Probing transverse nucleon structure at high momentum transfer
April 18-22, 2016
ECT* Trento

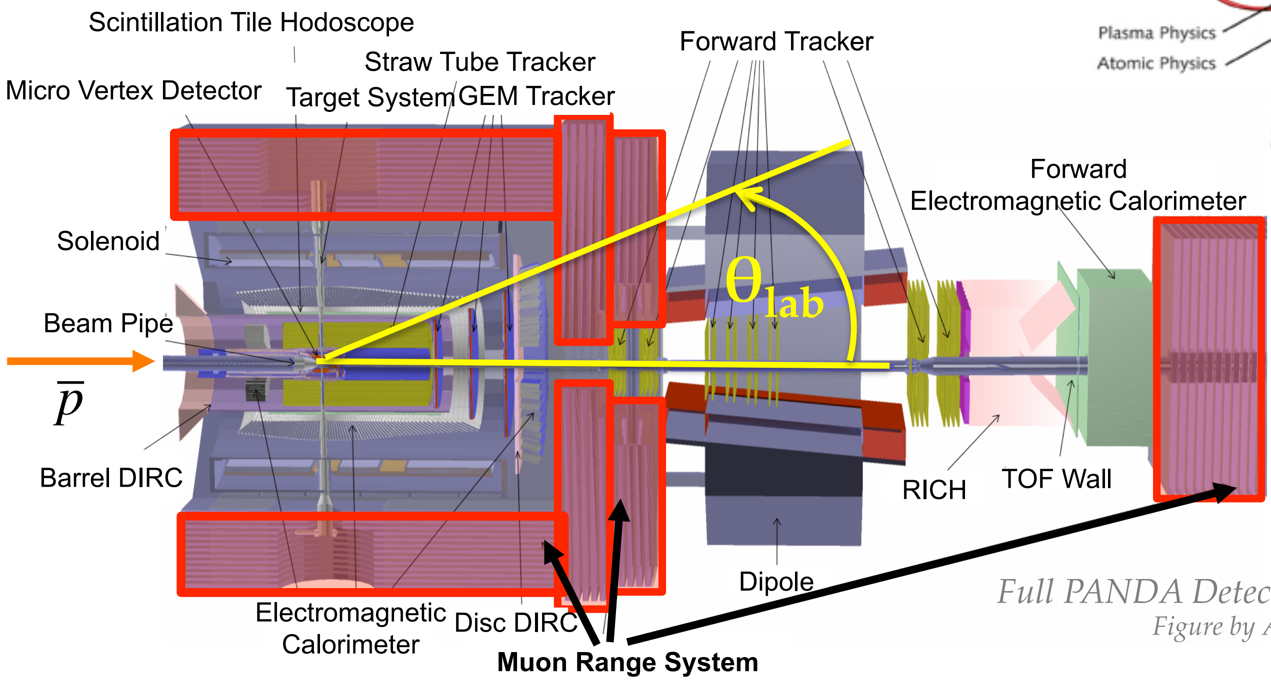
Feasibility studies on time-like proton electromagnetic form factors at PANDA-FAIR

Iris Zimmermann, Alaa Dbeyssi, Dmitry Khaneft
on behalf of the PANDA Collaboration

Helmholtz Institute Mainz
Johannes-Gutenberg University Mainz

The PANDA-Experiment at the high energy storage ring (HESR) @ FAIR (Darmstadt/Germany)

- Antiproton momenta in the range of 1.5 GeV/c up to 15 GeV/c
- Good energy and momentum resolution
- Design peak luminosity: 2 * 10 ^{32} cm^{-2} s^{-1}



Full PANDA Detector Simulation Geometry

Figure by A. Karavdina et al.

Electromagnetic Form Factors of the Proton

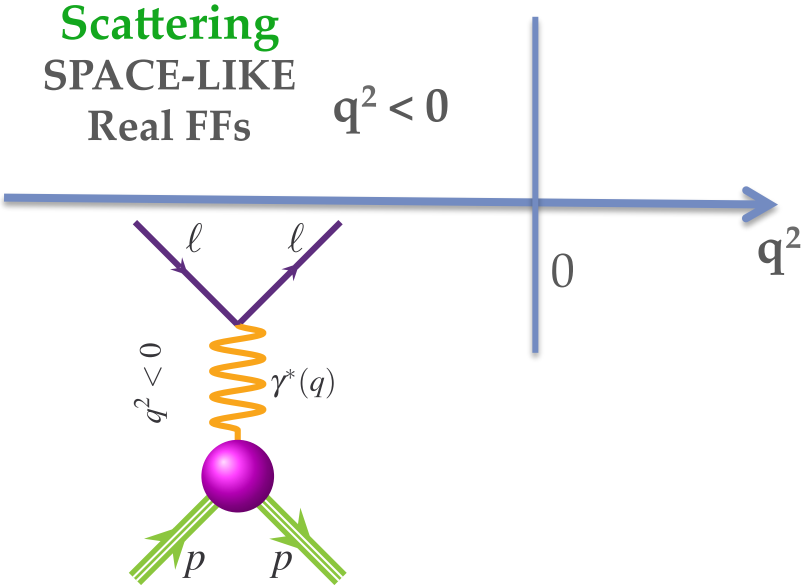
- **Internal structure and dynamics** of the proton
- **Hadronic vertex can be parametrized in terms of two Form Factors F_1 & F_2.**

$$\Gamma^{\mu} = F_1(q^2)\,\gamma^{\mu} + \frac{i\kappa}{2m_p}F_2(q^2)\,\sigma^{\mu\nu}q_{\nu}$$

- **Sachs Form Factors G_E & G_M:**

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m_p^2}F_2(q^2), \quad G_E(0) = 1$$
$$G_M(q^2) = F_1(q^2) + F_2(q^2), \quad G_M(0) = \mu_p$$

- In the Breit frame q=(0,**q**) and in non relativistic approach, **G_E** and **G_M** are the Fourier transforms of the **charge and magnetic spatial distributions** of the nucleon



Scattering

SPACE-LIKE

Real FFs

$q^2 < 0$

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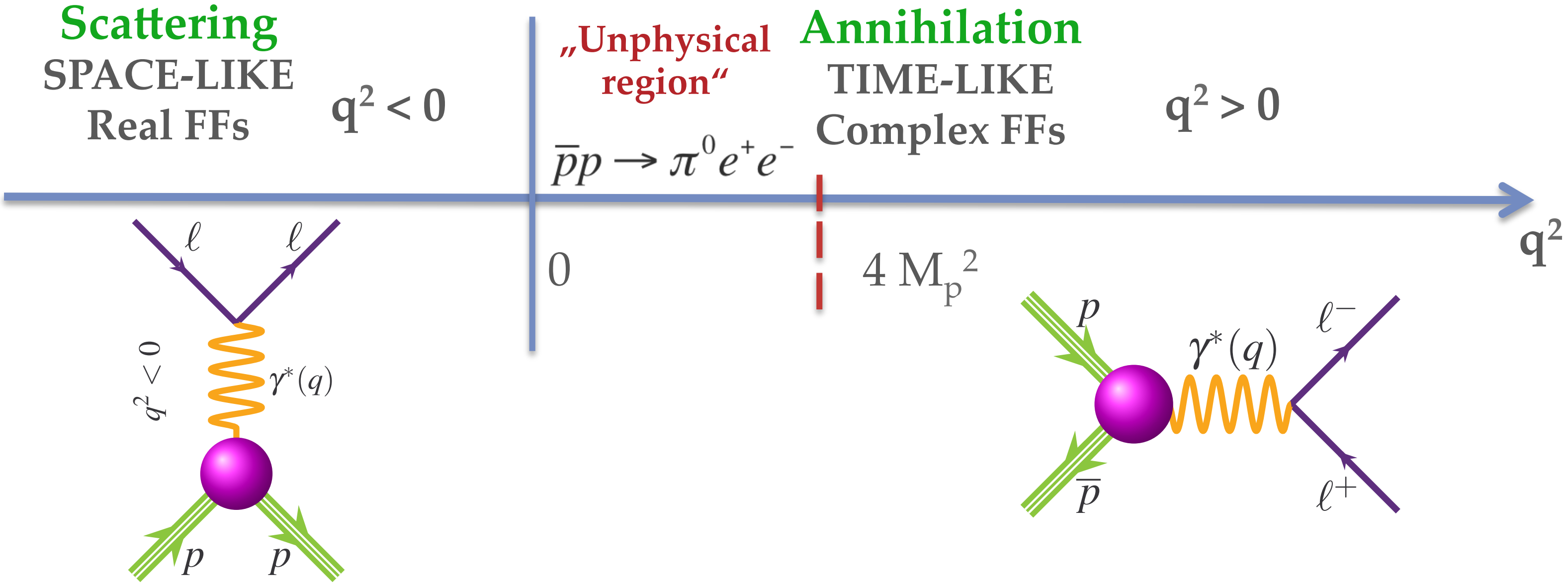

Scattering
SPACE-LIKE
Real FFs

$q^2 < 0$

„Unphysical region“

$\bar{p}p \rightarrow \pi^0 e^+ e^-$

Annihilation
TIME-LIKE
Complex FFs

$q^2 > 0$

Electromagnetic Form Factors of the Proton

Connection between Time-like & Space-Like Form Factors:

Dispersion relations based on **Unitarity & Analyticity**

- Internal structure and dynamics of the proton
- Hadronic vertex can be parametrized in terms of two Form Factors F_1 & F_2.

$$\Gamma^\mu = F_1(q^2)\gamma^\mu + \frac{i\kappa}{2m_p}F_2(q^2)\sigma^{\mu\nu}q_\nu$$

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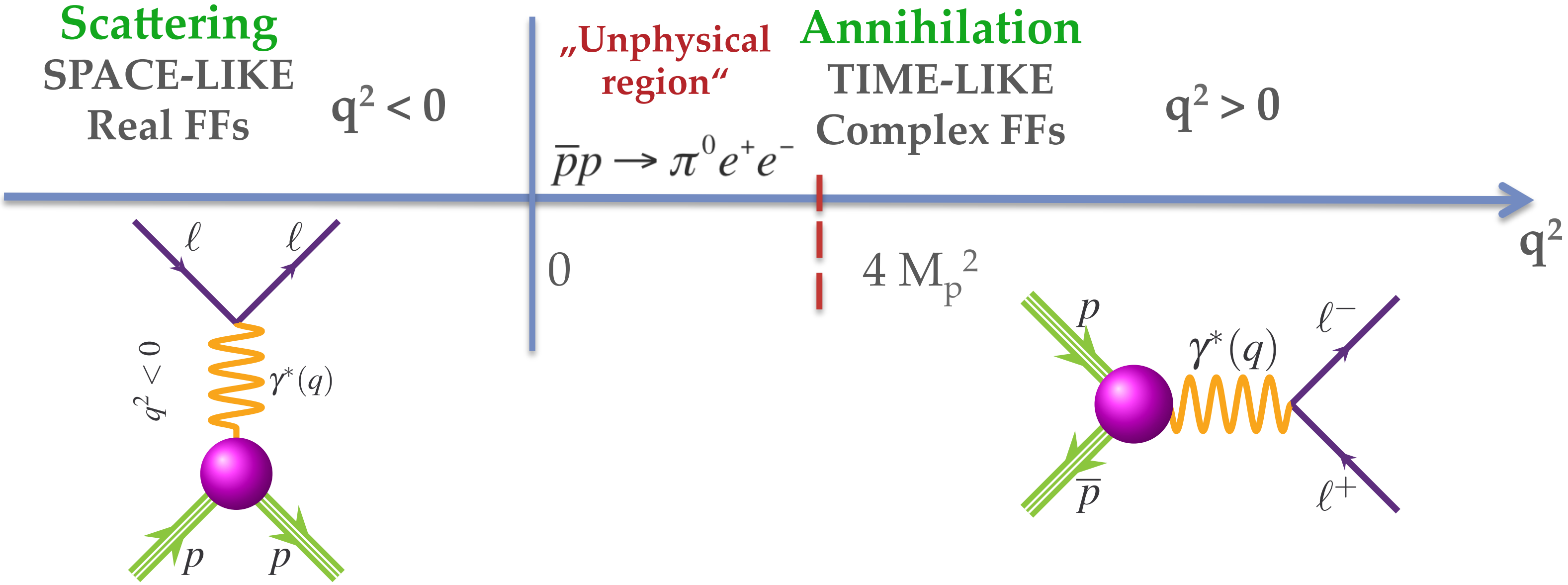

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SPACE-LIKE
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TIME-LIKE
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Electromagnetic Form Factors of the Proton

Connection between Time-like & Space-Like Form Factors:

Dispersion relations based on

Unitarity & Analyticity

- Unified frame for the description of form factors over whole kinematical region
- Predicitions for regions without experimental data

$$G(q^2)_{SL} = \frac{1}{\pi}\left[\int_{4m_\pi^2}^{4m_p^2} \frac{\mathrm{Im}\,G(s)}{s-q^2}\,ds + \int_{4m_p^2}^{\infty} \frac{\mathrm{Im}\,G(s)}{s-q^2}\,ds\right]$$

- Phys. Rep. 555 (2015) 1 and references therein

- Internal structure and dynamics of the proton
- Hadronic vertex can be parametrized in terms of two Form Factors F_1 & F_2.

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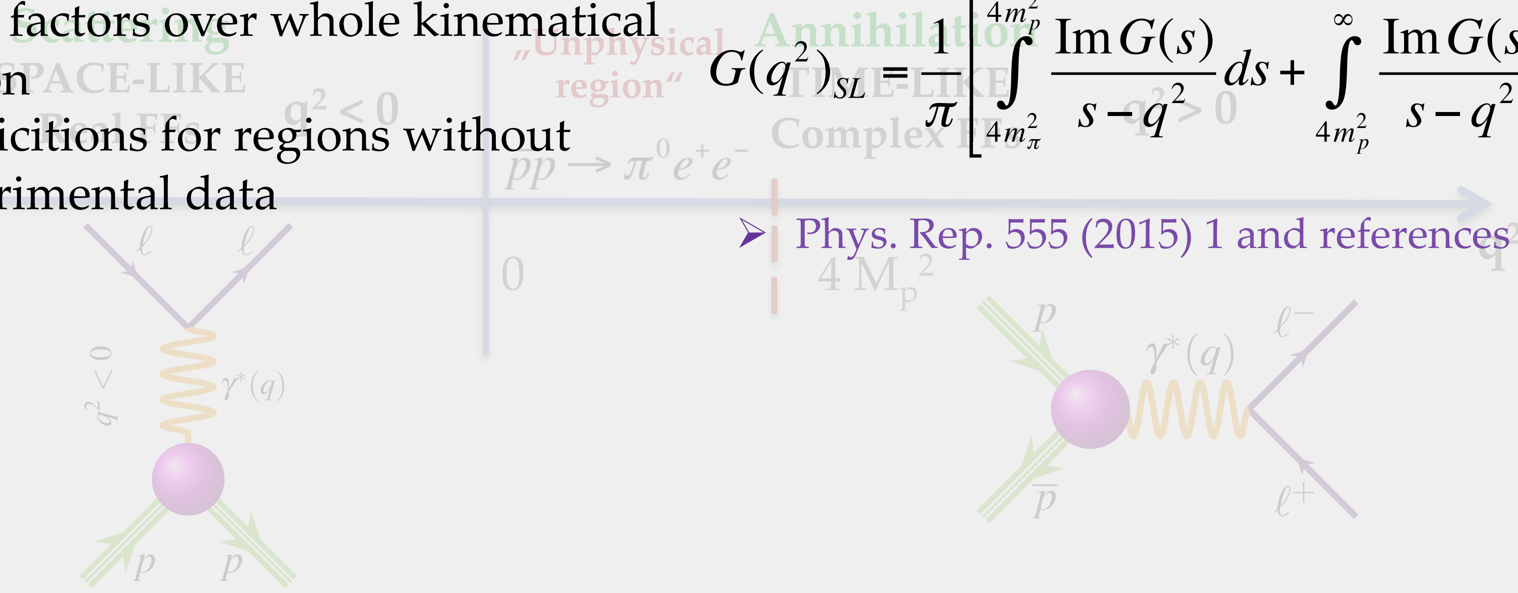

Electromagnetic Form Factors of the Proton

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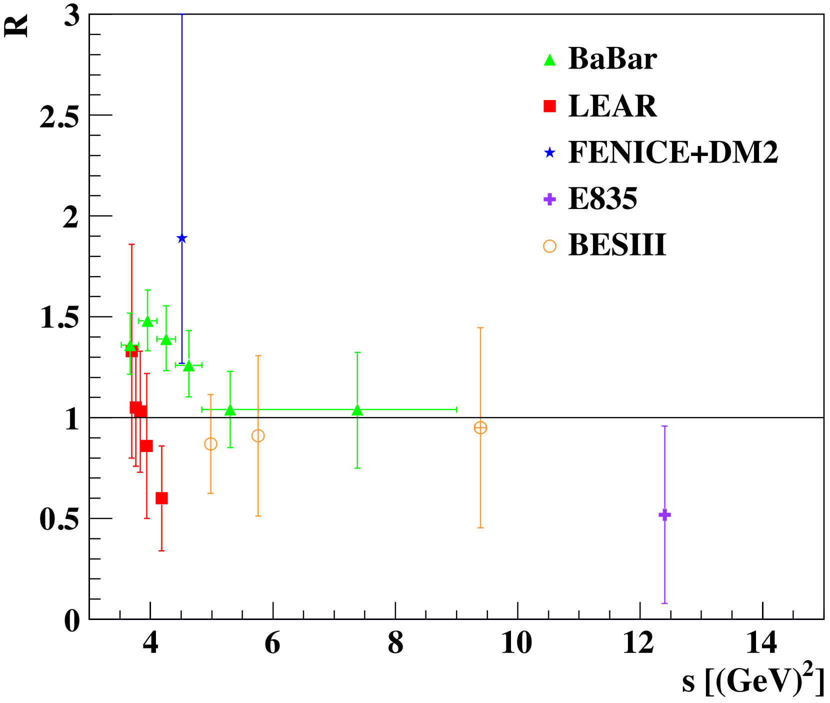
- Phys. Rep. 555 (2015) 1 and references therein

Asymptotic behaviour

$$\lim_{q^2\to-\infty}\left|G_{E,M}^{SL}(q^2)\right| = \lim_{q^2\to+\infty}\left|G_{E,M}^{TL}(q^2)\right|$$

- Phys. Lett. B 504, 291 (2001)

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

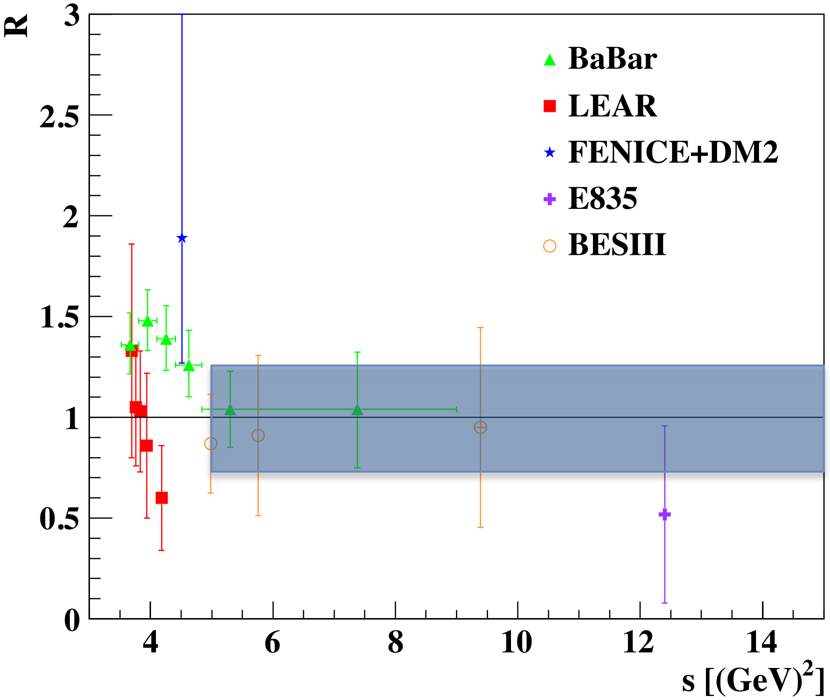
@ PS 170 (LEAR): $\bar{p}p \to e^+e^-$
- data collection at low energies

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): $e^+e^- \to \bar{p}p$
- Energy $\sqrt{s} = 1.92 - 2.00\ GeV$
- Uncertainty of R in agreement with BaBar data

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



@ BaBar (SLAC): $e^+e^- \to \bar{p}p\gamma$

- ➢ data collection over wide energy range

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@ CMD-3 (VEPP2000 collider, BINP):

- ➢ Energy scan $\sqrt{s} = 1-2\ GeV$
- ➢ Uncertainties comparable to the measurement by BaBar

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

Time-like electromagnetic proton form factors @ PANDA: The goals

- Differential cross section[1] of **signal reaction** $\boxed{\bar{p}p \rightarrow l^+l^- \quad l = \mu, e}$
  → Access to the **time-like, electromagnetic form factors of the proton, |G$_E$| and |G$_M$|** :

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

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

- High luminosity: **Measurement of signal angular distribution**
  - **Separate determination** of |G$_E$|, |G$_M$| over a **large kinematical region in the time-like region**
  - High precision measurement of the **ratio** $R = |G_E|/|G_M|$ at PANDA as well as the **proton effective form factor** $|F_p|^2 \propto \sigma_{tot}$

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

Time-like electromagnetic proton form factors @ PANDA: The goals

- **First time** measurement with **muons in final state**
- Form factor measurements with different final states:
  - **Study of radiative corrections**
  - **Consistency check** of proton form factor data
- Possibility to access the **relative phase** of proton time-like form factors:
  - $\bar{p}p \to l^+l^-$ **in the Born approximation:**
    - **Unpolarized cross section -> access to $|G_E|$ & $|G_M|$**
    - **Polarization observables -> access to relative phase $G_E G_M^*$:**

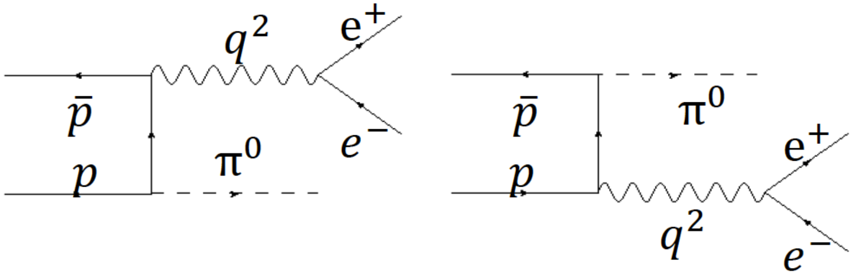
Single spin polarization observable $\left(\frac{d\sigma}{d\Omega}\right)_0 A_{1,y} \propto \sin 2\Theta \, \mathrm{Im}\left(G_M G_E^*\right)$

- A. Z. Dubnickova, S. Dubnicka & M.P. Rekalo Nuovo Cim. A109 (1996) 241-256

- Development of a **transverse polarized target for PANDA** in **Mainz**

Time-like electromagnetic proton form factors @ PANDA: The goals

- Access the **unphysical region:** $\bar{p}p \rightarrow \pi^0 e^+ e^-$



- M. P. Rekalo, Sov. J. Nucl. Phys. 1 (1965) 760
- C. Adamuscin, E.A. Kuraev, E. Tomasi-Gustafsson and F.E. Maas, Phys. Rev. C 75, 045205 (2007)
- Feasibility studies by J. Boucher, M. C. Mora-Espi; PhD thesis

- **Measurement of time-like proton form factors up to s ≈ 30 GeV^2 @ PANDA**
  - **Study the asymptotic behaviour of the form factors**

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

$$\frac{\sigma(\bar{p}p \rightarrow \pi^+\pi^-)}{\sigma(\bar{p}p \rightarrow l^+l^-)} \propto \left[10^5 - 10^6\right]$$

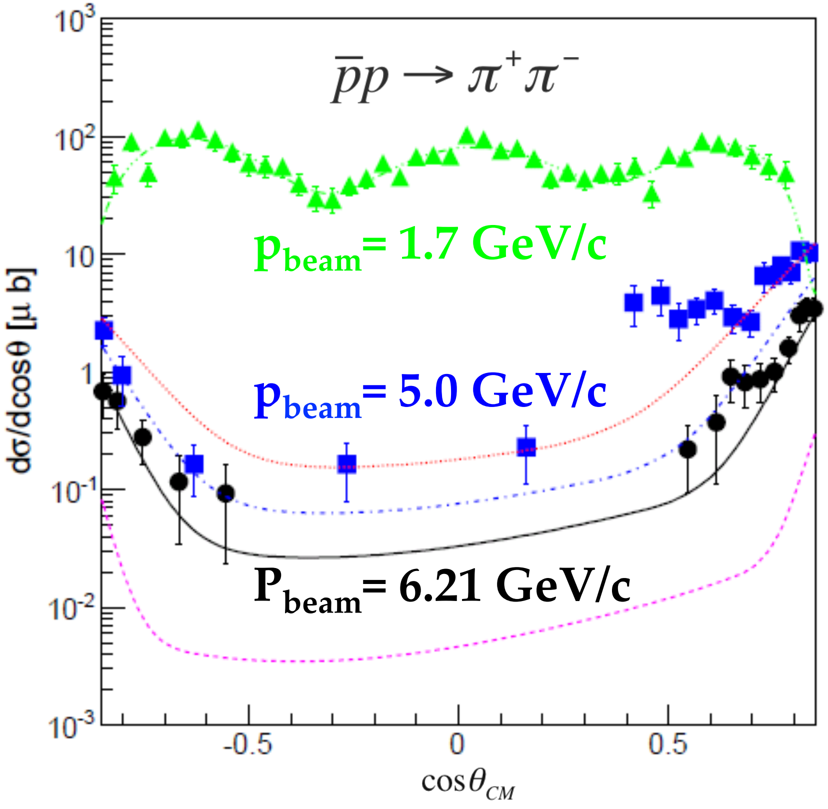
Good background rejection necessary →

Feasibility studies needed for both signal channels!

Feasibility studies: time-like proton form factors @ PANDA

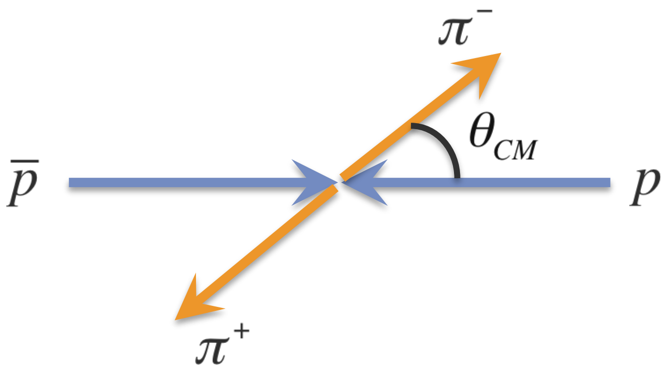
Background studies

- **New event generator** developed by Mainz working group (M. Zambrana et al.)



- J. Van de Wiele and S. Ong: Eur. Phys. J. A 46, 291-298 (2010)
- M. Sudol et al. EPJA44, 373 (2010)
- A. Dbeyssi, D. Khaneft, et al: Paper submitted to EPJA (2016)

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



$$\boxed{\frac{\sigma(\bar{p}p \rightarrow \pi^+\pi^-)}{\sigma(\bar{p}p \rightarrow l^+l^-)} \propto [10^5 - 10^6]}$$

- **Background rejection ~10^{-8} needed: Pollution < 1%**

- **For e^+e^-**: A **background rejection** of the order of **10^{-8}** will be achieved @ PANDA
- **For $\mu^+\mu^-$**: **background rejection** of the order of ~**10^{-6}** will be achieved @ PANDA

Feasibility studies: time-like proton form factors @ PANDA

A) Simulation & Analysis : Event selection

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

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

Simulation & Analysis

PandaRoot

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

p_{beam} [GeV/c]	**1.7**	**3.3**	**6.4**
s [GeV]^2	5.4	8.2	13.9

Two different methods have been tested

1) **Preselection:**

- **Method I: Each event** must contain **exactly one positive and one negative track**.
- **Method II:** Each event must contain **at least** one **positive and one negative track**.
  - "Best pair" selected

2) **Signal/Background separation based on:**

- **Kinematical variables**:
  - Production angles $(\theta^+ + \theta^-)_{CM}$
  - Invariant mass $M_{inv} = \sqrt{(p^+ + p^-)^2}$
  - Difference azimuthal angles $|\varphi^+ - \varphi^-|$
- Particle **Id**entification (PID): different subdetector information like **E**lectro**m**agnetic **C**alorimeter, **S**traw **T**ube **T**racker etc. contribute

Feasibility studies: time-like proton form factors @ PANDA

B) Simulation & Analysis : Event selection

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

Simulation & Analysis

PandaRoot

Event generation

Digitization

Reconstruction

Particle Identification

Event Analysis

p_{beam} [GeV/c]	**1.5**	**1.7**	**3.3**
s [GeV]^2	5.0	5.4	8.2

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**

2) **Signal/Background separation based on:**

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

A) Feasibility studies: time-like proton form factors @ PANDA for

$$\boxed{\bar{p}p \rightarrow e^{+}e^{-}}$$

Two independent methods: **Method I & Method II**

- Study of **precision** for $|G_E|$&$|G_M|$, **the form factor ratio R & effective form factor**
- Study of the **systematic effects** : Effects of the event generator model on the efficiency determination, effect of fluctuations and fit function

A. Dbeyssi, D. Khaneft, F. Maas, D. Marchand, M. C. M. Espi,
E. Tomasi-Gustafsson, M. Zambrana, I. Zimmermann et al.

A) Feasibility studies: time-like proton form factors @ PANDA for

$$\boxed{\bar{p}p \rightarrow e^{+}e^{-}}$$

Method I

Signal:

- Zichichi cross section[1] + PHOTOS
- Assuming $|G_E / G_M| = 1$
- **s [GeV^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^2]: 5.4, 8.2, 13.9**

Common features:

- Additional samples for signal efficiency determination
- **~10^6 events at each energy point**

Background:

- **New event generator** @ s = 5.4, 8.2, and 13.9 [GeV^2]
- **10^8 events at each energy point**

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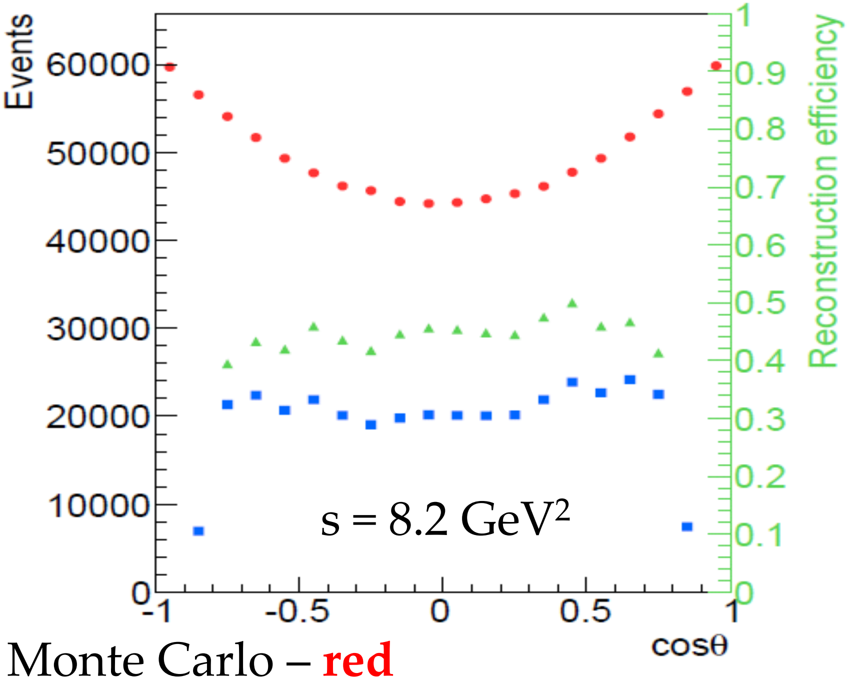
1) A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Nuovo Cim. 24, (1962) 170

A) Feasibility studies: time-like proton form factors @ PANDA for

$$\bar{p}p \to e^+e^-$$

Method I



Monte Carlo – **red**
Selected – **blue**
Efficiency – **green**

Efficiencies

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

- **Angular range** $|\cos\theta| \leq 0.8$
- **Good signal efficiency**
- **background suppression factor of ~10^{-8}**

A) Feasibility studies: time-like proton form factors @ PANDA

Statistical error on R, $|G_E|$ and $|G_M|$

Method I

1) Angular distribution of events

Precision on R

FIT FUNCTION 1:

$$\# events = L \times \frac{d\sigma}{d\cos\theta} = C_1\left[1+\cos^2\theta+\frac{R^2}{\tau}\sin^2\theta\right], \quad \tau = \frac{s}{M_p^2}$$

2) Cross section distribution of events

Precision on $|G_E|$ & $|G_M|$

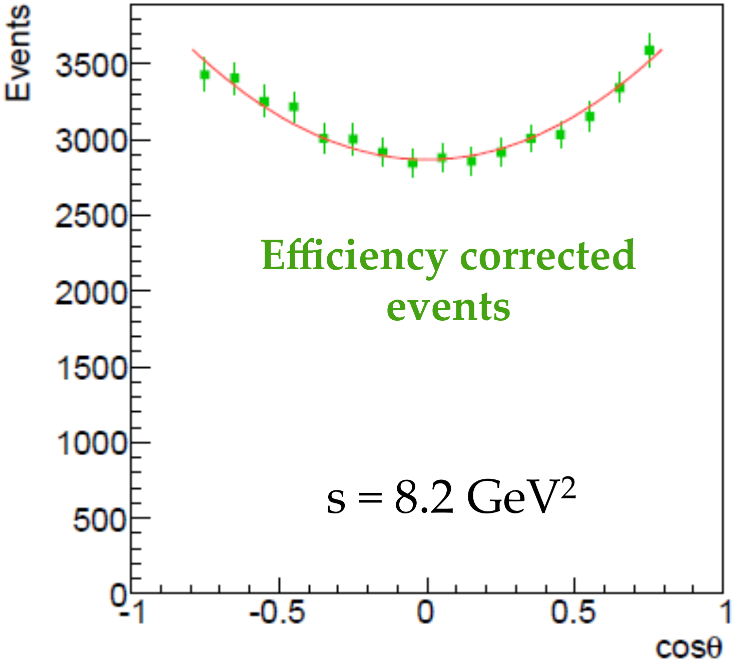
FIT FUNCTION 2:

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

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

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

p [GeV/c]	s [GeV^2]	$N_{phys}(e^+e^-)$
1.7	5.4	834800
3.3	8.2	49210
6.4	13.9	1466



Efficiency corrected events

s = 8.2 GeV^2

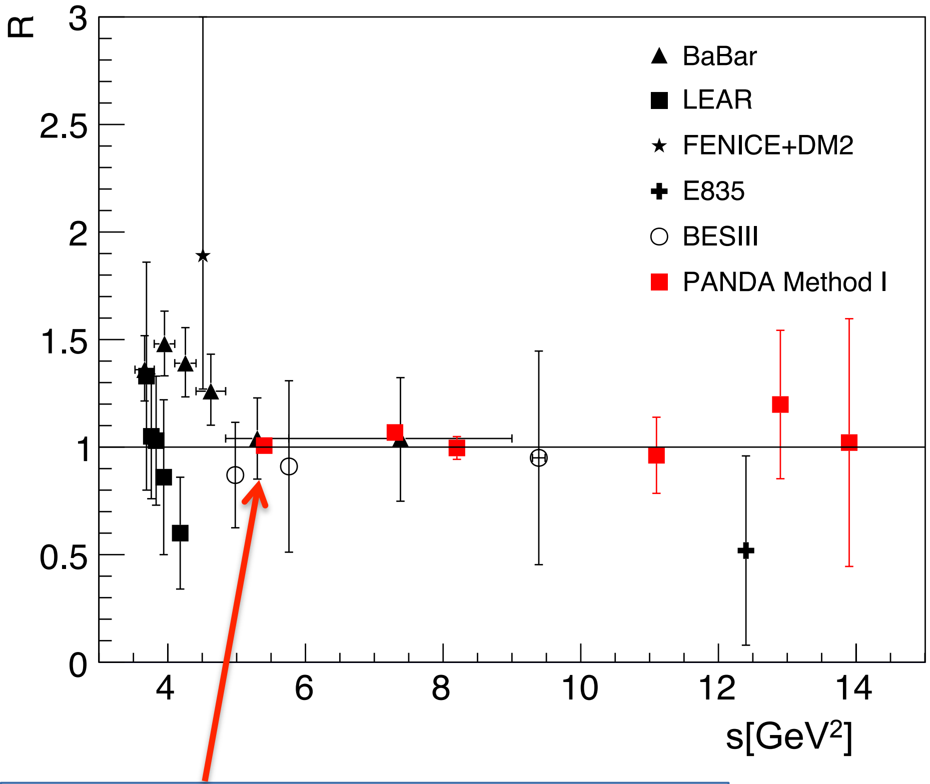
A) Feasibility studies: time-like proton form factors @ PANDA

Statistical error on R, $|G_E|$ and $|G_M|$

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

Method I

s [GeV²]	$\|G_E\|\pm\Delta\|G_E\|$	$\|G_M\|\pm\Delta\|G_M\|$
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%]**
13.9	0.011 ± 0.005 **[45.4%]**	0.011 ± 0.001 **[9.0%]**



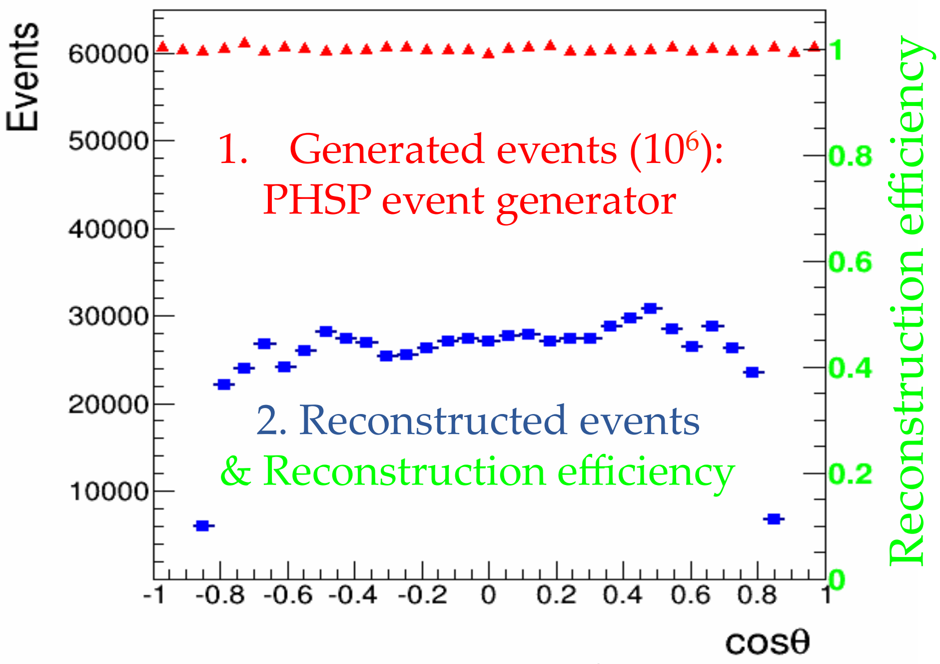
@ s=5.4 GeV²: precision on R of **1.5%**

A) Feasibility studies: time-like proton form factors @ PANDA

Statistical error on R, $|G_E|$ and $|G_M|$

$$\boxed{\bar{p}p \rightarrow e^+e^-}$$

Method II



s = 8.2 GeV^2

Efficiencies

	signal	**background**
s [GeV^2]	e^+e^-	$\pi^+\pi^-$
5.4	41.0%	$1.9 \cdot 10^{-6}$ %
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 ~ **10^{-8}**

A) Feasibility studies: time-like proton form factors @ PANDA

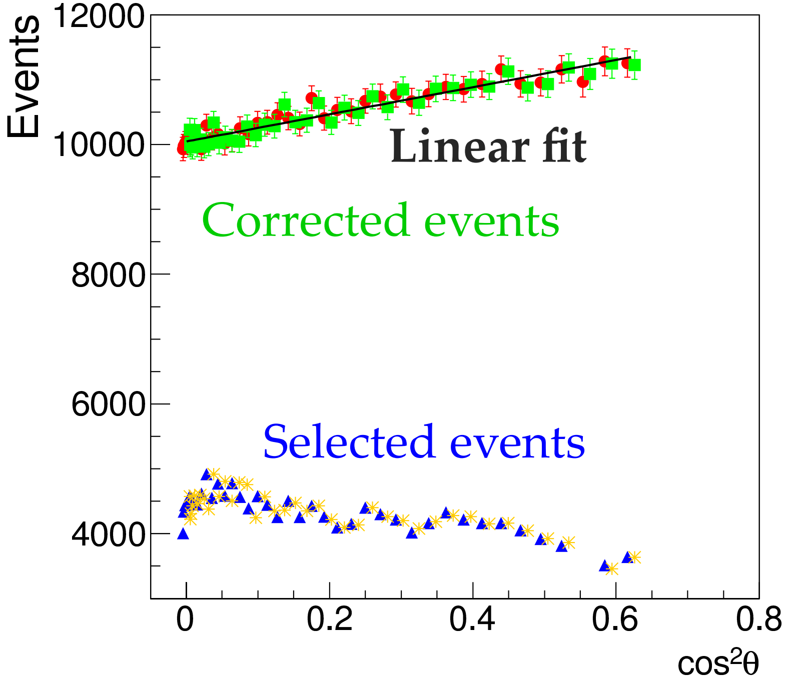
Statistical error on R, $|G_E|$ and $|G_M|$

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

Method II

- Independent sample for signal (**phase-space**) has been generated and reconstructed
- **Normalization** to the integrated counting rate $N_{phys}(e^+e^-)$
- **Weighting** by the differential cross section

Angular distribution of events



A) Feasibility studies: time-like proton form factors @ PANDA

Statistical error on R, $|G_E|$ and $|G_M|$

$$\boxed{\bar{p}p \rightarrow e^+e^-}$$

Method II

Linear fit function $\boxed{y = a + b\cos^2\theta}$

$a \equiv \sigma_0, \quad b \equiv \sigma_0 A$

$a \equiv \sigma_0 L, \quad b \equiv \sigma_0 A\, L$

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

$$A = \frac{\tau - R^2}{\tau + R^2}$$

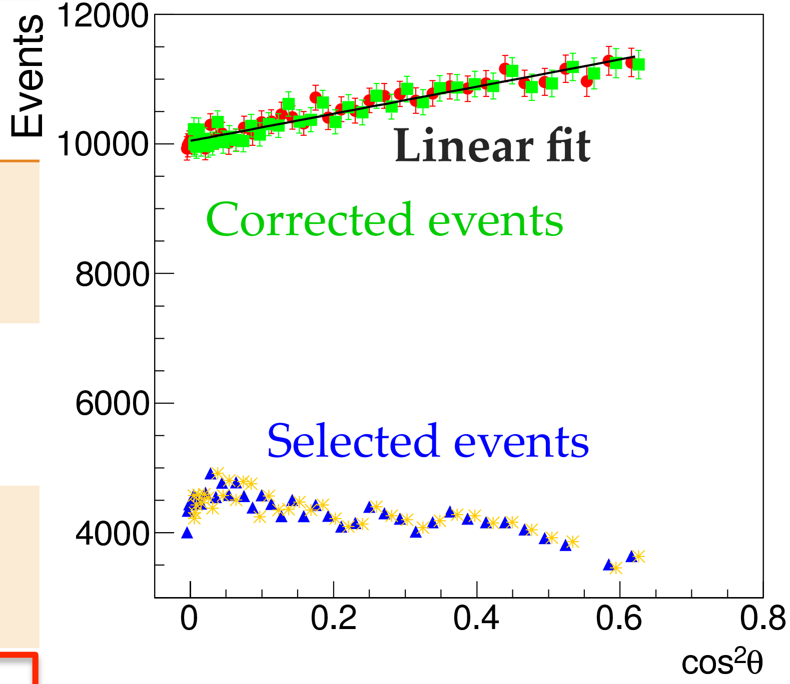
L = 2 fb^{-1}

$\Delta L/L = 3\%$

1) $\boxed{R = \sqrt{\tau\frac{1-A}{1+A}}}$

2) $\boxed{|G_M|^2 \propto \frac{(a+b)}{2}}$ $\boxed{|G_E|^2 \propto \tau \cdot \frac{(a-b)}{2}}$

Angular distribution of events

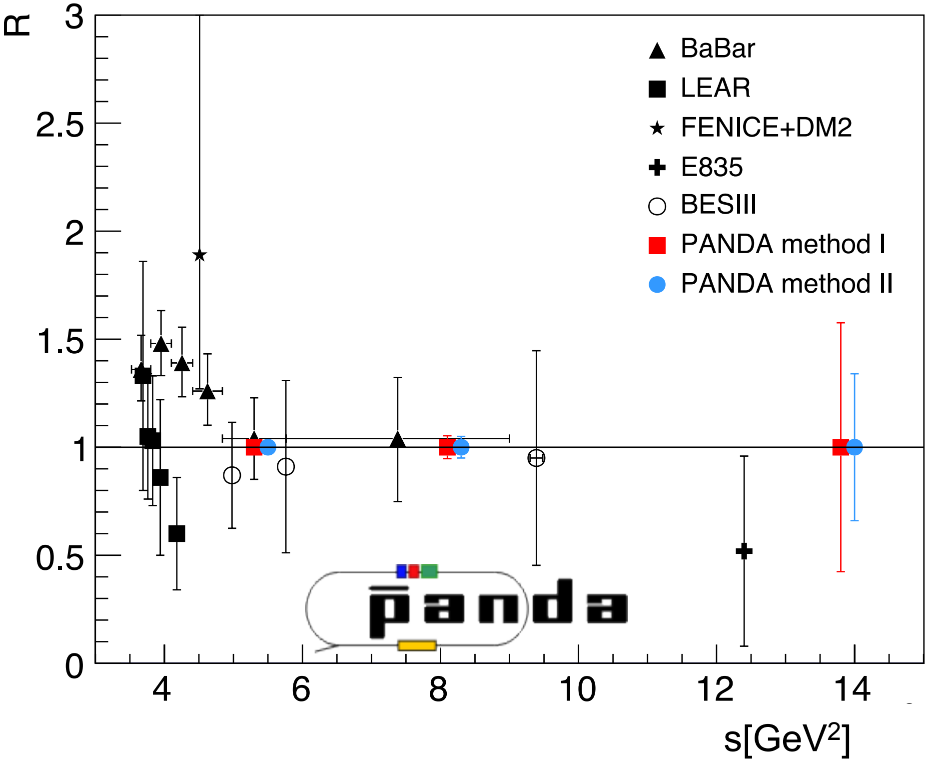


A) Feasibility studies: time-like proton form factors @ PANDA

Statistical error on R, $|G_E|$ and $|G_M|$

$$\boxed{\bar{p}p \longrightarrow e^+e^-}$$

- The **precisions** obtained at **5.4 GeV²** and **8.2 GeV²** are **compatible between Method I & Method II**
- **At 13.9 GeV²** the **error of R** was studied.
- Integrated luminosity of **L = 2 fb⁻¹**
  2*10³² cm⁻² s⁻¹ -> 4 months data taking



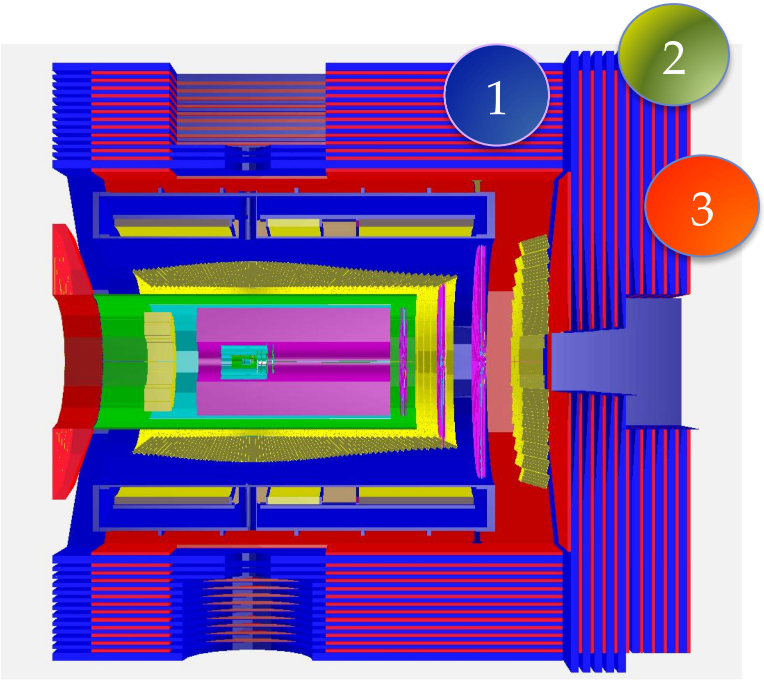
B) Feasibility studies: time-like proton form factors @ PANDA for

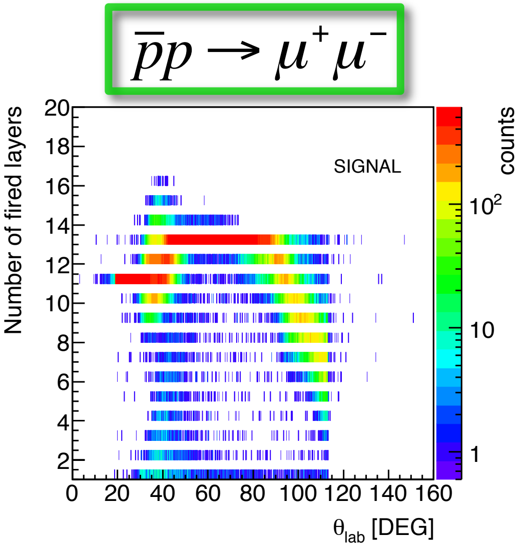
$$\boxed{\bar{p}p \rightarrow \mu^+\mu^-}$$

Study of the statistical error on R,
$|G_E|$ & $|G_M|$

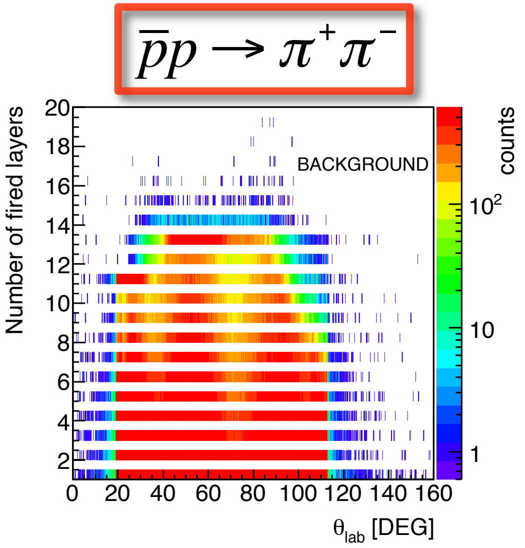
Feasibility studies: time-like proton form factors @ PANDA

The Muon Range System of PANDA





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



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

- **p_{beam} = 1.7 GeV/c**
- Particle candidates after preselection
- Negative charges & $|\cos\theta| \leq 0.8$

- **Analysis**: *„Hard cuts“ best method for signal-background separation?*

① **Barrel** : 13 detection layers

② **Overlap region Barrel & Endcap** : Hybrid tracking

③ **Muon Filter + Endcap**: in total 11 detection layers

(Not shown: **Forward Range System**: 16 detection layers)

→ No, we can **do better**!

Feasibility studies: time-like proton form factors @ PANDA

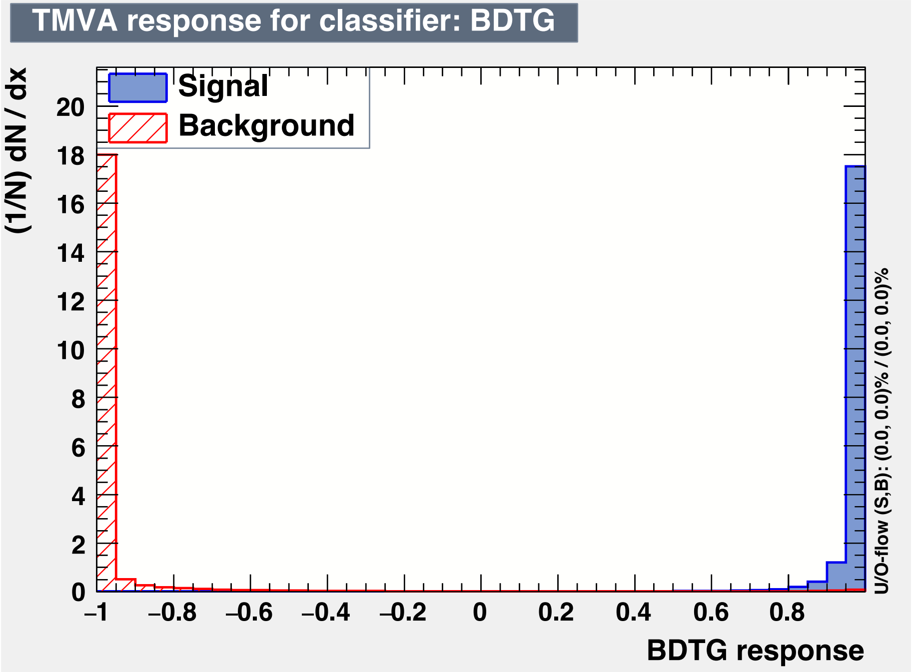
Multivariate Data Classification (MVA)

1) **Training of the classifiers:**
   - well-known training data samples (signal & background)
   - **18 input variables** for training, testing and evaluation:
     - **Kinematical variables**: invariant mass, $(\theta^{+} + \theta^{-})_{CM}$
     - **Detector observables** from Muon System, EMC, Straw Tube Tracker
   - **Boosted Decision Tree (BDTG)** shows **best performance**

2) **Application** of **trained classifier** on reconstructed data samples:
   - Cuts on **BDTG response** & **kinematical variables:**

Optimization of the Signal/Background separation

After Training:
Response of the Boosted Decision Tree



BDTG: Boosted Decision Trees based on gradient boosting technique

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Simulation & Analysis : Cut Configuration

Signal efficiencies (MVA)

@ $p_{beam} = 1.7$ GeV/c

	MVA (Boosted Decision Trees)						
	$M_{inv}(l^+l^-)$ [GeV^2]	$(\theta^+ + \theta^-)_{CM}$ [DEG]	BDTG	-	**Signal efficiency ε**	ε_B [10^{-5}]	**S-B ratio**
„Loose“	]2.2 ; 2.5[	> 179.95	> 0.9976		**0.212**	0.79	**1:7**
„Tight“	]2.2 ; 2.5[	> 179.95	> 0.9990		**0.116**	0.26	**1:4**

Analysis based on **HARD CUTS** : S-B ratios between **1:38** and **1:30** at the same signal efficiencies.

Application of MVA trained methods clearly **improves expected S-B ratio**

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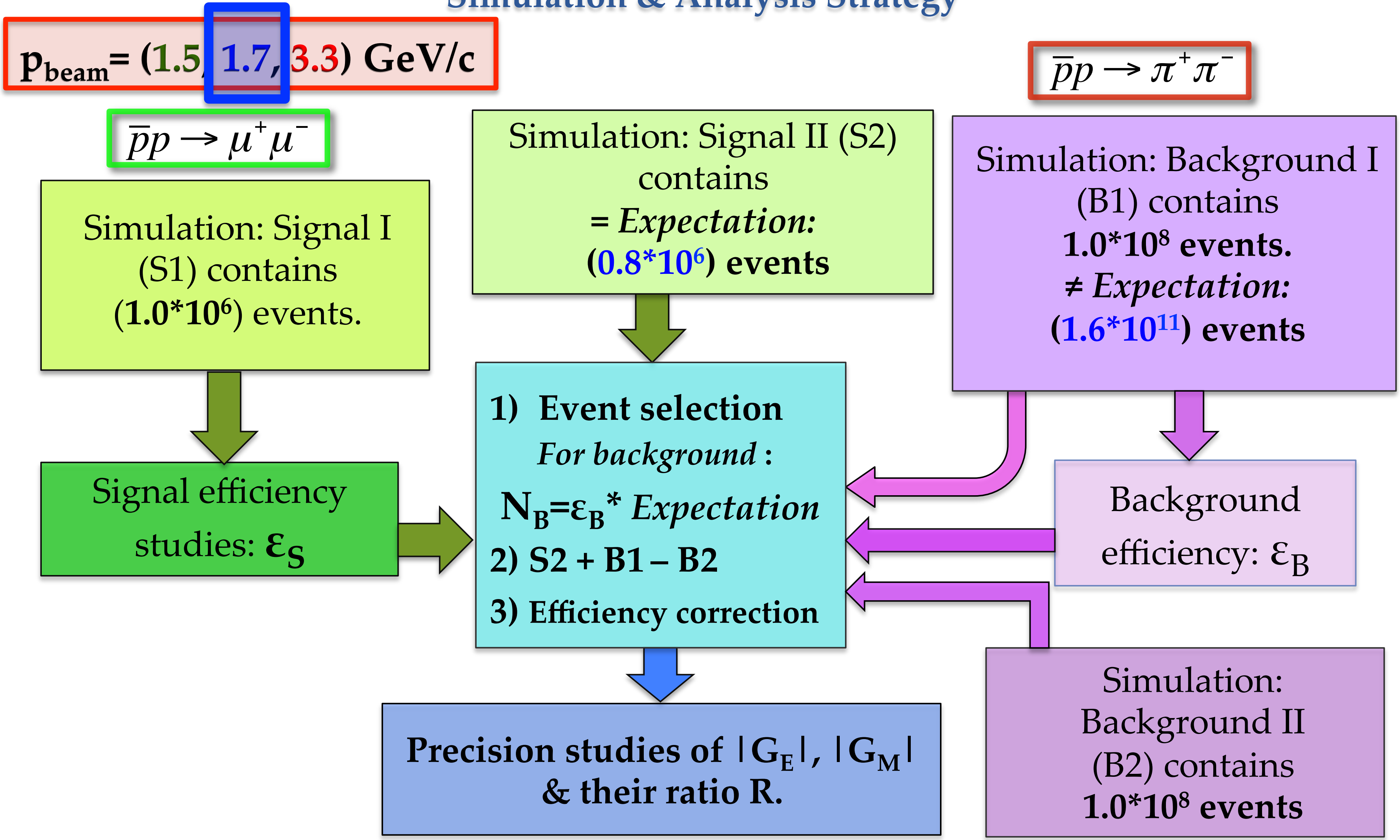
Simulation & Analysis Strategy



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

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

Simulation: Signal I (S1) contains (**1.0*10⁶**) events.

Signal efficiency studies: ε_S

Simulation: Signal II (S2) contains

= *Expectation:*

(0.8*10⁶) events

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

Simulation: Background I (B1) contains

1.0*10⁸ events.

≠ *Expectation:*

(1.6*10¹¹) events

1) Event selection

***For background* :**

$N_B=\varepsilon_B$* ***Expectation***

2) S2 + B1 – B2

3) Efficiency correction

Background efficiency: ε_B

Simulation: Background II (B2) contains

1.0*10⁸ events

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

Feasibility studies: time-like proton form factors @ PANDA

$\boxed{\bar{p}p \to \mu^+\mu^-}$

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

MVA & „Loose cuts“

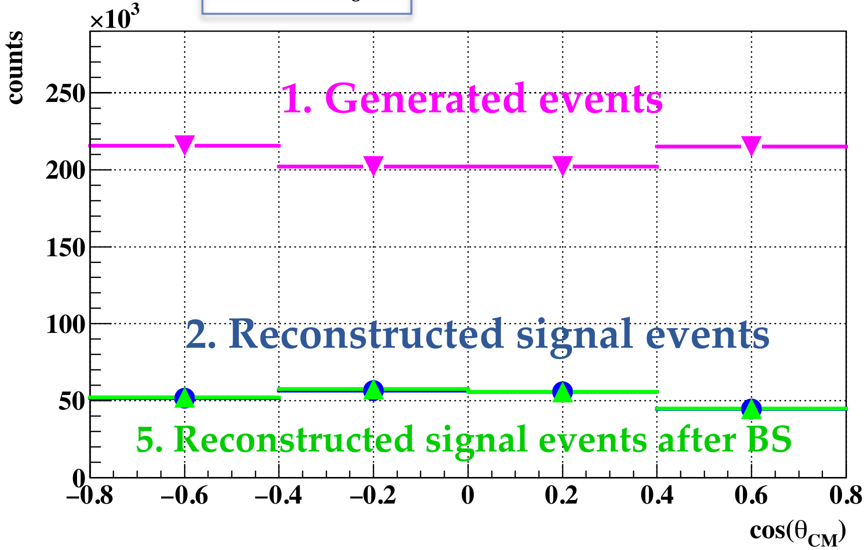
A) Extraction of R: Fit parameters are $P_{0,1} = \sqrt{L\cdot|G_{M,E}|^2}$

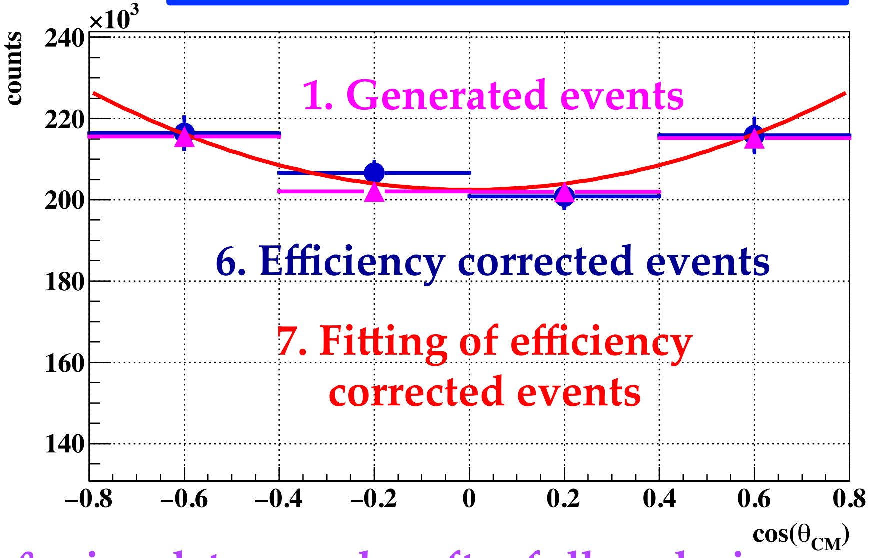
$$f(x) \propto \left[\frac{1}{\tau}(1-\beta^2x^2)\cdot P_1^2 + \left(1+\frac{4m_\mu^2}{s}+\beta^2x^2\right)P_0^2\right]$$

$$\boxed{R = \frac{P_1}{P_0}}$$

Integral of fit function in bin used.

- **Efficiency corrected signal angular distribution after full analysis**
- Extraction of $\mathbf{P_{0,1}}$ **from distribution of counts**
  ➔ Obtain ΔR/R





3. Summing up the reconstructed muon & pion data samples after full analysis

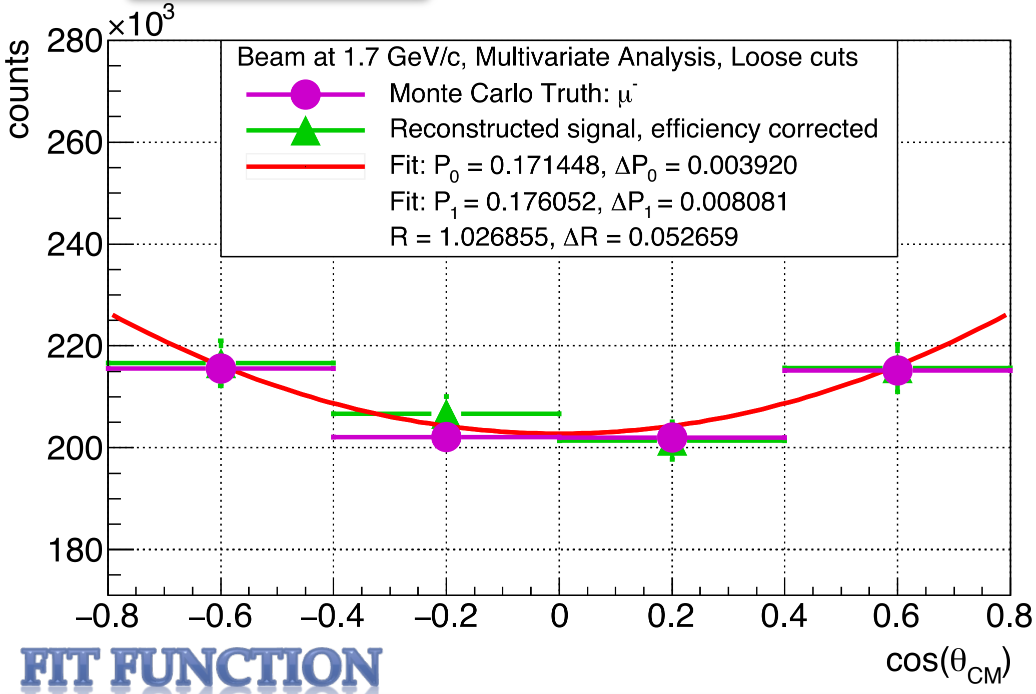
4. Background subtraction (BS) of independent pion data sample after full analysis

Feasibility studies: time-like proton form factors @ PANDA

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

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

Input for event generator: R=1



A) Extraction of R from signal angular distribution

@ p_{beam} = 1.7 GeV/c

- Extraction of $P_{0,1}$ from distribution of counts after full analysis
  - Obtain ΔR/R

MVA & „Loose cuts"

FIT FUNCTION

Fit parameters: $P_{0,1} = \sqrt{L \cdot |G_{M,E}|^2}$

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

$$C_1 \propto \frac{1}{s}\sqrt{\frac{s-4m_\mu^2}{s-4M_p^2}} \qquad \text{with } R = \frac{P_1}{P_0}$$

R = 1.027 ± 0.053

ΔR/R = 5.1%

Feasibility studies: time-like proton form factors @ PANDA

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

Statistical errors on $|G_E|$&$|G_M|$

B) Extraction of $|G_E|$ & $|G_M|$ **from cross section distribution**

- **L = 2 fb^{-1}, ΔL/L = 3%**
- **p_{beam} = 1.7 GeV/c, MVA & „Loose cuts“**
- **Efficiency corrected cross section distribution** of the signal **after full analysis**

$$\sigma_i = \frac{N_i}{W_i L} \quad \Delta\sigma_i = \frac{1}{W_i L} \cdot \sqrt{(\Delta N_i)^2 + \left(\frac{N_i \cdot \Delta L}{L}\right)^2}$$

σ_i: cross section in i-th bin
N_i: number of entries i-th bin
W_i: width of i-th bin

- Extraction of $|G_E|$ & $|G_M|$

FIT FUNCTION

Fit parameters: $P_{0,1} = \sqrt{|G_{M,E}|^2}$

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

RESULTS PRELIMINARY

$|G_M|$=0.121±0.005
$|G_E|$=0.124±0.011

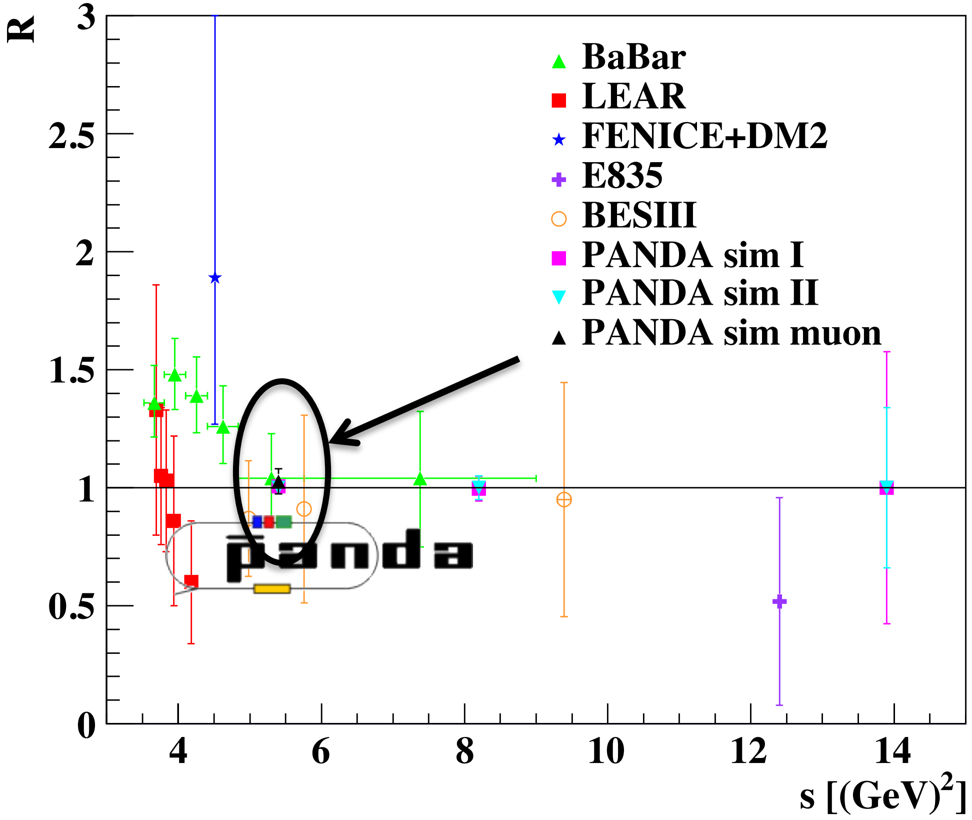
$\Delta|G_M|/|G_M|$=4.1%
$\Delta|G_E|/|G_E|$=8.6%

Feasibility studies: time-like proton form factors @ PANDA

Statistical error on R, $|G_E|$ & $|G_M|$

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

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



Precision on R, $|G_E|$&$|G_M|$	
p [GeV/c]	**1.7**
R=$|G_E|/|G_M|$	5.1%
$|G_E|$	8.6%
$|G_M|$	4.1%

-PRELIMINARY-

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

A) Feasibility studies for the signal reaction $\boxed{\bar{p}p \rightarrow e^{+}e^{-}}$

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

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

Two independent feasibility studies were performed:

- **High signal efficiency** of **39-54%**
- **Background rejection** factor of **~ 10^{8}**
- Extraction of **R** is possible for **$5.4 < s < 12.9$ [GeV^{2}] with**
  - precision in the range of **1.5–56.0%**
- With precise luminosity measurements extraction of will be possible for $|G_E|$&$|G_M|$in the range of **$5.4 < s < 12.9$ [GeV^{2}]** with
  - precision for $|G_E|$ in the range of **3.3–45.4%**
  - precision for $|G_M|$ in the range of **1.7–9.0%**
- The **effective form factor:** precision from **0.3% up to 62.4%** (at **s ~28 GeV^{2}**)

Feasibility studies: time-like proton form factors @ PANDA

Conclusion

B) Feasibility studies for the signal reaction $\bar{p}p \rightarrow \mu^{+}\mu^{-}$

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

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

  - @ **p = 1.7 GeV/c** a **precision on**
    - **R** of **5.1%,**
    - **|G_M|** of **4.1%** & **|G_E|** of **8.6%** could be achieved
  - Further studies for the **muonic channel** for beam momenta of **1.5** and **3.3 GeV/c** are **in progress**
  - Effect of different **fit functions, background fluctuations** and different **luminosities** on the **precision of R, |G_M|&|G_E|** is **under investigation**

The time-like electromagnetic proton form factors and their ratio R= |G_E|/|G_M| can be measured @ PANDA with unprecedented statistical accuracy

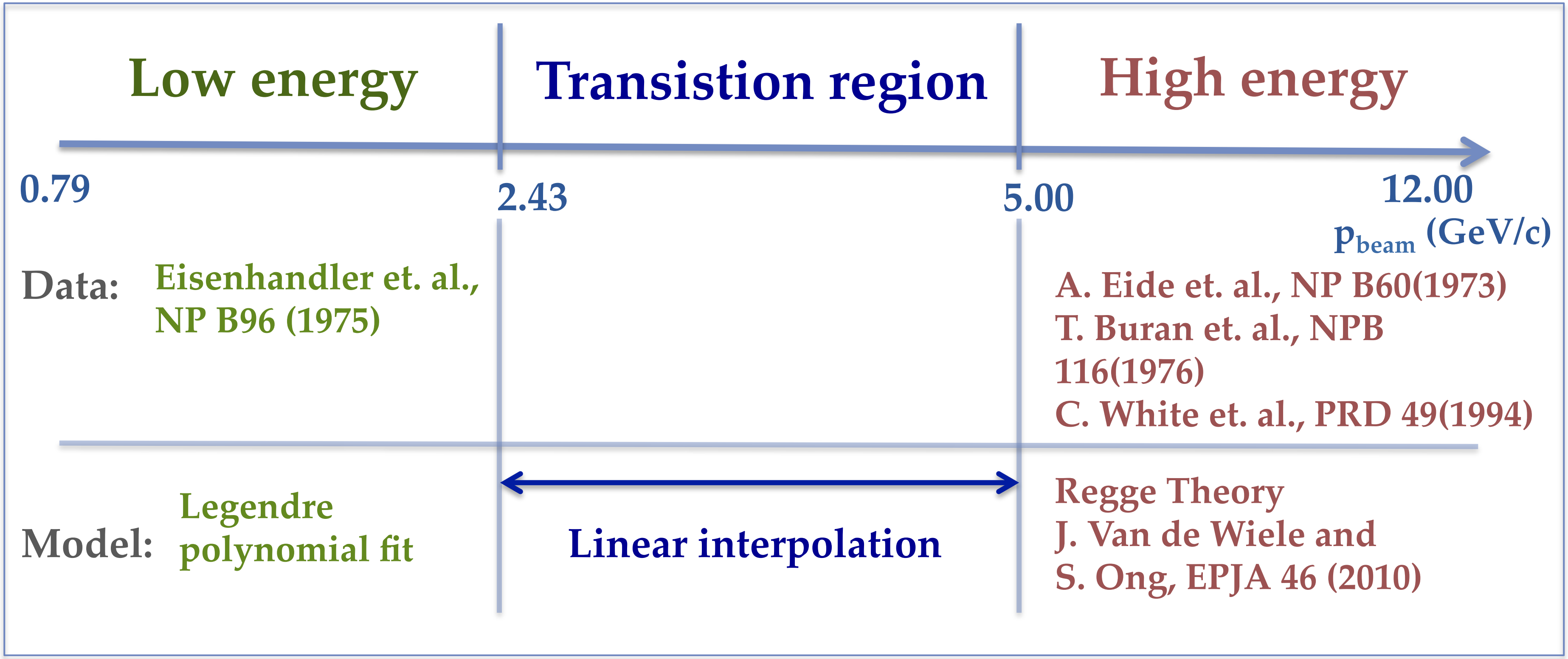
Backup slides

Feasibility studies: time-like proton form factors @ PANDA

Simulation & Analysis: Background studies

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

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



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 $\boxed{\bar{p}p \to \pi^+\pi^-}$ 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

Feasibility studies: time-like proton form factors @ PANDA

Simulation & Analysis : Cut Configuration

HARD CUTS vs. MVA

@ $p_{beam} = 1.7$ GeV/c

	HARD CUTS						
	$M_{inv}(l^+l^-)$ [GeV^2]	$(\theta^++\theta^-)_{CM}$ [DEG]	$P(\mu)_{MS}$	Iron thickness [cm]	**Signal efficiency ε**	ε_B [10^{-5}]	**S-B ratio**
„Loose“	]2.3 ; 2.38[	> 179.9505	> 0.99	30.00	**0.212**	4.06	**1:38**
„Tight“	]2.3 ; 2.38[	> 179.9608	> 0.99	42.00	**0.116**	1.79	**1:30**
	MVA (Boosted Decision Trees)						
	$M_{inv}(l^+l^-)$ [GeV^2]	$(\theta^++\theta^-)_{CM}$ [DEG]	BDTG	-	**Signal efficiency ε**	ε_B [10^{-5}]	**S-B ratio**
„Loose“	]2.2 ; 2.5[	> 179.95	> 0.9976		**0.212**	0.79	**1:7**
„Tight“	]2.2 ; 2.5[	> 179.95	> 0.9990		**0.116**	0.26	**1:4**

Application of MVA trained methods clearly **improves expected S-B ratio**

Feasibility studies: time-like proton form factors @ PANDA

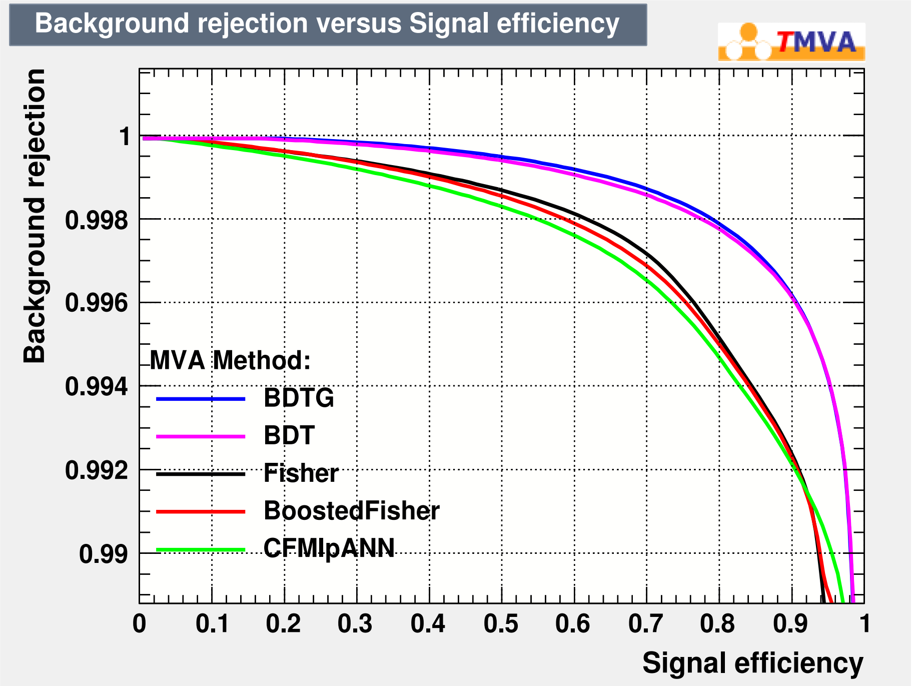
Multivariate Data Classification (MVA)

1) **Training of the classifiers:**
   - ➢ well-known training data samples (signal & background)
   - ➢ **19 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) **Application** of trained Boosted Decision Trees on reconstructed data samples:
   - ➢ Cuts on **BDTG 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

Feasibility studies: time-like proton form factors @ PANDA

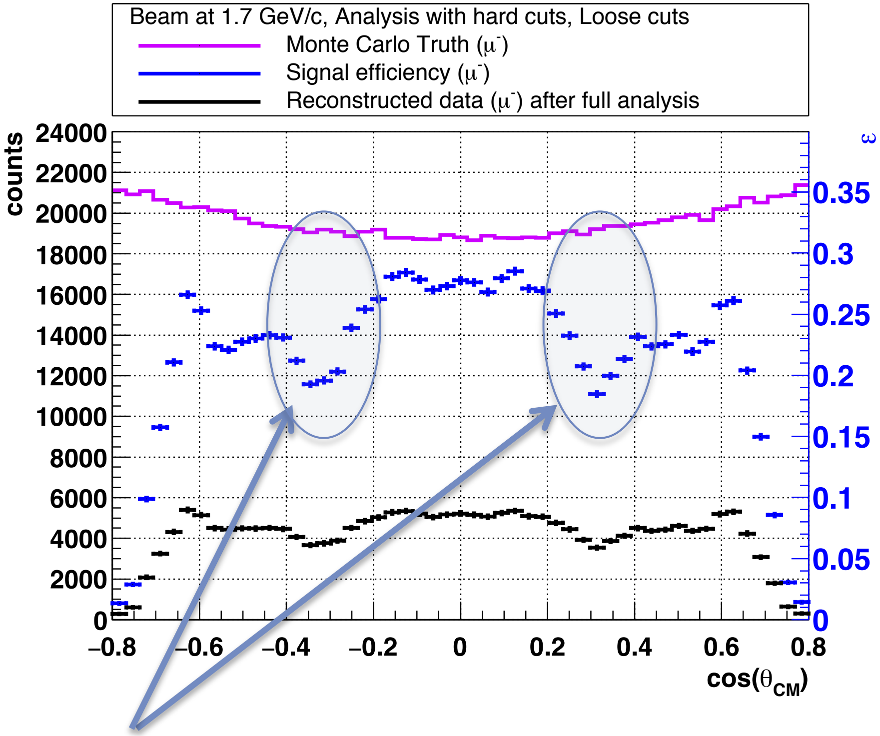
Signal efficiency studies

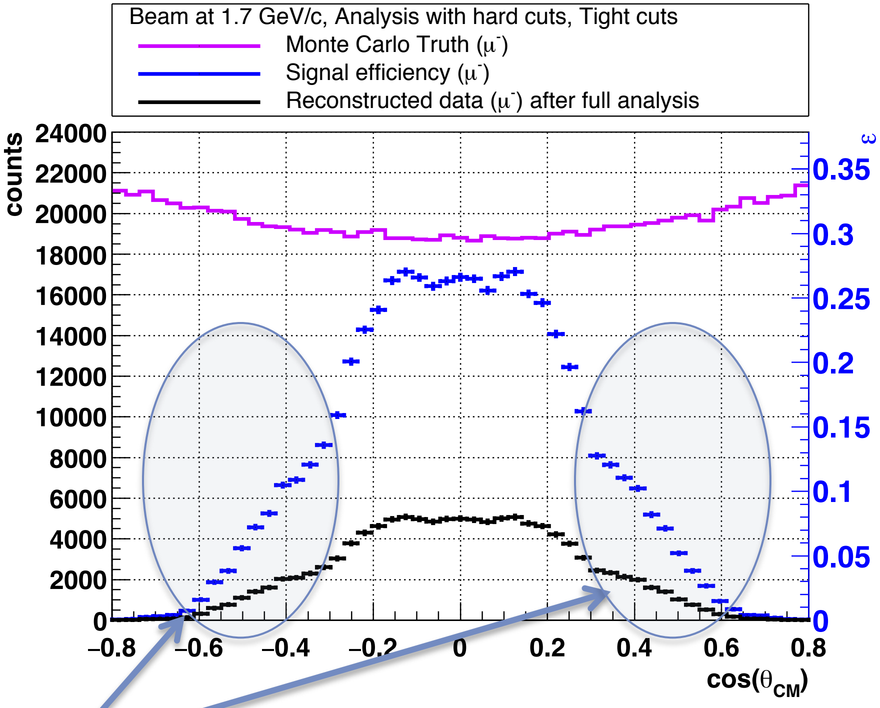
HARD CUTS

$p_{beam} = 1.7$ GeV/c

S-B ratio: 1:38

S-B ratio: 1:30





$P(\mu)_{MS} > 0.99$ „Loose cuts“

Iron thickness > 42 cm „Tight cuts“

Feasibility studies: time-like proton form factors @ PANDA

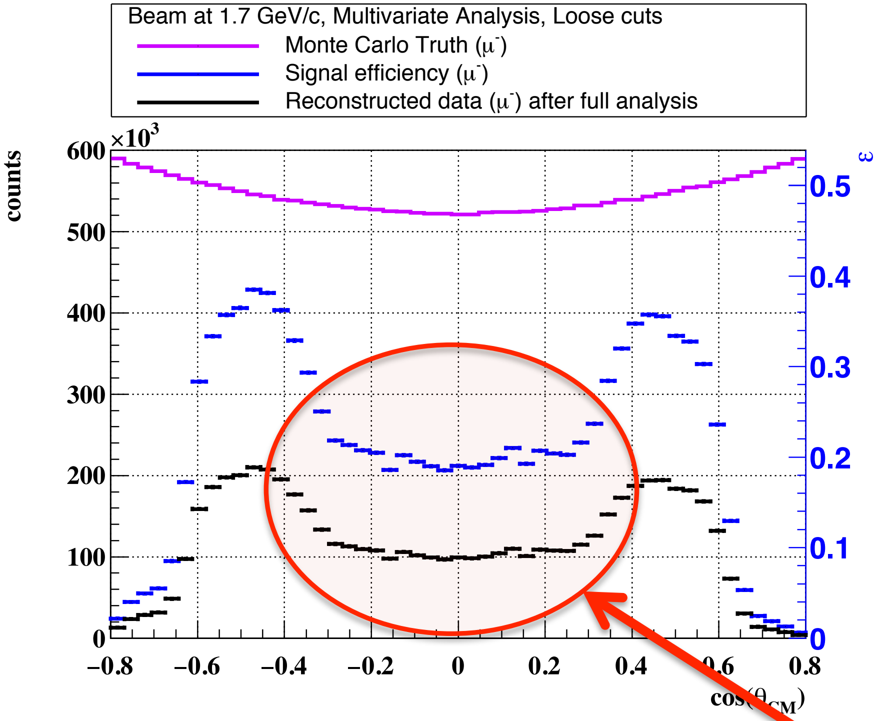
Signal efficiency studies

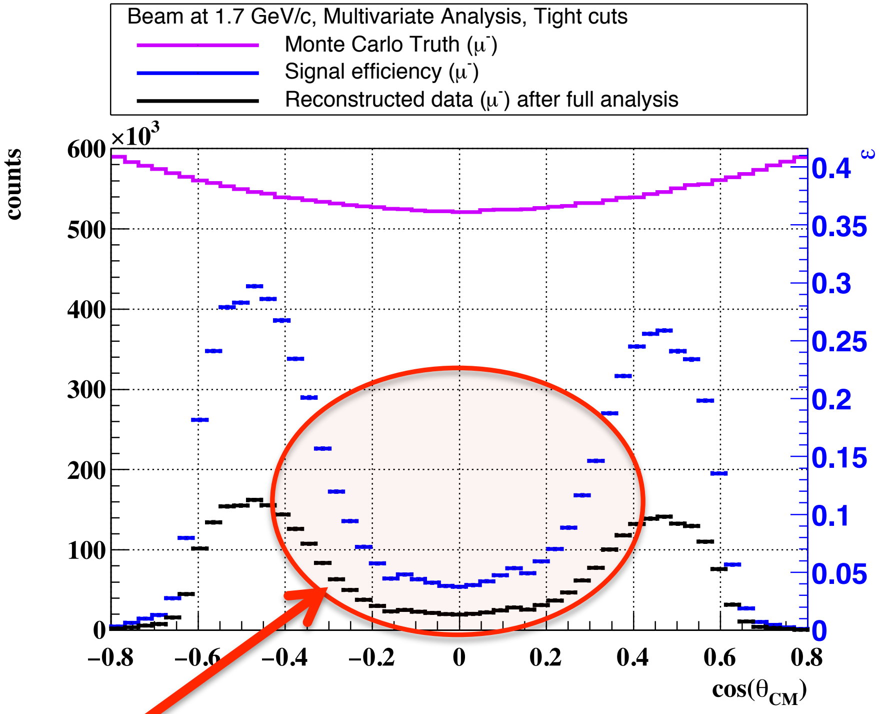
MVA

p_{beam} = 1.7 GeV/c

S-B ratio: 1:7

S-B ratio: 1:4





„Loose cuts“

Cut on BDTG

„Tight cuts“

(II) Feasibility studies: time-like proton form factors @ PANDA

Simulation & Analysis

R=1

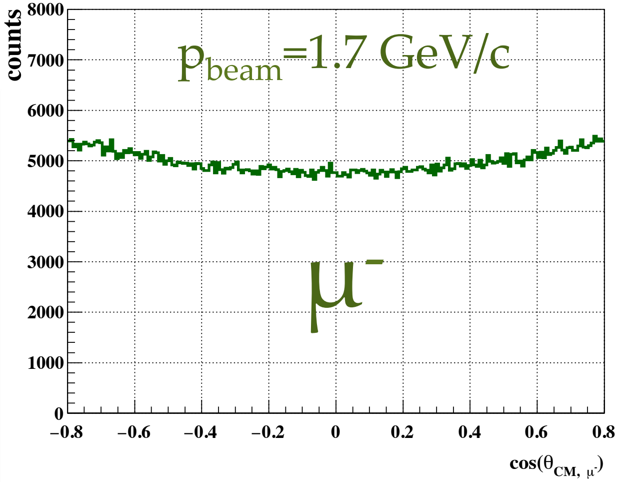
$$\boxed{\bar{p}p \to \mu^+\mu^-}$$

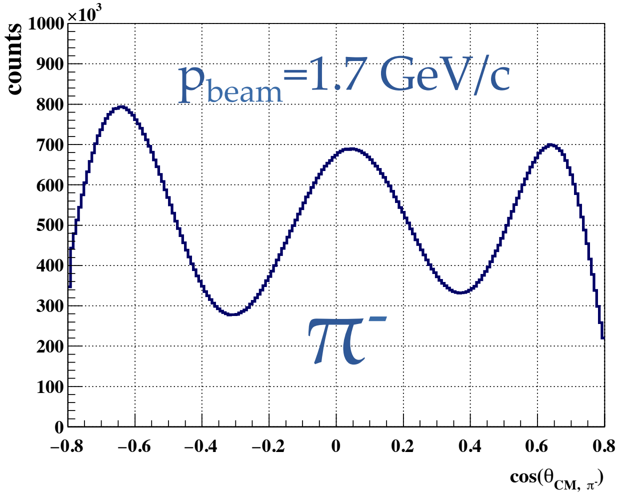
- **Signal:**
  - **$0.83*10^6$ events for 1.7 GeV/c**
  - **Cross section based event generation**
- **Background**
  - **~ 1.0 * 10^8 events using dedicated event generator[1]**
- **Analysis**:
  1. **data preselection**
  2. **signal/background separation** using **different methods:**

Cuts on kinematic variables/observables (Hard cuts)

Multivariate data classification (MVA)

Monte Carlo Event Generation





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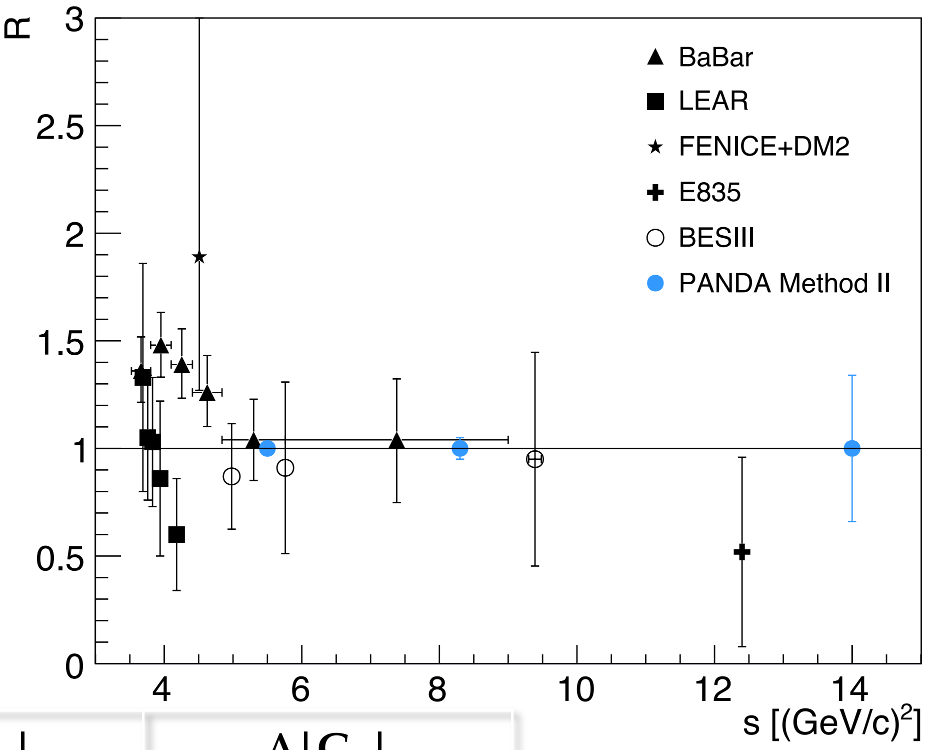
1) Zambrana, M.: Technical report 2011

A) Feasibility studies: time-like proton form factors @ PANDA

Statistical error on R, $|G_E|$ and $|G_M|$

Method II - Results

s [GeV²]	Input R	ΔR
5.4	1	0.014 [1.4%]
8.2	1	0.05 [5.0%]
13.9	1	0.407 [40.7%]



s [GeV²]	Input $|G_{E,M}|$	$\Delta|G_M|$	$\Delta|G_E|$
5.4	0.1215	0.002 [1.6%]	0.002 [1.6%]
8.2	0.0435	0.001 [2.3%]	0.002 [2.3%]
13.9	0.0110	0.001 [9.1%]	0.004 [9.1%]

Results: Hard cuts vs. MVA @ 1.7 GeV/c

	p_{beam} = 1.7 GeV/c	HARD CUTS		
	$L = 2\ fb^{-1}$	R±ΔR [%]	$\|G_E\| \pm \Delta\|G_E\|$ [%]	$\|G_M\| \pm \Delta\|G_M\|$ [%]
S/B: 1:38	„Loose“	0.968 ± 0.116 (12.0)	0.119 ± 0.016 (13.5)	0.123 ± 0.007 (6.0)
S/B: 1:30	„Tight“	0.994 ± 0.373 (37.6)	0.122 ± 0.041 (33.5)	0.123 ± 0.024 (19.2)
	p_{beam} = 1.7 GeV/c	MVA		
	$L = 2\ fb^{-1}$	R±ΔR [%]	$\|G_E\| \pm \Delta\|G_E\|$ [%]	$\|G_M\| \pm \Delta\|G_M\|$ [%]
S/B: 1:7	„Loose“	1.027 ± 0.053 (5.1)	0.124 ± 0.011 (8.6)	0.121 ± 0.005 (4.1)
S/B: 1:4	„Tight“	1.062 ± 0.058 (5.5)	0.128 ± 0.011 (8.6)	0.120 ± 0.005 (4.3)