Feasibility study: proton time-like electromagnetic form factors with the $\bar{\text{P}}$ANDA experiment

A. Dbeyssi[1], D. Khaneft[1], M. Zambrana[1], M.C. Mora Espí[1], Y. Wang[3], F. Maas[1], D. Marchand[2], E. Tomasi-Gustafsson[3]

[1]Helmholtz-Institut Mainz, Mainz, Germany
[2]Institut de Physique Nucléaire, CNRS-IN2P3, Univ. Paris-Sud, Université Paris-Saclay, 91406 Orsay cedex, France
[3]IRFU, SPHN, CEA, Saclay, France

$\bar{\text{P}}$ANDA Collaboration Meeting
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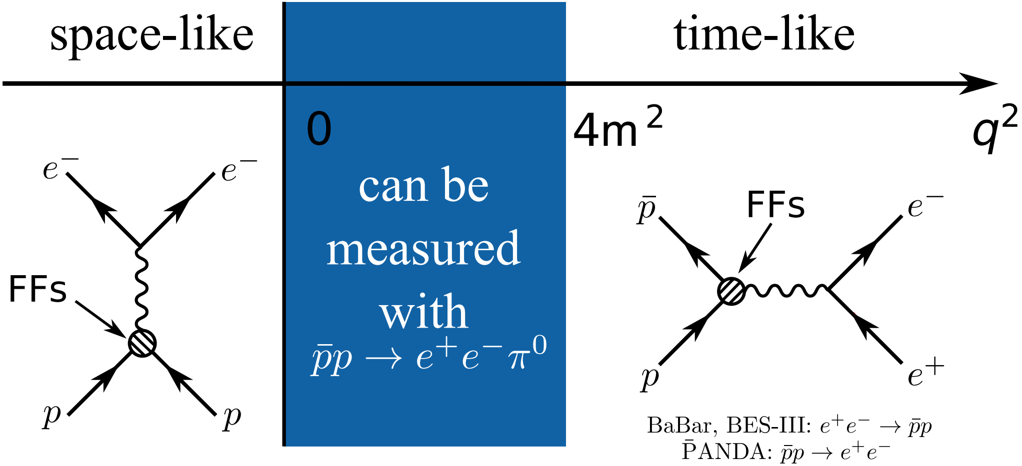
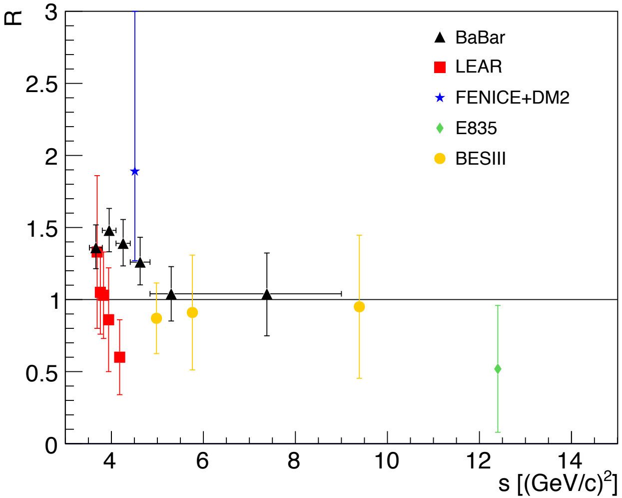


Electromagnetic form factors parameterize hadronic current
space-like q^2 $\to$ time-like s^2

How much do we know about FFs?

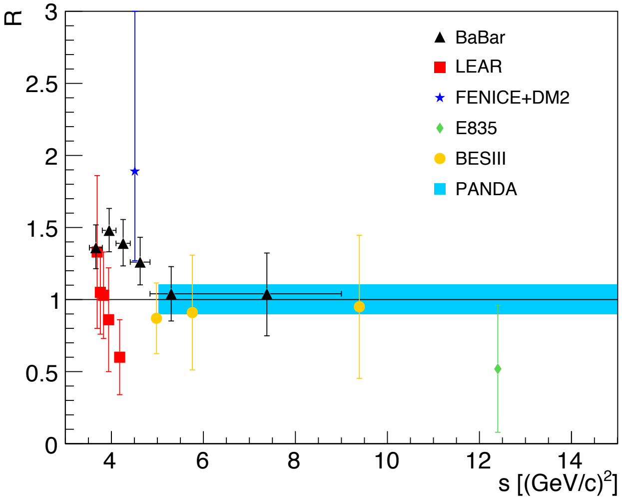
Published experimental data on $R = |G_E|/|G_M|$,
more data under analysis from BESIII and SND/Novosibirsk



How PANDA can contribute?

Kinematical reach of the PANDA experiment: 5.1-30.0 $[\mathrm{GeV/c}]^2$

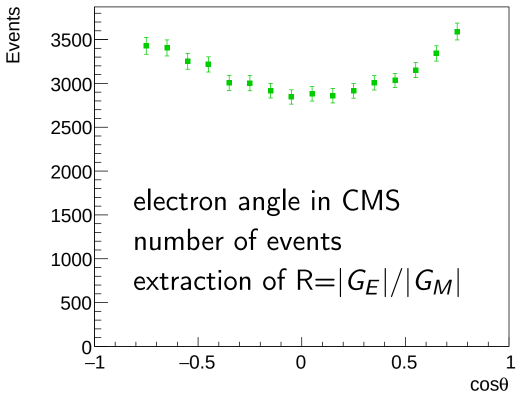
$$\sigma(\bar{p}p \to e^+e^-) \sim 1/s^2,\ R = |G_E|/|G_M|$$

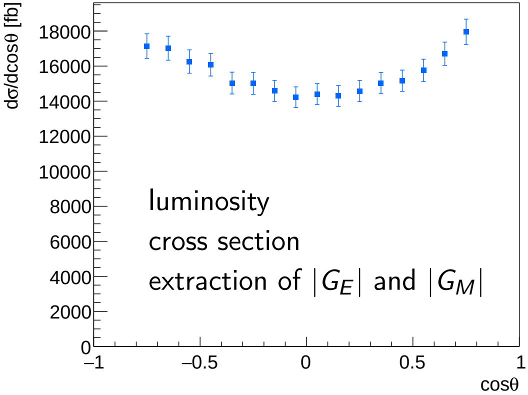


How to measure FFs?

Ingredients: $\frac{d\sigma}{d\cos\theta} = const(s)[|G_M|^2(1+cos^2\theta) + \frac{|G_E|^2}{\tau}(1-cos^2\theta)]$

- Angular distribution of $\bar{p}p \to e^+e^-$: R=$|G_E|/|G_M|$
- $\bar{p}p \to e^+e^-$ differential cross section, need luminosity: $|G_E|$ and $|G_M|$





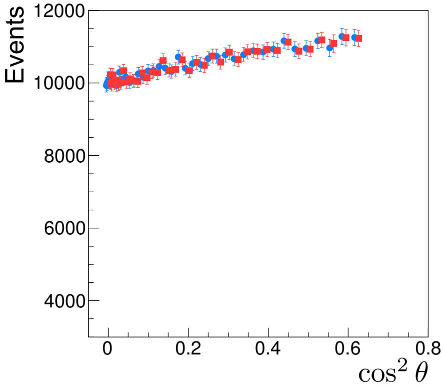
How to measure FFs – Method II

Another option? We can fit $\cos^2\theta$ distribution.
Advantage – linear fit.

$$y = a + b\cos^2\theta, \text{ with } a \equiv \sigma_0, \; b \equiv \sigma_0\mathcal{A}$$

$$\sigma_0 = \frac{\pi\alpha^2}{2\beta s}\left(|G_M|^2 + \frac{1}{\tau}|G_E|^2\right)$$

$$\mathcal{A} = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2} = \frac{\tau - \mathrm{R}^2}{\tau + \mathrm{R}^2}$$



Background – $\bar{p}p \to \pi^+\pi^-$

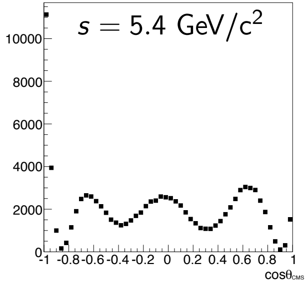
Background, including three-body final states, kinematically very different.
Background of two heavy charged particles (k^+k^-, etc) in the final state:

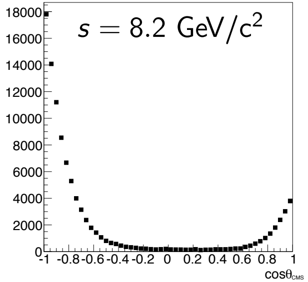
- Kinematically very different from signal
- Detector response very different from signal
- Cross section is high

The most challenging background is $\bar{p}p \to \pi^+\pi^-$ due to:

- Kinematically very similar to signal
- Detector response very similar to signal
- Cross section is by a factor of 10^6 higher

π^- from $\bar{p}p \to \pi^+\pi^-$





Background event generator

low energy	transition region	high energy
	6	9 $s\ (GeV/c)^2$
data: - Eisenhandler et. al., NP B96 (1975) model: - Legendre polynomial fit	interpolation	data: - A. Eide et. al., NP B60 (1973) - T. Buran et. al., NPB 116 (1976) - C. White et. al., PRD 49 (1994) model: - Regge Theory J. Van de Wiele and S. Ong, EPJA 46 (2010)

Event generator was developed in Mainz by M. Zambrana.

Cross section and expected number of events

	signal		background	
	$\bar{p}p \to e^+e^-$		$\bar{p}p \to \pi^+\pi^-$	
s $[\mathrm{GeV/c}]^2$	σ [pb]	N	σ [μb]	N
5.4	417.39	834800	101.06	$202.12 \cdot 10^9$
7.3	55.6	111100	13.09	$26.18 \cdot 10^9$
8.2	24.61	49210	2.95	$5.9 \cdot 10^9$
11.1	3.2	6503	0.56	$1.12 \cdot 10^9$
12.9	1.2	2328	0.23	$4.6 \cdot 10^8$
13.9	0.73	1466	0.16	$3.18 \cdot 10^8$

Integrated luminosity: $\mathcal{L} = 2fb^{-1}$

$|\cos\theta_{cm}| < 0.8$

Two Methods

Two Methods

Method I

Signal:

- Zichichi cross section* + PHOTOS
- Assuming $|G_E|/|G_M| = 1$
- s $[\mathrm{GeV/c}]^2$: 5.4, 7.3, 8.2, 11.1, 12.9, 13.9

*A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Nuovo Cim. 24, (1962) 170

Two Methods

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Method II

Signal:

- Flat angular distribution (phase space) + PHOTOS
- Scaled to the expected statistics
- s $[\text{GeV/c}]^2$: 5.4, 8.2, 13.9

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Two Methods

Method I

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- s [GeV/c]^2: 5.4, 7.3, 8.2, 11.1, 12.9, 13.9

Method II

Signal:

- Flat angular distribution (phase space) + PHOTOS
- Scaled to the expected statistics
- s [GeV/c]^2: 5.4, 8.2, 13.9

Common features:

- Additional samples for signal efficiency determination, $\sim 10^6$ events at each energy
- Background:
  M. Zambrana's event generator at s = 5.4, 8.2, and 13.9 [GeV/c]^2
  10^8 events at each energy

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Event selection criteria

Event selection criteria

Particle identification:

- PID_c [%] - combined probability
- PID_s [%] - individual detector probability
- dE/dx_{STT} [a.u.] - energy deposited in the central tracker
- E_{EMC}/p [GeV/(GeV/c)] - ratio of deposited energy in the EMC over reconstructed momentum
- EMC LM [a.u.] - lateral momentum
- EMC E1 [GeV] - energy deposited in the cluster's central crystal

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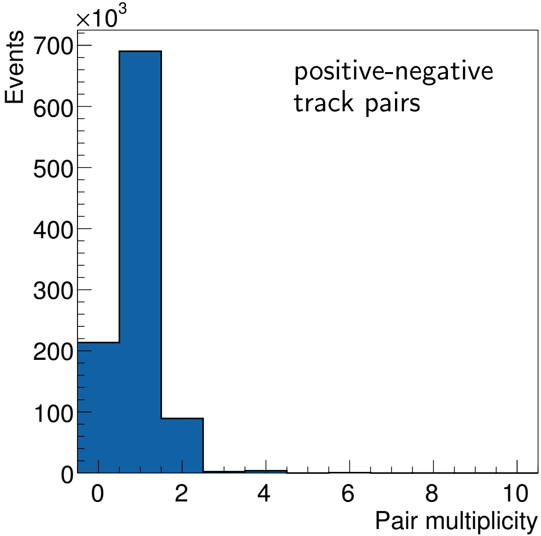
Kinematical cuts:

- $\theta + \theta'$ [degree] - sum of polar angles in the $\bar{p}p$ center of mass frame
- $|\phi - \phi'|$ [degree] - difference of azimuthal angles in the $\bar{p}p$ center of mass frame
- M_{inv} $[\mathrm{GeV/c}]^2$ - invariant mass

Step 0:
One positive and one negative track



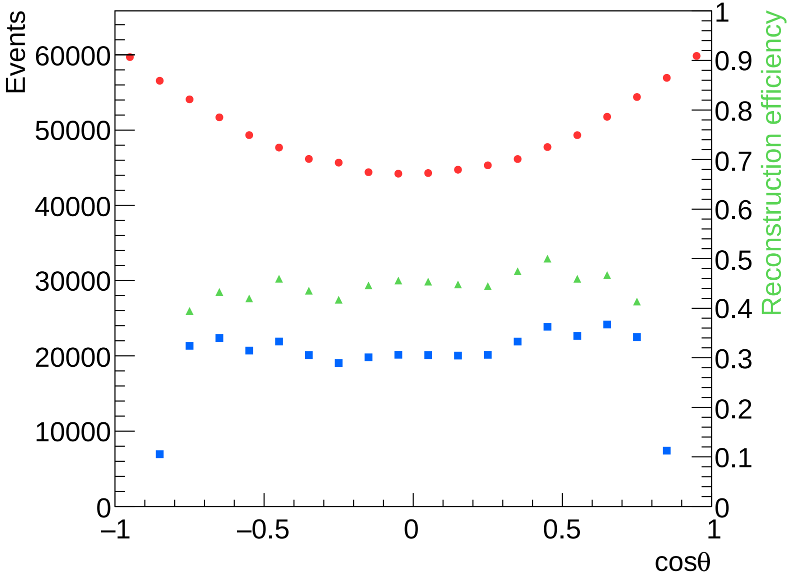
Method I – Signal event selection

Step 1:
Cut values used for analysis

s	$[\mathrm{GeV/c}]^2$	5.4	7.3	8.2	11.1	12.9	13.9
PID_c	[%]	>99	>99	>99	>99	>99	>99
PID_s	[%]	>10	>10	>10	>10	>10	>10
dE/dx_{STT}	[a.u.]	>5.8	>5.8	>5.8	>5.8	>5.8	>6.5
E_{EMC}/p	[GeV/(GeV/c)]	>0.8	>0.8	>0.8	>0.8	>0.8	>0.8
EMC LM	[a.u.]	<0.75	<0.75	<0.75	<0.75	-	-
EMC E1	[GeV]	>0.35	>0.35	>0.35	>0.35	>0.35	>0.35
$\theta + \theta'$	[degree]	$175 < \theta + \theta' < 185$					
$\lvert\phi - \phi'\rvert$	[degree]	$175 < \lvert\phi - \phi'\rvert < 185$					
M_{inv}	$[\mathrm{GeV/c}]^2$	-	-	>2.2	>2.2	>2.2	>2.7

Method I – Reconstruction efficiency

Monte Carlo – red
Selected – blue
Efficiency – green



Method I – Efficiency

	signal	background
s [GeV/c]^2	e^+e^-	$\pi^+\pi^-$
5.4	50.9%	$6.8 \cdot 10^{-6}$%
7.3	53.5%	-
8.2	46.3%	$2.0 \cdot 10^{-6}$%
11.1	46.2%	-
12.9	46.6%	-
13.9	38.7%	$2.9 \cdot 10^{-6}$%

Angular range $|\cos\theta| \leq 0.8$

Good signal efficiency, background suppression factor of 10^{-8}

Method I – Extraction of FFs

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- Angular distribution of events $\rightarrow R = |G_E|/|G_M|$
  Fit function:

$$\#events = \mathcal{L} \times \frac{d\sigma}{d\cos\theta} = C_1[(1 + cos^2\theta) + \frac{|R|^2}{\tau}(1 - cos^2\theta)]$$

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$$\#events = \mathcal{L} \times \frac{d\sigma}{d\cos\theta} = C_1[(1 + cos^2\theta) + \frac{|R|^2}{\tau}(1 - cos^2\theta)]$$

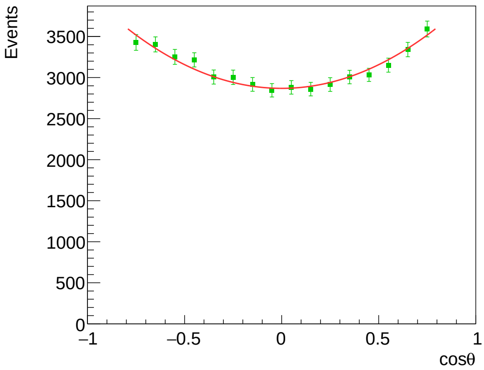
- Luminosity $\rightarrow$ cross section $\rightarrow |G_E|$ and $|G_M|$
  Fit function:

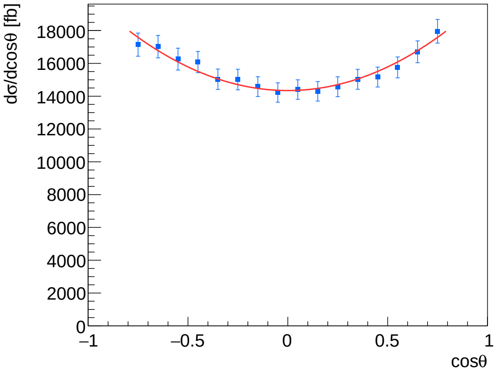
$$\frac{d\sigma}{d\cos\theta} = C[|G_M|^2(1 + cos^2\theta) + \frac{|G_E|^2}{\tau}(1 - cos^2\theta)]$$

$\Delta\mathcal{L}/\mathcal{L} = 3\%$ assumed for cross section calculation

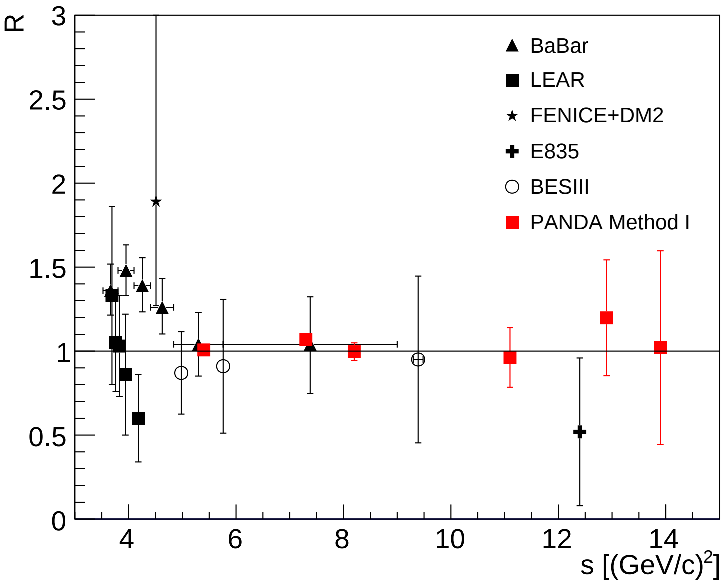
Method I – Events and cross section

Signal events (left) and cross section (right)





Method I – Results for R=$|G_E|/|G_M|$



Method I – Results for $|G_E$ and $/|G_M|$

Expected statistical uncertainties on $|G_E|$ and $|G_M|$ with $\Delta\mathcal{L}/\mathcal{L} = 3\%$

s [GeV/c]^2	$\lvert G_E\rvert \pm \Delta\lvert G_E\rvert$	$\lvert G_M\rvert \pm \Delta\lvert G_M\rvert$
5.4	0.122 ± 0.004 [3.3%]	0.121 ± 0.002 [1.7%]
7.3	0.062 ± 0.003 [4.8%]	0.058 ± 0.001 [1.7%]
8.2	0.044 ± 0.003 [6.8%]	0.044 ± 0.001 [2.3%]
11.1	0.019 ± 0.003 [15.8%]	0.020 ± 0.001 [5.0%]
12.9	0.015 ± 0.003 [20.0%]	0.012 ± 0.001 [8.3%]
13.8	0.011 ± 0.005 [45.4%]	0.011 ± 0.001 [9.0%]

Method II – Signal event selection

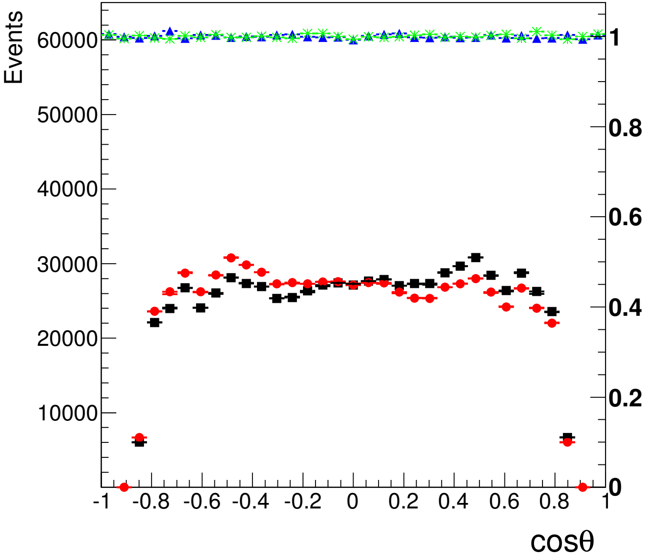
Step 0:
One negative and one positive track with $\theta + \theta'$ closest to 180°
Step 1:
Cut values used for analysis

s	[GeV/c]^2	5.4	8.2	13.9
PID$_c$	[%]	$>$99	$>$99	$>$99.5
PID$_s$	[%]	$>$10	$>$10	$>$10
dE/dx_{STT}	[a.u.]	$>$6.5	$>$5.8	0 or $>$6.5
E_{EMC}/p	[GeV/GeV/c]	$>$0.8	$>$0.8	$>$0.8
EMC LM	[a.u.]	$<$0.66	$<$0.75	$<$0.66
EMC E1	[GeV]	$>$0.35	$>$0.35	$>$0.35
$\theta + \theta'$	[degree]	$175 < \theta + \theta' < 185$		
$\lvert\phi - \phi'\rvert$	[degree]	$175 < \lvert\phi - \phi'\rvert < 185$		
M_{inv}	[GeV/c]^2	-	$>$2.2	$>$2.7

Differences in cuts with Method I are highlighted in blue

Method II – Reconstruction efficiency

Monte Carlo – green and blue
Selected events – black and red



Method II – Efficiency

	signal	background
s [GeV/c]^2	e^+e^-	$\pi^+\pi^-$
5.4	41%	$1.9 \cdot 10^{-6}\%$
8.2	44.6%	$9.8 \cdot 10^{-7}\%$
13.9	40.8%	$1.9 \cdot 10^{-6}\%$

Angular range $|\cos\theta| \leq 0.8$

Good signal efficiency, background suppression factor of 10^{-8}

Method II – Extraction of FFs

The ratio $R = |G_E|/|G_M|$, $|G_E|$, and $|G_M|$ can be extracted from $\cos^2\theta$ distribution using:

$$y = a + b\cos^2\theta, \text{ with } a \equiv \sigma_0,\ b \equiv \sigma_0\mathcal{A}$$

$$\sigma_0 = \frac{\pi\alpha^2}{2\beta s}\left(|G_M|^2 + \frac{1}{\tau}|G_E|^2\right)$$

$$\mathcal{A} = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2} = \frac{\tau - \mathrm{R}^2}{\tau + \mathrm{R}^2}$$

Similar to the Method I:

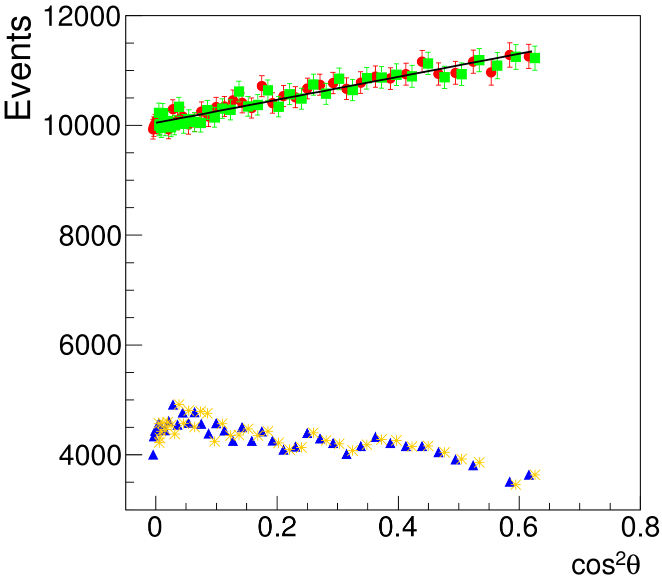
- Angular distribution of events $\rightarrow$ $R = |G_E|/|G_M|$
- Luminosity $\rightarrow$ cross section $\rightarrow$ $|G_E|$ and $|G_M|$

Method II – Events

Selected events – blue and orange

Corrected events – green and red

Fit – black

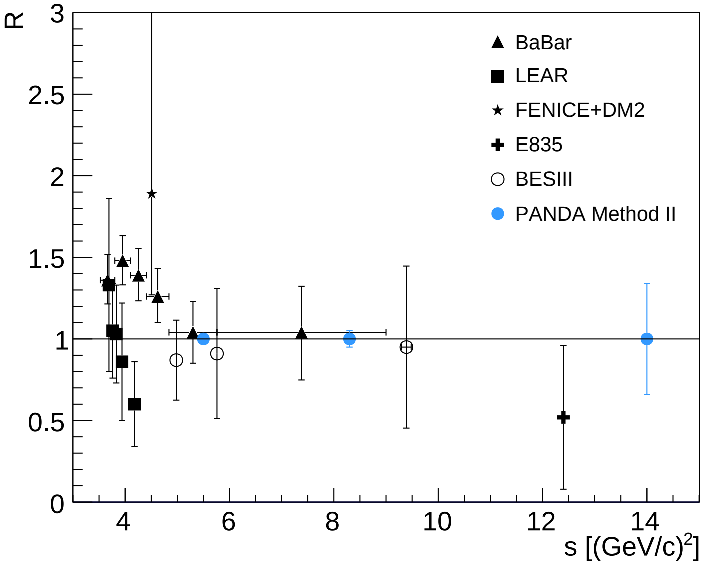


Method II – Results

The simulation input and expected statistical errors on R=$|G_E|/|G_M|$, $|G_E|$, and $|G_M|$.

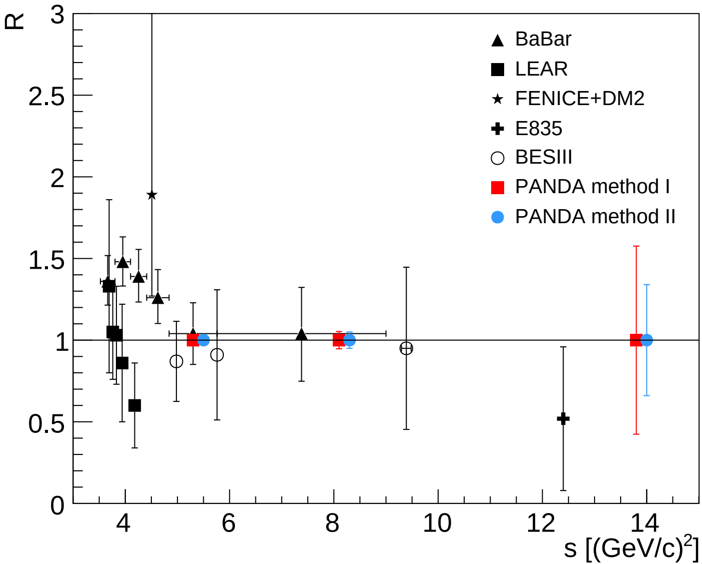
	input		input		
s [GeV/c]^2	R	ΔR	$\lvert G_{E,M}\rvert$	$\Delta\lvert G_M\rvert$	$\Delta\lvert G_E\rvert$
5.4	1	0.014 [1.4%]	0.1215	0.002 [1.6%]	0.002 [1.6%]
8.2	1	0.050 [5.0%]	0.0435	0.001 [2.3%]	0.002 [2.3%]
13.9	1	0.407 [40.7%]	0.0110	0.001 [9.1%]	0.004 [9.1%]

Method II – Results



Two methods – Results

Method I and Method II are equivalent



Summary

Two independent feasibility studies were performed:

- Good signal efficiency of 39-54%
- Background rejection factor of $\sim 10^8$
- Extraction of $R = |G_E|/|G_M|$ is possible for $5.4 < s < 12.9[GeV/c]^2$
  – precision 1.5–56%
- With precise luminosity measurements extraction of $|G_E|$ and $|G_M|$ will be possible for $5.4 < s < 12.9[GeV/c]^2$
  – precision for $|G_E|$ 3.3–45.4%
  – precision for $|G_M|$ 1.7–9.0%
- We studied reduced luminosity case (See talk by A. Dbeyssi):
  - Reduced range for FFs measurements: $5.4 < s < 10.0[GeV/c]^2$
  - Relative error scales as $\sqrt{10}$

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  - Relative error scales as $\sqrt{10}$

Thanks for listening!

Method II – Extraction of FFs

The ratio $R = |G_E|/|G_M|$, $|G_E|$, and $|G_M|$ can be extracted by fitting the $\cos^2\theta$ distribution by the following fit function:

$$y = a + b\cos^2\theta, \text{ with } a \equiv \sigma_0,\ b \equiv \sigma_0\mathcal{A}$$

$$\sigma_0 = \frac{\pi\alpha^2}{2\beta s}\left(|G_M|^2 + \frac{1}{\tau}|G_E|^2\right),$$

$$\mathcal{A} = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2} = \frac{\tau - \mathrm{R}^2}{\tau + \mathrm{R}^2},$$

$$\mathrm{R} = \sqrt{\tau\frac{1-\mathcal{A}}{1+\mathcal{A}}},\ \ \Delta\mathrm{R} = \frac{1}{\mathrm{R}}\frac{\tau}{(1+\mathcal{A})^2}\Delta\mathcal{A}.$$

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$$y = a + b\cos^2\theta, \text{ with } a \equiv \sigma_0,\ b \equiv \sigma_0\mathcal{A}$$

$$\sigma_0 = \frac{\pi\alpha^2}{2\beta s}\left(|G_M|^2 + \frac{1}{\tau}|G_E|^2\right),$$

$$\mathcal{A} = \frac{\tau|G_M|^2 - |G_E|^2}{\tau|G_M|^2 + |G_E|^2} = \frac{\tau - \mathrm{R}^2}{\tau + \mathrm{R}^2},$$

$$|G_M|^2 = \frac{(a+b)}{2\mathcal{N}},\ |G_E|^2 = \tau\frac{(a-b)}{2\mathcal{N}},\ \mathcal{N} = \frac{\Pi\alpha^2}{2\beta s}\mathcal{L},$$

$$\Delta|G_M|^2 = \frac{1}{2\mathcal{N}}\sqrt{(\Delta a)^2 + (\Delta b)^2},\ \Delta|G_E|^2 = \frac{\tau}{2\mathcal{N}}\sqrt{(\Delta a)^2 + (\Delta b)^2}.$$

Simulations

Software used for the simulations:

- PandaRoot version revision 25544
- FairSoft version apr13
- Geant4 for particle propagation

The following macros were used in the present work. The only difference was in sim_complete.C where different event generators were used:

- sim_complete.C
- digi_complete.C
- reco_complete.C
- pid_complete.C