Results from the OLYMPUS* Experiment at DESY

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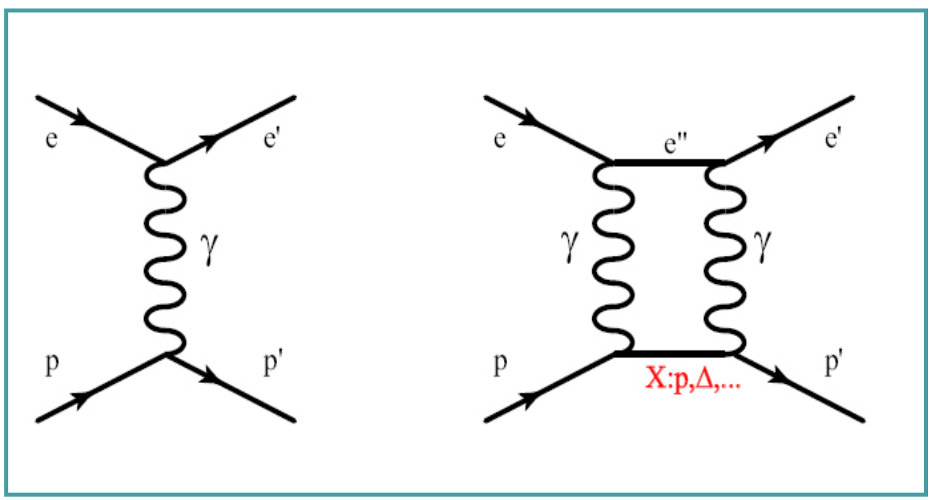
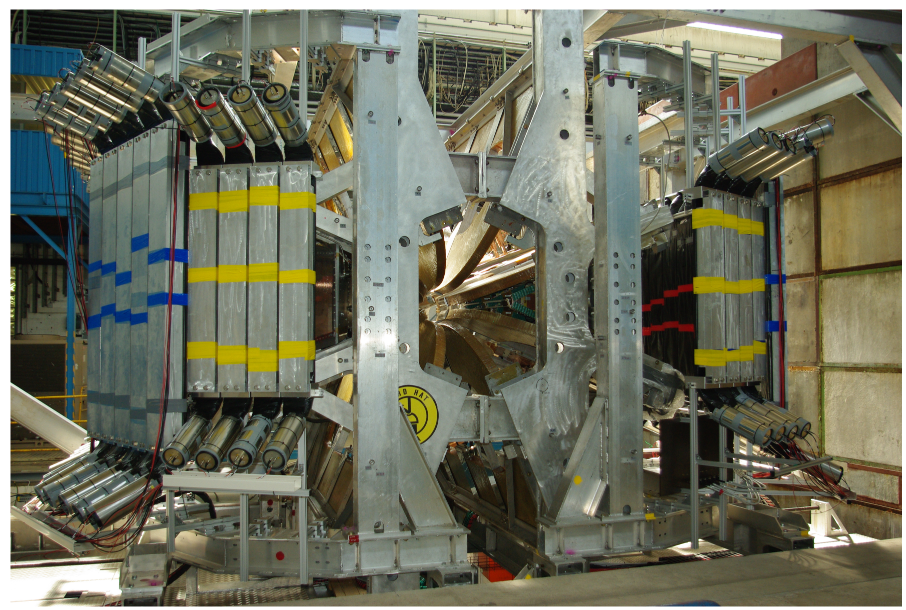
Outline

- **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





OLYMPUS @ DESY

Nucleon elastic form factors …

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

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

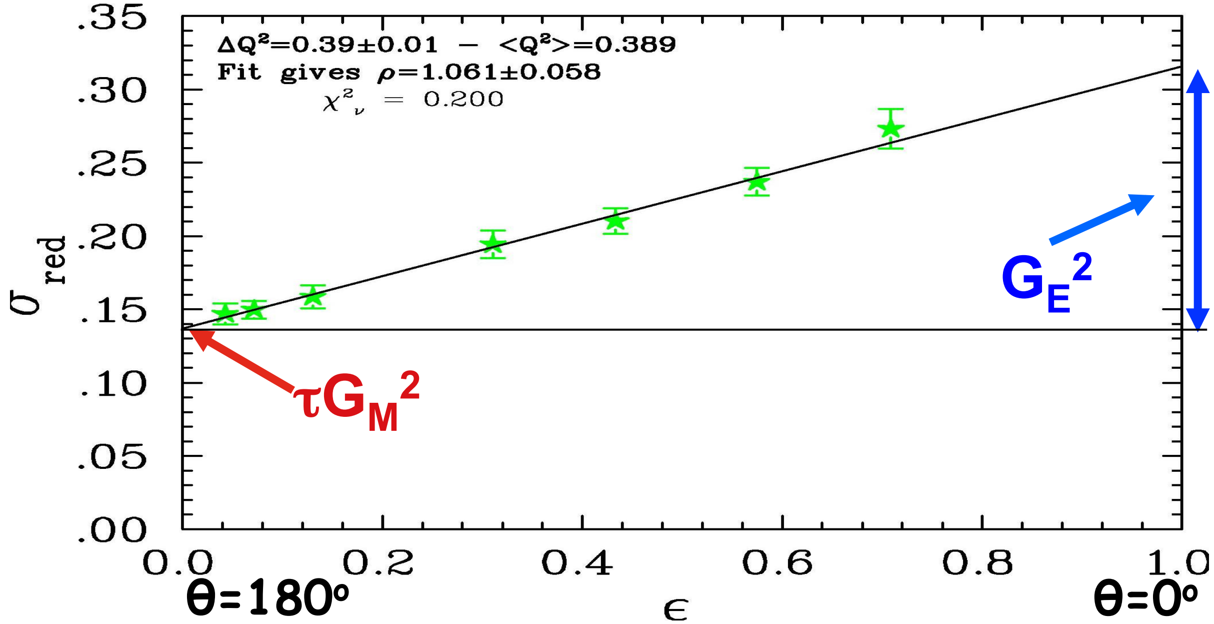
- Rigorous tests of nucleon models
- Determined by quark structure of the nucleon
- Role of orbital angular momentum and diquark correlation
- Ultimately calculable by Lattice-QCD
- Input to nuclear structure and parity violation experiments

G. Miller,
PRC68, 022201 (2003)

60+ years of ever increasing activity

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

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**

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

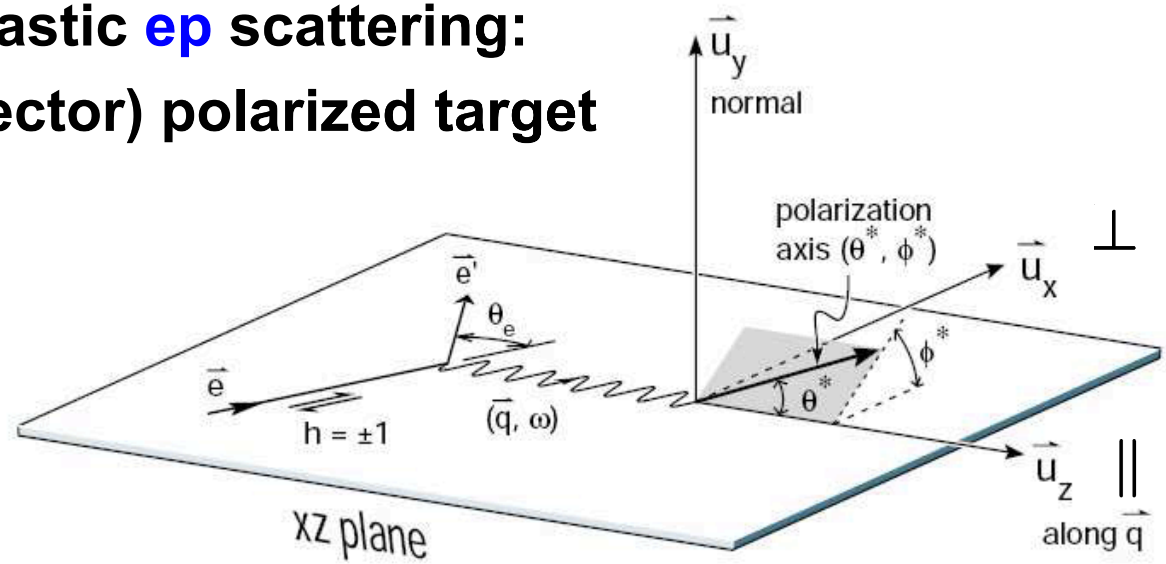
$$= \frac{G_E^2(Q^2) + \tau G_M^2(Q^2)}{1+\tau} + 2\tau G_M^2(Q^2)\tan^2\frac{\theta}{2}$$

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

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**

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

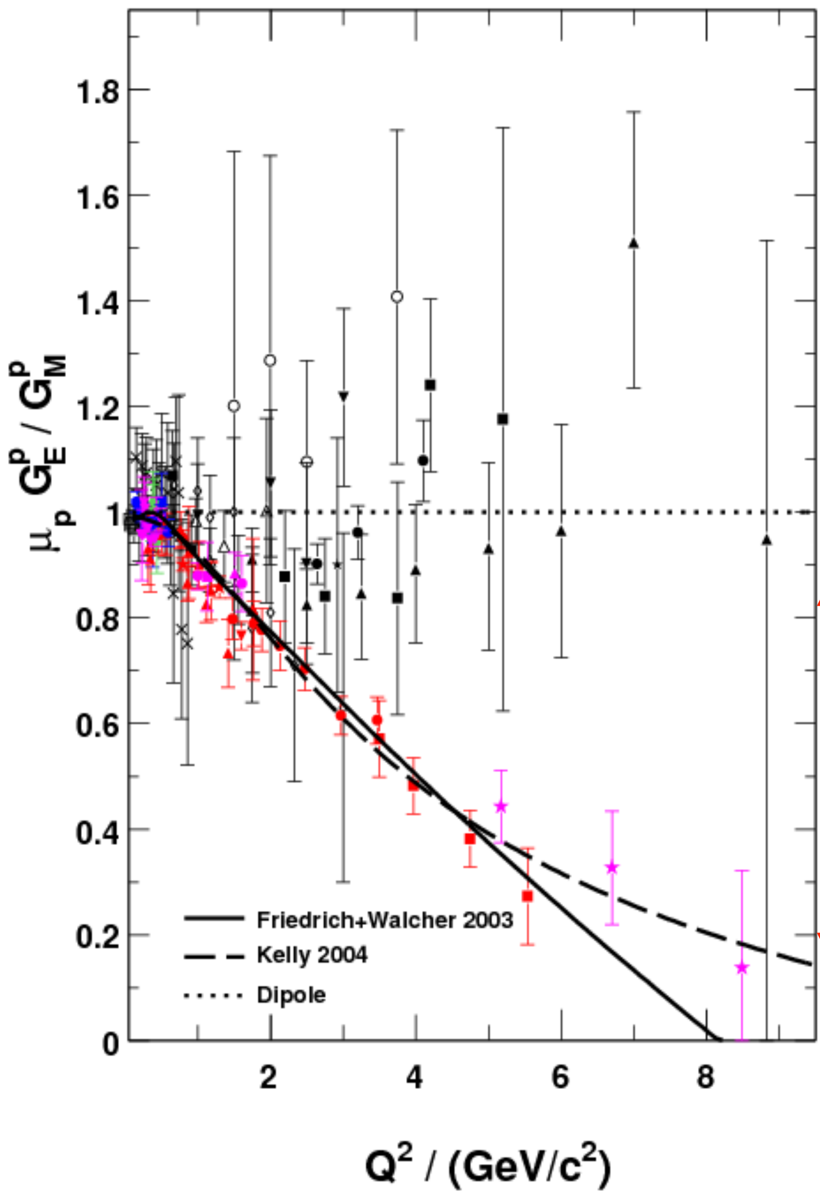
- **Asymmetry ratio ("Super ratio")**

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

  independent of polarization or analyzing power

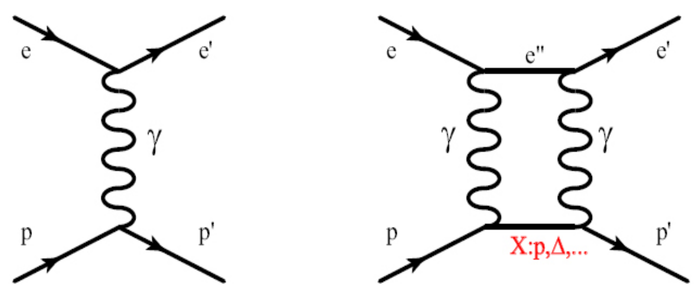
Akhiezer & Rekalo (1968), Dombey (1969)
Arnold, Carlson & Gross (1984),
Donnelly & Raskin (1986)

Proton form factor ratio



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

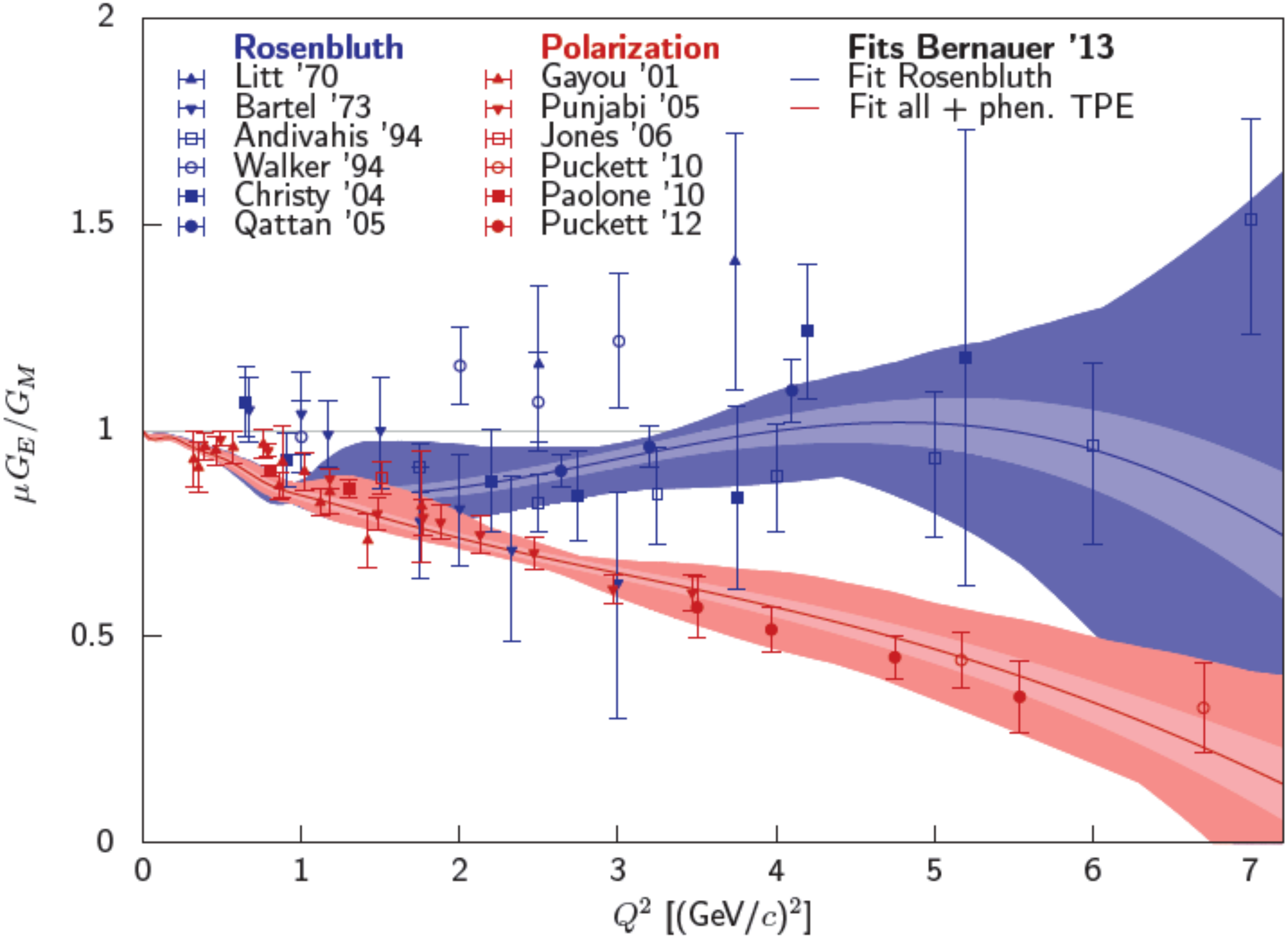


Dramatic discrepancy!

>800 citations

Another look

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

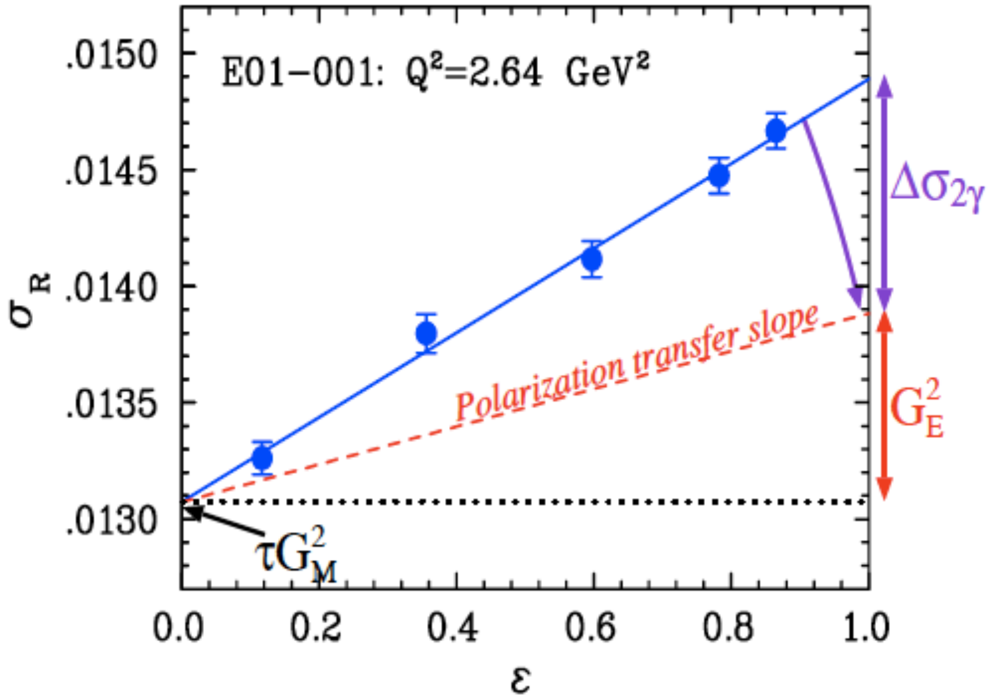


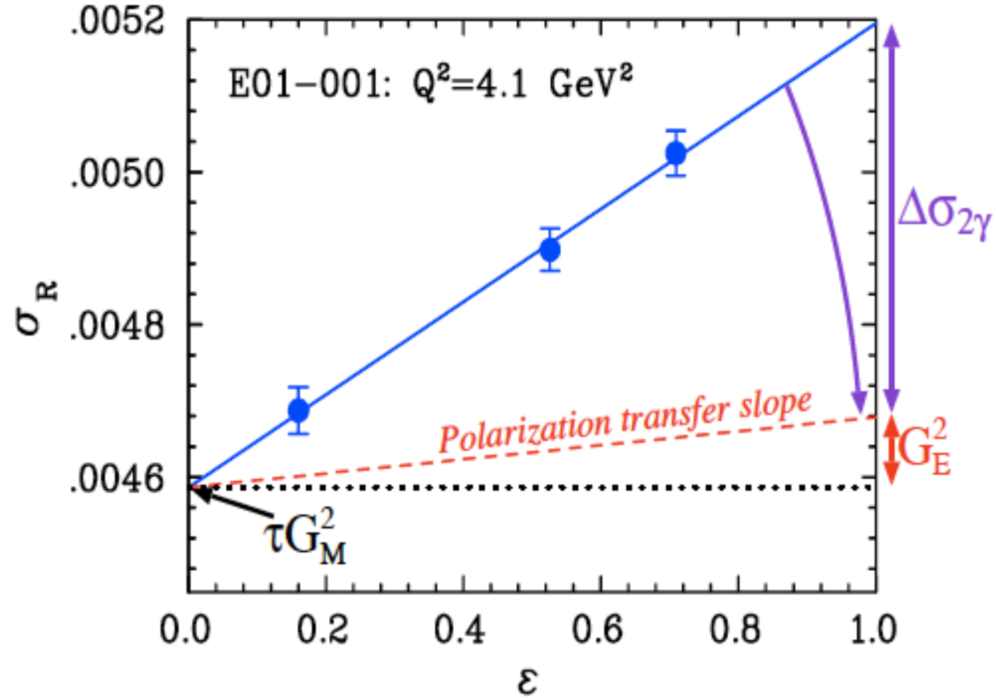
Up to $Q^2 < 2$ (GeV/c)^2 : Form factor discrepancy small

Both Rosenbluth and polarization data deviating from scaling

Effect of two-photon exchange

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



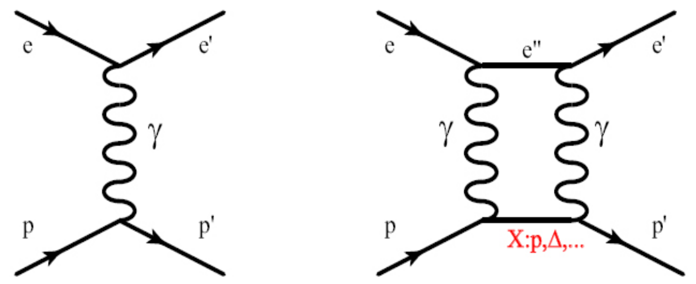


by construction, theorists sought mechanism that affects the "slope" in the Rosenbluth plot (ε-dependence)

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

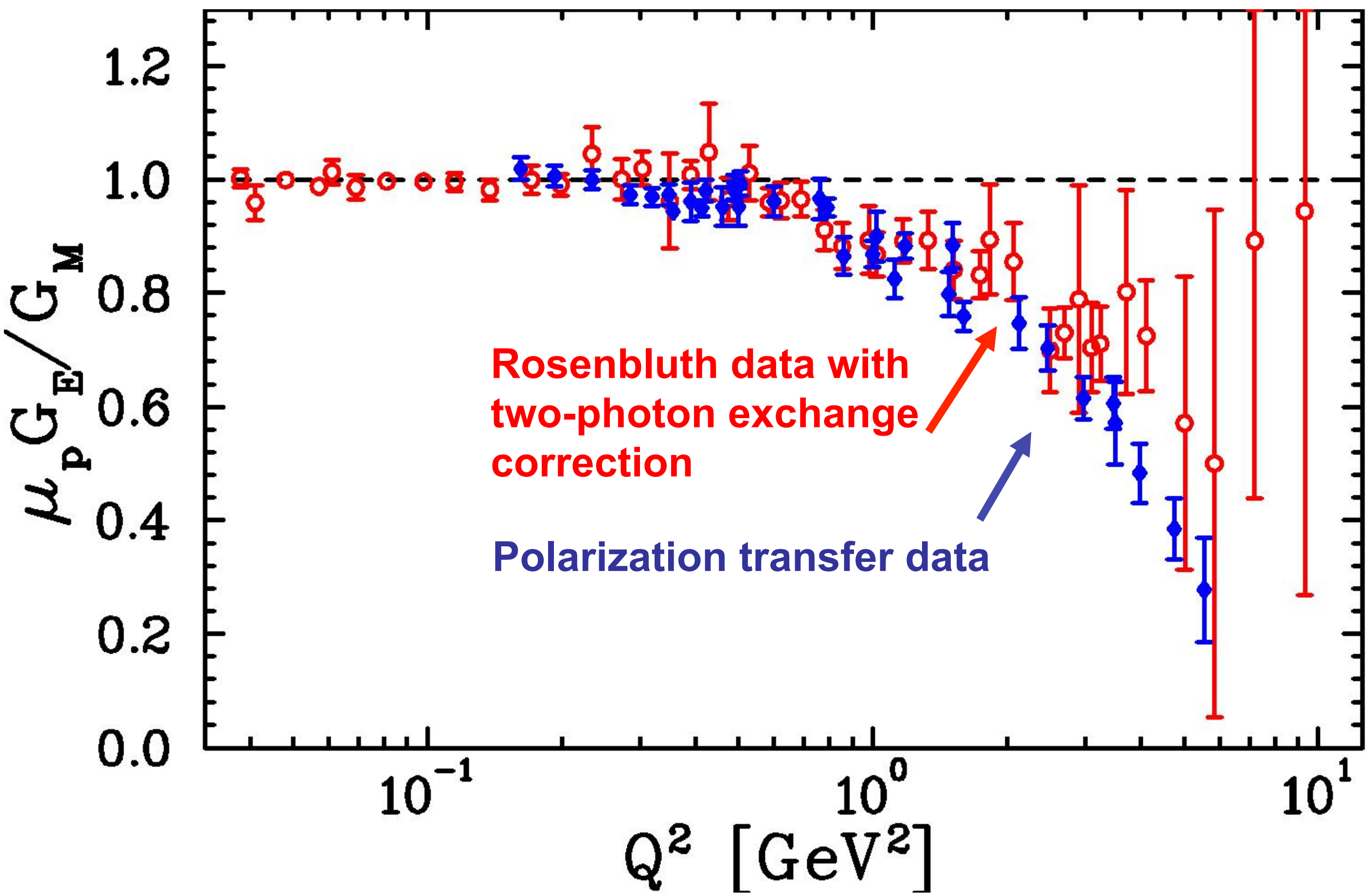
Two-photon exchange: exp. evidence

Two-photon exchange theoretically suggested

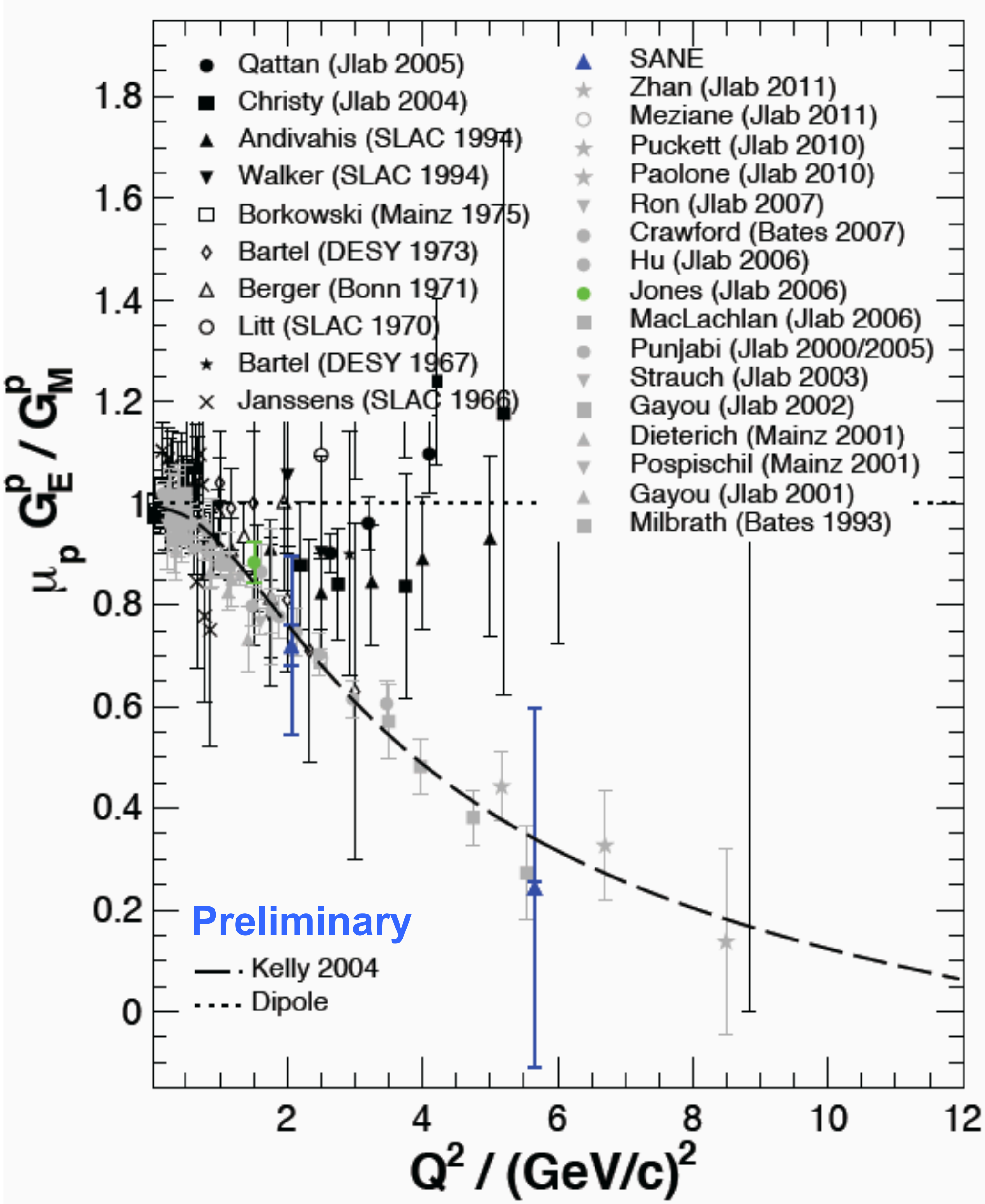


TPE can explain form factor discrepancy

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



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

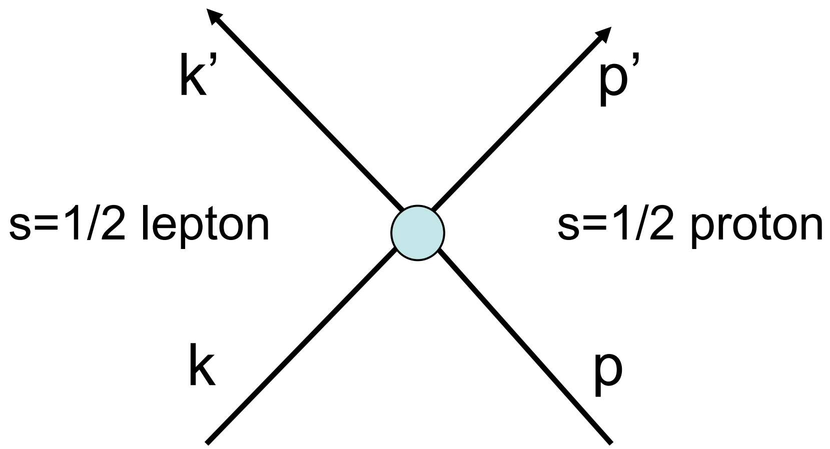
RSS /Hall C: $Q^2 \approx 1.5$ (GeV/c)^2

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

Elastic ep scattering beyond OPE



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

Kinematical invariants :

$$Q^2 = -(p-p')^2$$
$$\nu = K \cdot P = (s-u)/4$$

Next-to Born approximation:

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

($m_e = 0$)

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

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

$$\tilde{G}_E \equiv \tilde{G}_M - (1+\tau)\,\tilde{F}_2$$
$$\tilde{G}_E(\nu,Q^2) = G_E(Q^2) + \delta\tilde{G}_E$$

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

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

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

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

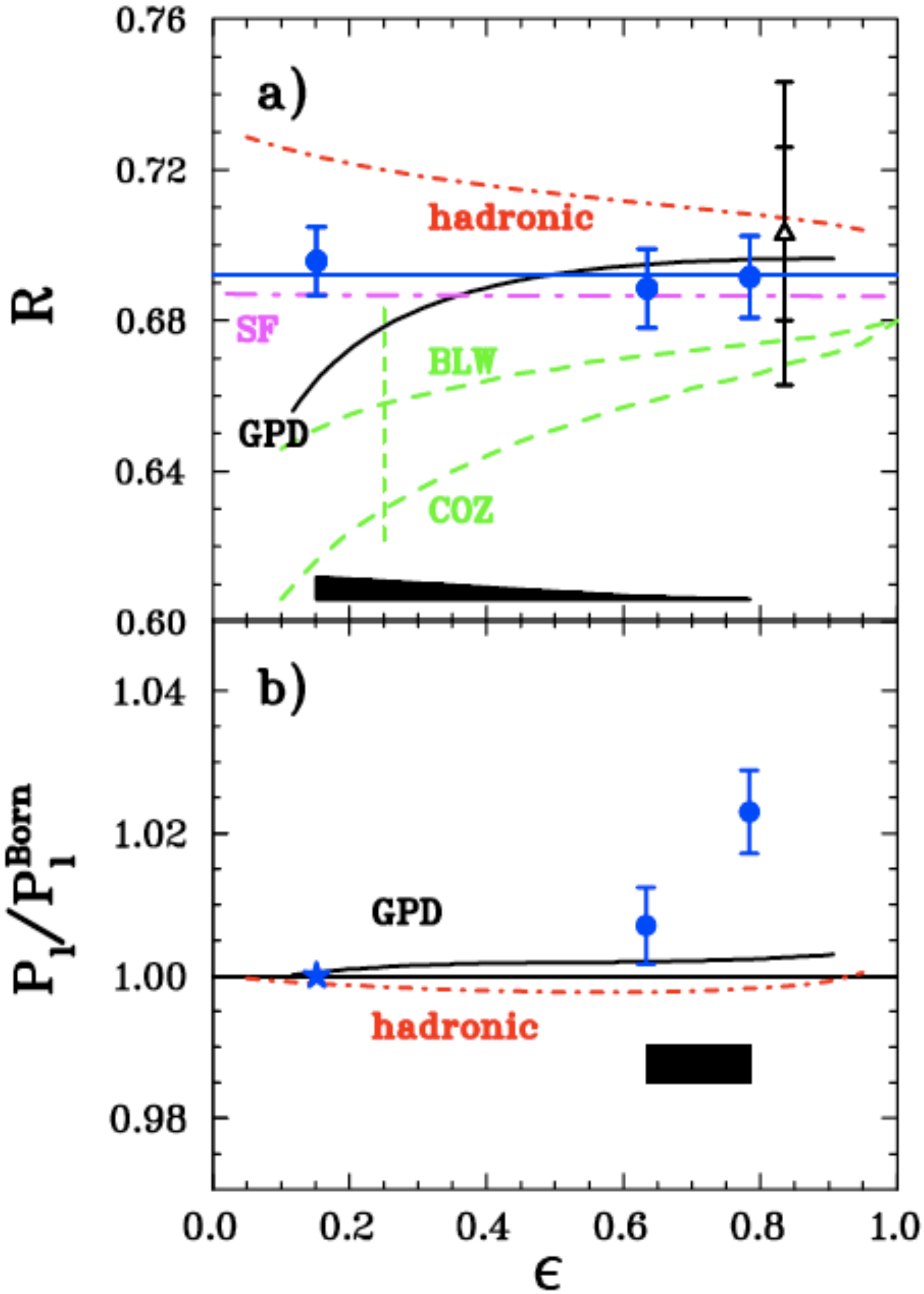
Born Approximation | **Beyond Born Approximation**

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

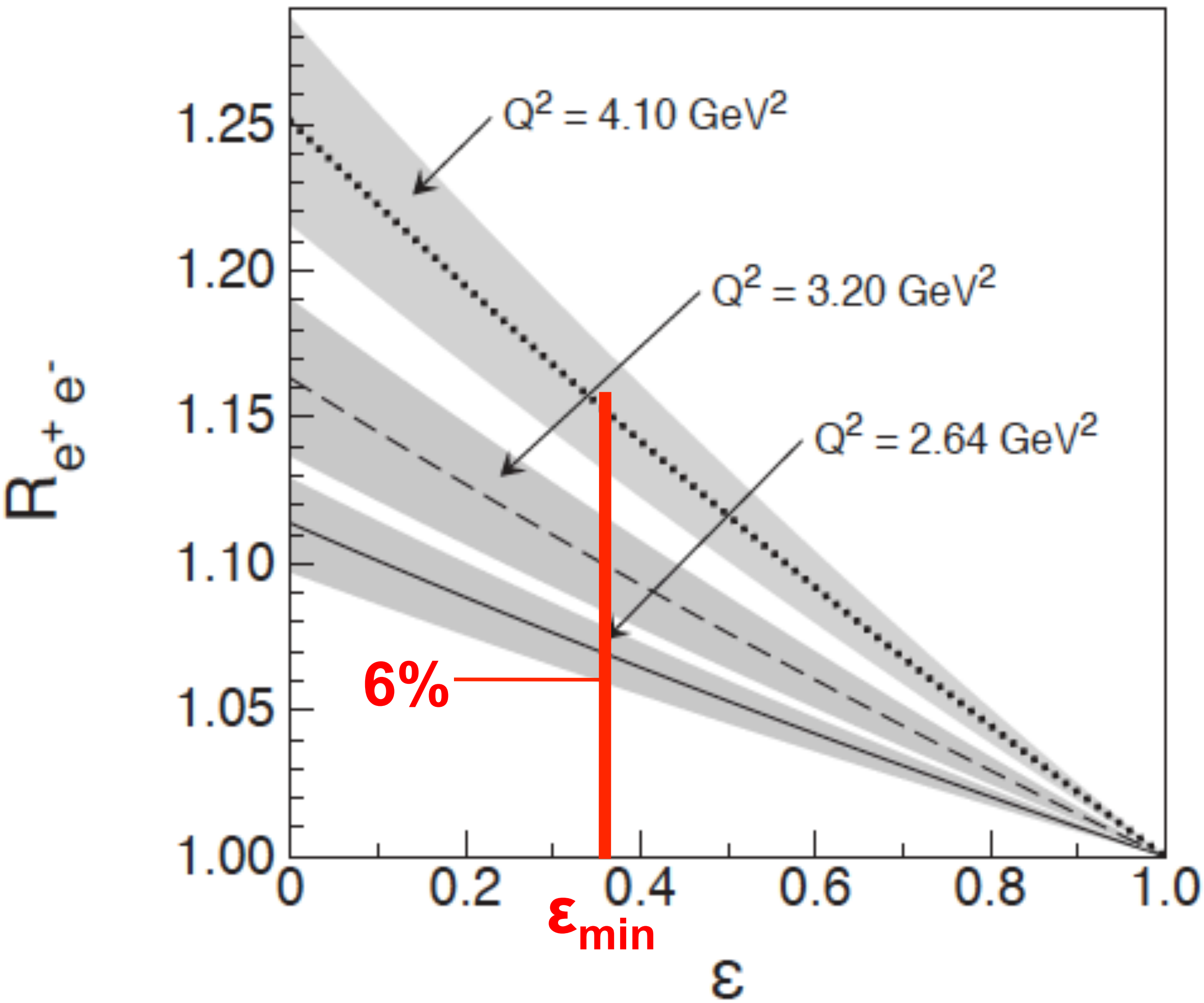
➔ **no effect in P_t/P_l**
➔ **some effect in P_l**

Expect larger effect in e+/e-!

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

Empirical extraction of TPE amplitudes

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



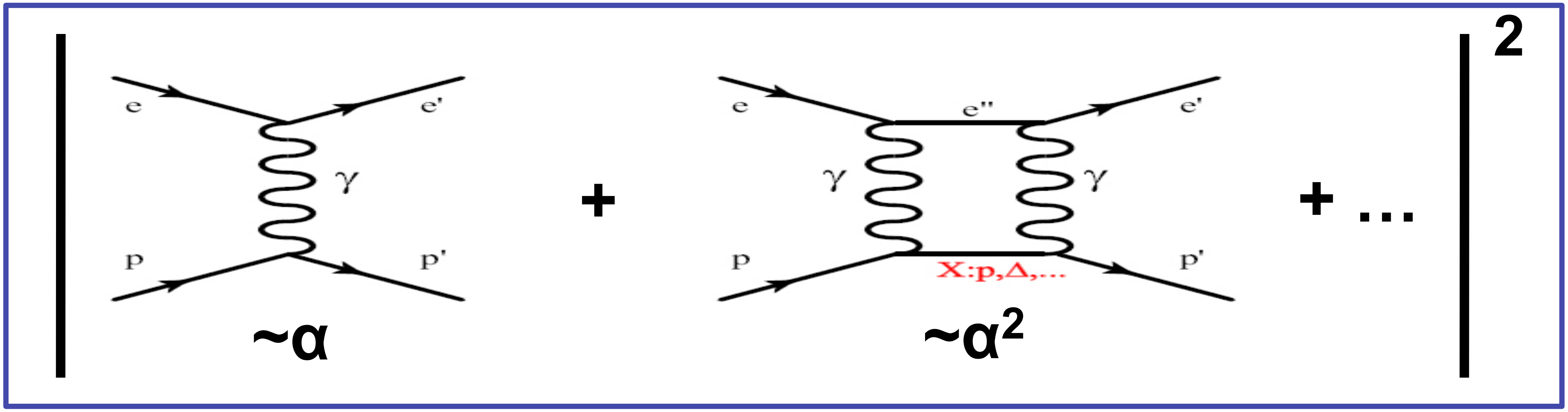
grows with Q^2!

Expect ~6% effect for OLYMPUS@2.0GeV

ε_{min}>0.35, Q^2<2.2 $(GeV/c)^2$

OLYMPUS

Lepton-proton elastic scattering



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

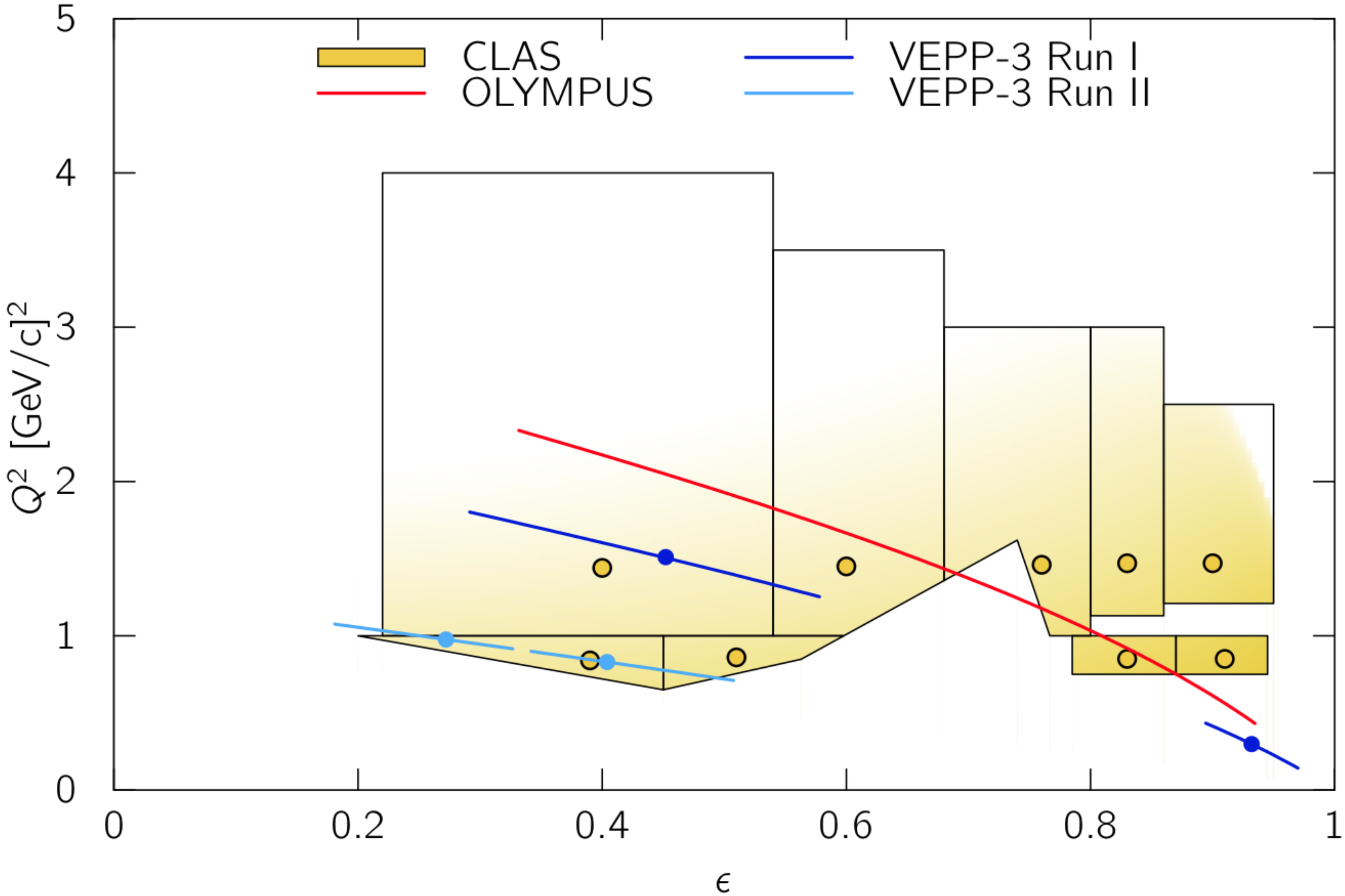
$$\sigma_{e^{\pm}p} = |\mathcal{M}_{1\gamma}|^2 \pm 2\Re\{\mathcal{M}_{1\gamma}^{\dagger}\mathcal{M}_{2\gamma}\} + \cdots$$

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

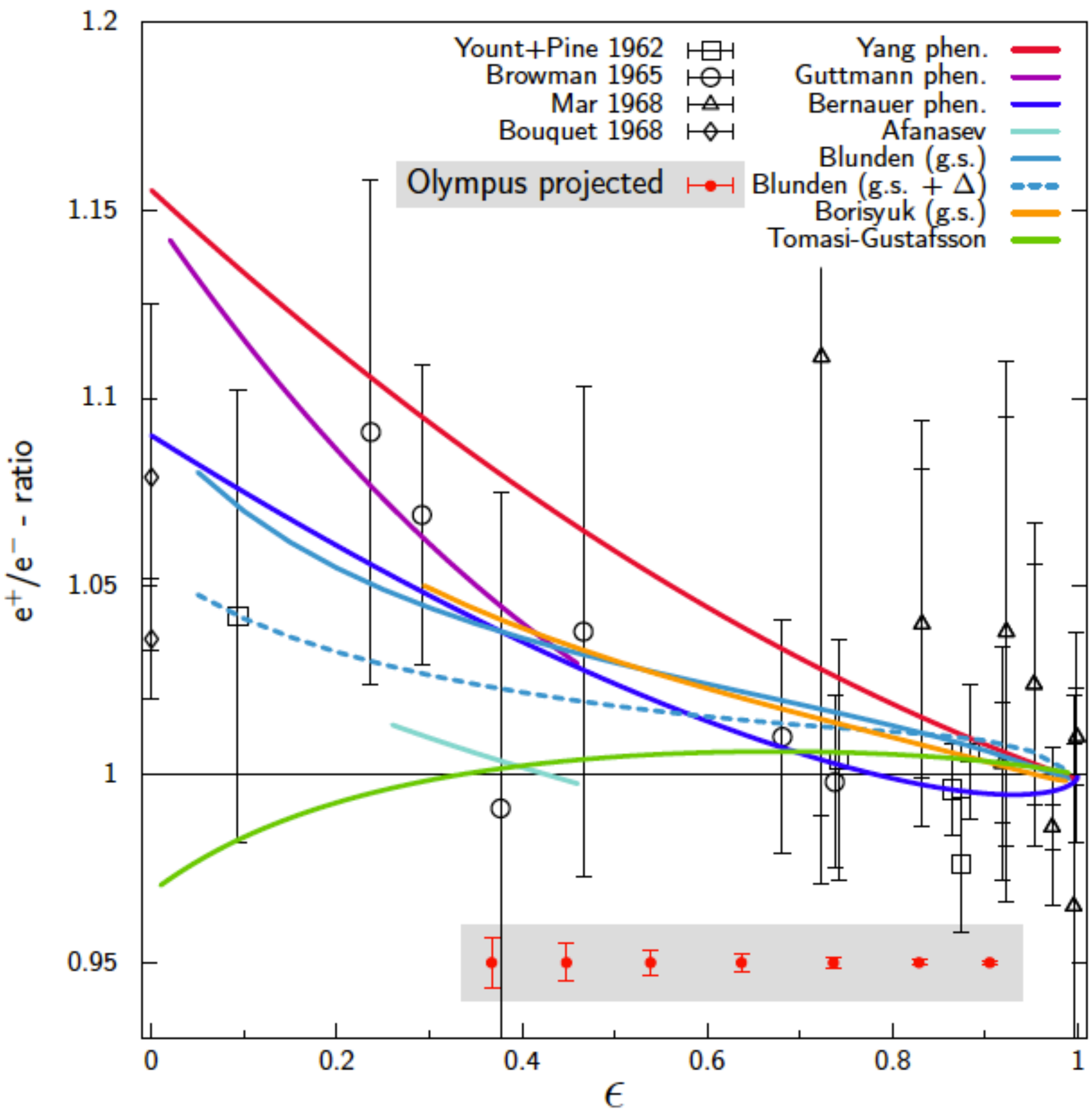
$$\frac{\sigma_{e^+p}}{\sigma_{e^-p}} \approx 1 + 4\frac{\Re\{\mathcal{M}_{1\gamma}^{\dagger}\mathcal{M}_{2\gamma}\}}{|\mathcal{M}_{1\gamma}|^2}$$

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**



Projected results for OLYMPUS



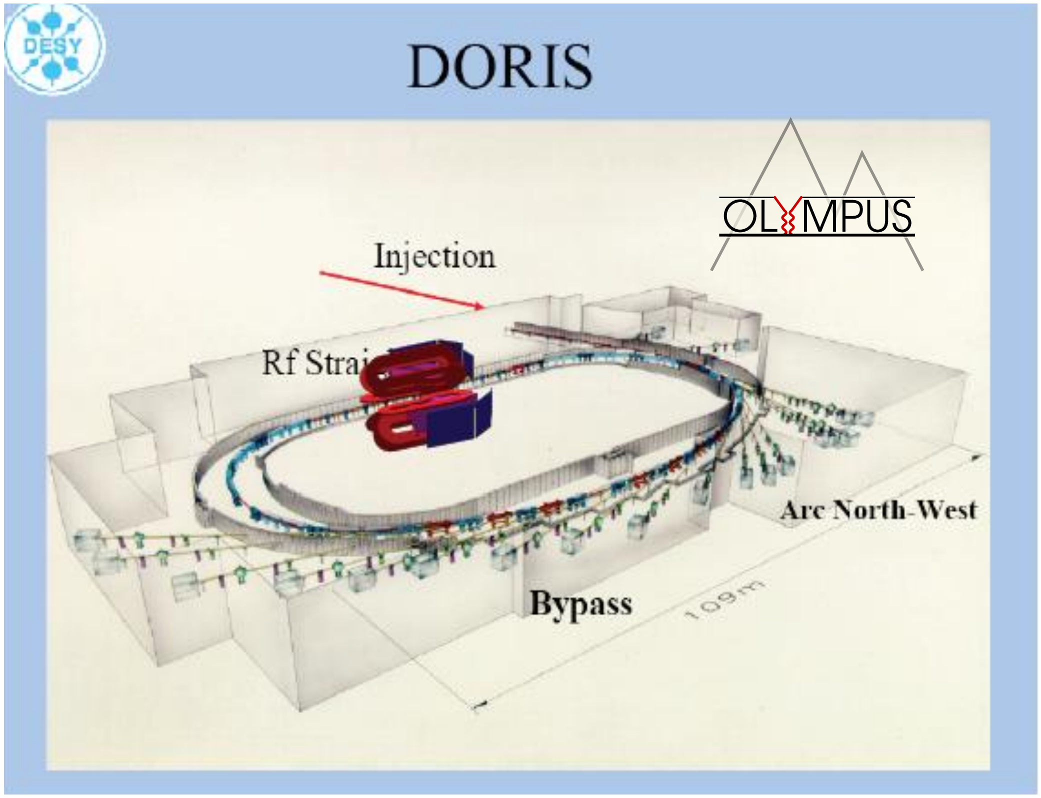
Data from 1960's

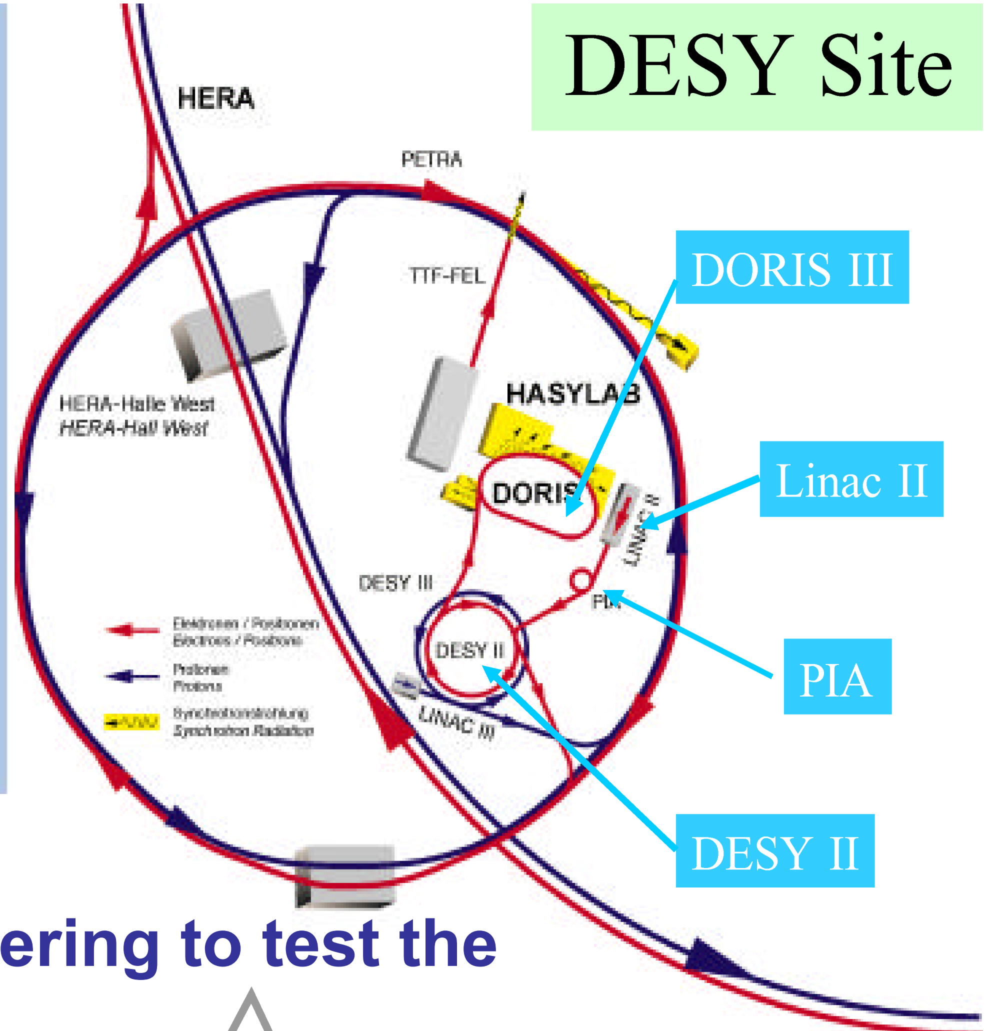
Many theoretical predictions with little constraint

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

OLYMPUS @ DORIS/DESY





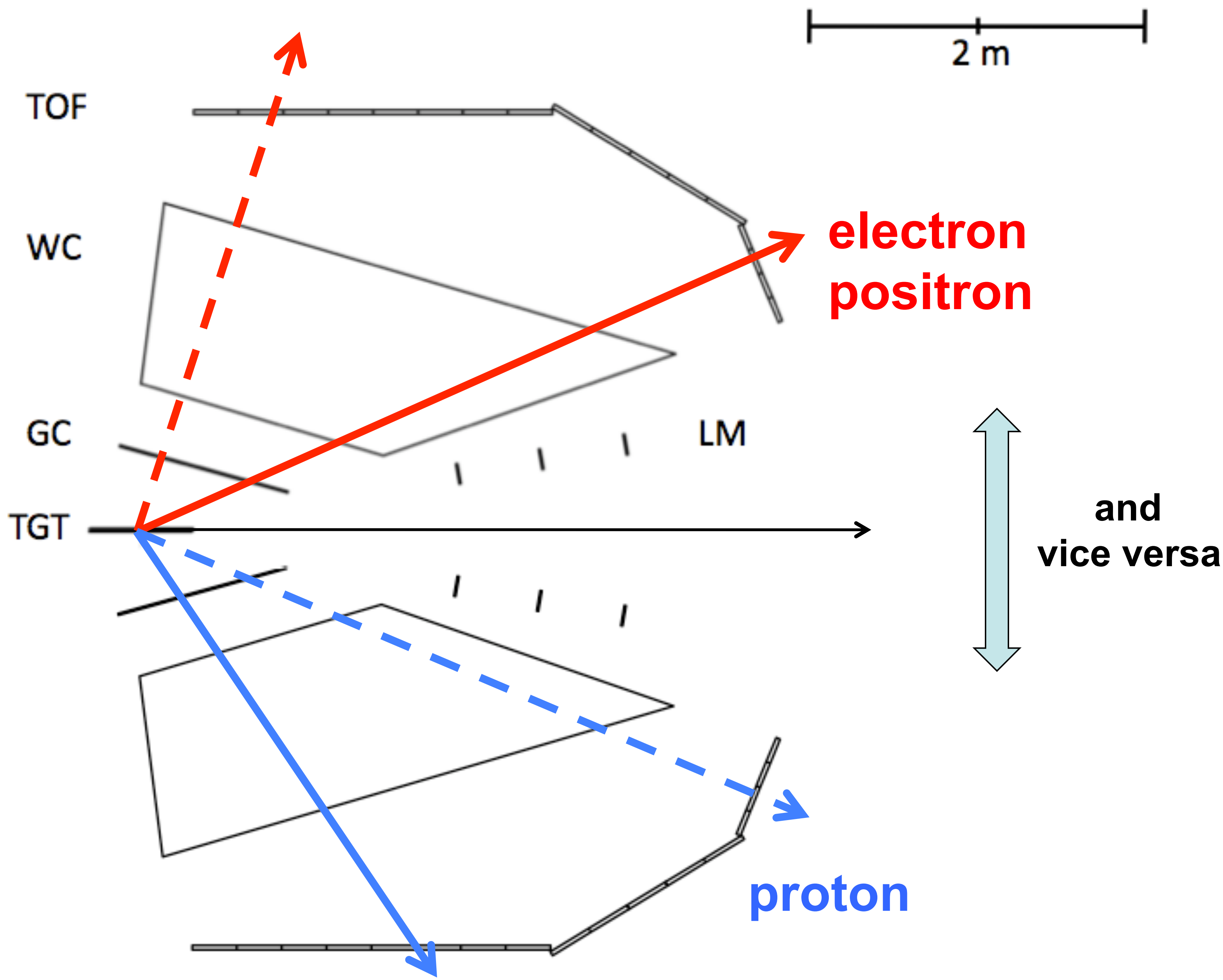
pOsitron-proton and
eLectron-proton elastic scattering to test the
hYpothesis of
Multi-
Photon exchange
Using
DoriS

The OLYMPUS experiment

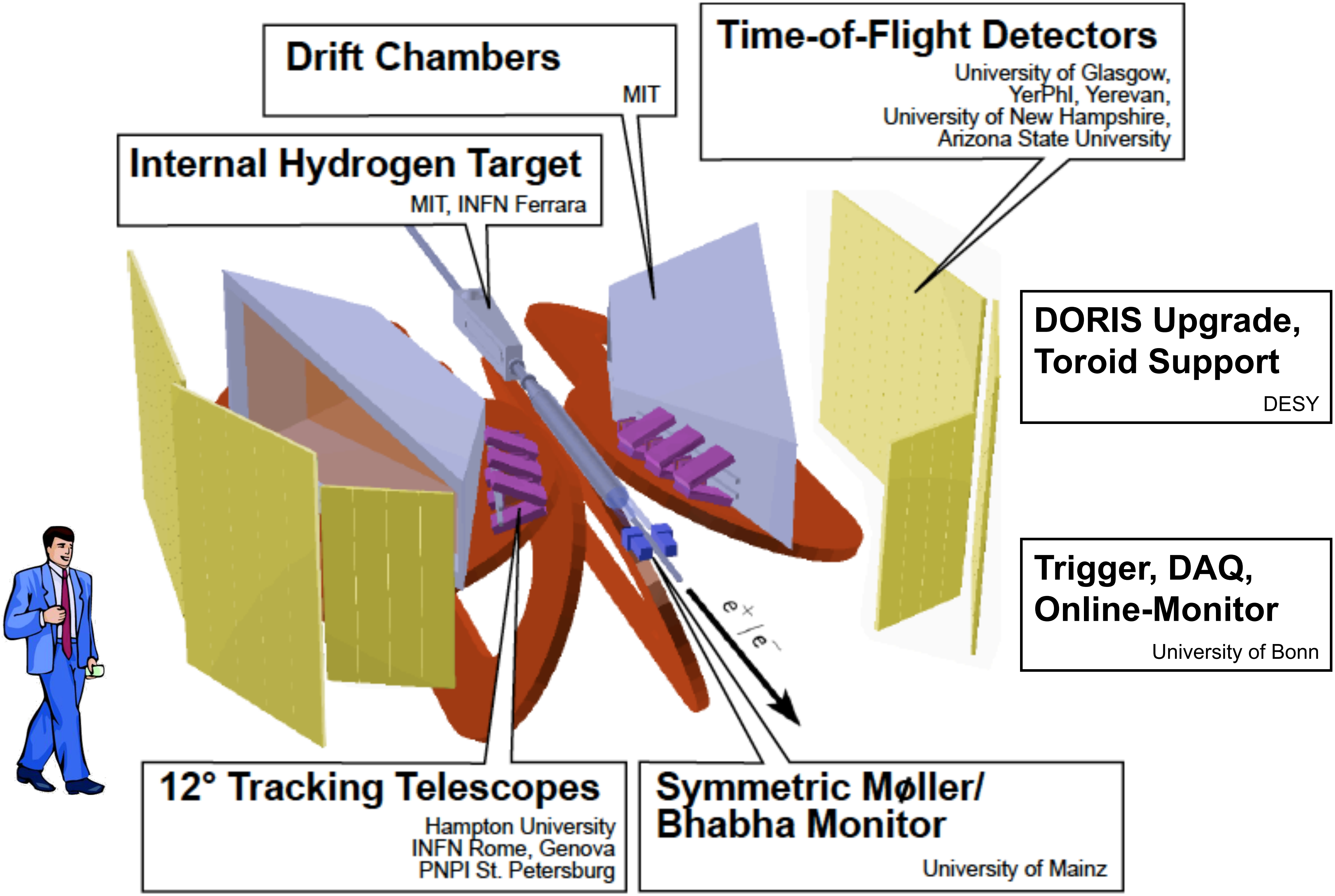
- Electrons/positrons (100mA) in 2.0–4.5 GeV storage ring
  DORIS at DESY, Hamburg, Germany
- Unpolarized internal hydrogen target (buffer system)
  $3x10^{15}$ at/cm^2 @ 100 mA → L = $2x10^{33}$ / (cm^2s)
- Large acceptance detector for e-p in coincidence
  BLAST detector from MIT-Bates available
- 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.

OLYMPUS kinematics at 2.0 GeV

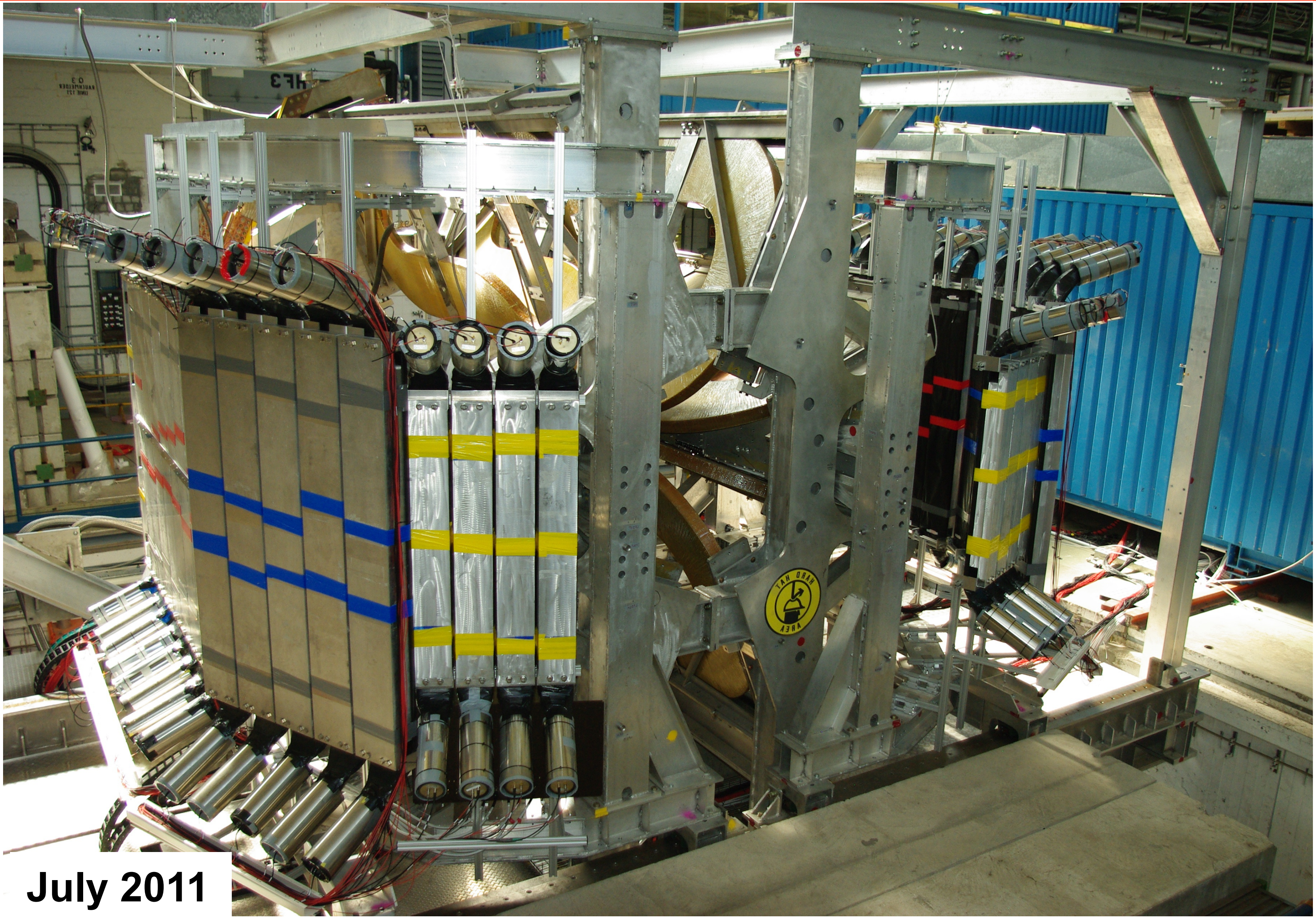


The designed OLYMPUS detector



based on a figure by R. Russell

The realized OLYMPUS detector

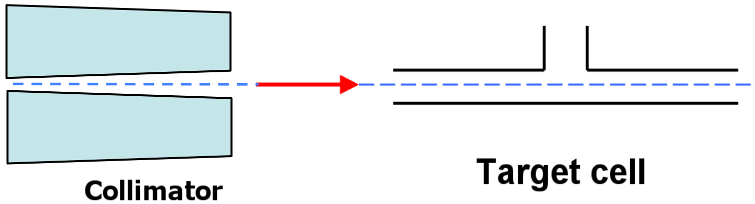


Apparatus: ***"The OLYMPUS Experiment"*, R. Milner *et al.*, NIMA 741, 1 (2014)**

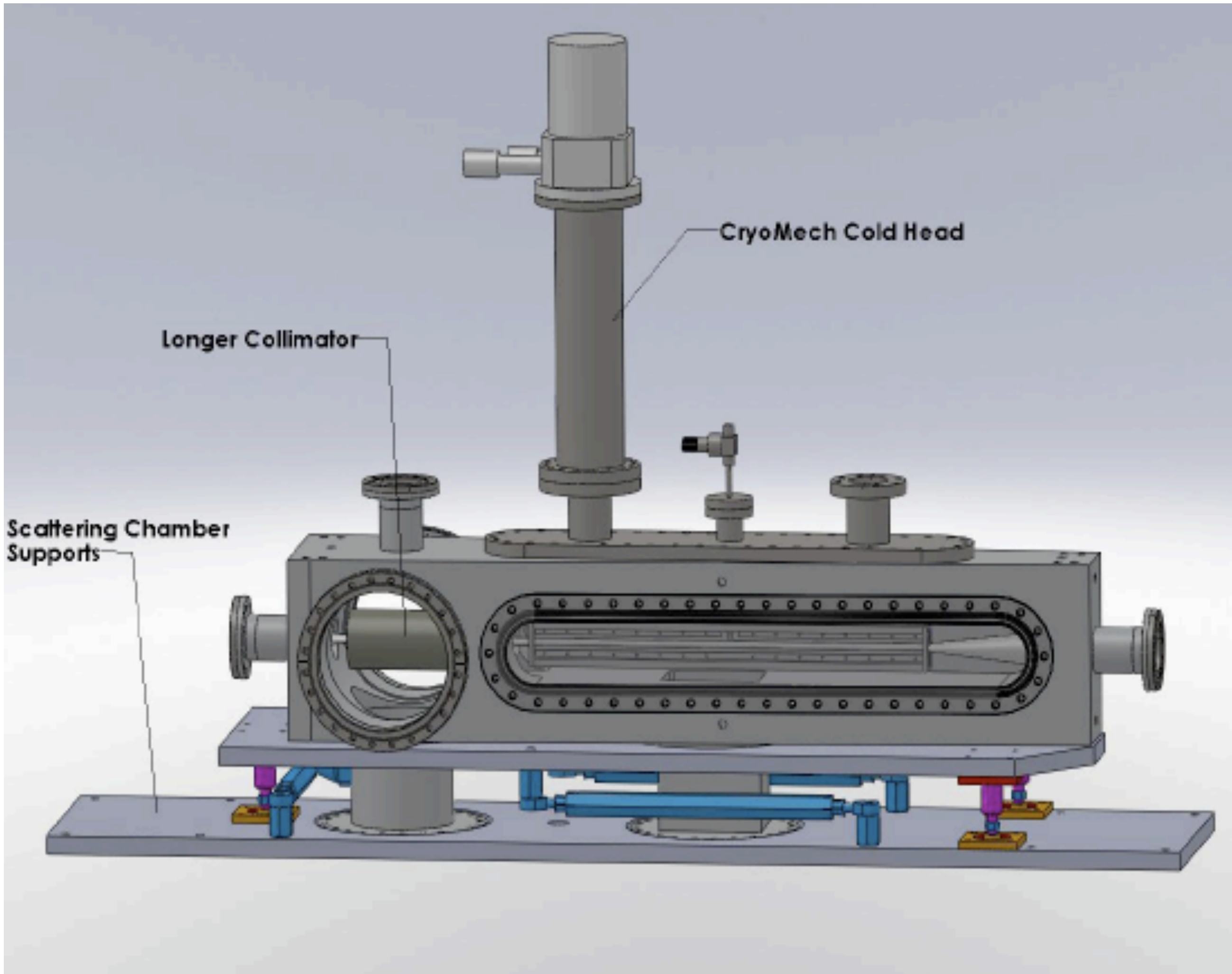
Target: ***"The OLYMPUS internal hydrogen target"*, J.C. Bernauer, NIMA 755, 20 (2014)**

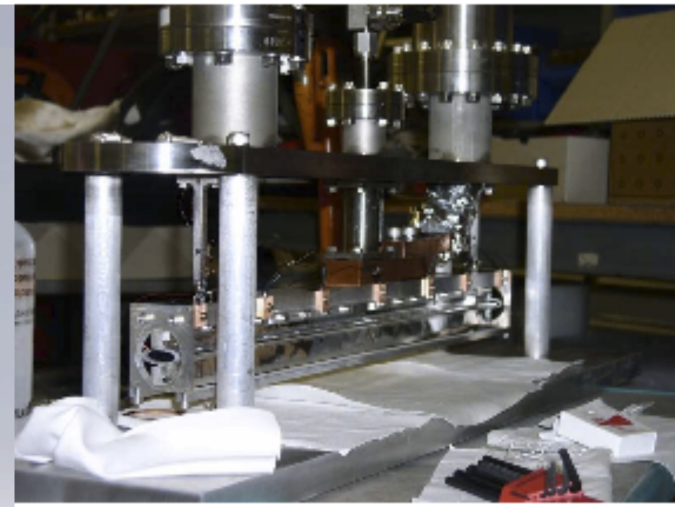
Magnet: ***"Measurement and tricubic interpolation of the magnetic field for the OLYMPUS experiment"*, J.C. Bernauer *et al.*, NIMA 823, 9 (2016)**

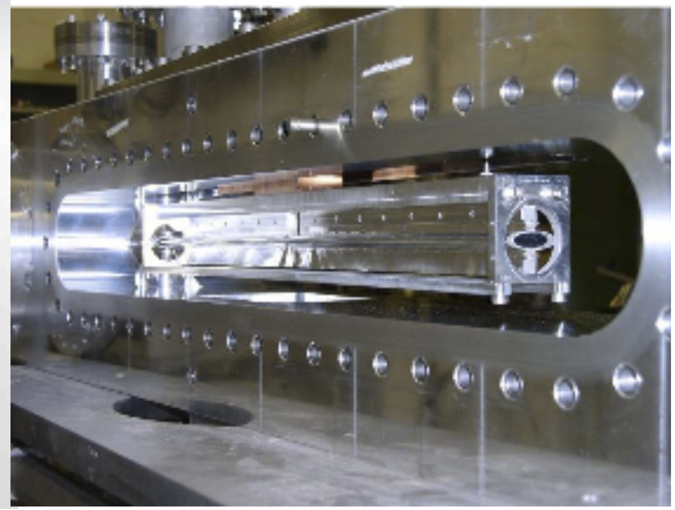
Target and vacuum system



MIT
INFN Ferrara



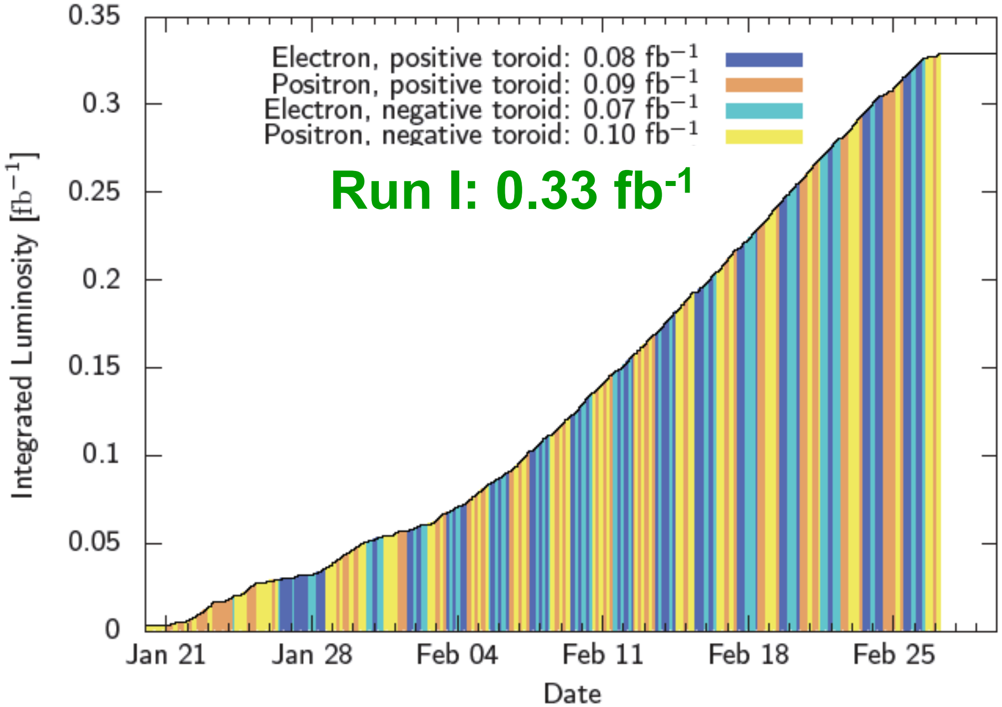


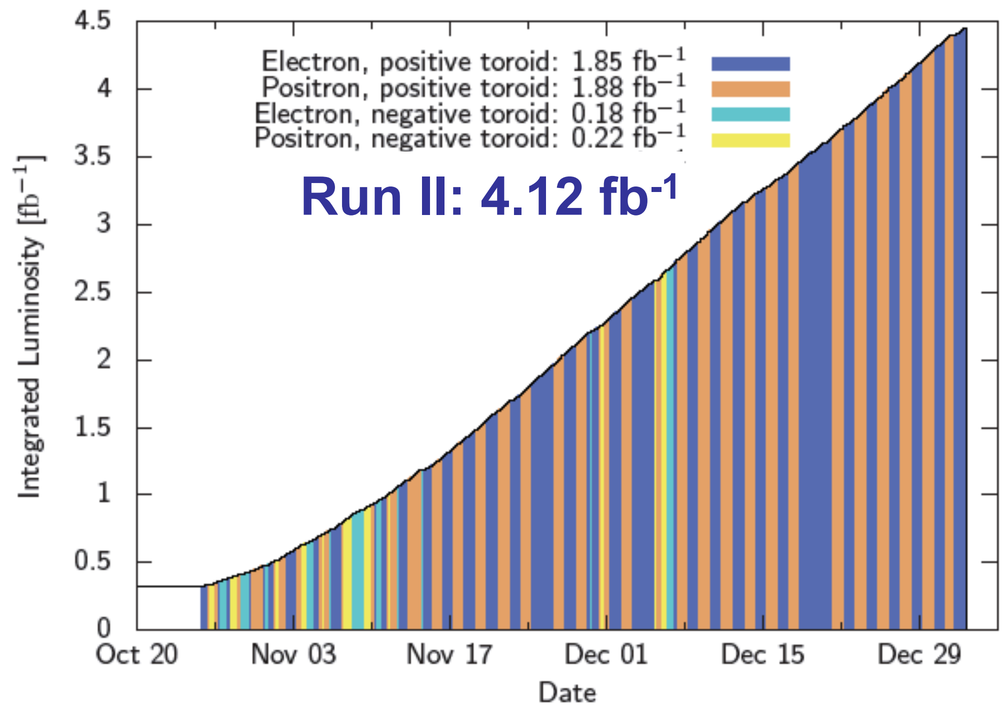


Designed and built in 2010
Very stable operation

"The OLYMPUS Internal Hydrogen Target", J.C. Bernauer *et al.*, NIMA 755, 20 (2014)

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}

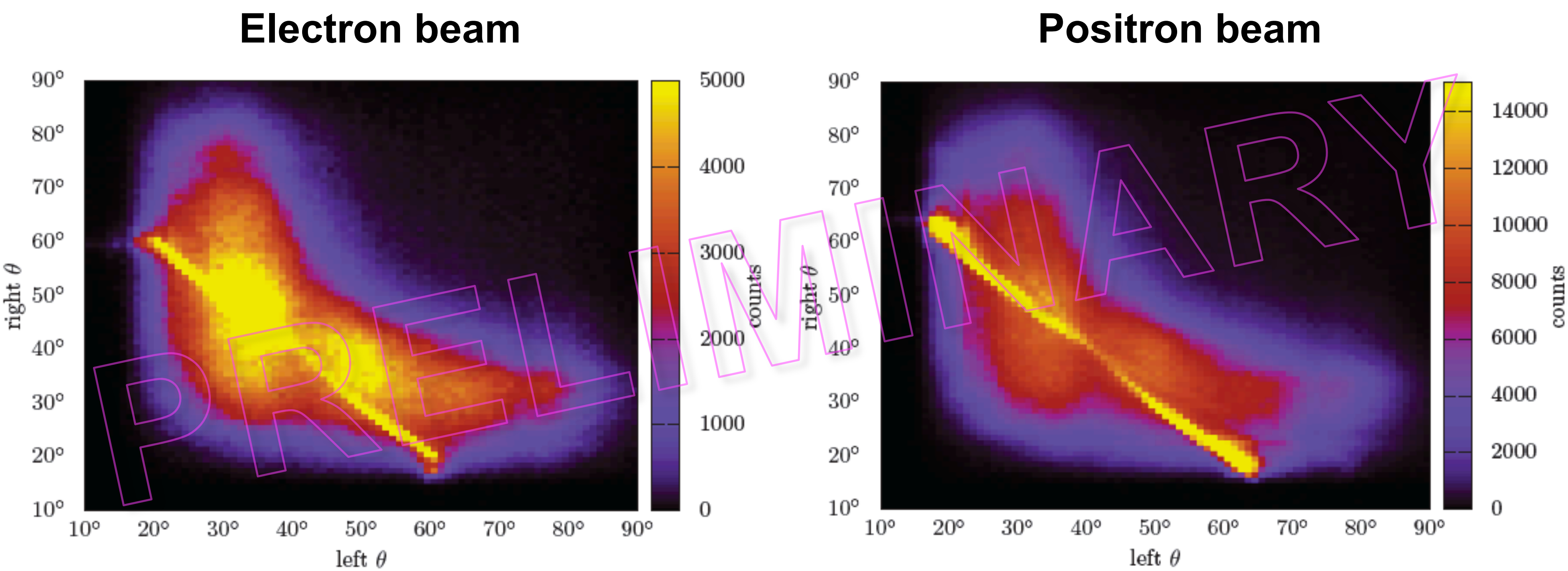
- Summer 2012 Repairs and upgrades

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 Nov 2016**

Event selection

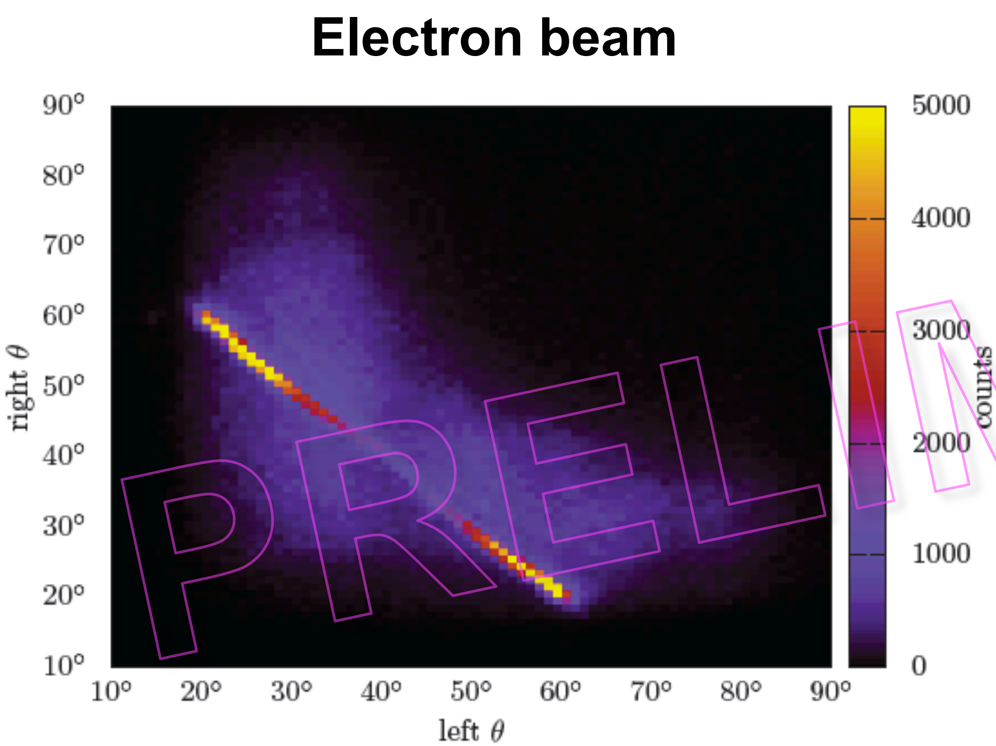
Based on 100 runs (~2% of the data)

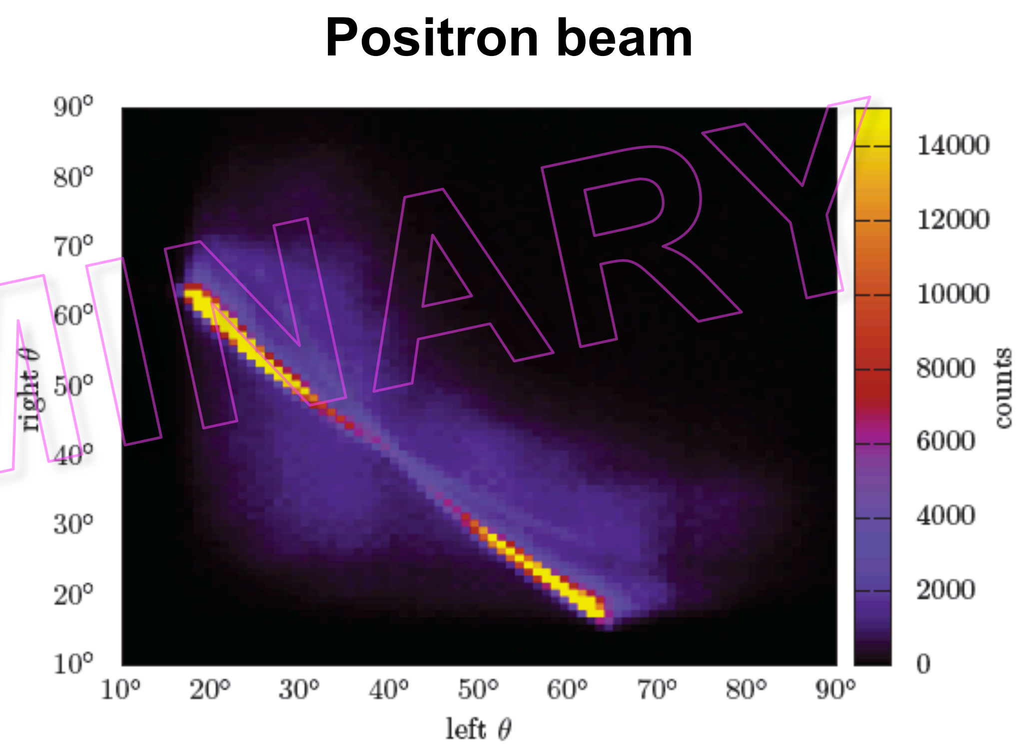


Polar angle in the right sector versus polar angle in left sector

Event selection

Based on 100 runs (~2% of the data)



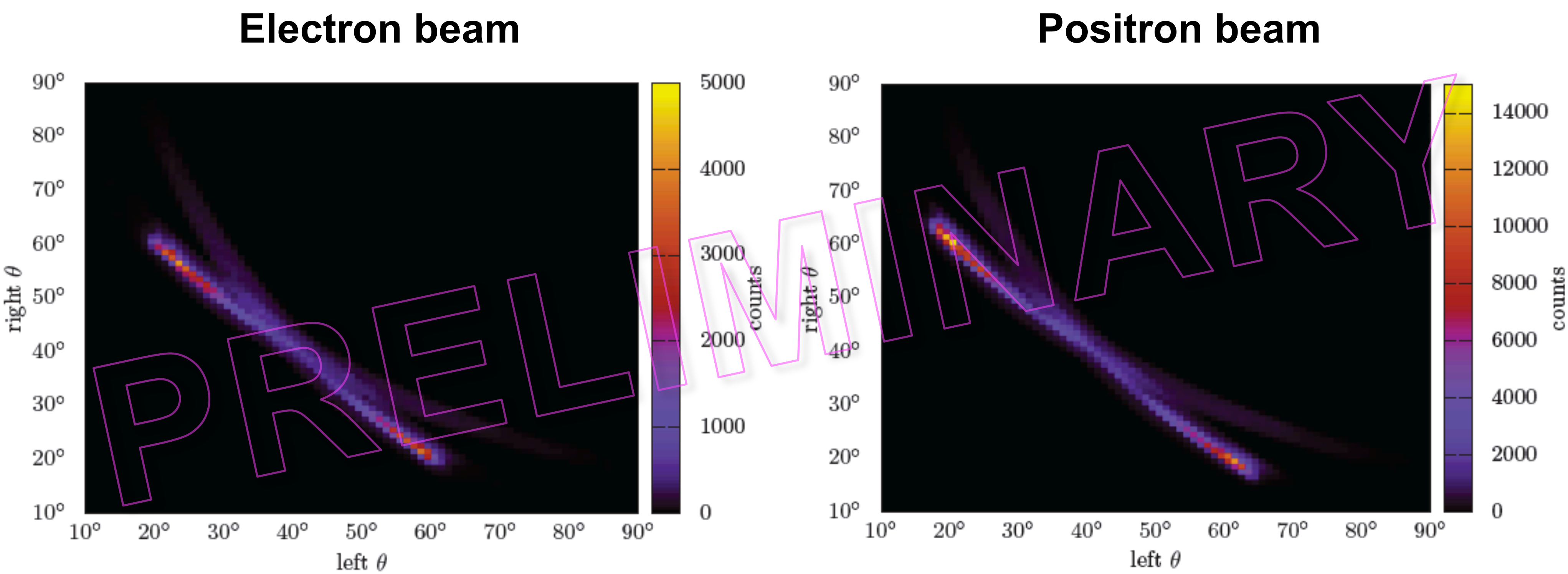


Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees

A. Schmidt (MIT)

Event selection

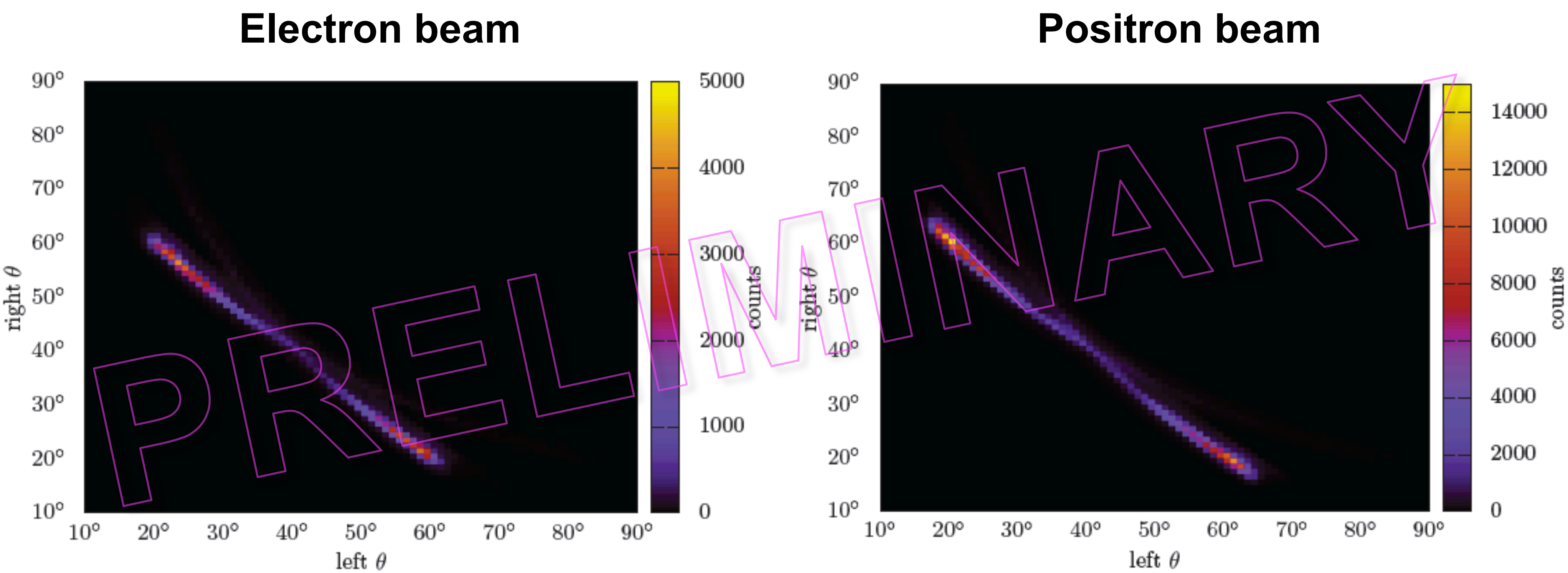
Based on 100 runs (~2% of the data)



Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees
Common vertex ±100 mm

Event selection

Based on 100 runs (~2% of the data)



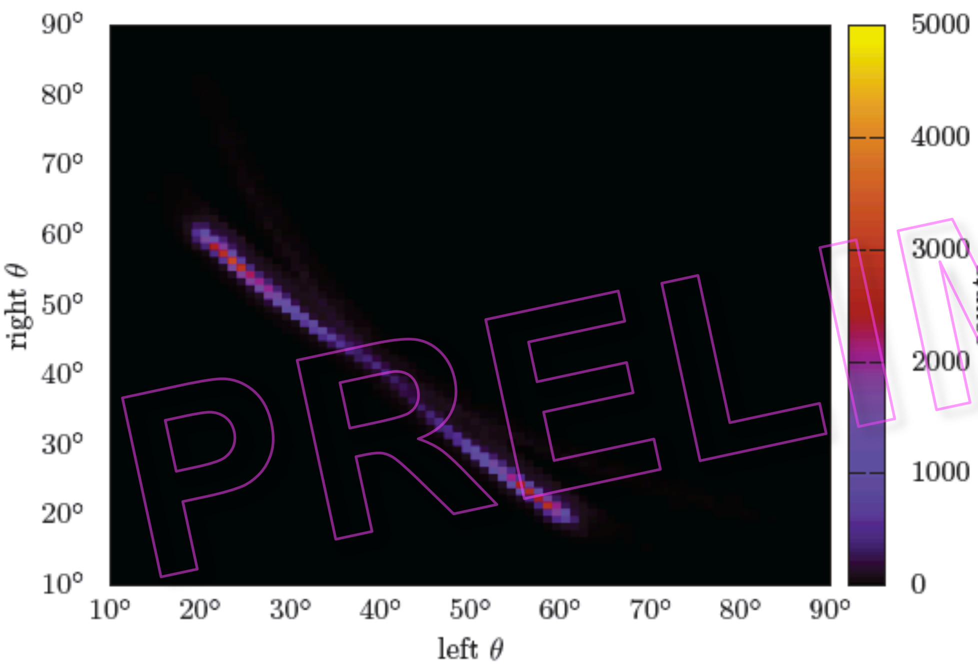
Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees
Common vertex ±100 mm
Polar angle kinematic cut $|\theta_l - \theta_l(\theta_p)| < 5$ degrees

A. Schmidt (MIT)

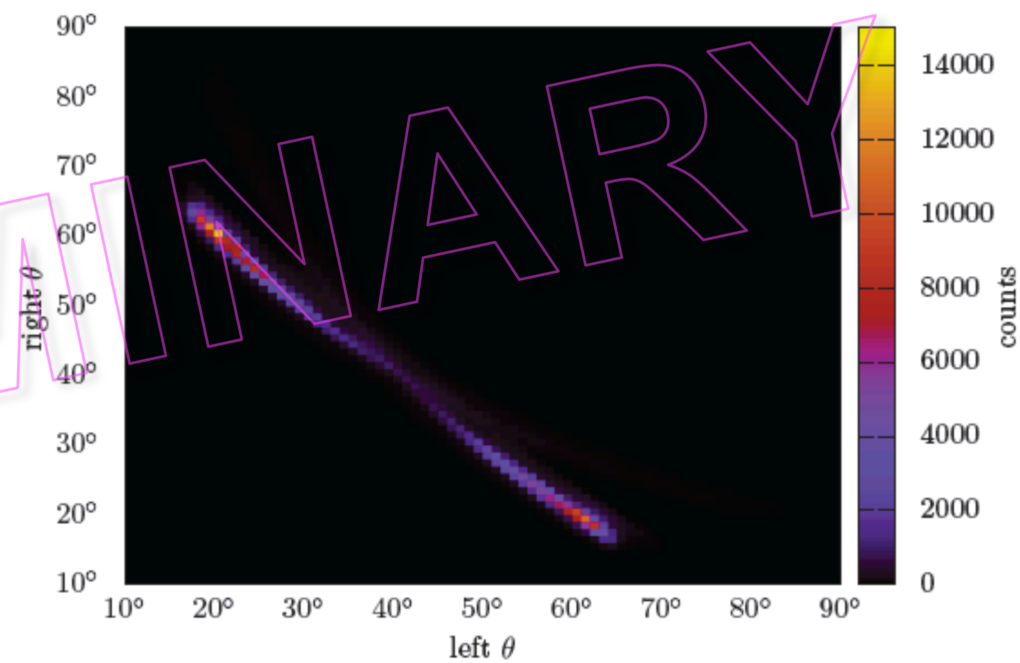
Event selection

Based on 100 runs (~2% of the data)

Electron beam



Positron beam

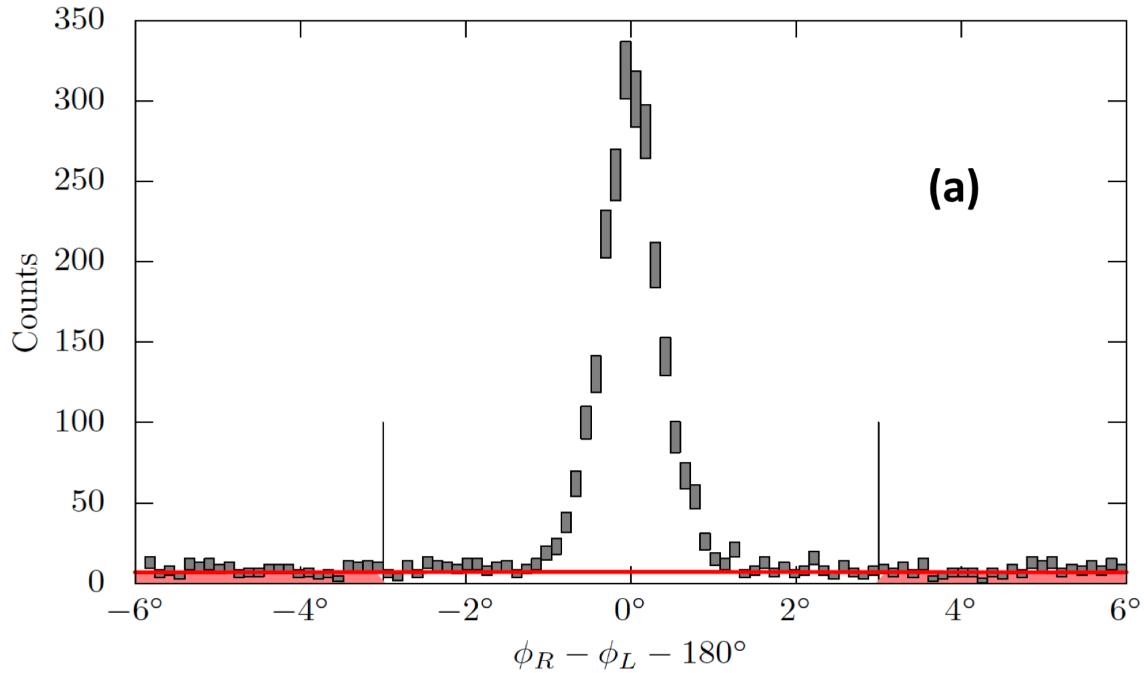


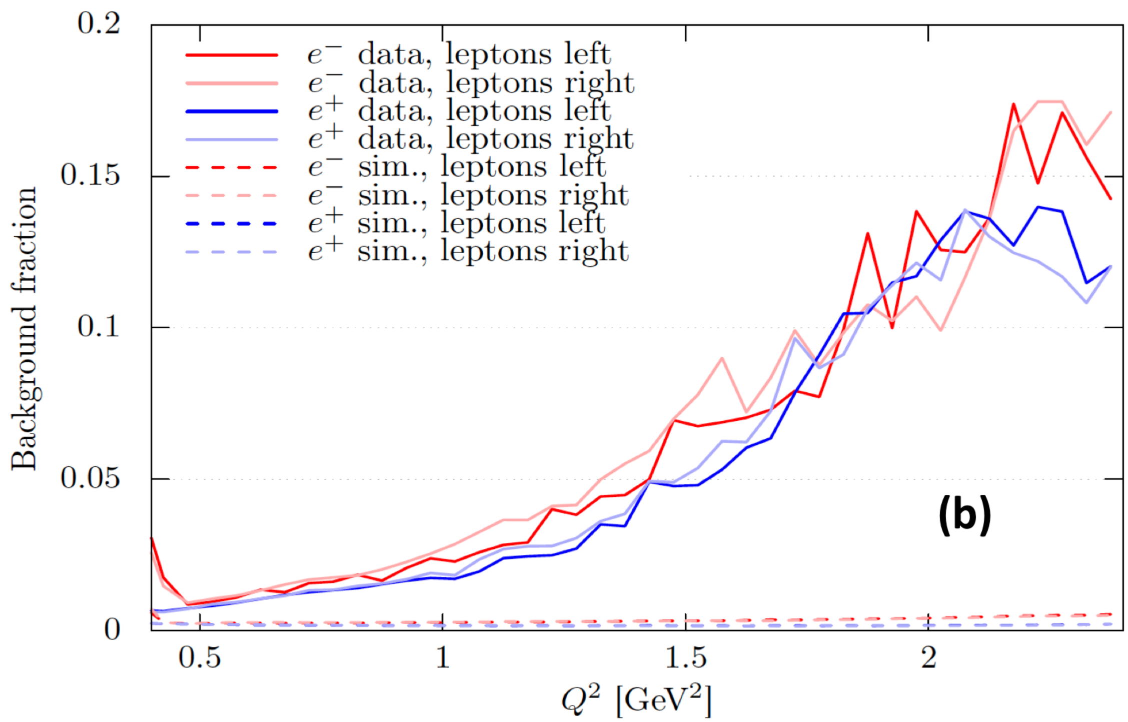
Polar angle in the right sector versus polar angle in left sector
Coplanarity cut ±5 degrees
Common vertex ±100 mm
Polar angle kinematic cut $|\theta_l - \theta_l(\theta_p)| < 5$ degrees
Momentum kinematic cut $|P_p - P_p(\theta_p)| < 400$ MeV/c

Only for illustration – final analysis more sophisticated

A. Schmidt (MIT)

Backgrounds

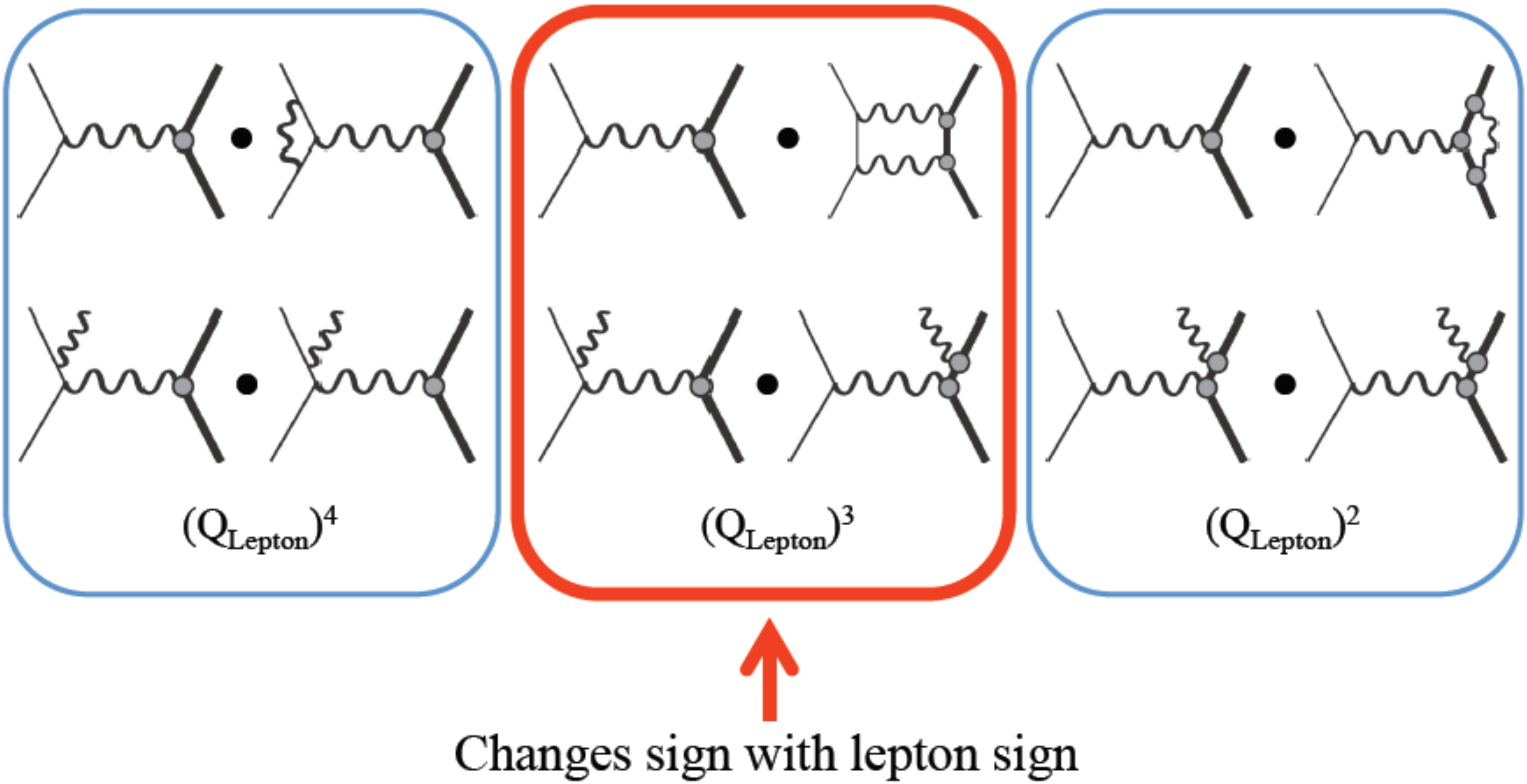




- **Coplanarity peak for background estimation**
- **Backgrounds range from negligible at forward angles to 15-20% at large angles**
- **Mostly independent of species**

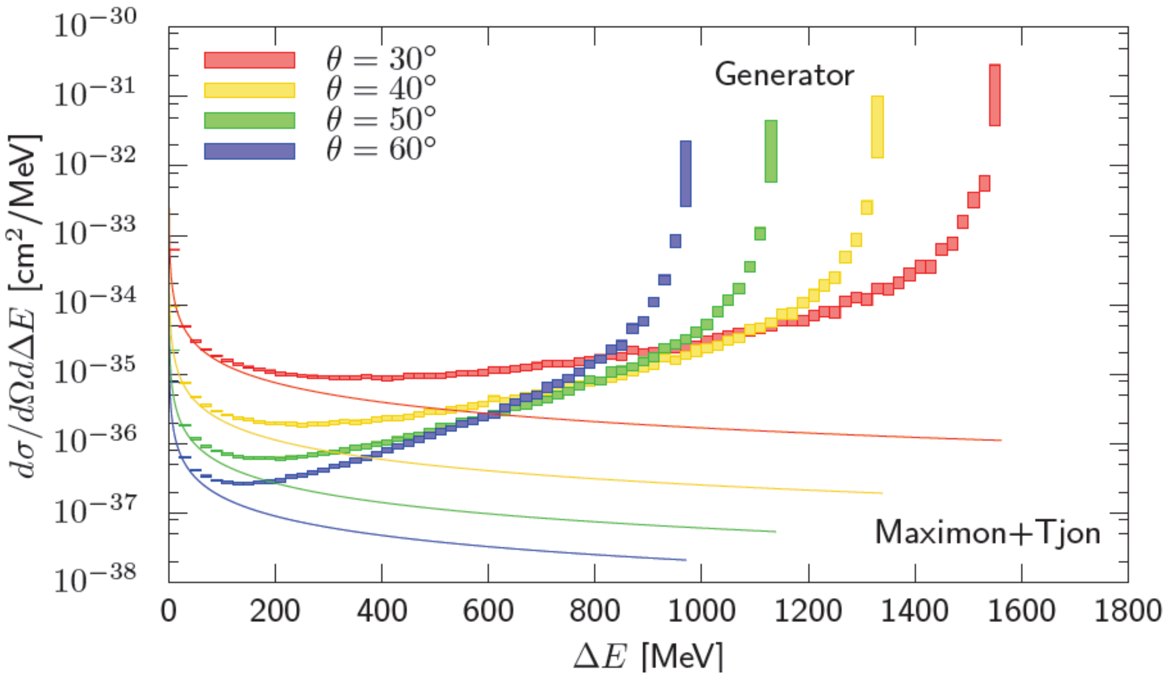
Radiative corrections of order α^3

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

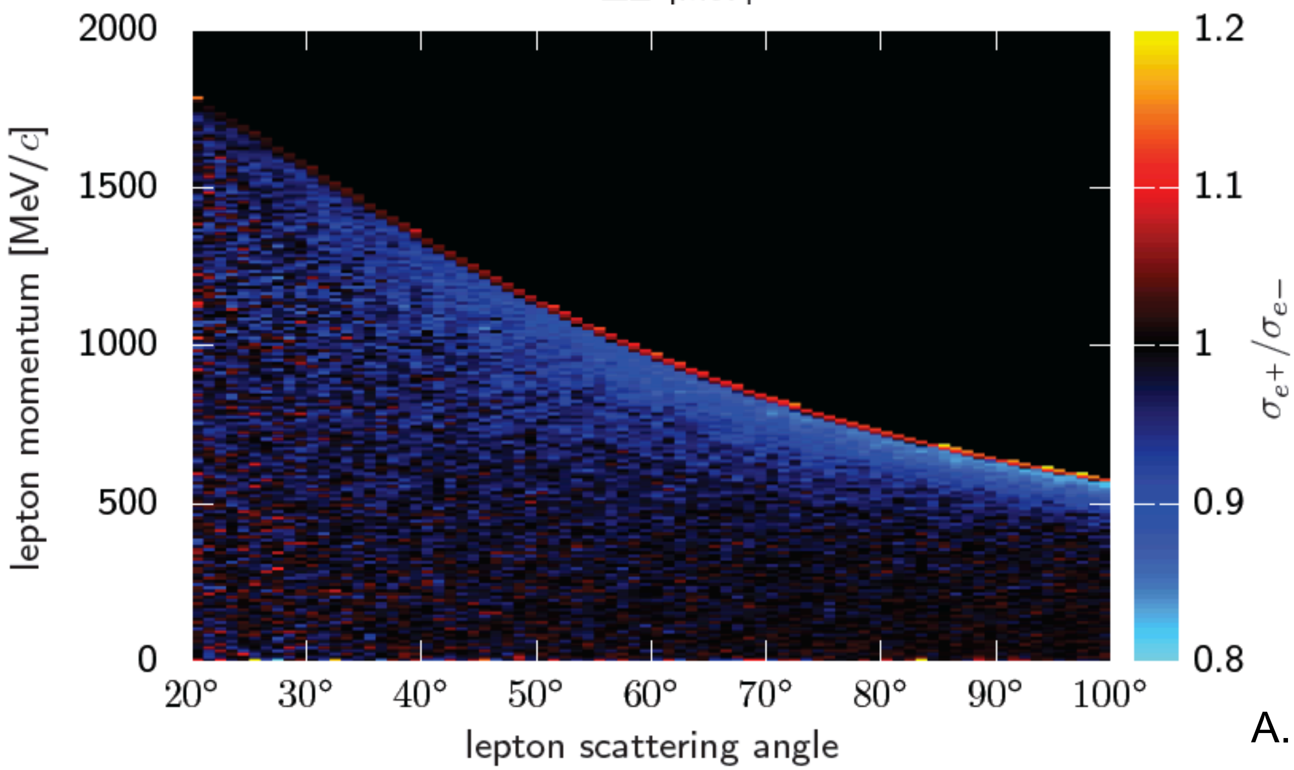


A. Schmidt, R. Russell, J. Bernauer (MIT)

MIT radiative generator



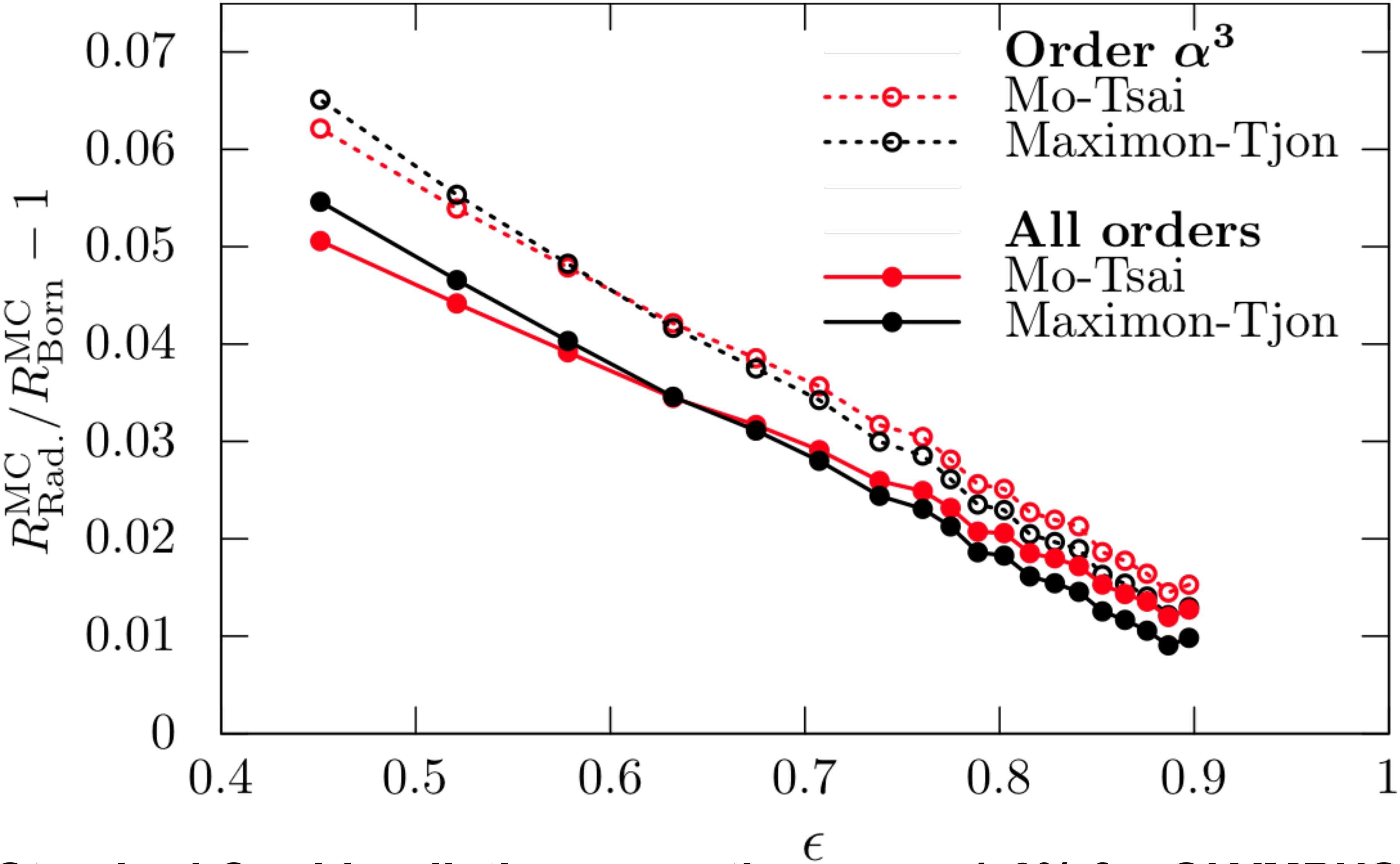
- **Avoids approximations**
- **Agreement with Maximon&Tjon (soft photons) at low ΔE**
- **Excellent agreement with VEPP-3 generator at O(α³)**



Effect on σ_{e+}/σ_{e-}

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

MIT radiative generator

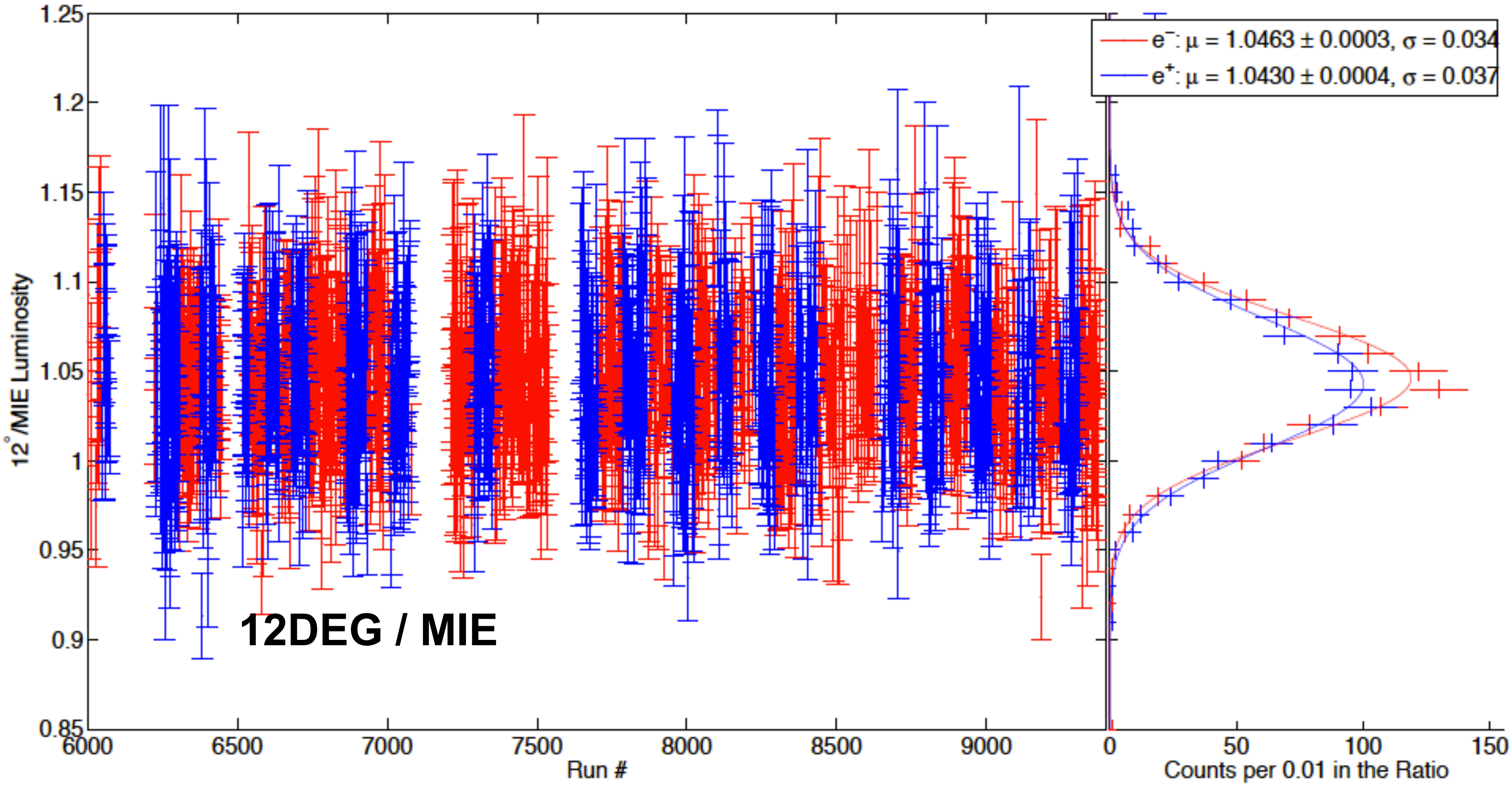


- **Standard C-odd radiative corrections are ~1-6% for OLYMPUS**
- **Variation due to higher orders at ~1% level**

B.S. Henderson *et al.*, arXiv:1611.04685v2, accepted by PRL

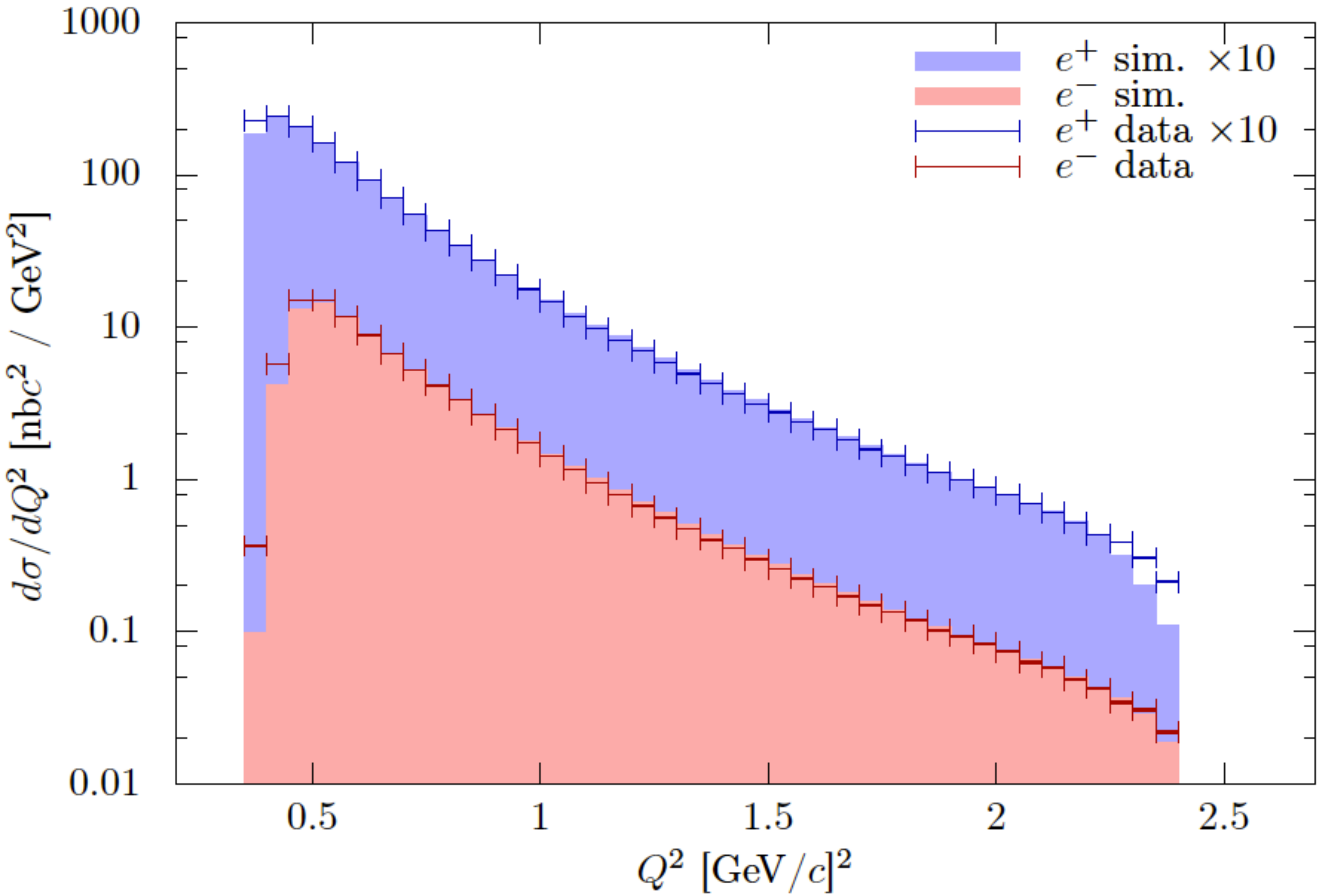
Luminosity

- 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



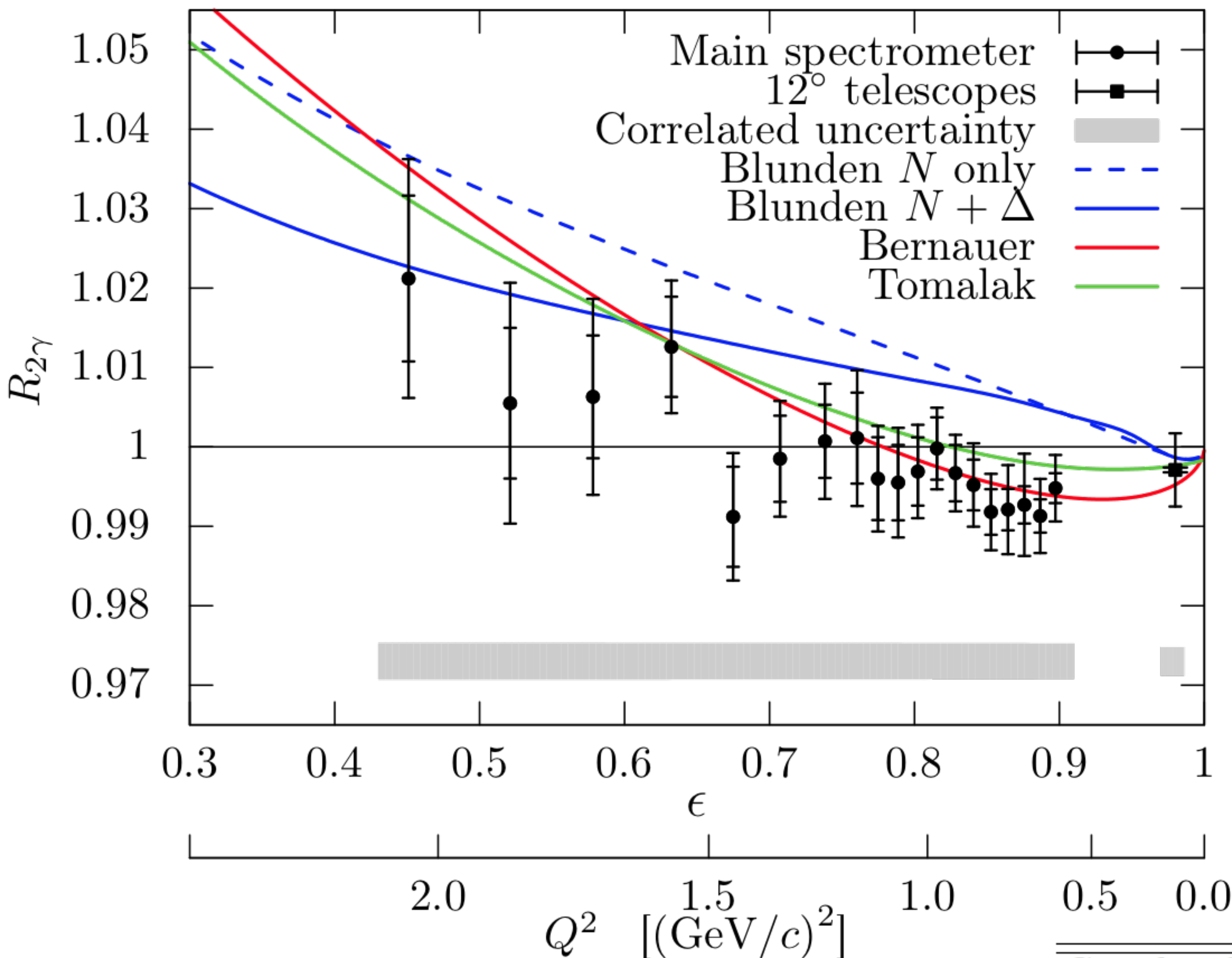
A. Schmidt, B. Henderson (MIT)

Yields



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

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 !

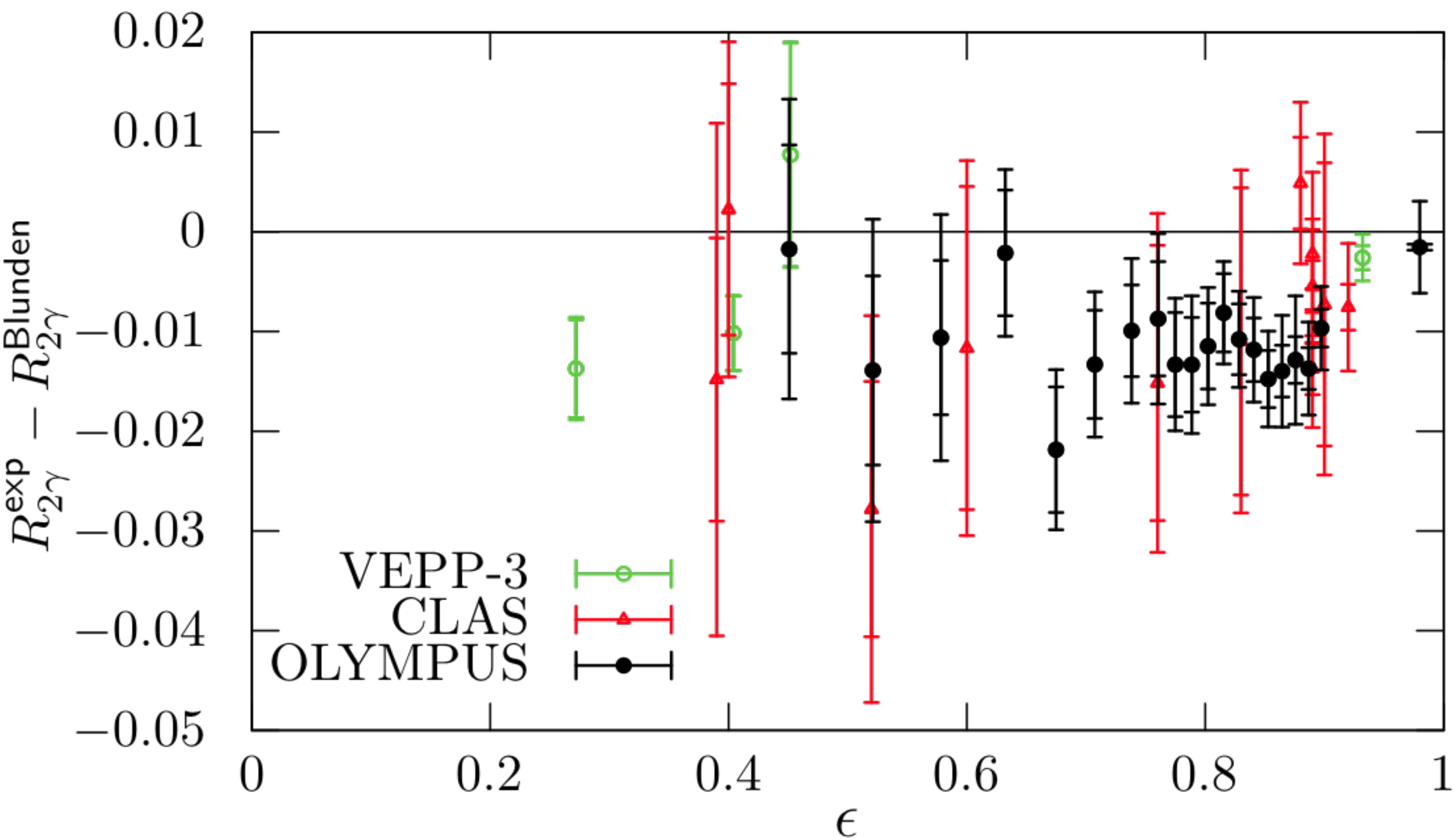
- **Below Hadronic Model by Blunden at low Q^2**
- **Good agreement with phenomenology**

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

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%

B.S. Henderson *et al.*, arXiv:1611.04685v2, accepted by PRL

Comparison with VEPP-3 and CLAS



- OLYMPUS, VEPP-3 and CLAS all in agreement
- Hard TPE observed by VEPP-3 and OLYMPUS below Blunden
- Limited precision for CLAS

Summary and outlook

- 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 for a definitive test of 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 $Q^2 < 2.5$ $(GeV/c)^2$
  - ➔ required to be tested at higher $Q^2 > 2.5$ $(GeV/c)^2$ with future experiments (e.g. by adding positron source to CEBAF, or by conceiving internal-target experiment at storage ring or ERL)
- Need to improve theoretical precision for radiative corrections !

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

Backup

Proton form factor experiments

Recoil polarization and polarized target (Jlab)

E04-108 – high-Q^2 recoil polarization (Gep-III) – published (2010)
E04-019 – ε dependence of recoil pol. (2-Gamma) – published (2011)
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-SBS) – proposed

Unpolarized cross sections (Jlab)

E12-07-108 – high-Q^2 unpolarized (GMp) – completed running (2016)
E05-017 – high-Q^2 Rosenbluth (Super-Rosen) – analysis in progress

Positron-electron comparisons

Novosibirsk / VEPP-3 – published (2015)
CLAS / Jlab – published (2015)
OLYMPUS / DESY – accepted by PRL (2016)

Proton radius measurements

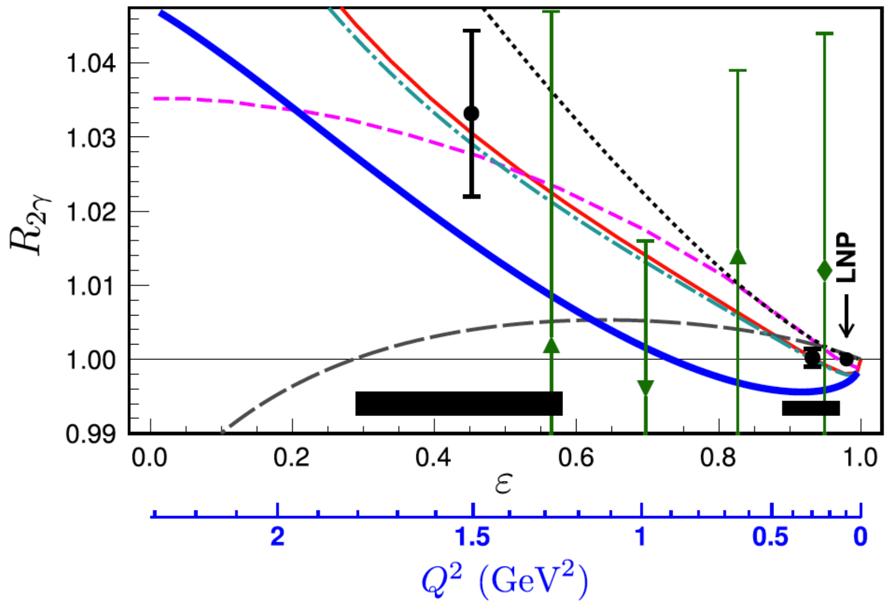
PSI / (muonic hydrogen Lamb shift, HFS) – published (2010, 2013)
MAMI / A1 (e-scattering) – published (2010, 2014)
MAMI / A1 (ISR) – pilot data released (2016)
Jlab / PRad (e-scattering) – completed running (2016)
PSI / MUSE ($e^{\pm}$, $\mu^{\pm}$ scattering) – proposed (2016-2019)

Comparison of e^+/e^- experiments

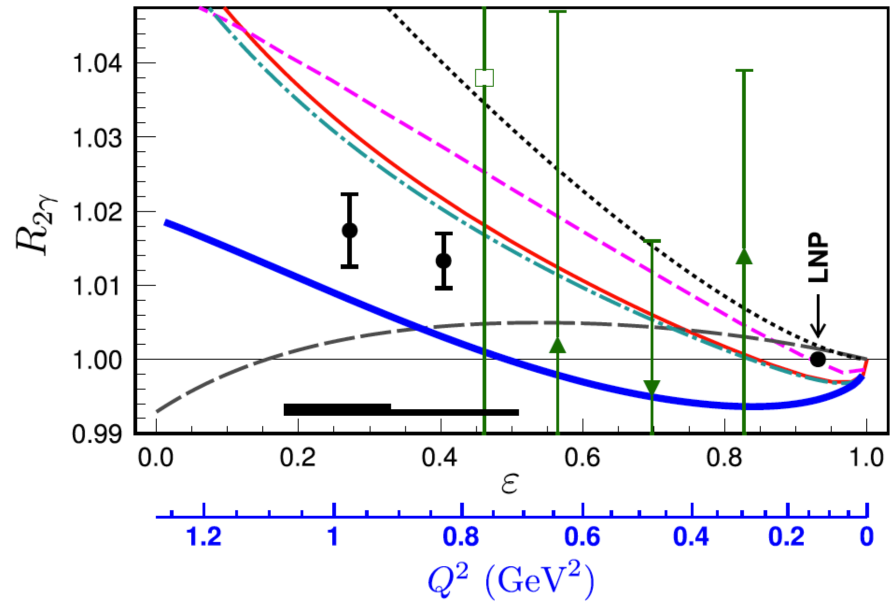
	VEPP–3 Novosibirsk	OLYMPUS DESY	EG5 CLAS JLab
beam energy	2 fixed	1 fixed	wide spectrum
equality of $e^\pm$ beam energy	measured	measured	reconstructed
e^+/e^- swapping frequency	half-hour	24 hours	simultaneously
e^+/e^- lumi monitor	elastic low-Q^2	elastic low-Q^2, Möller/Bhabha	from simulation
energy 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	PRL accepted 2016	2015

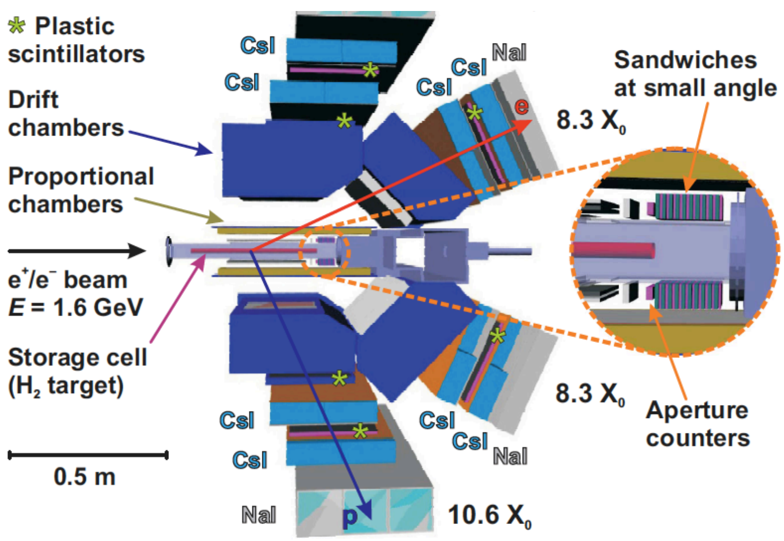
TPE experiments: Novosibirsk/VEPP-3

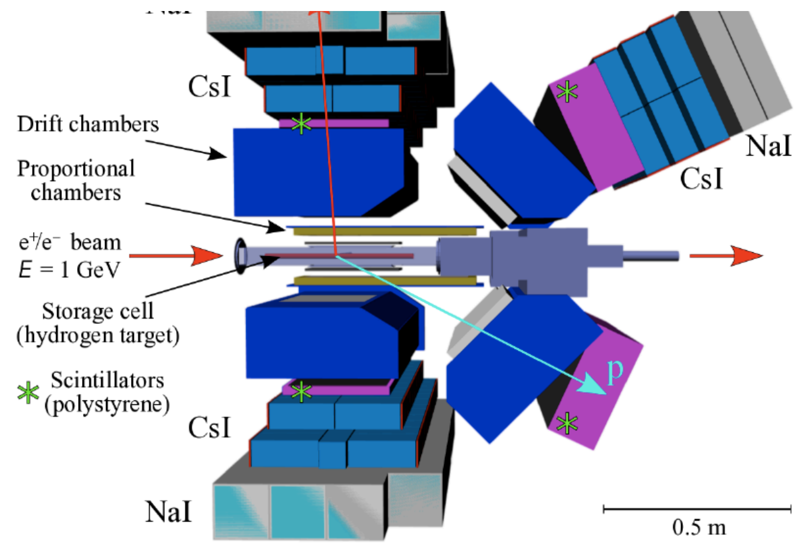
Run I (2009)
E=1.6 GeV



Run II (2011/12)
E=1.0 GeV

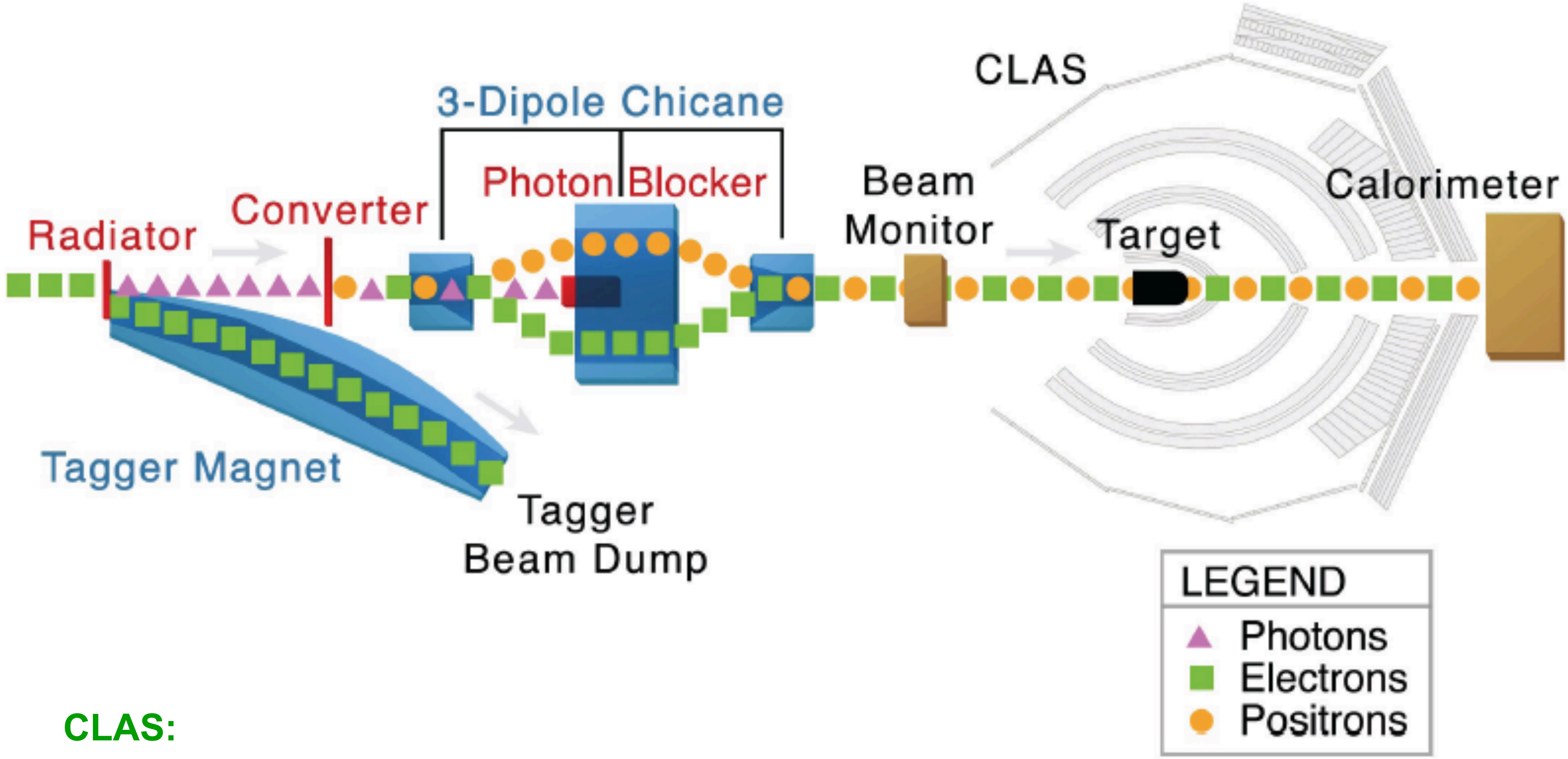






I.A. Rachek *et al.*, PRL 114, 062005 (2015)

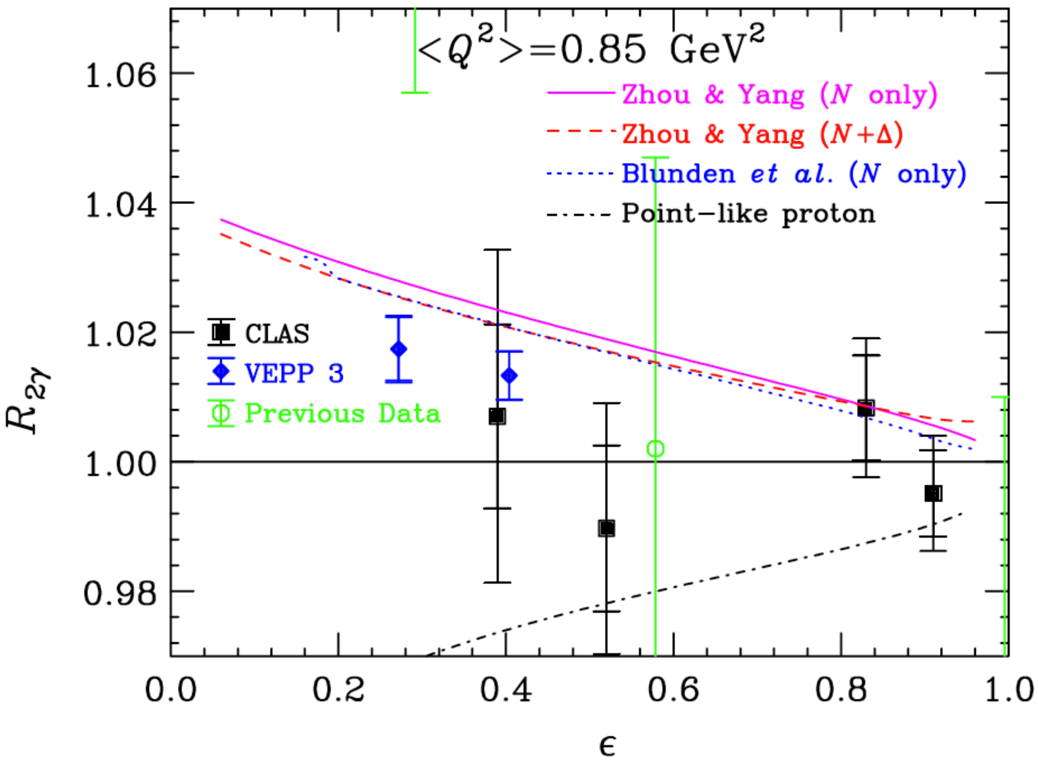
TPE experiments: CLAS (E04-116)

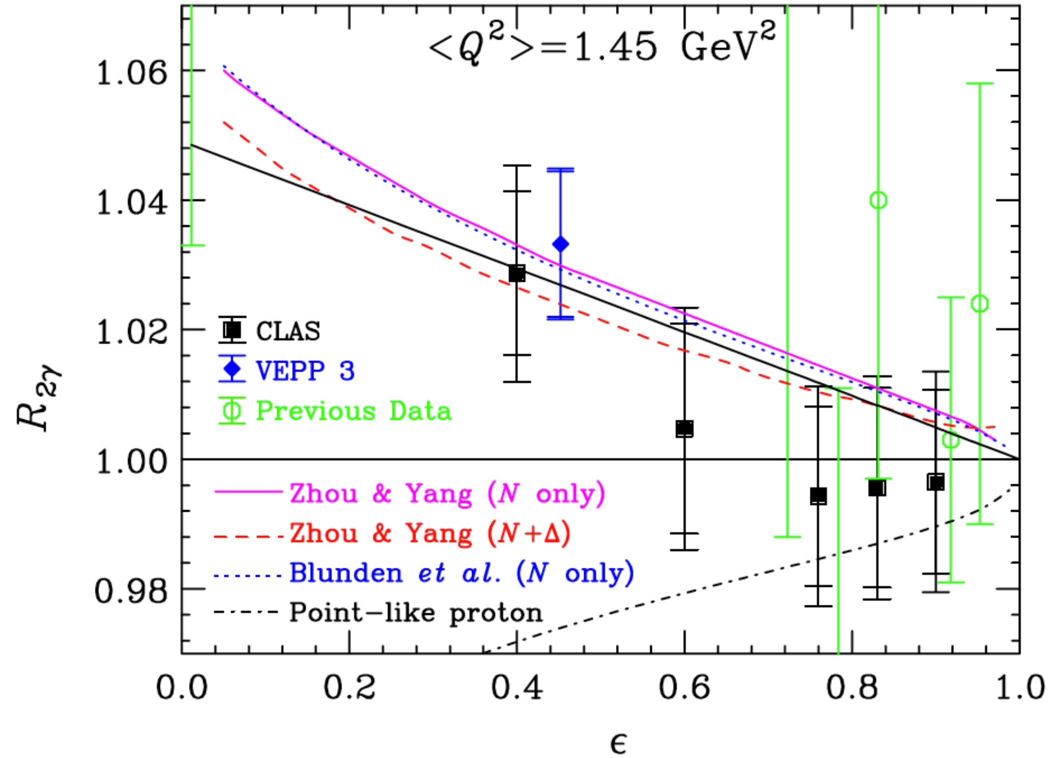


CLAS:
D. Rimal *et al.*, arXiv:1603.00315v1
D. Adikaram *et al.,* PRL 114, 062003 (2015)

TPE experiments: CLAS (E04-116)

ε dependence





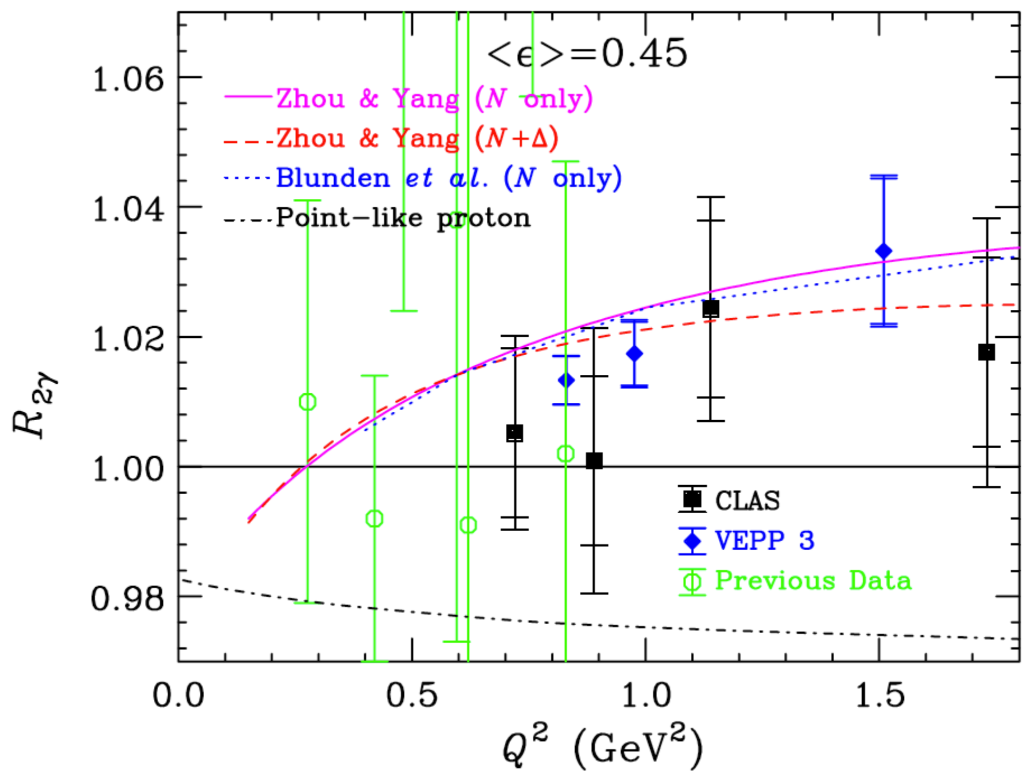
CLAS:
D. Rimal *et al.*, arXiv:1603.00315v1
D. Adikaram *et al.*, PRL 114, 062003 (2015)

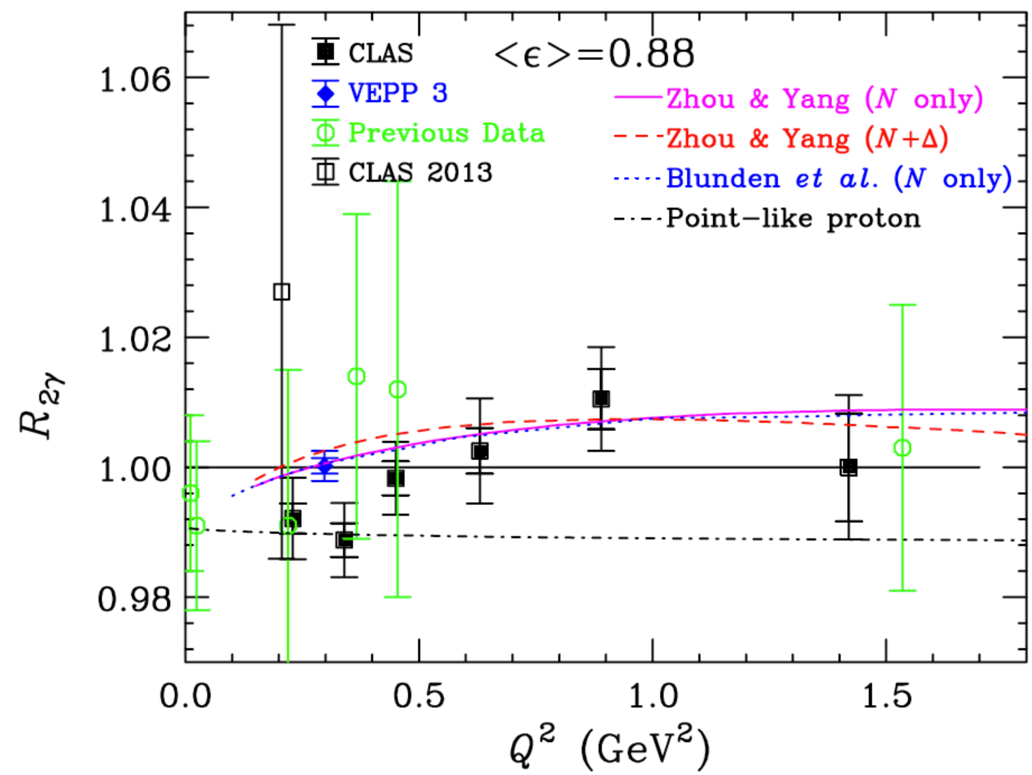
VEPP-3:
I.A. Rachek *et al.*, PRL 114, 062005 (2015)

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

TPE experiments: CLAS (E04-116)

Q² dependence





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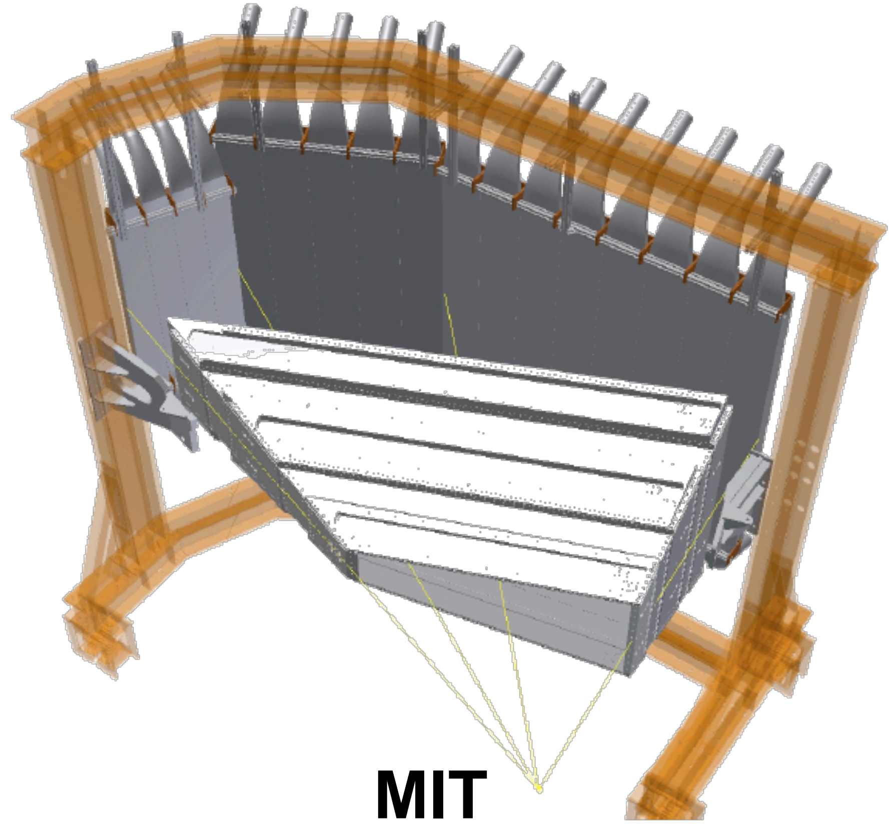
VEPP-3:
I.A. Rachek *et al.*, PRL 114, 062005 (2015)

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

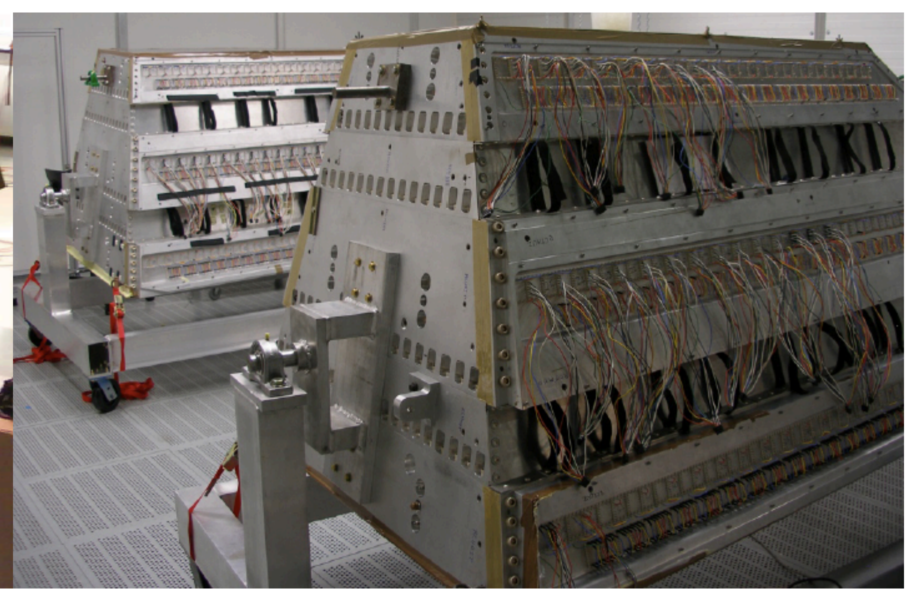
Wire chambers and TOF scintillators

- 2x18 TOFs for PID, timing and trigger
- 2 WCs for PID and tracking (z,θ,φ,p)
- WC and TOF refurbished from BLAST
  WC re-wired at DESY
  TOF rewrapped, efficiency tested
- Installed in OLYMPUS Apr-May 2011
- Stable operation



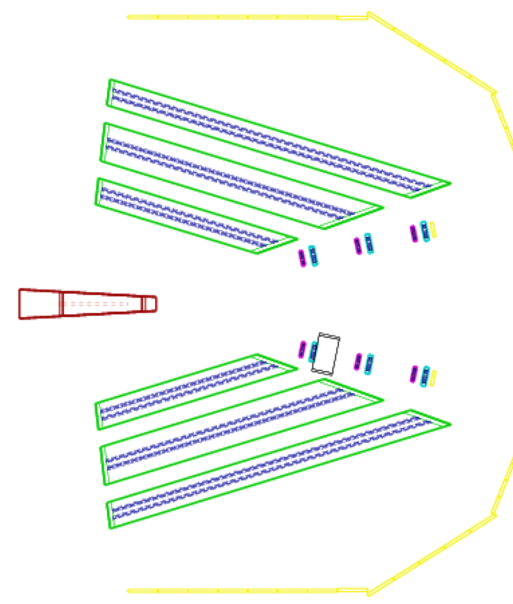
Glasgow, Yerevan, UNH, ASU

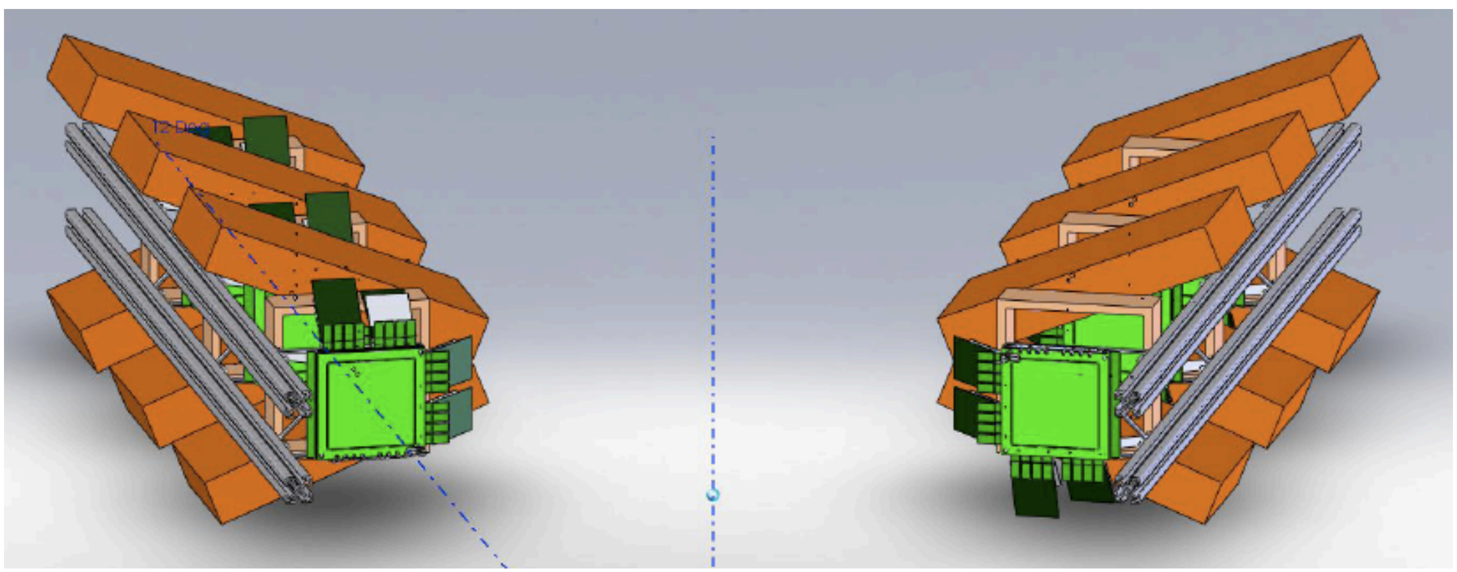
MIT



Luminosity monitors: GEM + MWPC

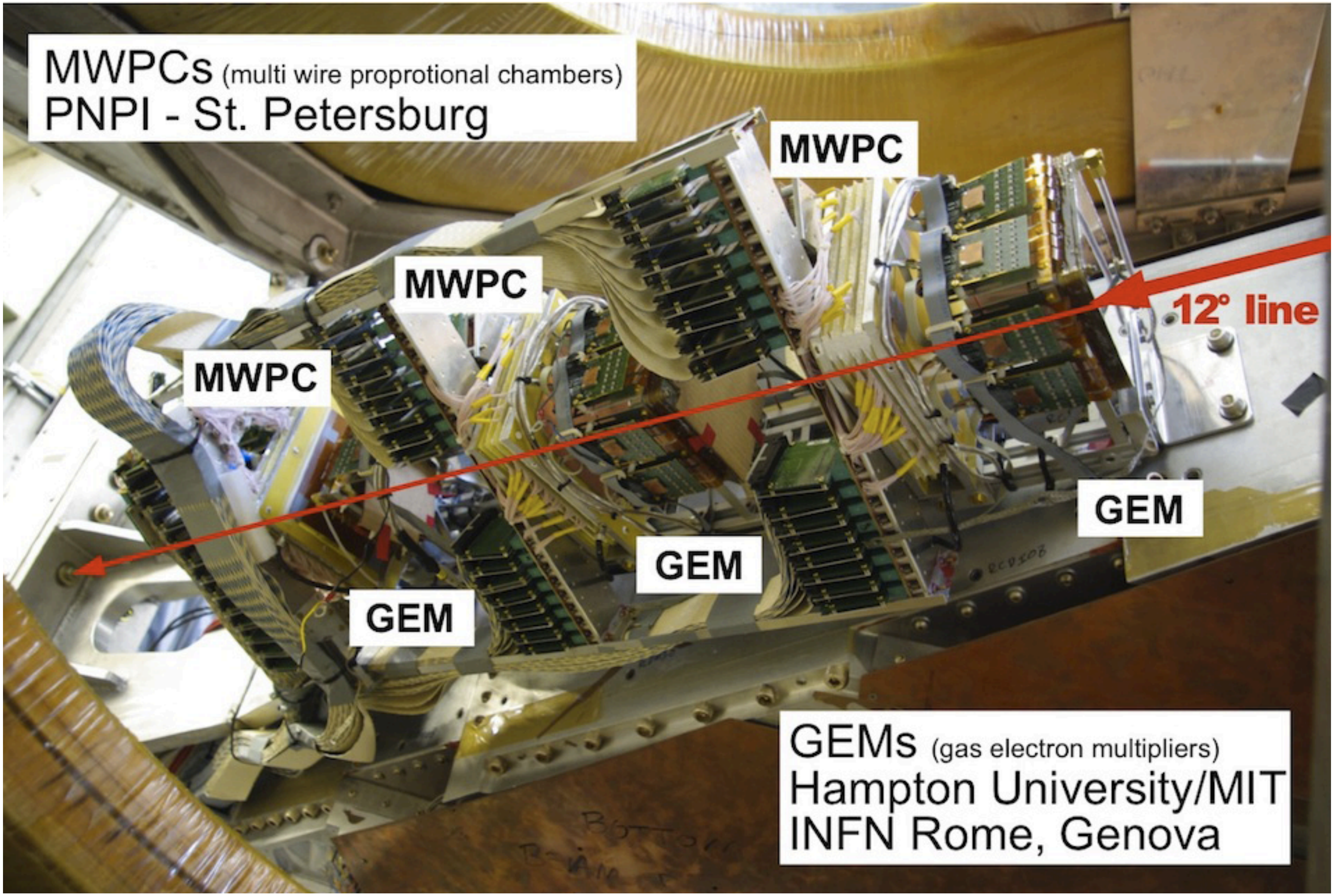
- Forward elastic scattering of lepton at 12°
  in coincidence with proton in main detector
- Two GEM + MWPC telescopes with
  interleaved elements operated independently
- SiPM scintillators for triggering and timing
- Sub-percent (relative) luminosity measurement
  per hour at 2.0 GeV
- High redundancy – alignment, efficiency
  Two independent groups (Hampton/INFN, PNPI)





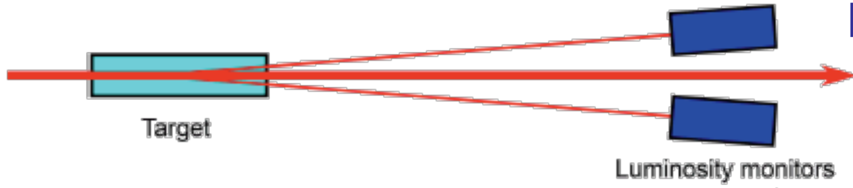
Designed to fit into forward cone

Luminosity monitors: GEM + MWPC

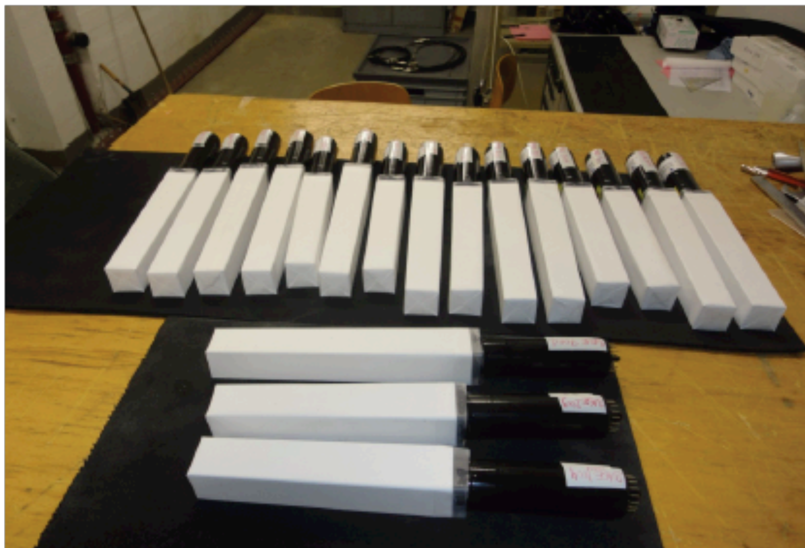


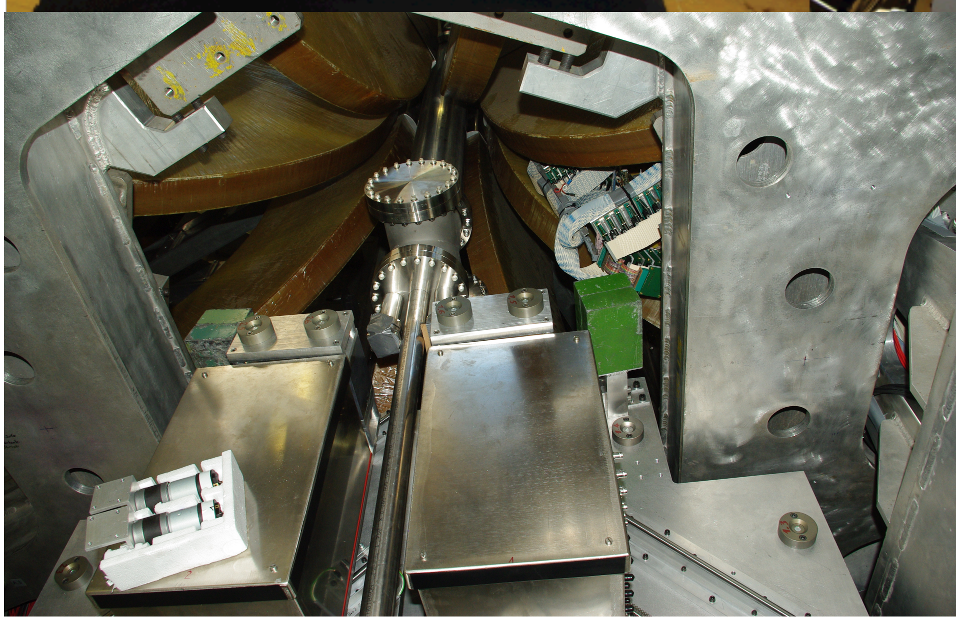
Telescopes of three GEMs and MWPCs interleaved
Mounted on wire chamber forward end plate
Extensively tested at DESY test beam facility

Symmetric Møller/Bhabha monitor



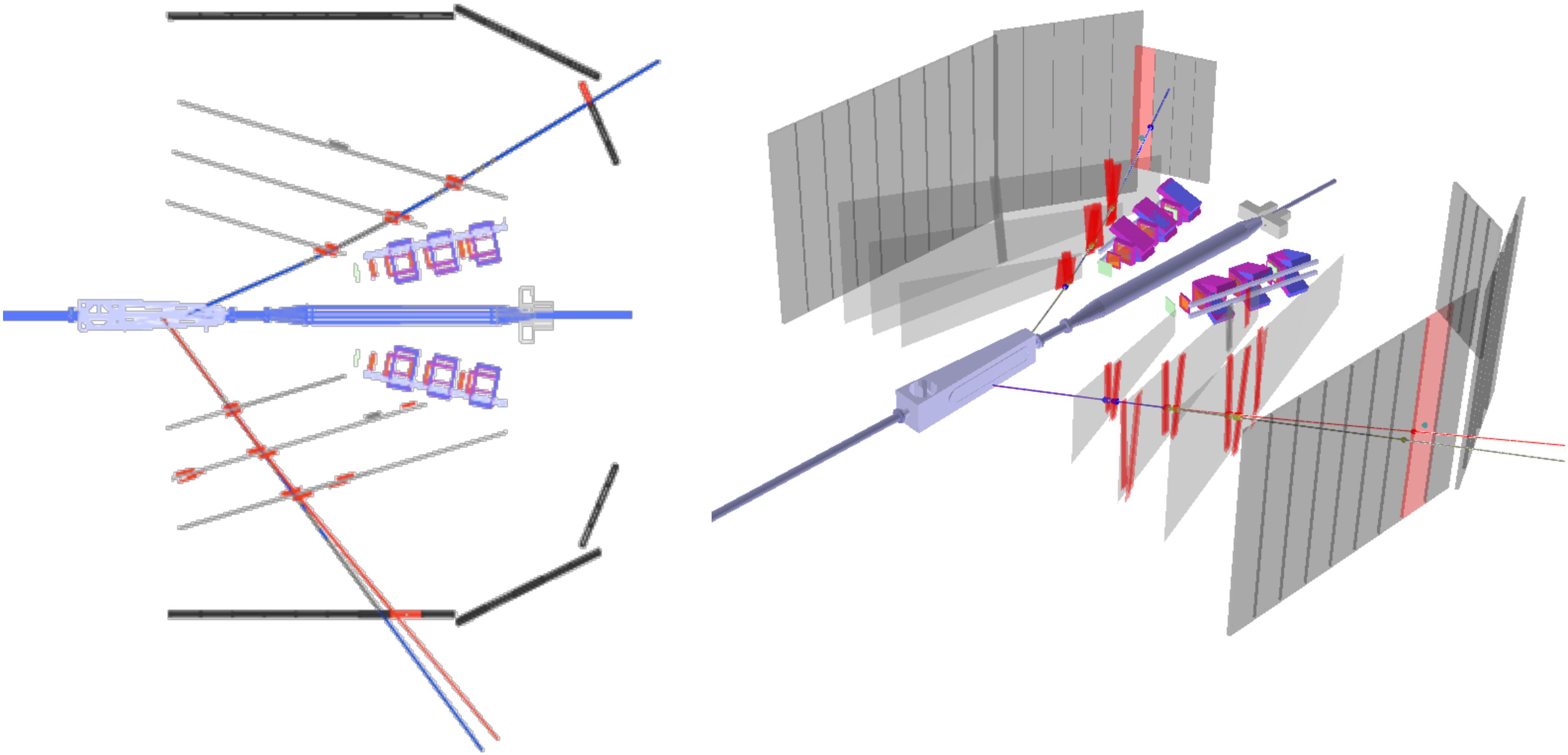
Mainz University





- **Symm. angle 1.3° @ 2.0 GeV**
- **Matrix of 3x3 PbF_2 crystals**
- **Tested at DESY and MAMI**

Event display (3D)

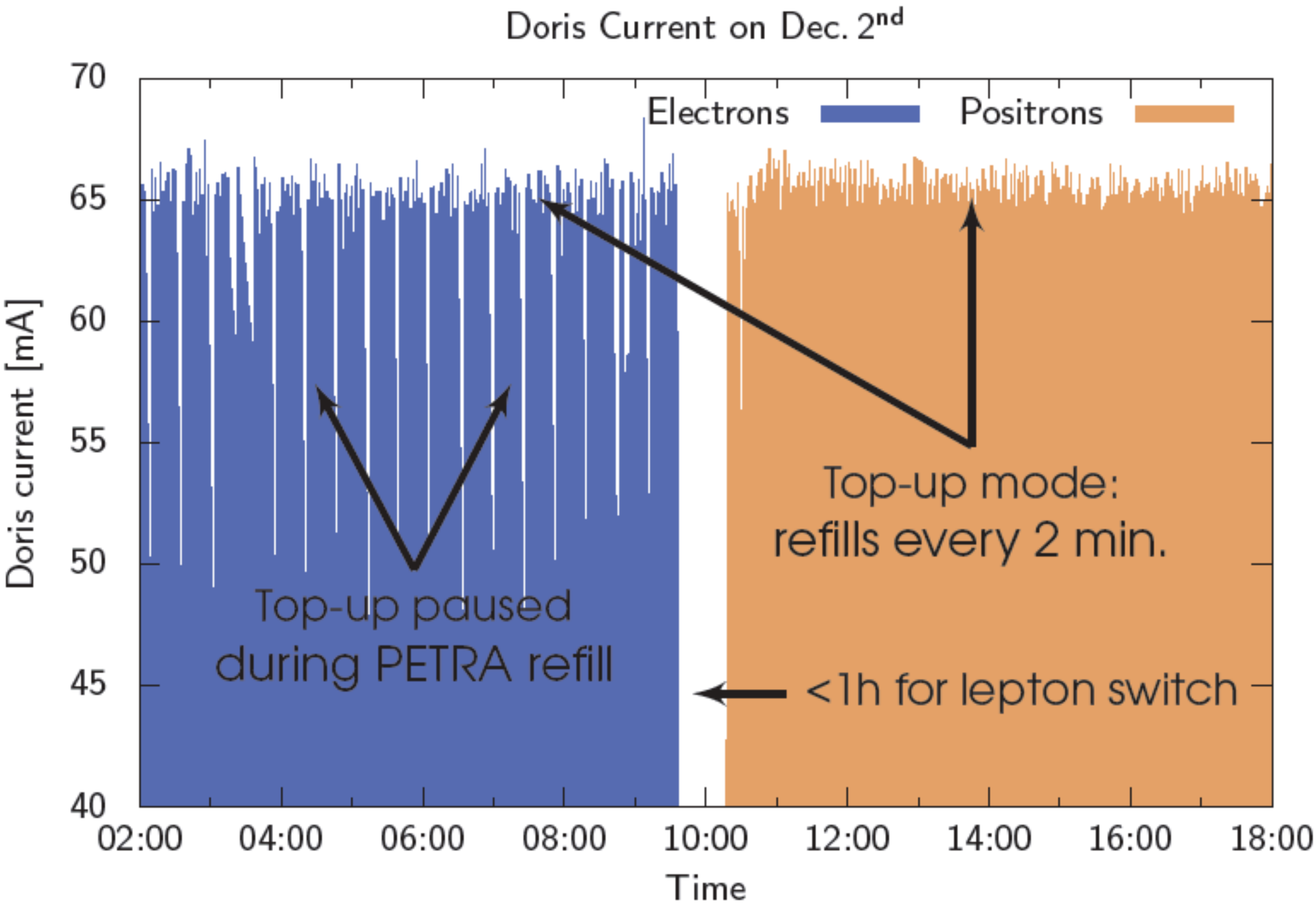


Run 4975, event 78

C. O'Connor (MIT)

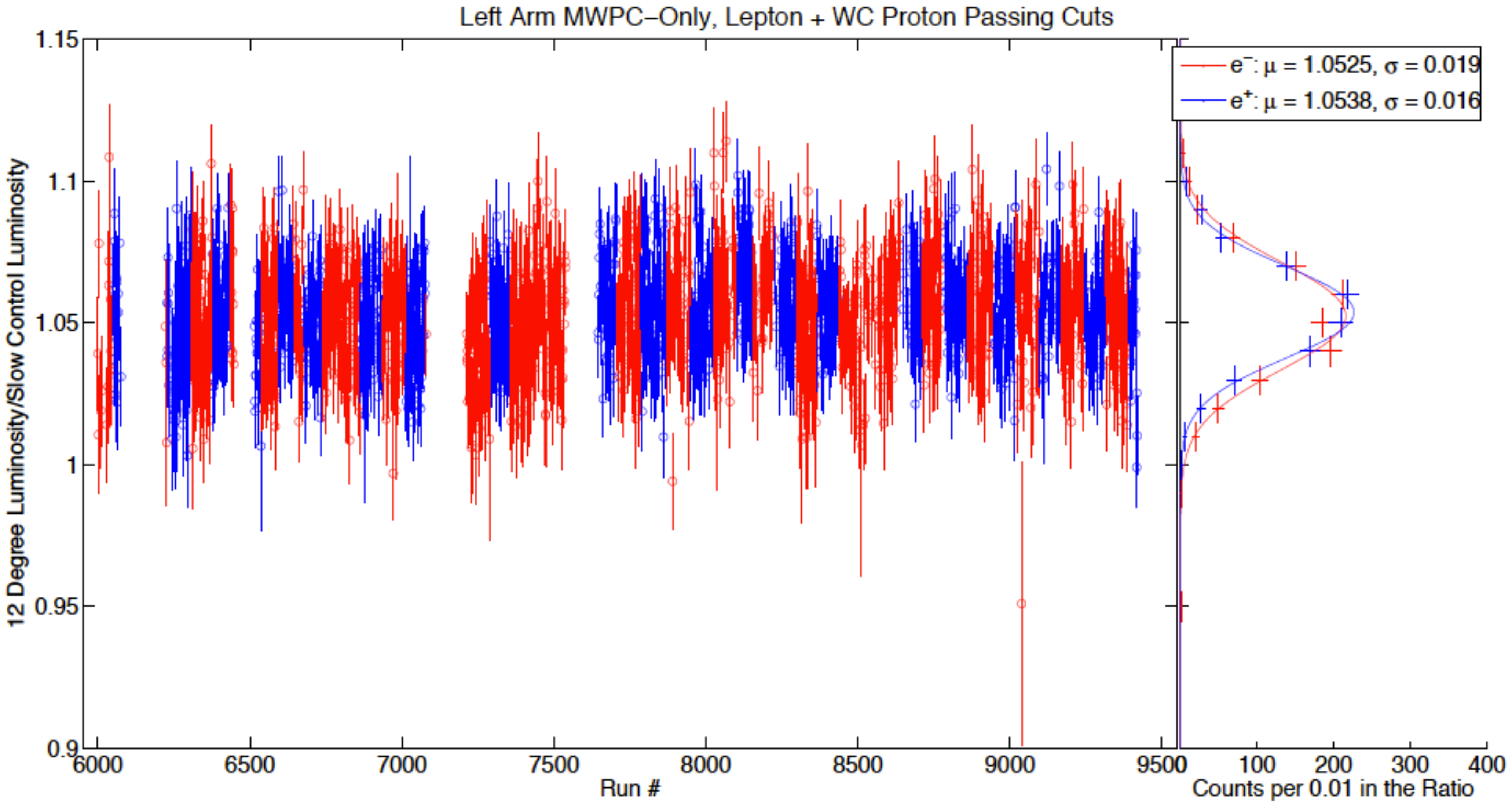
Performance of DORIS

- DORIS top-up mode established
- Typically 65mA / 0.5 sccm
- Refills every ~2 minutes by few mA
- PETRA refills every 30 minutes



Luminosity monitoring

12DEG-L / SC

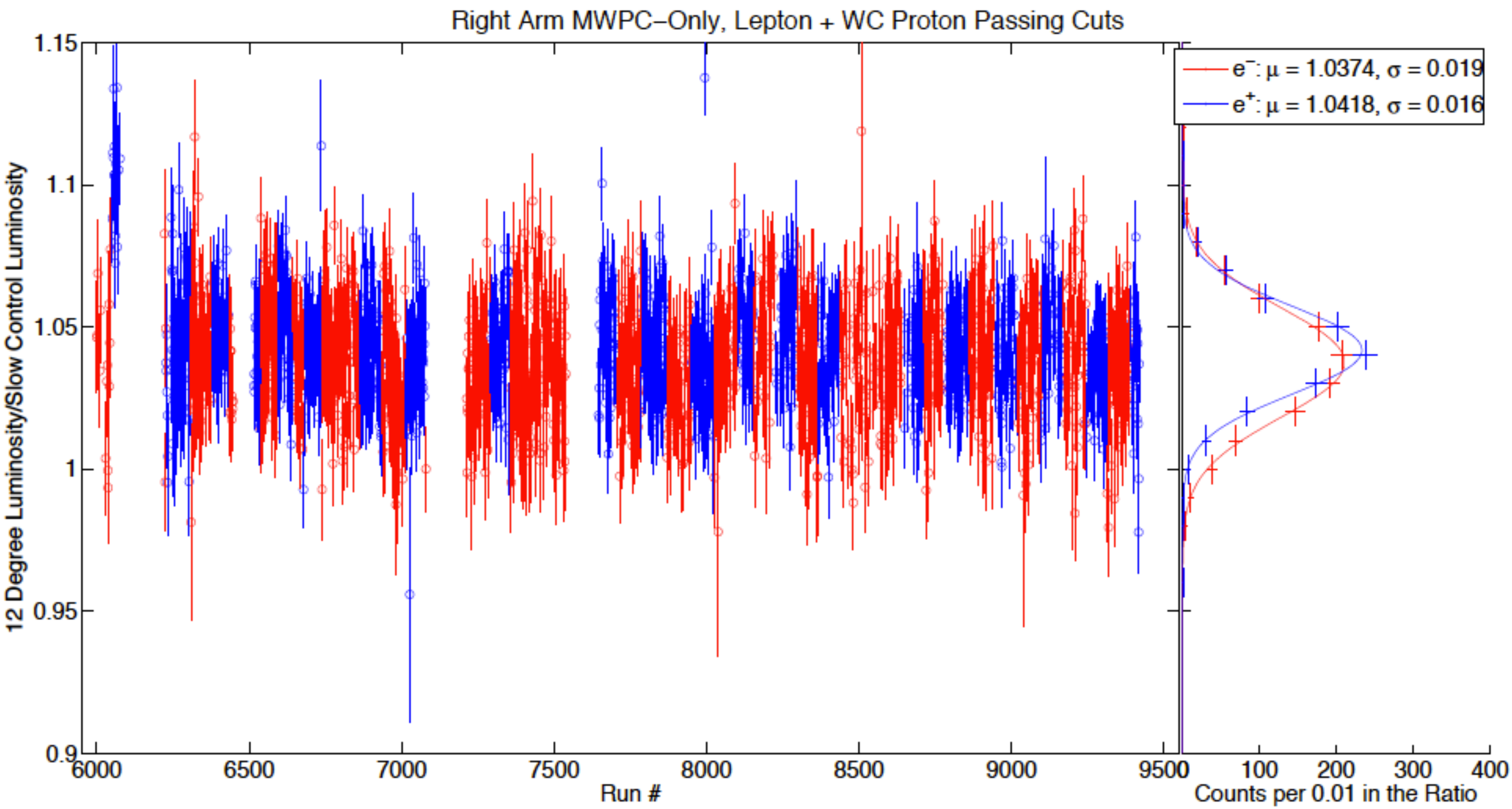


B. Henderson (MIT)

Luminosity monitoring

OLYMPUS

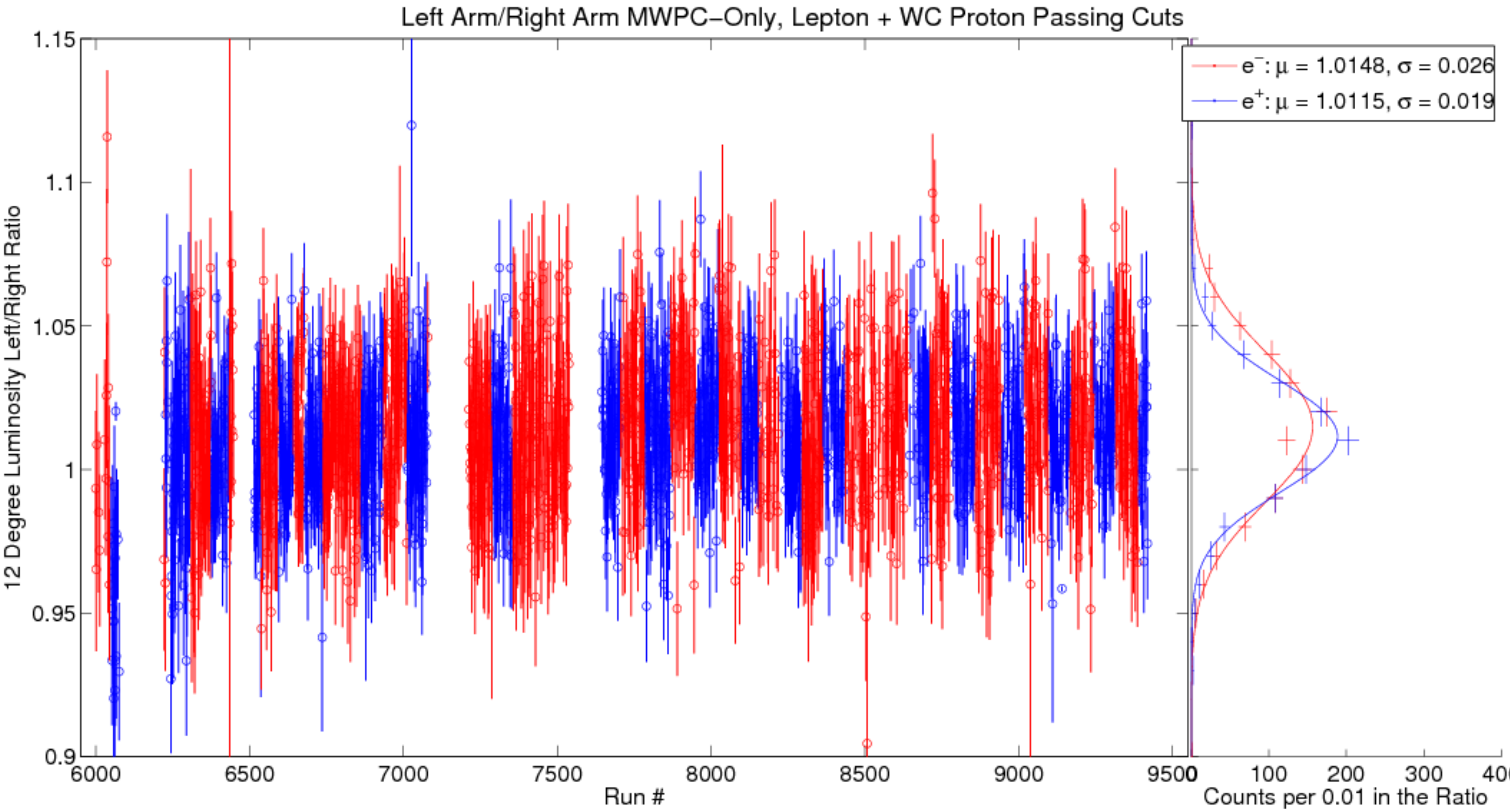
12DEG-R / SC



B. Henderson (MIT)

Luminosity monitoring

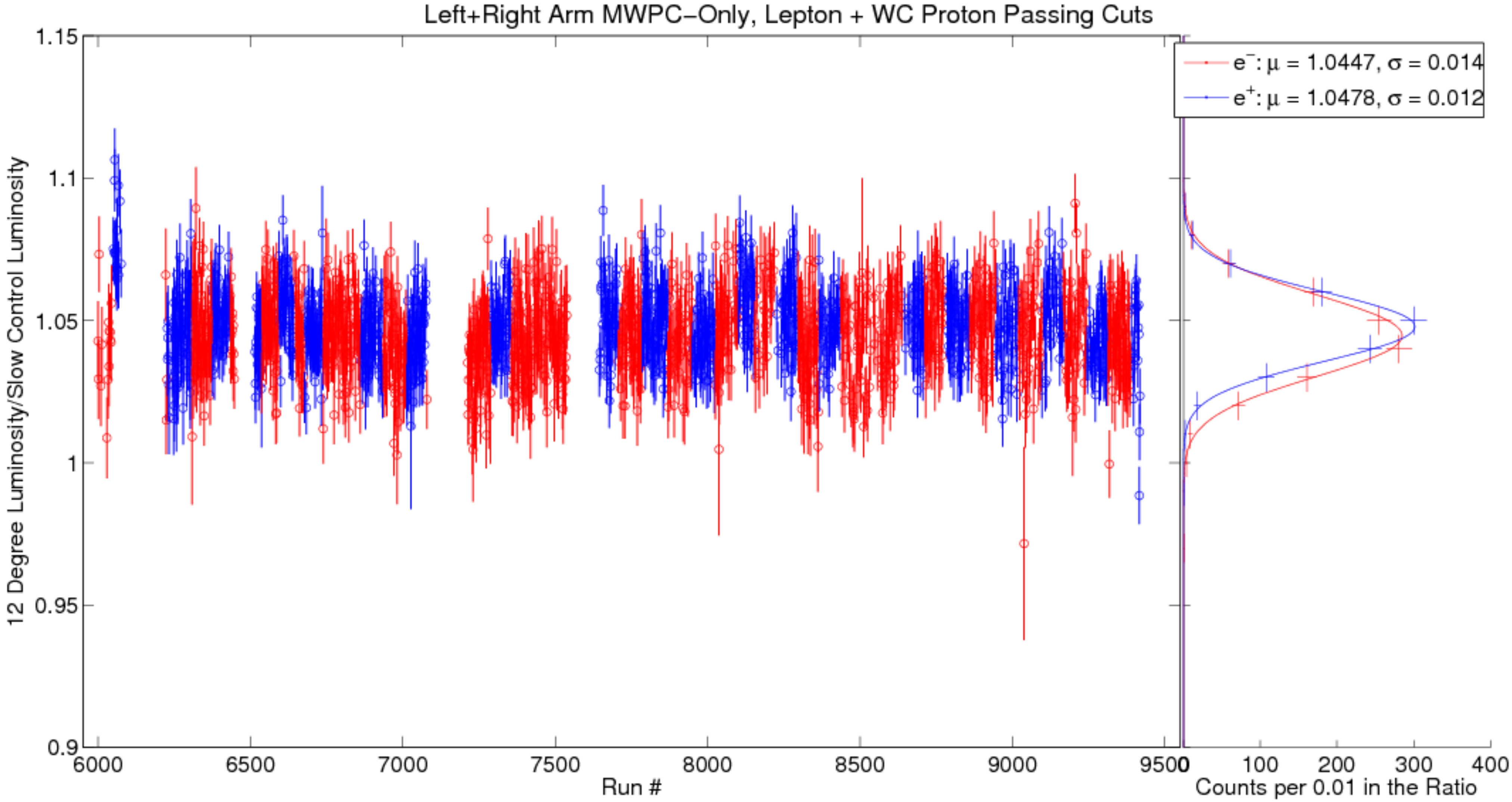
12DEG-L / R



B. Henderson (MIT)

Luminosity monitoring

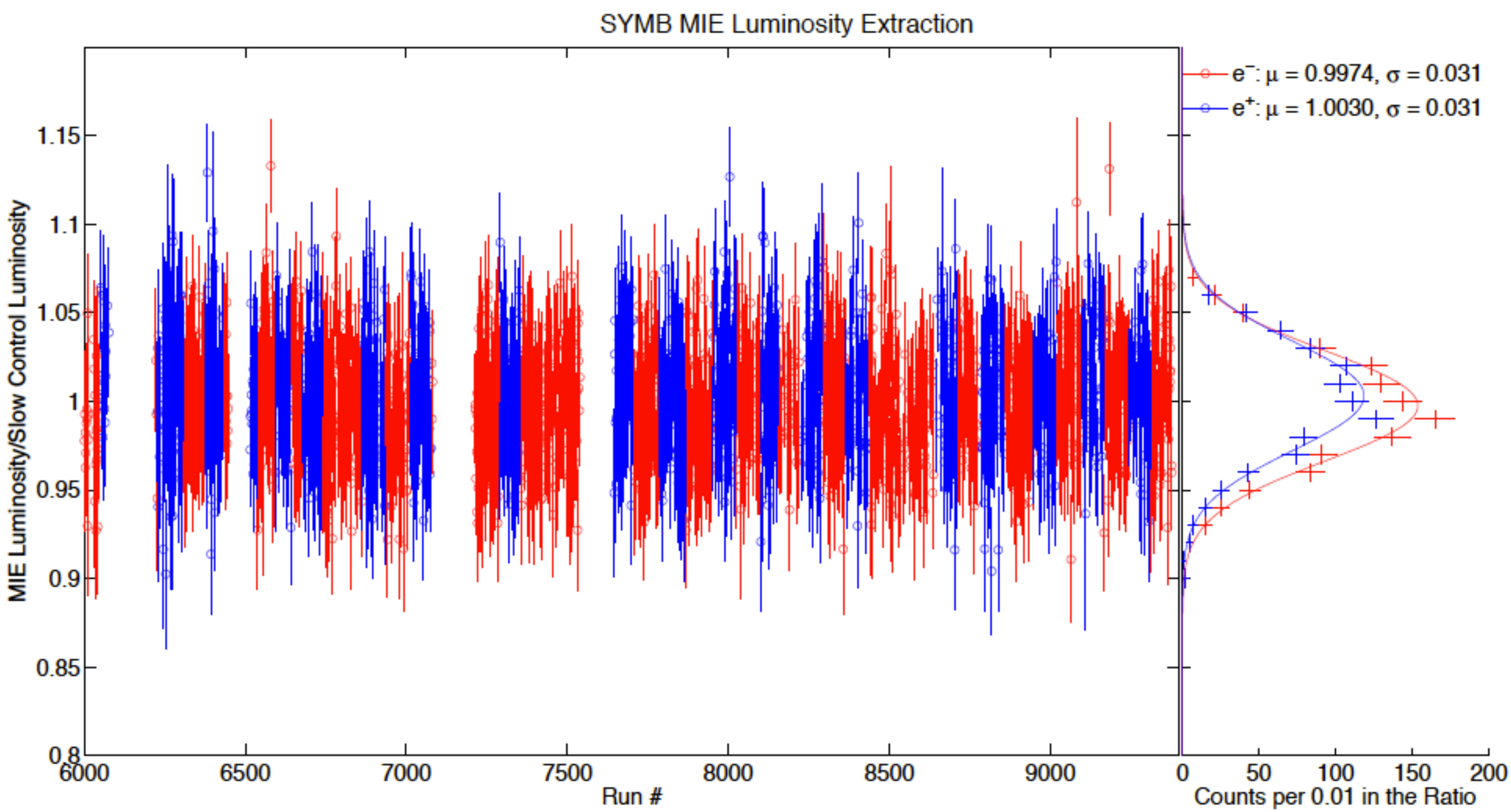
12DEG L+R / SC



B. Henderson (MIT)

Luminosity monitoring

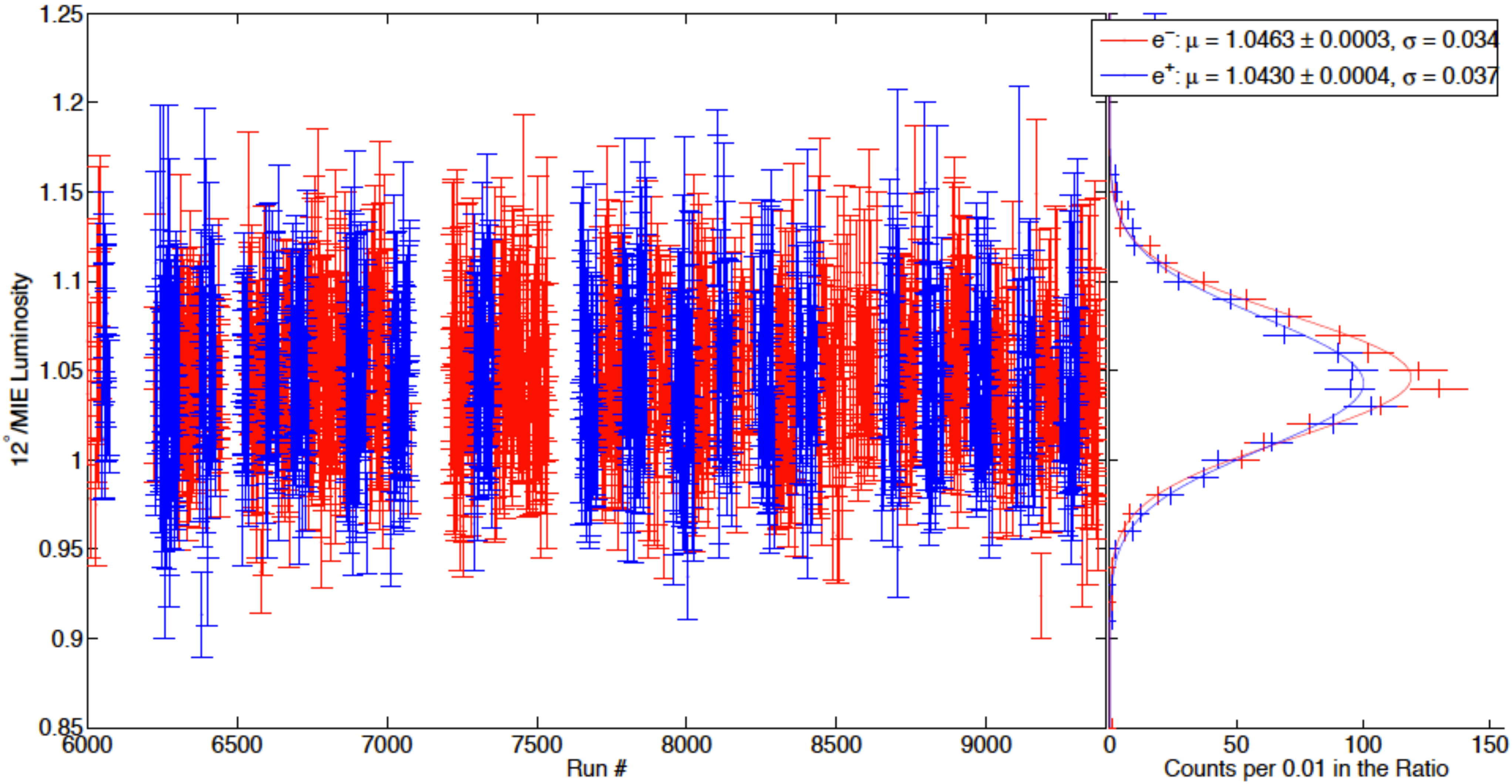
MIE / SC



A. Schmidt, B. Henderson (MIT)

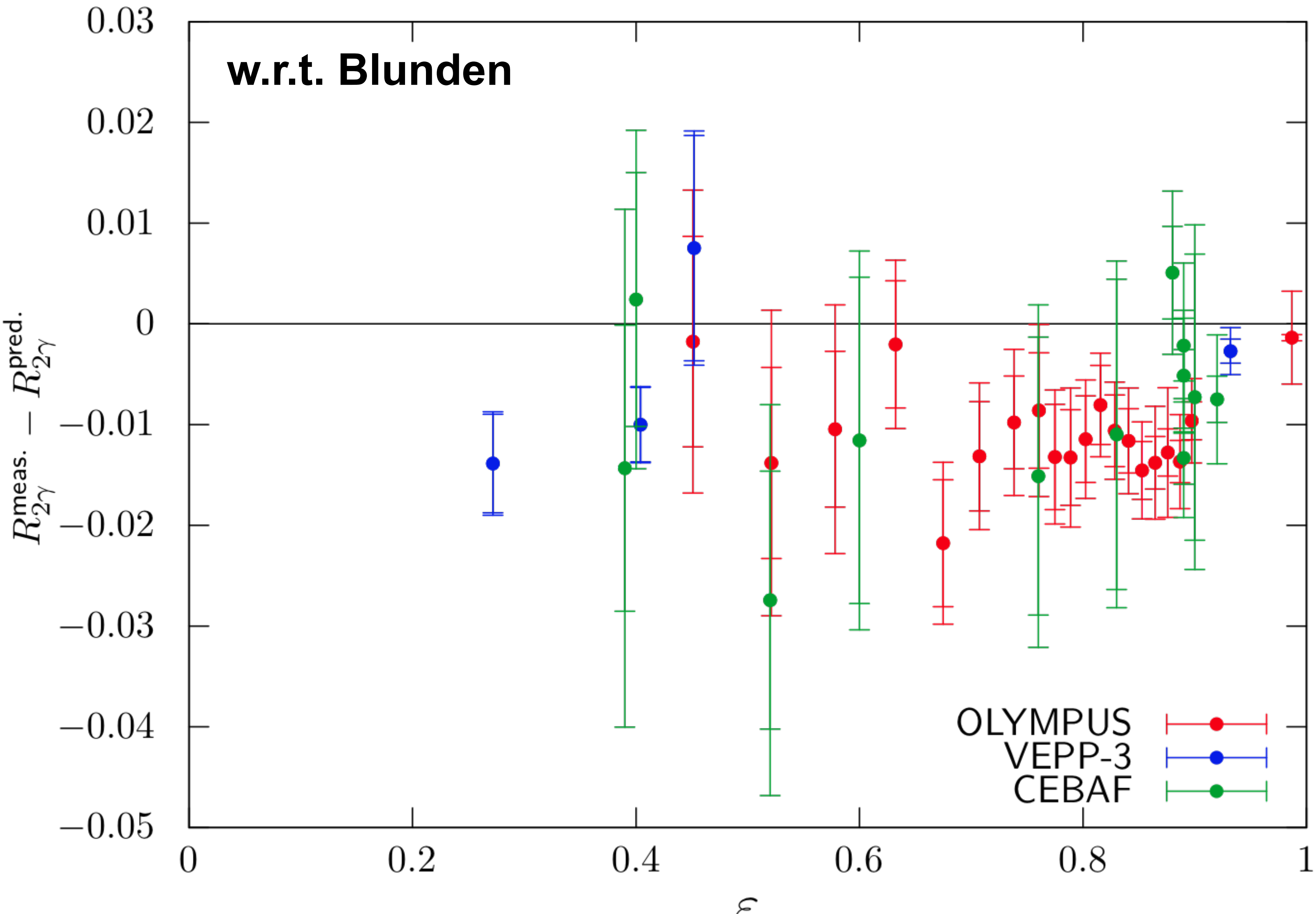
Luminosity monitoring

12DEG / MIE



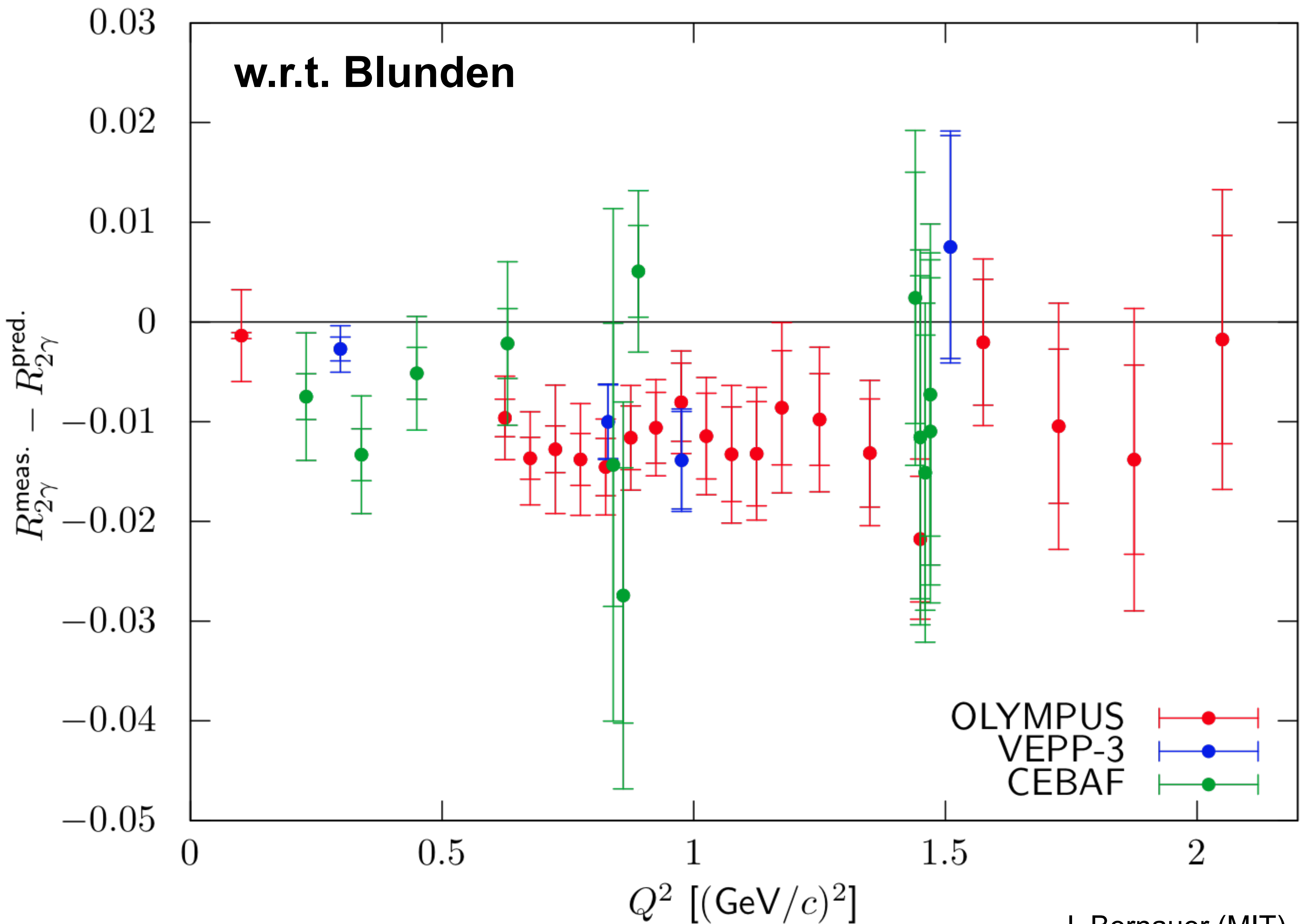
A. Schmidt, B. Henderson (MIT)

Comparison with VEPP-3 and CLAS



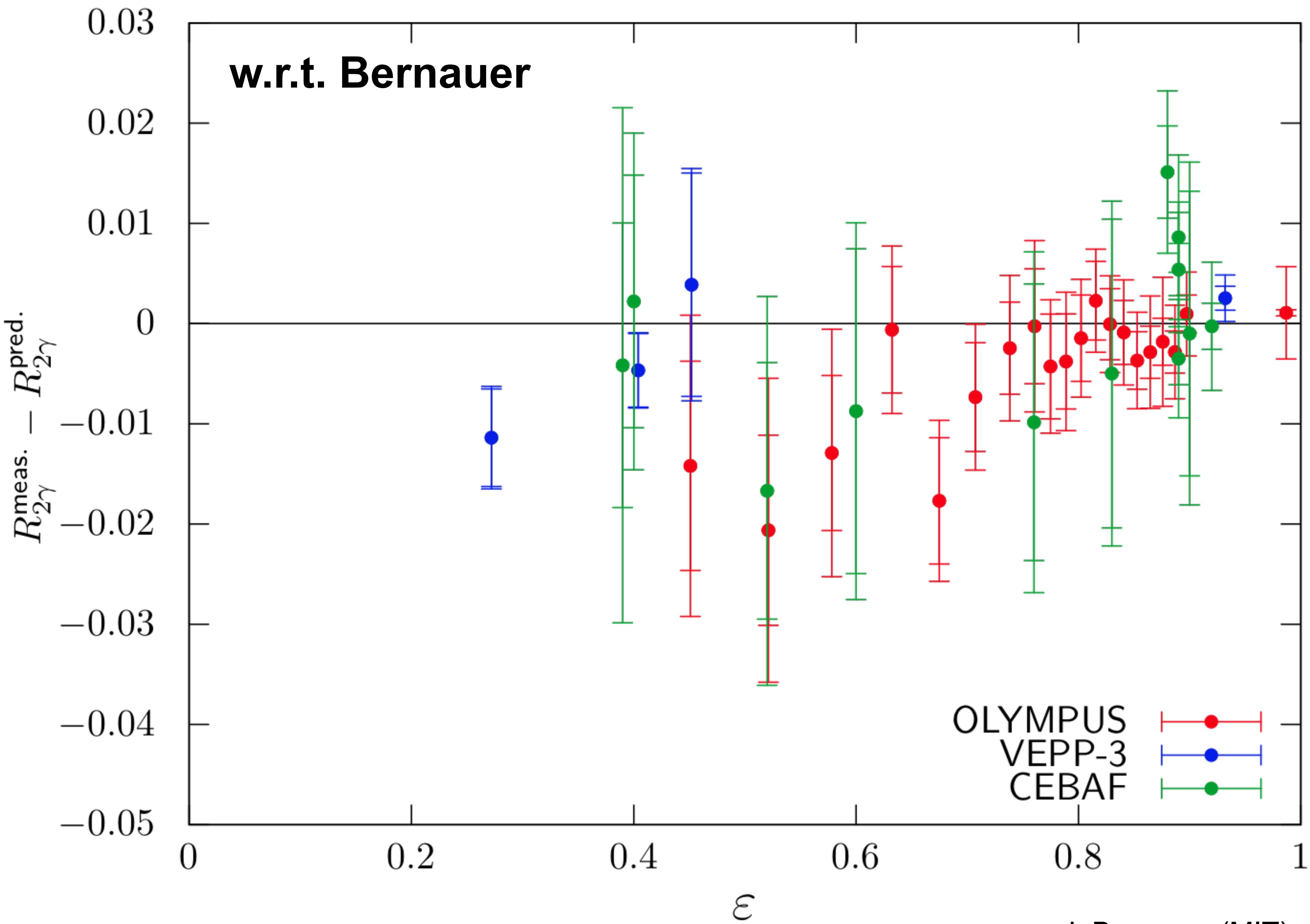
J. Bernauer (MIT)

Comparison with VEPP-3 and CLAS



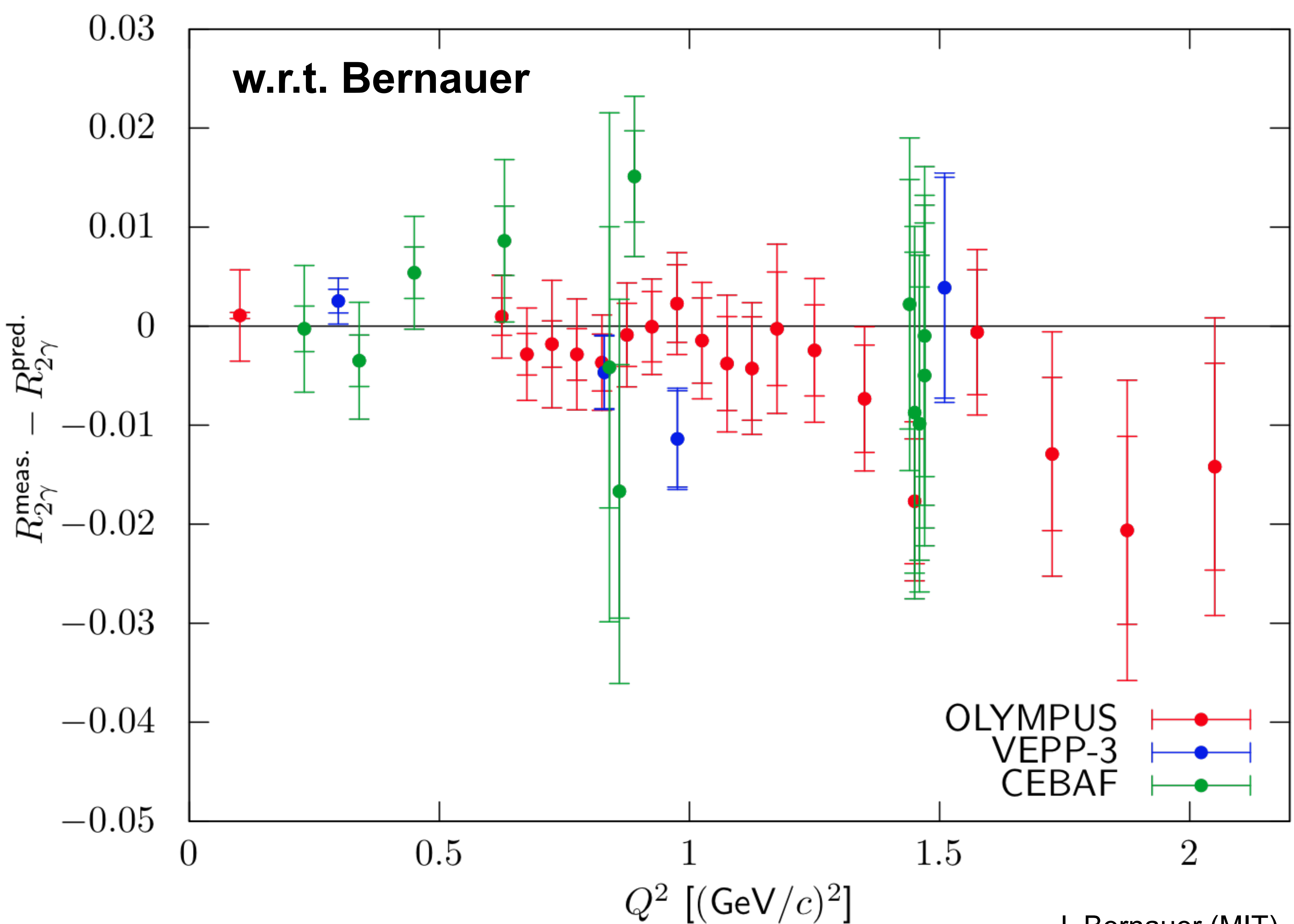
J. Bernauer (MIT)

Comparison with VEPP-3 and CLAS



J. Bernauer (MIT)

Comparison with VEPP-3 and CLAS

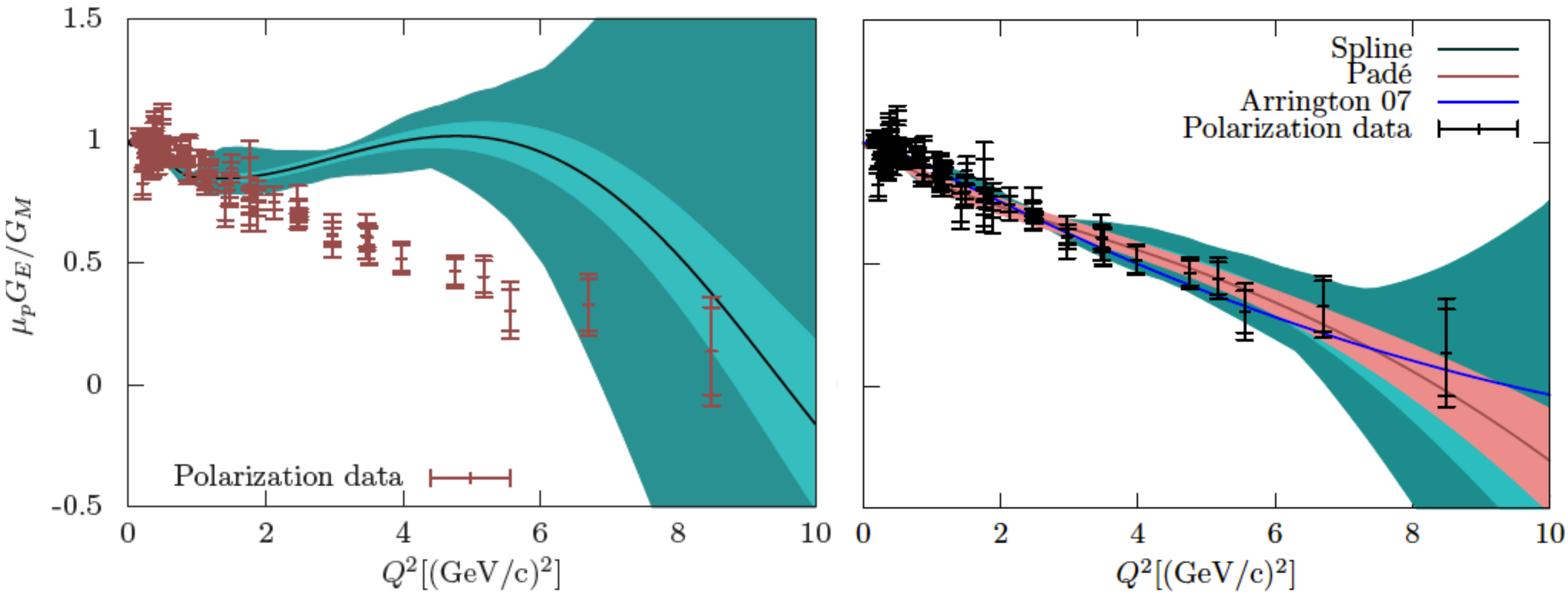


J. Bernauer (MIT)

Global analysis

Fit to unpolarized data

Fit including polarized data + TPE parameterization



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