Proton form factors: Interesting at all scales

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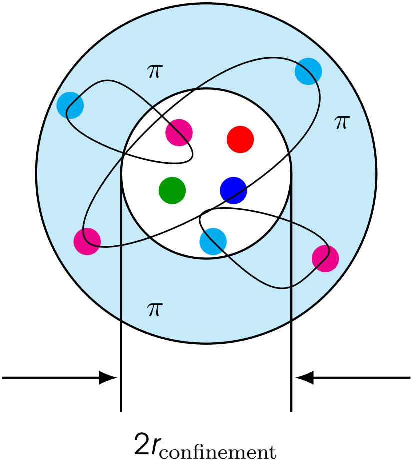
SPhN Seminar Saclay, October 2013

Massachusetts Institute of Technology

Overview

- Motivation
- High Q^2: Two-Photon-Exchange
- Middle Q^2: Pushing the precision boundary
- Low Q^2: The size of the proton
- New data

What is a proton?



Cross section and form factors for elastic e-p scattering

The cross section:

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

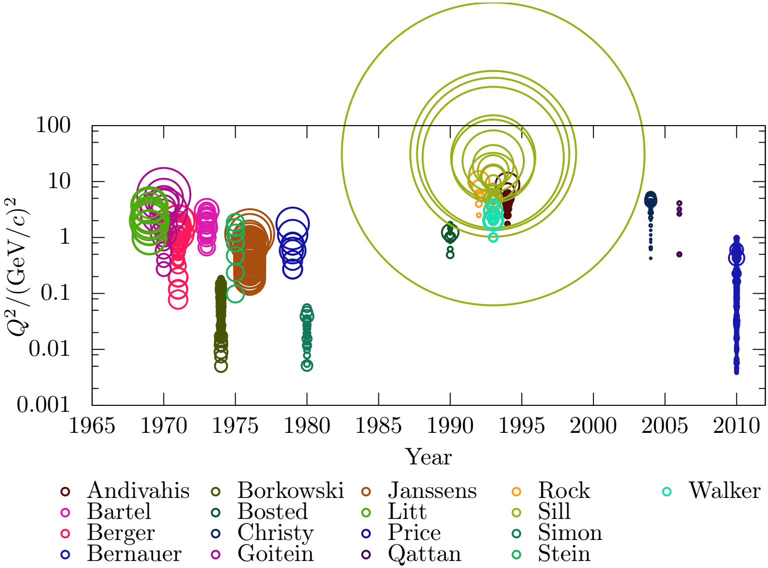
with:

$$\tau = \frac{Q^2}{4m_p^2}, \quad \varepsilon = \left(1 + 2(1+\tau)\tan^2\frac{\theta_e}{2}\right)^{-1}$$

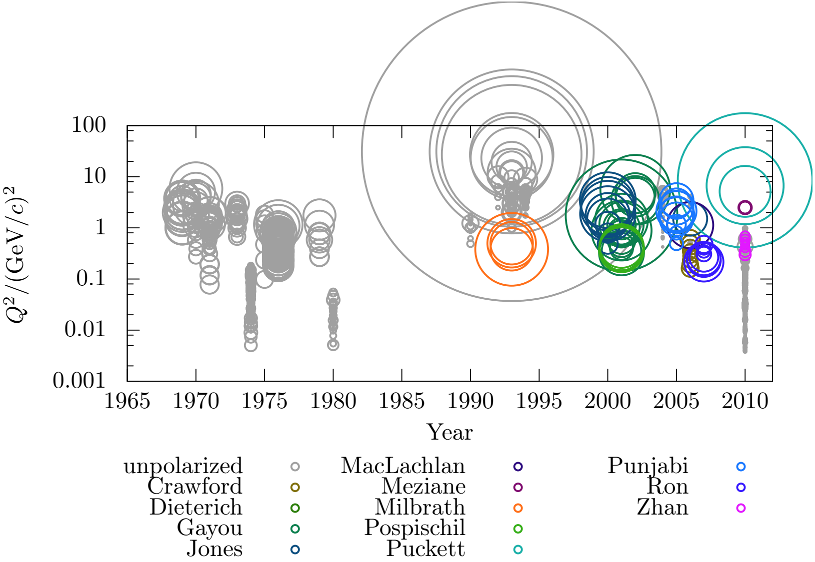
Fourier-transform of $G_E,\ G_M \longrightarrow$ spatial distribution (Breit frame)

$$\left\langle r_E^2\right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}G_E}{\mathrm{d}Q^2}\right|_{Q^2=0} \qquad \left\langle r_M^2\right\rangle = -6\hbar^2 \left.\frac{\mathrm{d}\left(G_M/\mu_p\right)}{\mathrm{d}Q^2}\right|_{Q^2=0}$$

Unpolarized: Rosenbluth



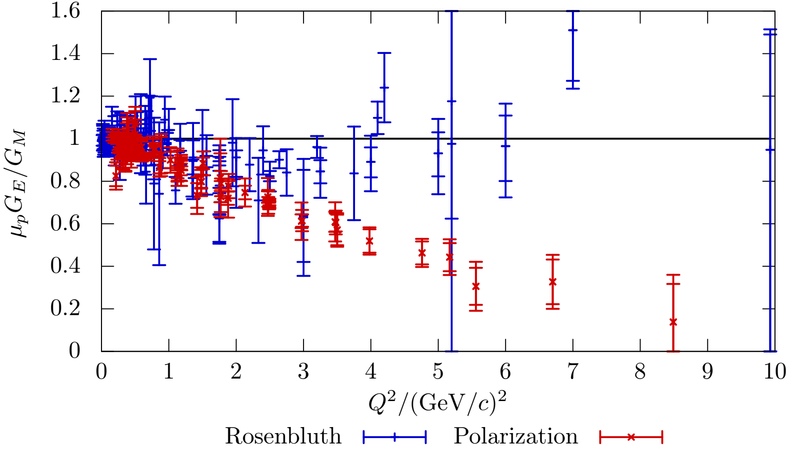
Polarized: Ratio



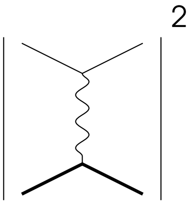
Large Q^2

Q^2 Q^2 Q^2

Ratio: Difference!



Most likely solution: Two Photon Exchange



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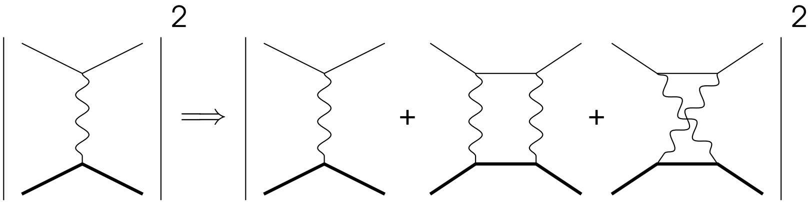
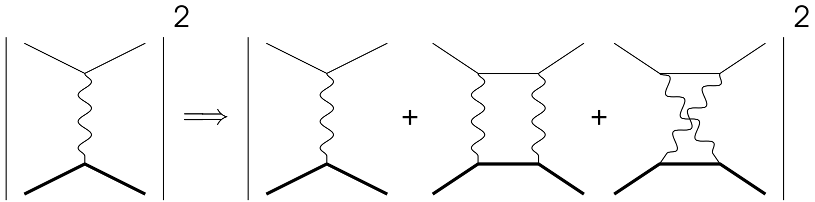


Two-Photon-Exchange

- Not in standard radiative corrections
- Off-shell proton!
- How to handle high momenta in loop?

Most likely solution: Two Photon Exchange



Two-Photon-Exchange

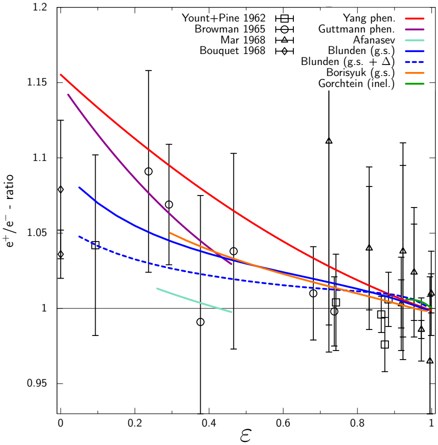
- Not in standard radiative corrections
- Off-shell proton!
- How to handle high momenta in loop?

Measurement

- Rosenbluth/polarized reconciled?
- How to treat the hadron line?

Measure TPE

- Interference term changes sign with lepton sign!
- Measured in the 1960s
- Not much data
- A lot of predictions!



Three modern experiments

Novosibirsk/VEPP-3

- Analysis in progress
- 1.6/1 GeV beam
- No magnetic field

CLAS/Jlab

- Analysis in progress
- e^- to γ to $e^{+/-}$ -beam

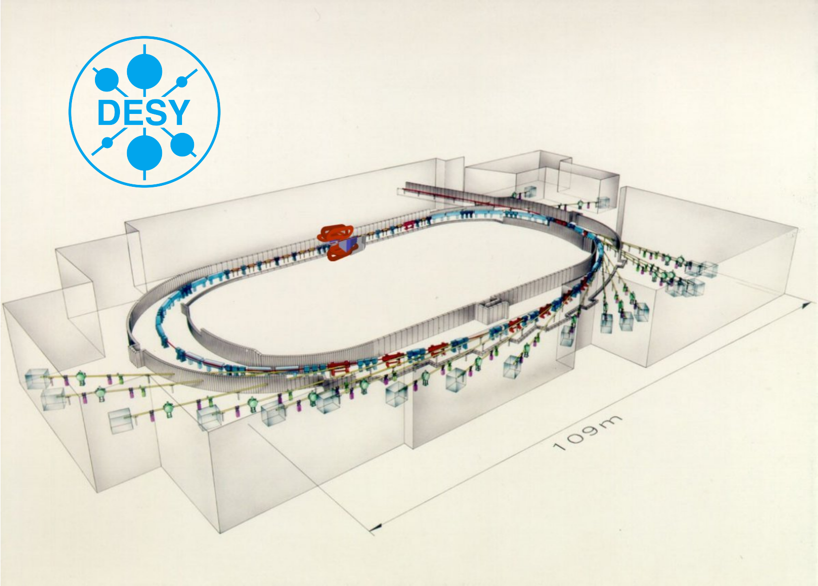
OLYMPUS

- Doris/DESY
- 2 GeV beam
- data taking finished 01/2013

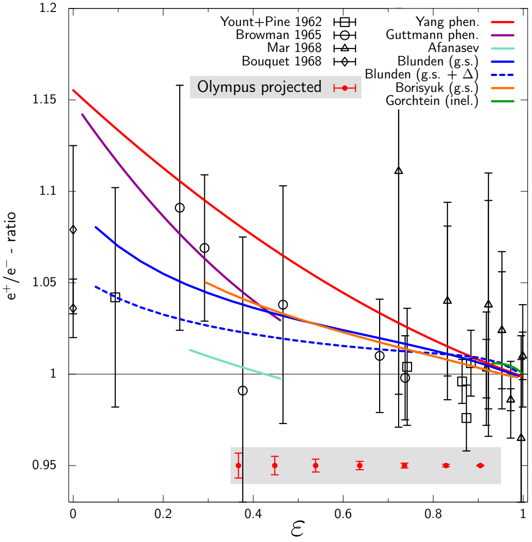
The OLYMPUS collaboration

- Arizona State University, USA
- DESY, Hamburg, Germany
- Hampton University, USA
- INFN, Bari, Italy
- INFN, Ferrara, Italy
- INFN, Rome, Italy
- MIT Laboratory for Nuclear Science, Cambridge, USA
- St. Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- University of Bonn, Bonn, Germany
- University of Glasgow, United Kingdom
- University of Mainz, Mainz, Germany
- University of New Hampshire, USA
- Yerevan Physics Institute, Armenia

At DESY: DORIS

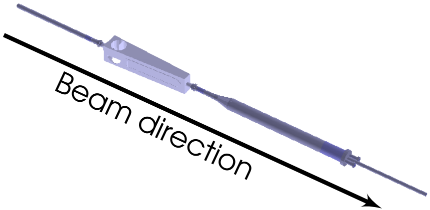


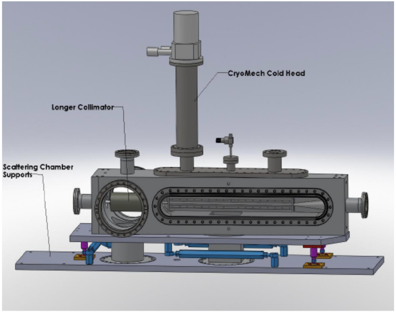
Projected performance

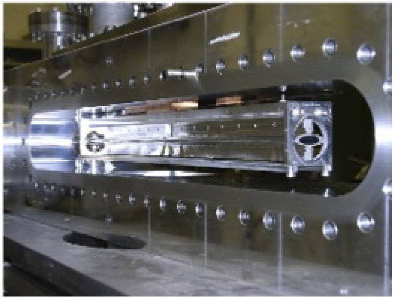


2 GeV beam, Q^2-range: 0.6 to 2.2 GeV^2

Target / Vacuum

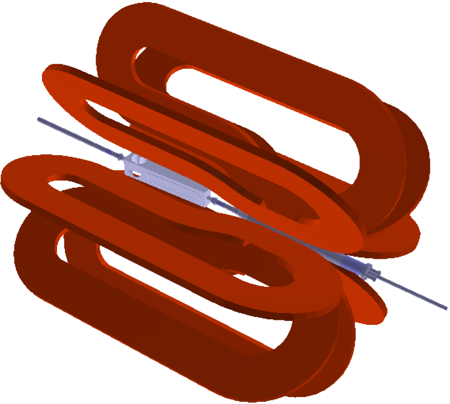






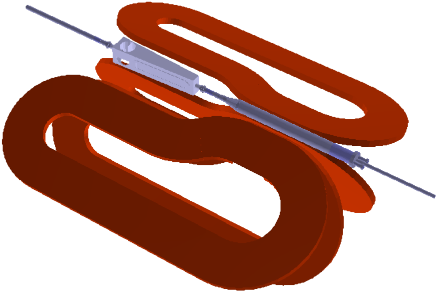
- Open cell design
- Cryogenic
- Target density: $3 \cdot 10^{15}\ \mathrm{cm}^{-2}$
- Multi-stage pump system

Toroid



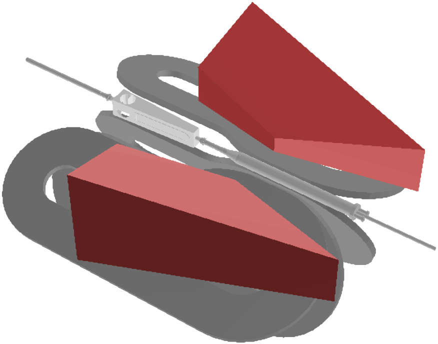
- From BLAST
- $\pm$5000 A = 75% of BLAST
- $\Longrightarrow$ Peak field: 2.8 kG
- 8 coils

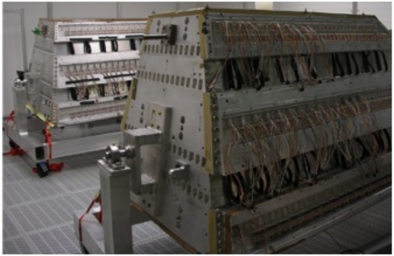
Toroid



- From BLAST
- $\pm$5000 A = 75% of BLAST
- $\Longrightarrow$ Peak field: 2.8 kG
- 8 coils
- 4 shown

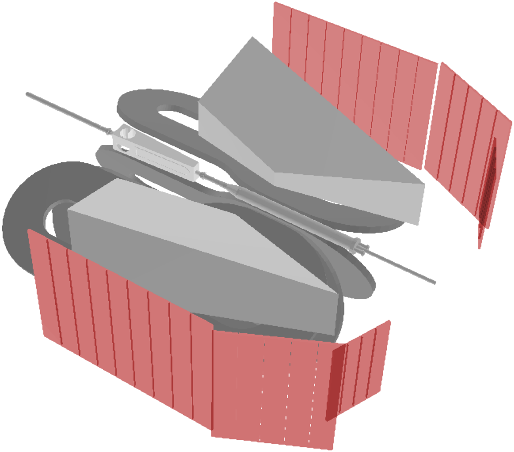
Wire chamber





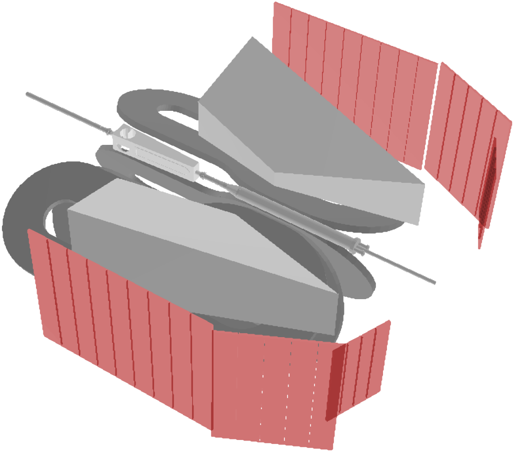
- From BLAST
- HDC design, 3 signal wires
- completely rewired
- $2 \cdot 3$ planes / chamber, 3 chambers / side
- 10° stereo angle

Time Of Flight



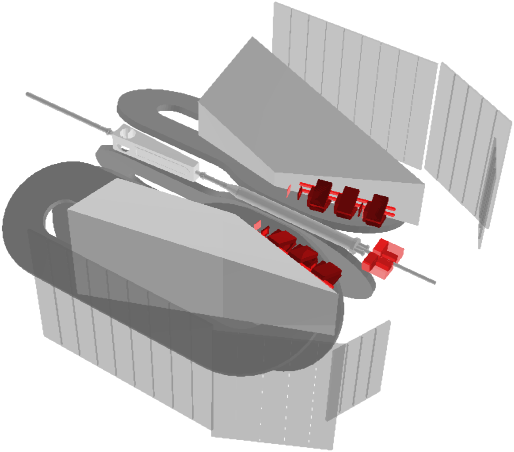
- From BLAST
- Rewrapped, tested
- Trigger
  - Top/bottom coinc.
  - kinematically constrained

Time Of Flight



- From BLAST
- Rewrapped, tested
- Trigger
  - Top/bottom coinc.
  - kinematically constrained
  - + 2nd level WC

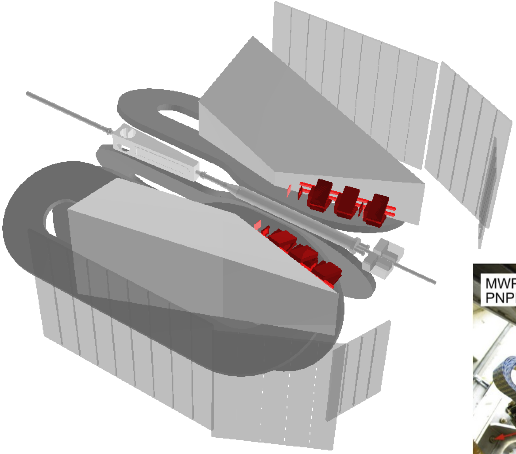
Luminosity



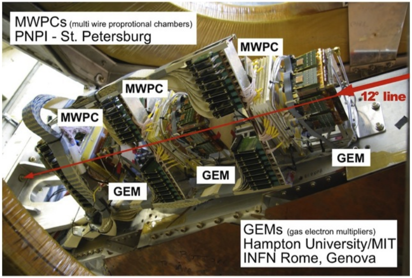
Tight control crucial!
Redundant systems:

- 12°-detector (Hampton, PNPI)
- Symmetric Møller/Bhabha (Mainz)

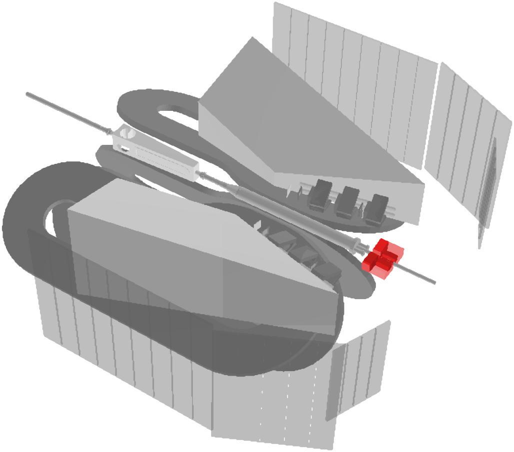
12°-detector

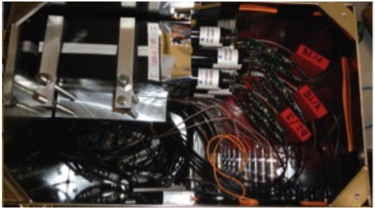


- 3 GEM (Hampton) + 3 MWPC (PNPI) each
- highly redundant
- SiPM trigger scintillators

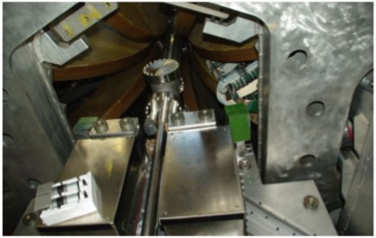


Symmetric Møller/Bhabha





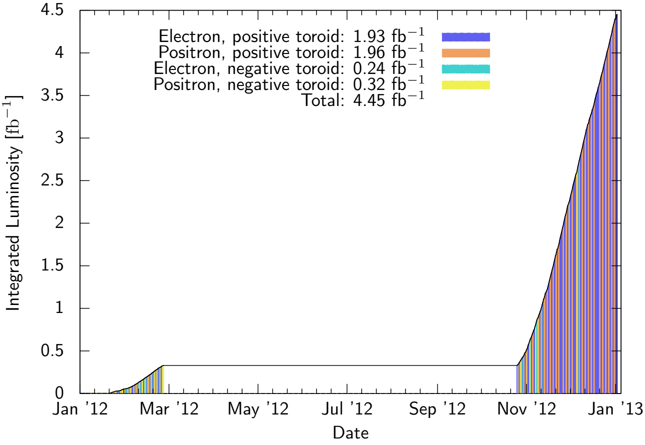
- 2×9 crystals (Mainz)
- 1.3° symmetric angle
- high rate, no deadtime



Timeline

OLYMPUS full proposal	September 2008
Experiment funded by DOE	January 2010
BLAST moved to Germany	Spring 2010
Target test experiment	February 2011
Drift chambers installed	Spring 2011
Luminosity monitors installed	Summer 2011
Olympus roll-in	July 2011
First full Olympus test	August 2011
Sym. Møller/Bhabha installed	Fall 2011
First data run	January 2012
Second data run	October-December 2012
DORIS shut down	January 2013

Luminosity

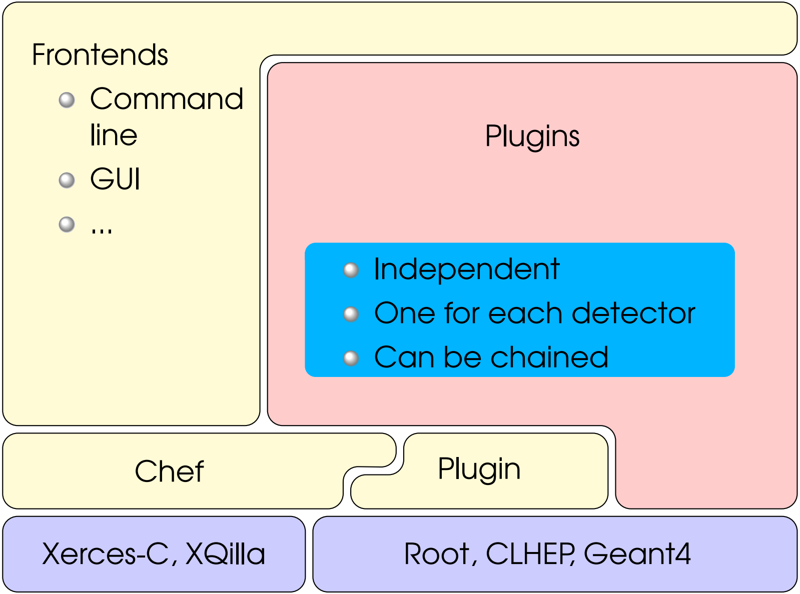


- Exceeded goal for integrated luminosity: > 4 fb^{-1}

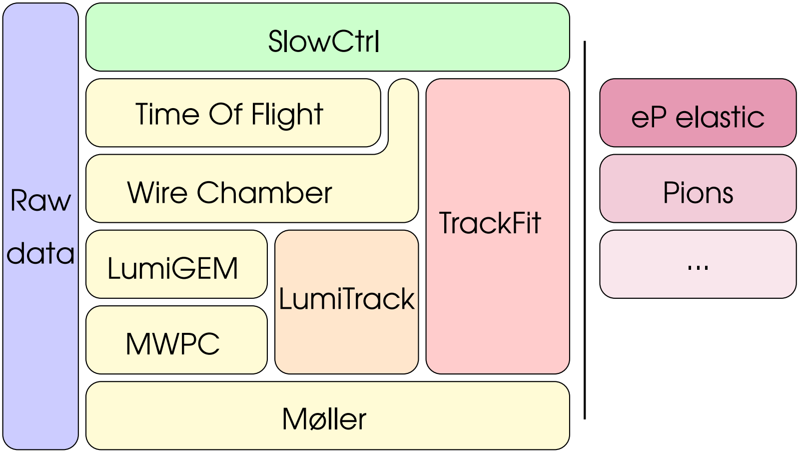
Analysis

CAVEAT: The analysis has just started. All plots are preliminary.

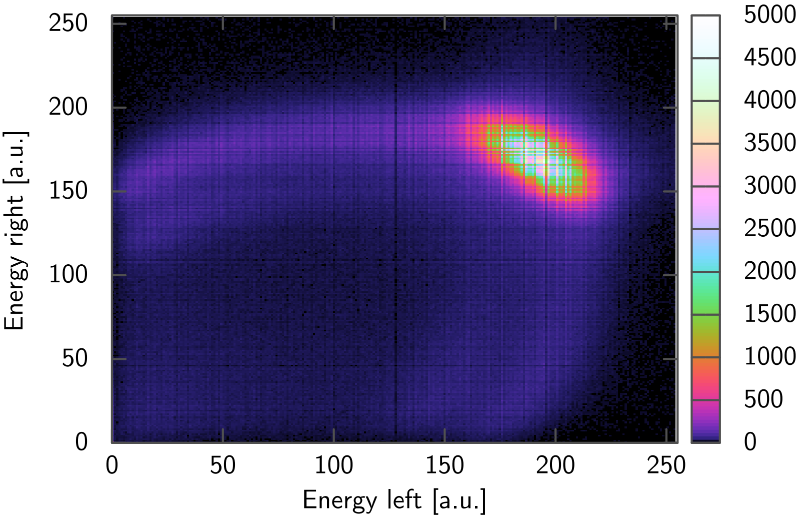
Analysis software stack: Cooker



Plugin System



Symmetric Møller - Coincidence



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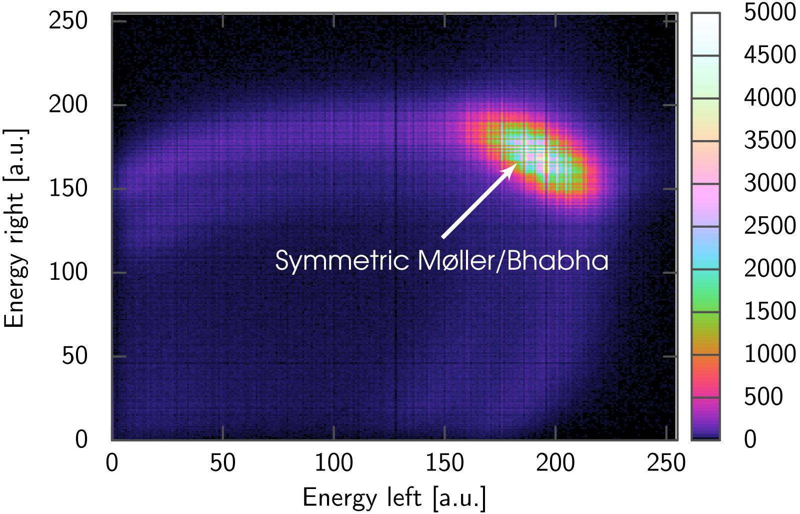
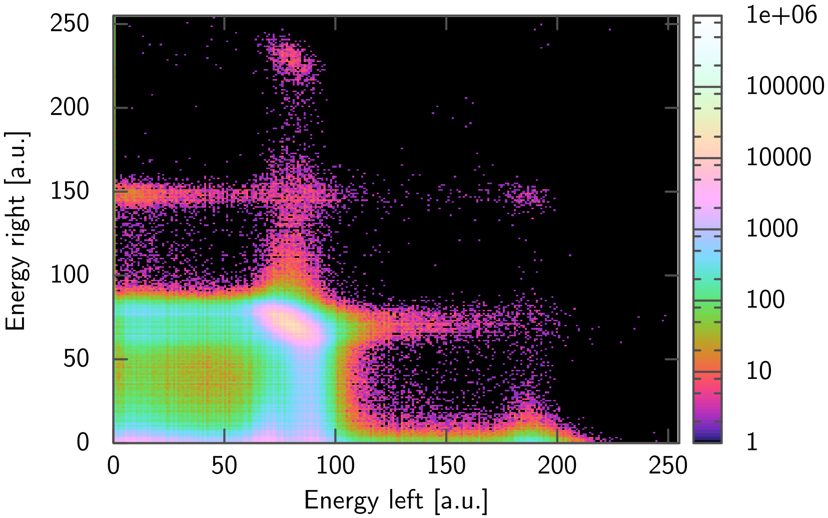
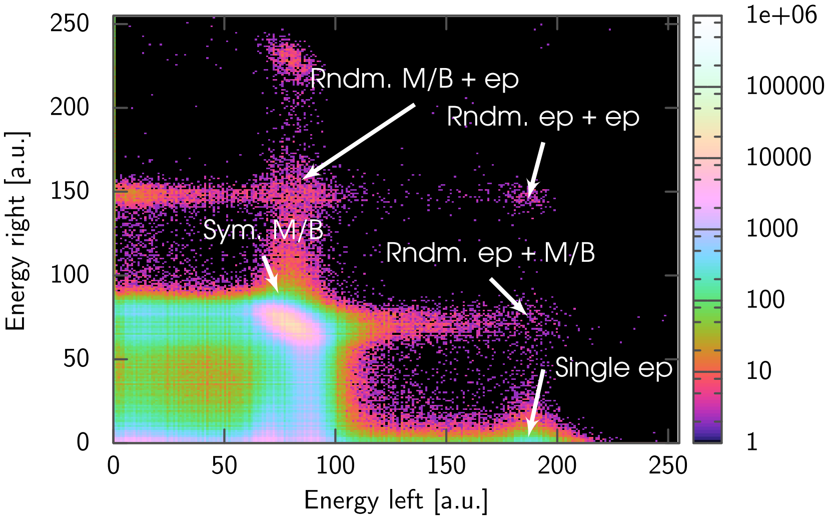


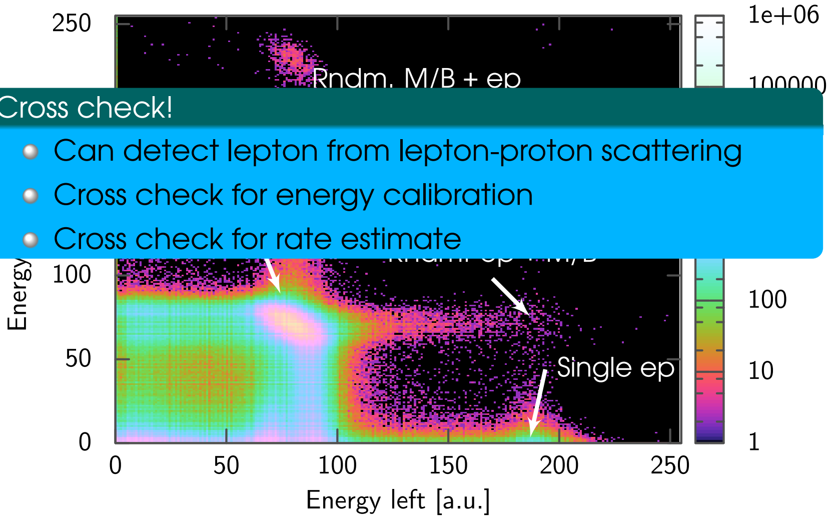
Symmetric Møller - Left Master



Symmetric Møller - Left Master



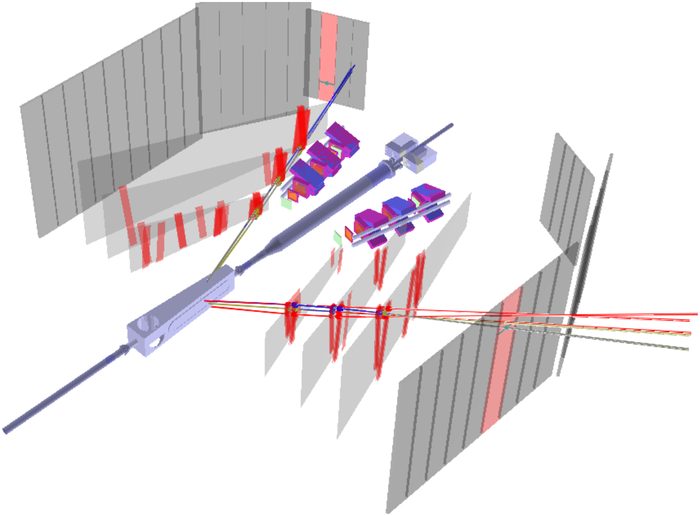
Symmetric Møller - Left Master



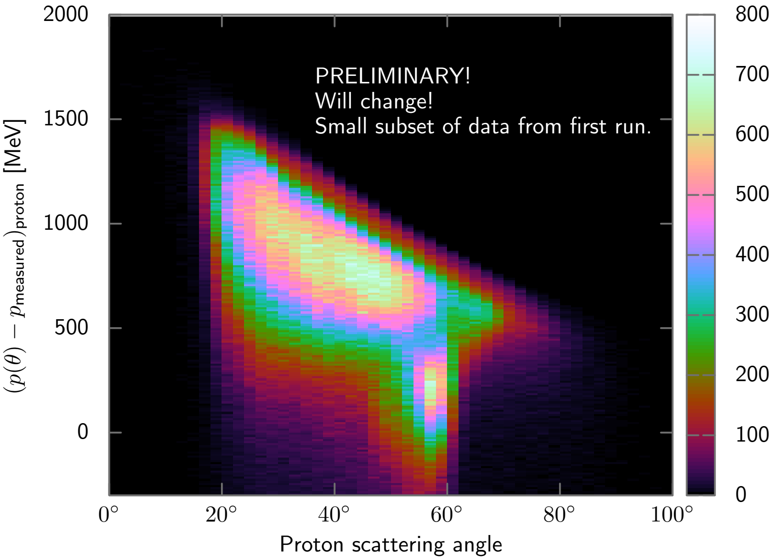
Cross check!

- Can detect lepton from lepton-proton scattering
- Cross check for energy calibration
- Cross check for rate estimate

Wire chamber / Event-Display



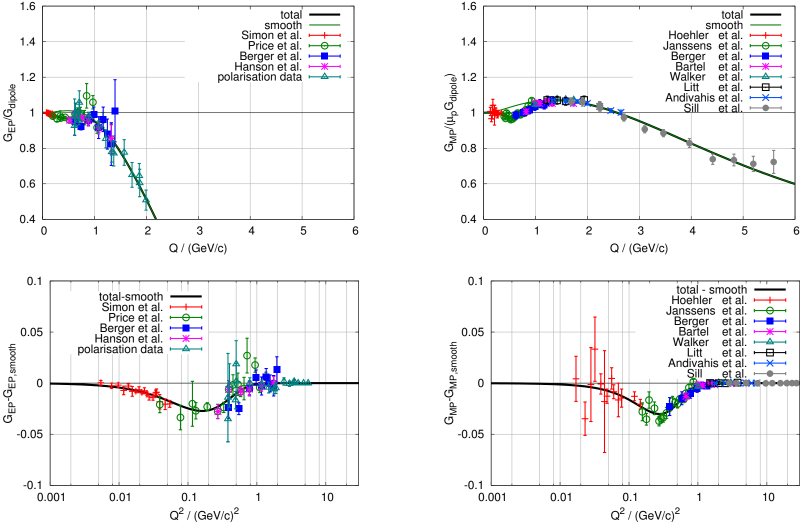
Reconstructed proton momentum



Middle Q^2

$$Q^2 \quad Q^2 \quad Q^2$$

Motivation: Structure



(see J. Friedrich and Th. Walcher, Eur. Phys. J. A **17** (2003) 607)

High-precision p(e,e′)p measurement at MAMI

Three spectrometer facility of the A1 collaboration:

Design goal: High precision

- Statistical precision: 20 min beam time for <0.1%

Design goal: High precision through redundancy

- Statistical precision: 20 min beam time for <0.1%
- Control of luminosity and systematic errors:

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Redundancy!

Design goal: High precision through redundancy

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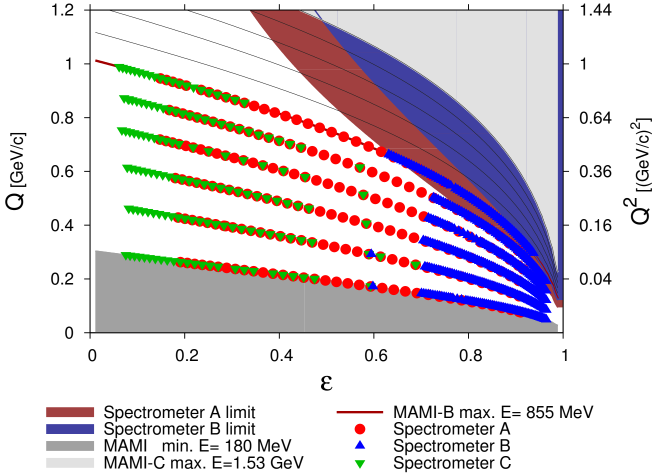
Redundancy!

- Redundant beam current measurement
  Foerster probe $\Longleftrightarrow$ pA-meter

- Redundant luminosity:
  current $\times$ density $\times$ target length $\Longleftrightarrow$ spectrometer as monitor

- Overlapping acceptance
- Where possible: Measure at the same scattering angle with two spectrometers

Measured settings

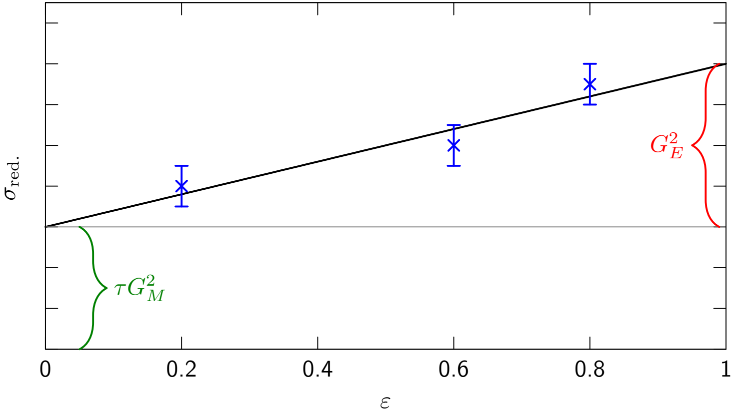


1400 settings

How to extract the form factors?

Two methods:

1. Classical Rosenbluth separation



How to extract the form factors?

Two methods:

1. Classical Rosenbluth separation
2. "Super-Rosenbluth separation": Fit of form factor models directly to the measured cross sections
   - Feasible due to fast computers.
   - All data at all Q^2 and ε values contribute to the fit, i.e. full kinematical region used, no projection (to specific Q^2) needed.
   - Easy fixing of normalization.

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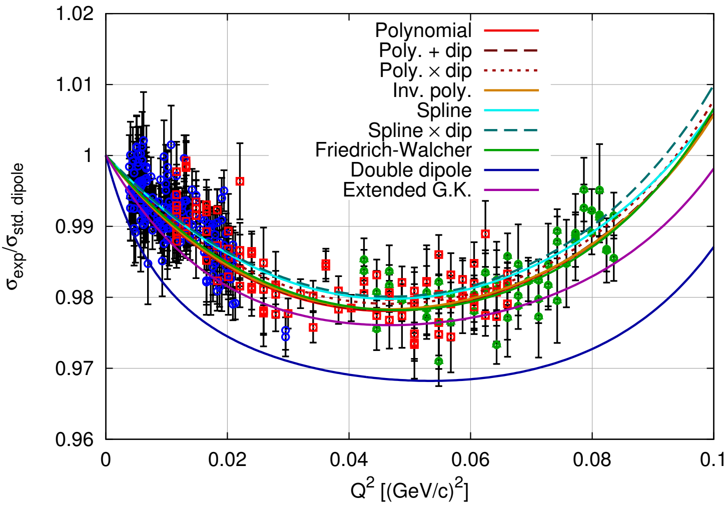
For radii extraction: Needs a fit anyway!
Classical Rosenbluth: Extracted G_E and G_M highly correlated! $\Longrightarrow$Error propagation very involved.

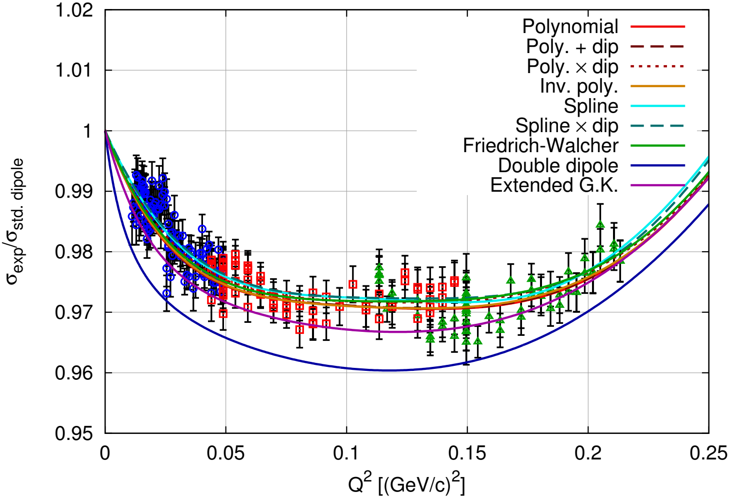
Models

- Dipole, double Dipole
- Friedrich / Walcher phenomenological ansatz
- extended Gari-Krümpelmann (VMD), Lomon et al.
- Polynomials (+/$\times$ dipole)
- Splines

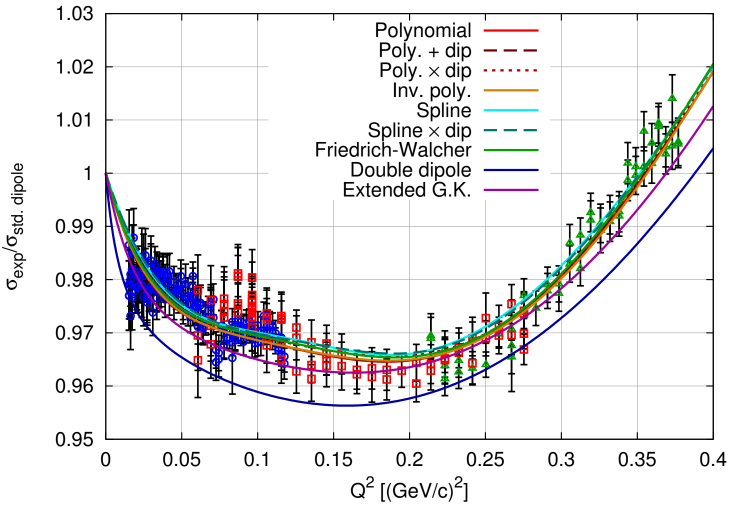
Cross sections: 180 MeV



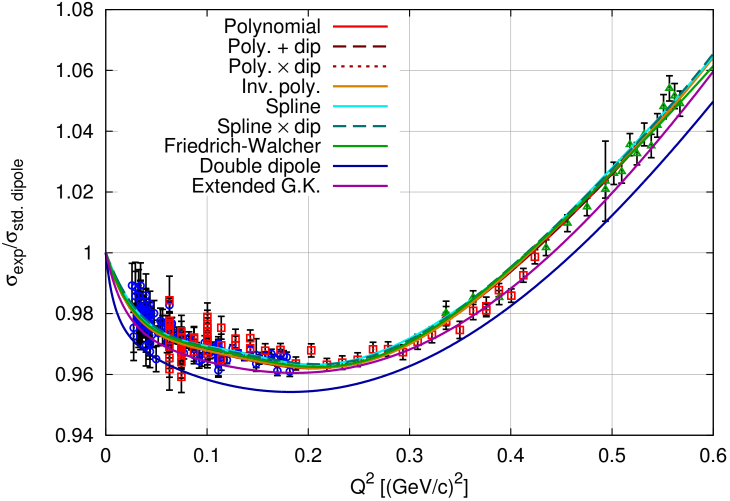
Cross sections: 315 MeV



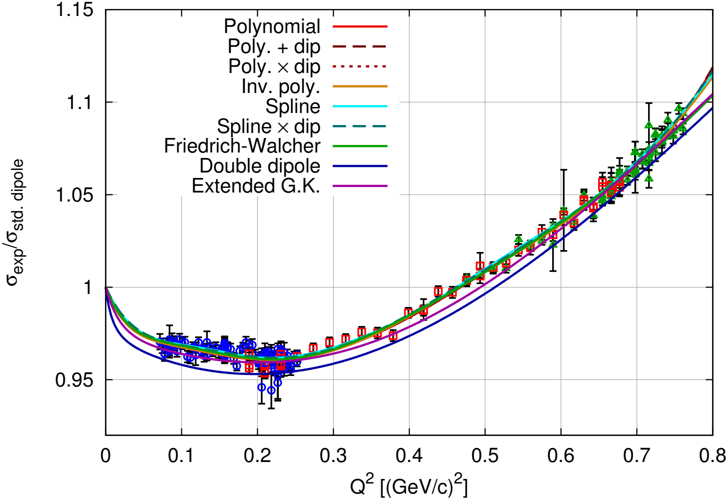
Cross sections: 450 MeV



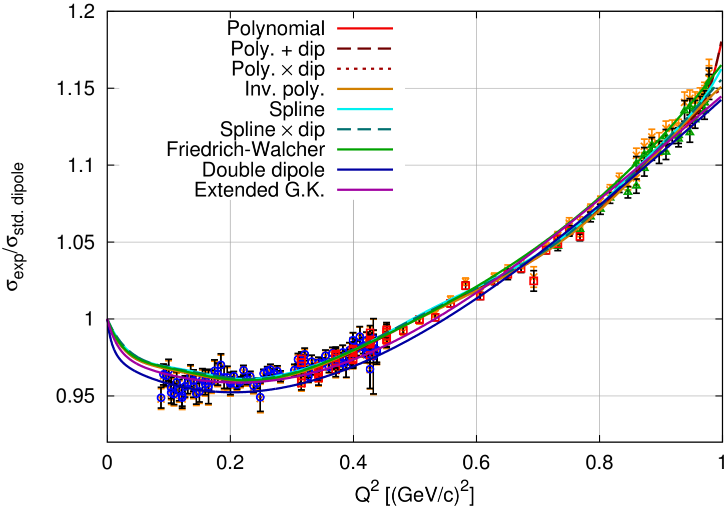
Cross sections: 585 MeV

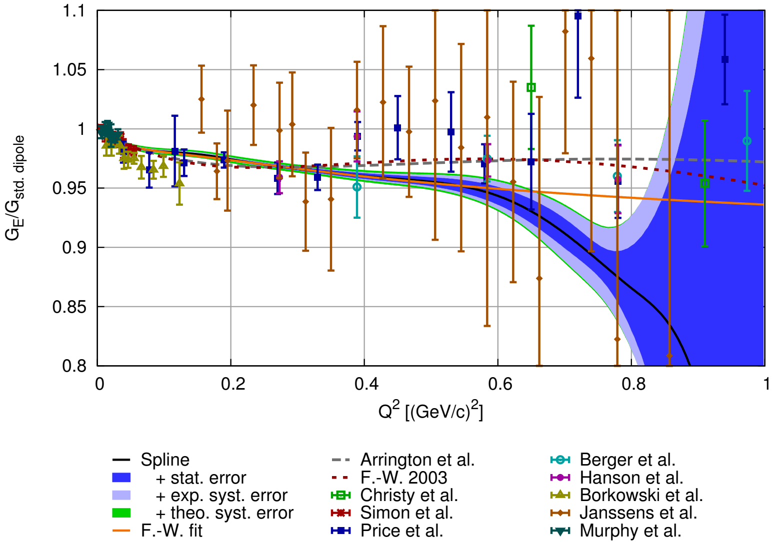


Cross sections: 720 MeV



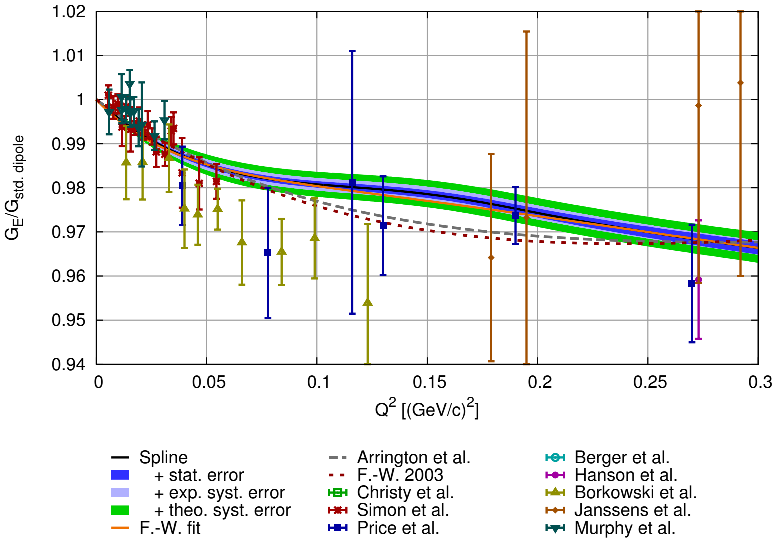
Cross sections: 855 MeV





1.1
1.05
1
0.95
0.9
0.85
0.8
0
0.2
0.4
0.6
0.8
1
$G_E/G_{std. dipole}$
Q^2 [(GeV/c)^2]
Spline
+ stat. error
+ exp. syst. error
+ theo. syst. error
F.-W. fit
Arrington et al.
F.-W. 2003
Christy et al.
Simon et al.
Price et al.
Berger et al.
Hanson et al.
Borkowski et al.
Janssens et al.
Murphy et al.

G_E - low Q^2


1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
0.94
0
0.05
0.1
0.15
0.2
0.25
0.3
$G_E/G_{std. dipole}$
Q^2 [(GeV/c)^2]
Spline
+ stat. error
+ exp. syst. error
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F.-W. fit
Arrington et al.
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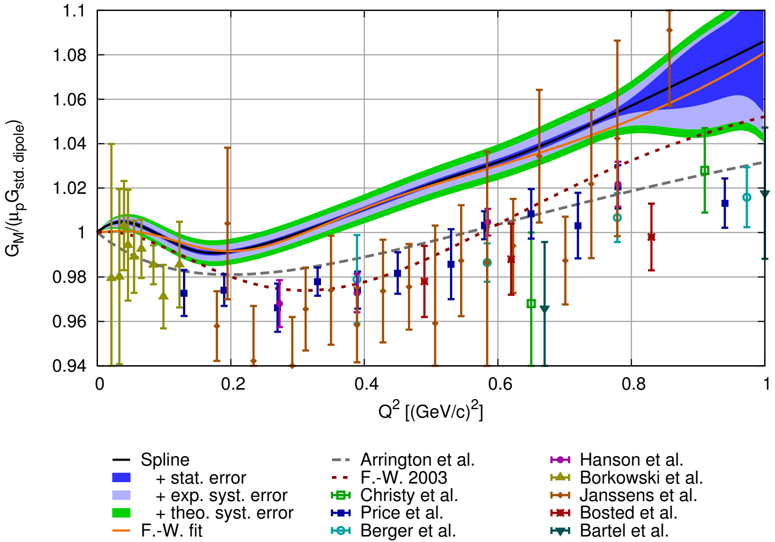
G_M



1.1
1.08
1.06
1.04
1.02
1
0.98
0.96
0.94
0
0.2
0.4
0.6
0.8
1
$G_M/(\mu_p G_{std.\ dipole})$
Q^2 [(GeV/c)^2]
Spline
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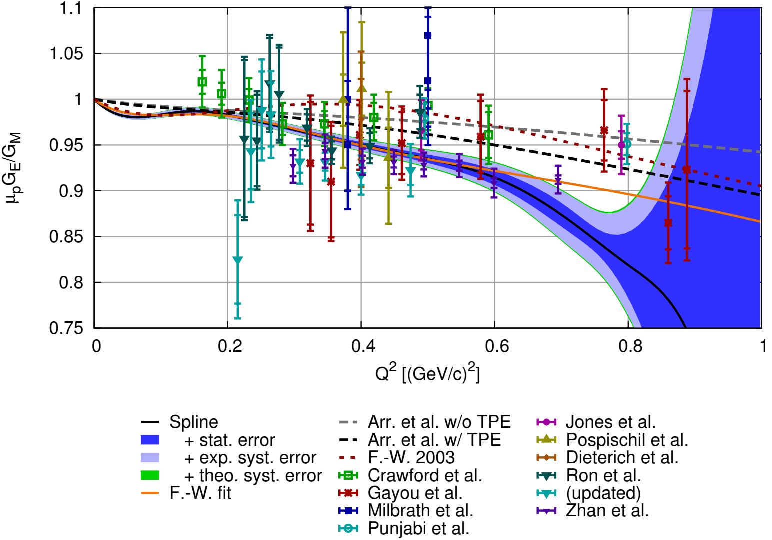

1.1
1.05
1
0.95
0.9
0.85
0.8
0.75
0
0.2
0.4
0.6
0.8
1
$\mu_p G_E/G_M$
Q^2 [(GeV/c)^2]
Spline
+ stat. error
+ exp. syst. error
+ theo. syst. error
F.-W. fit
Arr. et al. w/o TPE
Arr. et al. w/ TPE
F.-W. 2003
Crawford et al.
Gayou et al.
Milbrath et al.
Punjabi et al.
Jones et al.
Pospischil et al.
Dieterich et al.
Ron et al.
(updated)
Zhan et al.

Inclusion of world data

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- Two models:
  - Splines with **variable** knot spacing
    $\Longrightarrow$ Adapt knot density to data density
  - Padé-Expansion
    $\Longrightarrow$ Low(er) flexibility, for comparison

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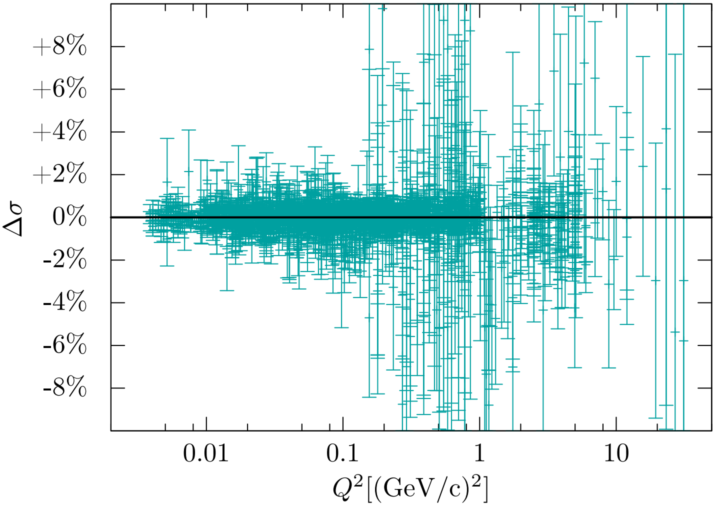
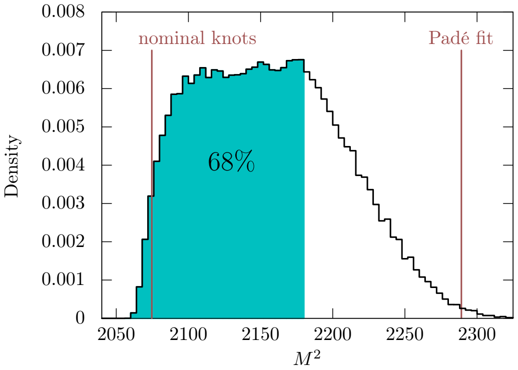
It works!



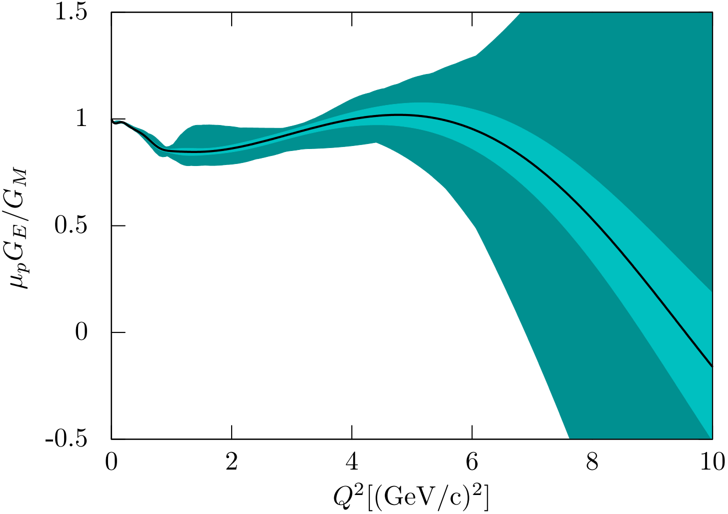
Model dependence

- Vary spline model knots
- Select the 68% best tries.
- Construct envelope of models.



Band will cover at least 68% of all model variations!

Form factor ratio G_E/G_M



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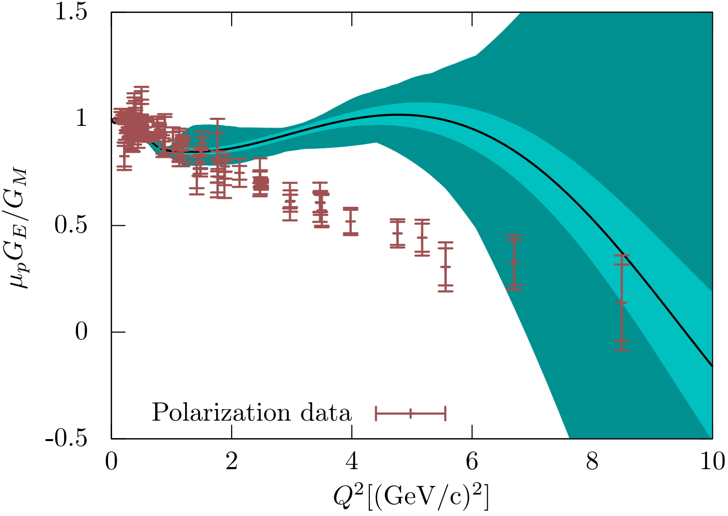

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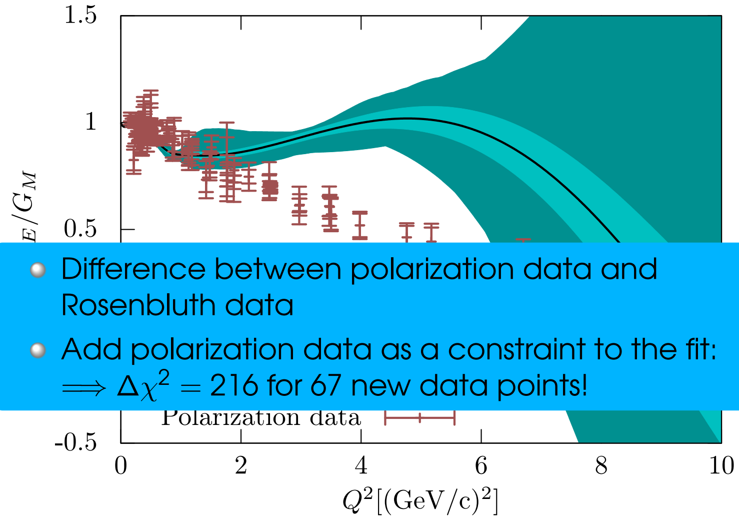


- Difference between polarization data and Rosenbluth data
- Add polarization data as a constraint to the fit: $\Longrightarrow \Delta\chi^2 = 216$ for 67 new data points!

Two Photon Exchange - A parametrisation

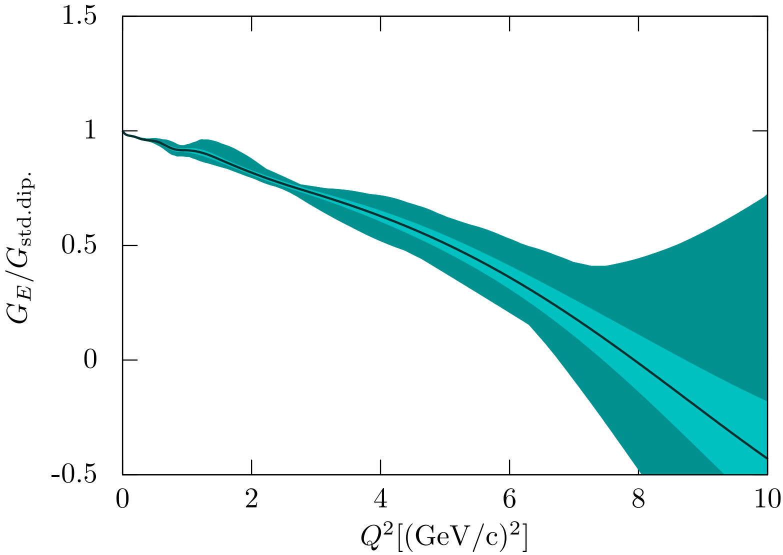
- Available data is sparse
- Mostly Q^2 dependence
- Few data on ε dependence

Two Photon Exchange - A parametrisation

- Available data is sparse
- Mostly Q^2 dependence
- Few data on ε dependence
- Only possible to fit simple model
- In addition to Feshbach Coulomb-correction!

$$\delta = a \cdot (1 - \varepsilon) \cdot \log \left(1 + b \cdot Q^2 \right)$$

G_E fit incl. polarized data



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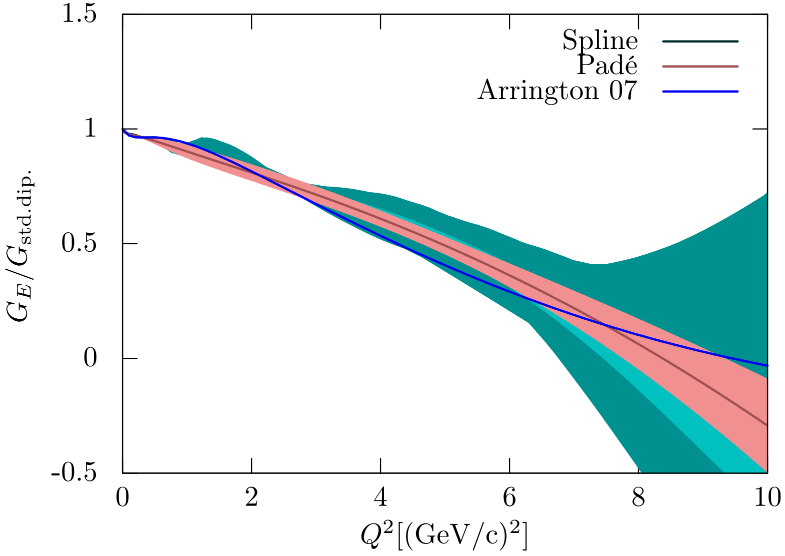
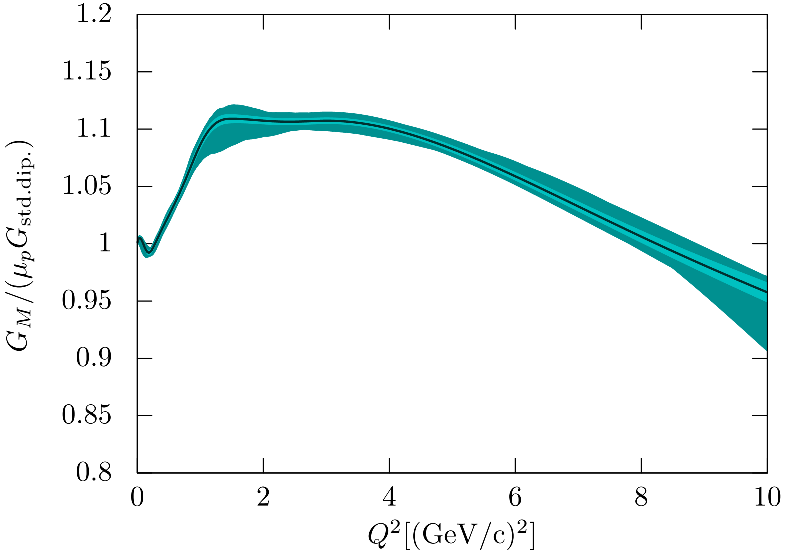
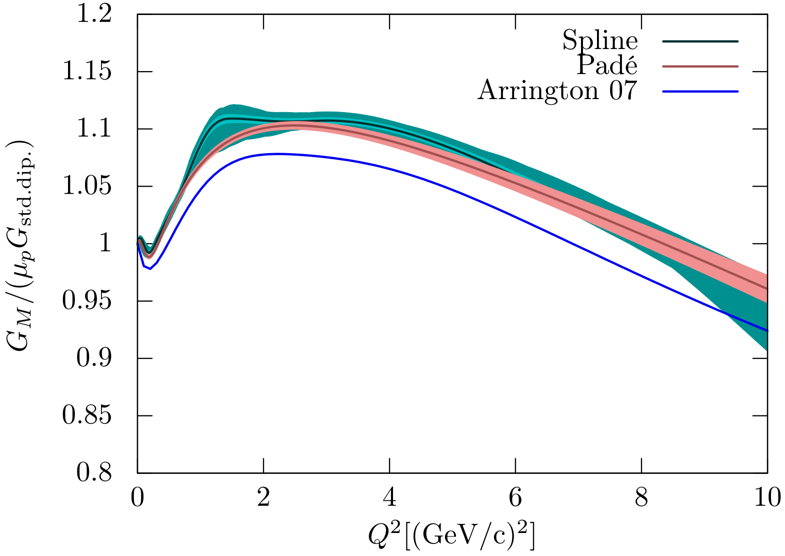


G_M fit incl. polarized data



G_M fit incl. polarized data



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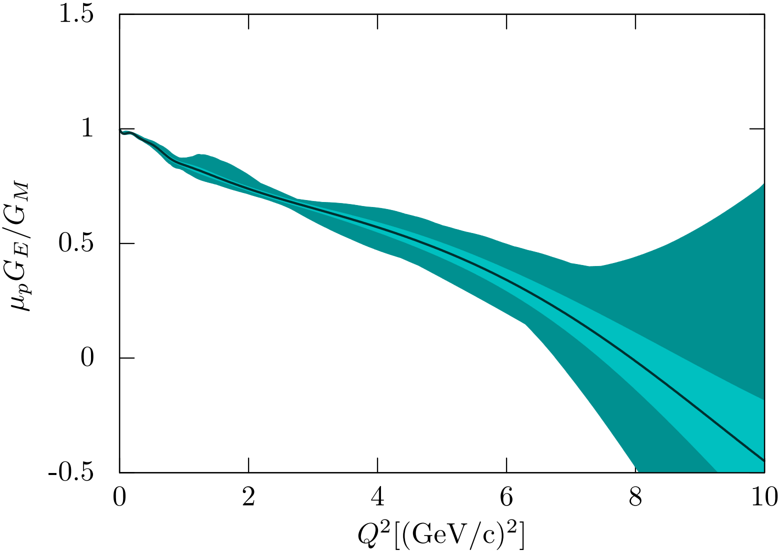

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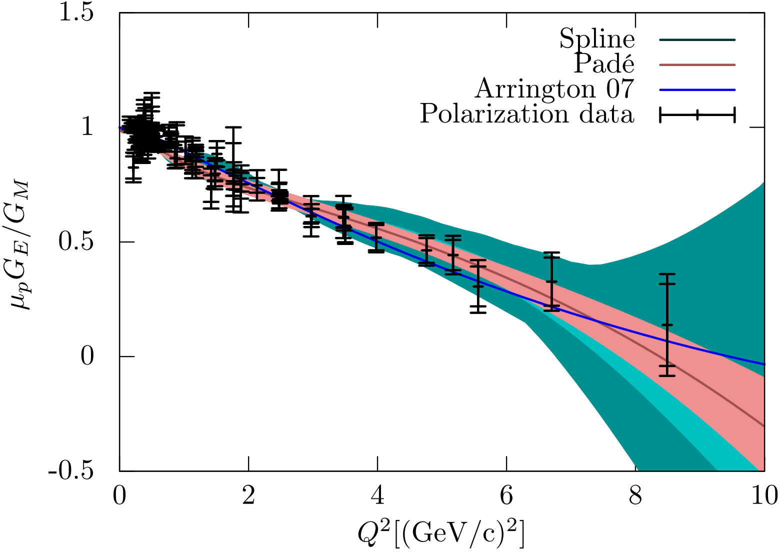
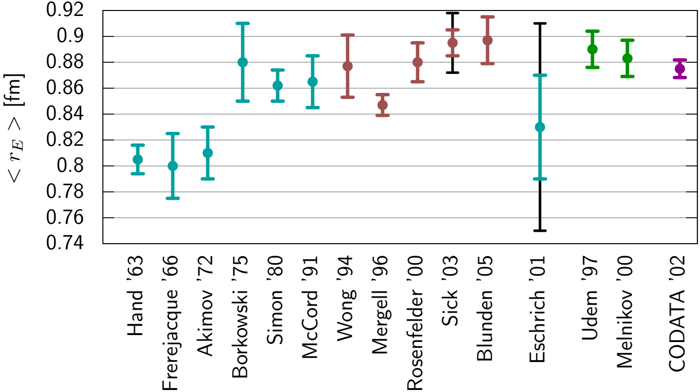


Low Q^2

Q^2 Q^2 Q^2

Radius



0.92
0.9
0.88
0.86
0.84
0.82
0.8
0.78
0.76
0.74
$< r_E >$ [fm]
Hand '63
Frerejacque '66
Akimov '72
Borkowski '75
Simon '80
McCord '91
Wong '94
Mergell '96
Rosenfelder '00
Sick '03
Blunden '05
Eschrich '01
Udem '97
Melnikov '00
CODATA '02

Electric and magnetic radius

Final result from flexible models

$$\left\langle r_E^2 \right\rangle^{\frac{1}{2}} = 0.879 \pm 0.005_{\mathrm{stat.}} \pm 0.004_{\mathrm{syst.}} \pm 0.002_{\mathrm{model}} \pm 0.004_{\mathrm{group}}\ \mathrm{fm},$$

$$\left\langle r_M^2 \right\rangle^{\frac{1}{2}} = 0.777 \pm 0.013_{\mathrm{stat.}} \pm 0.009_{\mathrm{syst.}} \pm 0.005_{\mathrm{model}} \pm 0.002_{\mathrm{group}}\ \mathrm{fm}.$$

Results with world data

	$\left\langle r_E^2 \right\rangle^{\frac{1}{2}}$	$\left\langle r_M^2 \right\rangle^{\frac{1}{2}}$
+ Rosenbluth data	0.878	0.772
+Rosenbluth and Polarization data	0.878	0.769

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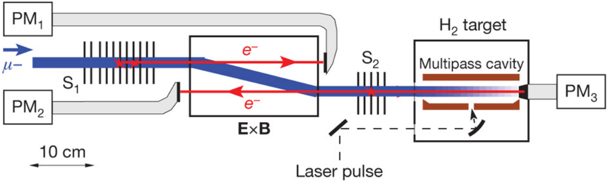
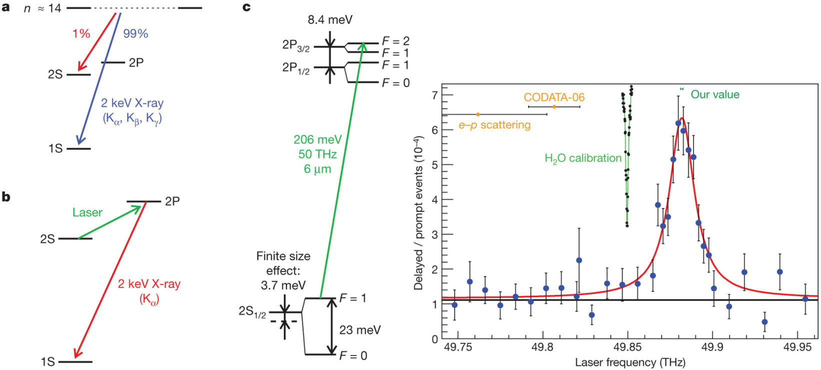
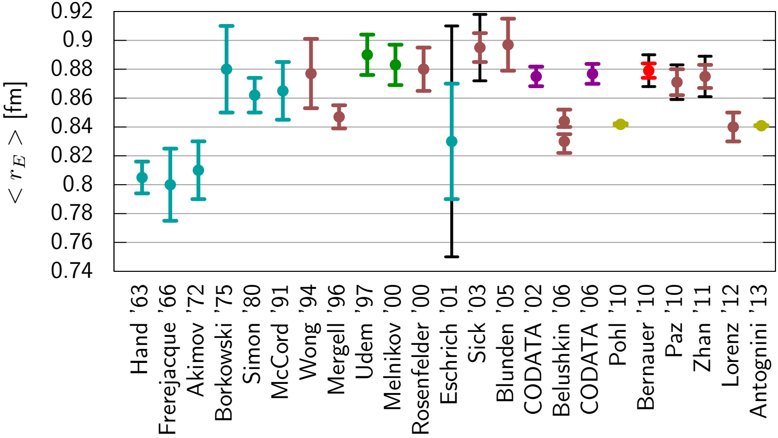
(Eur.Phys.J. D33 (2005) 23-27: Zemach and magnetic radius of the proton from the hyperfine splitting in hydrogen: 0.778(29) fm)

Lamb Shift: muonic Hydrogen

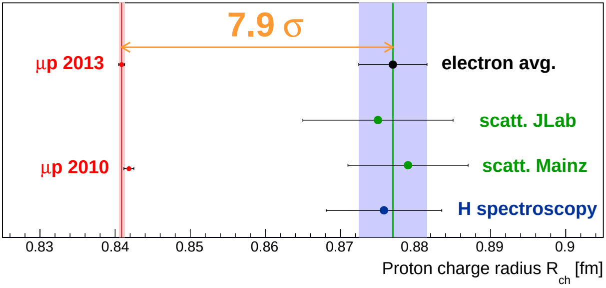




Timeline of proton radius results (current)



Puzzle!



- Many ideas
- Some disproved
- None accepted
- Need more data

New Data!

- Hyperfine measurements:
  - Heavier Nuclei
  - electronic Hydrogen
- Radius from scattering
  - Deuterium (Mainz)
  - Proton: ISR (Mainz), Small angle scattering (JLab)
- Form factors
  - Low Q^2 polarized (JLab)
  - MAMI-C (1.6 GeV)
  - High precision cross section at high Q^2 (JLab)
- Two photon exchange
  - VEPP-3
  - JLab
  - Olympus

Interesting at all scales

- Precision measurements drive precise understanding (through puzzles!)
  - Radius
  - Two photon exchange
- More data will come