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Feasibility studies for the measurement of time-like electromagnetic proton form factors in reactions of

$$\bar{p}p \rightarrow \mu^+\mu^-$$

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Feasibility studies for the measurement of time-like electromagnetic proton form factors using $\bar{p}p \rightarrow \mu^+\mu^-$

- Differential cross section[1] of **signal reaction** $\bar{p}p \rightarrow \mu^+\mu^-$
  → Access to the **time-like, electromagnetic form factors of the proton, G_E and G_M**:

$$\frac{d\sigma}{d\cos\theta_{CM}} \propto \frac{\beta_{l^-}}{\beta_{\bar{p}}} \cdot \frac{|G_M|^2}{s} \left[\left(1 + \frac{4m_{l^-}^2}{s} + \beta_{l^-}^2 \cos\theta_{CM}\right) + \frac{R^2}{\tau}\left(1 - \beta_{l^-}^2 \cos\theta_{CM}\right) \right]$$

- **Extraction** of $|G_E|$ and $|G_M|$ and their ratio **R from reconstructed signal angular distribution** after full analysis and efficiency correction.

$$R = \frac{|G_E|}{|G_M|}$$

- **Strong background**, mainly $\bar{p}p \rightarrow \pi^+\pi^-$

$$\frac{\sigma(\bar{p}p \rightarrow \mu^+\mu^-)}{\sigma(\bar{p}p \rightarrow \pi^+\pi^-)} \propto 10^{-6}$$

Good background rejection needed!

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

Feasibility studies: time-like proton form factors @ PANDA

Simulation & Analysis

$\bar{p}p \rightarrow \mu^+\mu^-$ | $\bar{p}p \rightarrow \pi^+\pi^-$

Simulation & Analysis

PandaRoot

- Event generation
- Digitization
- Reconstruction
- Particle Identification
- Event Analysis

p_{beam} [GeV/c]	1.5	1.7	2.5	3.3
s [GeV^2]	5.08	5.40	6.77	8.20

Physical expectation

p_{beam} [GeV/c]	1.5	1.7	2.5	3.3
$\mu^+\mu^-$	$1.28 \cdot 10^{6}$	$8.30 \cdot 10^{5}$	$1.78 \cdot 10^{5}$	$4.97 \cdot 10^{4}$
$\pi^+\pi^-$	$2.65 \cdot 10^{11}$	$2.01 \cdot 10^{11}$	$4.52 \cdot 10^{10}$	$5.93 \cdot 10^{9}$

Event generation

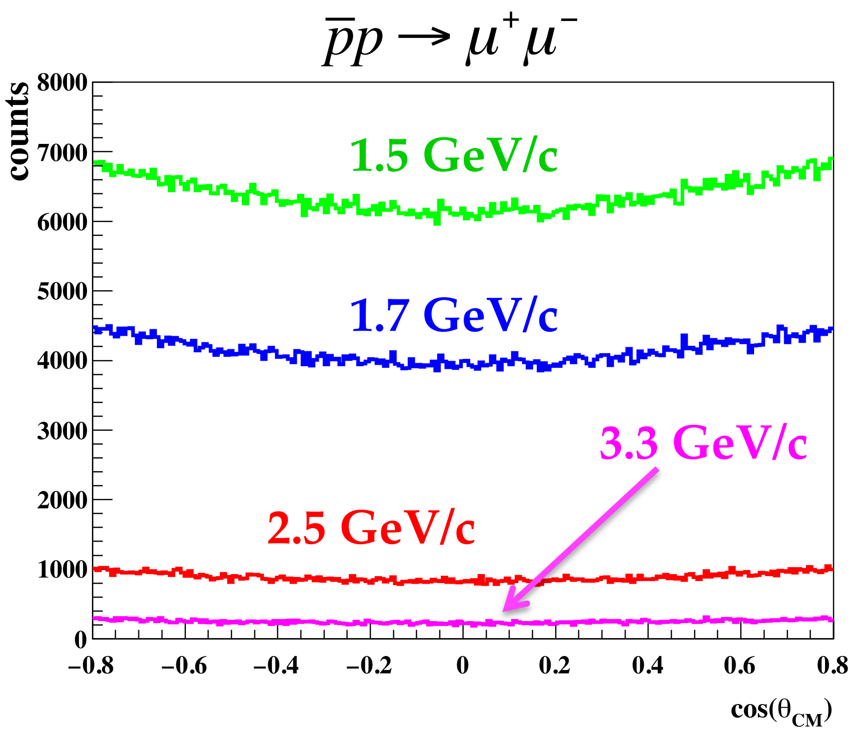
- Generator input: R=1
- Modified dipole parametrization for $|G_M|$[1]
- Time-integrated luminosity: L=2 fb^{-1}
- $|\cos\theta_{CM}| \leq 0.8$

1) Tomasi-Gustafsson, E. ; Rekalo, M.P., Phys. Lett. B 504, 291-295. 2001

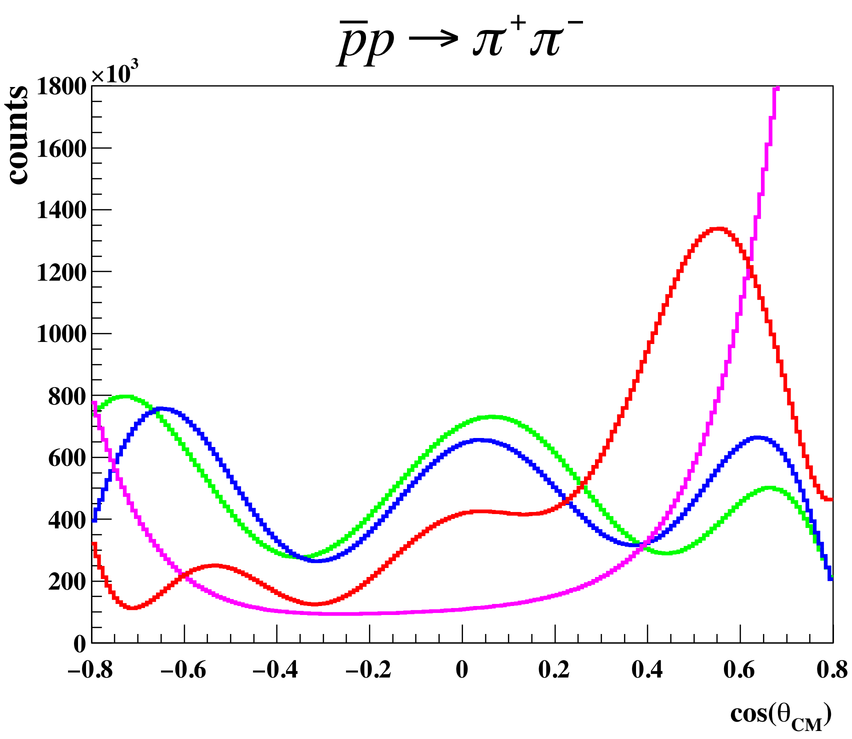
L = 2 fb-1

Event generation
Angular distributions of generated events

Signal



Background



Feasibility studies: time-like proton form factors @ PANDA

Simulation & Analysis : Event selection

$\bar{p}p \rightarrow \mu^+\mu^-$ | $\bar{p}p \rightarrow \pi^+\pi^-$

Simulation & Analysis

PandaRoot

- Event generation
- Digitization
- Reconstruction
- Particle Identification
- Event Analysis

p_{beam} [GeV/c]	**1.5**	**1.7**	**2.5**	**3.3**
$\sqrt{s}$ [GeV]	2.25	2.32	2.6	2.86

1) <u>Preselection</u>

- Each event must contain **at least** one **positive and one negative track**.
  - "Best pair" selected
- **Both tracks** must show **hits inside the Muon System**
- **Non-zero initial particle momentum at Muon System**

<u>2) Signal/Background separation based on:</u>

- **Multivariate data classification (Boosted Decision Trees) + cuts**
- **Kinematical variables**:
  - Production angles $(\theta^+ + \theta^-)_{CM}$
  - Invariant mass $M_{inv} = \sqrt{(p_+ + p_-)^2}$
  - Difference in azimuthal angles $|\varphi^+ - \varphi^-|$
- **Detector observables** from **Muon System, EMC** and **STT**

Feasibility studies: time-like proton form factors @ PANDA

Simulation & Analysis : Strategy

p_{beam}= (1.5, 1.7, 2.5, 3.3) GeV/c

$\bar{p}p \rightarrow \mu^+\mu^-$

Simulation: Signal I (S1) with **high statistics: > 10^7 events**

↓

Signal efficiency studies: ε_S

Simulation: Signal II (S2) contains *Number of expected events*

↓

1) Event selection

2) Background subtraction:

S2* + B2 – B1****

3) Efficiency correction

↓

Precision studies of $|G_E|$, $|G_M|$ & their ratio R.

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

Simulation: Background I (B1) contains **$1.0*10^8$ events**

≠ Number of expected events

↓

Background efficiency: ε_B

Simulation: Background II (B2) contains **$1.0*10^8$ events**

***After signal analysis**

****After *background* analysis**

Analysis:

Cut configurations & Effect of background fluctuations

@ p_{beam} = 1.5, 1.7, 2.5 & 3.3 GeV/c

Feasibility studies: time-like proton form factors @ PANDA
Cut configuration & Signal efficiency

	MVA utilizing Boosted Decision Trees (BDT)							
	p_{beam} [GeV/c]	$M_{inv}(\mu^+\mu^-)$ [GeV^2]	$\lvert\varphi^+ - \varphi^-\rvert$ [DEG]	$(\theta+\theta^-)_{CM}$ [DEG]	BDT	Signal efficiency ε	ε_B [10^{-6}]	S-B ratio
„Loose“ „Medium“	1.5	]2.1 ; 2.4[	]175 ; 185[	]179.65 ; 185[	> 0.300 > 0.340	**0.369** **0.227**	17.7 6.0	1:10 1:5
„Loose“ „Medium“	1.7	]2.2 ; 2.5[	]175 ; 185[	]179.65 ; 185[	> 0.335 > 0.343	**0.274** **0.245**	11.2 9.04	1:10 1:9
„Medium“ „Tight“	2.5	]2.4 ; 2.8[	]175 ; 185[	]179.0 ; 185[	> 0.230 > 0.234	**0.391** **0.312**	67.2 61.3	1:31 1:29
„Loose“ „Medium“	3.3	]2.6 ; 3.1[	]175 ; 185[	]179.0 ; 185[	> 0.300 > 0.306	**0.372** **0.349**	23.6 20.4	1:8 1:7

Background subtraction possible! -> Influence of background fluctuations?

How to study the effect of background fluctuations on the statistical precision of R, $|G_E|$ & $|G_M|$?

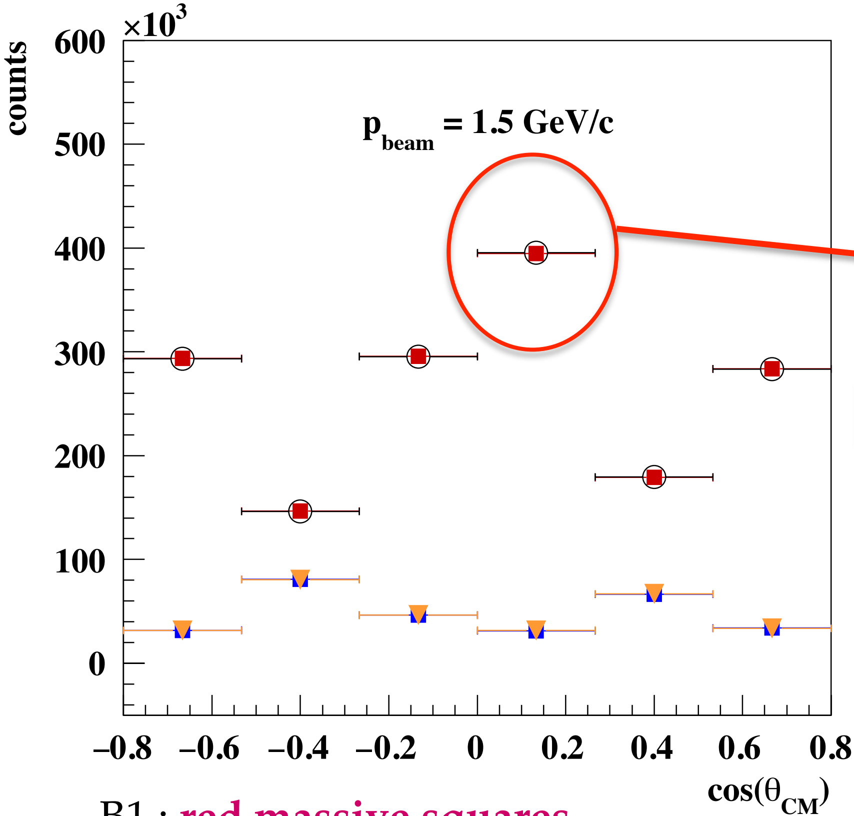
- Analysis based on MVA: **Background suppression factors ~ 10^{-6}**
  - **Physical expectation:** up to ***10^{11}*** events
  - **Simulation:** ***10^{8}*** events

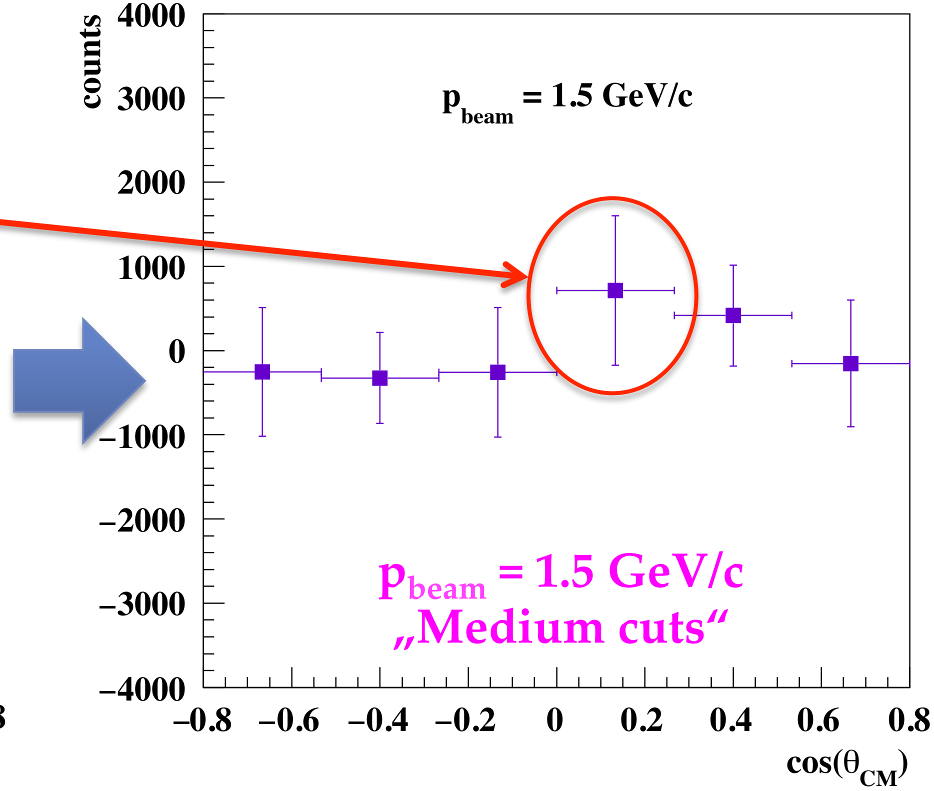
- Construct background distributions **with expected statistics after full analysis**
  - **Change cut on BDT response** for **both B1 and B2**
- **Background subtraction** from reconstructed signal (S2):

  S2 + (B2-B1)

  - Study *effect of fluctuations* in **background data samples** on the **precision of $|G_E|$, $|G_M|$ & R**.

How to study the effect of background fluctuations on the statistical precision of R, |G_E| & |G_M|?





B1 : **red massive squares**
B2: open circles
S2+B2-B1: yellow triangles down
S2 : **blue massive squares**

Background difference (B2-B1):
violet massive squares

Analysis:

Precision of $|G_E|$, $|G_M|$ and $R=|G_E|/|G_M|$

@ p_{beam} = 1.5, 1.7, 2.5 & 3.3 GeV/c

Feasibility studies: time-like proton form factors @ PANDA

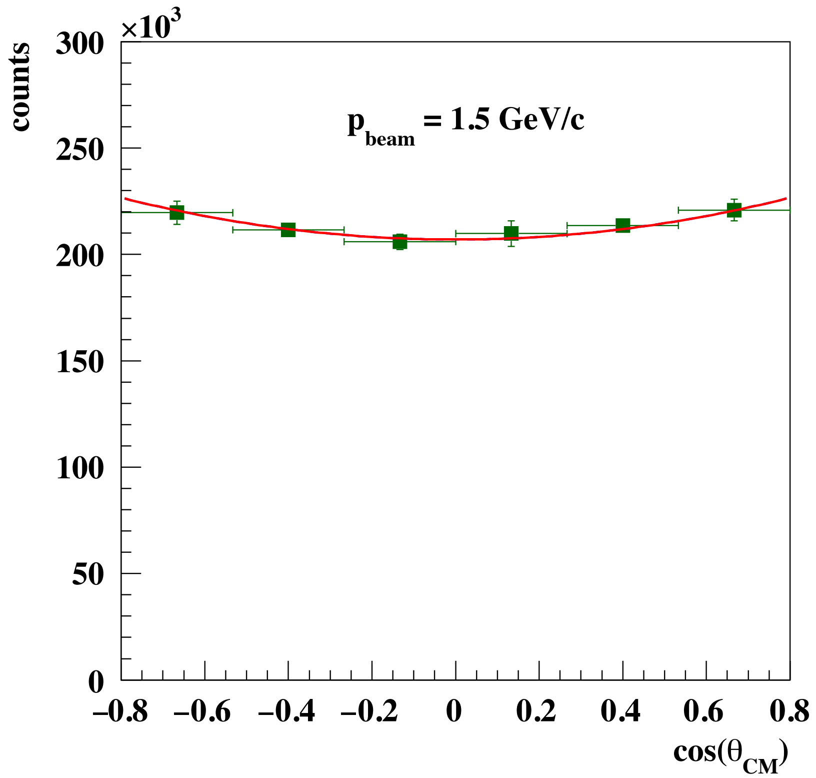
Statistical precision on R=|G_E|/|G_M|

FIRST FIT FUNCTION

Fit function 1: Fit parameter R (= P_1)

$$f_1(x) \propto P_0\left[\frac{1}{\tau}(1-\beta^2x^2)\cdot P_1^2 + 1 + \frac{4m_\mu^2}{s} + \beta^2x^2\right]$$

1 Extraction of **P_0 & P_1 from distribution of counts: direct extraction of R**



p_{beam} = 1.5 GeV/c

MVA

„Medium cuts“

1

R=1.032 ±0.060

ΔR/R = 5.77%

χ^2/ndf = 0.26

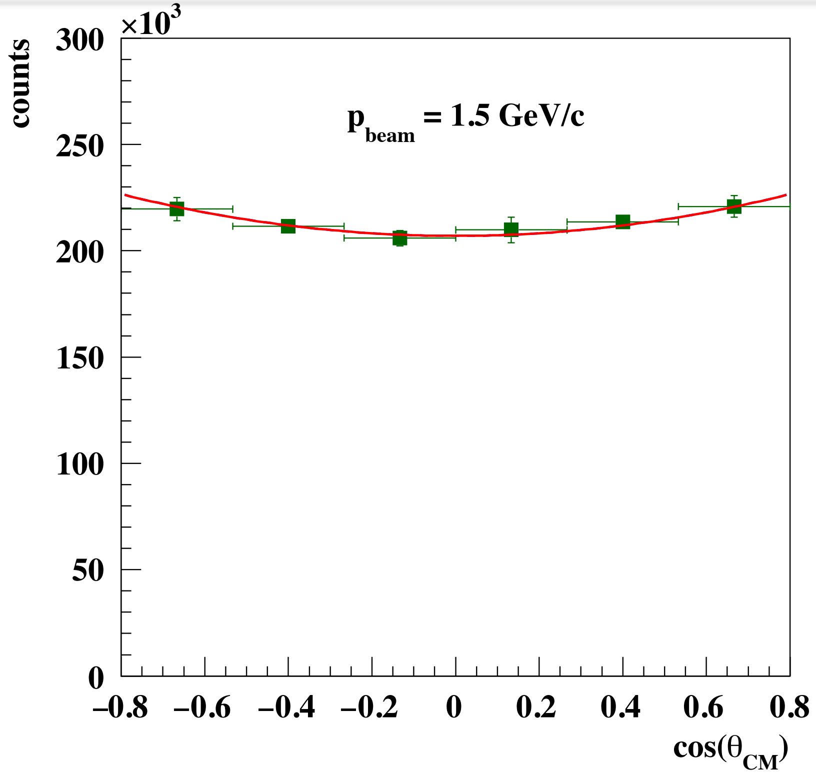
Feasibility studies: time-like proton form factors @ PANDA

Statistical precision on $|G_E|$ & $|G_M|$

SECOND FIT FUNCTION

Fit function 2: Fit parameters are $|G_E|$ & $|G_M|$

$$f_B(x) \propto C_1 \cdot \left[\frac{1}{\tau}(1-\beta^2 x^2)\cdot P_1^2 + \left(1 + \frac{4m_\mu^2}{s} + \beta^2 x^2\right) P_0^2 \right]$$



2 Direct extraction of $|G_E|$ & $|G_M|$ from efficiency corrected signal angular distribution after background subtraction

p_{beam} = 1.5 GeV/c

MVA

„Medium cuts“

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

2

$|G_E|$=0.1433±0.0055

$|G_M|$=0.1388± 0.0028

$\Delta|G_E|/|G_E|$=3.81%

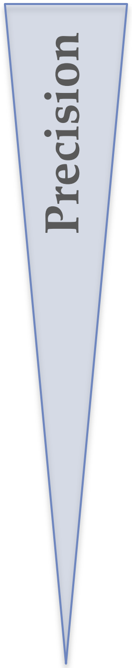
$\Delta|G_M|/|G_M|$=1.98%

Statistical precision on R=|G_E|/|G_M|

PRELIMINARY

$$signal\ pollution = \frac{B2 - B1}{S2 + B2 - B1}$$

p_{beam} [GeV/c]	Cut configuration	R±ΔR	ΔR/R [%]	χ^2/ndf	|signal pollution| [%]
1.5	„Loose“ „Medium“	1.008 ± 0.052 1.032 ± 0.060	5.14 5.77	1.193 0.260	0.36 0.05
1.7	„Loose“ „Medium“	0.921 ± 0.080 0.969 ± 0.082	8.64 8.50	2.012 2.164	0.16 0.05
2.5	„Loose“ „Tight“	0.919±0.167 0.924±0.158	18.12 17.06	0.745 0.436	4.84 2.02
3.3	„Loose“ „Medium“	1.165±0.293 1.004±0.291	25.16 29.02	1.005 1.477	3.04 3.72



Statistical precision on $|G_E|$ & $|G_M|$

PRELIMINARY

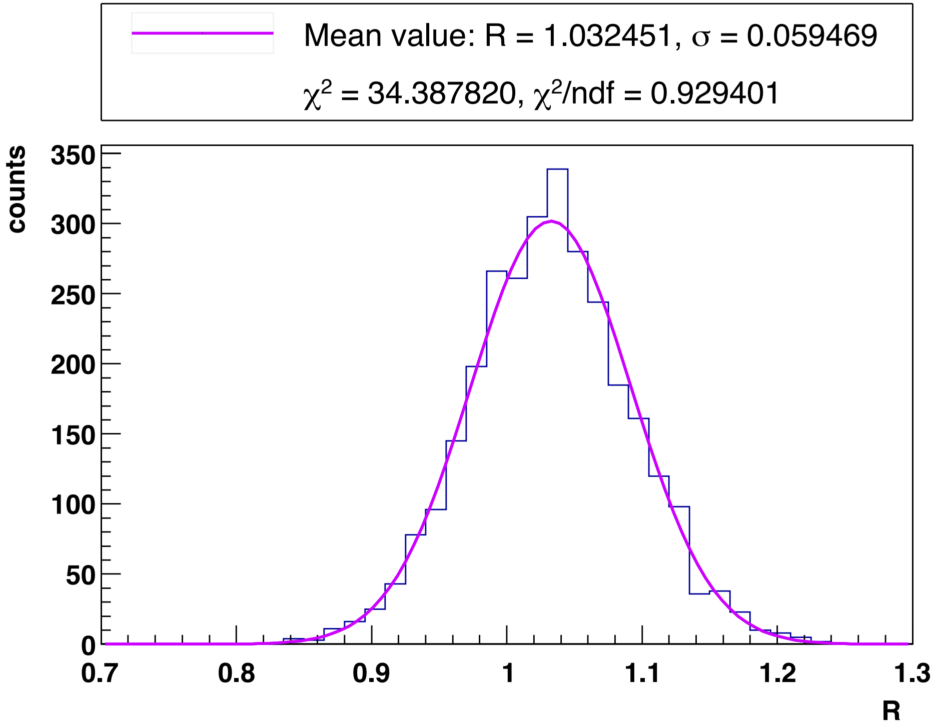
p_{beam} [GeV/c]	Cut config.	$\lvert G_E \rvert$	$\Delta \lvert G_E \rvert$	$\lvert G_E \rvert / \Delta \lvert G_E \rvert$ [%]	$\lvert G_M \rvert$	$\Delta \lvert G_M \rvert$	$\lvert G_M \rvert / \Delta \lvert G_M \rvert$ [%]
1.5	„Medium“	0.1433	0.0055	**3.81**	0.1388	0.0028	**1.98**
1.7	„Medium“	0.1180	0.0071	**6.01**	0.1217	0.0031	**2.52**
2.5	„Tight“	**0.0648**	**0.0085**	**13.11**	**0.0702**	**0.0029**	**4.09**
3.3	„Medium“	0.0430	0.0091	**21.15**	0.0429	0.0033	**7.76**

Choose cut configuration at each p_{beam} with **smallest signal pollution**

$$signal\ pollution = \frac{B2 - B1}{S2 + B2 - B1}$$

Systematic error: Effect of the binning

How does the mean value of R and its standard deviation depend on the binning?



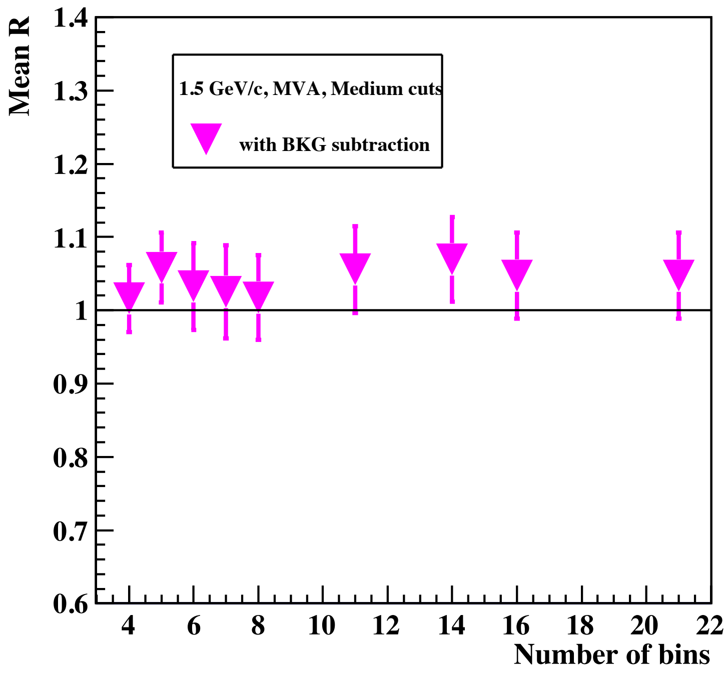
- Resample histograms of **S1, S2, B1, B2 with** **random number generator** (TRandom3) **3000 times**.
- **Perform** **full analysis** and **extract R values** **and** **their errors**
- Determine **mean R** and **sigma** from R distribution
- Repeat for **different number of bins**

Systematic error: Effect of the binning

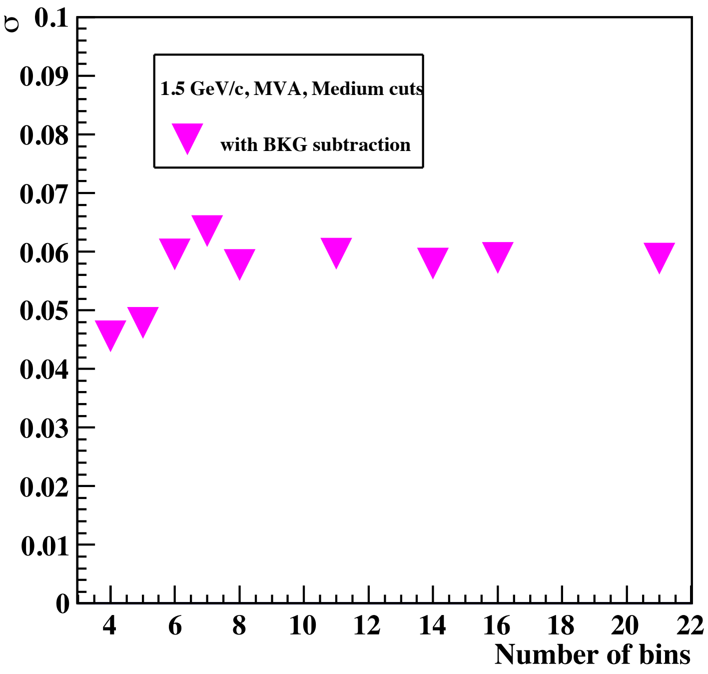
How does the mean value of R and its standard deviation depend on the binning?

p_{beam} = 1.5 GeV/c, Medium Cuts

Mean values of R



Standard deviation

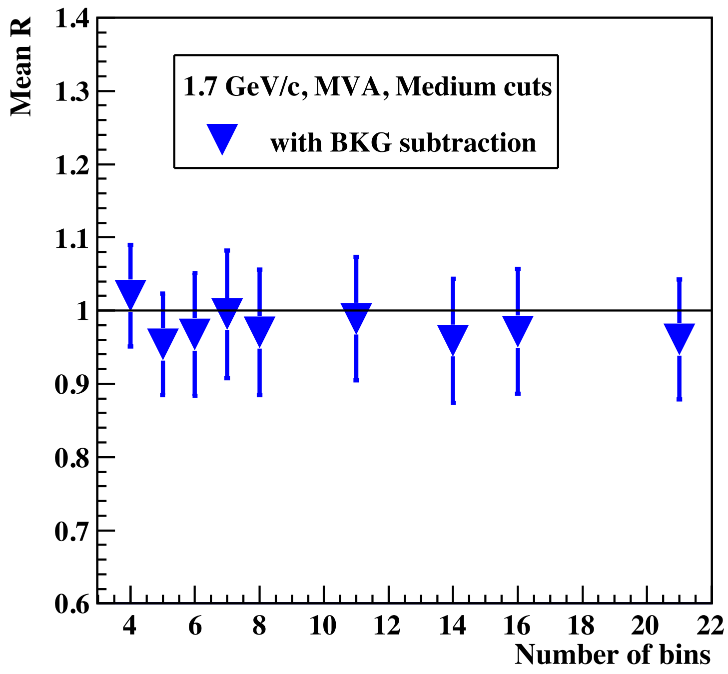


Systematic error: Effect of the binning

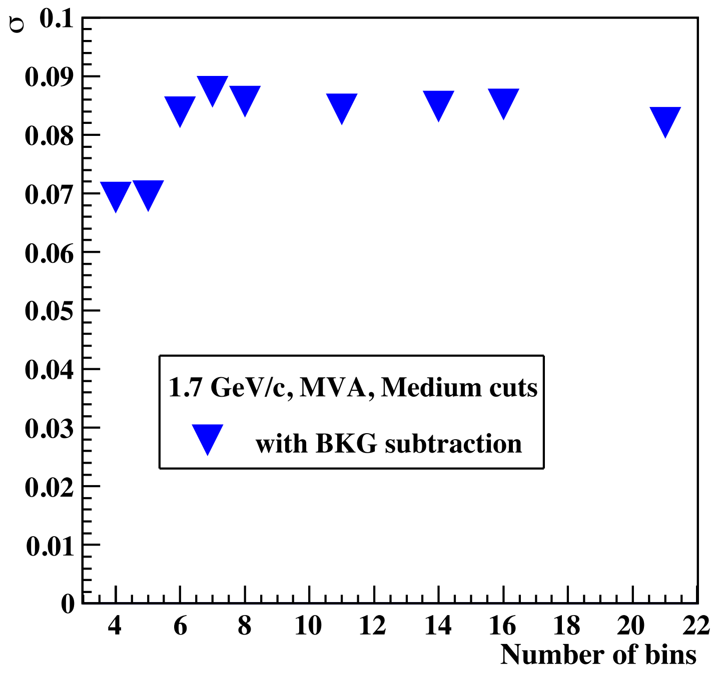
How does the mean value of R and its standard deviation depend on the binning?

p_{beam} = 1.7 GeV/c, Medium cuts

Mean values of R



Standard deviation



Choose 6 bins or more -> determine deviation from 16 bins:
Contribution to systematic error

Influence of the background distribution shape

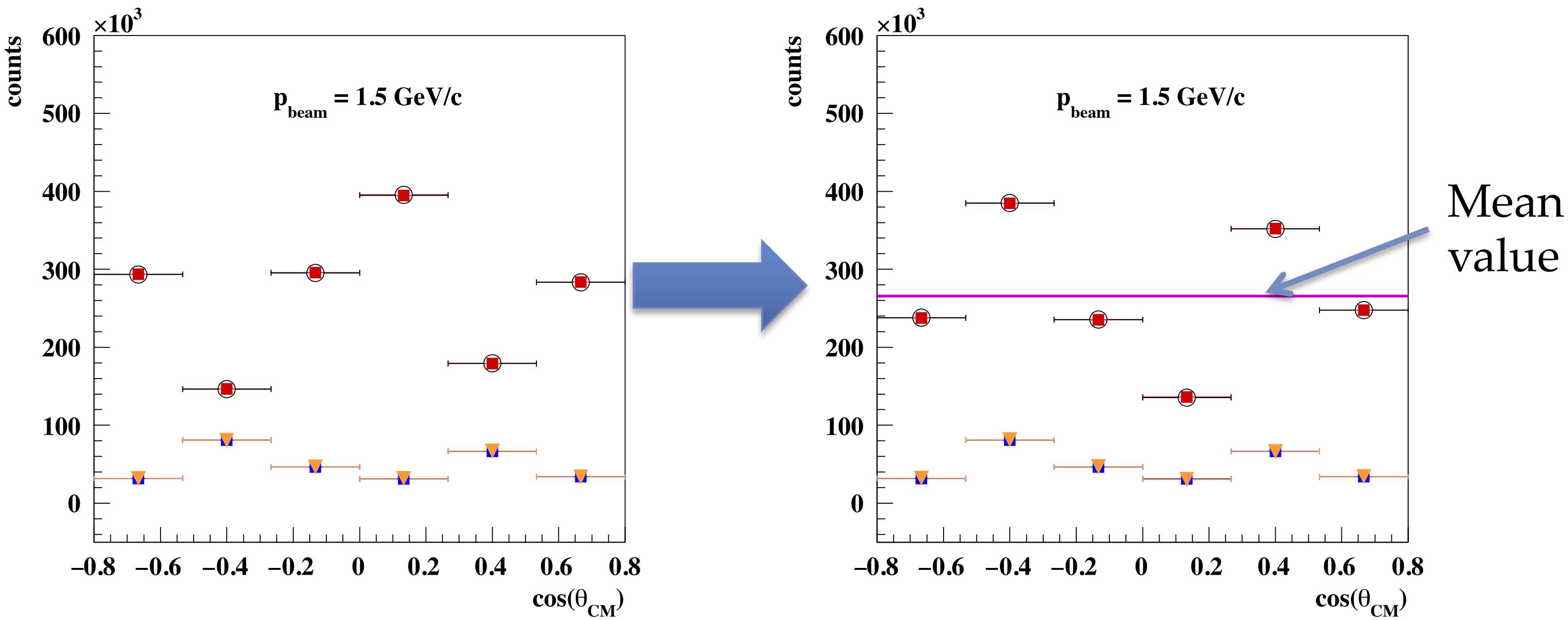
How does the extracted value of R and its error depend on the background distribution shape?

✓ Expected number of events
✗ Without real data no knowledge about the shape

Medium cuts, 1.5 GeV/c

- **An attempt**: **Mirror background distributions** around **mean value of the histogram contents** and **perform analysis** -> How do the results change?

Original background distributions | **Inverted** background distributions

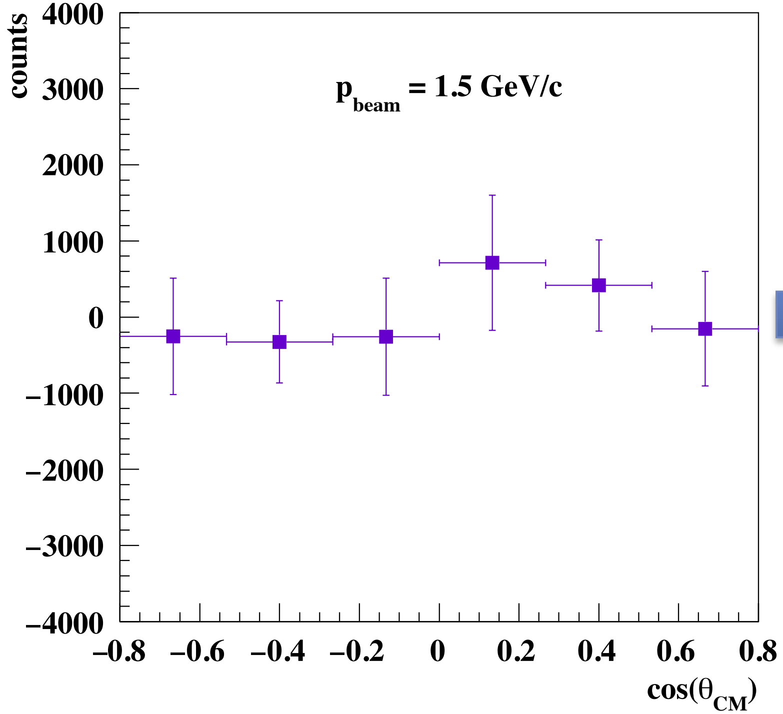


Influence of the background distribution shape

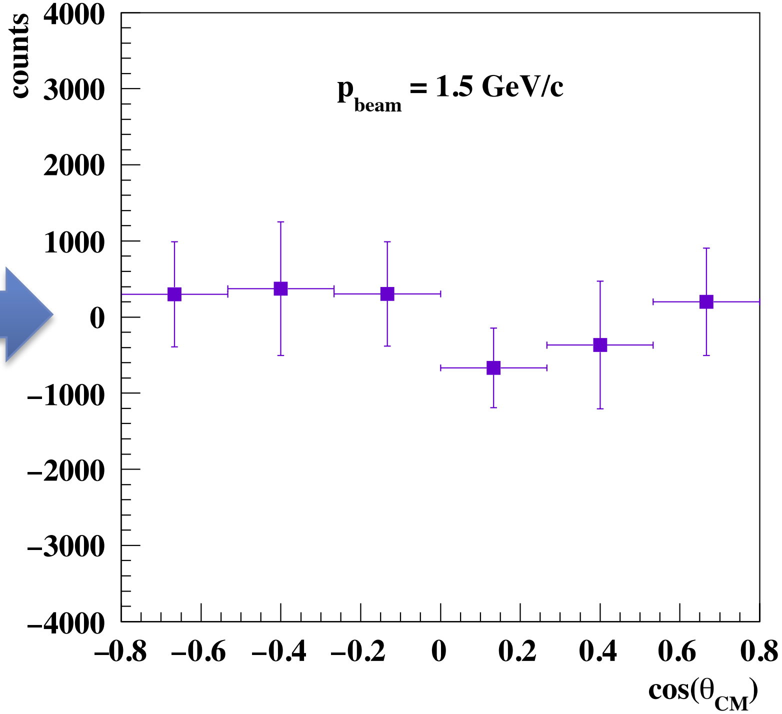
How does the extracted value of R and its error depend on the background distribution shape?

Medium cuts, 1.5 GeV/c

Original background difference: B2 – B1



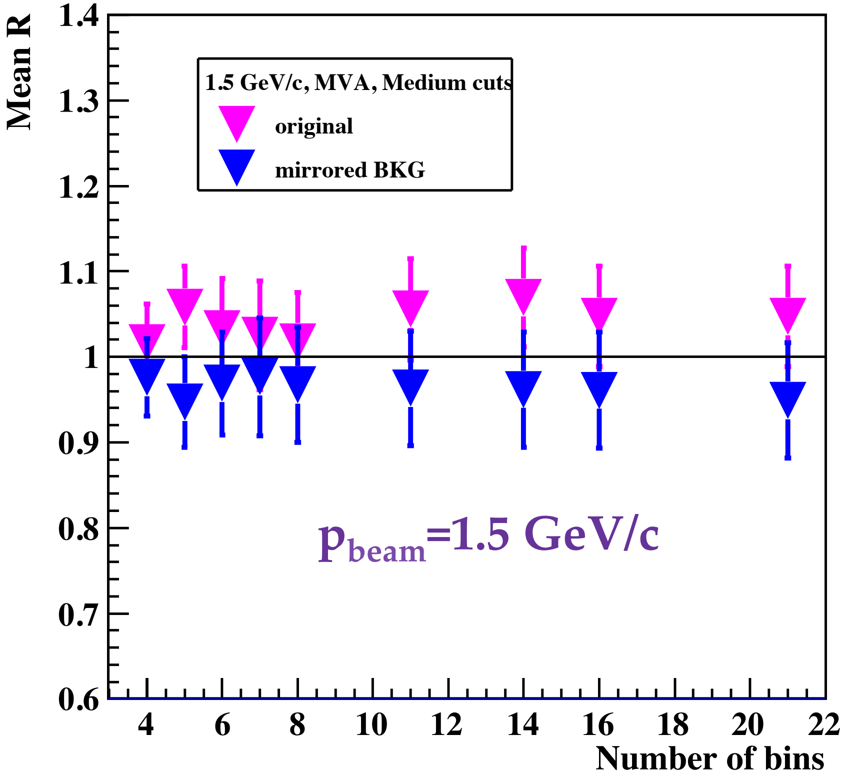
Mirrored BKG distributions: difference B2 – B1

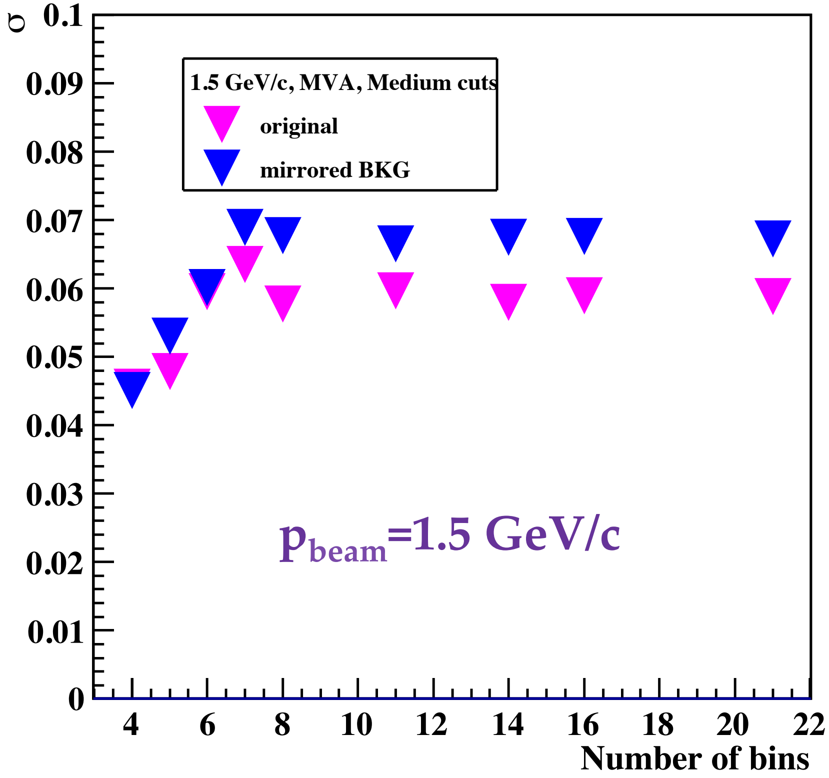


Influence of the background distribution shape

How does the mean value of R and its error depend on the background distribution shape?

Medium cuts, 1.5 GeV/c





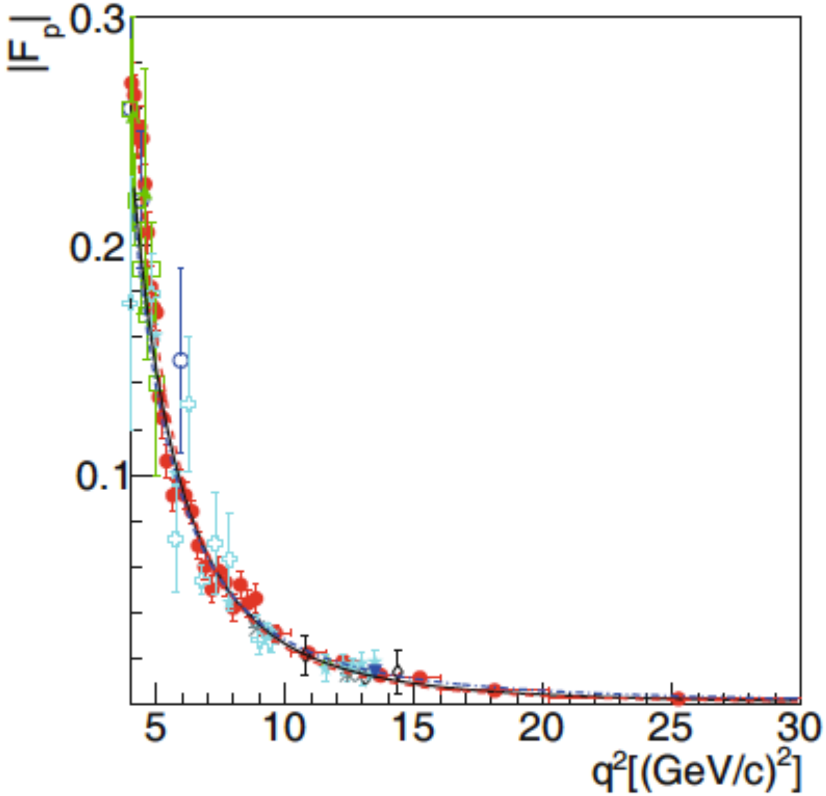
The influence of the background shape is visible in this „extreme“ scenario

Feasibility studies: time-like proton form factors @ PANDA

Effective Form Factor of the proton

$\bar{p}p \rightarrow \mu^+\mu^-$

Effective proton Form Factor



$$|F_p|^2 \propto \sigma_{\text{int}}$$

Highest precision on R, $|G_E|$&$|G_M|$

q^2 [GeV²]	$\lvert F_p\rvert \pm \Delta\lvert F_p\rvert$	$\Delta\lvert F_p\rvert/\lvert F_p\rvert$ [%]
5.08	0.1609 ± 0.0005	**0.31**
5.40	0.1388 ± 0.0011	**0.79**
6.77	0.0808 ± 0.0011	**1.36**
8.20	0.0513 ± 0.0008	**1.56**

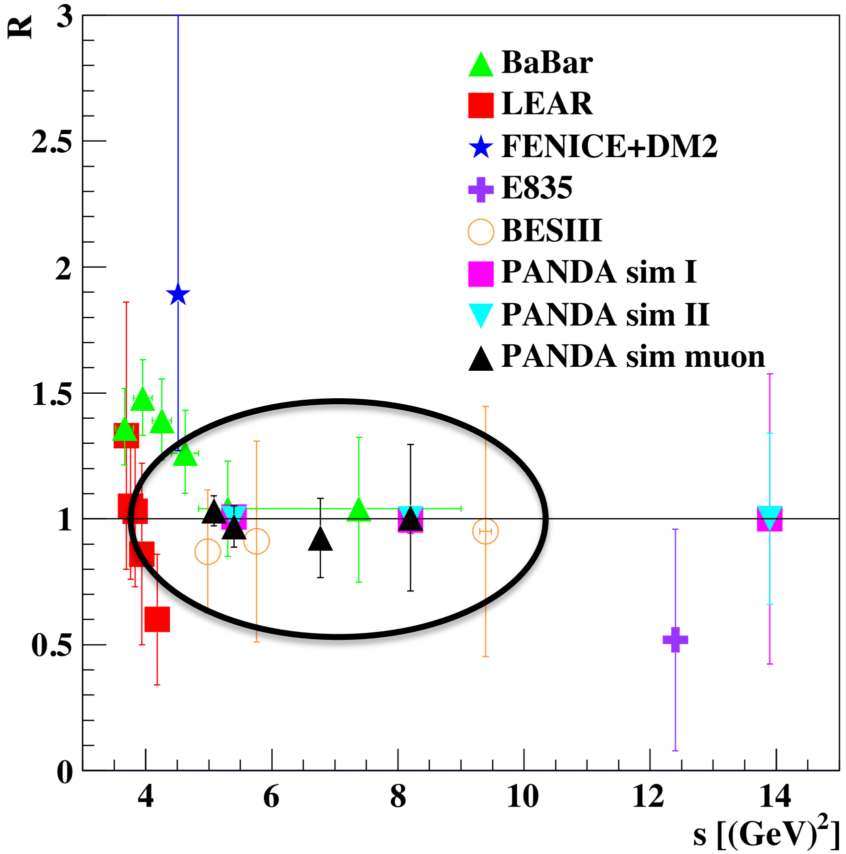
-PRELIMINARY-

Feasibility studies: time-like proton form factors @ PANDA

Statistical precision on R

$$\bar{p}p \rightarrow \mu^+\mu^-$$

World data on R = |G_E|/|G_M|



Total Precision ΔR/R

s [GeV²]	Stat.	Binning	Total
5.08	5.8 %	1.5 %	**6.0 %**
5.40	8.5 %	0.3 %	**8.5 %**
6.77	17.1 %	4.5 %	**17.7 %**
8.20	29.0 %	4.1 %	**29.3 %**

-PRELIMINARY-

Feasibility studies: time-like proton form factors @ PANDA

Summary & Outlook

- Monte Carlo simulation & analysis for **signal** and main **background** channel

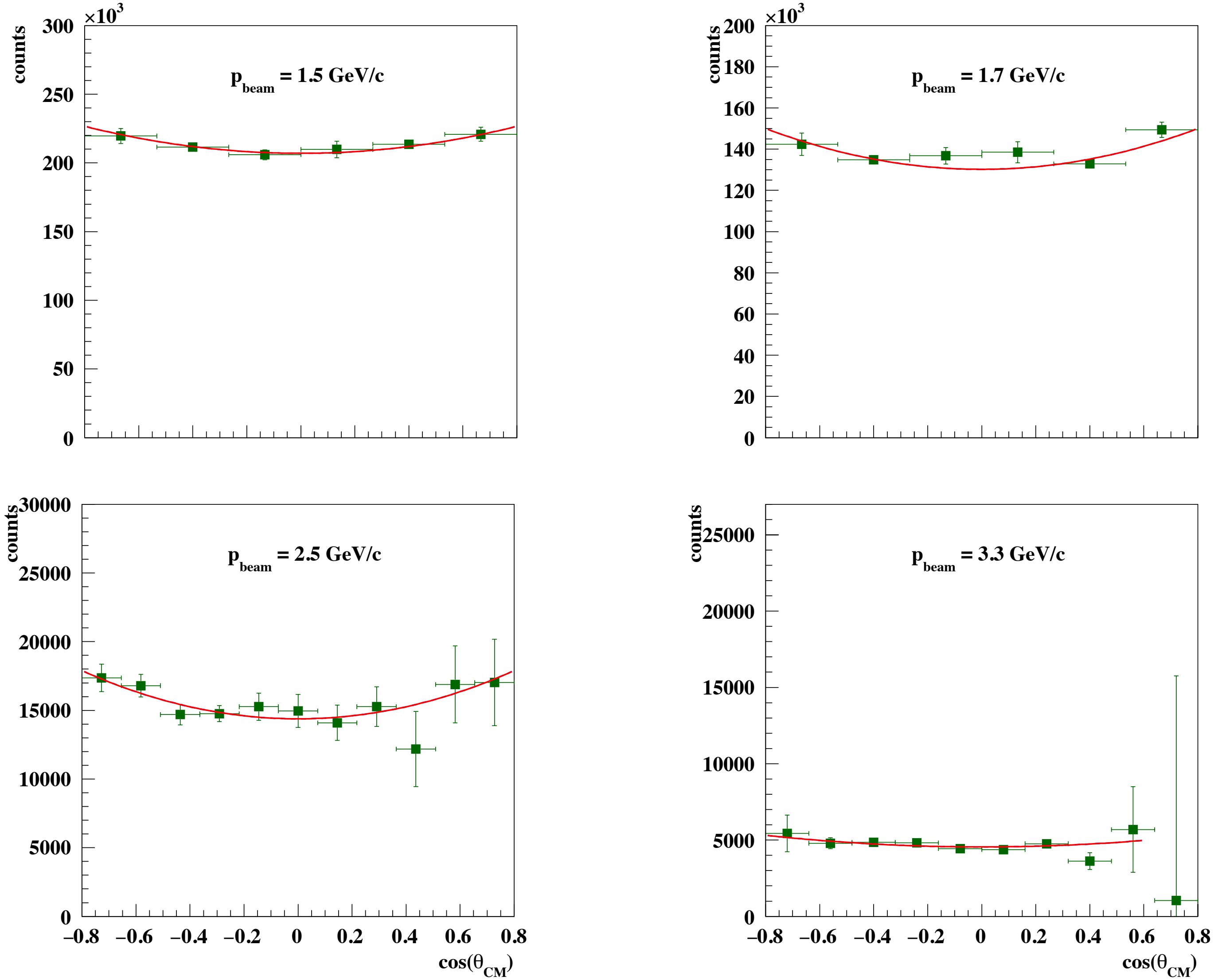
$\bar{p}p \rightarrow \mu^+\mu^-$ $\bar{p}p \rightarrow \pi^+\pi^-$

- **Feasibility studies on $\mu^+\mu^-$:**
  - At **p_{beam} between 1.5 and 3.3 GeV/c** a **statistical precision for**
    - **R between 5.8% and 29.0% (total precision: 6.0% and 29.3%)**
    - **$|G_M|$ between 2.0% and 7.8%**
    - **$|G_E|$ between 3.8% and 21.2%**
    - **Effective proton form factor between 0.3% and 1.6%**

    could be achieved.
- Check **contribution of radiative corrections** in simulation (PHOTOS)
- **Day-1 EMP physics: Study for muon channel at 1.5 GeV/c in progress**
- **Release Note** has been **updated** and is under review within the working group
- Complete **PANDA reviewing process for journal publication** will **start soon**

Thank you for your attention!

Fitting the efficiency corrected signal angular distributions



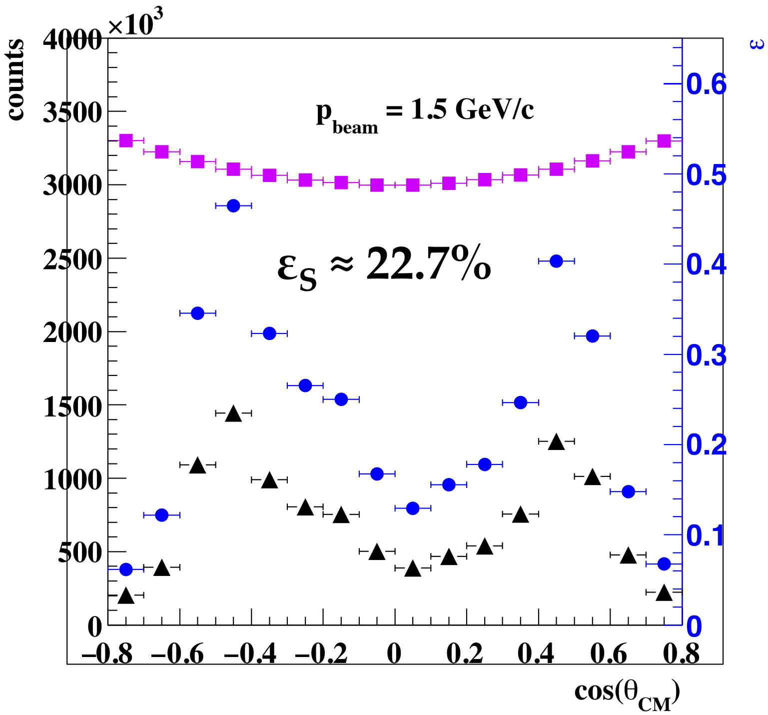
L = 2 fb^{-1}

Signal efficiency studies

p_{beam} = 1.5 GeV/c

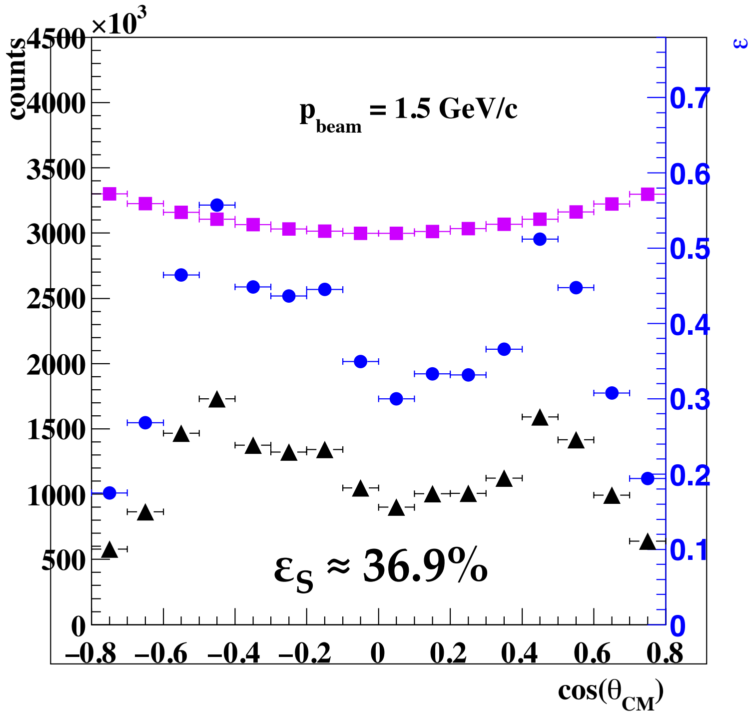
MVA

S-B ratio: 1:5



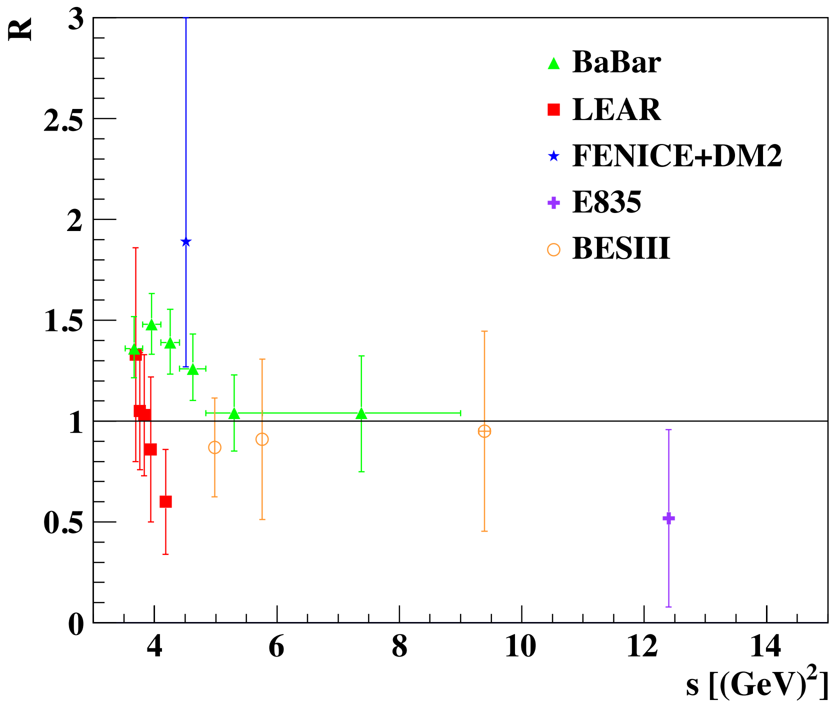
„Medium cuts“

S-B ratio: 1:10



„Loose cuts“

Data on the time-like proton form factor ratio $R=|G_E|/|G_M|$



BaBar: Phys. Rev. D88 072009
LEAR: Nucl.Phys.J., B411:3-32. 1994
BESIII: arXiv:1504.02680. 2015
CMD-3: arXiv:1507.08013v2 (2015)

@ BaBar (SLAC): $e^+e^- \to \bar{p}p\gamma$
- data collection over wide energy range

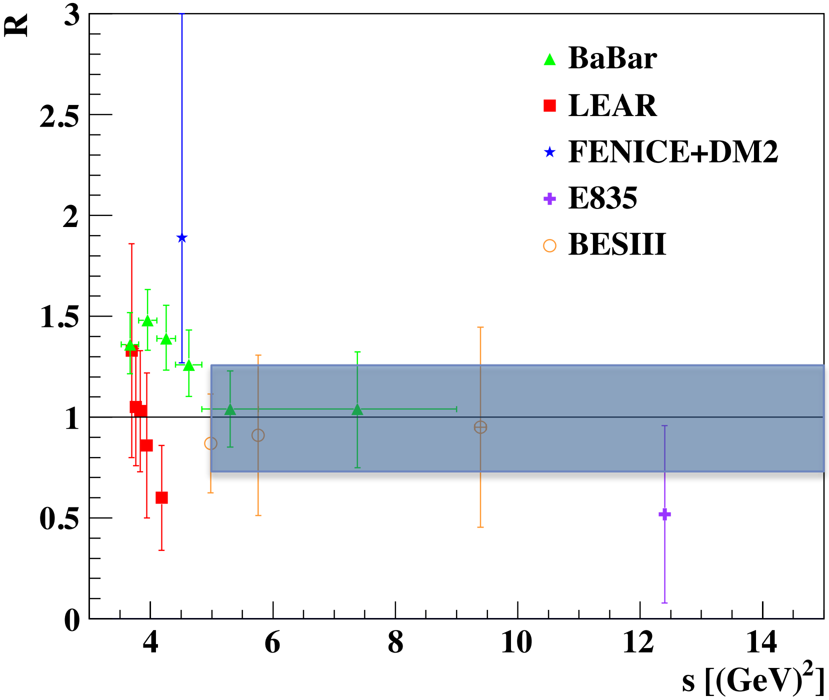
@ PS 170 (LEAR): $\bar{p}p \to e^+e^-$
- data collection at low energies

Data from BaBar & LEAR show inconsistencies

@ BESIII: $e^+e^- \to \bar{p}p$
- Measurement at different energies
- Uncertainties comparable to previous experiments

@ CMD-3 (VEPP2000 collider, BINP):
- Energy scan $\sqrt{s} = 1-2\ GeV$
- Uncertaincy comparable to the measurement by BaBar

Data on the time-like proton form factor ratio $R=|G_E|/|G_M|$



@ BaBar (SLAC): $e^+e^- \rightarrow \bar{p}p\gamma$
- data collection over wide energy range

@ PS 170 (LEAR): $\bar{p}p \rightarrow e^+e^-$
- data collection at low energies

Data from BaBar & LEAR show inconsistencies

@ BESIII: $e^+e^- \rightarrow \bar{p}p$
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LEAR: Nucl.Phys.J., B411:3...1994
BESIII: arXiv:1504.026...0. 2015
CMD-3: arXiv:1507.08...13v2 (2015)

PANDA: Measurement in the large range of s = **5.1 – 30.0 [GeV²]** with unprecedented precision

Feasibility studies: time-like proton form factors @ PANDA

Simulation & Analysis: Background studies

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

- **New event generator** developed by Mainz working group (M. Zambrana et al.)
- Based on two different parametrizations

	Low energy	Transition region	High energy
p_{beam} (GeV/c)	0.79 – 2.43	2.43 – 5.00	5.00 – 12.00
Data:	Eisenhandler et. al., NP B96 (1975)		A. Eide et. al., NP B60(1973) T. Buran et. al., NPB 116(1976) C. White et. al., PRD 49(1994)
Model:	Legendre polynomial fit	Linear interpolation	Regge Theory J. Van de Wiele and S. Ong, EPJA 46 (2010)

Feasibility studies: time-like proton form factors @ PANDA
Background

- Background including **three-body final states**: kinematically very different from signal
- Background of **two heavy charged particles** (K^+K^-, etc.)

in the final state:

  - Cross section is high, but…
  - **Detector response** (Straw Tube Tracker, Cherenkov detector, …) **very different** from signal

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

- **Kinematically very similar** to signal
- **Detector response very similar** to signal
- Cross section is by a factor of $\mathbf{10^6}$ higher than signal cross section

Feasibility studies: time-like proton form factors @ PANDA

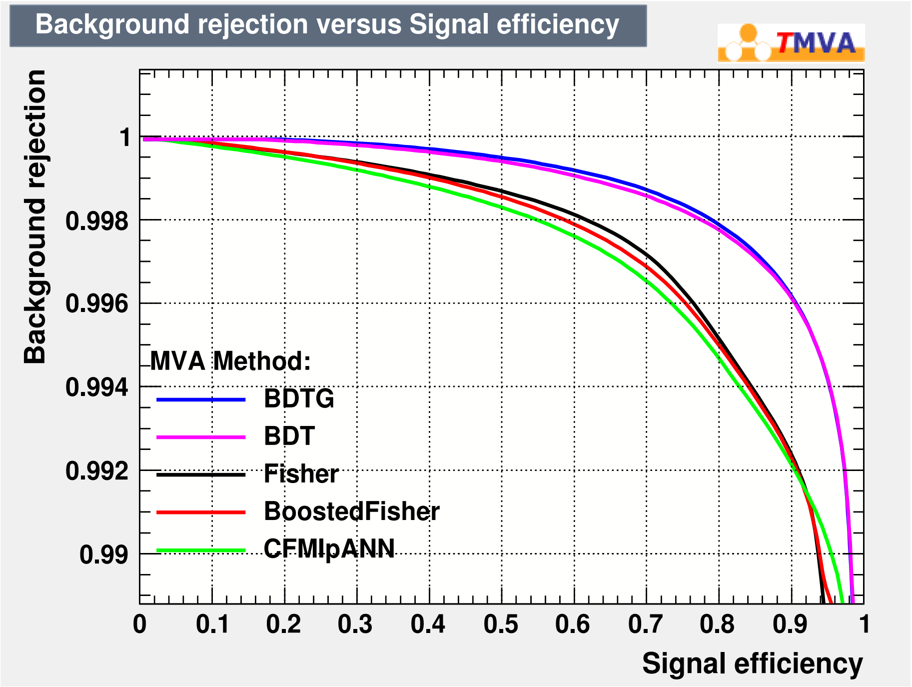
Multivariate Data Classification (MVA)

1) <u>**Training of the classifiers:**</u>
   - well-known training data samples (signal & background)
   - **a set of input variables** for training, testing and evaluation:
     - Kinematical variables (invariant mass, $(\theta^{+}+\theta^{-})_{CM}$, $|\varphi^{+}-\varphi^{-}|$)
     - Detector observables from Muon System, EMC, Straw Tube Tracker
   - **Boosted Decision Trees** show **best performance**

2) <u>**Application**</u> of **trained Boosted Decision Trees** on reconstructed data samples:
   - Cuts on **BDT response** & **kinematical variables:**

Optimization of the Signal/Background separation

Receiver Operating Characteristic (ROC)



BDT(G): Boosted Decision Trees using gradient (adaptive) boosting technique
CFMlpANN: Neural network
Fisher: linear discriminant analysis