OLYMPUS

DESY PRC

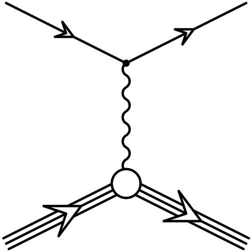
D.K. Hasell for the OLYMPUS Collaboration

March 21, 2017

Nucleon Form Factors

One photon exchange approximation

$$\gamma^{\mu} F_1^N(Q^2) + i\sigma^{\mu\nu} q_{\nu} \frac{\kappa}{2M} F_2^N(Q^2)$$



Electric and magnetic form factors

$$G_E^N(Q^2) = F_1^N(Q^2) - \tau\kappa F_2^N(Q^2)$$

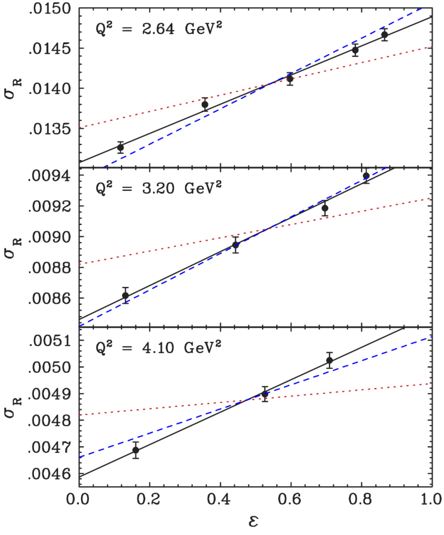
$$G_M^N(Q^2) = F_1^N(Q^2) + \kappa F_2^N(Q^2)$$

Rosenbluth cross section

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} \left[\left(\frac{G_E^{N\,2} + \tau G_M^{N\,2}}{1+\tau}\right) + 2\tau G_M^{N\,2} \tan^2\frac{\theta}{2}\right] \qquad \tau = \frac{Q^2}{4M_N^2}$$

$$\left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{\tau G_M^{N\,2} + \epsilon G_E^{N\,2}}{\epsilon(1+\tau)} \qquad \epsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta}{2}\right)^{-1}$$

Measuring Form Factors - Rosenbluth Technique



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

$$\sigma_R = \epsilon(1+\tau)\left(\frac{d\sigma}{d\Omega}\right) / \left(\frac{d\sigma}{d\Omega}\right)_{Mott} = \tau G_M^{N\,2} + \epsilon G_E^{N\,2}$$

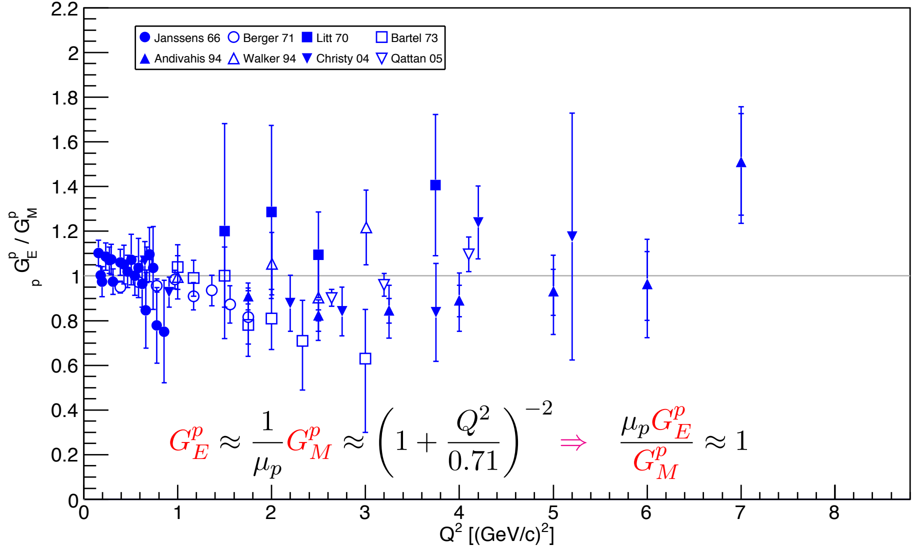
Vary E and θ to measure σ_R at different ϵ but same Q^2 and plot:

- Slope $\rightarrow$ $G_E^{N\,2}$
- Intercept $\rightarrow$ $G_M^{N\,2}$
- G_M^N dominates at high Q^2
- σ_R decreases quickly with Q^2

Blue dashed $\rightarrow$ FF ratio $= 1$

Red dotted $\rightarrow$ polarized measure

Form Factor Ratio $\mu_p G_E^p / G_M^p$ - Rosenbluth Technique



Measuring Form Factors - Polarized Techniques

In polarization transfer experiments $\vec{e}p \to e\vec{p}$

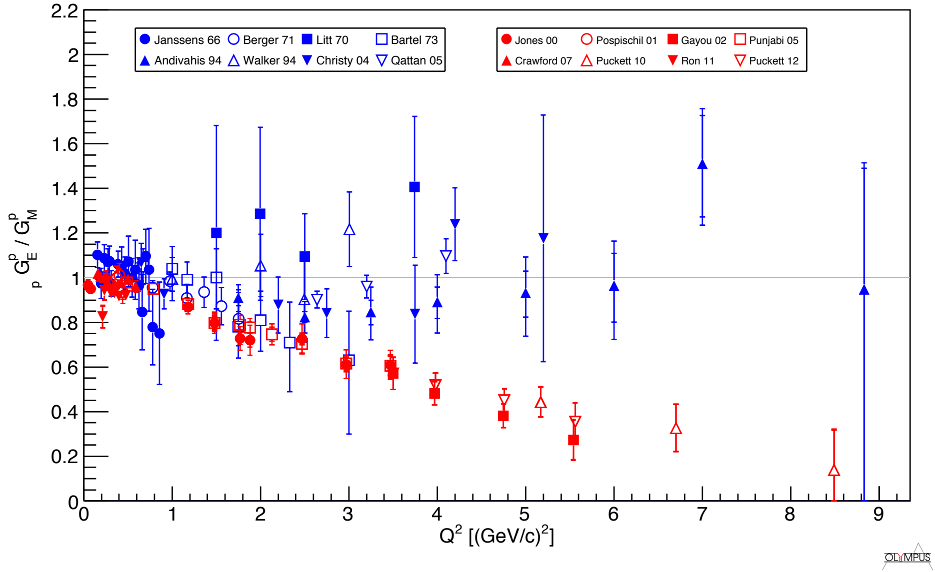
$$\mu_p \frac{G_E}{G_M} = -\mu_p \sqrt{\frac{\tau(1+\epsilon)}{2\epsilon}}\, \frac{P_T}{P_L} = -\mu_p \frac{E+E'}{2M_p} \tan\frac{\theta_e}{2}\, \frac{P_T}{P_L}$$

where P_T and P_L are the polarizations of the recoil proton.

This is a simpler and more accurate measurement for $\mu_p G_E/G_M$ particularly at higher Q^2

It is also possible to determine $\mu_p G_E/G_M$ from $\vec{e}\,\vec{p} \to e\,p$ by measuring the asymmetries (see Crawford 07).

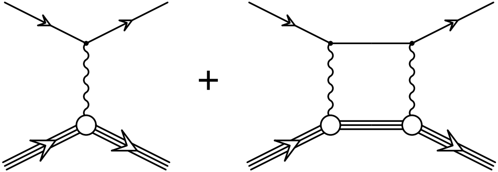
Discrepancy in Form Factor Ratio $\mu_p G_E^p / G_M^p$?



Proposed Explanation - Two Photon Exchange (TPE)

Thought to be a small effect

- suppressed by order α
- included (?) in radiative corrections

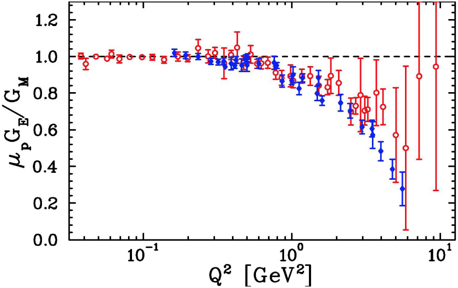


But hard TPE difficult

- intermediate p, Δ, ...

But calculations suggest it can resolve the discrepancy

Need a definitive experiment



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

Definitive Measure of Two-Photon Contribution

Measure $\sigma_{e^+p}/\sigma_{e^-p}$

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

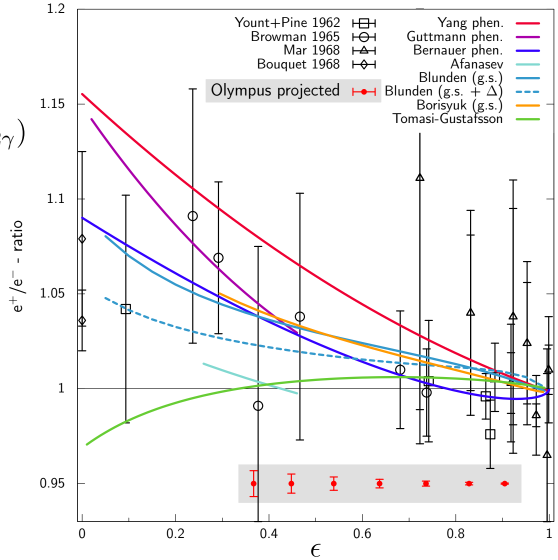
Existing data

- low Q^2
- large uncertainties

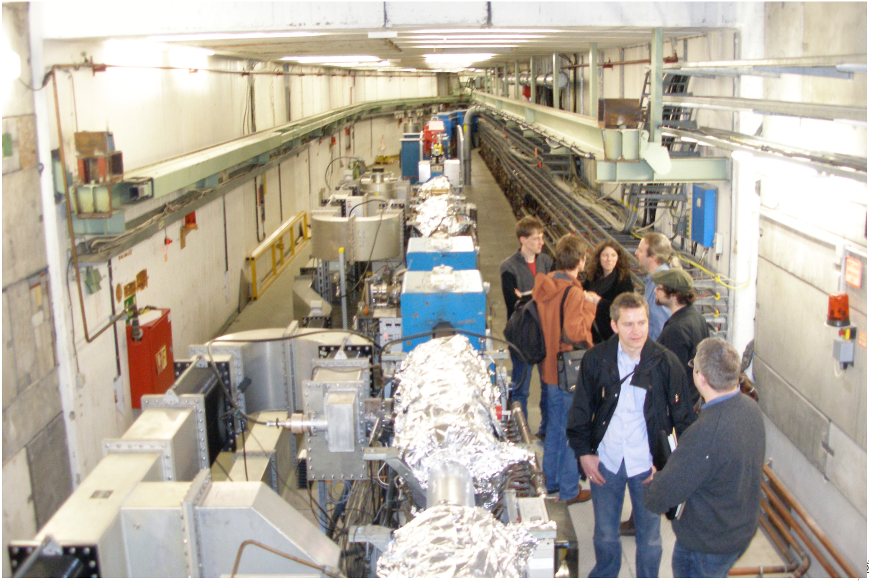
Various predictions

OLYMPUS Proposal

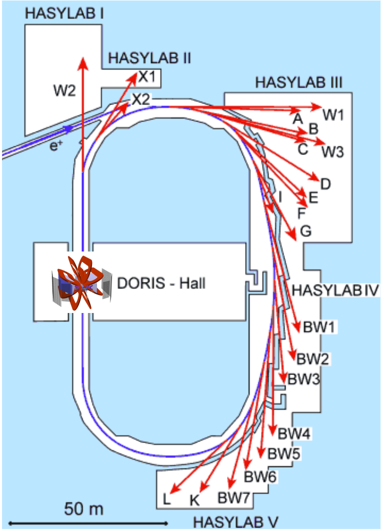
- expected precision



DORIS Before OLYMPUS



DORIS Ring



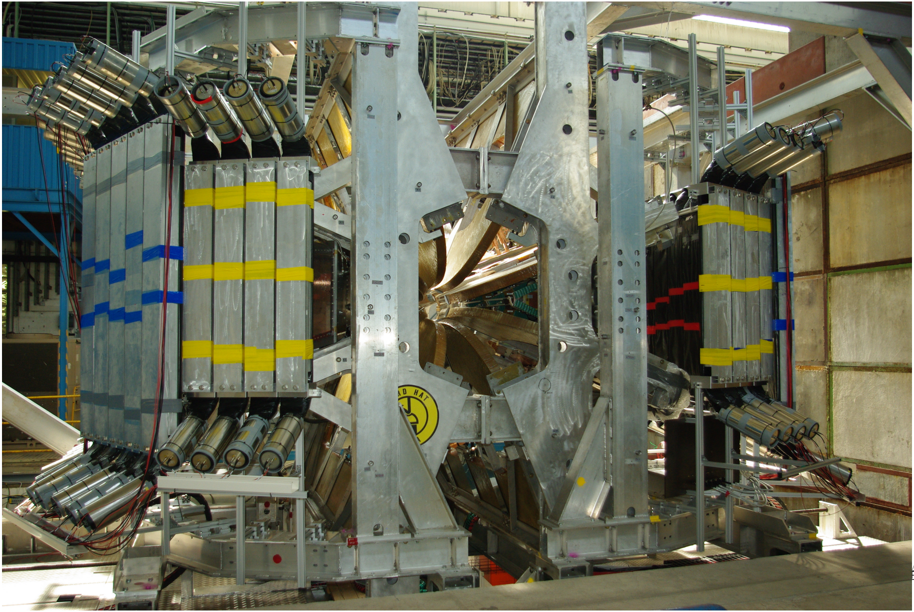
Extensive modifications to DORIS

- move RF cavities, ARGUS
- provide cooling water, power
- open pit, move shielding walls
- synchrotron radiation studies
- redo beam optics
- and much more

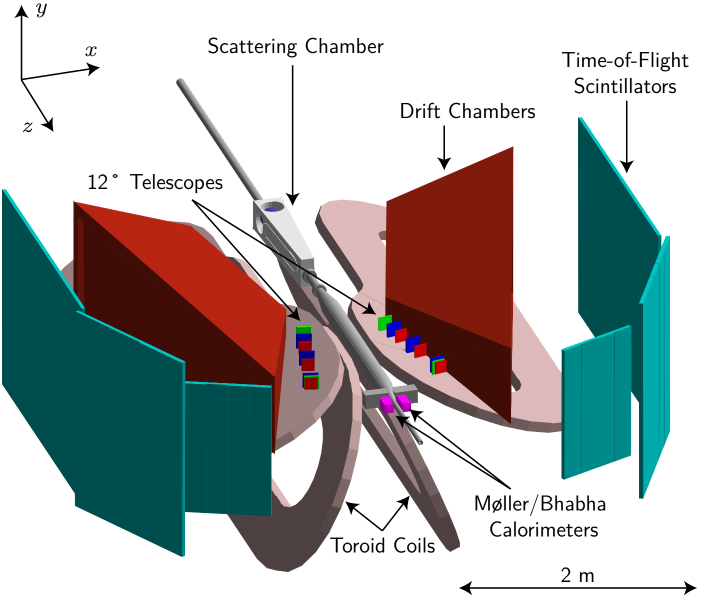
Great support from DESY !

- MEA, MKK
- DORIS operations
- Jan Hausschildt
- Frank Brinker

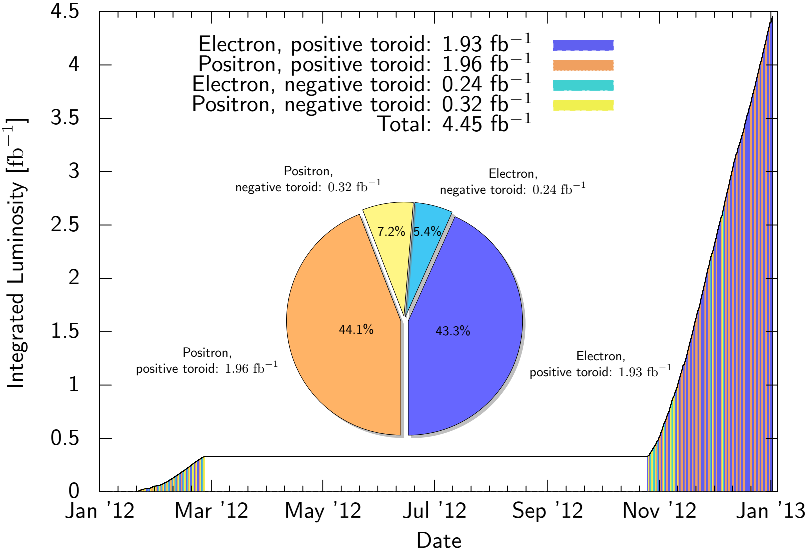
OLYMPUS Detector



Detector Overview



Luminosity



Electron, positive toroid: 1.93 fb^{-1}
Positron, positive toroid: 1.96 fb^{-1}
Electron, negative toroid: 0.24 fb^{-1}
Positron, negative toroid: 0.32 fb^{-1}
Total: 4.45 fb^{-1}
Positron, negative toroid: 0.32 fb^{-1}
Electron, negative toroid: 0.24 fb^{-1}
7.2%
5.4%
44.1%
43.3%
Positron, positive toroid: 1.96 fb^{-1}
Electron, positive toroid: 1.93 fb^{-1}
Integrated Luminosity [fb^{-1}]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Jan '12
Mar '12
May '12
Jul '12
Sep '12
Nov '12
Jan '13
Date

Luminosity

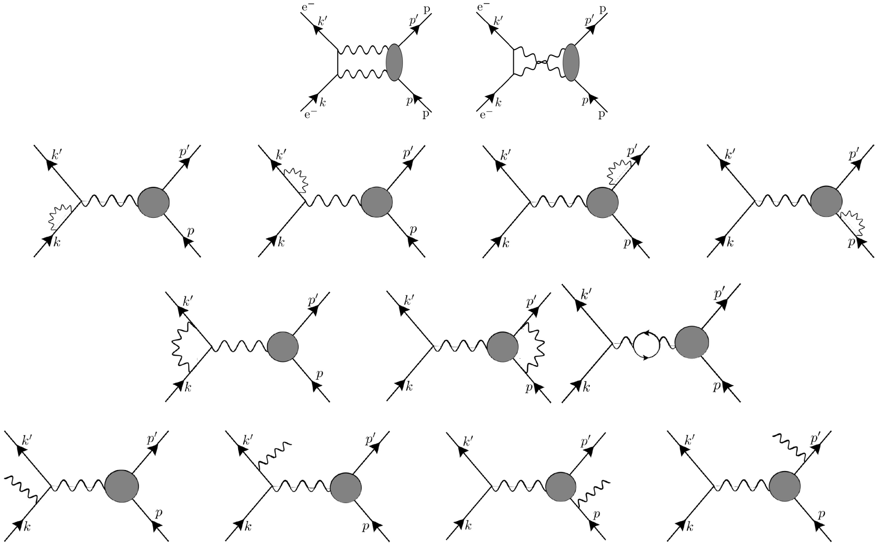
Three measures of luminosity are consistent:

- slow control using Brian's molecular flow calculation
  - 2 % between beam species, 5 % absolute
- 12° MWPC with coincident proton in WC
  - 0.46 % between beam species, 2.4 % absolute
- multi-interaction events $(e^{\pm}e \to e^{\pm}e) + (e^{\pm}p \to e^{\pm}p)$ in SYMB
  - 0.1 % statistical, 0.27 % systematic

Choose to use multi-interaction events, MIE, as the most accurate:

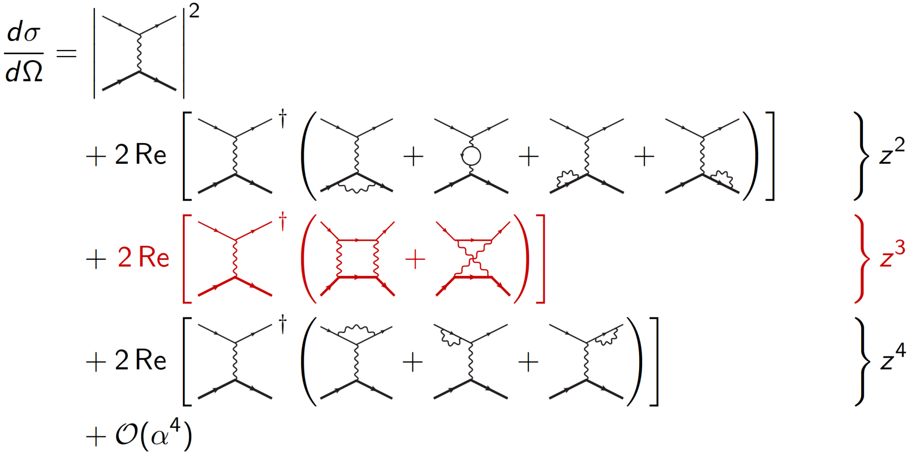
- negligible TPE at 1.29°
  - $\langle Q^2 \rangle = 0.002$ GeV^2, $\langle \epsilon \rangle = 0.99975$
- allows measurement of TPE at 12°
  - $R_{2\gamma} = 0.9975 \pm 0.010 \pm 0.0053$
  - $\langle Q^2 \rangle = 0.165$ GeV^2, $\langle \epsilon \rangle = 0.98$

Radiative Correction Terms to Consider



Lauren Ice, ASU

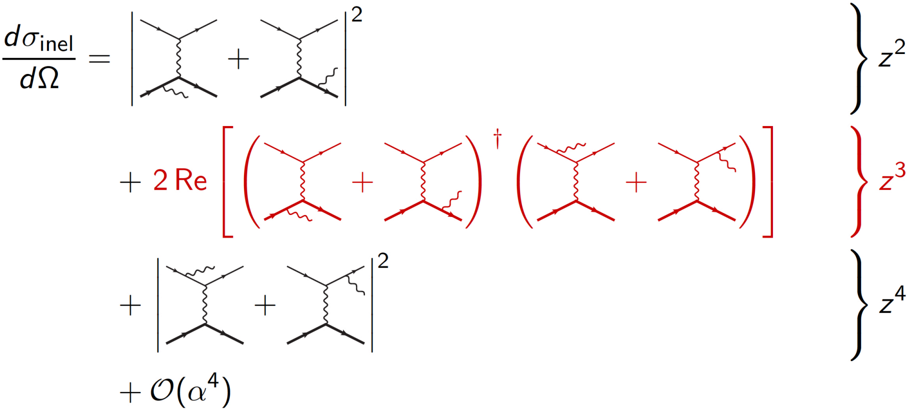
Radiative Corrections in Elastic Cross Section



Rebecca Russell, MIT

Even powers of z same for electron and positron scattering

Radiative Corrections from Inelastic Processes

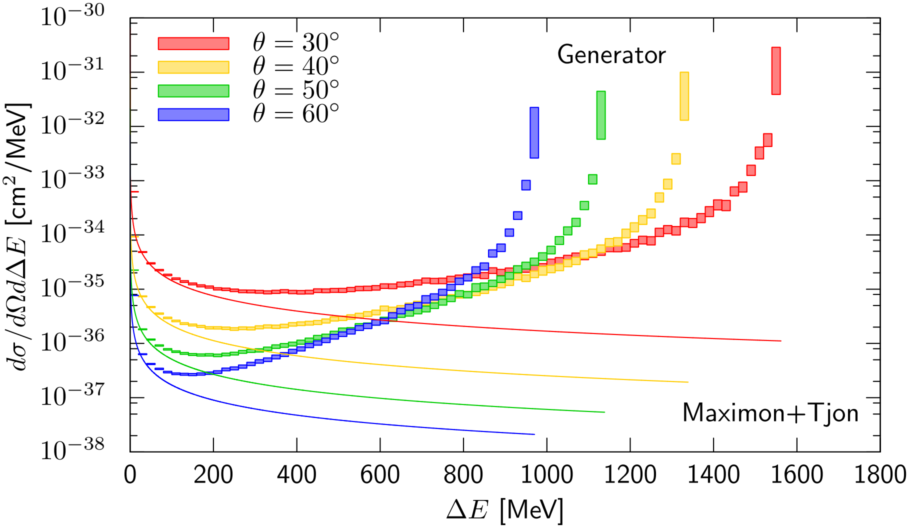


Rebecca Russell, MIT

Inelastic IR divergences cancel with elastic divergences

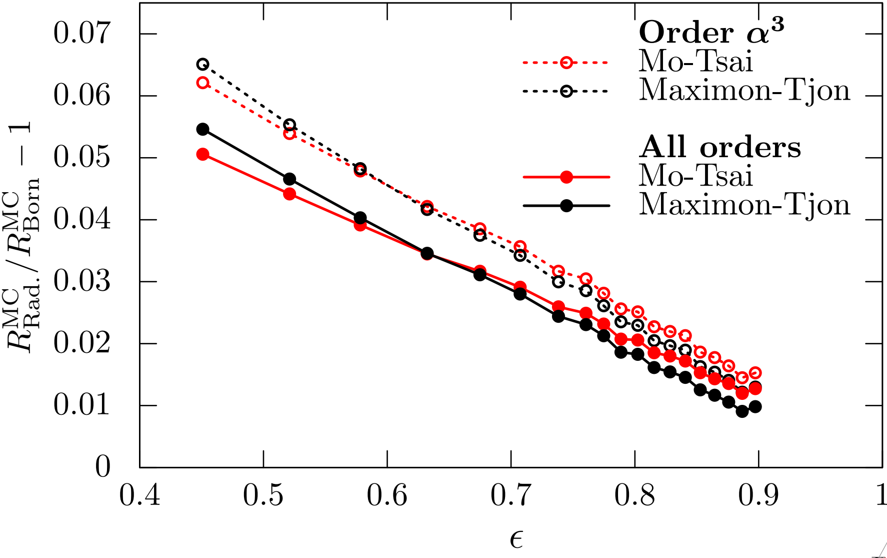
- must separate "hard" and "soft" parts in two-photon exchange
- "soft" part included in radiative corrections, "hard" part measured
- prescriptions defining "soft" - *e.g.* Mo-Tsai, Maximon-Tjon

Radiative Corrections Depend on Experiment

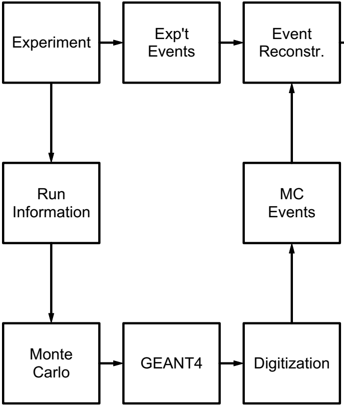


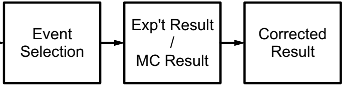
Jan Bernauer, Rebecca Russell, and Axel Schmidt, MIT

Radiative Corrections in OLYMPUS



Schematic of Analysis Procedure





Specific to each analysis

$$R_{2\gamma} = \frac{N_{e^+p}^{Data}}{N_{e^-p}^{Data}} \times \frac{N_{e^-p}^{MC}}{N_{e^+p}^{MC}} \times \frac{\mathcal{L}_{e^+p}}{\mathcal{L}_{e^-p}}$$

Common to all analyses

Analysis Procedure

All analyses share the following:

- based on the same run list and same tracked data files
- use the same tracked, radiatively generated, MC files
    - based on the same detector calibration, simulation, and digitization
- results normalized with MIE and binned in the same Q^2 and ϵ bins

Analyses are independent in the following:

- philosophy in selecting elastic candidates vary
- order, selection, and size of applying cuts are different

Four analyses combined for final result (Axel, Rebecca, Brian, and Jan)

- results and statistical uncertainty simply averaged
- variance added to uncorrelated uncertainty in quadrature

Systematic Uncertainties

OLYMPUS control of systematics

- left / right symmetric detector $\rightarrow$ two independent measurements
- $R_{2\gamma}$ is a ratio so many efficiencies cancel
- four independent analyses that can be examined and combined

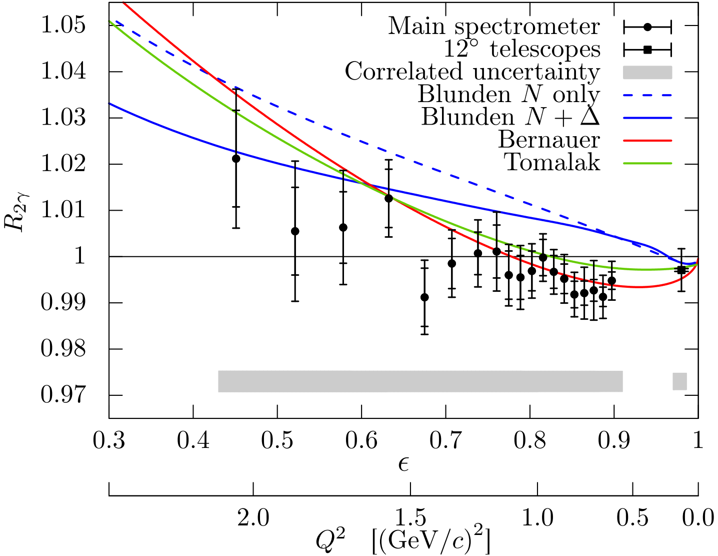
Correlated systematic uncertainties

- luminosity (MIE) - 0.36%
- beam energy - 0.04%–0.13%
- beam and detector geometry - 0.25%
- total - 0.46%

Uncorrelated systematic uncertainties

- track efficiency - 0.25%
- event selection and background subtraction - 0.25%–1.17%
- total - 0.37%–1.20%

OLYMPUS Results



OLYMPUS Results

OLYMPUS results:

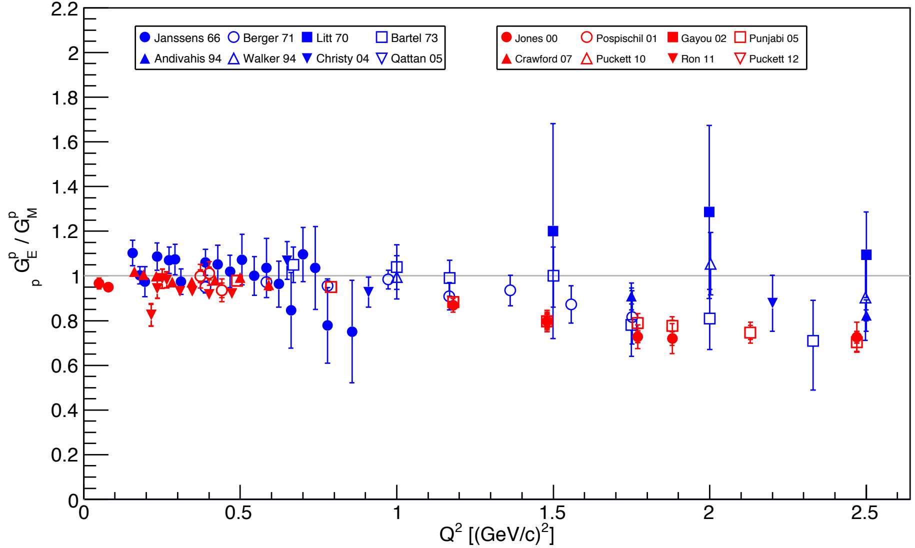
- plot used exponentiated Maximon-Tjon prescription
- shows small two-photon effect
- below theoretical calculations
- reasonable agreement with phenomenological predictions

However, slope with decreasing ϵ or increasing Q^2

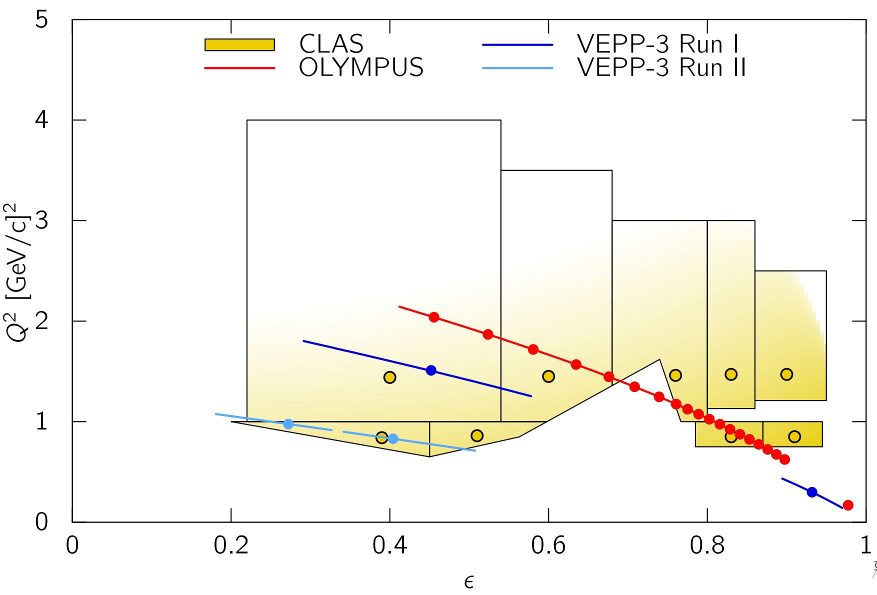
Suggests that there is an observed effect

Should we be surprised ?

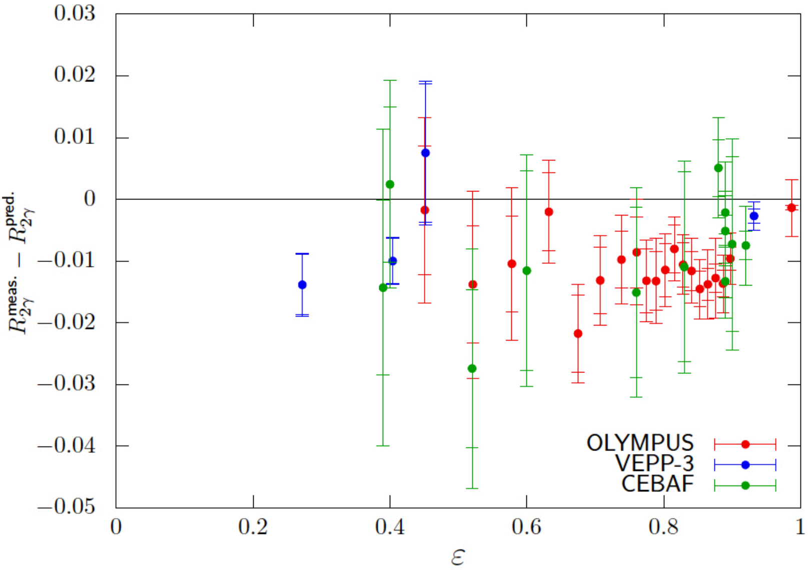
Discrepancy in Form Factor Ratio $\mu_p G_E^p / G_M^p$



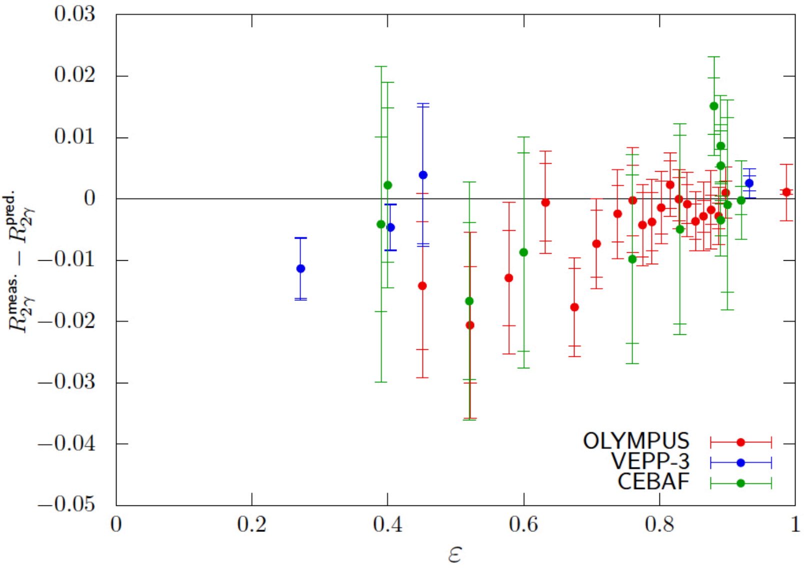
Kinematic Reach versus ϵ



Comparison with Blunden N + Δ



Comparison with Bernauer



OLYMPUS Results Published in Physical Review Letters

PRL 118, 092501 (2017) PHYSICAL REVIEW LETTERS week ending 3 MARCH 2017

Hard Two-Photon Contribution to Elastic Lepton-Proton Scattering Determined by the OLYMPUS Experiment

B. S. Henderson,[1] L. D. Ice,[2] D. Khaneft,[3] C. O'Connor,[1] R. Russell,[1] A. Schmidt,[1] J. C. Bernauer,[1,*] M. Kohl,[4,†] N. Akopov,[5] R. Alarcon,[2] O. Ates,[4] A. Avetisyan,[5] R. Beck,[6] S. Belostotski,[7] J. Bessuille,[1] F. Brinker,[8] J. R. Calarco,[9] V. Carassiti,[10] E. Cisbani,[11] G. Ciullo,[10] M. Contalbrigo,[10] R. De Leo,[12] J. Diefenbach,[4] T. W. Donnelly,[1] K. Dow,[1] G. Elbakian,[5] P. D. Eversheim,[6] S. Frullani,[11] Ch. Funke,[6] G. Gavrilov,[7] B. Gläser,[3] N. Görrissen,[8] D. K. Hasell,[1] J. Hauschildt,[8] Ph. Hoffmeister,[6] Y. Holler,[8] E. Ihloff,[1] A. Izotov,[7] R. Kaiser,[13] G. Karyan,[8,‡] J. Kelsey,[1] A. Kiselev,[7] P. Klassen,[6] A. Krivshich,[7] I. Lehmann,[13] P. Lenisa,[10] D. Lenz,[8] S. Lumsden,[13] Y. Ma,[3] F. Maas,[3] H. Marukyan,[5] O. Miklukho,[7] R. G. Milner,[1] A. Movsisyan,[5,§] M. Murray,[13] Y. Naryshkin,[7] R. Perez Benito,[3] R. Perrino,[12] R. P. Redwine,[1] D. Rodríguez Piñeiro,[3] G. Rosner,[13] U. Schneekloth,[8] B. Seitz,[13] M. Statera,[10] A. Thiel,[6] H. Vardanyan,[5] D. Veretennikov,[7] C. Vidal,[1] A. Winnebeck,[1] and V. Yeganov[5]

(OLYMPUS Collaboration)

Summary

OLYMPUS has finished the analysis for $R_{2\gamma}$.

Results show a small hard two-photon effect increasing with Q^2.

Results are lower than theoretical calculations but in reasonable agreement with phenomenological predictions.

Radiative corrections and prescription for handling "soft" TPE important.

Further theoretical and experimental work is needed.

The OLYMPUS Collaboration

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Arizona State University
Deutsches Elektronen-Synchrotron
Hampton University
Istituto Nazionale di Fisica Nucleare, Bari
Istituto Nazionale di Fisica Nucleare, Ferrara
Istituto Nazionale di Fisica Nucleare, Rome
Massachusetts Institute of Technology
Saint Petersburg Nuclear Physics Institute
Rheinische Friedrich-Wilhelms-Universität Bonn
University of Glasgow
Johannes Gutenberg-Universität Mainz
University of New Hampshire

On behalf of the OLYMPUS Collaboration

We acknowledge the support of

DESY PRC and

DESY Directorate

Prof. Joachim Mnich

Thank You

Timeline

2005

- May - BLAST Experiment ends
- November - BLAST@ELSA, @DORIS

2007

- May - seminars DESY, Zeuthen, and PRC
- June - Letter of Intent

2008

- September - OLYMPUS proposal
- December - cond. approval DESY + PRC

2009

- August - Technical Design Report
- September - technical review

2010

- January - approval and funding
- February - disassemble BLAST and ship
- July - start modifications and assembly

2011

- January - install target and test
- February - ring run tests
- July - roll into DORIS ring
- August–December - service day test runs

2012

- February - first data run
- July - repair target, other improvements
- October - December - second data run

2013

- January - collected cosmic data
- February–May - optical survey, field map
- June–July - disassemble OLYMPUS

2016

- October - most of the analysis complete
- 7 PhD's

Seven PhD Theses

GEM Luminosity Monitors for the OLYMPUS Experiment to Determine the Effect of Two-Photon Exchange

- Ozgur Ates (HU), May 2014.

A Measurement of the Two-Photon Exchange Effect in Elastic Electron-Proton Scattering with OLYMPUS

- Rebecca Russell (MIT) September, 2016

A Precision Measurement of the $e^{+}p/e^{?}p$ Elastic Scattering Cross Section Ratio at the OLYMPUS Experiment

- Brian Henderson (MIT), September, 2016

Measuring the Lepton Sign Asymmetry in Elastic Electron-Proton Scattering with OLYMPUS

- Axel Schmidt (MIT), September, 2016

Seven PhD Theses

Measurement of the Two-Photon Exchange Contribution to Lepton-Proton

- Lauren Ice (ASU), November, 2016

The Contribution of Two Photon Exchange in Elastic Lepton-Proton Scattering

- Colton O'Connor (MIT), December, 2016

Investigation of the Proton Structure in the Space-like Domain and Feasibility Study of the Proton Electromagnetic Form Factor Measurements in the Time-like Region

- Dmitry Khaneft (Mainz), submitted March, 2017

Published Papers

The OLYMPUS Experiment,
Milner, R. *et al*. Nucl. Instr. Meth. **A741** (2014) 1–17.

The OLYMPUS Internal Hydrogen Target,
Bernauer, J.C. *et al*. Nucl. Instr. Meth. **A755** (2014) 20–27.

Measurement and tricubic interpolation of the magnetic field for the OLYMPUS experiment,
Bernauer, J.C. *et al*, Nucl. Instr. Meth. **A823** (2016) 9–14.

Design and Performance of a Lead Fluoride Detector as a Luminosity Monitor,
Pérez Benito, R. *et al*, Nucl. Instr. Meth. **A826** (2016) 6–14.

Hard Two-Photon Contribution to Elastic Lepton-Proton Scattering Determined by the OLYMPUS Experiment,
Henderson, B.S. *et al*. Phys. Rev. Lett. **118** (2017) 092501.

Planned Papers

Yields: e^-, e^+, and $e^- + e^+$ - Jan and Axel - April ?

Luminosity MIE - Axel - March

12° result - Brian - March

Target simulation - Brian - March

SYMB analysis - Doug, Colton, and Dmitry - April

Radiative Corrections - Axel and Rebecca - April

Tracking - Jan, Axel, and Rebecca - May

Time of Flight - Lauren - March

DORIS - Uwe and Frank - May ?

GEM - Michael - July ?

MWPC - Stan - unlikely

OLYMPUS long paper - Doug - August

Recent Presentations

Michael Kohl - Jerusalem, Israel, January 2

Jan Bernauer - JLab, January 13

Axel Schmidt - Bormio, January 26

Axel Schmidt - DESY HH and Zeuthen, January 31 and February 1

Colton O'Connor - APS Meeting, Washington DC, January 28

Michael Kohl - GHP Meeting, Washington DC, February 2

Douglas Hasell - DESY PRC - Hamburg, Germany, March 21

Future Presentations

DIS - Birmingham, UK, April 3-7 - Dmitry

FFK - Warsaw, Poland, May 15–19 - Jan

Sant'Angelo d'Ischia - Naples, Italy May 15–19 - Doug ?

NSTAR - Columbia, SC, August 20-23 - Michael and Jan

Lomonosov - Moscow, Russia, August 24–30 - Uwe and Michael

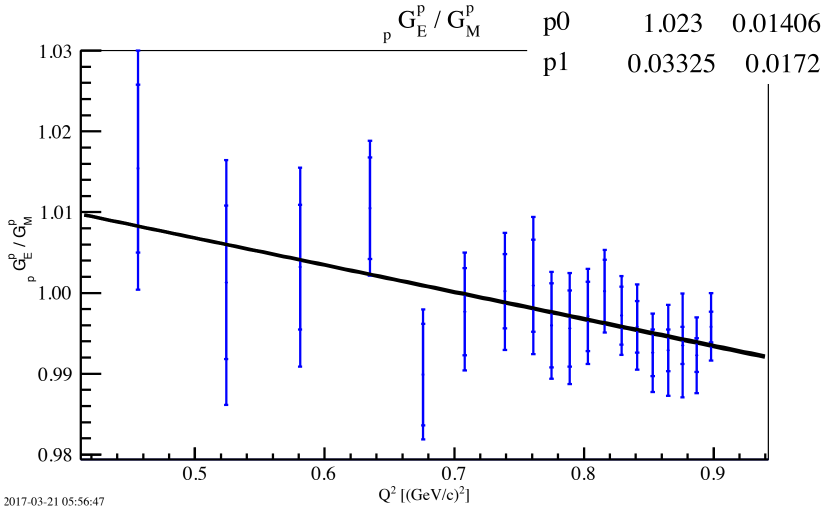
PANIC 2017 - Bejing, China, September 1–5 - Brian

Hadron 2017 - Salamanca, Spain, September 25-29 - Lauren/Jan/Axel

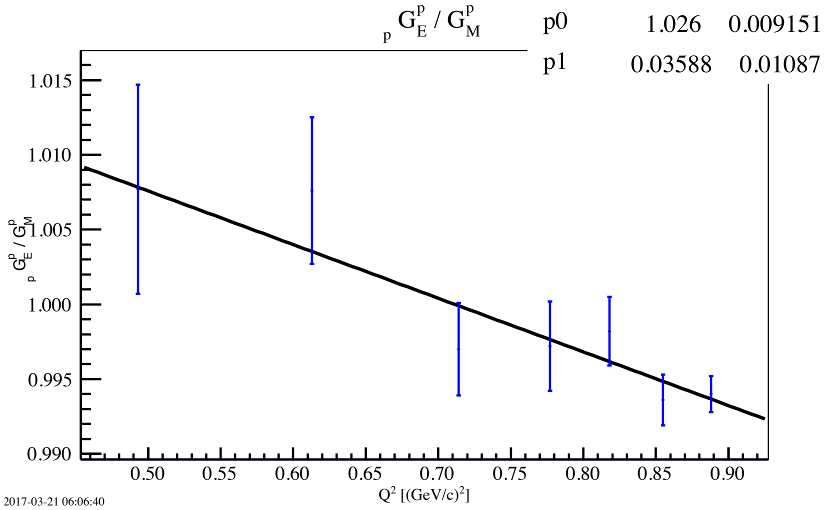
APS DNP - Pittsburgh, PA, October 25–28 - Axel

EINN - Paphos, Cyprus, October 29 – November 4 - Doug

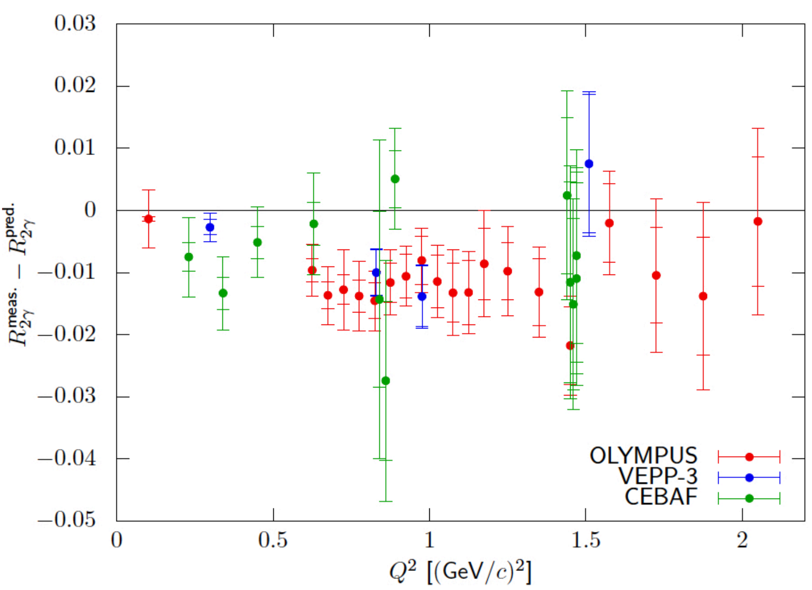
Fit to OLYMPUS $R_{2\gamma}$



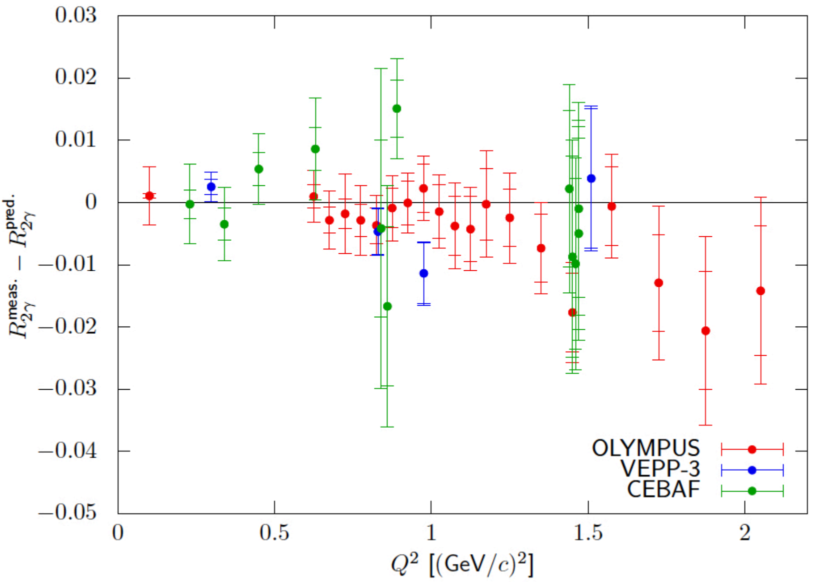
Fit to Rebinned OLYMPUS $R_{2\gamma}$



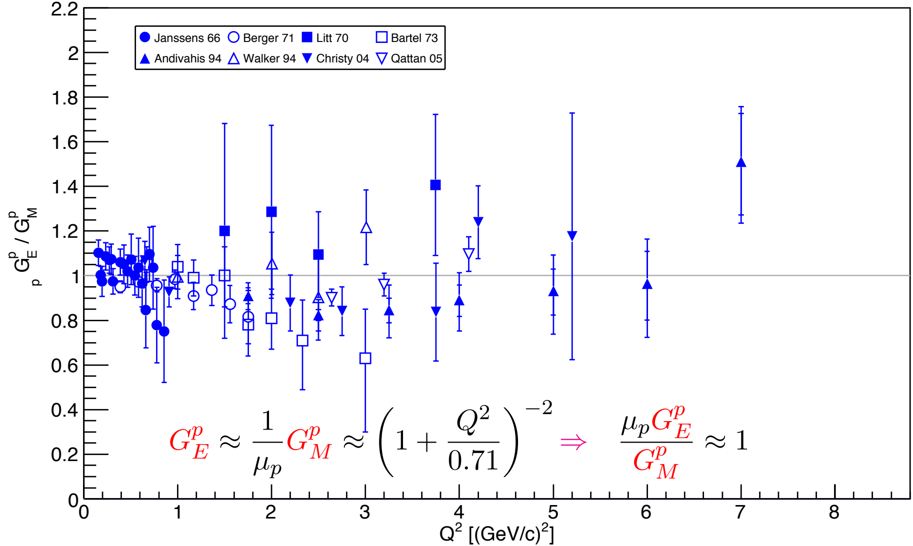
Comparison with Blunden N + Δ



Comparison with Bernauer

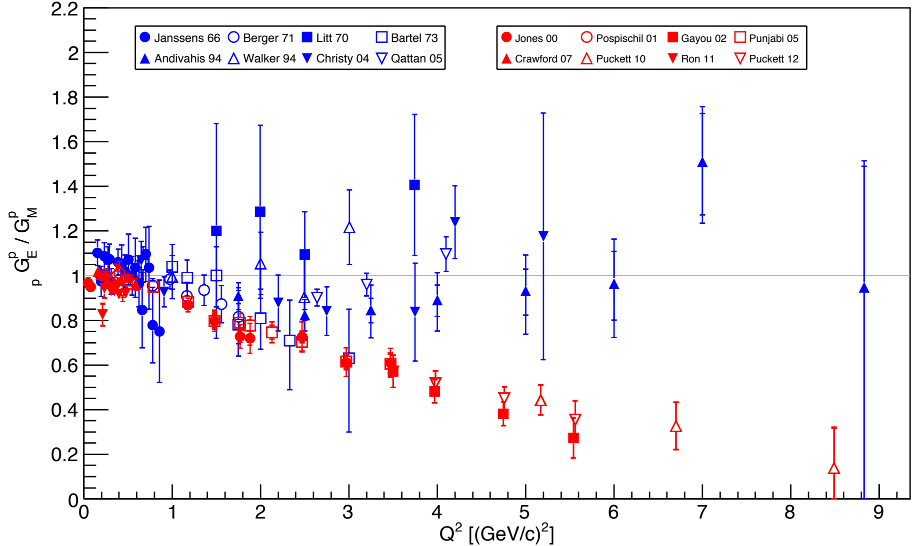


Form Factor Ratio $\mu_p G_E^p / G_M^p$ - Rosenbluth Technique



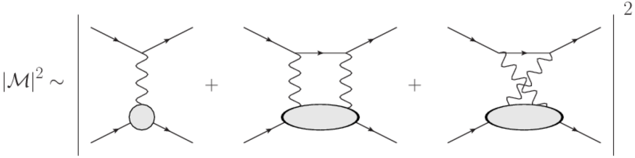
$$G_E^p \approx \frac{1}{\mu_p} G_M^p \approx \left(1 + \frac{Q^2}{0.71}\right)^{-2} \Rightarrow \frac{\mu_p G_E^p}{G_M^p} \approx 1$$

Discrepancy in Form Factor Ratio $\mu_p G_E^p / G_M^p$?



Measure Contribution of Hard, Two-Photon Exchange

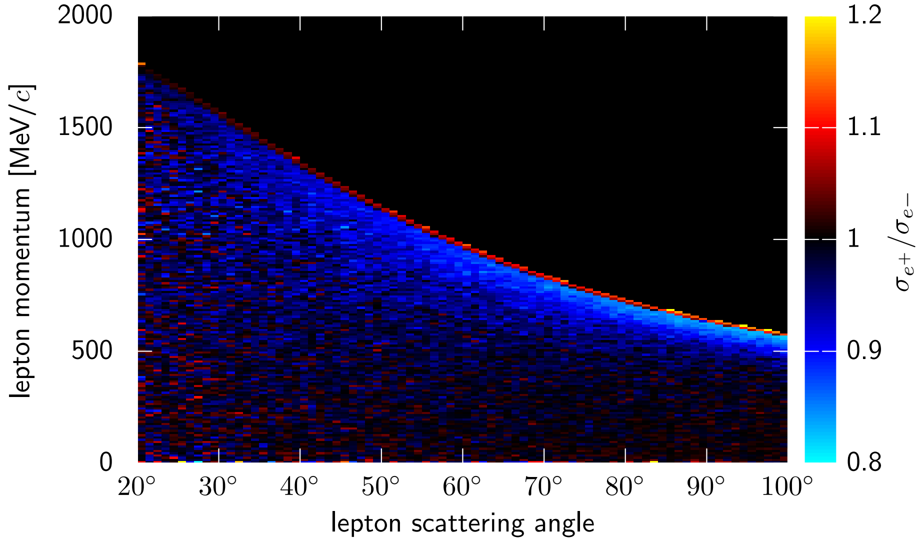
Discrepancy thought to arise from significant two-photon contribution to elastic electron-proton scattering.



Interference between single-photon and two-photon exchange proportional to lepton charge cubed, z^3, but suppressed by an additional factor of α.

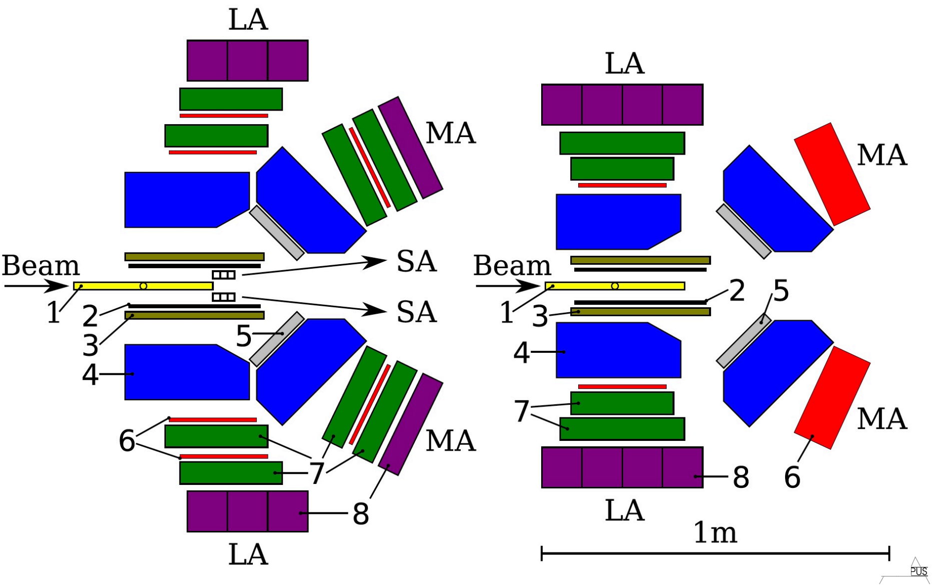
Suggests comparing positron-proton and electron-proton elastic scattering as the interference term changes sign.

Radiative Corrections



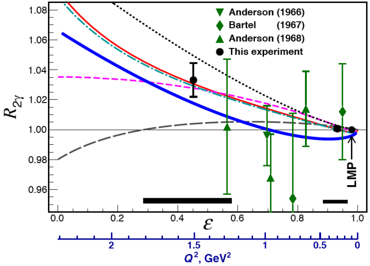
Jan Bernauer, Rebecca Russell, and Axel Schmidt, MIT

VEPP-3 TPE Configuration

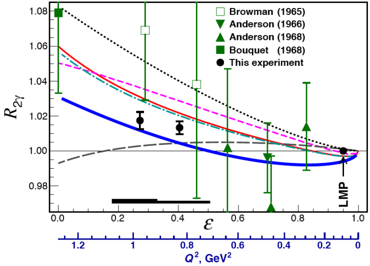


Novosibirsk Results - STORI'14, St. Goar, Germany

Run-I (2009):
$E_{\mathrm{beam}} = 1.594$ GeV



Run-II (2011–2012):
$E_{\mathrm{beam}} = 0.998$ GeV



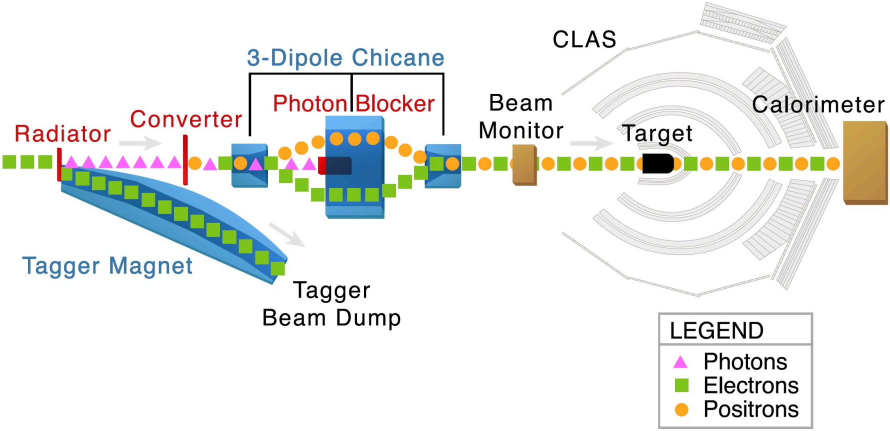
Theoretical predictions:

....	*I. A. Qattan, et al.,*	Phys. Rev. C **84** (2011) 054317	:Parametrization
———	*P. G. Blunden, et al.,*	Phys. Rev. C **72** (2005) 034612	:hadronic TPE calculation
-·-·-	*D. Borisyuk and A. Kobushkin,*	Phys. Rev. C **78** (2008) 025208	:dispersion relations
- - - -	*E. Tomasi-Gustafsson, et al.,*	Phys. Atom. Nucl. **76** (2013) 937	:"analytical model"
- - - -	*J. Arrington and I. Sick,*	Phys. Rev. C **70** (2004) 028203	:Coulomb corrections
———	*J. C. Bernauer, et al.,*	Phys. Rev. C **90** (2014) 015206	:Global *ep* data fit

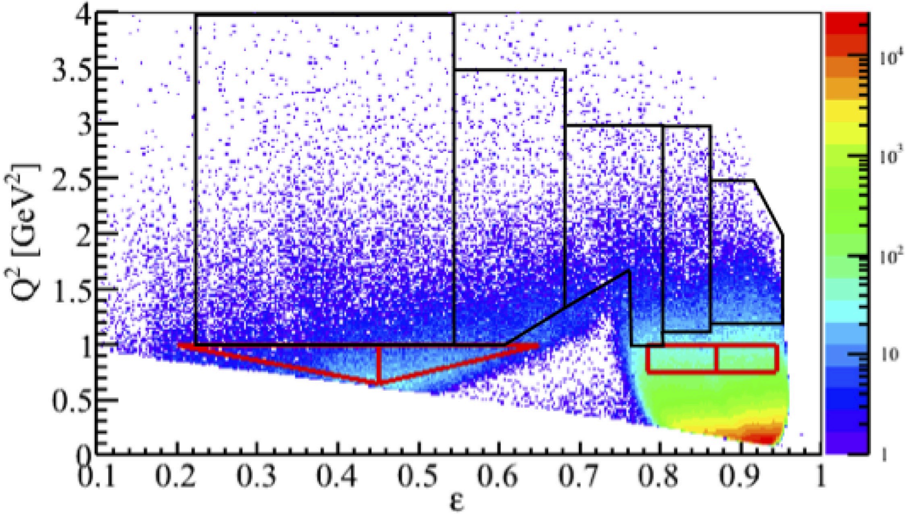
- *LMP – Luminosity Monitoring Point – set to* $R_{2\gamma} = 1$*;*
- *error bars are statistical errors, black bands show* ε*-bin width and systematic uncertainties;*
- *the standard radiative corrections are taken into account (according to arXiv:1401.2959).*

courtesy of Alexander Gramolin, JLab

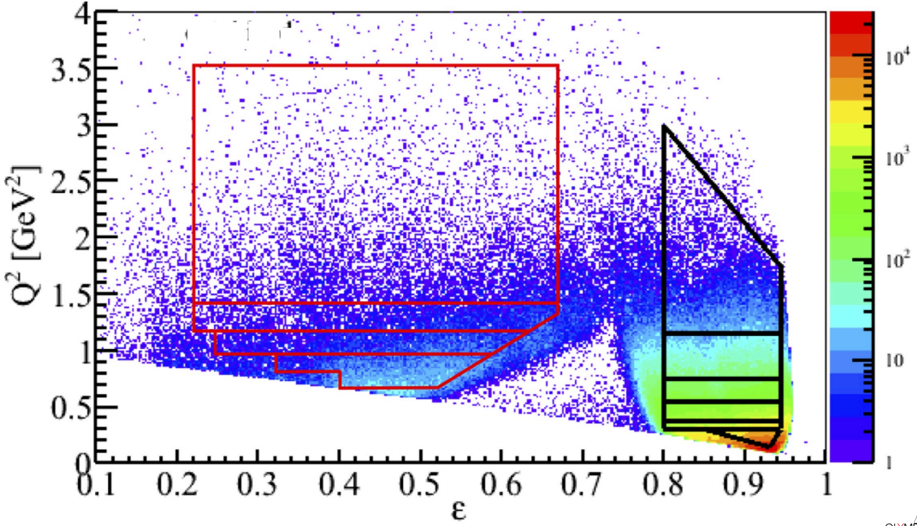
CLAS TPE Configuration



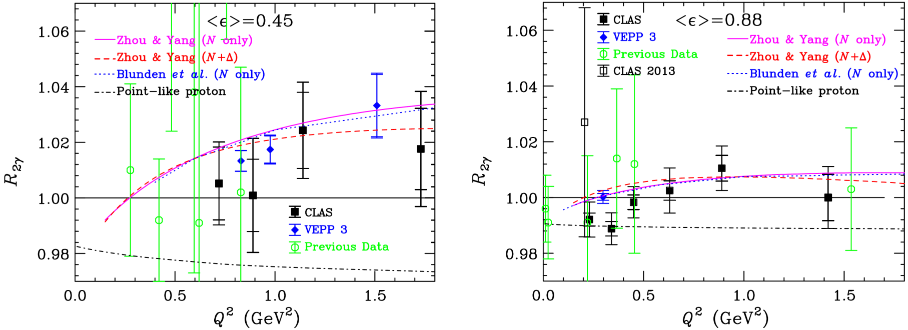
CLAS Bins for ϵ Dependence



CLAS Bins for Q^2 Dependence

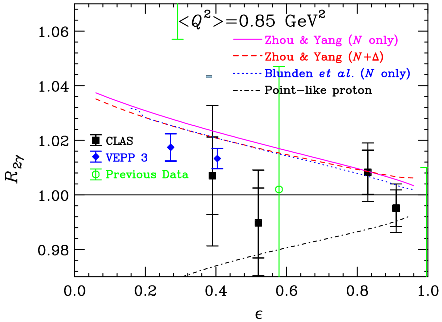


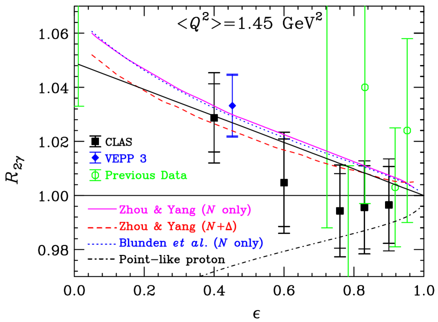
CLAS, VEPP-3, and Previous Results versus Q^2



arXiv:1603.00315v1 [nucl-ex] 1 Mar 2016

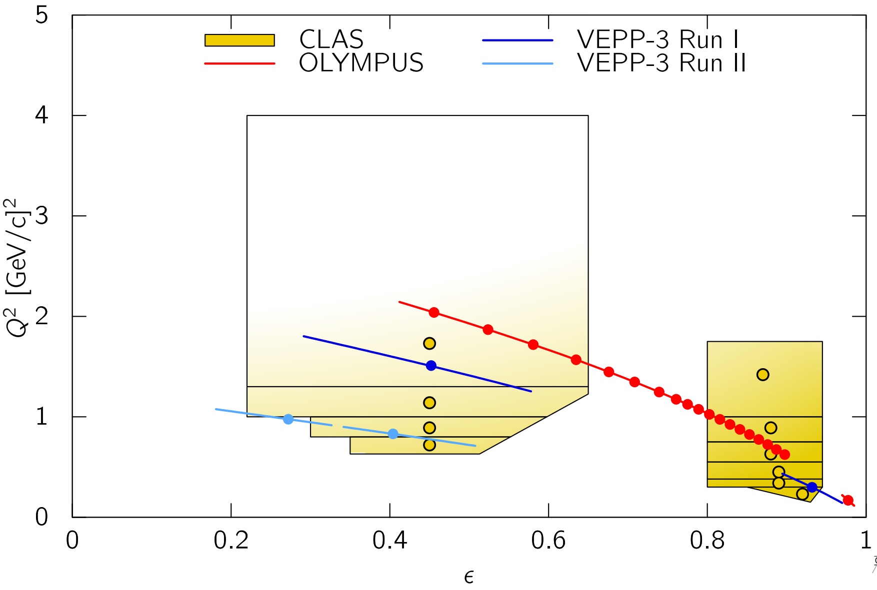
CLAS, VEPP-3, and Previous Results versus ϵ





arXiv:1603.00315v1 [nucl-ex] 1 Mar 2016

Kinematic Reach versus Q^2



Analysis Procedure

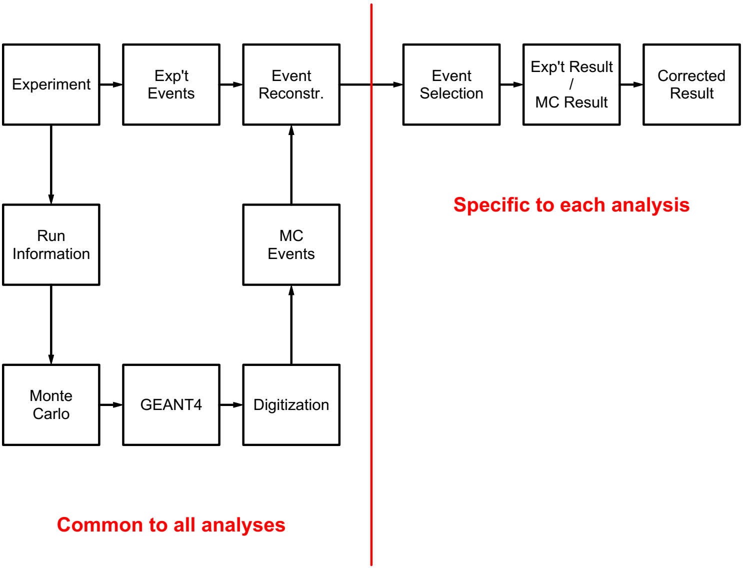
All analyses share the following:

- based on the same run list
- use the same tracked data files
- use the same tracked, radiatively generated, MC files
  - based on the same detector calibration, simulation, and digitization
- results are binned in the same Q^2 and ϵ bins
- yields normalized with the same luminosity determination (MIE)

Analyses are independent in the following:

- philosophy in selecting elastic candidates vary
- order, selection, and size of applying cuts are different

Schematic of Analysis Procedure



Luminosity

Three measures of luminosity are consistent:

- slow control using Brian's molecular flow calculation
  - 2 % relative, 5 % absolute
- 12° MWPC with coincident proton in WC
  - 0.46 % relative, 2.4 % absolute
- multi-interaction events, MIE, in SYMB
  - 0.1 % statistical, 0.27 % systematic

Choose to use MIE measure as the most accurate:

- negligible TPE at 1.29°
  - $\langle Q^2 \rangle = 0.002$ GeV^2, $\langle \epsilon \rangle = 0.99975$
- allows measurement of TPE at 12°
  - $R_{2\gamma} = 0.9975 \pm 0.010 \pm 0.0053$
  - $\langle Q^2 \rangle = 0.165$ GeV^2, $\langle \epsilon \rangle = 0.98$

Luminosity from Slow Control (SC)

Independent of beam species

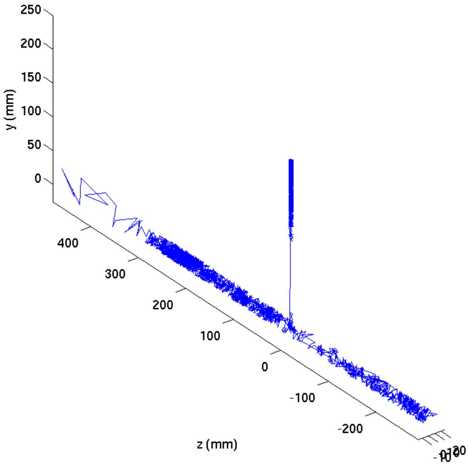
- beam current
- gas flow (mass flow controller)
- conductance of target cell

Molecular flow simulation

- Brian Henderson
- cell geometry and temperature
- including Wakefield suppressors

SC luminosity

- relative ~ 1 %
- absolute 3–4 %



12° MWPC

Left and Right 12° telescopes

- 2 scintillator tiles, 3 triple GEMs (HU), and 3 MWPCs (PNPI)
- GEMs not currently used in the analysis
- track leptons in 12° telescope
  - inclusive and exclusive (coincident with protons in WC)

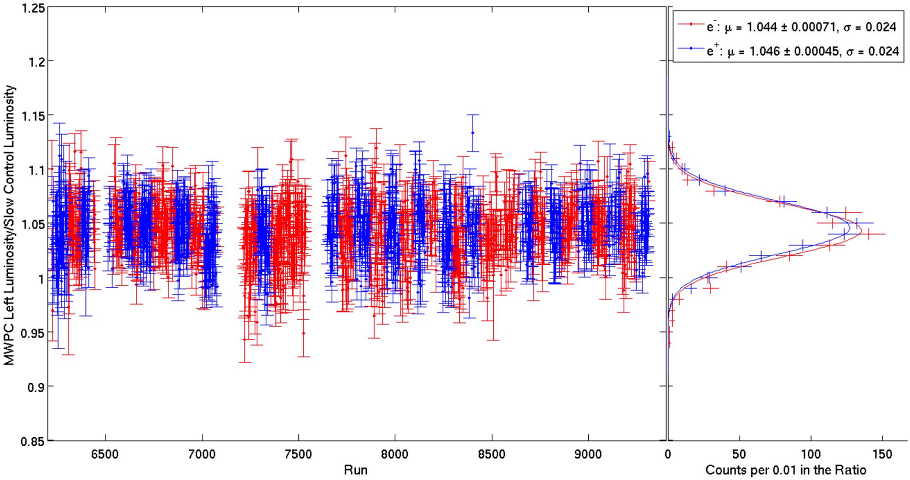
Improved hit finding, tracking, and analysis

- Brian Henderson
- compare with radiative Monte Carlo simulation using SC luminosity
  - uncertainty from ep elastic scattering cross section around 12°

Two independent measures of luminosity: left and right

- relative < 0.5 %
- absolute < 3 %

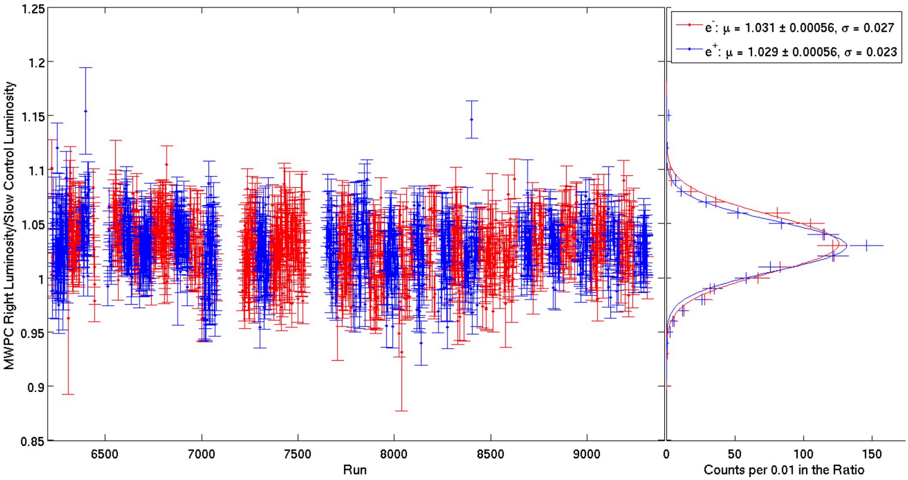
Left 12° MWPC / MC(SC)



e^-: $\mu = 1.044 \pm 0.00071$, $\sigma = 0.024$

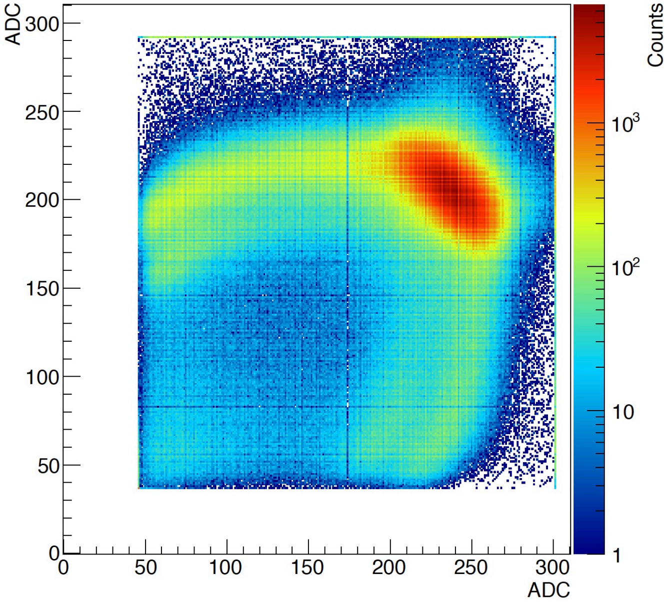
e^+: $\mu = 1.046 \pm 0.00045$, $\sigma = 0.024$

Right 12° MWPC / MC(SC)



e^-: $\mu = 1.031 \pm 0.00056$, $\sigma = 0.027$
e^+: $\mu = 1.029 \pm 0.00056$, $\sigma = 0.023$

Symmetric Møller / Bhabha (SYMB)



Symmetric Møller / Bhabha (SYMB)

Symmetric PbF_2 calorimeters

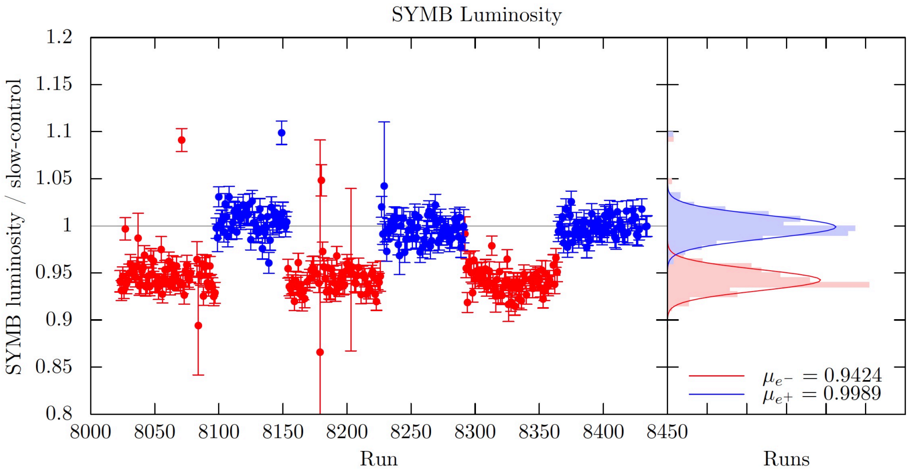
- 21 mm diameter aperture in lead collimator
- at 1.29° left and right of beam axis
- dedicated electronics and readout system for high rate
  - produced histograms sent to DAQ $\sim$ every minute
  - dead time free

Should be our best luminosity monitor

- high statistics, < 1 % in each run
- independent of ep scattering process
- cross sections calculable from QED

But . . .

Symmetric Møller / Bhabha (SYMB)



5.8 % discrepancy between beam species.

Symmetric Møller / Bhabha (SYMB)

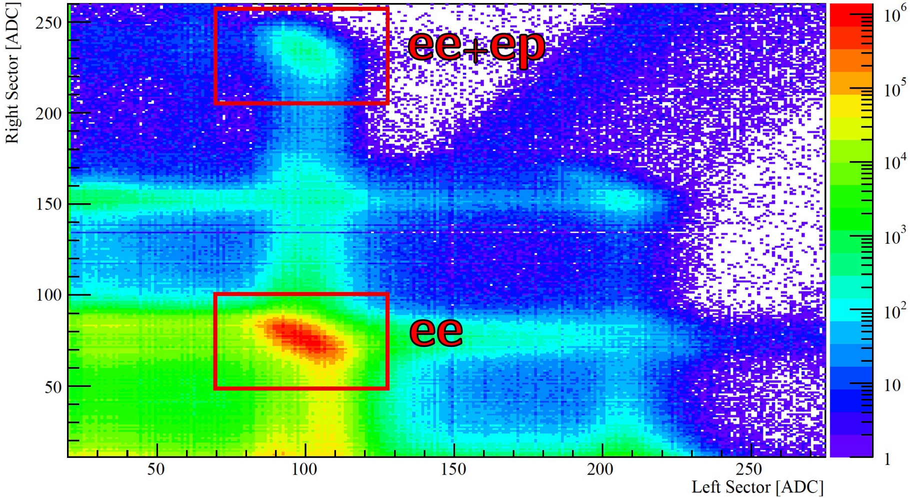
18 months of investigation - Colton O'Connor and Dmitry Khaneft

- two independent Møller / Bhabha event generators
  - annihilation, radiative corrections, pile-up events, noise, *etc.*
  - agreed with each other and various external generators
- effect of varying cuts around coincidence peak
- magnetic field: on, off, reversed
- beam current, position, slope, emittance
- position and orientation of collimator and calorimeter
- time dependence
- electronics, ADCs, LED pulser, pedestals, gains, BPM, *etc.*
- satellite peaks

Indications of effects but not enough to remove 5.8 % discrepancy

- effects not seen in other luminosity measurements

ep Pile-Up in SYMB



ep Pile-Up in SYMB

In the SYMB Left master histogram

- Axel Schmidt
- coincidence (pile-up) of $e^{\pm}e$ and $e^{\pm}p$
- independent of Møller / Bhabha cross section

$$\mathcal{L} = \frac{N_{e^{\pm}e\,+\,e^{\pm}p} \cdot t_{live} \cdot f_{bunch}}{N_{e^{\pm}e} \cdot \sigma_{e^{\pm}p}}$$

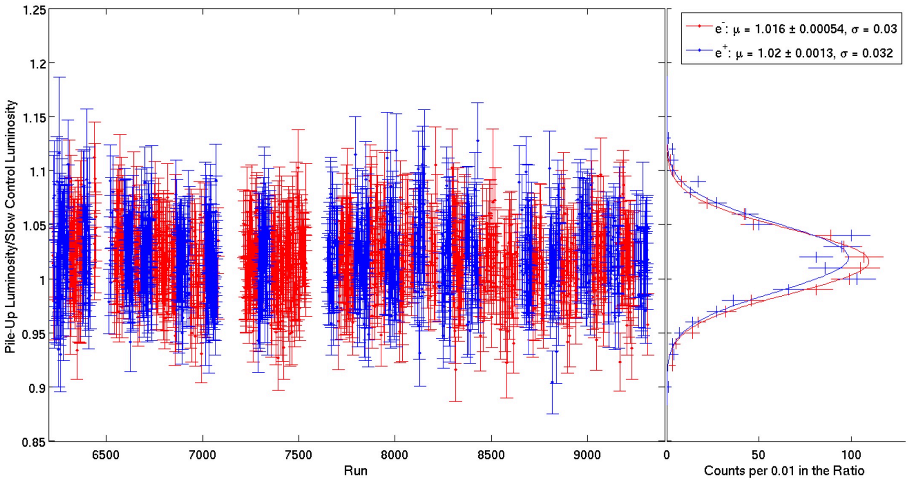
- statistics about 10^4 poorer than normal SYMB

Unfortunately no corresponding SYMB Right master histogram

- ADC range different

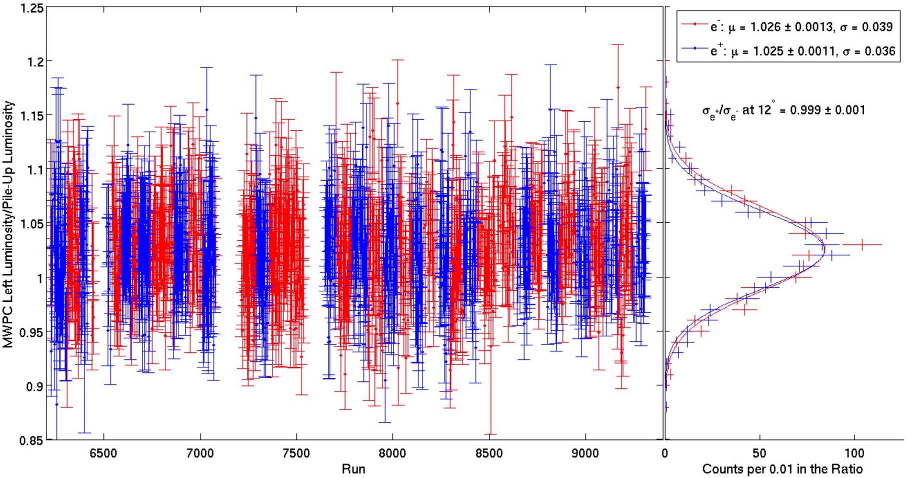
But, agrees with SC and 12°

Pile-Up / MC(SC)



$$e^-:\ \mu = 1.016 \pm 0.00054,\ \sigma = 0.030$$
$$e^+:\ \mu = 1.020 \pm 0.00130,\ \sigma = 0.032$$

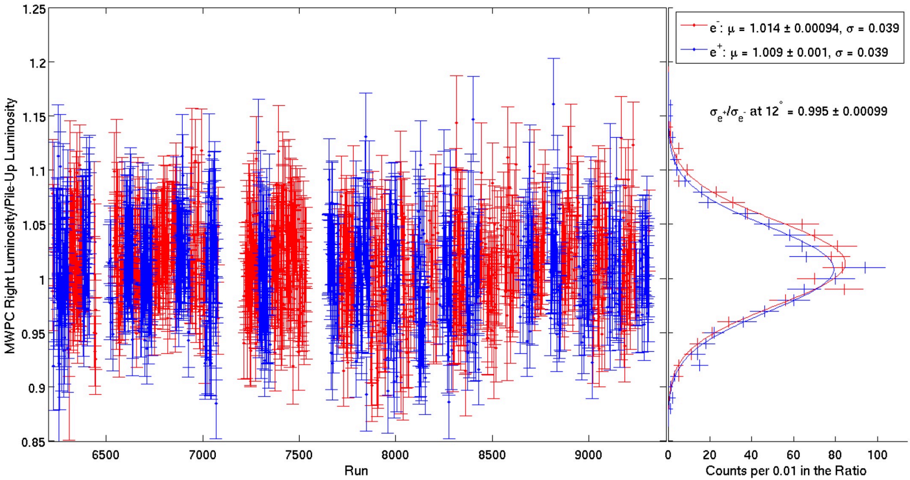
Left 12° MWPC / Pile-Up



e^{-}: $\mu = 1.026 \pm 0.0013,\ \sigma = 0.039$

e^{+}: $\mu = 1.025 \pm 0.0011,\ \sigma = 0.036$

Right 12° MWPC / Pile-Up



e^-: $\mu = 1.014 \pm 0.0009$, $\sigma = 0.039$

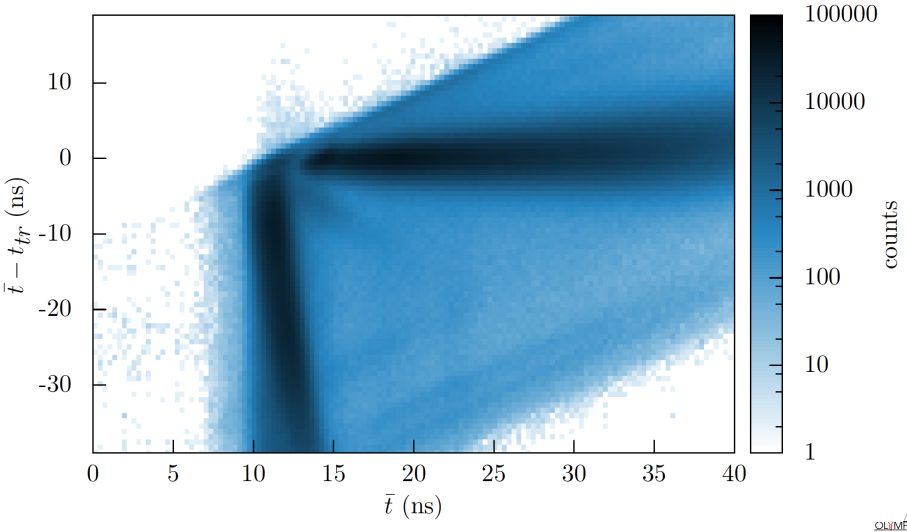
e^+: $\mu = 1.009 \pm 0.0010$, $\sigma = 0.039$

Rebecca Russell's Analysis

Loose cuts to select usable tracks:

- $|Z| < 350$ mm, $|\phi| < 18°$
- $\#$ WC hits > 7, $\#$ hits per WC chamber ≥ 1
- ToF bar $\#$ and ToF Y consistent with track criteria
- bar-by-bar, 2D, $\bar{t} - t_{tr}$ separation for protons / positrons

Rebecca Russell's Bar-by-Bar, 2D, particle ID



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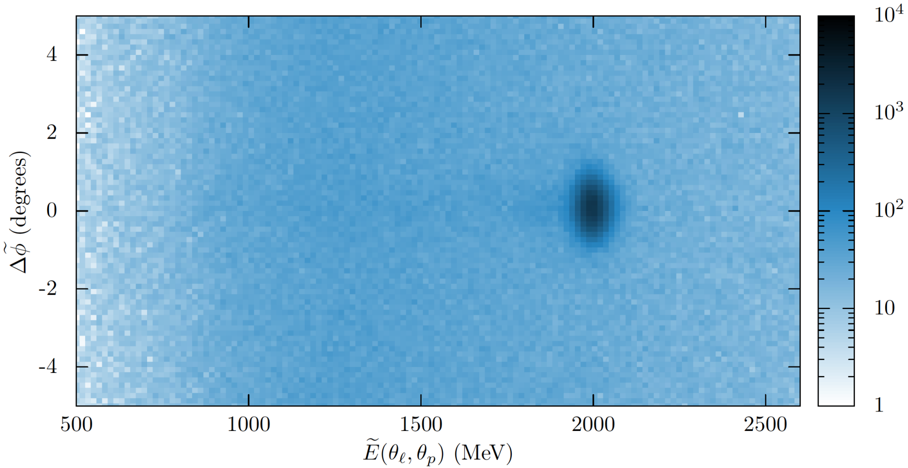
- $\#$ WC hits > 7, $\#$ hits per WC chamber ≥ 1
- ToF bar $\#$ and ToF Y consistent with track criteria
- bar-by-bar, 2D, $\bar{t} - t_{tr}$ separation for protons / positrons

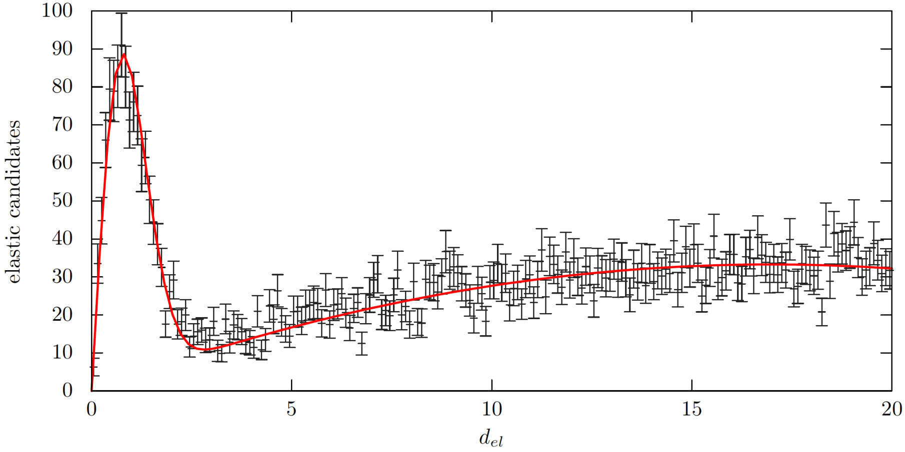
Elastic event selection:

- pairs of correct-sign leptons and protons in opposing sectors
- $\Delta z < 10$ cm, $z_p < 30$ cm
- loose cuts on calculated momenta and beam energy
- loose cut on event time
- 5-6 σ elliptical cut on 2D beam energy and coplanarity distribution
- background subtraction of 2D distribution for each Q^2 bin

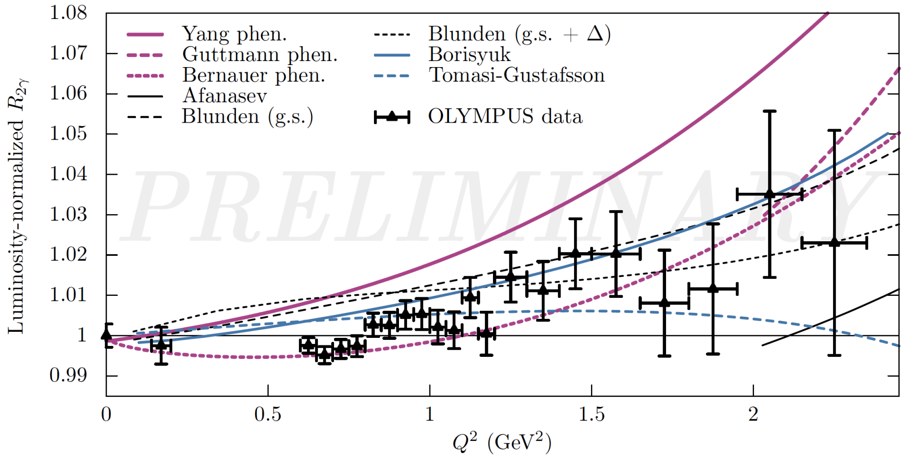
Rebecca Russell's Final, 2D, event selection



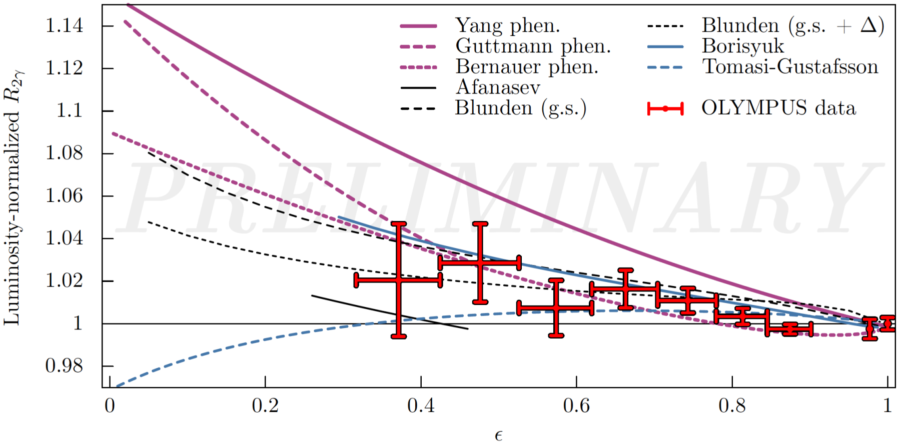
Rebecca Russell's Background projection (sample)



Rebecca Russell's Ratio versus Q^2



Rebecca Russell's Ratio versus ϵ

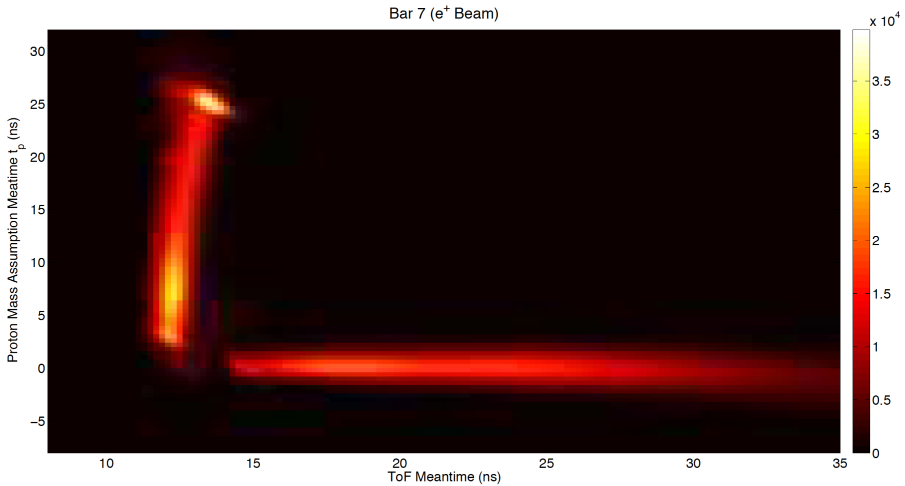


Brian Henderson's Analysis

Select events with right-sign lepton and proton tracks in opposing sectors

- verify particle ID with ToF timing information (bar-by-bar)

Brian Henderson's Bar-by-Bar, 2D, particle ID



Brian Henderson's Analysis

Select events with right-sign lepton and proton tracks in opposing sectors

- verify particle ID with ToF timing information (bar-by-bar)

Track selection cuts

- $|\phi| < 11.5°$, $|z| < 350$ mm

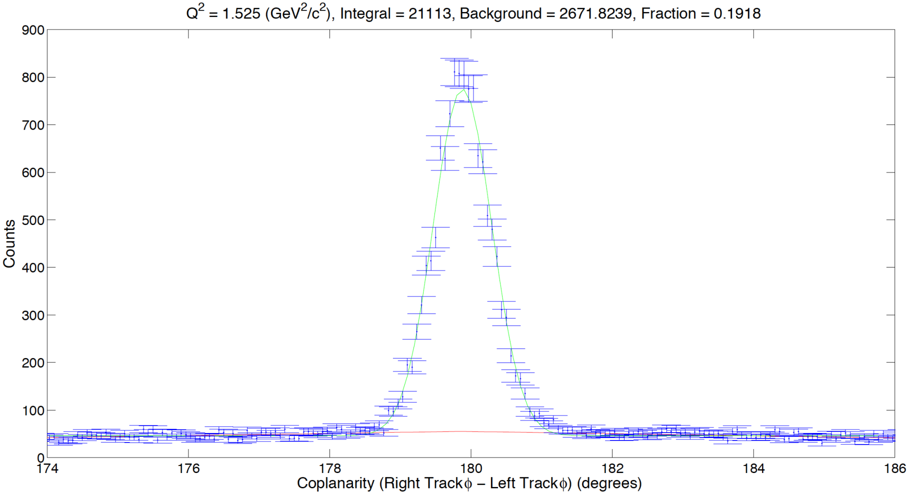
Select elastic events based on large number of loose kinematic cuts

- $|\Delta t| < 5$ ns, $|\Delta z| < 175$ mm, $|\Delta\theta| < 7°$
- $|\Delta E_{beam,p}| < 1000$ MeV, $|\Delta E_{beam,\theta}| < 350$ MeV,
- missing energy $\Delta E'_\theta/E'^2 < 0.0048$ MeV^{-1}
- longitudinal momentum $\Delta p_z > -500$ MeV
- coplanarity$|\Delta\phi| < 7.5°$

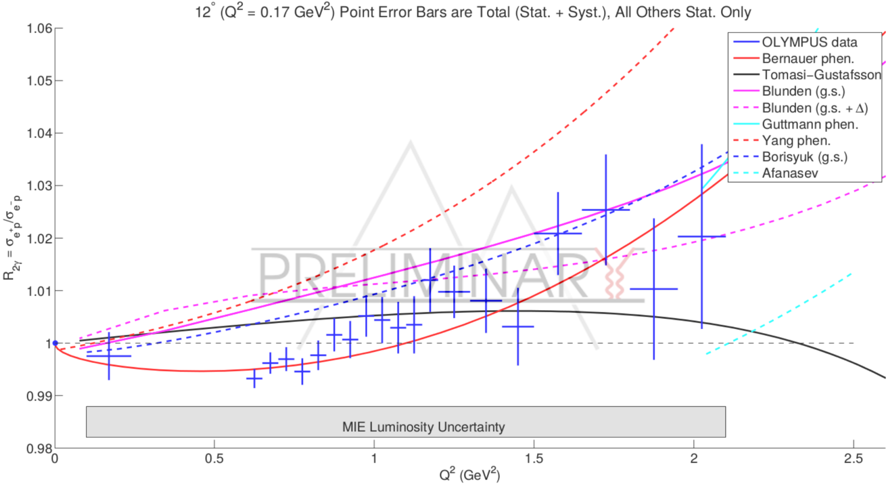
Background subtraction bin-by-bin on coplanarity distribution

- triangular background fit

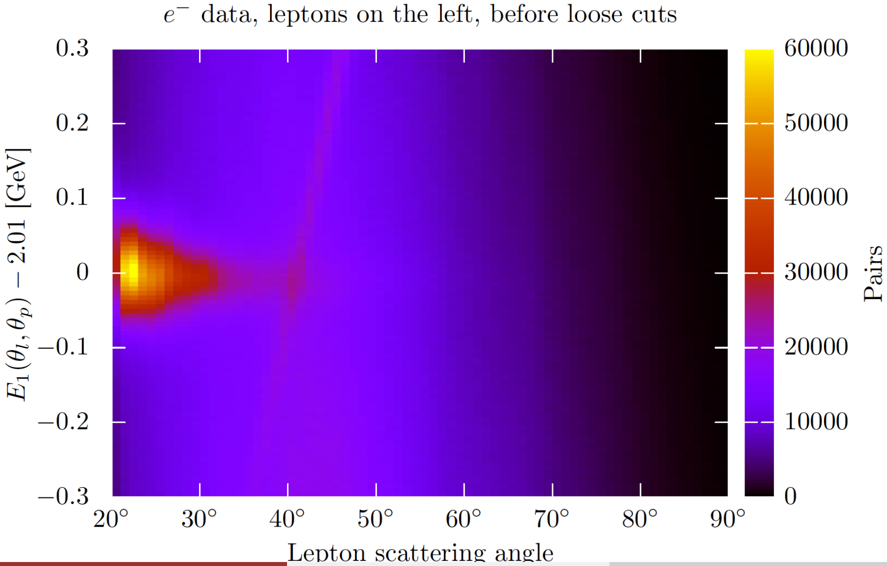
Brian Henderson's Bin-by-Bin Background Subtraction



Brian Henderson's Ratio versus Q^2



Axel Schmidt's Track Selection - Before Cuts



Axel Schmidt's Analysis

Loose cuts on 7 kinematic variable to select lepton-proton pairs

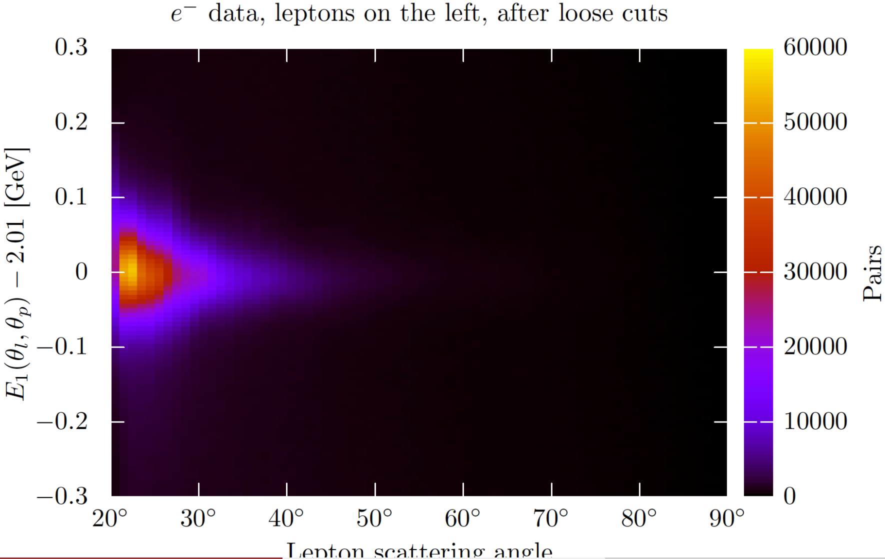
- $|\Delta Z| < 100$ mm, $|\Delta\phi| < 6°$, $|\Delta E_{beam,\theta}| < 0.3$ GeV
- lepton mass squared from ToF timing < 1 GeV^2
- proton mass squared from ToF timing < 1.5 GeV^2
- lepton inverse momentum $|\Delta 1/p_{l,\theta}| < 1$ GeV^{-1}
- proton inverse momentum $|\Delta 1/p_{p,\theta}| < 1$ GeV^{-1}
- all cuts greater than 5σ
- ToF timing to resolve positron-proton ambiguity

Fitted cuts as a function of θ on mass squared and inverse momentum

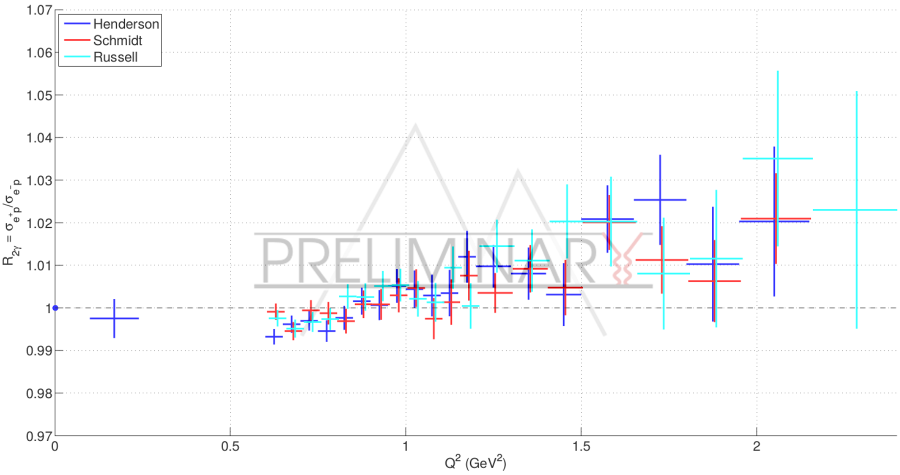
- calculate "score" and cut at $\approx 5\sigma$
- apply fiducial cuts

Subtract background under coplanarity distribution

Axel Schmidt's Track Selection - After Cuts



Ratio from All Theses versus Q^2



Ratio from Combined versus Q^2