PANDA Collaboration Meeting
June 06-09, 2017
HIM, Mainz

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

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

Iris Zimmermann

Helmholtz-Institut Mainz
Johannes-Gutenberg University Mainz

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**:

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

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

- **Extraction** of $|G_E|$ and $|G_M|$ and their ratio **R from reconstructed signal angular distribution** after full analysis and efficiency correction.
- **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]	2.25	2.32	2.6	2.86

Physical expectation

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

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

Feasibility studies: time-like proton form factors @ PANDA

Simulation & Analysis : Signal selection

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

Simulation & Analysis

PandaRoot

- Event generation
- Digitization
- Reconstruction
- Particle Identification
- Signal selection

p_{beam} [GeV/c]	1.5	1.7	2.5	3.3
√s [GeV]	2.25	2.32	2.6	2.86

1) Preselection

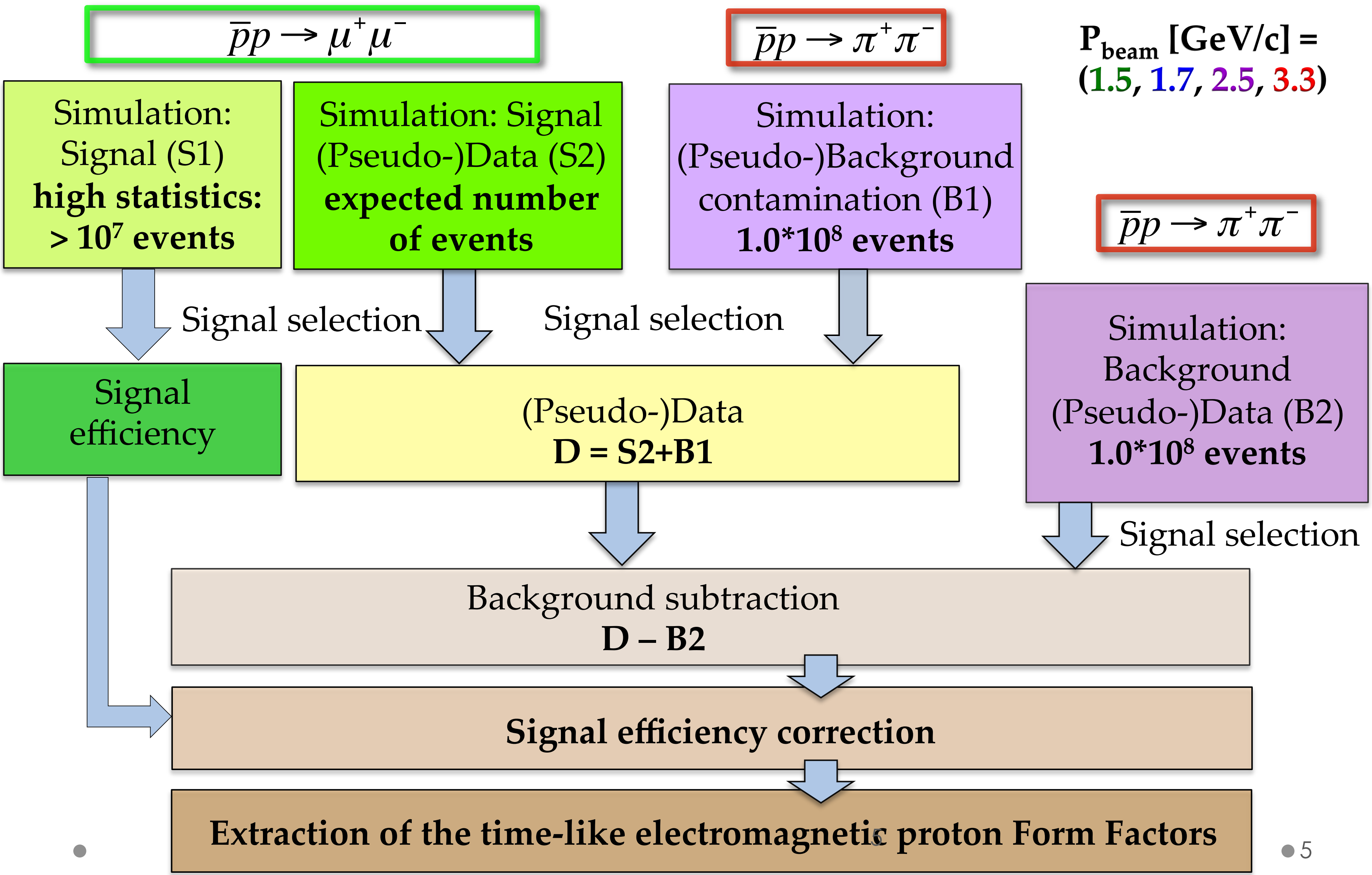
- Each event must contain **at least** one **positive and one negative track**.
  - "Best pair" selected
- **Both tracks** must show **hits inside the Muon System**
- **Non-zero initial particle momentum at Muon System**

2) Signal/Background separation based on:

- **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



Analysis:

Cut configurations & Signal efficiencies

@ 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**
1.5	]2.1 ; 2.4[	]175 ; 185[	]179.65 ; 185[	> 0.297 > 0.335 > 0.365	**0.380** **0.244** **0.151**	19.1 7.0 2.8	**1:10** **1:6** **1:4**
1.7	]2.2 ; 2.5[			> 0.290 > 0.335 > 0.360	**0.445** **0.274** **0.186**	33.6 11.2 5.64	**1:18** **1:10** **1:7**
2.5	]2.4 ; 2.8[			> 0.234 > 0.280 > 0.300	**0.531** **0.334** **0.242**	59.6 17.5 9.20	**1:28** **1:13** **1:10**
3.3	]2.6 ; 3.1[			> 0.310 > 0.320 > 0.340	**0.333** **0.295** **0.222**	15.2 13.0 7.78	**1:7** **1:5** **1:4**

-> Apply background subtraction!

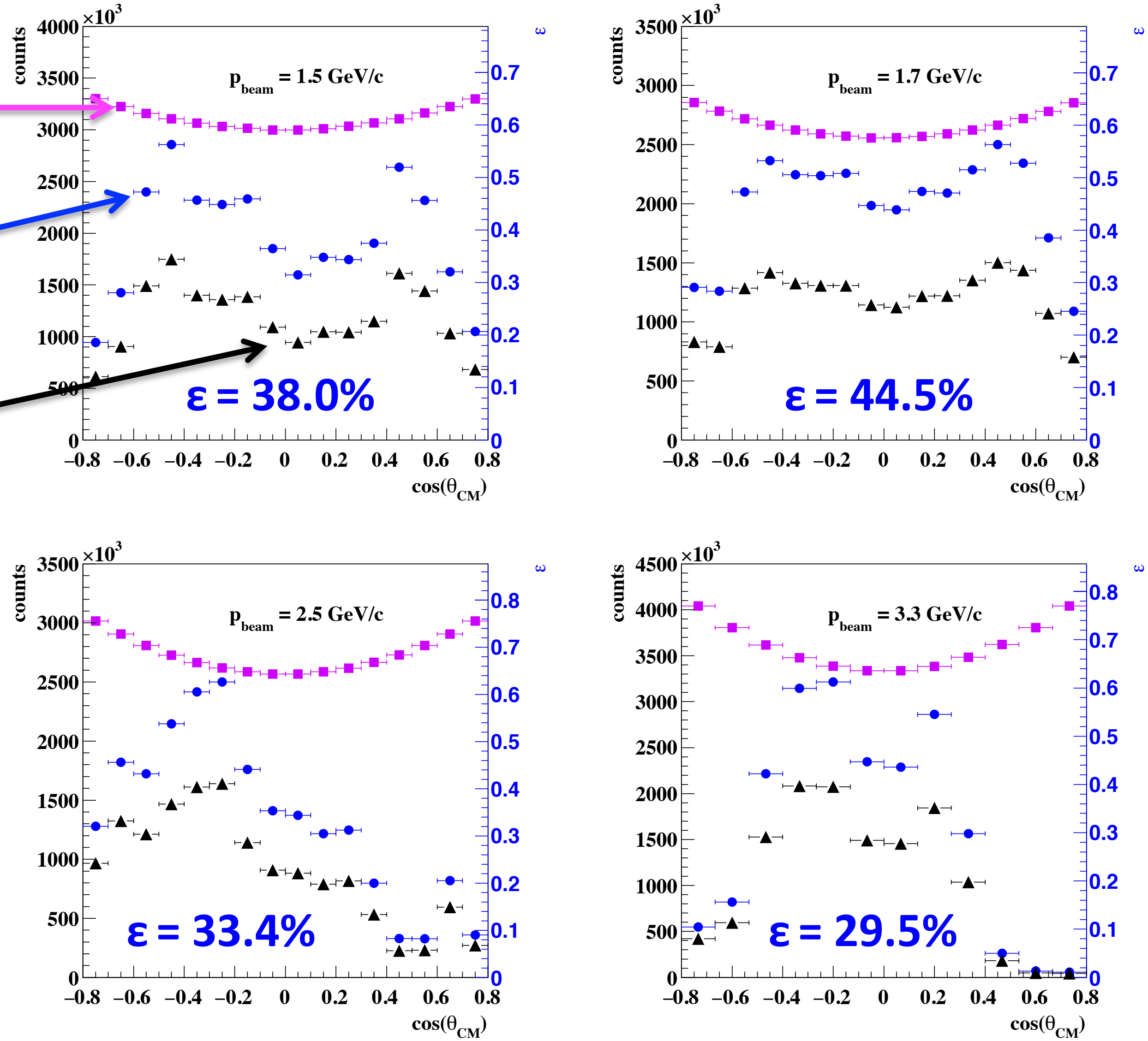
Feasibility studies: time-like proton form factors @ PANDA

Cut configuration & Signal efficiency

Monte Carlo Signal (S1)

Signal efficiency ε

Selected signal counts (S1)



Analysis:

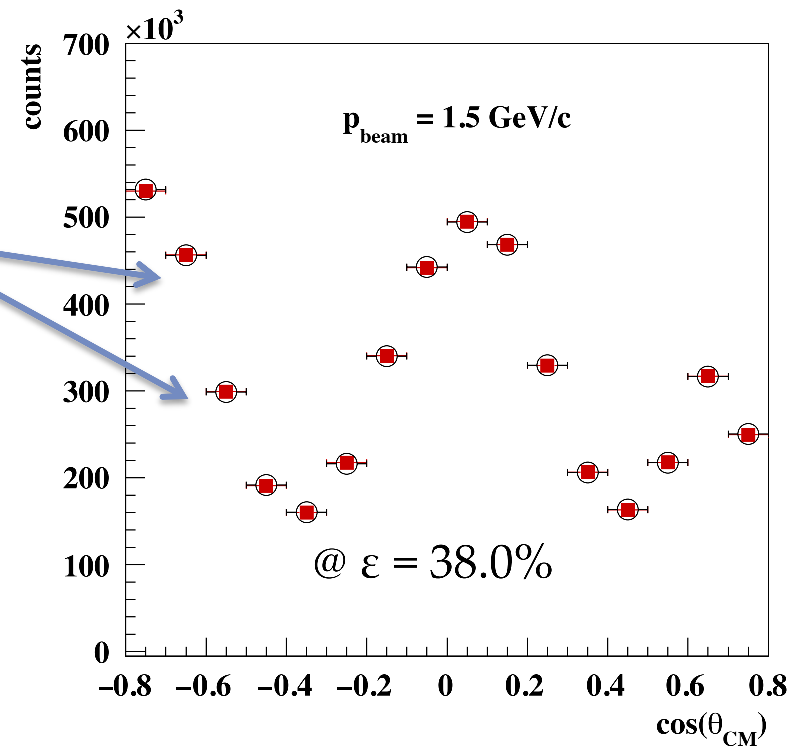
Background contamination

Feasibility studies: time-like proton form factors @ PANDA
Pion background contamination

Question: How to obtain the angular distribution of the expected pion background contamination after signal selection?

Answer: 1) Apply signal selection on B1-> Obtain suppression factor
2) Calculate **expected background contamination:** $\mathbf{N_{B1}}$
3) Change cut on BDT response until $\mathbf{N_{B1}}$ is reached
4) Apply on B2 -> Obtain $\mathbf{N_{B2}}$

N_{B1} : black open circles
N_{B2} : red massive squares



Now we can include a background subtraction in our study:

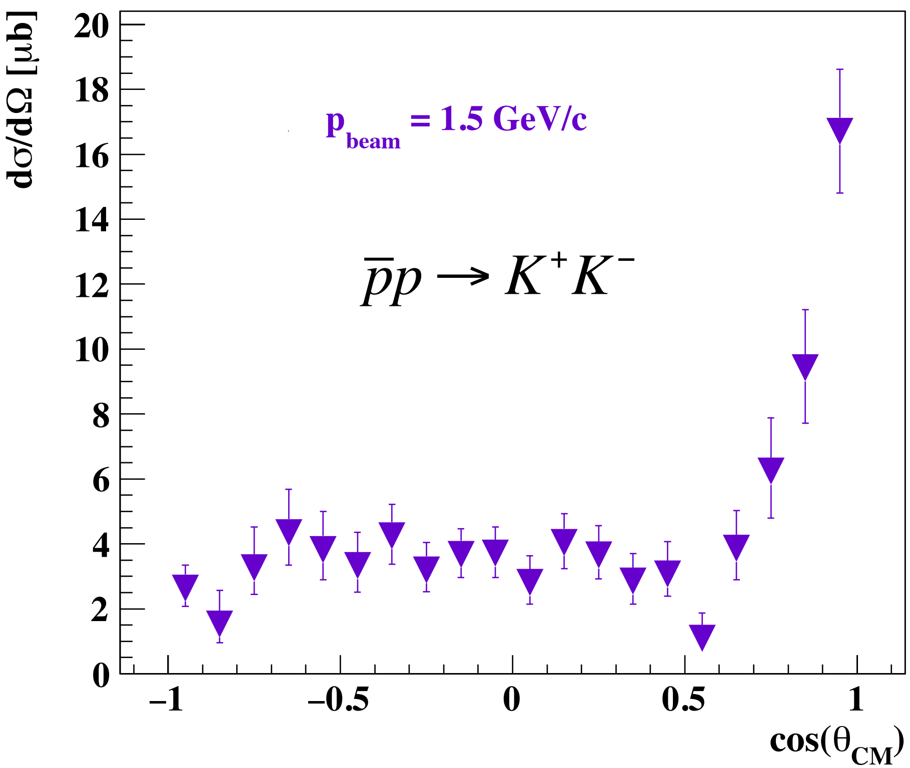
S2 + B1 – B2

-> only **background fluctuations** remain in the selected signal data

Feasibility studies: time-like proton form factors @ PANDA

Kaon background contamination

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



Data from Eisenhandler et al., Nuclear Phys. B, Vol.96, 109-154 (1975)

Estimate kaon suppression factor @ p_{beam} = 1.5 GeV/c:

- **PHSP simulation** + reconstruction of 10^8 events:

with

- $L = 2\ fb^{-1}$
- $|\cos\theta_{CM}| \leq 0.8$

N_{K+K-} = 2 fb^{-1} x 68.19 μb = **1.3638 x 10^{11} events**

- Apply signal analysis @ maximal ε = 38.0% : 2 events left -> (CL=95%, 6 events)

➔ **Kaon suppression factor ~ 10^{-8}**

➔ **Signal pollution <1%**

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

Analysis Strategy

1) **S2** + **B1** = **Data**
2) Background subtraction: **Data** – **B2**
3) Apply efficiency correction
4) Fit **efficiency corrected data**

Fit function 1: Fit parameter R (= P_1)

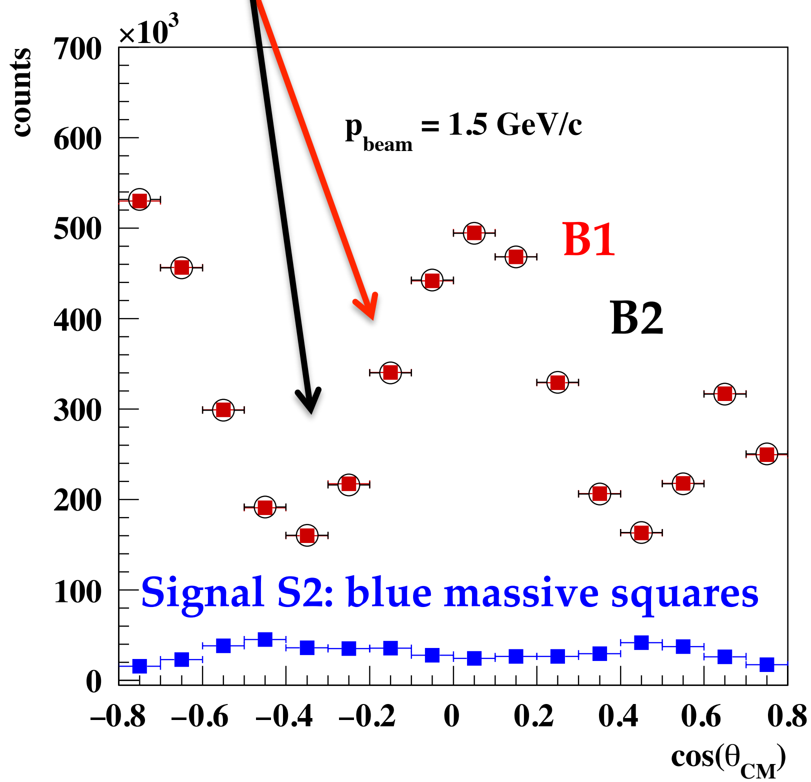
$$f_1(x) \propto P_0\left[\frac{1}{\tau}(1-\beta^2x^2)\cdot P_1^2 + 1 + \frac{4m_\mu^2}{s} + \beta^2x^2\right]$$

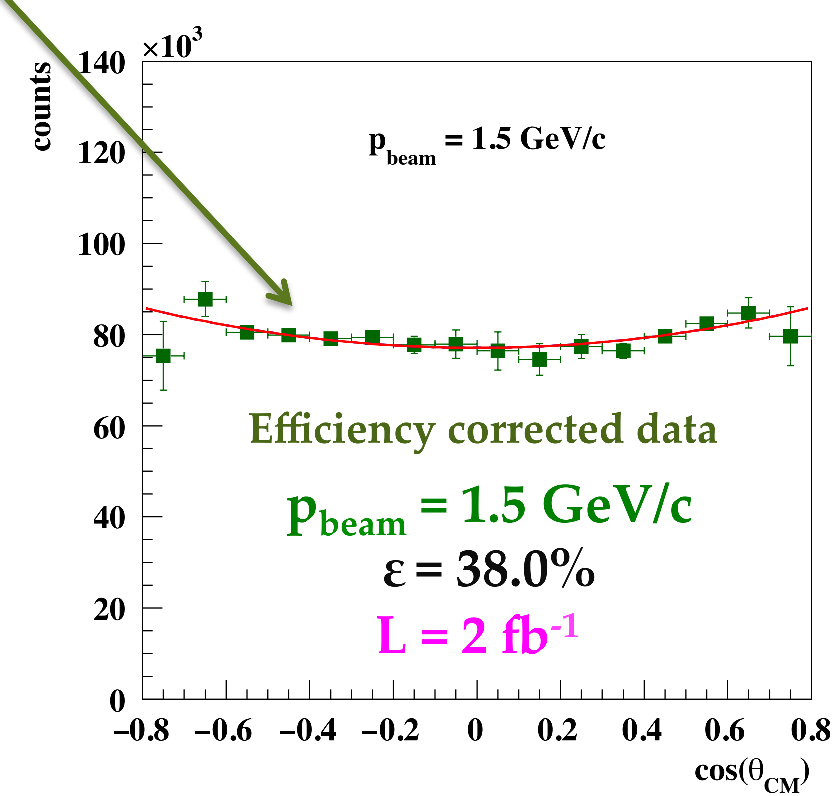
Fit function 2: Fit parameters $L^*|G_E|^2$ & $L^*|G_M|^2$

$$f_2(x) \propto C_1\cdot\left[\frac{1}{\tau}(1-\beta^2x^2)\cdot P_1^2 + \left(1+\frac{4m_\mu^2}{s}+\beta^2x^2\right)P_0^2\right]$$

Background B1: red massive squares

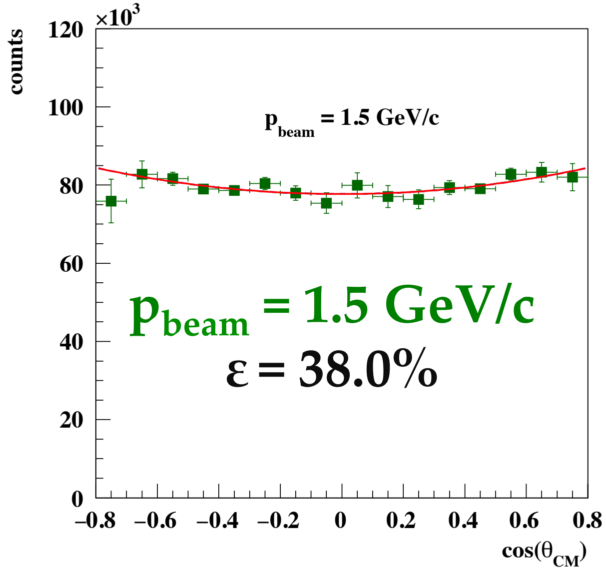
Background B2: black open circles

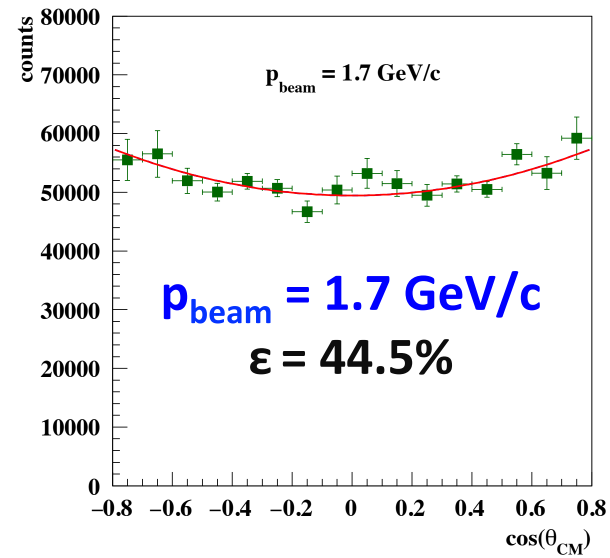


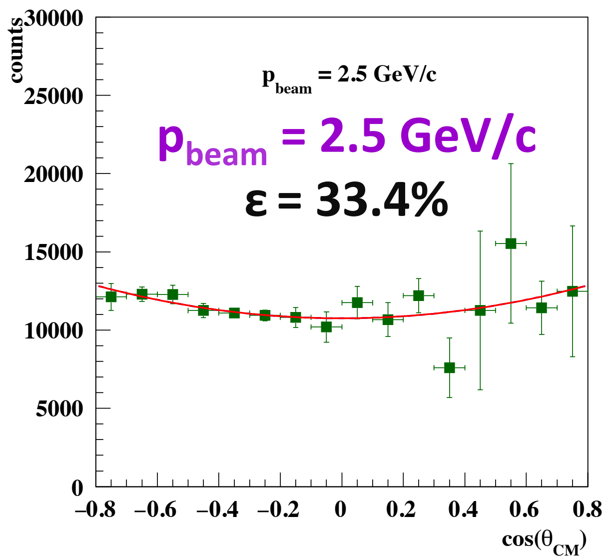


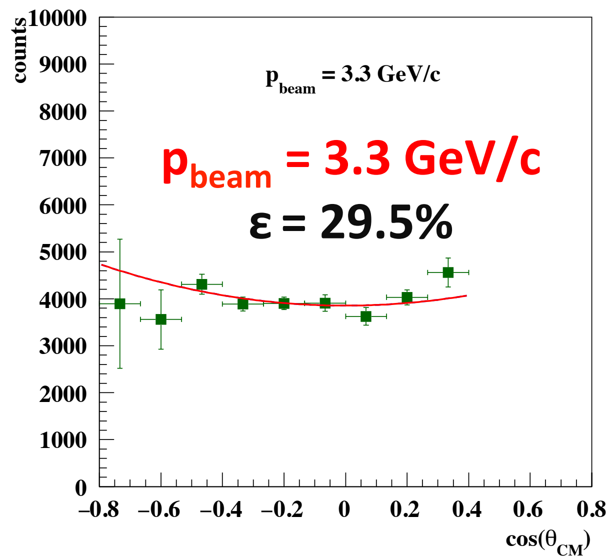
Feasibility studies: time-like proton form factors @ PANDA

Cut configuration & Signal efficiency





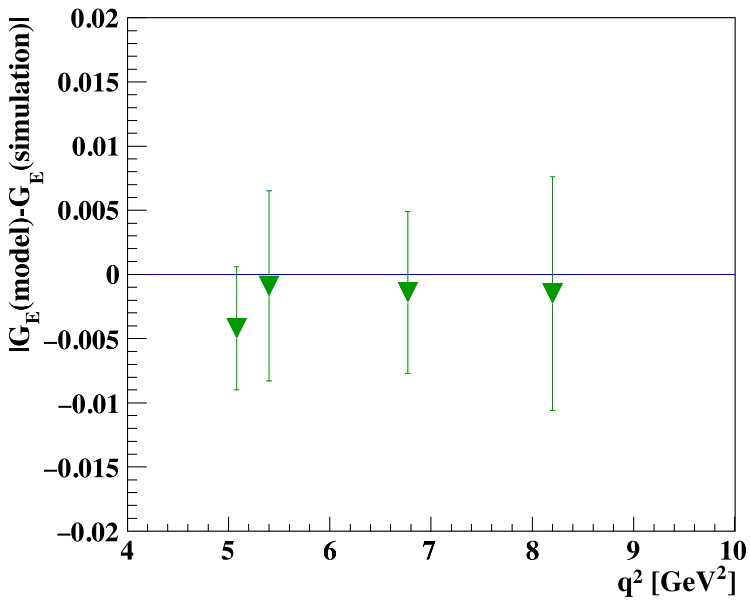


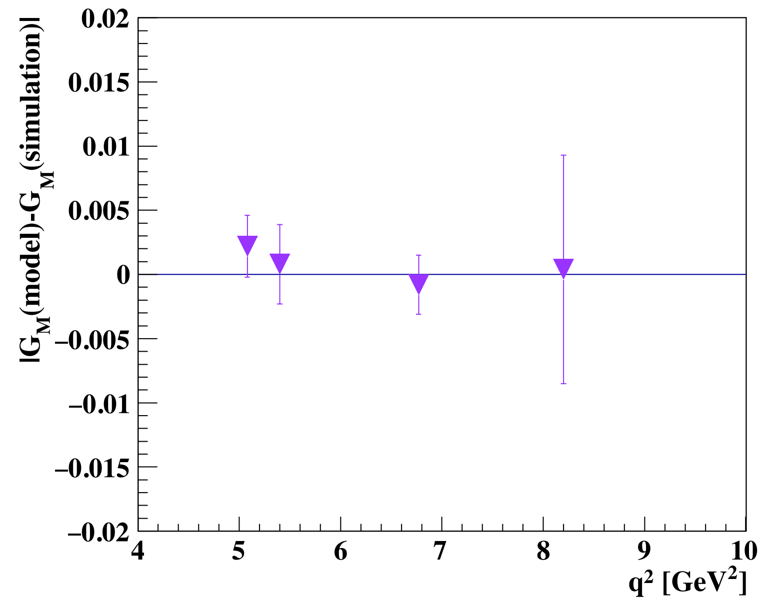


Statistical precision on $|G_E|$&$|G_M|$

- PRELIMINARY -

p_{beam} [GeV/c]	Signal efficiency ε [%]	$\|G_E\|$	$\Delta\|G_E\|$	$\|G_E\|/\Delta\|G_E\|$ [%]	$\|G_M\|$	$\Delta\|G_M\|$	$\|G_M\|/\Delta\|G_M\|$ [%]
1.5	38.0	0.1445	0.0048	**3.33**	0.1381	0.0024	**1.76**
1.7	44.5	0.1222	0.0065	**5.32**	0.1205	0.0031	**2.59**
2.5	33.4	0.0717	0.0063	**8.79**	0.0711	0.0023	**3.28**
3.3	29.5	0.0451	0.0089	**19.66**	0.0432	0.0034	**7.96**

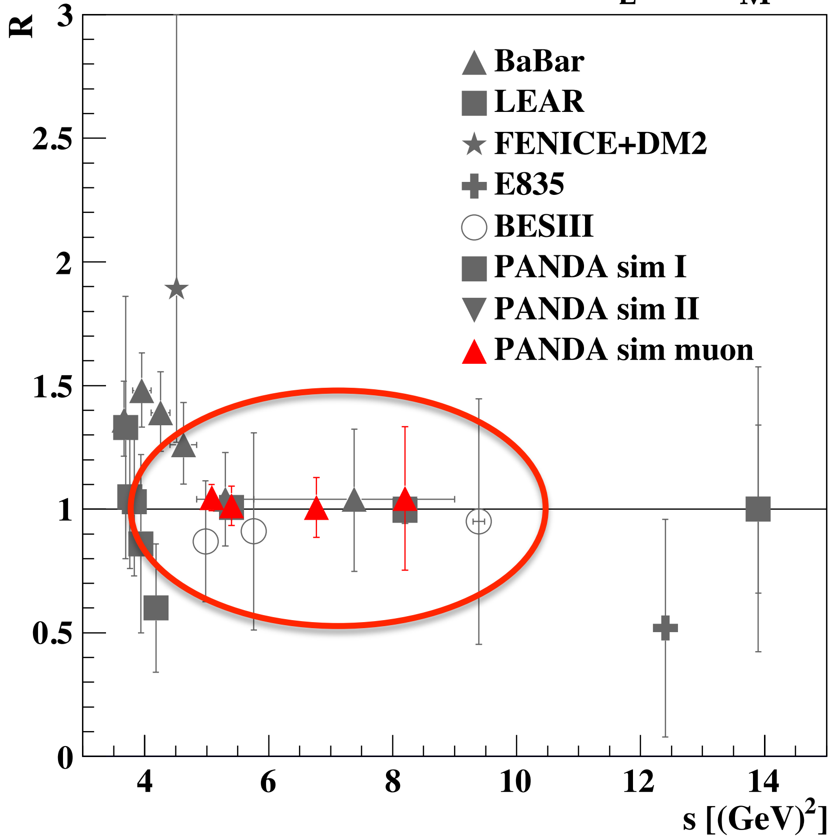




Statistical precision on $R=|G_E|/|G_M|$

PRELIMINARY

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



p_{beam} [GeV/c]	ε [%]	R±ΔR	ΔR/R [%]	χ^2/ ndf
1.5	38.0	1.0467±0.0529	5.06	0.643
1.7	44.5	1.0141±0.0798	7.86	1.051
2.5	33.4	1.0071±0.1206	11.98	0.585
3.3	29.5	1.0440±0.2899	27.76	1.219

Highest precision @ pbeam = 1.5 GeV/c : Δ R/R ≈ 5.1%

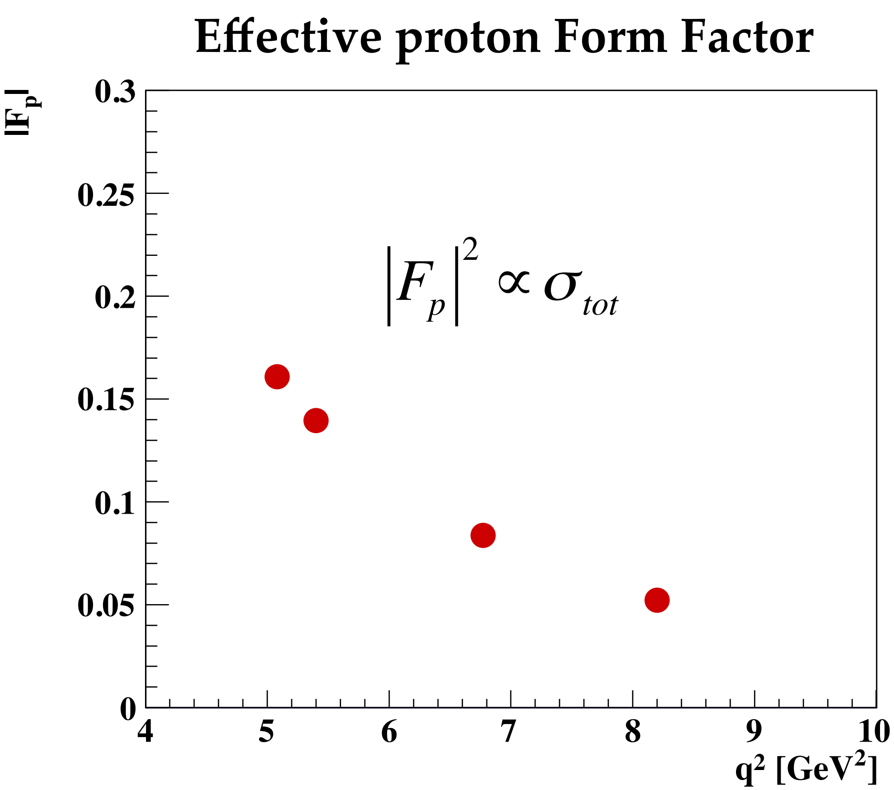
Total uncertainty

PRELIMINARY	p_{beam} [GeV/c]	Statistical uncertainty [%]	Systematical uncertainties		Total uncertainty [%]
			Luminosity [%]	Binning [%]	
$\|G_E\|/\Delta\|G_E\|$ [%]	1.5	3.33	2.0	-	3.88
	1.7	5.32		-	5.68
	2.5	8.79		-	9.01
	3.3	19.66		0.44	19.77
$\|G_M\|/\Delta\|G_M\|$ [%]	1.5	1.76	2.0	-	2.66
	1.7	2.59		-	3.27
	2.5	3.28		-	3.84
	3.3	7.96		0.06	8.21
$\Delta R/R$ [%]	1.5	5.06	-	-	5.06
	1.7	7.86		-	7.86
	2.5	11.98		-	11.98
	3.3	27.76		0.37	27.76

Feasibility studies: time-like proton form factors @ PANDA

Effective Form Factor of the proton

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



Statistical uncertainty on $|F_p|$

q^2 [GeV²]	$\|F_p\| \pm \Delta\|F_p\|$	$\Delta\|F_p\|/\|F_p\|$ [%]
5.08	0.1608 ± 0.0005	**0.31**
5.40	0.1395 ± 0.0011	**0.79**
6.77	0.0838 ± 0.0009	**1.07**
8.20	0.0523 ± 0.0007	**1.34**

-PRELIMINARY-

Analysis:

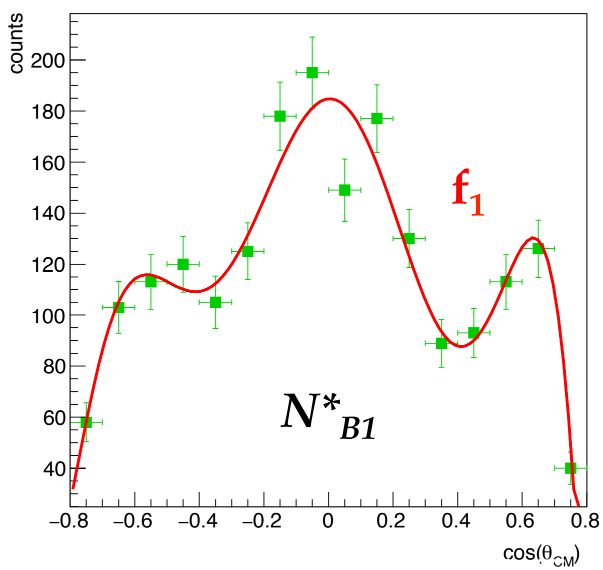
Alternative method to obtain pion background distribution @ p_{beam} = 1.5 GeV/c and ε = 38.0%

Feasibility studies: time-like proton form factors @ PANDA
Pion background contamination

Question: Is there a different way to obtain the angular distribution of the pion background contamination?

Answer: This can be done at high signal efficiencies, e.g. **ε = 38.0%**

How to: 1) Apply signal selection on B1-> Obtain distribution (N^*_{B1})
2) Calculate **expected background contamination:** $\mathbf{N_{B1}}$
3) Fit distribution of N^*_{B1} -> Obtain function $\mathbf{f_1}$



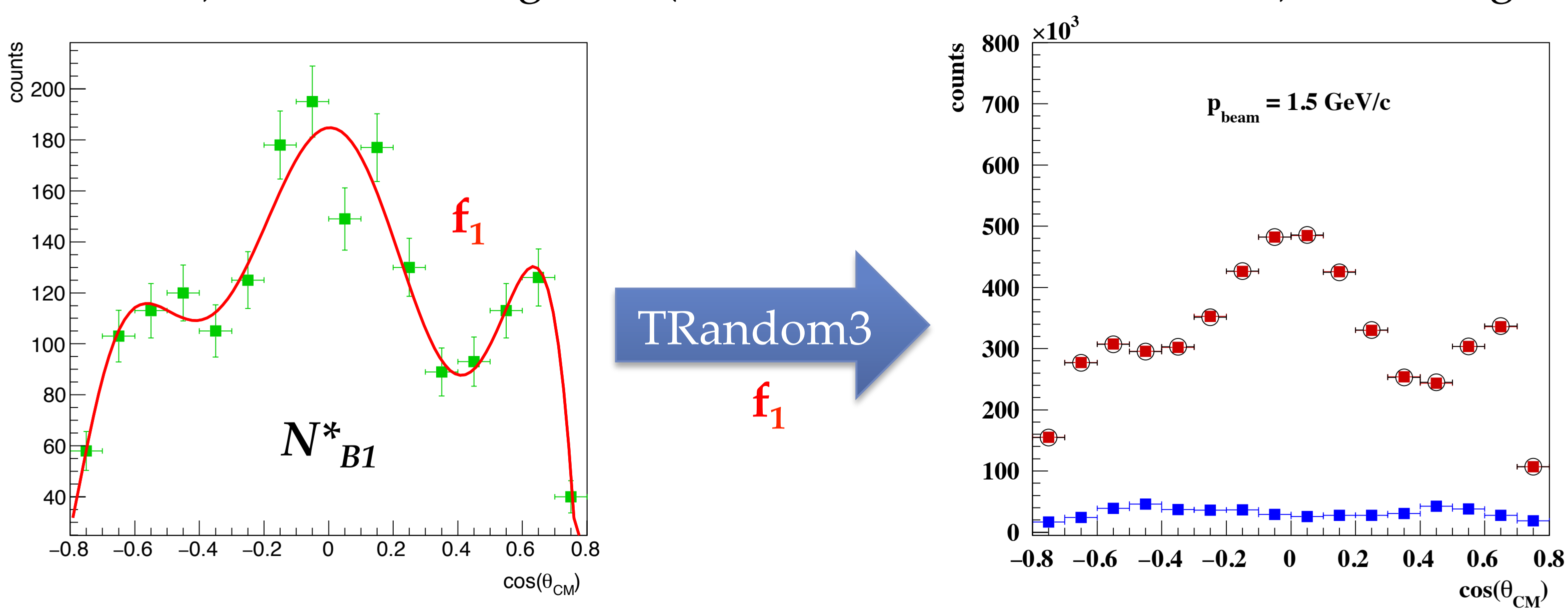
N^*_{B1}: pion counts after signal selection (B1)
= 1914 counts

Feasibility studies: time-like proton form factors @ PANDA
Pion background contamination

Question: Is there a different way to obtain the angular distribution of the pion background contamination?

Answer: This can be done at high signal efficiencies, e.g. **ε = 38.0%**

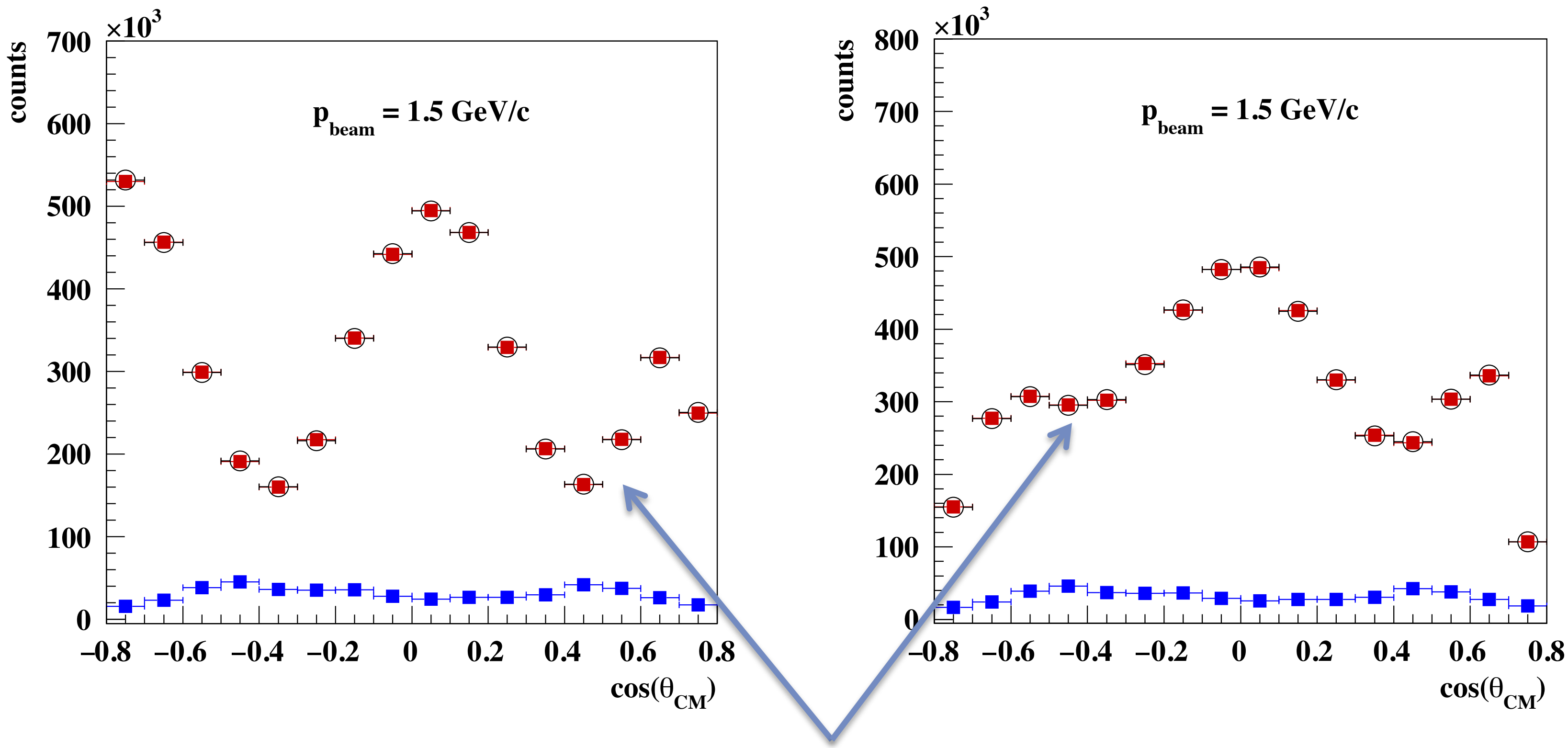
How to: 1) Apply signal selection on B1-> Obtain distribution (N^*_{B1})
2) Calculate **expected background contamination:** $\mathbf{N_{B1}}$
3) Fit distribution of N^*_{B1} -> Obtain function **f_1**
4) Fill new histograms (Random Number Generator) according to **f_1**



Feasibility studies: time-like proton form factors @ PANDA

Pion background contamination

Original method | **Alternative method**

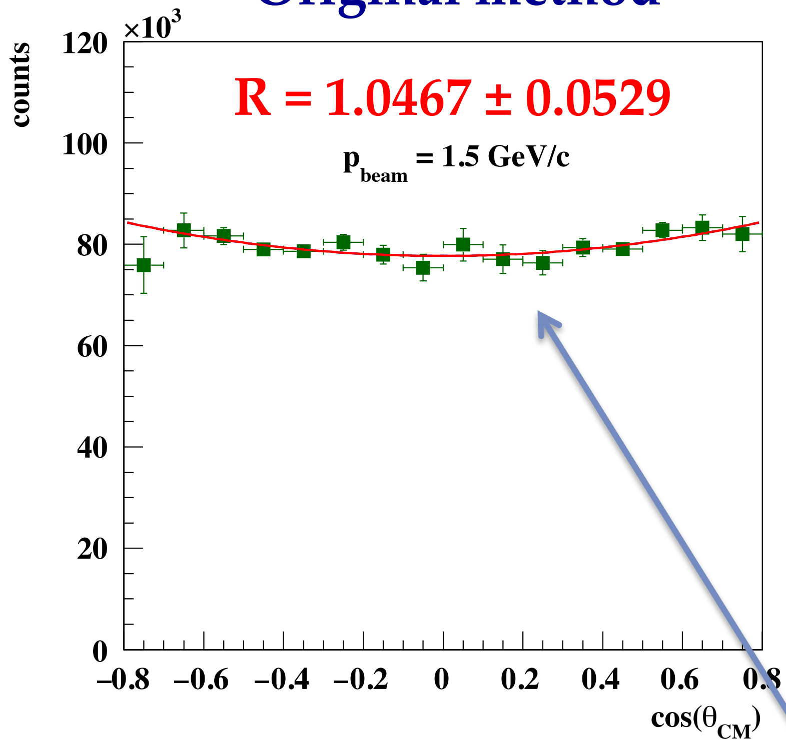


Background distributions

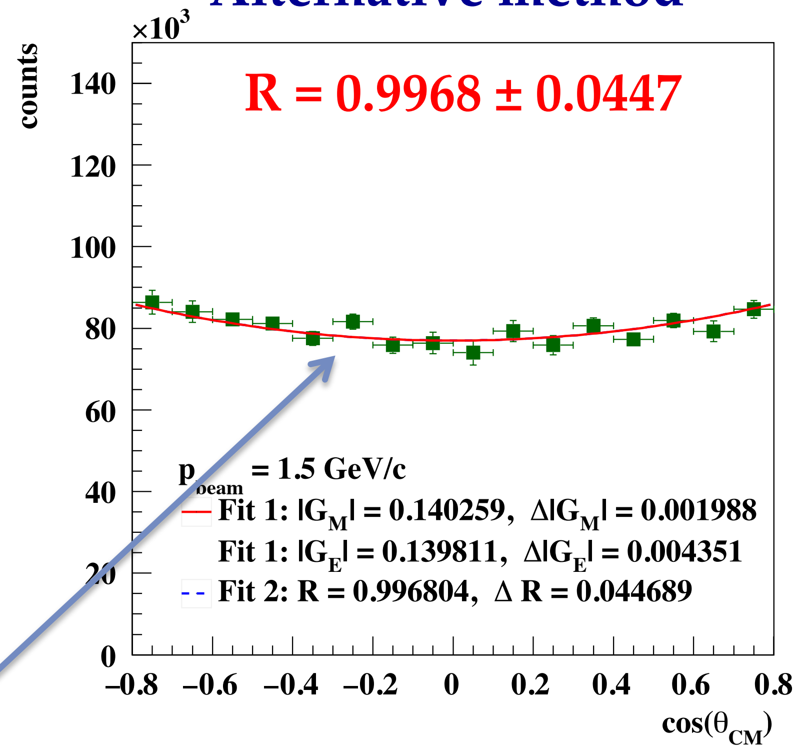
Feasibility studies: time-like proton form factors @ PANDA

Pion background contamination

Original method



Alternative method



Efficiency corrected, selected signal data after background subtraction

Alternative method confirms original method to obtain pion background distribution @ 1.5 GeV/c.

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 $\mu^+\mu^-$:**
  - For **p_{beam} between 1.5 and 3.3 GeV/c** a **total precision of**
    - **R between 5.1% and 27.8%**
    - **$|G_M|$ between 2.7% and 8.2%**
    - **$|G_E|$ between 3.9% and 19.8%**
    - **A statistical precision on the effective proton form factor between 0.3% and 1.3%**

    could be achieved.
  - Suppression factor for **di-kaon channel** ~ 10^{-8} -> **signal pollution < 1%**
  - **Alternative method** using **more realistic background shape confirms result** on R @ 1.5 GeV/c and ε = 38.0% -> repeat study at different beam momenta
- **Updated Release Note** is currently under discussion on the PANDA forum
- **Day1 simulation** (0.1 fb^{-1}, reduced Panda Detector setup) planned (software not ready)
  - Estimation: Statistical precision **approx. 20% at p_{beam} = 1.5 GeV/c**

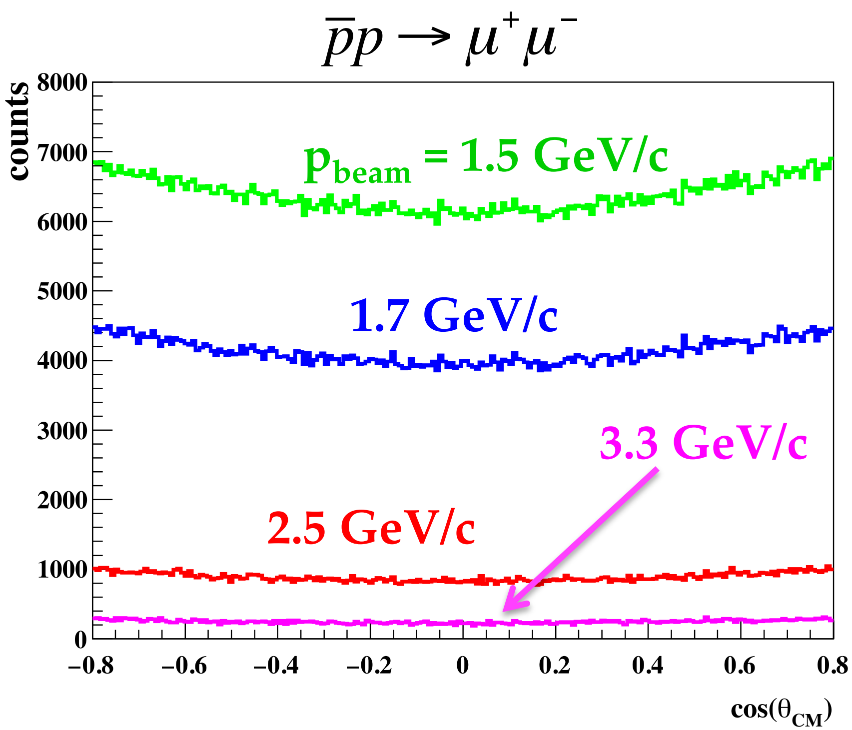
Thank you for your attention!

Feasibility studies: time-like proton form factors @ PANDA

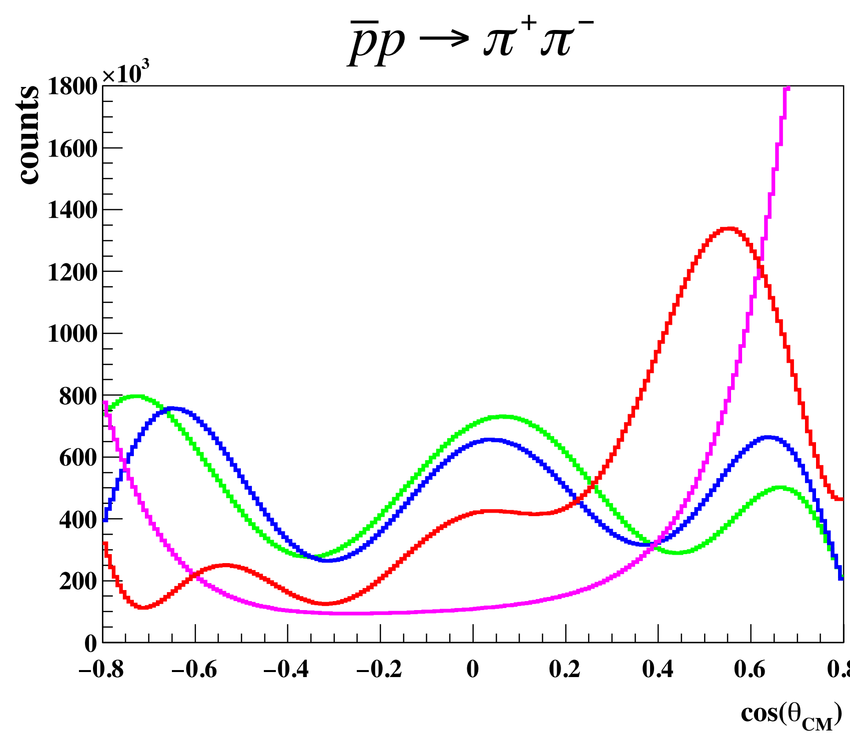
Angular distributions of generated events

$L = 2\ fb^{-1}$

Signal

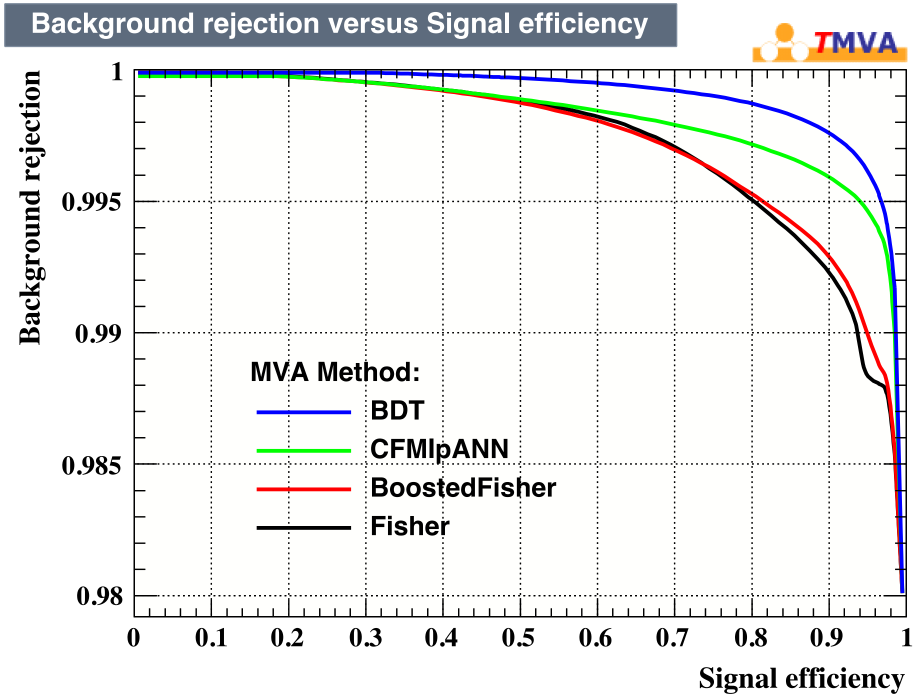


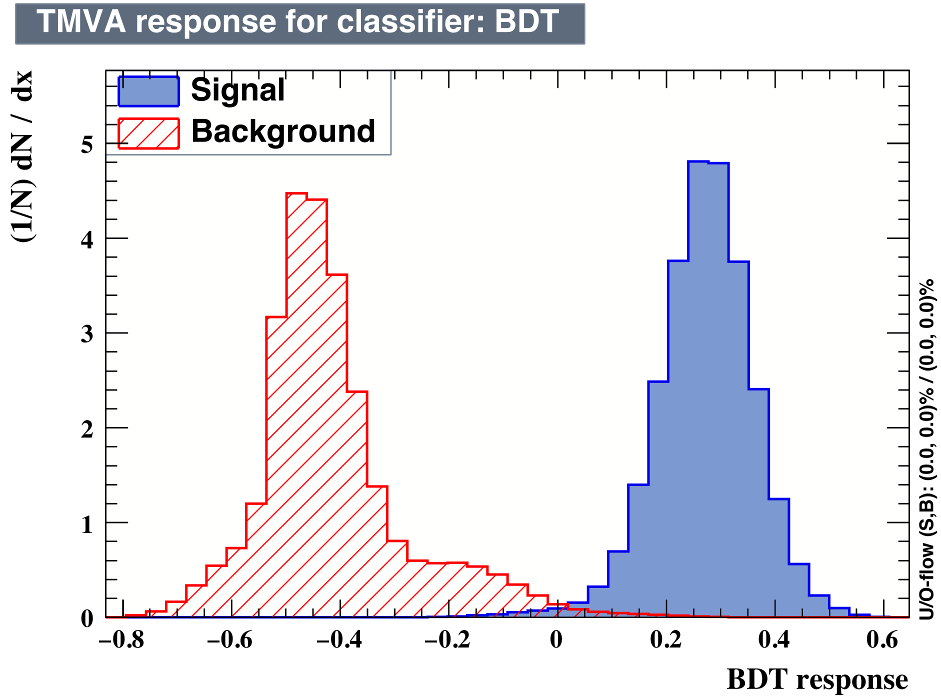
Background



Feasibility studies: time-like proton form factors @ PANDA

Signal/Background separation: Multivariate Data Classification





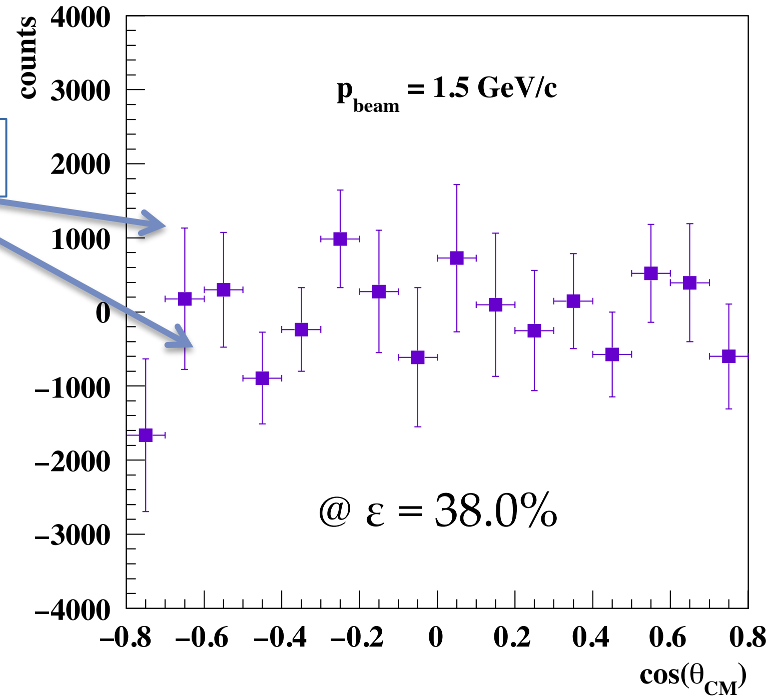
- Training & evaluation using simulated signal / background samples
- Choose classification method with best performance: **Boosted Decision Trees (BDT)**
- Application on data
- Cut on BDT response : Signal/Background separation

Feasibility studies: time-like proton form factors @ PANDA
Pion background contamination

Question: How to study the influence of background fluctuations on the extracted values of R, ΔR?

Answer: 1) Apply signal selection on B1-> Obtain suppression factor
2) Calculate **expected background contamination:** $\mathbf{N_{B1}}$
3) Change cut on BDT response until $\mathbf{N_{B1}}$ is reached
4) Apply on B2 -> Obtain $\mathbf{N_{B2}}$

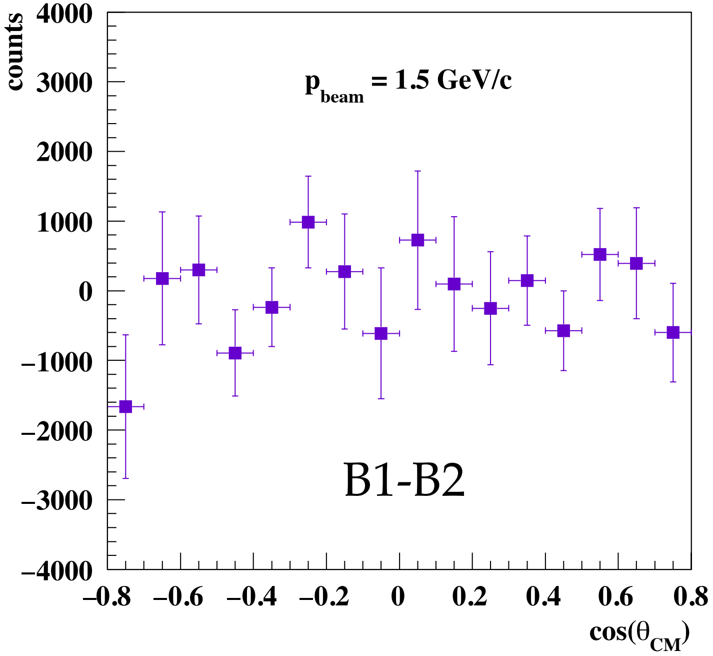
N_{B1}-N_{B2} : violet massive squares



Background fluctuations = Difference of the background distributions

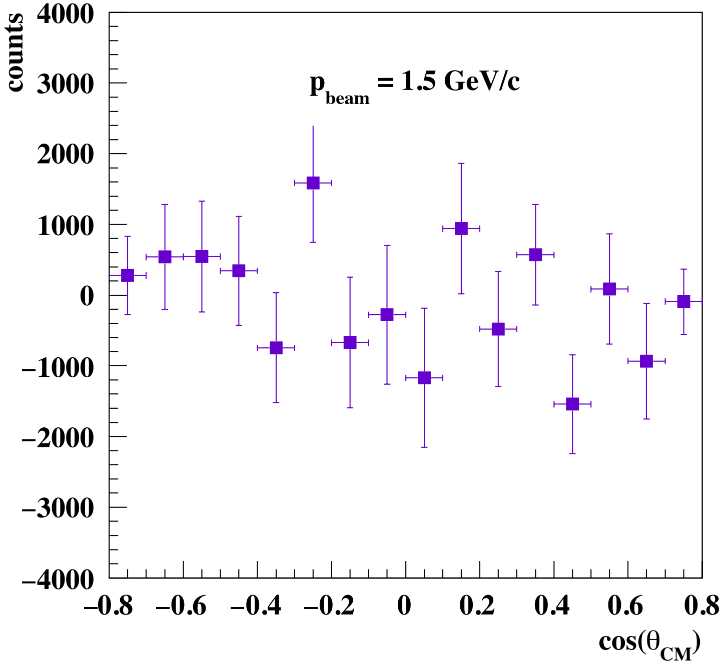
Old BKG

ε = 38.04%

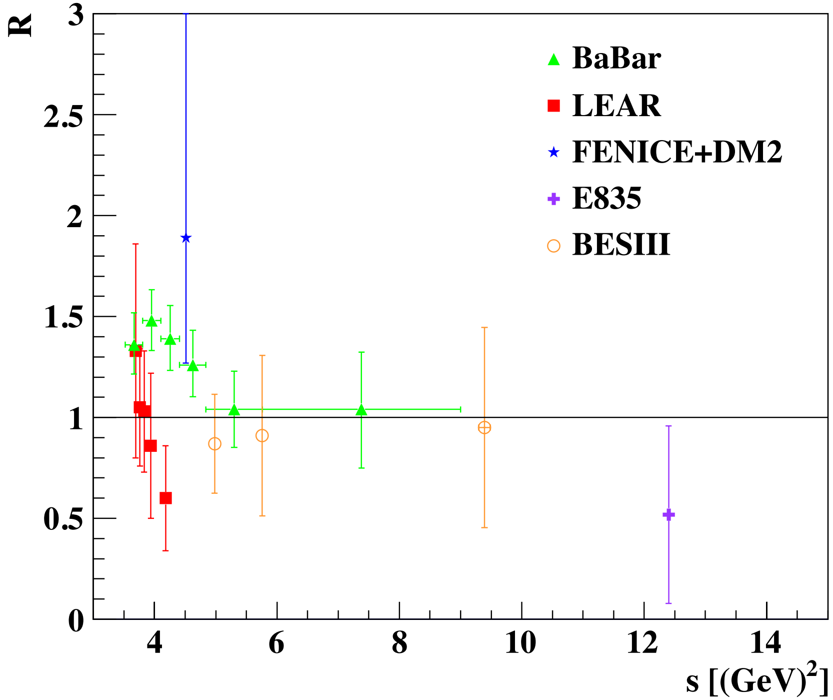


New BKG

ε = 38.04%



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

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**

0.79 — 2.43 — 5.00 — 12.00 p_{beam} (GeV/c)

Data:
- Low energy: Eisenhandler et. al., NP B96 (1975)
- High energy: A. Eide et. al., NP B60(1973); T. Buran et. al., NPB 116(1976); C. White et. al., PRD 49(1994)

Model:
- Low energy: Legendre polynomial fit
- Transition region: Linear interpolation
- High energy: 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 $\bar{p}p \to \pi^+\pi^-$ due to:

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