Electromagnetic form factors in the time like region with $\bar{\text{P}}$ANDA

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Outline

1. **Introduction**
   - Electromagnetic Form Factors in the time like region
   - Measurement of the electromagnetic Form Factors
   - Available data
2. **P̄ANDA detector**
3. **Simulations and analysis**
   - Description of the analysis
   - Electron analysis
   - Muon analysis
4. **Conclusions and Outlook**

Electromagnetic Form Factors

Parameterize the hadronic current in the matrix element for elastic electron scattering and its crossed process annihilation.

Matrix element for e-p scattering:

$$M = \frac{e^2}{q^2}\bar{u}(k_2)\gamma^{\mu}u(k_1)\bar{u}(p_2)\left[F_1(q^2)\gamma_{\mu} + i\frac{\sigma_{\mu\nu}q^{\nu}}{2M}F_2(q^2)\right]u(p_1)$$

F_1: Dirac FF
F_2: Pauli FF

One can define the Sachs Form Factors as:

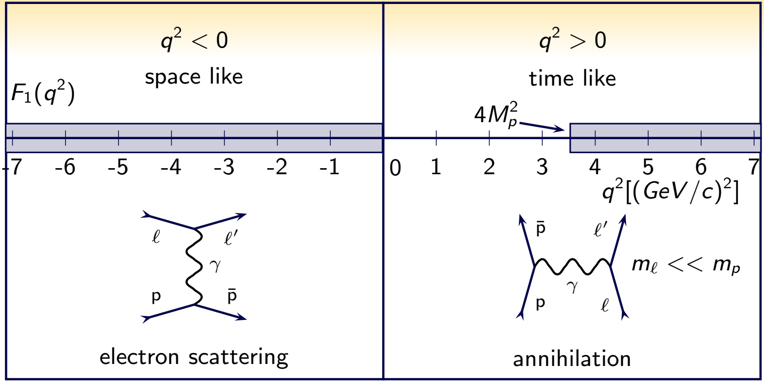
$$G_e = F_1 + \tau F_2$$

$$G_m = F_1 + F_2$$

where $\tau = \frac{q^2}{4M^2c^4}$

- Depend on transferred momentum, q^2.
- We are interested in measuring the Electromagnetic Form Factors in time-like region.

Space-like and Time-like regions



- No threshold
- Real functions
- Fourier transform of spatial charge and magnetization distribution
- Well known

- Threshold at $q^2 = 4M_p^2$
- Complex functions
- Fourier transform of the response of nucleon in time domain
- Not well known

Space-like and Time-like regions are conected by DISPERSION RELATIONS.

Access to time-like form factors

We can access via the reactions $\bar{p}p \longrightarrow \ell^+\ell^-$

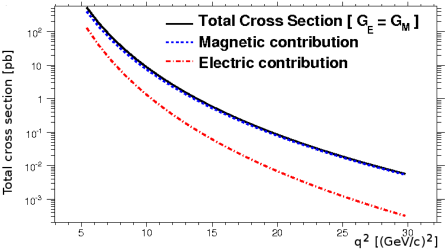
Cross Section $\bar{p}p \longrightarrow \ell^+\ell^-$

$$\frac{d\sigma}{d\cos\theta} = \frac{\pi\alpha^2(\hbar c)^2}{8M_p\sqrt{\tau\left(\tau-1\right)}}\left[|G_m|^2\left(1+\cos^2\theta\right)+\frac{|G_e|^2}{\tau}\left(1-\cos^2\theta\right)\right]$$

- With high statistics one can measure the angular distribution.
- Knowing the luminosity one can calculate the diferential cross section.

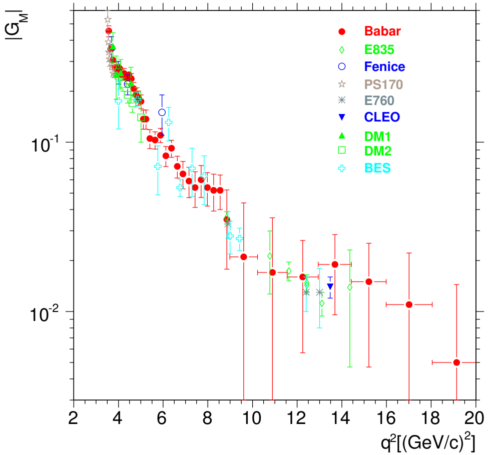
$$\frac{d\sigma}{d\cos\theta} = \frac{1}{L}\frac{d^2N}{dt\cdot d\cos\theta}$$

- The total cross section can be calculated from the total number of signal events.



World data on time-like electromagnetic Form Factors

Available data so far had low statistics except BABAR and PS170 experiments.

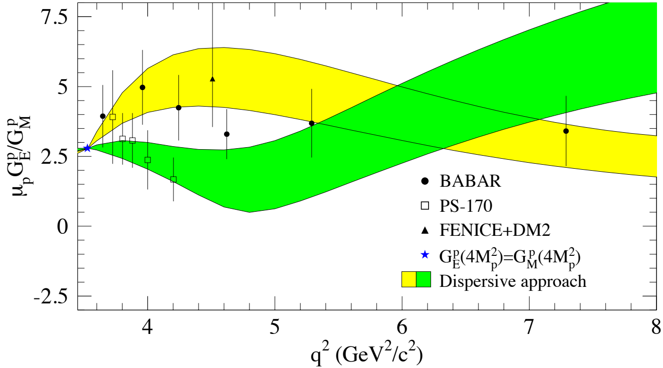


- Assumption of equality between G_e and G_m (Valid strictly only at threshold).

- BABAR:3284 events
- E835: 206 events
- Fenice: 25 and 69 events
- PS170: 3667 events
- E760: 29 events
- CLEO: 14 events
- DM1: 63 events
- DM2: 172 events
- BES: 90 events

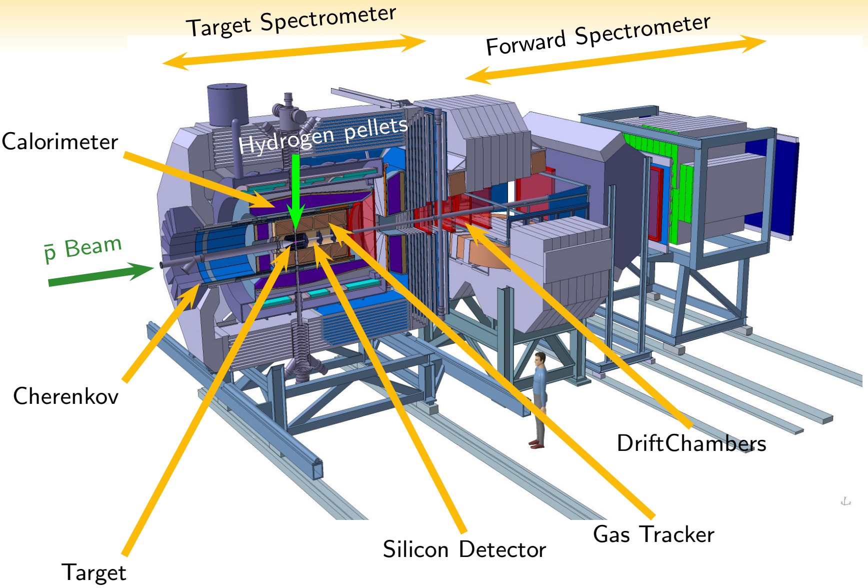
Fit to Form Factors data using dispersion relations

RATIO



- A fit to the data (using also results in space-like region) show the possibility of G_e/G_m being 0, 1 or even 3
- Discrepancies between BABAR and PS-170 experiments.

P̄ANDA detector setup



$\bar{\text{P}}$ANDA challenges and capabilities

1.- Nucleon structure studies: Measurement of FF in time-like region.
2.- Physics case:

- Study of reaction by the signal channels $\bar{p}p \to e^+e^-$ and $\bar{p}p \to \mu^+\mu^-$.
- Background channels:
  - $\bar{p}p \to \pi^+\pi^- \to$ 10^6 times higher than signal in average.
  - $\bar{p}p \to \pi^0\pi^0$
  - $\bar{p}p \to \pi^0\gamma$
  - $\bar{p}p \to \gamma\gamma$
- Challenge: Good suppression of pions as background.

3.- Panda Detector:

- High Luminosity: $L = 2 \cdot 10^{32}\,\text{cm}^{-2}\text{s}^{-1}$
- Good tracking system.
- Good PID capabilities.

$\longrightarrow$ SIMULATION

Simulation and analysis description

1.- EvtGen.

2.- GEANT4.

3.- Digitization.

4.- Cluster and track finding.

5.- Reconstruction.

- Candidates selection: Reconstrucction of events.
- Particle Identification: Using different likelihood levels on different detectors $\longrightarrow$ PID lists for different particle hypothesis (e, μ, p, π and K):
  - Charged
  - Very loose
  - Loose
  - Tight
  - Very Tight

  (Increasing likelihood level from top to bottom)

SIMULATION

6.- Kinematical fits to reconstructed tracks.

7.- Final event selection: Cuts on particle candidate properties.

8.- Results: Fit to reconstructed angular distribution.

ANALYSIS

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  (Increasing likelihood level from top to bottom)

6.- Kinematical fits to reconstructed tracks.
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ELECTRON ANALYSIS

Simulated events for analysis using electrons

Signal:

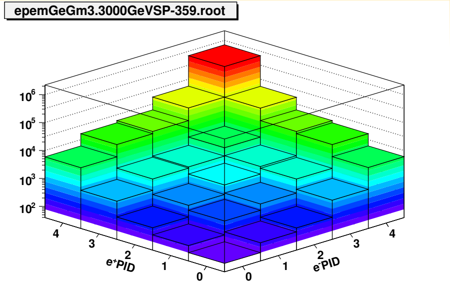
p (GeV/c)	1.7	2.9	3.0	3.7	4.9	5.9	6.4	7.9	10.9
q^2 [(GeV/c)^2]				8.2		12.9		16.7	
e^+e^-									
$G_e = 0$	10^6	10^6	10^6	10^6	10^6	10^6	10^6	10^6	10^6
$G_e = G_m$	10^6	10^6	10^6	10^6	10^6	10^6	10^6	10^6	10^6
$G_e = 3 \cdot G_m$	10^6	10^6	10^6	10^6	10^6	10^6	10^6	10^6	10^6

Background:

p (GeV/c)	3.7	5.9	7.9
q^2 [(GeV/c)^2]	8.2	12.9	16.7
$\pi^+\pi^-$	10^8	10^8	$2 \cdot 10^8$
$\pi^0\pi^0 \longrightarrow$			
$\gamma\gamma + \gamma\gamma$	10^6	10^6	10^6
$\gamma\gamma + \gamma e^+e^-$	10^6	10^6	10^6
$\gamma e^+e^- + \gamma e^+e^-$	10^6	10^6	10^6

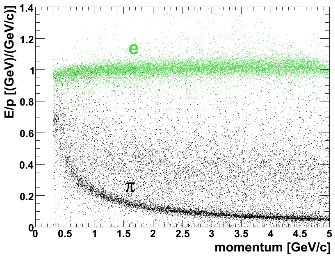
1 event - 2 s cpu time $\rightarrow \approx$ 6 cpu years in only 1 machine for 1 channel background simulation.

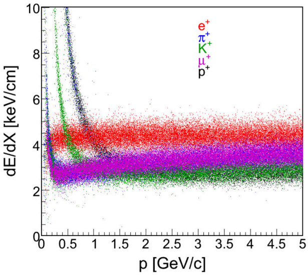
Particle identification



electron PID cuts:

- (0) Charged particles
- (1) Very Loose (VL) > 20%
- (2) Loose (L) > 85%
- (3) Tight (T) > 99%
- (4) Very Tight (VT) > 99.8% + 10%/detector





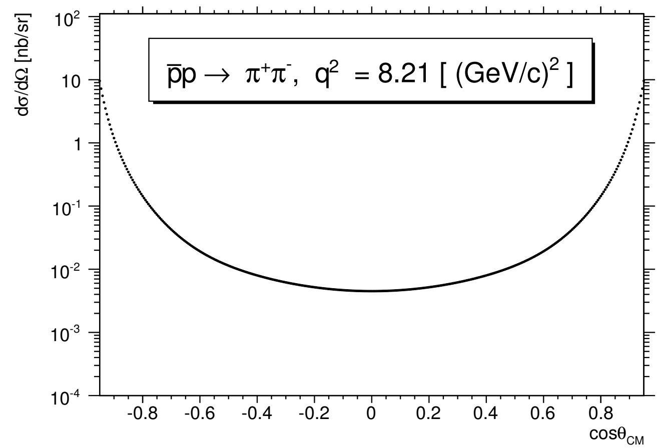
Kinematical fit

- E and p have been measured for each track.
- 4-constraints fit (E, p, m, r_0) performed with some particle hypothesis (e, μ, p, π and K).
- Calculated the fit confidence level for each hypothesis.

Kinematical fit:

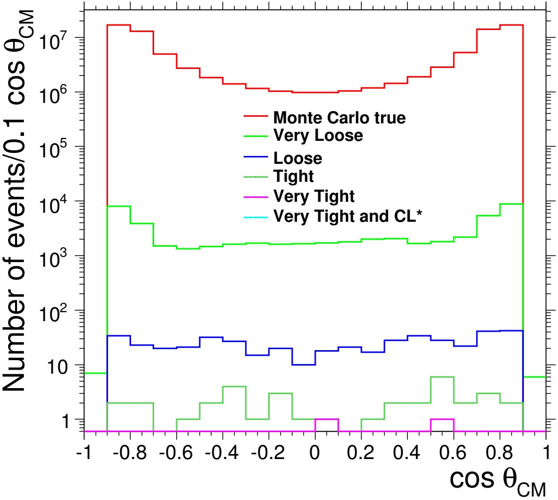
- CL(e^+e^-) $> 10\cdot$ CL($\pi^+\pi^-$)
- CL(e^+e^-) $> 10^{-3} \longrightarrow$ Necessary to suppress the whole π^0 background.

$\bar{p}p \rightarrow \pi^+\pi-$ cross section



- $\bar{p}p \rightarrow \pi^+\pi^-$ cross section is not well known.
- A model fitting the existing experimental data has been done as imput for the simulation.

Test of background suppression: $\bar{p}p \rightarrow \pi^+\pi^-$



$p = 3.3\,\mathrm{GeV/c}$; $q^2 = 8.2\,(\mathrm{GeV/c})^2$

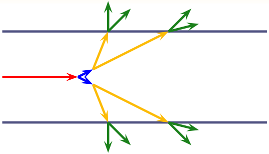
Angular distribution of charged pions:

Background suppression with cuts:

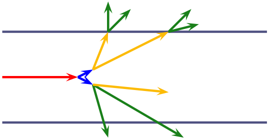
- PID constraints: 2 misidentified pions.
- CL and PID constraints: Background suppression of 10^8

Test of background suppression: $\bar{p}p \longrightarrow \pi^0\pi^0$

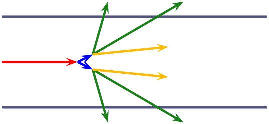
Normal decay:



1 Dalitz decay:



2 Dalitz decays



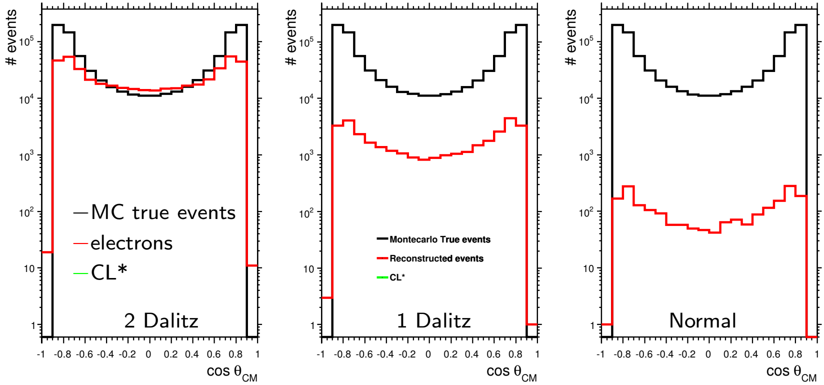
$\longrightarrow$ protons
$\longrightarrow$ pions
$\longrightarrow$ photons
$\longrightarrow$ electrons

- Normal decay: Does not produce electrons near the vertex.
- 1 Dalitz decay: Produces 2 electrons near the vertex.
- 2 Dalitz decays: Produce 4 electrons near the vertex.

- Electrons from conversion of photons in the beam pipe are easily discriminated by kinematical constraints.
- Electrons from Dalitz decay can be confused with signal electrons.

Test of background suppression: $\bar{p}p \to \pi^0\pi^0$

Angular distribution of neutral pions: $p = 5.9\,\mathrm{GeV/c}$; $q^2 = 12.9\,(\mathrm{GeV/c})^2$



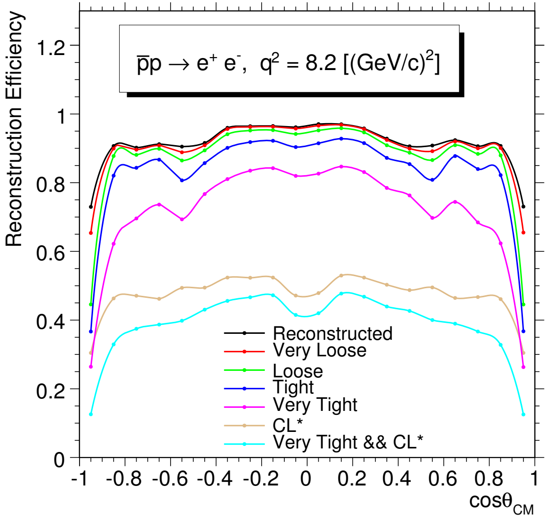
- CL constraints suppress all background.
- PID constraints are not usefull.

Branching ratios:

$\Gamma_{2\gamma}/\Gamma_{tot} = 98.798\%$

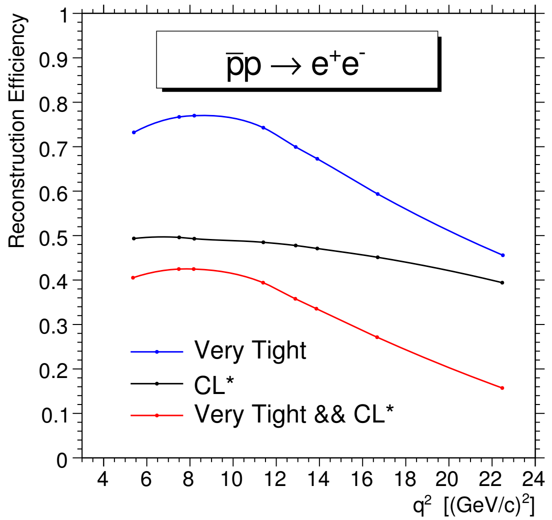
$\Gamma_{e^+e^-\gamma}/\Gamma_{tot} = 1.198\%$

Signal: Reconstruction efficiency
$G_e = G_m$; $p = 3.3$ **GeV/c**; $q^2 = 8.2$ **(GeV/c)^2**



- PID cuts don't represent a big suppression in efficiency.
- CL cut represents about 50% of signal reduction.
- After combination of PID and CL cuts the efficiency is about 40%.

Signal: Reconstruction efficiency $G_e = G_m$ vs q^2



- At higher energies, the efficiency is smaller than at lower energies.
- In comparison with the expected statistics the angular distribution reconstruction is more difficult at higher energies.
- Results for $G_e = 0$ and $G_e = 3Gm$ are simmilar.

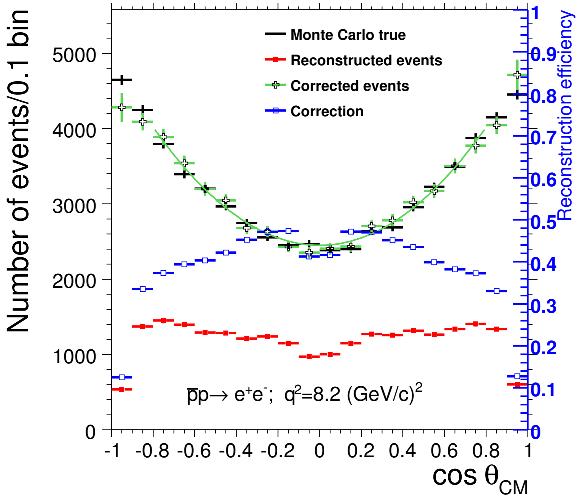
Realistic statistics

Signal e^+e^-:

At full luminosity ($\mathfrak{L} = 2 \cdot 10^{32}$ cm^{-2}s^{-1}) and 10^7 s of measurement time, corresponding approximately to 116 days, the expected number of events is the following:

s(GeV/c)^2	Nr. events
5.40	$1.07 \cdot 10^6$
7.43	$1.24 \cdot 10^5$
7.64	$1.03 \cdot 10^5$
8.20	$6.47 \cdot 10^4$
11.03	9078
12.90	3204
13.86	1985
16.69	572
22.29	81

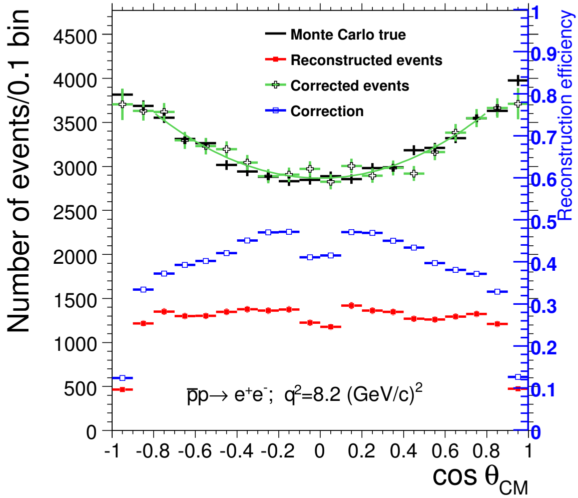
Signal: Angular distribution



$G_e = 0$;
$p = 3.3\,\mathrm{GeV/c}$;
$q^2 = 8.2\,(\mathrm{GeV/c})^2$

- Realistic statistics: 64 000 events.
- Good angular distribution reconstruction after acceptance correction.
- The acceptance correction have been calculated using 1 000 000 events and isotropical distribution simulation.

Signal: Angular distribution



$G_e = G_m$;
$p = 3.3\,\mathrm{GeV/c}$;
$q^2 = 8.2\,(\mathrm{GeV/c})^2$

- Realistic statistics: 64 000 events.
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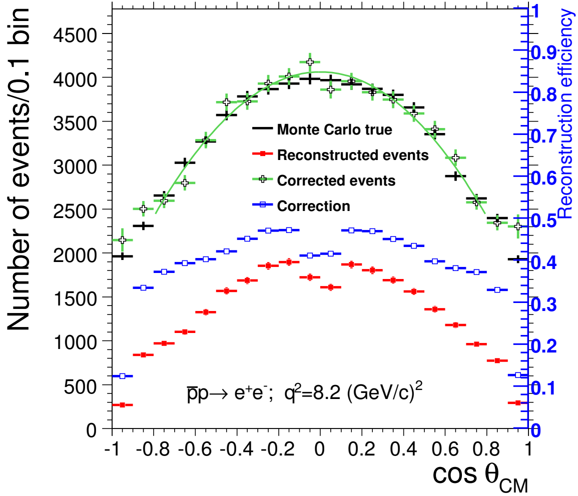
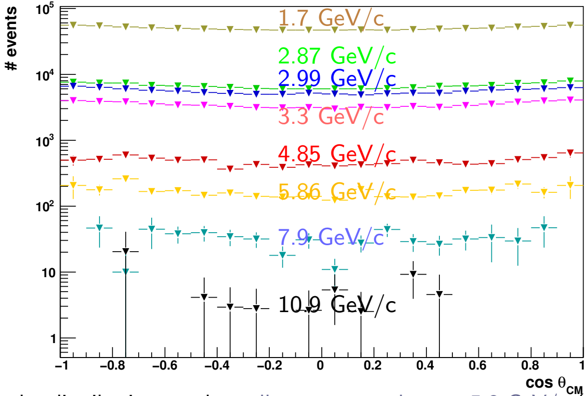
Signal: Angular distribution



$G_e = 3G_m$;
$p = 3.3$ GeV/c;
$q^2 = 8.2\,(\mathrm{GeV/c})^2$

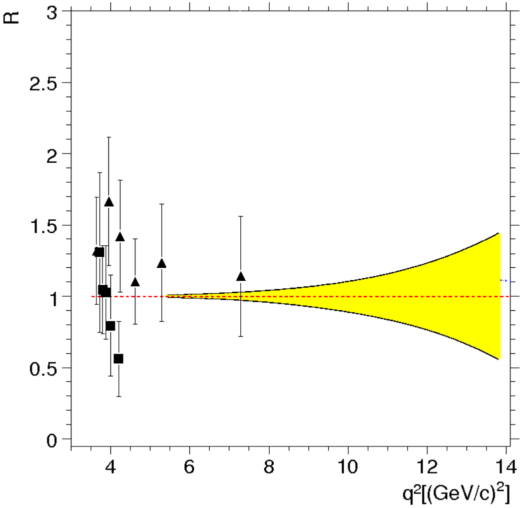
- Realistic statistics: 64 000 events.
- Good angular distribution reconstruction after acceptance correction.
- The acceptance correction have been calculated using 1 000 000 events and isotropical distribution simulation.

Reconstructed and corrected angular distributions for $\bar{p}p \rightarrow e^+e^-$ and $G_e = G_m$ at different energies



- Angular distribution can be well reconstructed up to 5.8 GeV/c (12.9 $(\text{GeV/c})^2$).
- At higher energies is still possible to use the integrated cross section for G_e/G_m calculation.

Results for G_e/G_m



- Squares and triangles represent the values calculated in BABAR and PS170 experiments.
- Our results (for the case of $G_e = G_m$) will be distributed around the red horizontal dashed line.
- The error bars of our calculations (only statistical) are represented by the yellow band.
- The errors are a factor 10 smaller than those calculated up to now.

MUON ANALYSIS

Simulated events for analysis using muons

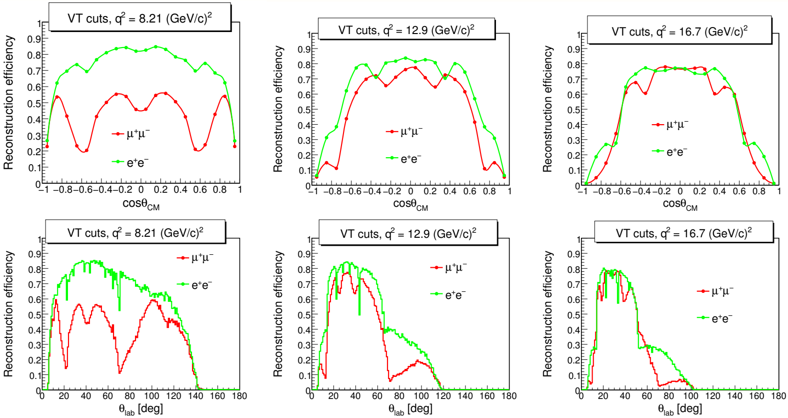
Signal:

p (GeV/c)	1.7	3.3	5.9	7.9
q^2 [(GeV/c)^2]	5.4	8.2	12.9	16.7
$\mu^+\mu^-$				
$G_e = 0$	10^6	10^6	10^6	
$G_e = G_m$	10^6	10^6	10^6	
$G_e = 3 \cdot G_m$	10^6	10^6	10^6	

Background:

p (GeV/c)	1.7	3.3	5.9	7.9
q^2 [(GeV/c)^2]	5.4	8.2	12.9	16.7
$\pi^+\pi^-$		10^8	10^8	$2 \cdot 10^8$

Comparison of electron and muon detection efficiencies



Plots by Gosia Sudol

Muon efficiency is lower than electron efficiency, due to partial implementation of the muon detector in the simulation.

Test of muon identification with different cuts

muon PID:

1. Very Loose (VL) $> 20\%$
2. Loose (L) $> 45\%$
3. Tight (T) $> 70\%$
4. Very Tight (VT) $> 85\%$
5. Likelihood (LH) $> 90\%$
6. LH $> 95\%$

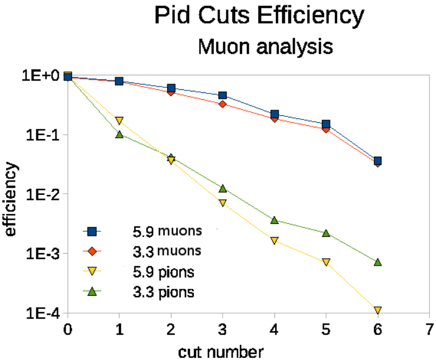
Kinematical fit:

1. $\mathrm{CL}(\mu^+\mu^-) > 10\times\mathrm{CL}(\pi^+\pi^-)$
2. $\mathrm{CL}(\mu^+\mu^-) > 50\times\mathrm{CL}(\pi^+\pi^-)$
3. $\mathrm{CL}(\mu^+\mu^-) > 100\times\mathrm{CL}(\pi^+\pi^-)$
4. $\mathrm{CL}(\mu^+\mu^-) > 150\times\mathrm{CL}(\pi^+\pi^-)$
5. $\mathrm{CL}(\mu^+\mu^-) > 200\times\mathrm{CL}(\pi^+\pi^-)$
6. $\mathrm{CL}(\mu^+\mu^-) > 300\times\mathrm{CL}(\pi^+\pi^-)$

1. $\mathrm{CL}(\mu^+\mu^-) > 10^{-9}$
2. $\mathrm{CL}(\mu^+\mu^-) > 10^{-3}$
3. $\mathrm{CL}(\mu^+\mu^-) > 10^{-2}$
4. $\mathrm{CL}(\mu^+\mu^-) > 0.1$
5. $\mathrm{CL}(\mu^+\mu^-) > 0.4$
6. $\mathrm{CL}(\mu^+\mu^-) > 0.5$

Background suppression: Only PID cuts

3.3 GeV/c - 8.2 $(GeV/c)^2$
5.9 GeV/c - 12.9 $(GeV/c)^2$

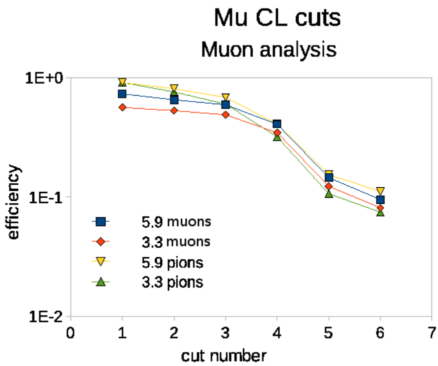


1. VL
2. L
3. T
4. VT
5. LH > 90%
6. LH > 95%

- The signal to noise ratio increases with LH level.
- The final cut has been selected to:

LH > 95%

Background suppression: Only kinematical fit cuts



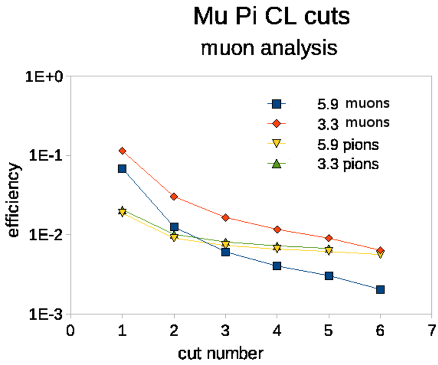
3.3 GeV/c - 8.2 $(\mathrm{GeV/c})^2$
5.9 GeV/c - 12.9 $(\mathrm{GeV/c})^2$

1. $\mathrm{CL}(\mu^+\mu^-) > 10^{-9}$
2. $\mathrm{CL}(\mu^+\mu^-) > 10^{-3}$
3. $\mathrm{CL}(\mu^+\mu^-) > 10^{-2}$
4. $\mathrm{CL}(\mu^+\mu^-) > 0.1$
5. $\mathrm{CL}(\mu^+\mu^-) > 0.4$
6. $\mathrm{CL}(\mu^+\mu^-) > 0.5$

- The μ CL cut affects in the same way signal and background
$\mathrm{CL}(\mu^+\mu^-) > 10^{-3}$

Background suppression: Only kinematical fit cuts

3.3 GeV/c - 8.2 $(\text{GeV}/c)^2$
5.9 GeV/c - 12.9 $(\text{GeV}/c)^2$



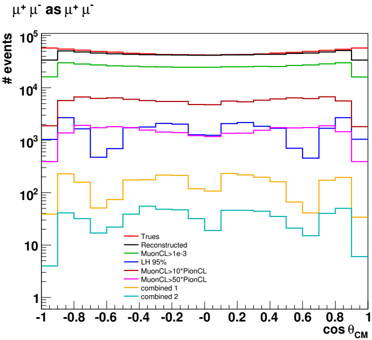
1. $\text{CL}(\mu^+\mu^-) > 10\times\text{CL}(\pi^+\pi^-)$
2. $\text{CL}(\mu^+\mu^-) > 50\times\text{CL}(\pi^+\pi^-)$
3. $\text{CL}(\mu^+\mu^-) > 100\times\text{CL}(\pi^+\pi^-)$
4. $\text{CL}(\mu^+\mu^-) > 150\times\text{CL}(\pi^+\pi^-)$
5. $\text{CL}(\mu^+\mu^-) > 200\times\text{CL}(\pi^+\pi^-)$
6. $\text{CL}(\mu^+\mu^-) > 300\times\text{CL}(\pi^+\pi^-)$

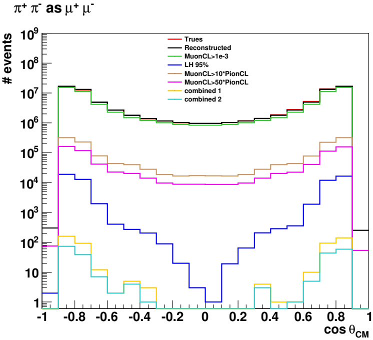
- More restrictive cuts reduce the signal to noise ratio
- $\text{CL}(\mu^+\mu^-) > 10\times\text{CL}(\pi^+\pi^-)$
and
- $\text{CL}(\mu^+\mu^-) > 50\times\text{CL}(\pi^+\pi^-)$

Cuts effect on muons and pions angular distributions at 3.3 GeV/c - 8.2 $(\mathrm{GeV}/c)^2$

Signal: 1 000 000 events
Expected: 64 000 events

Background: 93 415 000 events
Expected: $\approx 64 \cdot 10^9$ events



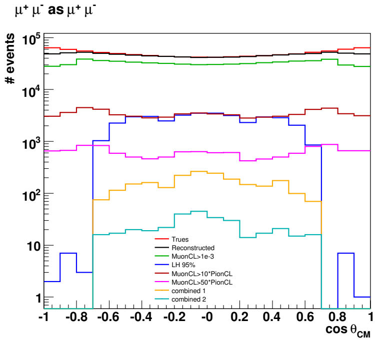


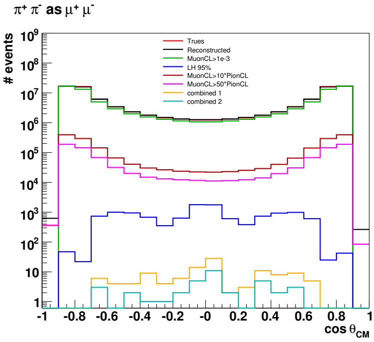
Combined 1: LH $> 95\%$, $\mathrm{CL}(\mu) > 10^{-3}$ and $\mathrm{CL}(\mu) > 10\ \mathrm{CL}(\pi)$
Combined 2: LH $> 95\%$, $\mathrm{CL}(\mu) > 10^{-3}$ and $\mathrm{CL}(\mu) > 50\ \mathrm{CL}(\pi)$

Cuts effect on muons and pions angular distributions at 5.9 GeV/c - 12.9 $(\mathrm{GeV/c})^2$

Signal: 1 000 000 events
Expected: 3 000 events

Background: 112 165 000 events
Expected: $\approx 3\cdot 10^9$ events





Combined 1: LH $> 95\%$, $CL(\mu) > 10^{-3}$ and $CL(\mu) > 10\ CL(\pi)$
Combined 2: LH $> 95\%$, $CL(\mu) > 10^{-3}$ and $CL(\mu) > 50\ CL(\pi)$

Conclusions and Outlook

ELECTRON ANALYSIS:

- Measurement of G_e/G_m is possible up to about 14 $(\mathrm{GeV/c})^2$ by measurement of angular distribution.
- At higher energies is still possible to use the integrated cross section for Form Factors measurement.
- The error bars are reduced by a factor 10 in comparison with previous experiments.
- $\pi^+\pi^-$ background can be suppressed by a factor 10^8.
- $\pi^0\pi^0$ background can be discriminated by kinematical constraints.

MUON ANALYSIS:

- High background suppression implies drastic signal reduction in case of muons.
- Complete implementation of muon detectors in new software is needed.

P̄ANDA detector at FAIR next to GSI seems to be of high utility for our measurements.