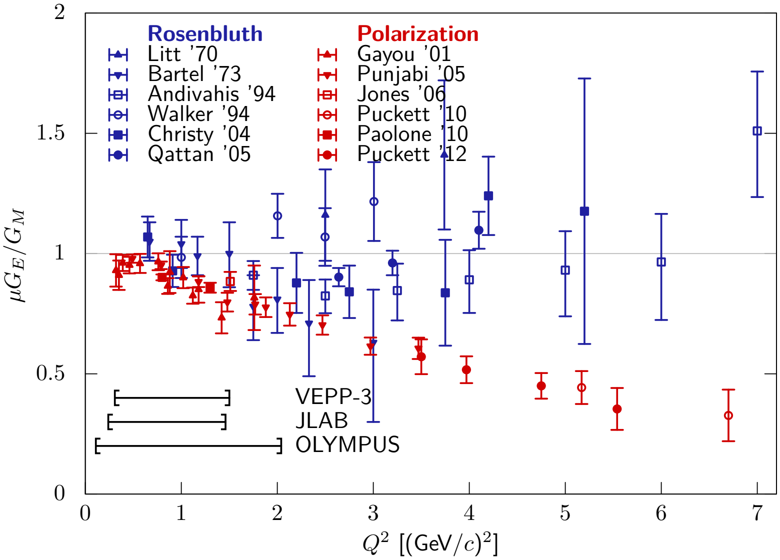
Two-photon exchange: What we know, and what we want to do next.

Jan C. Bernauer

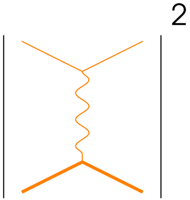
Proton Radius Puzzle workshop - Mainz - July 2018

Massachusetts Institute of Technology

At large Q^2, we have a puzzle



Expected explanation: Two Photon Exchange



$$\sigma_{exp} \propto \left| M_{1\gamma} \right|^2$$

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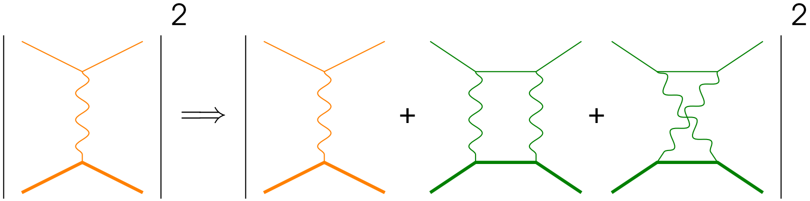

$$\sigma_{exp} \propto \left|M_{1\gamma}\right|^2 \pm 2\mathfrak{R}\left\{M_{1\gamma}^{\dagger} M_{2\gamma}\right\} + \cancel{\left|M_{2\gamma}\right|^2}$$

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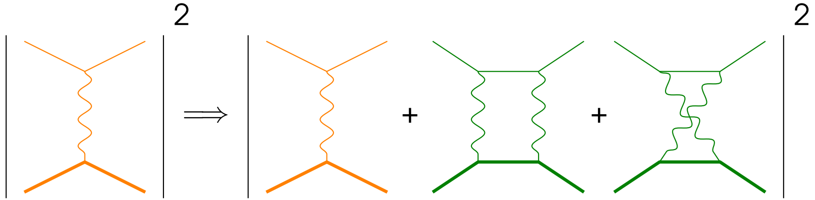

$$\sigma_{exp} \propto \left|M_{1\gamma}\right|^2 \pm 2\Re\left\{M_{1\gamma}^{\dagger} M_{2\gamma}\right\} + \cancel{\left|M_{2\gamma}\right|^2}$$

Rosenbluth:

$$\sigma_{exp} = \sigma_{1\gamma}\left(1 + \delta_{TPE}\right)$$

Negligible correction for polarization data

Extract TPE from existing data

We have a global fit of cross sections from unpolarized experiments

- c.s., so (anti)-correlation right
- new radiative corrections
- Good total and individual χ^2

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- bad χ^2, better radiative corrections do not resolve discrepancy!

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Make ansatz for TPE correction:

$$\delta_{TPE} = \delta_{\text{Feshbach}} + \delta_{\text{model}}$$

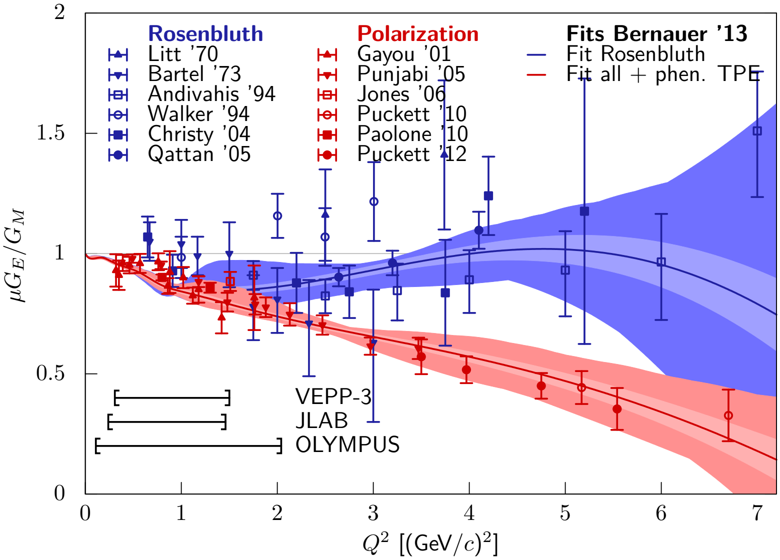
δ_{Feshbach} is known $Q^2 \to 0$ limit

$$\delta_{\text{model}} = a \cdot (1 - \varepsilon) \cdot \log\left(1 + b \cdot Q^2\right)$$

- Recover good χ^2!

(See: Phys. Rev. C 90, 015206 (2014))

Fits for ratio



Can we measure TPE directly?

Direct measurements of TPE:

- Verify that TPE is the cause
- Instruct theory how to calculate hadronic part (QCD!)

How to measure?

- Mixed term changes sign with lepton charge sign

$$R_{2\gamma} = \frac{\sigma(e^+p)}{\sigma(e^-p)} = \frac{N^{e^+}_{exp}}{N^{e^-}_{exp}} \Big/ \frac{N^{e^+}_{MC}}{N^{e^-}_{MC}} = 1 - 2\delta_{TPE}$$

Direct measurement: Three modern experiments

CLAS

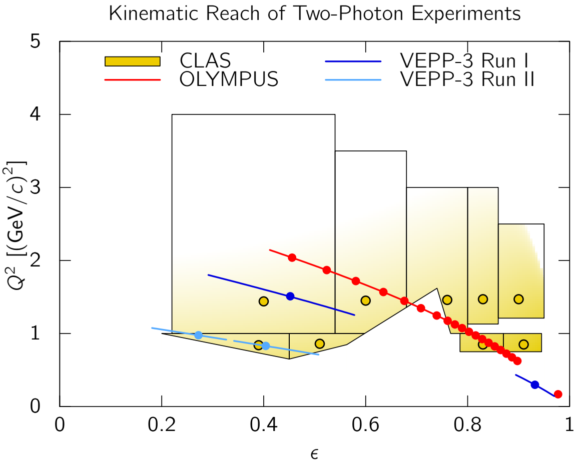
- e^- to γ to $e^{+/-}$ -beam
- Phys. Rev. C 95, 065201 (2017)
- PRL 114, 062003

VEPP-3

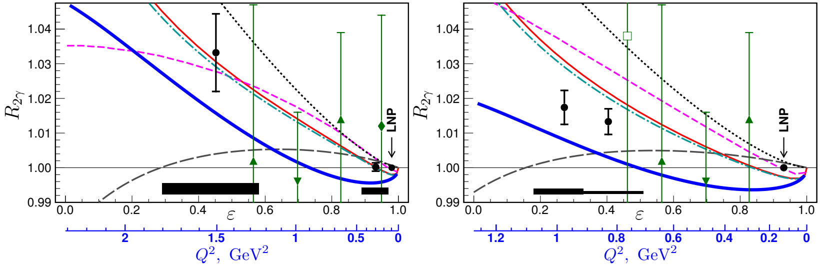
- 1.6/1 GeV beam
- no field
- Phys. Rev. Lett. 114, 062005 (2015)

OLYMPUS

- DORIS @ DESY
- 2 GeV beam
- Phys. Rev. Lett. 118, 092501 (2017)



VEPP-3 results (I. A. Rachek et al., Phys. Rev. Lett 114, 062005)



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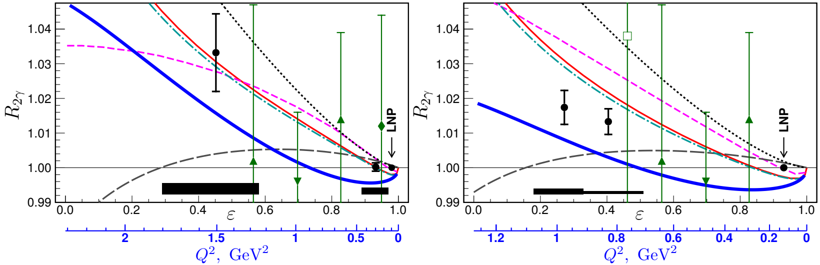

	$R_{2\gamma}^{\mathrm{LNP}}$	$\frac{\chi^2}{n_{\mathrm{d.f.}}}$
Borisyuk and Kobushkin	1	2.14
Blunden, et al.	1	2.94
Bernauer, et al.	1	4.19
Tomasi-Gustafsson, et al.	1	5.09
Arrington and Sick	1	7.72
Qattan, et al.	1	25.0
No hard TPE ($R_{2\gamma} \equiv 1$)	1	7.97

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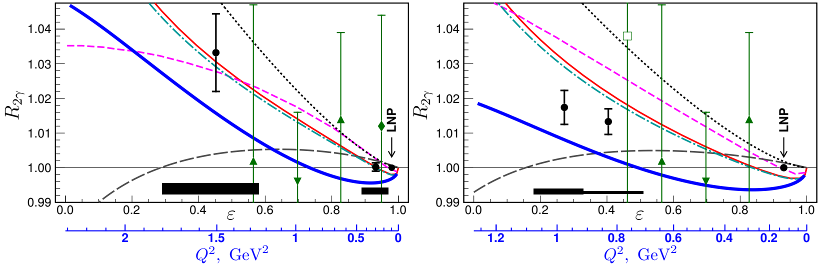
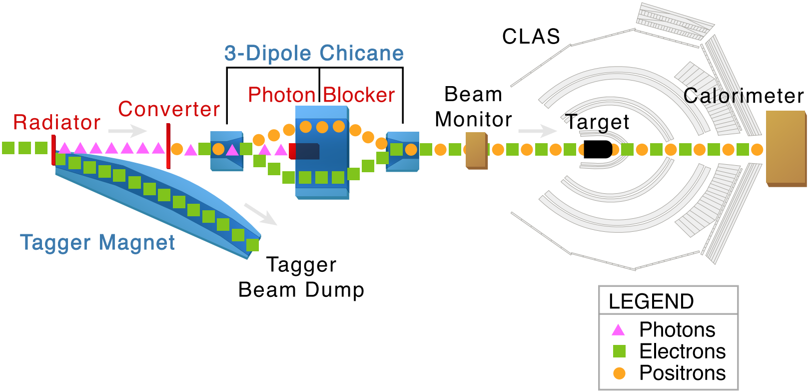
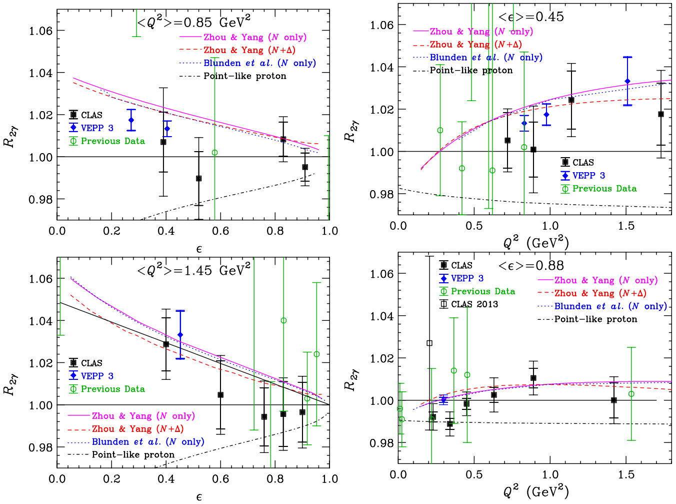


	$R_{2\gamma}^{\mathrm{LNP}}$	$\frac{\chi^2}{n_{\mathrm{d.f.}}}$	$R_{2\gamma}^{\mathrm{LNP}}$ Run-I	Run-II	$\frac{\chi^2}{n_{\mathrm{d.f.}}}$
Borisyuk and Kobushkin	1	2.14	0.998	0.997	3.80
Blunden, et al.	1	2.94	0.998	0.997	4.75
Bernauer, et al.	1	4.19	0.997	0.995	1.00
Tomasi-Gustafsson, et al.	1	5.09	1.001	1.001	5.97
Arrington and Sick	1	7.72	1.000	1.000	8.18
Qattan, et al.	1	25.0	1.000	1.002	22.0
No hard TPE ($R_{2\gamma} \equiv 1$)	1	7.97	1	1	7.97

CLAS (D. Rimal et al., arXiv:1603.00315 , D. Adikaram et al., Phys. Rev. Lett 114, 062003)



CLAS (D. Rimal et al., arXiv:1603.00315 , D. Adikaram et al., Phys. Rev. Lett 114, 062003) (color adjusted)

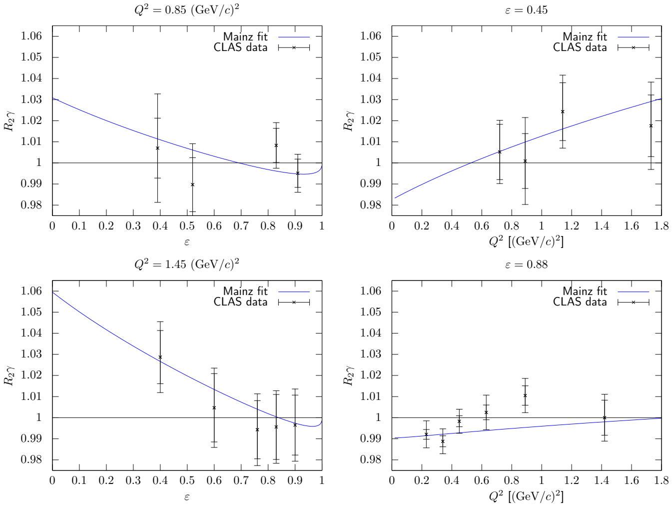


Comparison with predictions:

- 12 non-overlapping points from CLAS
- 4 Vepp-3 points

	$\frac{\chi^2}{n_{d.f.}}$
Z & Y (N)	1.09
Z & Y (N+Δ)	1.03
Blunden (N)	1.06
No TPE	2.10
Point-proton	6.96

CLAS data + Mainz fit



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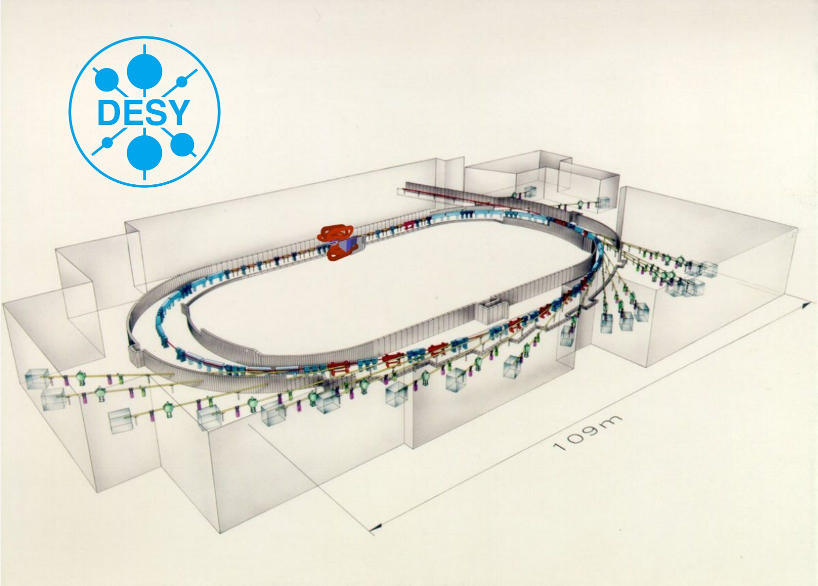
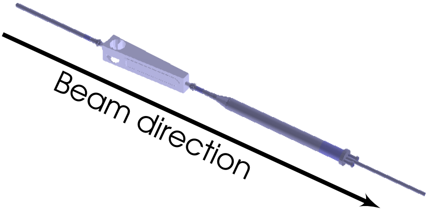
Mainz	0.666

OLYMPUS at DESY/DORIS



Anatomy of the OLYMPUS detector



- Target chamber with target cell

R. Milner et al., NIMA 741 (2014) 1-17

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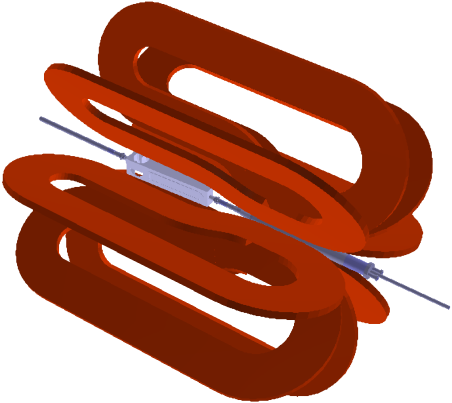

- Target chamber with target cell
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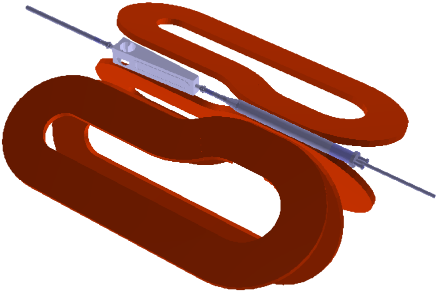

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- Toroid magnet coils (half shown)

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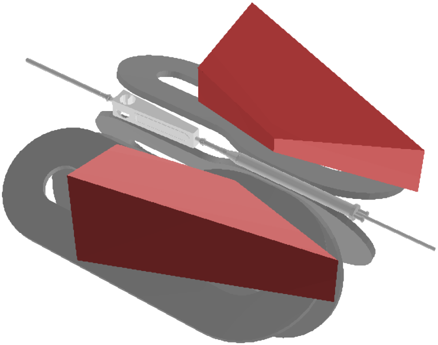

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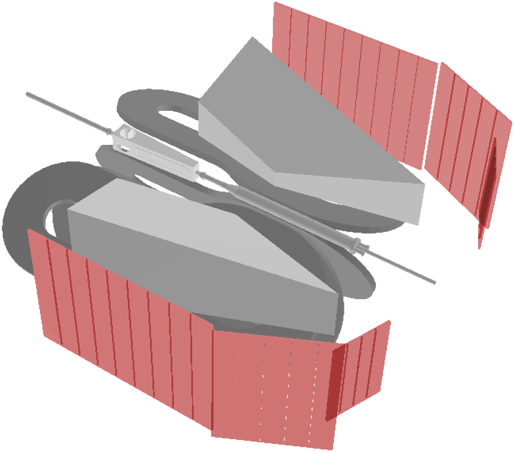

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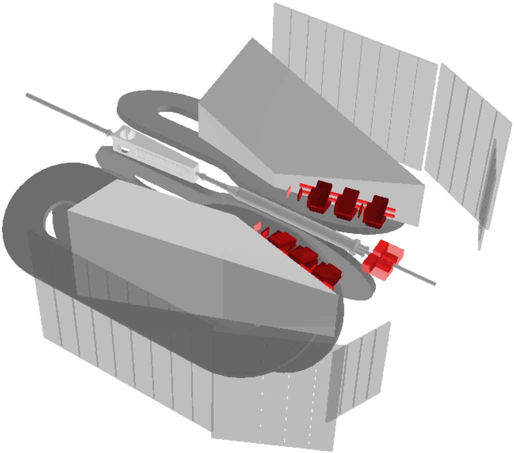
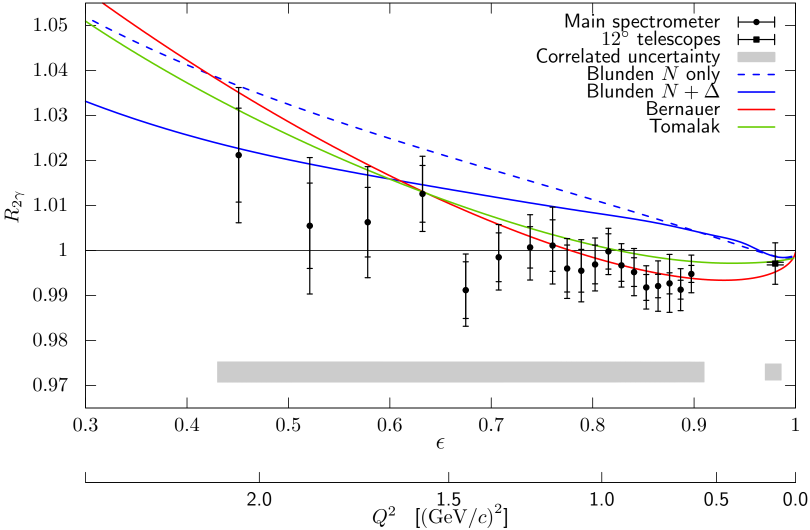


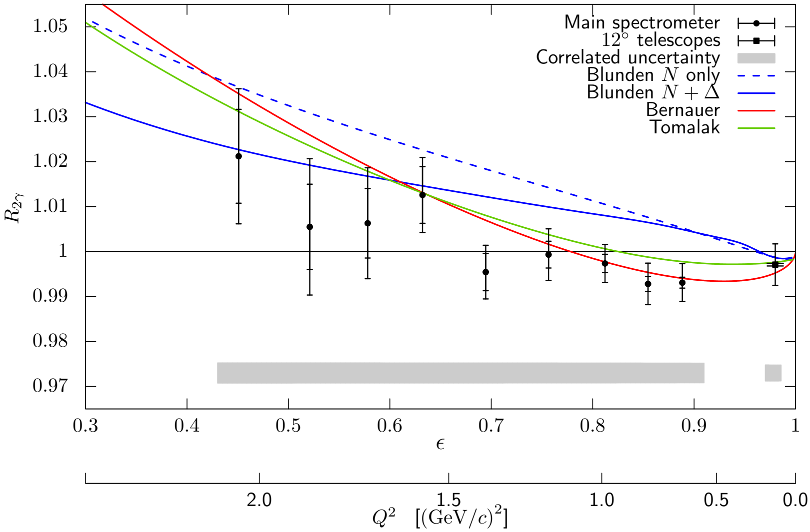
- Target chamber with target cell
- Toroid magnet coils (half shown)
- Drift chambers
- Time of flight scintillators
- Dual luminosity monitors
  - 12°-detector
  - Symmetric Møller/Bhabha

R. Milner et al., NIMA 741 (2014) 1-17

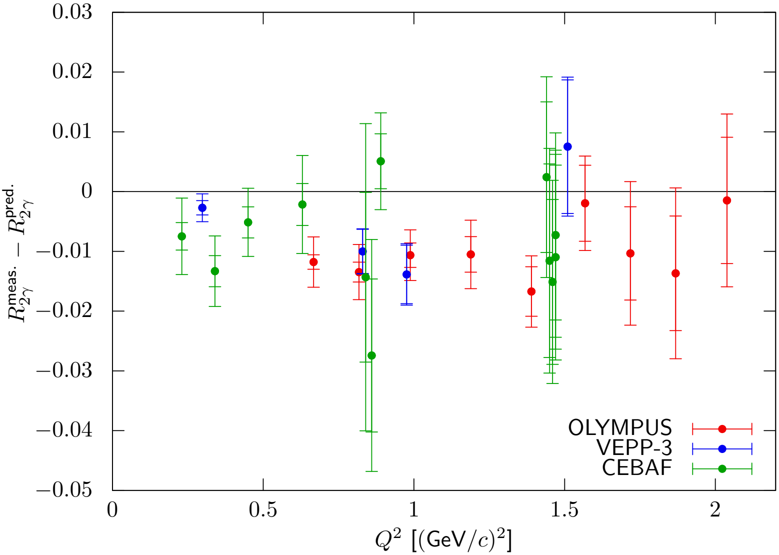
OLYMPUS results (B. Henderson et al., Phys. Rev. Lett. 118, 092501 (2017))



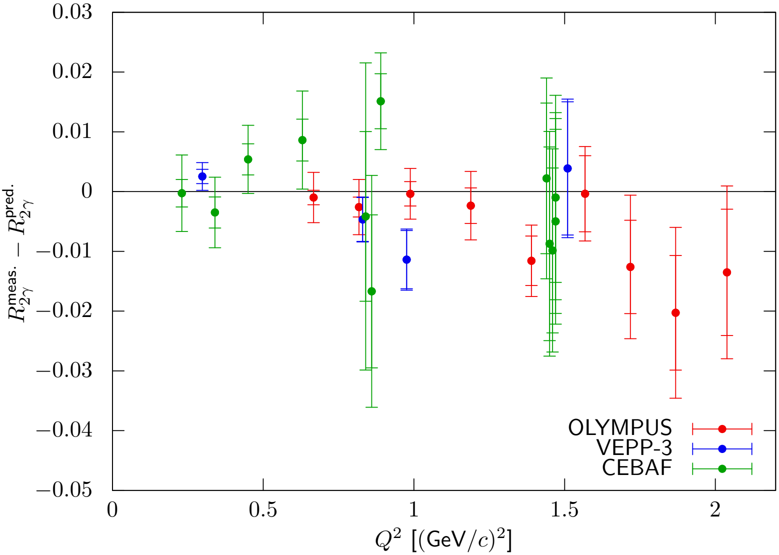
OLYMPUS results re-binned



Difference of data to prediction: Blunden's hadronic calculation



Difference of data to prediction: Bernauer et al. phenomenological prediction



χ^2 of the world data set

	VEPP-3	CLAS		OLYMPUS		World
	$\frac{\chi^2}{n_{\text{d.f.}}}$	$\frac{\chi^2}{n_{\text{d.f.}}}$	N.	$\frac{\chi^2}{n_{\text{d.f.}}}$	N.	$\frac{\chi^2}{n_{\text{d.f.}}}$
No hard TPE	7.97	0.84	0.43σ	0.65	0.75σ	1.53
Blunden	4.01	0.70	1.23σ	0.73	2.14σ	1.088
Bernauer	1.95	0.58	-0.40σ	0.49	0.45σ	0.679

- CLAS and OLYMPUS have too large errors
- Vepp-3 rules out no hard TPE
- Blunden et al get slope right, but large normalization shifts.
    - Probability for worse shift in same direction: $< 0.4\%$
- Phenomenological fit clearly prefered by all three experiments

My view on this

- For the measured values, good agreement with phenomenological extraction.

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$\longrightarrow$Can not extract G_E and G_M from Rosenbluth exps!

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$\longrightarrow$Can not trust polarization based exps on G_E/G_M?

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Need new measurements at relevant kinematics

Planned experiments

Positron beams of the right energy and intensity are scarce.

- Short term: New test beam at DESY. Intensity limits $E_{Beam} \leq 3\,\text{GeV}$
- Long term: JLab contemplates positron source. CLAS12 ideal. LOI for PAC46.

And the radius?

	r_e (fm)	r_m (fm)
(ours) McKinley/Feshbach	0.879	0.777
Borisyuk/Kobuskin	0.876	0.803
Arrington/Sick	0.875	0.769
Blunden et al.	0.875	0.799

All good?

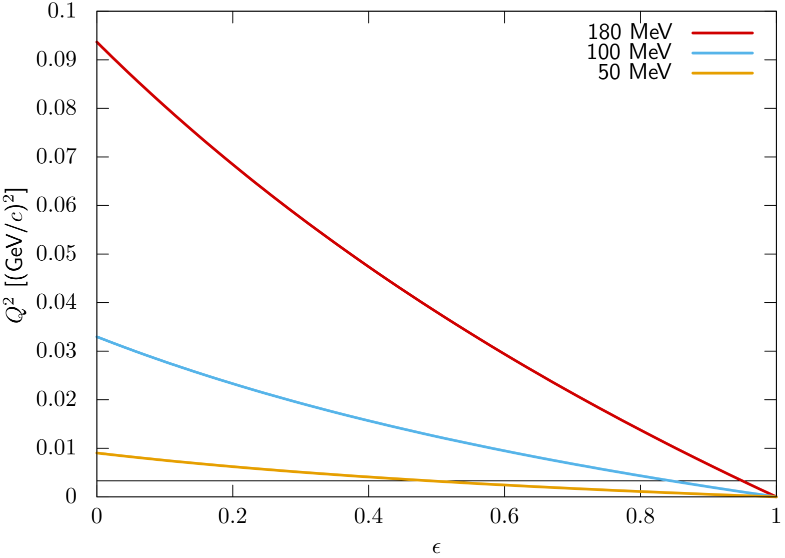
"All" calculations very similar for forward scattering, small Q^2. Feshbach limit.
If current theory fails for large Q^2, can we trust for small Q^2.
In other words: Is the Feshbach limit "mostly" correct.

We need to test this!

Two ways to test:

- Direct measurement. Needs positrons
- Observe non-linearities in Rosenbluth: needs many and extreme ε

Low-Q , small ε is hard



The way ahead

Question: Which planned experiments aim at low-Q^2, small ε?

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Answer: none

The way ahead

Question: Which planned experiments ~~aim at~~ also measure low-Q^2, small ε?

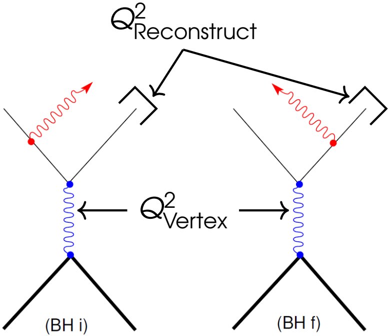
Answer: ...

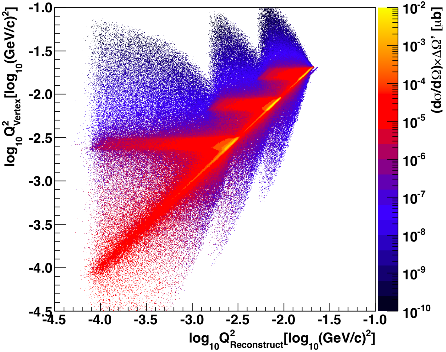
Three ways to get to lower Q^2

$$Q^2 = 4EE'\sin^2\frac{\theta}{2}$$

- Smaller scattering angle $\longrightarrow$ PRad$\longrightarrow \epsilon \approx 1$
- Lower beam energy $\longrightarrow$ MESA
- Initial State Radiation

ISR method

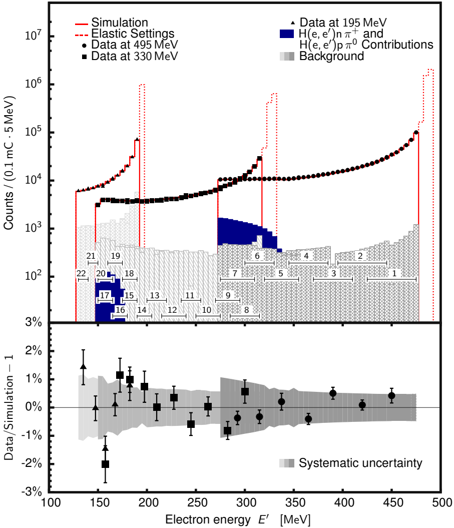




- Use initial state radiation to reduce effective beam energy
- Have to subtract FSR

ISR at MAMI

- ISR $\longrightarrow$ small E $\longrightarrow$ small Q^2
- Extract F.F. from radiative tail
- Or: test radiative tail description



See: arXiv:1612.06707

ISR at MAMI

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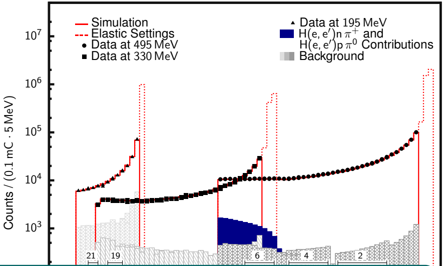
- Extract FF from



Status

- Published: PLB 771:194-198
- Radiative correction correct on the 1% level deep in the tail!
- Radius extraction not competitive in precision
- In principle: Could be redone at larger scattering angle
- But: rates small

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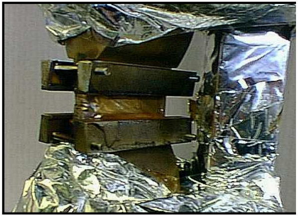
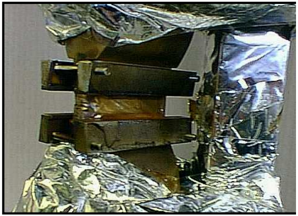


Target dominant source of uncertainty

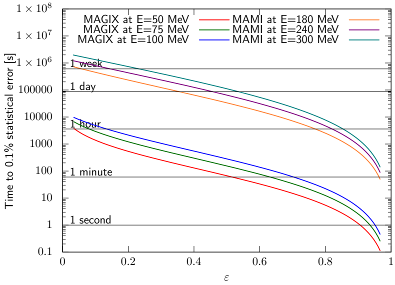
- For Mainz data, systematic errors dominate
  - Background from target walls
  - Acceptance correction for extended target
- Eliminate with jet target
  - point-like
  - no walls
  - but less density
- Rinse, repeat with D,^{3}He,^{4}He, ...

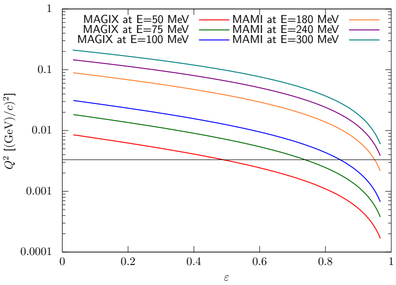


$\Downarrow$

Mainz future plans

- Repeat ISR with new target
- Use new target also for classic approach





Took first data in April! Full MAMI experiment next year, MESA 2021. See talk by Yimin.

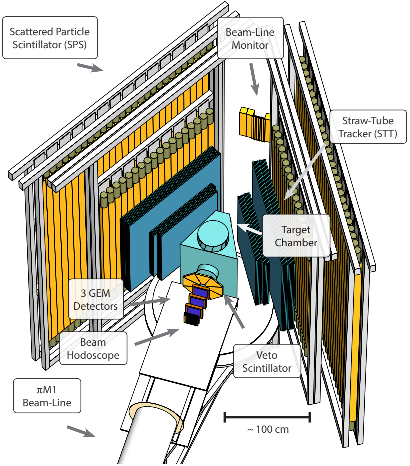
MUSE - Muon Scattering Experiment at PSI

World's most powerful low-energy $e/\pi/\mu$-beam:

Direct comparison of *ep* and μp!

- Beam of $e^+/\pi^+/\mu^+$ or $e^-/\pi^-/\mu^-$ on liquid H_2 target
  - Species separated by ToF, charge by magnet
- Absolute cross sections for *ep* and μp
- Ratio to cancel systematics
- Charge reversal: test TPE
- Momenta 115-210 MeV/c $\Rightarrow$ Rosenbluth G_E, G_M

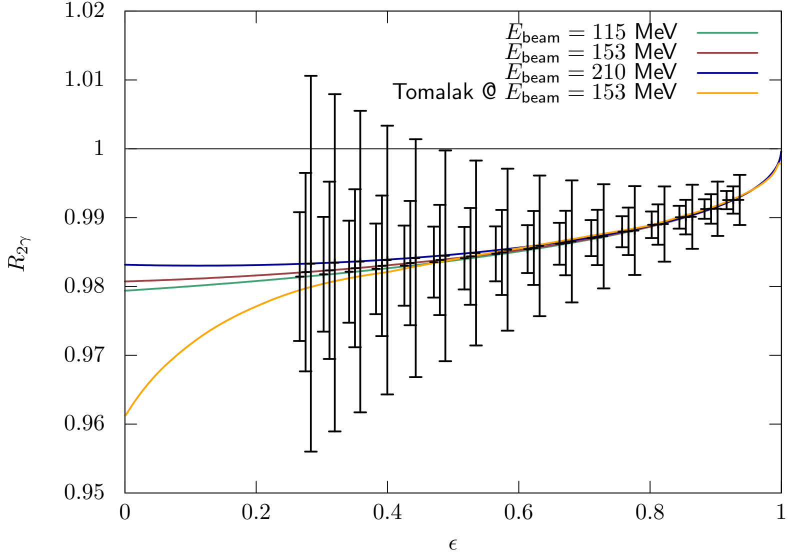
Experiment layout



R. Gilman et al., arXiv:1303.2160 (nucl-ex)

- Secondary beam $\Longrightarrow$ track beam particles
- Low flux (5 MHz)$\Longrightarrow$ large acceptance
- Mixed beam $\Longrightarrow$ PID in trigger

MUSE projected errors ($e^{\pm}$only)



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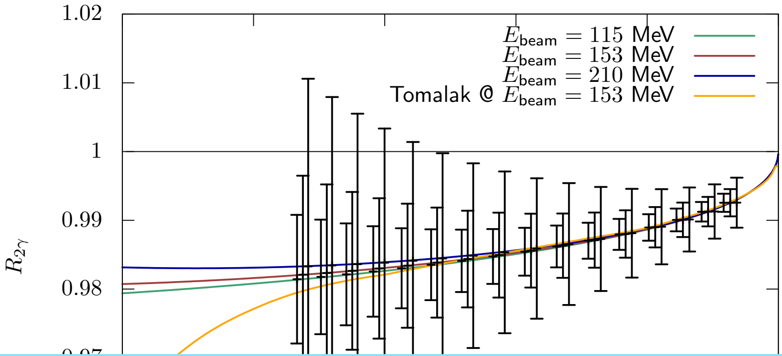

- Can test ϵ behavior important for electric radius
- Maybe test theory
- Cannot test ϵ behavior important for magnetic radius
- Low-ϵ experiment at PSI not feasible.

Other experiments

- Many ultra-low-Q^2 measurements for proton radius
- Active target (Hydrogen TPC)
  - Mainz
    - might be modified to look at back angles
  - COMPASS
    - ultra-high momentum muons

What about polarization?

- Measure asymmetries $A_\perp$ and $A_{||}$ to get ff ratio
- At high Q^2: Measure c.s.$\rightarrow$ G_M, + ratio gives G_E

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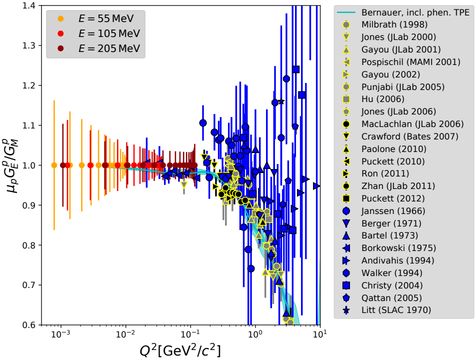
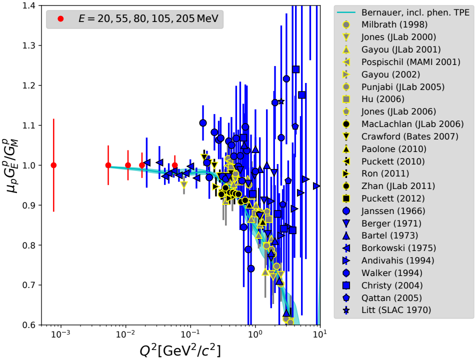
- At high Q^2: Measure c.s. $\rightarrow$ G_M, + ratio gives G_E
- At low Q^2: Measure c.s. $\rightarrow$ G_E, + ratio gives G_M
- Two possibilities:
  - Classic: 1 spectrometer
  - Advanced: 2 spectrometer
    - measure $A_\perp$ and $A_{||}$ at the same time

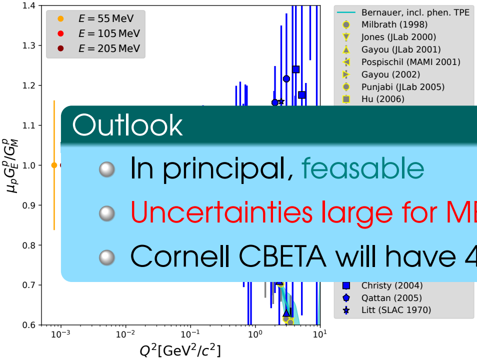
Polarization at MESA

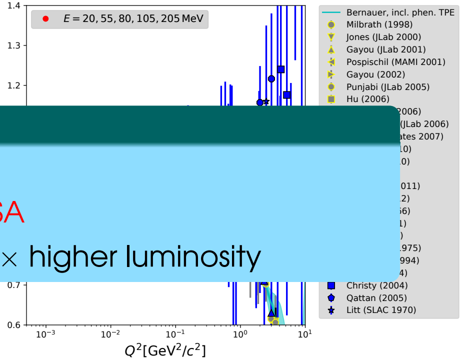




Plots and rate calculation by Sören Schlimme

Polarization at MESA





Outlook

- In principal, feasable
- Uncertainties large for MESA
- Cornell CBETA will have $40\times$ higher luminosity

Plots and rate calculation by Sören Schlimme

Summary

- Form factor ratio puzzle not 100% resolved.
- Low Q^2 TPE needs to be checked!
- Many experiments, but essentially all aim to measure proton radius
- Few will produce data useful for test of TPE (also: G_M) , or could be extended to do so.
- Need a dedicated program. Need strong motivation to do so!