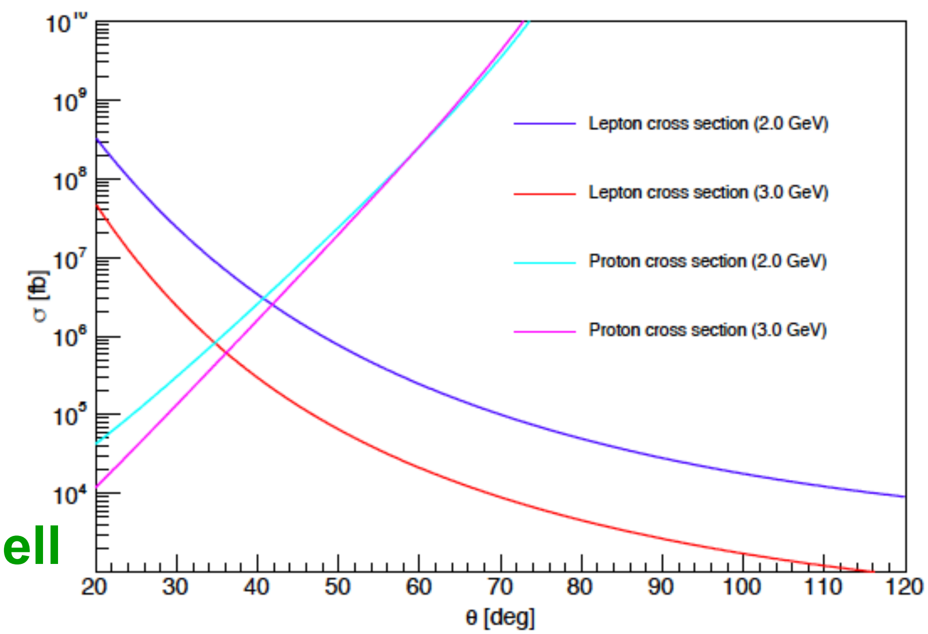
OLYMPUS-II (or “Above-OLYMPUS”) at DESY

- **Considering test beamline to extract e^+/e^- beams from DESY-II (0.5-6.3 GeV, 12.5 Hz repetition, 30/60nA)**
- **$PbWO_4$ calorimeter arrays;**
  A4 liquid hydrogen target (Mainz)



θ	Q^2 $(\mathrm{GeV/c})^2$	ϵ	$d\sigma/d\Omega$ fb	Events/day
30°	1.69	0.825	2.41×10^6	8.91×10^4
50°	3.00	0.554	6.51×10^4	2.42×10^3
70°	3.82	0.329	8.94×10^3	3.30×10^2
90°	4.29	0.184	2.65×10^3	9.80×10^1
110°	4.57	0.096	1.20×10^3	4.44×10^1





D. Hasell

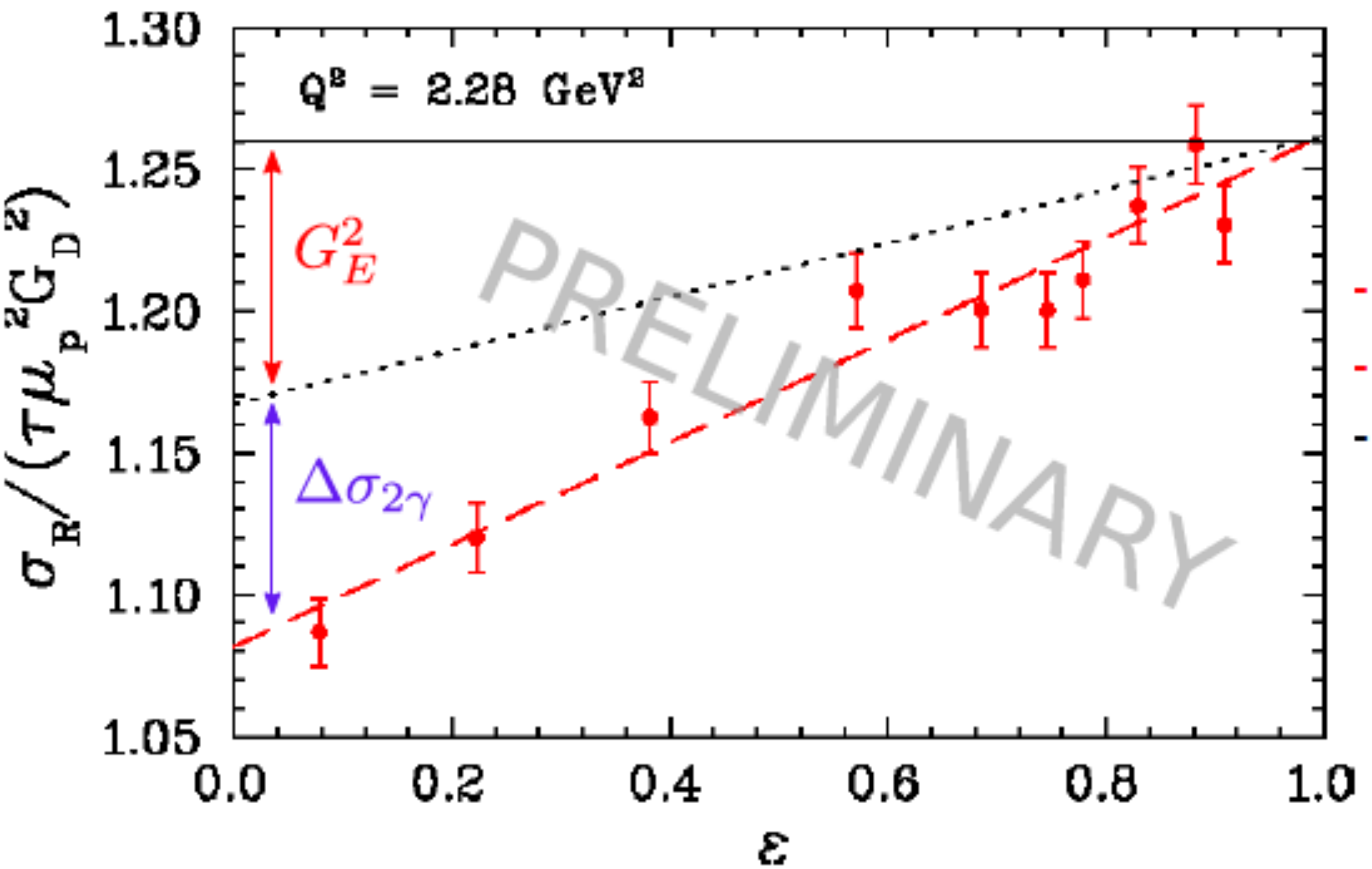
Summary

- The limits of OPE have been reached with the achieved precision
  - ➔ Large discrepancy between unpolarized and polarized data
  - ➔ Nucleon elastic form factors, particularly G_E^p under doubt
- The TPE hypothesis is suited to remove form factor discrepancy, however calculations of TPE are model-dependent
- New observables: ε dependence of polarization transfer, ε-nonlinearity of cross sections, single-spin asymmetries, e^+/e^- comparisons
- Positron/electron comparisons to test TPE: VEPP-3, CLAS, OLYMPUS
- OLYMPUS: Hard TPE found to be
  - ➔ consistent with other TPE experiments but more precise
  - ➔ smaller than expected by standard hadronic theory at low Q^2
  - ➔ consistent with phenomenology at $Q^2 < 2.5\ (\mathrm{GeV}/c)^2$
- Need to improve theoretical precision for radiative corrections !
- TPE is to be tested at higher $Q^2 > 2.5\ (\mathrm{GeV}/c)^2$ with future experiments (e.g. with positron source at CEBAF or extracted beams at DESY)
- Broader Impact:
  - ➔ gamma-Z box in PVES; TPE effects in eA and inelastic scattering;
  - ➔ Proton radius puzzle: elastic $\{\mu,e\}^{\pm}p$ scattering with MUSE@PSI

Backup

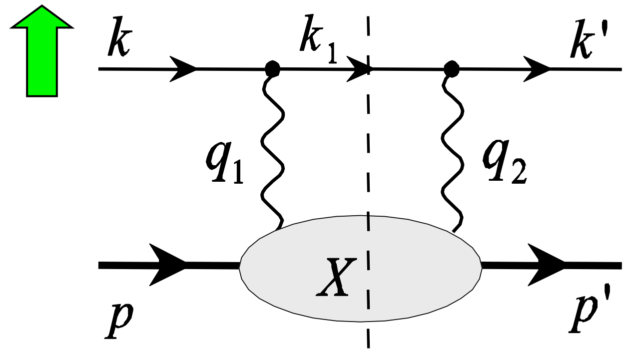
PRELIMINARY RESULTS

- Rosenbluth separation:
  - linear fit to extract FF ratio
  - second fit (not shown) with data shifted by δ_{slope} for systematics
  - $\Delta\sigma_{2\gamma}$ separates TPE size from G_E^2 slope



- this E05-017
- dashed: linear fit
- dotted: PTprediction

Imaginary part: Single-spin asymmetries



spin of beam OR target
NORMAL to scattering plane

$$s = (k+p)^2$$

on-shell intermediate state ($M_X = W$)

$$A_n = -\frac{1}{(2\pi)^3}\frac{e^2\,(1-\varepsilon)}{8\,Q^2}\int_{M^2}^{s} dW^2\,\frac{|\vec{k}_1|^2}{4\sqrt{s}}\int d\Omega_{k1}\,\frac{1}{Q_1^2\,Q_2^2}\,\mathcal{I}\left(L_{\alpha\mu\nu}H^{\alpha\mu\nu}\right)$$

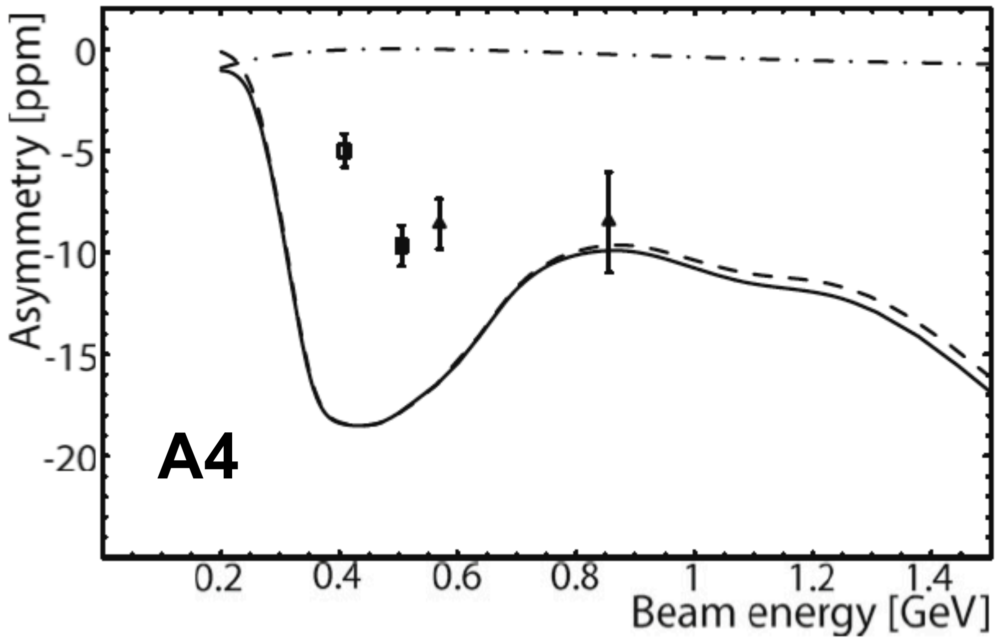
E.g. target normal spin asymmetry

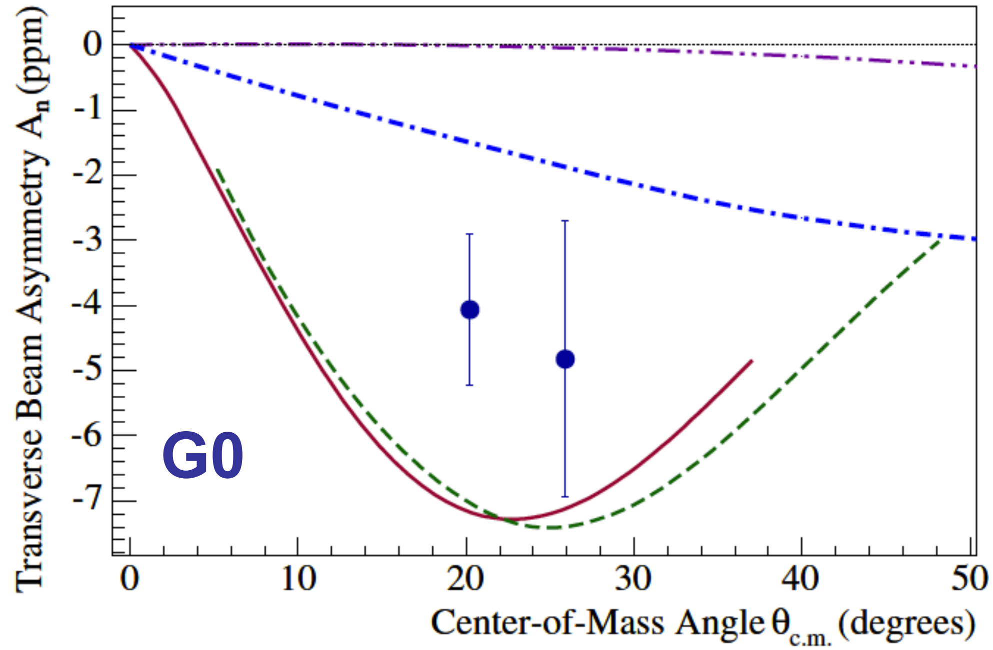
$$A_n = \sqrt{\frac{2\,\varepsilon\,(1+\varepsilon)}{\tau}}\,\frac{1}{\sigma_R}\quad\left\{-G_M\,\mathcal{I}\left(\delta\tilde{G}_E+\frac{\nu}{M^2}\tilde{F}_3\right)\right.$$
$$\left.+G_E\,\mathcal{I}\left(\delta\tilde{G}_M+\left(\frac{2\varepsilon}{1+\varepsilon}\right)\frac{\nu}{M^2}\tilde{F}_3\right)\right\},$$

⇧**Beam:** **PVES at Bates, MAMI and Jlab;**
⇧**Target:** **(Quasi-)elastic: E05-015: ^{3}He⇧(e,e'), E08-005: ^{3}He⇧(e,e'n)**
Deep inelastic: E07-013; HERMES p⇧(e,e')

Inherited from M. Vanderhaeghen

Beam-normal single spin asymmetry



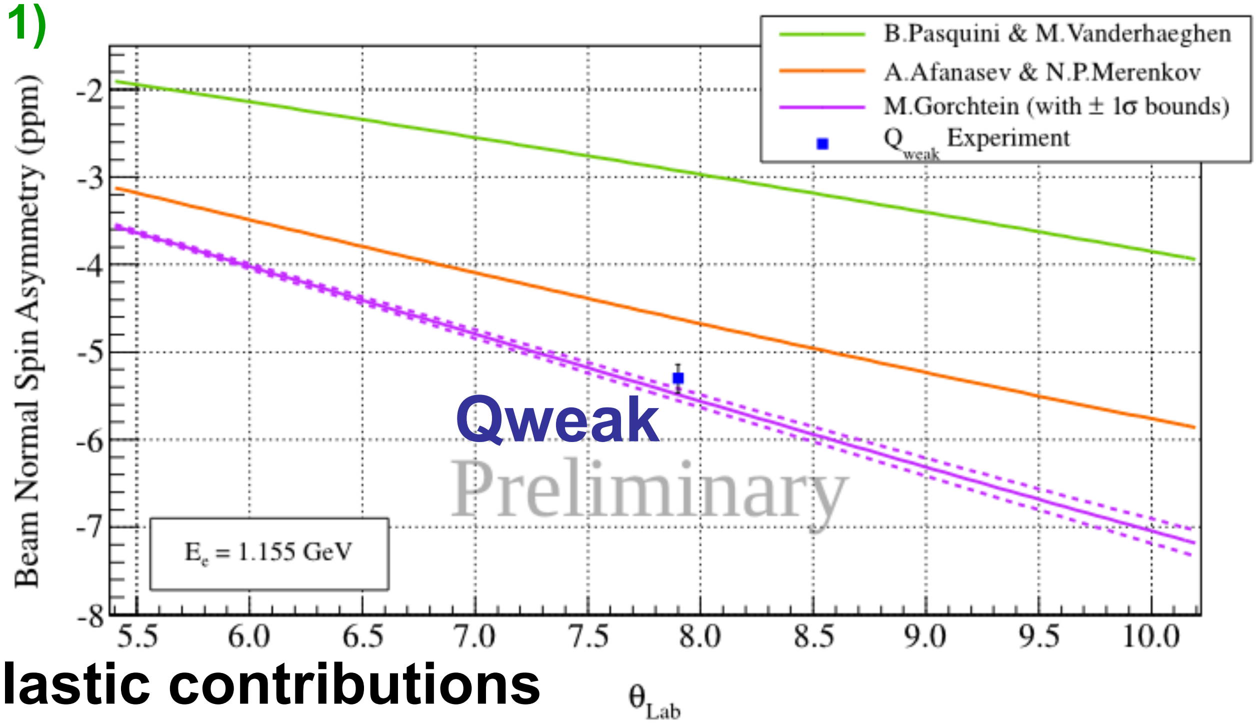


F. Maas *et al.*, PRL 99, 092301 (2005);
S. Baunack, EPJ ST198, 343 (2011)

D. Armstrong *et al.*, PRL 99, 092301 (2007)

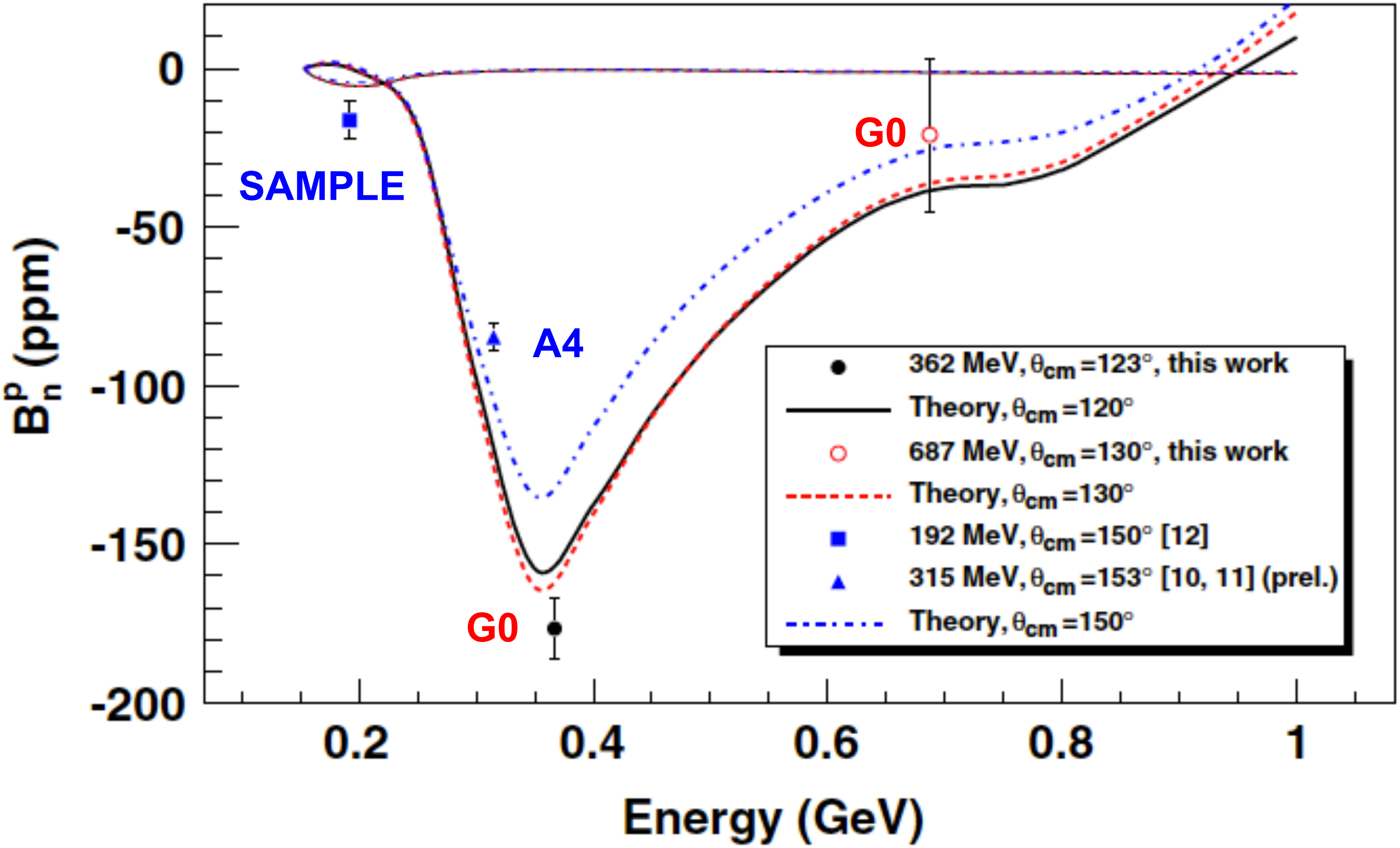
p(e⇧,e') at forward angles

Qweak (preliminary):
A_n= (−5.35±0.07±0.15) ppm
B.P. Waidyawansa, PAVI2014, arXiv:1604.04602



BNSSA's dominated by inelastic contributions

Beam-normal single spin asymmetry

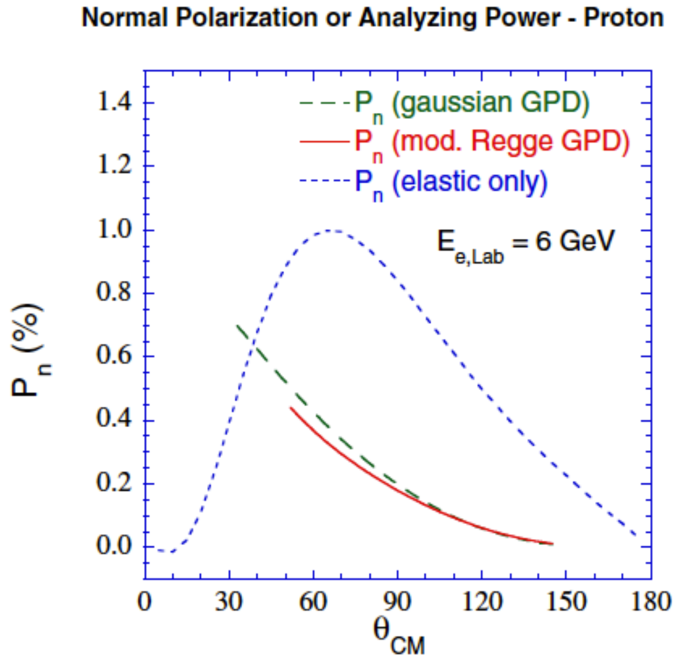


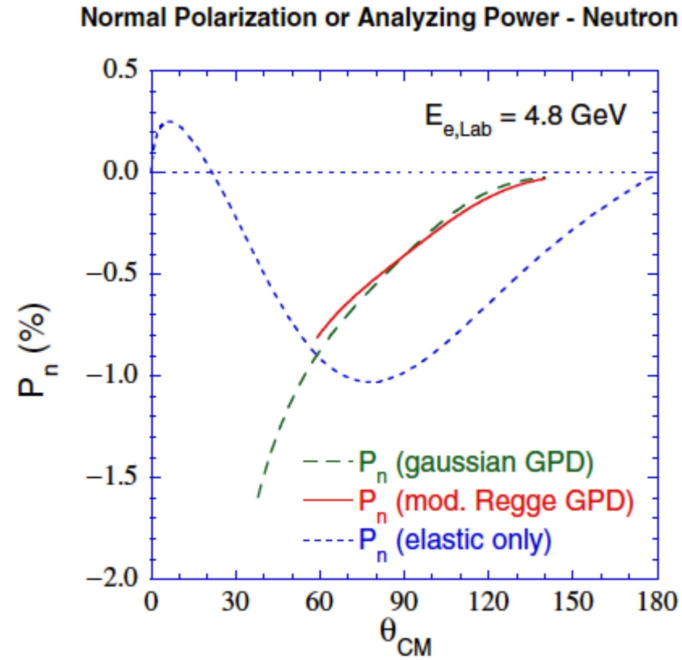
p(e⇧,e') at backward angles:

G0 bwd: D. Androic *et al.*, PRL 107, 022501 (2011)
A4 bwd: S. S. Baunack, EPJ ST198, 343 (2011)
SAMPLE: S. Wells *et al.*, PRC 63, 064001 (2001)

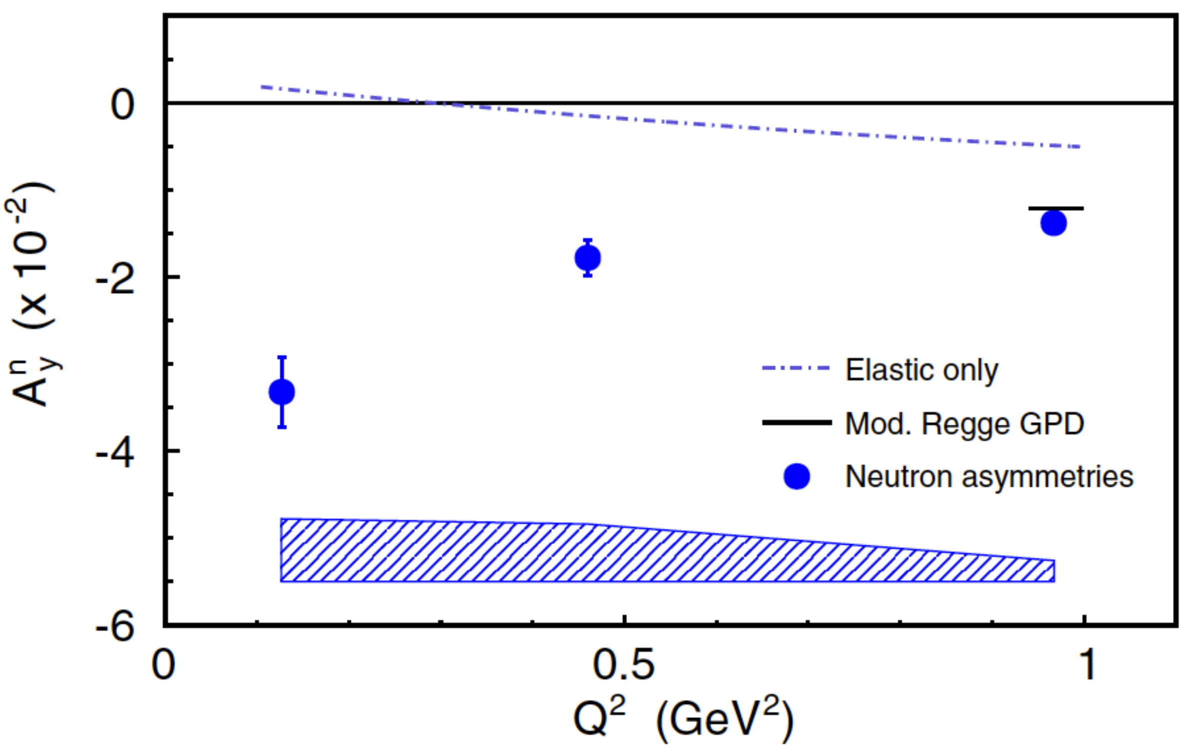
BNSSA's dominated by inelastic contributions

Target-normal single spin asymmetry





A. Afanasev *et al.*,
PRD 72, 013008 (2005)
(elastic)
%-level asymmetries
opposite sign for p&n



^{3}He⇧(e,e'): E05-015 (quasielastic)

Y.-W. Zhang *et al.*,
PRL 115, 172502 (2015)

Theory:
Y.C. Chen *et al.*,
PRL 93, 122301 (2004)

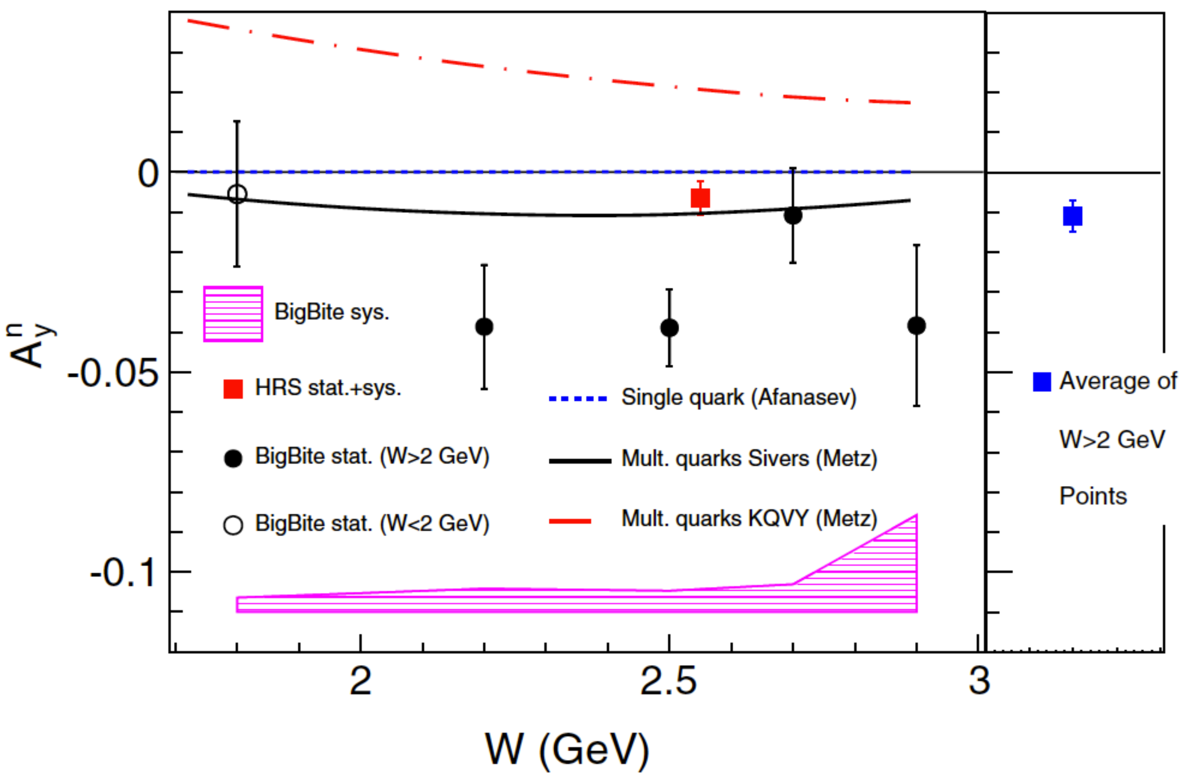
Further:

^{3}He⇧(e,e'n): E08-005 (quasielastic)

Target-normal single spin asymmetry

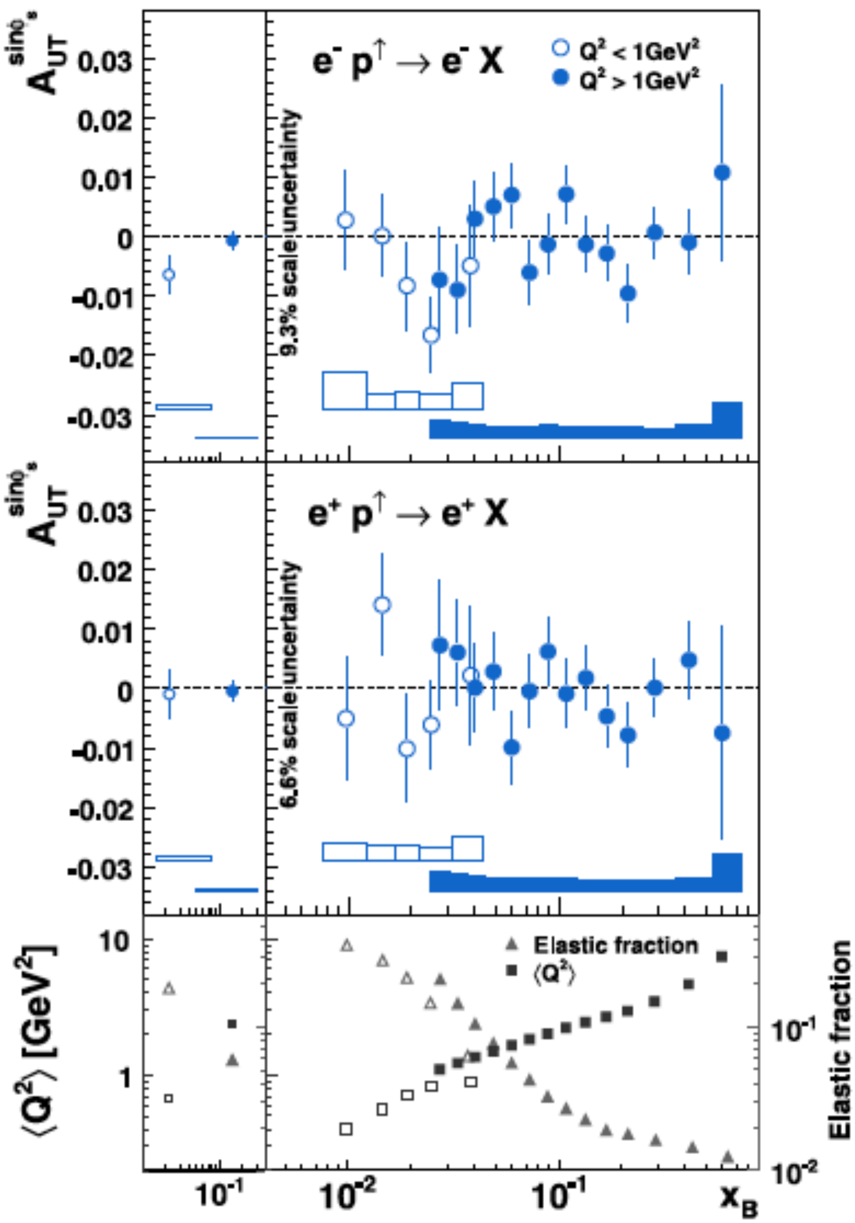
^{3}He⇧(e,e')X: E07-013 (DIS)

J. Katich *et al.*, PRL 113, 022502 (2014)



p⇧(e,e')X: HERMES (DIS)

A. Airapetian *et al.*, PLB 682, 351 (2010)



Single-quark: 10^{-4}-level asymmetries

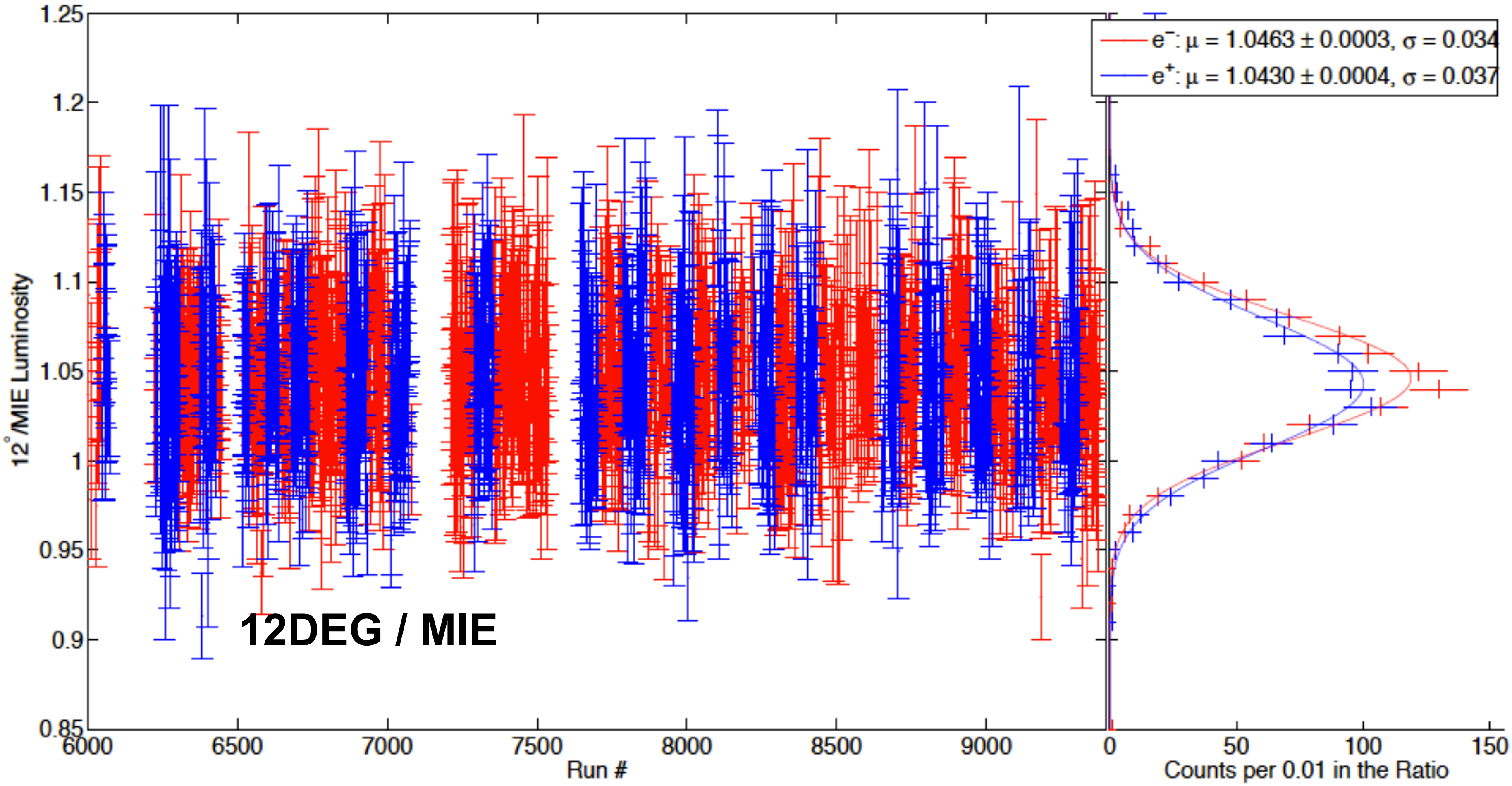
A. Afanasev *et al.*, PRD77, 014028 (2008)

Multi-quark: %-level asymmetries

A. Metz *et al.*, PRD 86, 094039 (2012)

Luminosity monitoring

- Five redundant systems: Slow Control, SYMB, MIE, 12DEG-L,R
- Absolute luminosity from each rate to a few %
- Ratio of e^+/e^- luminosities for $R_{2\gamma}$ to sub %
- Time variation, mean and variance, systematics from comparisons
- Excellent agreement between SC, MIE, and 12DEG-L,R
- Final luminosity ratio from MIE, using 12DEG for high-ε data point

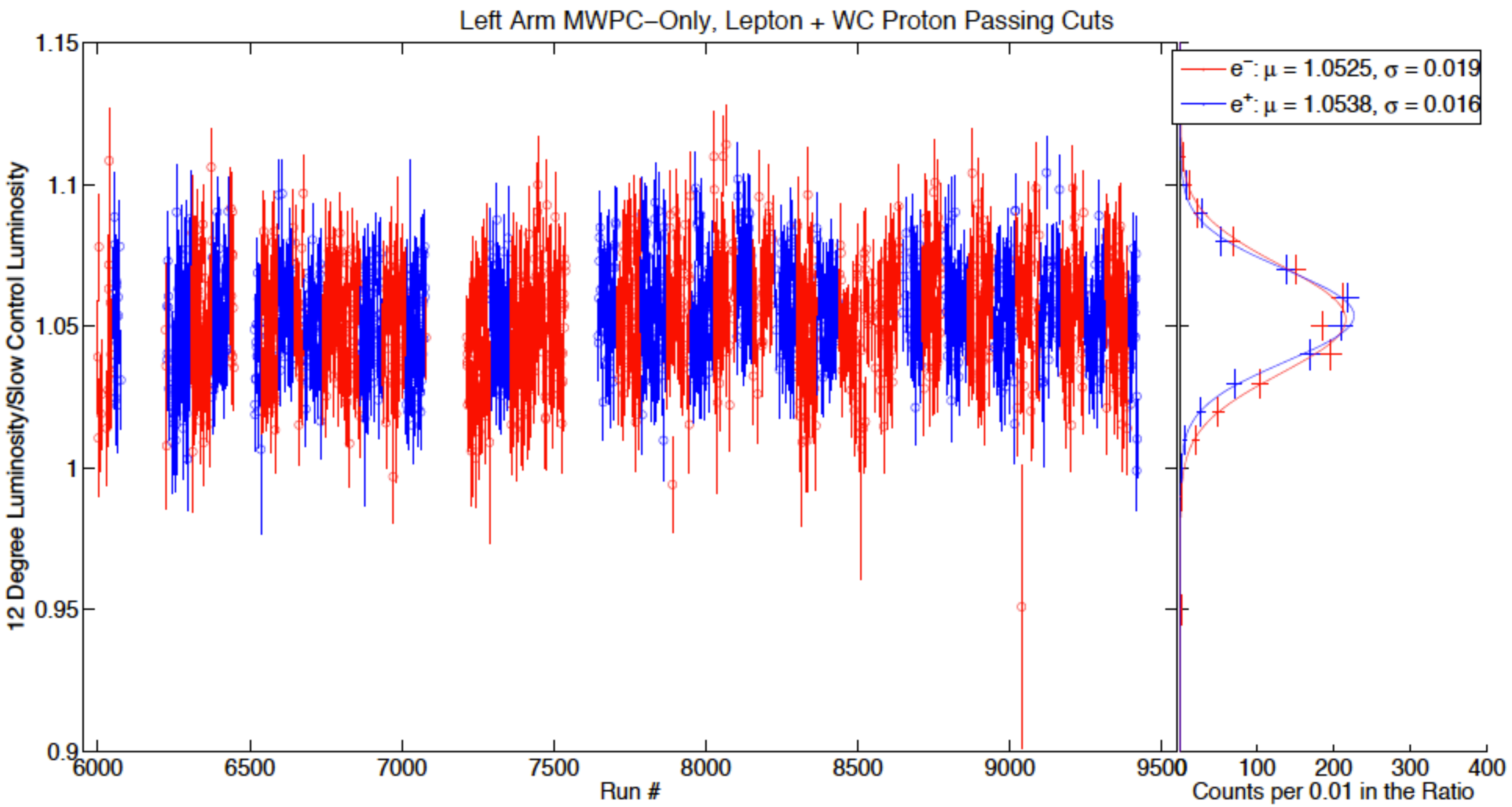


A. Schmidt, B. Henderson (MIT)

Luminosity monitoring

OLYMPUS

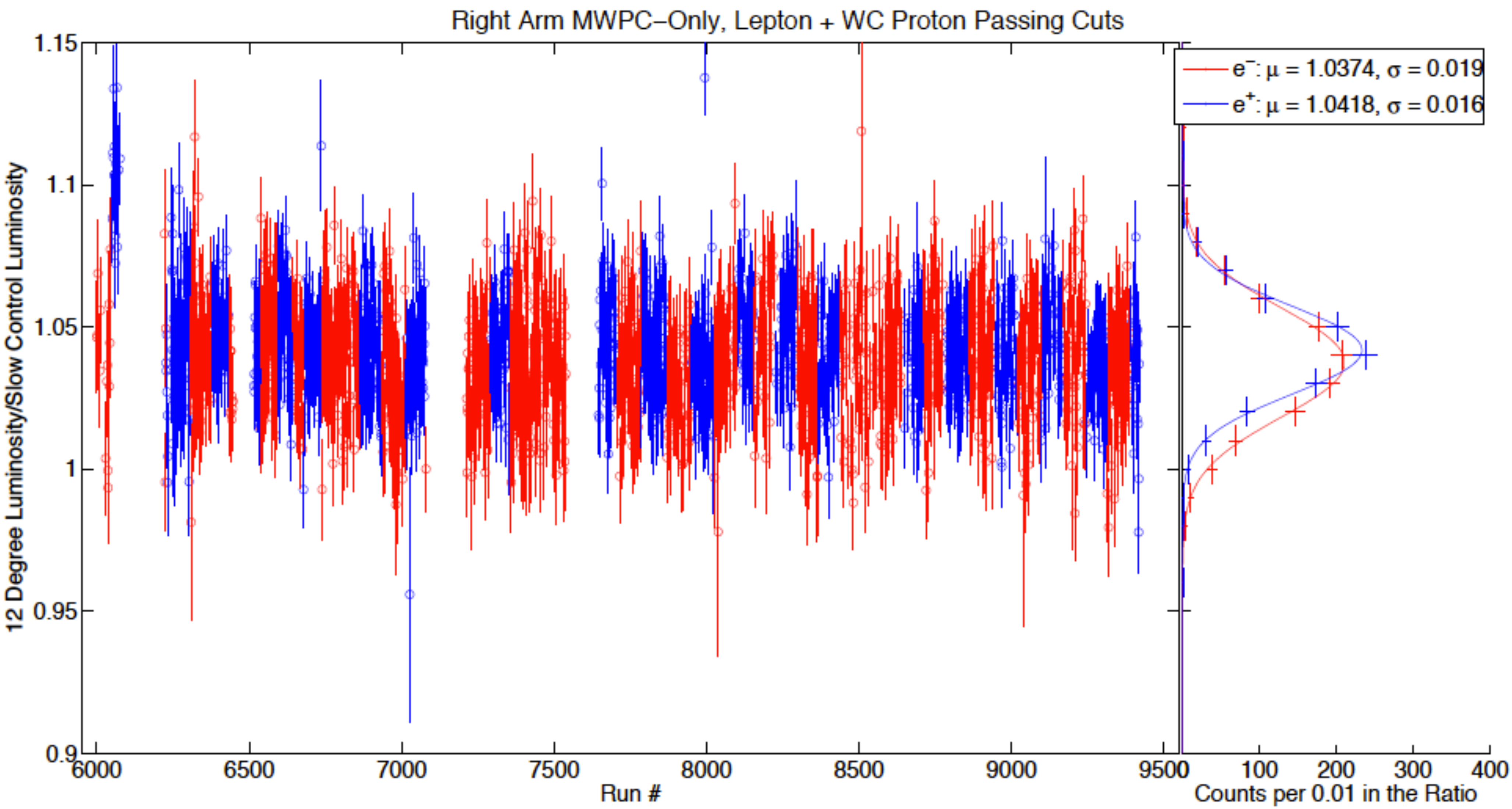
12DEG-L / SC



B. Henderson (MIT)

Luminosity monitoring

12DEG-R / SC

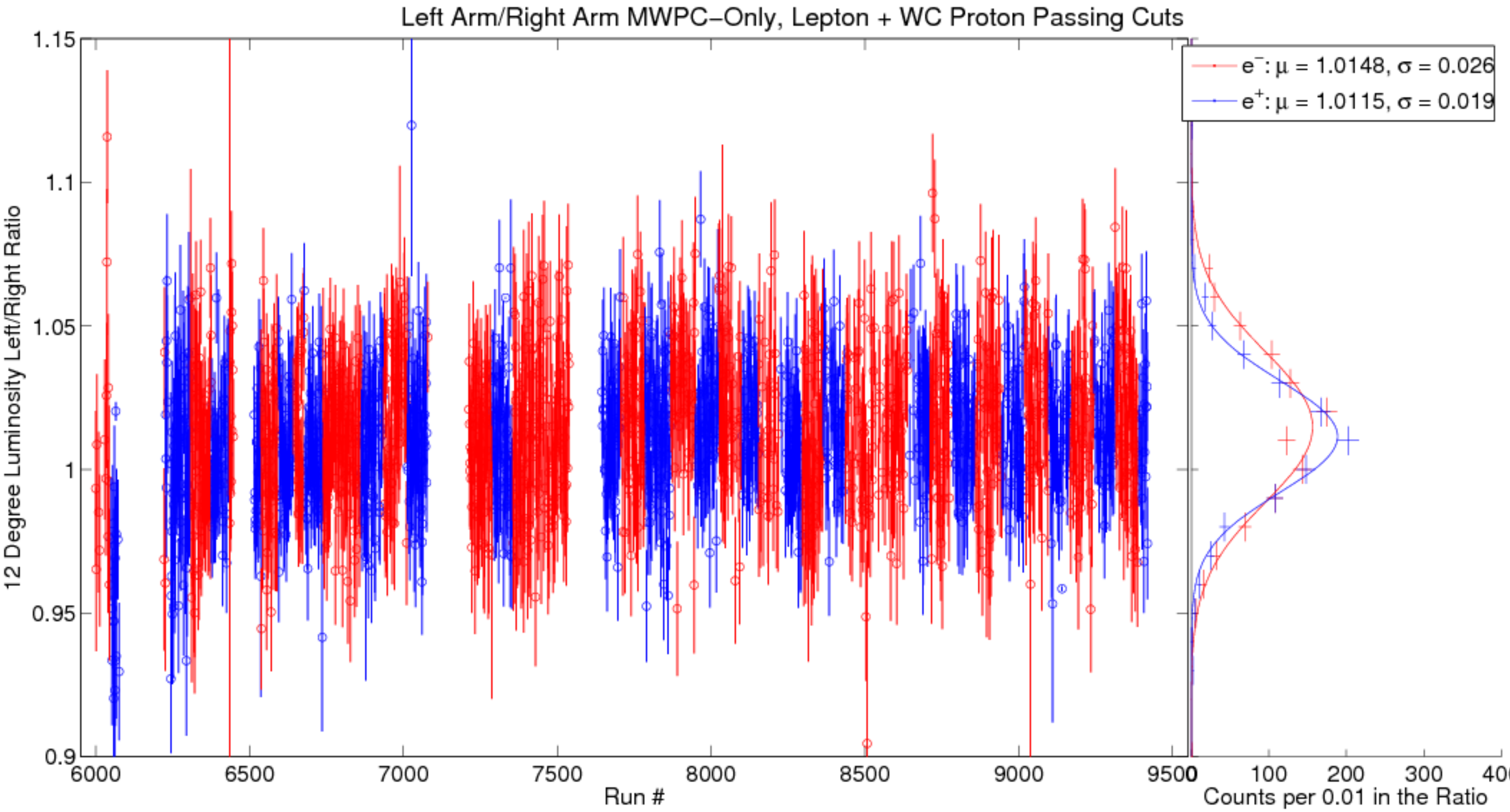


B. Henderson (MIT)

Luminosity monitoring

OLYMPUS

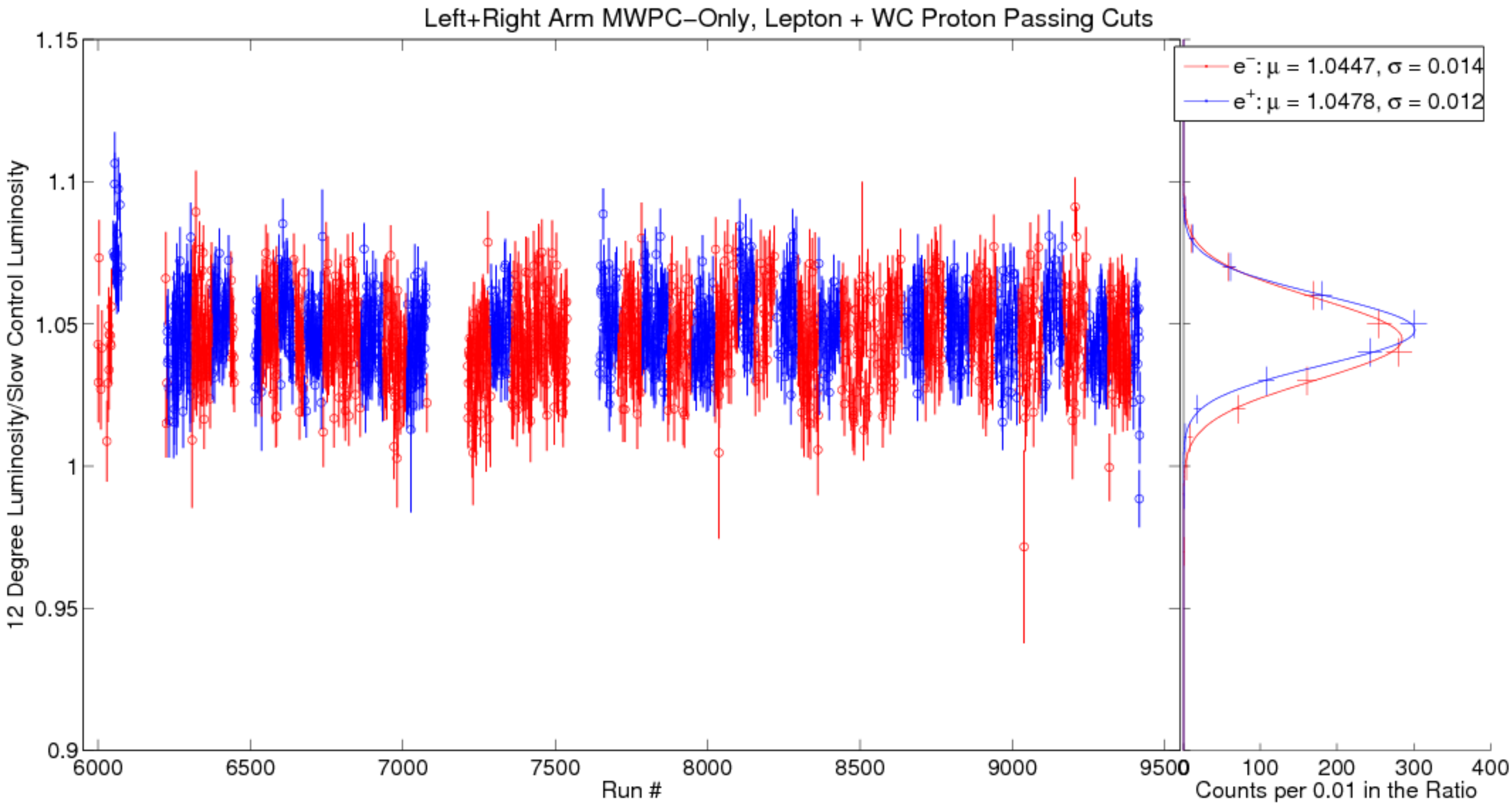
12DEG-L / R



B. Henderson (MIT)

Luminosity monitoring

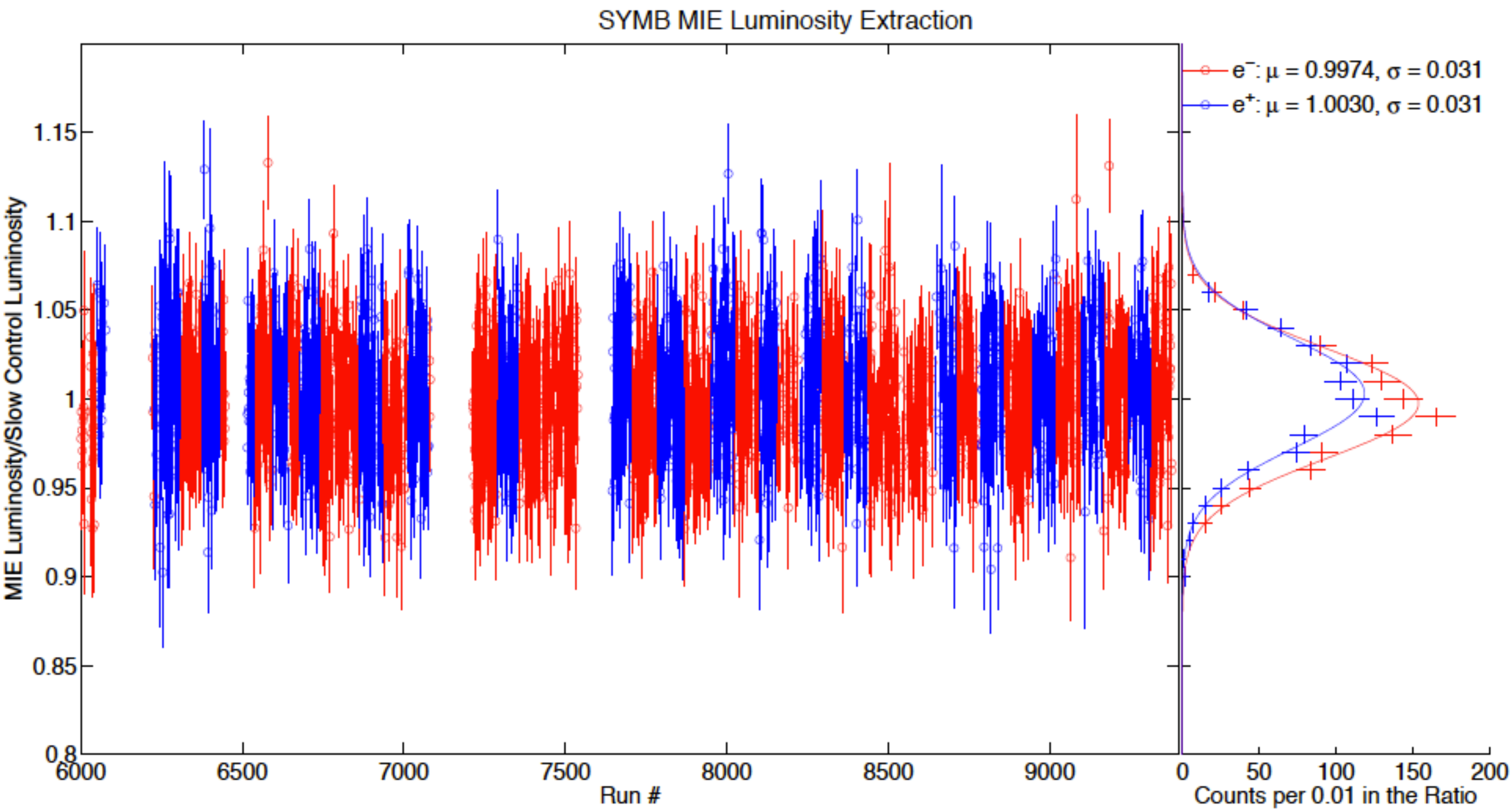
12DEG L+R / SC



B. Henderson (MIT)

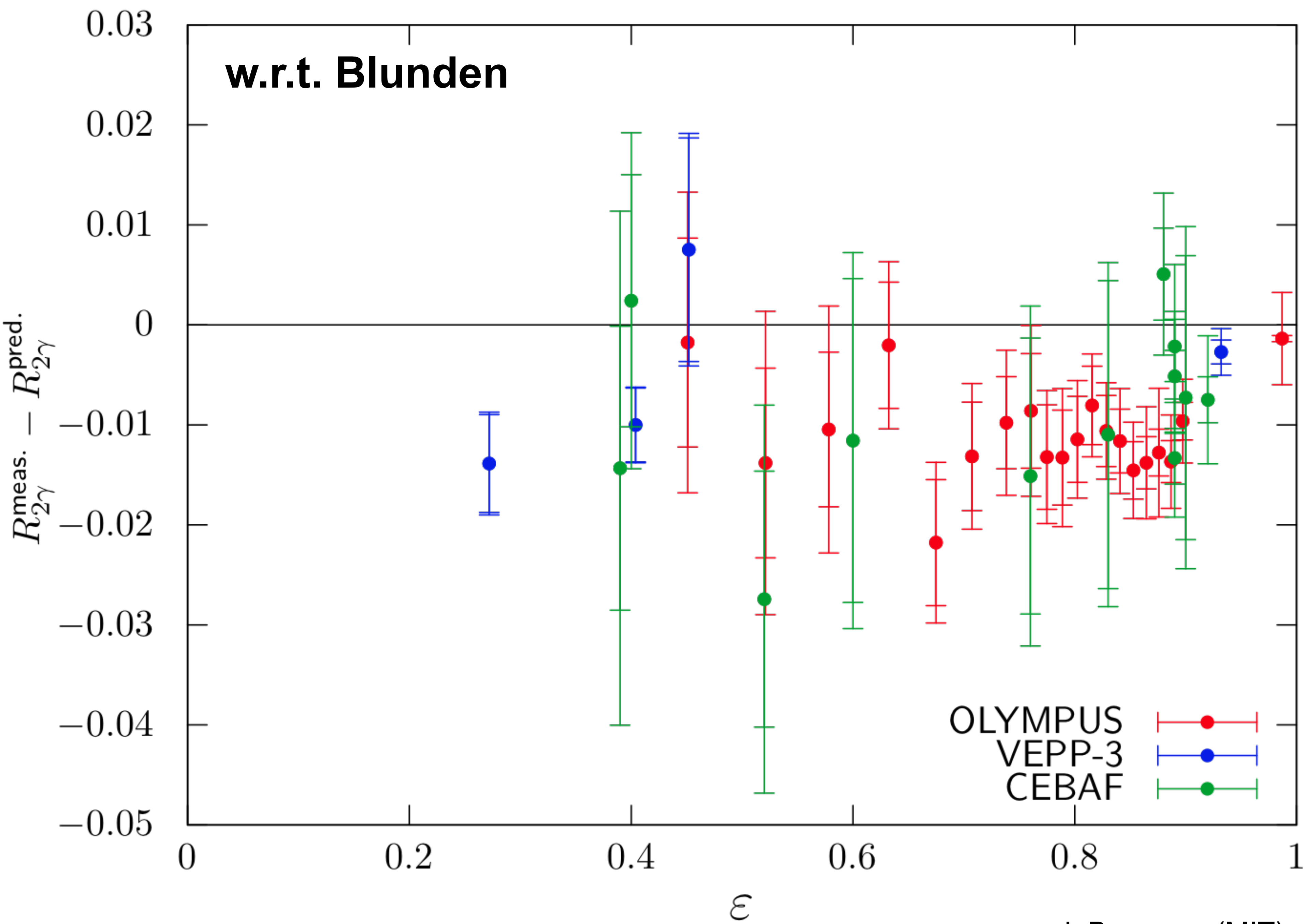
Luminosity monitoring

MIE / SC



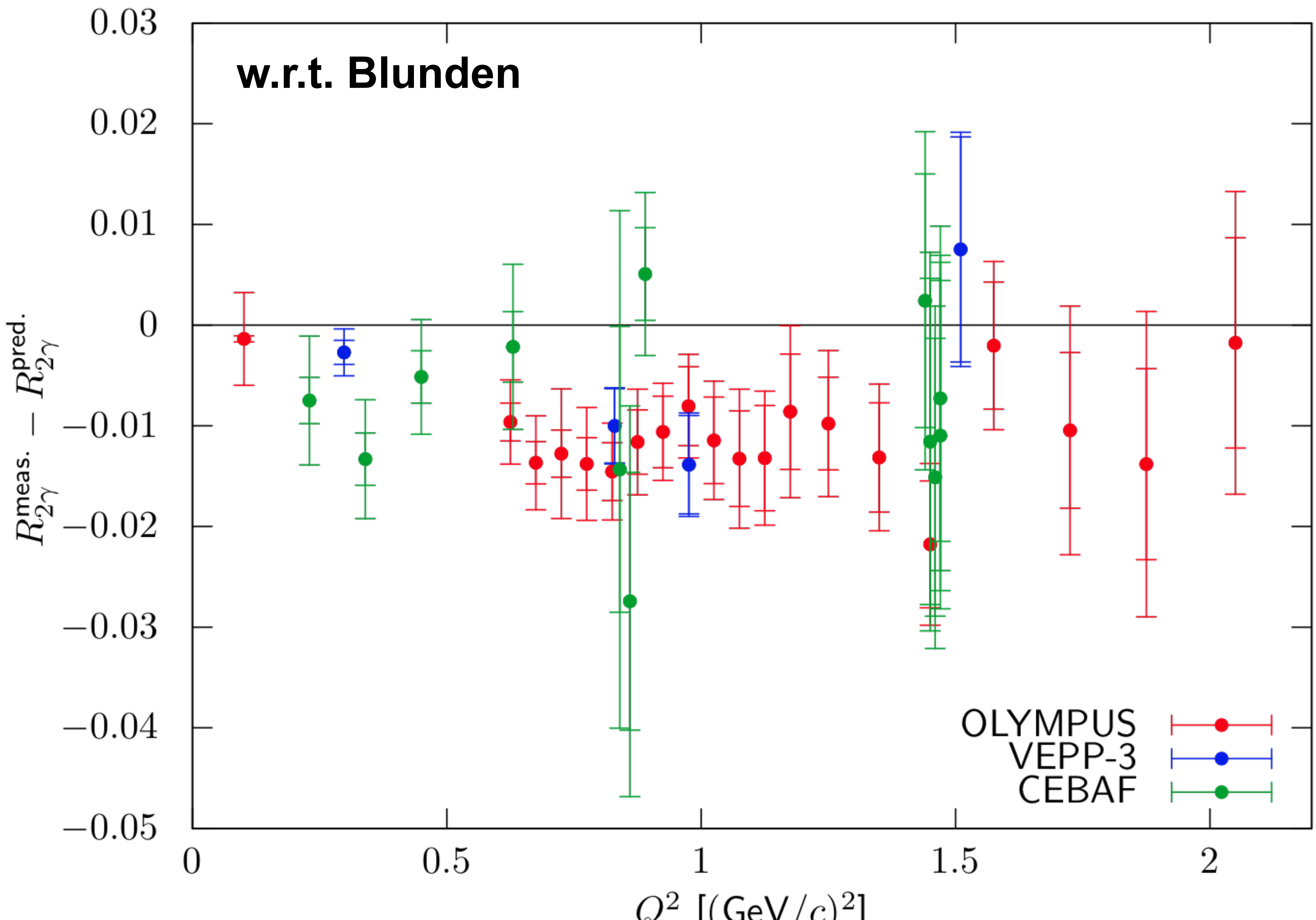
A. Schmidt, B. Henderson (MIT)

Comparison with VEPP-3 and CLAS



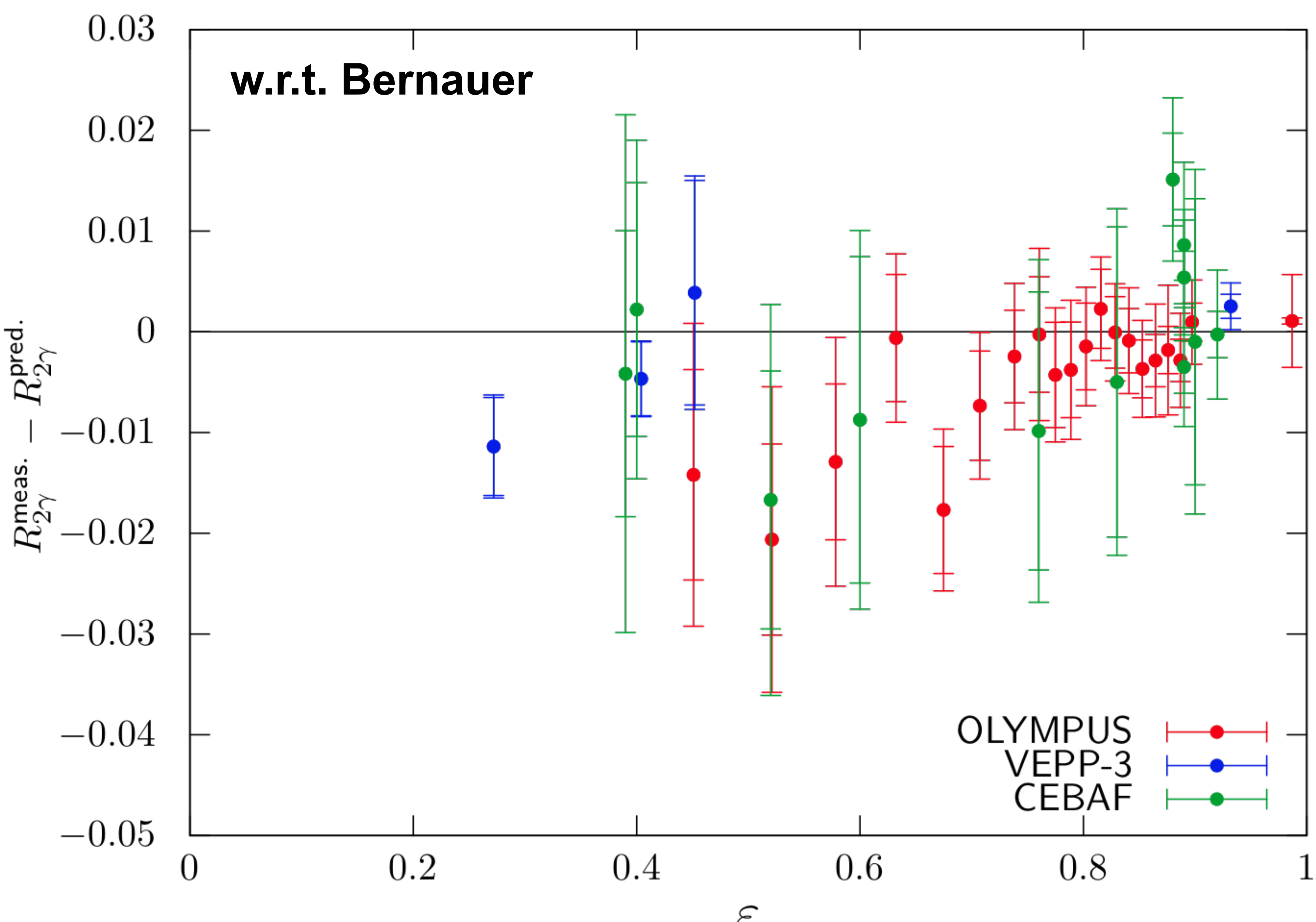
J. Bernauer (MIT)

Comparison with VEPP-3 and CLAS



J. Bernauer (MIT)

Comparison with VEPP-3 and CLAS



J. Bernauer (MIT)

Comparison with VEPP-3 and CLAS