HIM
Helmholtz-Institut Mainz

Feasibility studies for the measurement of time-like electromagnetic form factors of the proton at PANDA-FAIR

I. Zimmermann, A. Dbeyssi, D. Khaneft

on behalf of the PANDA Collaboration

Baryon Form Factors: Where do we stand?

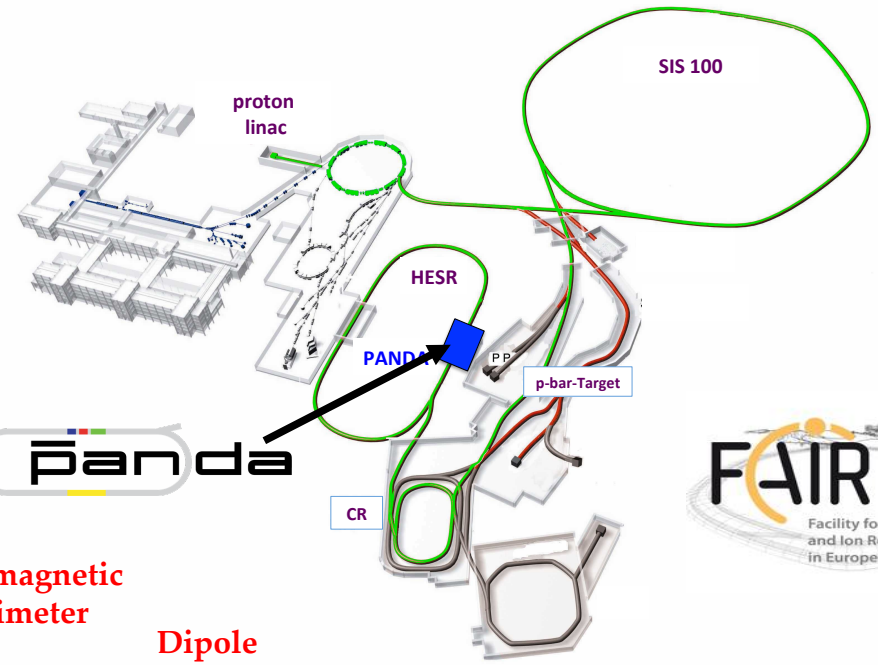
668. WE-Heraeus-Seminar

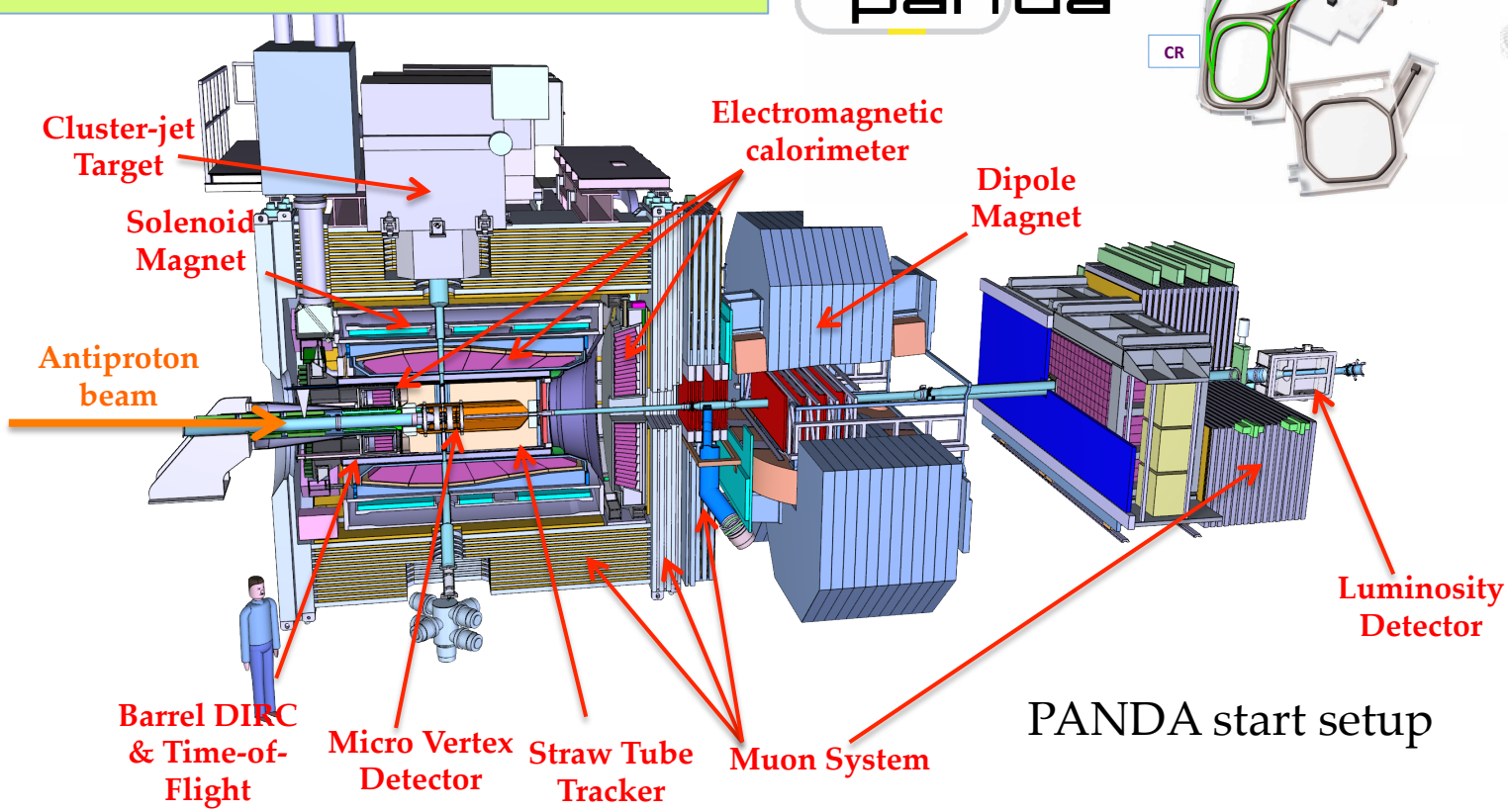
April 23 - 27, 2018 – Physikzentrum Bad Honnef

PANDA @ High Energy Storage Ring (FAIR/Darmstadt)

Antiproton production @ FAIR

- Proton Linac 70 MeV
- Accelerate proton in SIS 18 / 100
- Antiproton production on Cu target
- Collection in CR, Storage in HESR
- Antiproton beam momenta in the range of 1.5 GeV/c – 15 GeV/c
- High momentum resolution
- FAIR Start Version: Luminosity $10^{31} cm^{-2} s^{-1}$





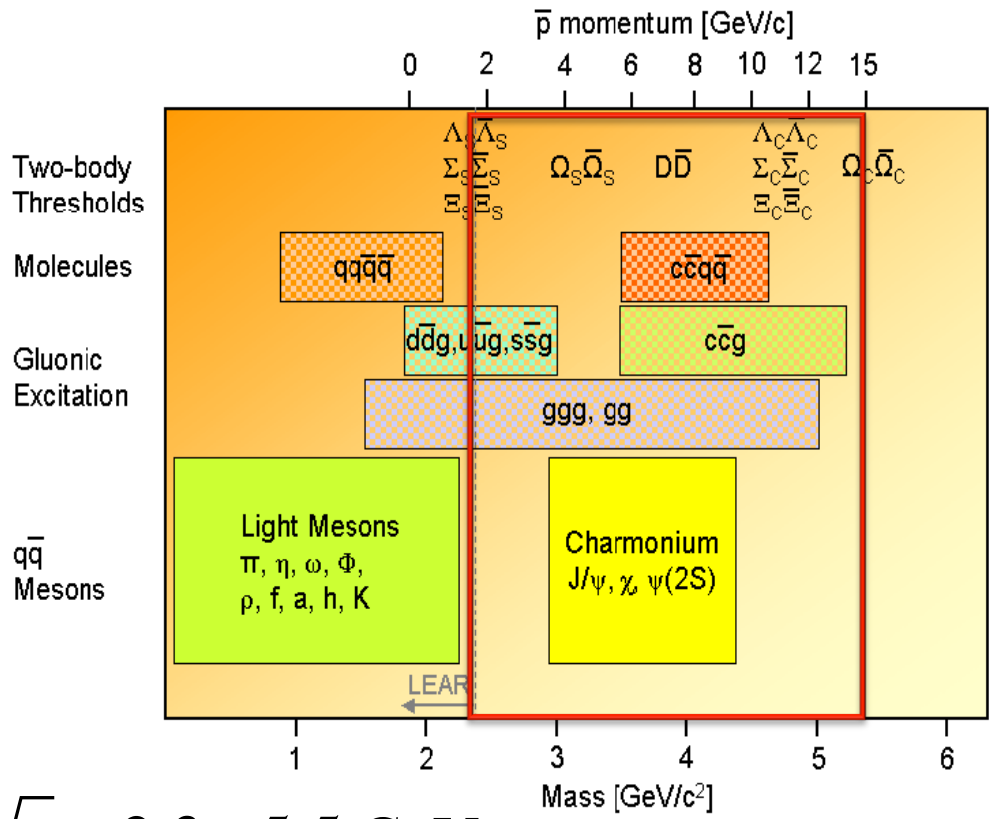
PANDA start setup

PANDA @ High Energy Storage Ring (FAIR/Darmstadt)

More than 460 physicists from 75 institutions in 19 countries

PANDA Physics Program

- Hadron Spectroscopy
  - Charmonium
  - Light mesons
  - Gluonic excitations
  - Open charm
  - (Multi) strange baryons
- **Nucleon structure**
- Hypernuclear physics
- Hadrons in the nuclear medium

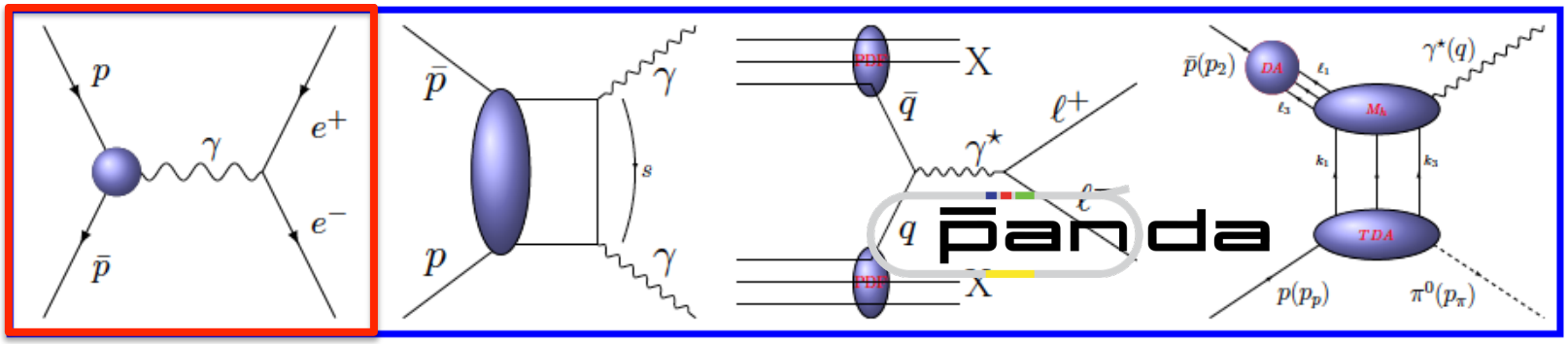


$$\sqrt{s} = 2.3 - 5.5 \text{ GeV}$$

ArXiV:0903.3905

Electromagnetic Processes at PANDA

PANDA will provide a large set of **electromagnetic processes**



- **Electromagnetic Form Factors of the proton (FFs) in the time-like region**
- Generalized Distribution Amplitudes (GDAs)
- Transverse Momentum Dependent Parton Distribution Functions (TMD-PDFs)
- Transition Distribution Amplitudes (TDAs)

Electromagnetic Form Factors of the Proton

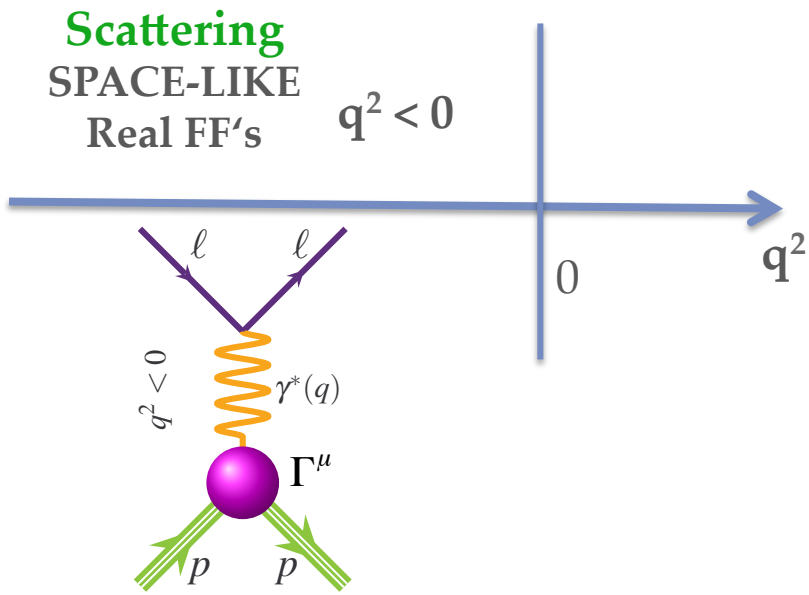
- **Describe internal structure** of the proton
- **Hadronic vertex can be parametrized in terms of two Form Factors F_1 & F_2.**

$$\Gamma^{\mu} = F_1(Q^2)\gamma^{\mu} - F_2(Q^2)\frac{i\sigma^{\mu\nu}q_{\nu}}{2M_p}, \quad Q^2 = -q^2$$

- **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, $\mathbf{G_E}$ and $\mathbf{G_M}$ are the Fourier transforms of the **charge and magnetic spatial distributions** of the nucleon



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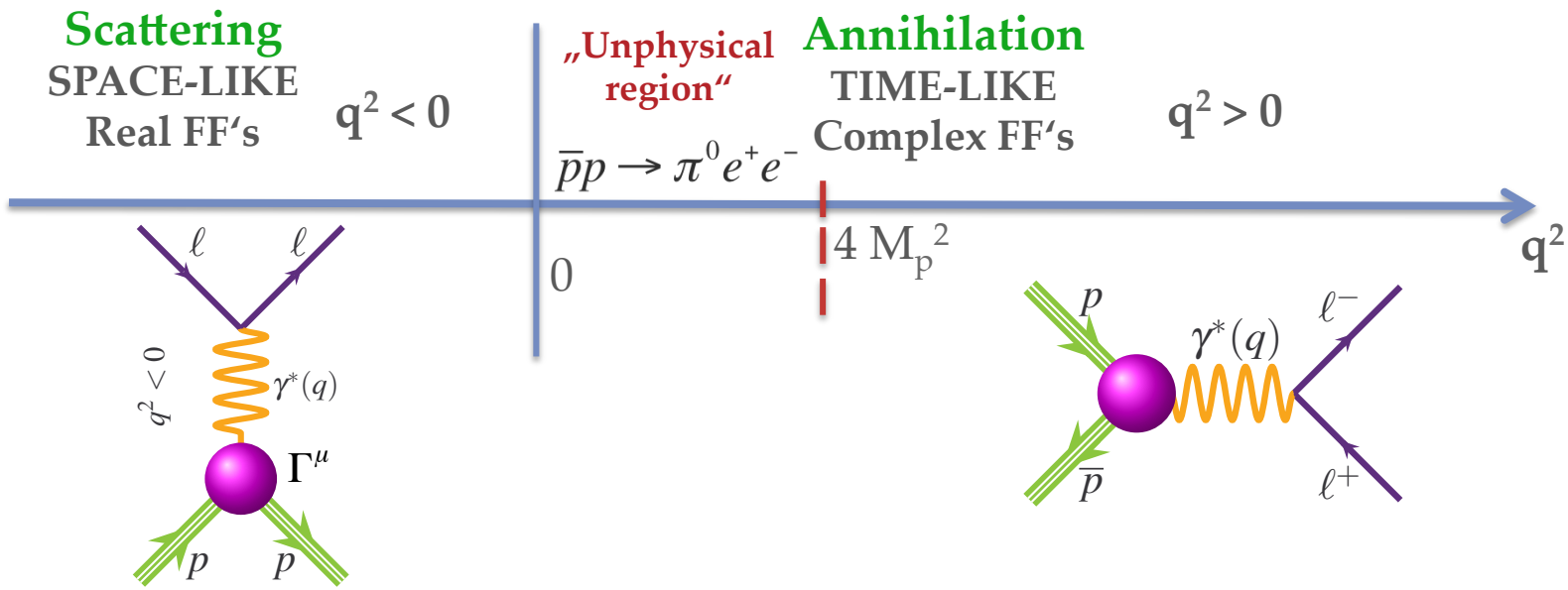

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Time-like & Space-Like Form Factors are connected via

Dispersion relations

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

Asymptotic behavior of the Form Factors

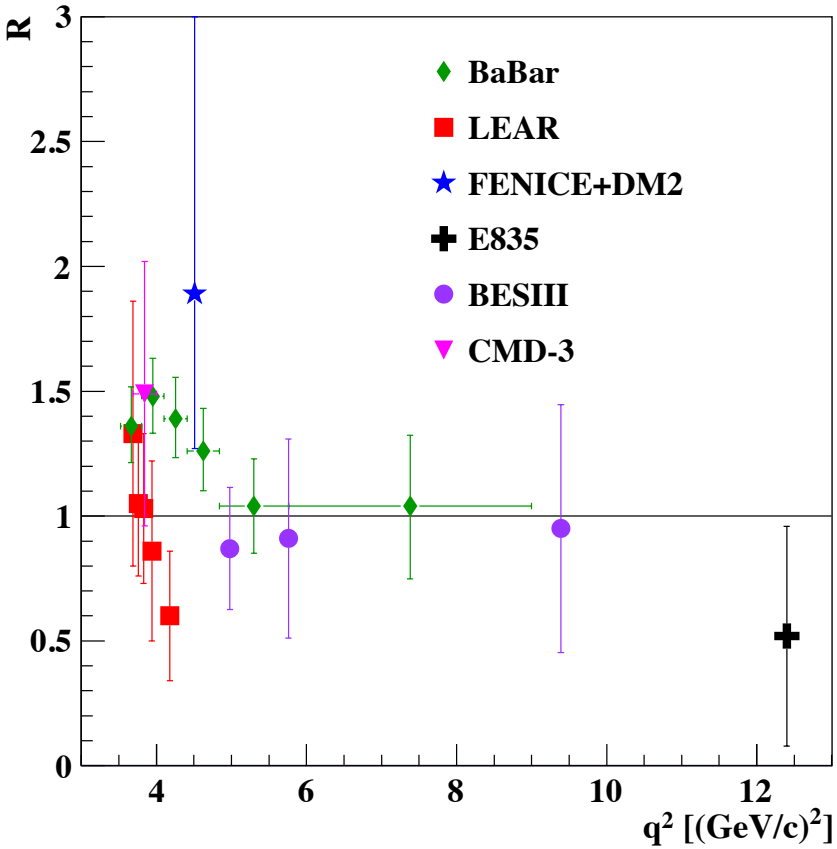
$$\lim_{q^2 \to -\infty} F_{1,2}^{SL}(q^2) = \lim_{q^2 \to +\infty} F_{1,2}^{TL}(q^2)$$

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

Threshold value ($q^2 = 4M^2_p$)

$$G_E(4M_p^2) = G_M(4M_p^2) \rightarrow R = \frac{|G_E(4M_p^2)|}{|G_M(4M_p^2)|} = 1$$

World 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): $e^+e^- \rightarrow \bar{p}p\gamma$

- 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 different trends

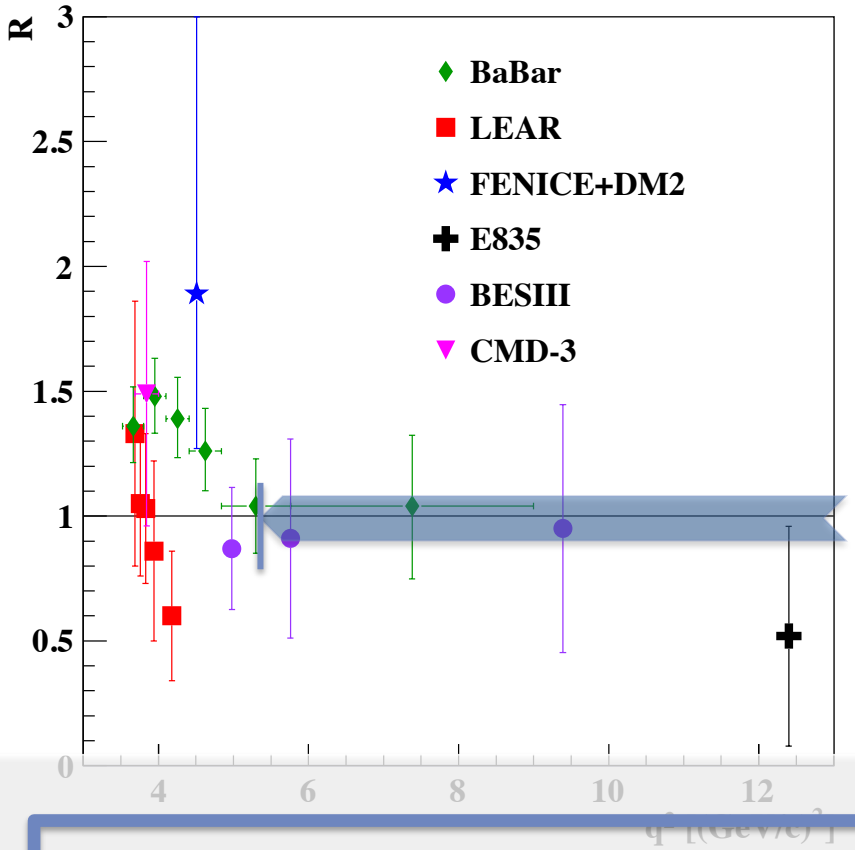
@ BESIII: $e^+e^- \rightarrow \bar{p}p$

- Measurement at different energies
- Uncertainties comparable to previous experiments

@ CMD-3 (VEPP2000 collider, BINP):

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

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



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- Uncertainty comparable to the measurement by BaBar

PANDA: Measurement over wide range of $5.1 \leq q^2 \leq 30.0$ [(GeV/c)²] with high precision

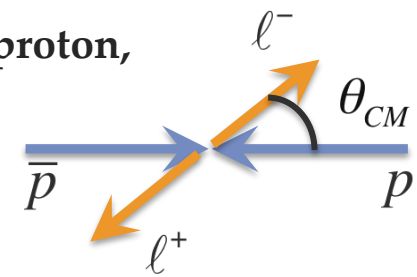
Test of theoretical models & predictions!

BaBar: Phys. Rev. D87 (2013)
LEAR: Nucl. Phys. B411 (1994)
BESIII: arXiv:1504.02680 (2015)
CMD-3: arXiv:1507.08013v2 (2015)

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

- Differential cross section[1] of **signal reaction** $\bar{p}p \rightarrow \ell^+\ell^- \quad \ell = \mu, e$

  → Access to the **time-like, electromagnetic form factors of the proton, $|G_E|$ and $|G_M|$** :



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

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

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

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

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

- **Form factor measurements different final states:** $\bar{p}p \rightarrow \ell^+\ell^- \quad \ell = \mu, e$
  - First time measurement with muons in final state
  - Study of radiative corrections
  - Consistency check of proton form factor data
  - Test of lepton universality
- **Possibility to access the relative phase of proton time-like form factors**:

  $\bar{p}p \rightarrow \ell^+\ell^-$ 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 $$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{1,y} \propto \sin 2\Theta \, \mathrm{Im}\left(G_M G_E^*\right)$$

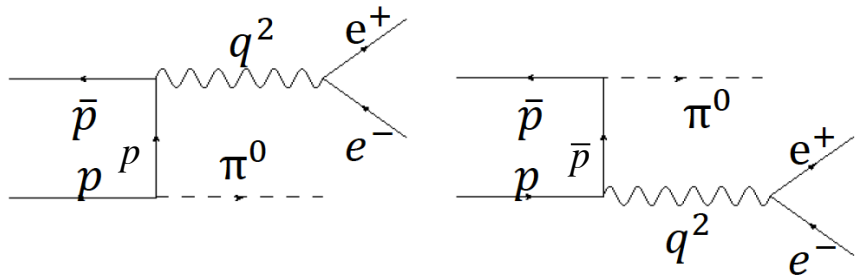
- **A. Z. Dubnickova, S. Dubnicka & M.P. Rekalo Nuovo Cim. A109 (1996) 241-256**

  - Development of a transverse polarized target for PANDA in Mainz

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

- Access the **unphysical region, where no data exist so far**

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



- 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
- J. Guttmann, M. Vanderhaeghen, Phys.Lett. B 719, 136 (2013)

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

- **Strong hadronic background**, mainly $\bar{p}p \rightarrow \pi^+\pi^-, \bar{p}p \rightarrow \pi^+\pi^-\pi^0$

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

- E.W. Singh et al.: EPJA52, 325 (2016)

Background rejection factor 10^{-8} needed
-> expected signal pollution < 1%

Feasibility studies needed for all signal channels!

Feasibility studies: time-like proton form factors for PANDA

$$\bar{p}p \rightarrow \ell^+\ell^- \ (\ell = e, \mu)$$

Study of the statistical and total uncertainty on
R, $|G_E|$ & $|G_M|$, $|F_p|$ and σ

Feasibility studies: time-like proton form factors @ PANDA

Monte Carlo Simulation Studies

$\bar{p}p \rightarrow \ell^+\ell^- \; (\ell = e, \mu)$ $\bar{p}p \rightarrow \pi^+\pi^-$

Standard chain
Simulation & Analysis
with **PANDARoot**:

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

p_{beam} [GeV/c]	1.5	1.7	2.5	3.3	6.4
s [GeV^2]	5.1	5.4	6.8	8.2	13.9

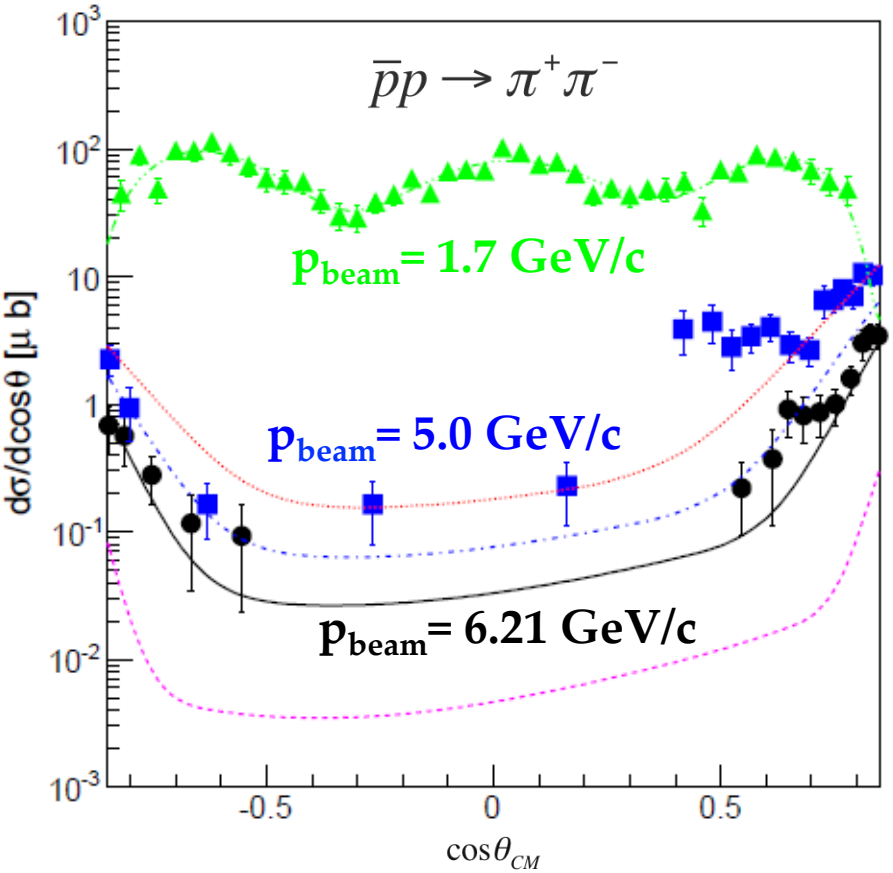
Event selection:

- **Preselection:** **One positive** and **one negative particle** per event
- **Cuts on kinematical variables**: **Production angles** (back-to-back in center-of-mass system), & **Invariant Mass.**
- **Signal/Background separation** based on:
  - For e^+e^- : Different subdetector information like **E**lectro**m**agnetic **C**alorimeter, **S**traw **T**ube **T**racker etc. contribute to particle identification
  - For $\mu^+\mu^-$: **Boosted Decision Trees** + cuts. **Detector information MAINLY from M**uon **R**ange **S**ystem

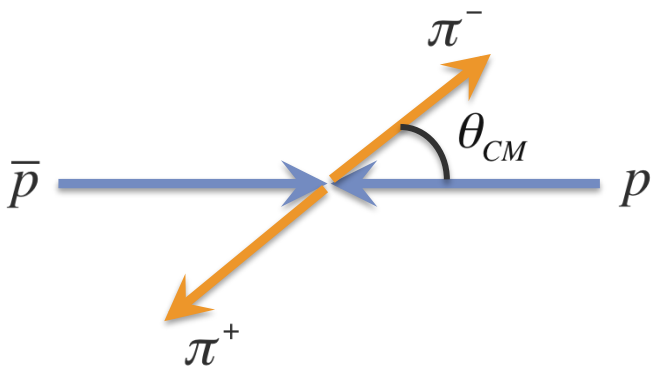
Feasibility studies: time-like proton form factors @ PANDA

Monte-Carlo Simulation studies

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



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



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

- J. Van de Wiele and S. Ong: EPJA46, 291-298 (2010)
- M. Sudol et al.: EPJA44, 373 (2010)
- E.W. Singh et al.: EPJA52, 325 (2016)

Data are from
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)

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

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

- Study of **precision** for $|G_E|$&$|G_M|$, **the form factor ratio R & effective form factor**
- Study of the **systematic effects** : generator model, fluctuations and fit function
- **Method I**: event generator based on physical cross section & expected events are simulated
- **Method II**: 10^6 events + flat Phase Space (PHSP) event generator + weighting

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

Signal efficiency & Background rejection

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

Method I

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

- Zichichi cross section[1] + PHOTOS
- Assuming $R = |G_E|/|G_M| = 1$
- **s [GeV²]: 5.4, 8.2, 13.9**
- **L = 2 fb^{-1}**

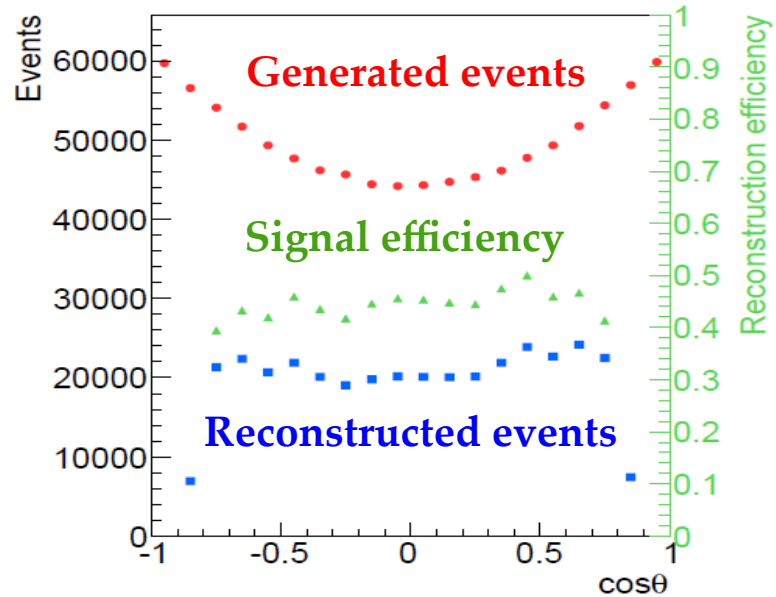
- Additional samples for signal efficiency determination **~10^6 events**

- **Total signal efficiencies** between **39%** and **51%**

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

- **New event generator** @ s = 5.4, 8.2, and 13.9 [GeV²]
- **10^8 events at each energy point**

- **Background rejection ~ 10^{-8}**
  Signal pollution < 1%



$$|\cos\theta| \leq 0.8$$

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

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

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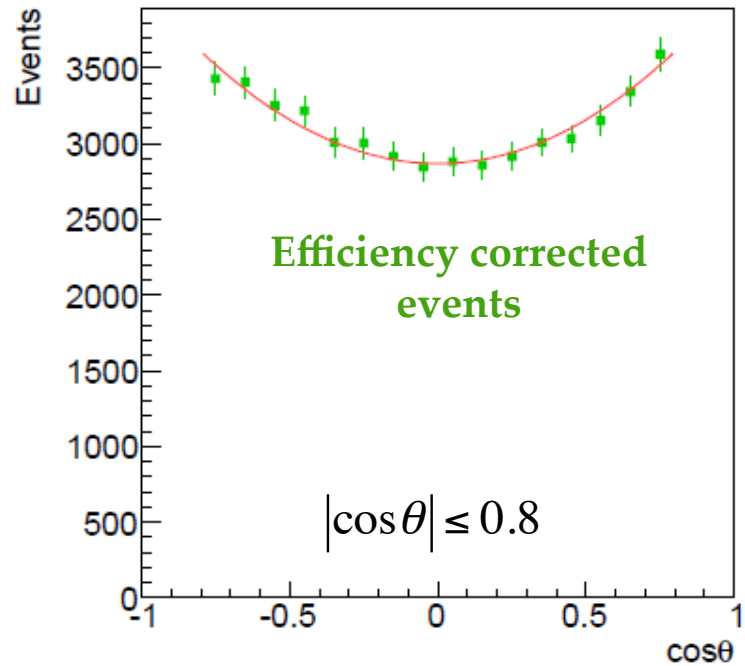


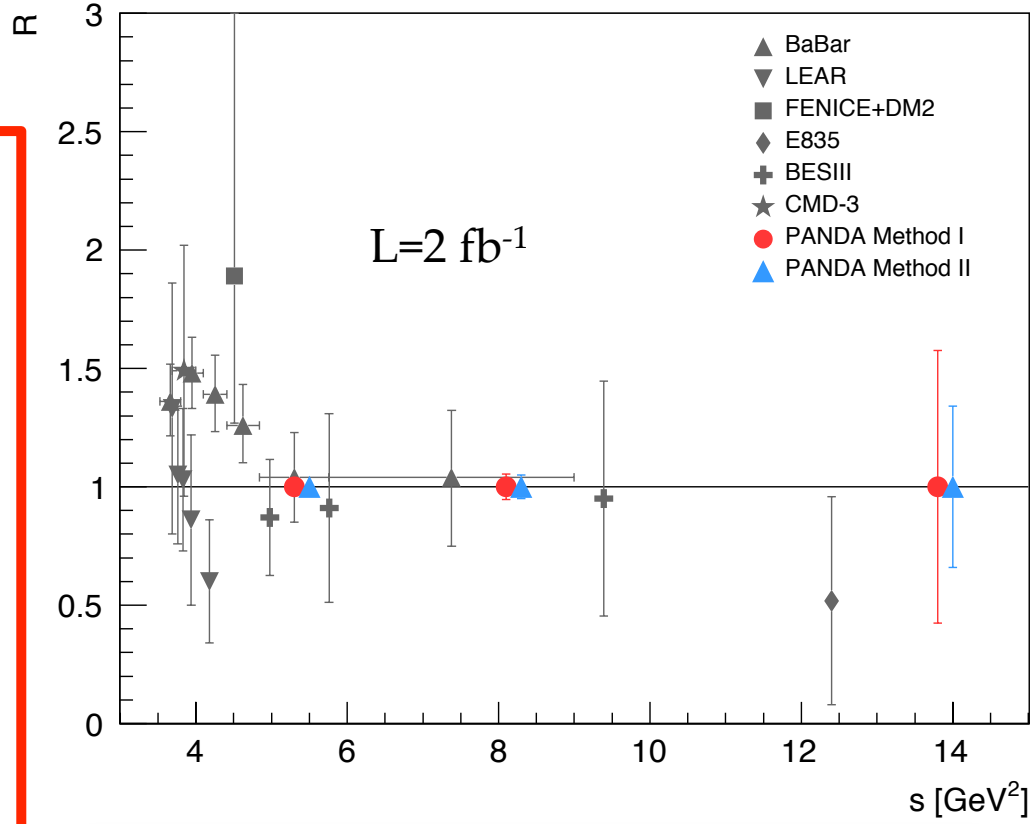
Extraction of FF´s & R±ΔR from **efficiency corrected signal distribution**

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

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

Statistical & total relative uncertainty on R, $|G_E|$ and $|G_M|$

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



Results

Statistical relative uncertainty (MI)

- $\Delta|G_E|/|G_E|$: 0.9% - 48%
- $\Delta|G_M|/|G_M|$: 0.4% - 9.4%
- $\Delta R/R$: 1.3% - 56%
- $\Delta|F_p|/|F_p|$: 0.3% - 6.0%

- Systematic uncertainties: Luminosity measurement & Background contamination.

Total relative uncertainty (MI)

- $\Delta|G_E|/|G_E|$: 2.2% - 48%
- $\Delta|G_M|/|G_M|$: 3.5% - 9.7%
- $\Delta R/R$: 3.3% - 57%

Time-like electromagnetic proton form factors can be measured with high precision @ PANDA using the electron channel

- E.W. Singh et al.: EPJA52, 325 (2016)

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

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

Study of the statistical and total relative uncertainty on R,
$|G_E|$ & $|G_M|$

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

Signal efficiency

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

Analysis : Boosted Decision Trees & Cuts

$|\cos\theta| \leq 0.8$

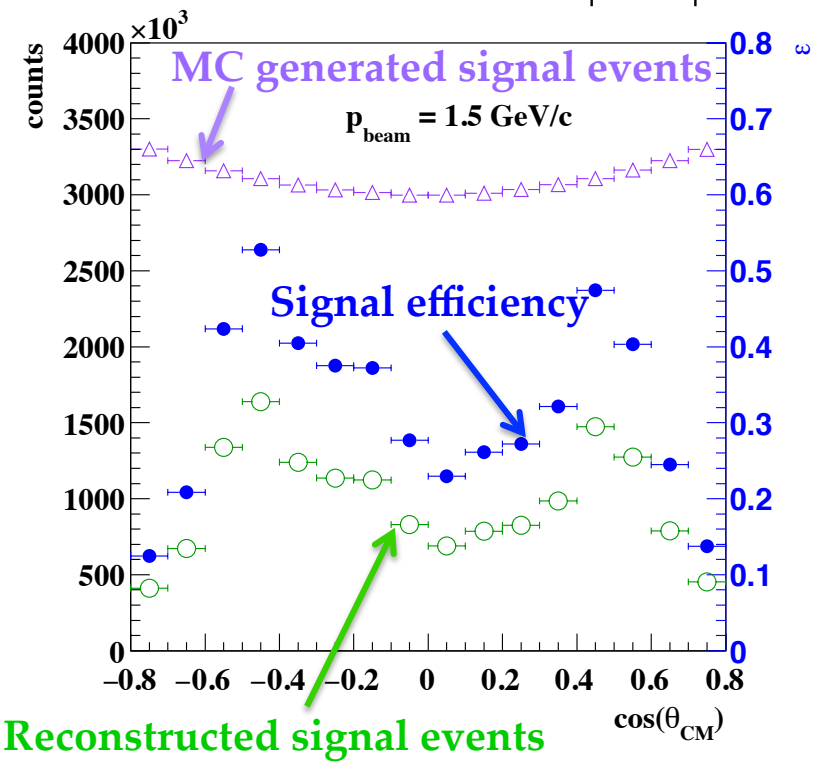
Signal: $\bar{p}p \rightarrow \mu^+\mu^-$

- Follows physical cross section
- Assuming $R = |G_E|/|G_M| = 1$
- **L = 2 fb^{-1}**
- **s [GeV^2]: 5.1, 5.4, 6.8, 8.2**

Total signal efficiency between 24% and 35%

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

- **New event generator @ s [GeV^2]= 5.1, 5.4, 6.8, 8.2**
- **Two samples (1*10^8) at each energy point:**
  - **Studying background rejection,**
  - **Effects of background subtraction**



- **Background rejection factor ~ 10^{-5} - 10^{-6}**
- **Expected signal/background ratio: between 1:4 and 1:9 at q^2 = 5.1 (GeV/c)^2**

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

Study effects of background subtraction

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

How to obtain the background contamination?

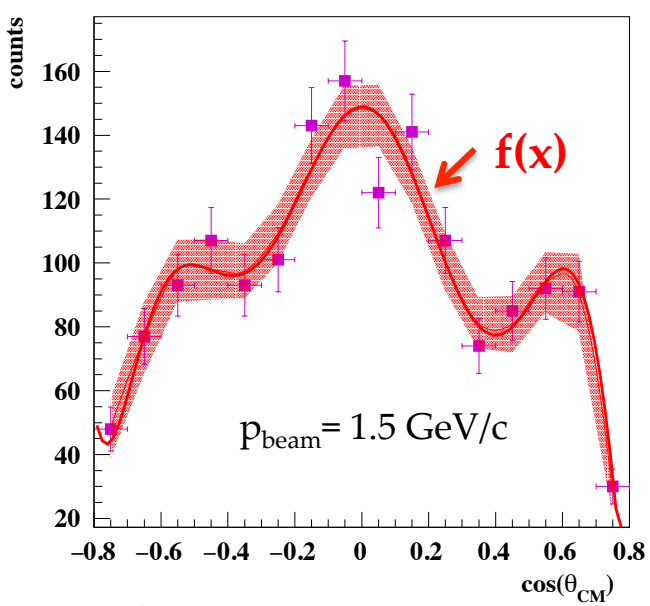
L=2 fb^{-1}

- **Background rejection factor ~ 10^{-5} - 10^{-6}**

- **Expected signal/background ratio: between 1:4 and 1:9 at q^2 = 5.1 (GeV/c)^2**
- **Background subtraction** removes pion background contamination

q^2 [GeV/c]^2	$N_{phys}(\mu^+\mu^-)$	$N_{phys}(\pi^+\pi^-)$
5.1	1.28 x 10^6	2.65 x 10^{11}
5.4	8.30 x 10^5	2.02 x 10^{11}
6.8	1.78 x 10^5	4.52 x 10^{10}
8.2	4.97 x 10^4	5.93 x 10^9

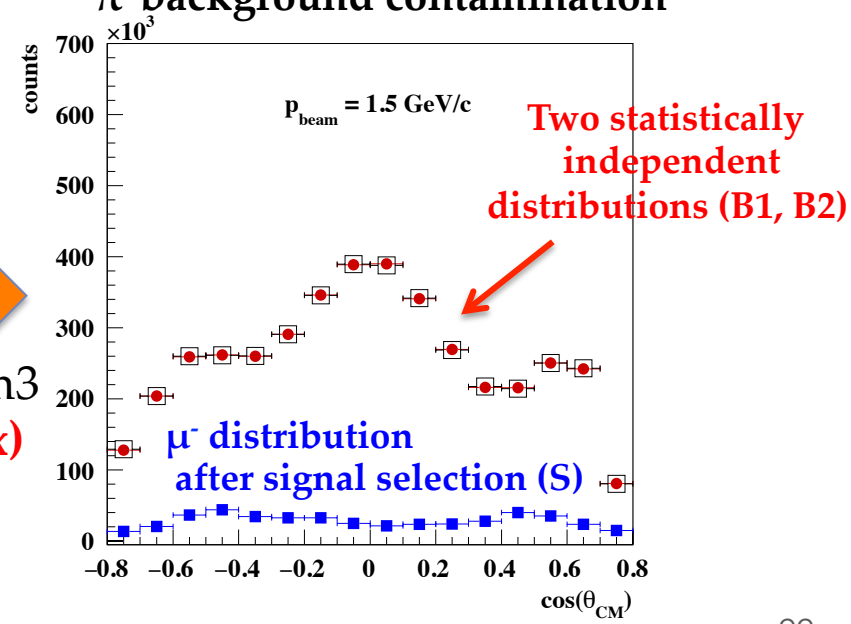
Residual π^- counts after signal selection



10^8 events were generated

TRandom3 using **f(x)**

π^- background contamination



Background subtraction: (S+B1) – B2

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

Statistical relative uncertainty on R, $|G_E|$ & $|G_M|$

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

Analysis : Extraction of $|G_{E,M}|$ and R

$|\cos\theta| \leq 0.8$

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

- Follows physical cross section
- Assuming $R = |G_E|/|G_M| = 1$
- **L = 2 fb^{-1}**
- **s [GeV^2]: 5.1, 5.4, 6.8, 8.2**

Total signal efficiency between 24% and 35%

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- **Two samples (1*10^8) at each energy point:**
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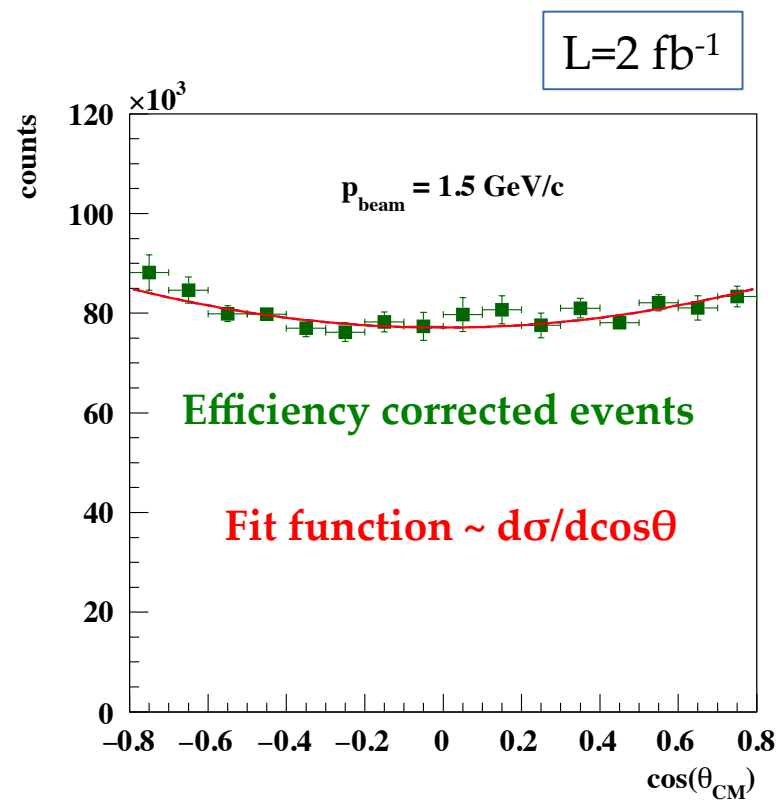
  - **Effects of background subtraction**

- **Extraction of $|G_{E,M}|$ and R from efficiency corrected μ^- distribution (after background subtraction)**



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

Statistical & total relative uncertainty

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

Results

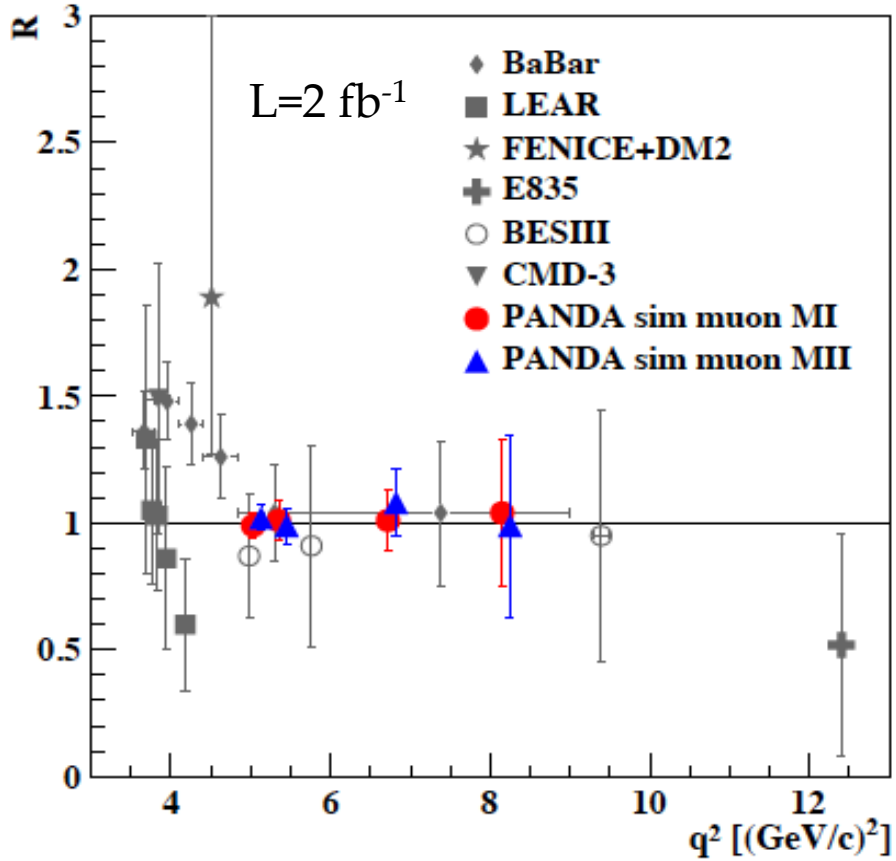
Statistical relative uncertainty (MII)

- $\Delta|G_E|/|G_E|$: 3.1% - 27%
- $\Delta|G_M|/|G_M|$: 1.5% - 9.6%
- $\Delta R/R$: 5.0% - 37%

- $\Delta|F_p|/|F_p|$: 0.33% - 0.99%
- $\Delta\sigma/\sigma$: 0.65% - 2.72%

Method I uses different (unrealistic) shape of the pion background contamination -> check influence of shape

Method II uses more realistic shape of pion background contamination than Method I



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

Statistical & total relative uncertainty

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

Results

Statistical relative uncertainty (MII)

- $\Delta|G_E|/|G_E|$: 3.1% - 27%
- $\Delta|G_M|/|G_M|$: 1.5% - 9.6%
- $\Delta R/R$: 5.0% - 37%

- $\Delta|F_p|/|F_p|$: 0.33% - 0.99%
- $\Delta\sigma/\sigma$: 0.65% - 2.72%

Total relative uncertainty (MII)

- $\Delta|G_E|/|G_E|$: 3.7% - 27%
- $\Delta|G_M|/|G_M|$: 2.5% - 9.9%
- $\Delta R/R$: 5.0% - 37%

Systematical uncertainties

- Luminosity measurement ~ 4% relative systematical uncertainty
  -> contributes with 2% relative uncertainty to $|G_{E,M}|$
- Choice of cuts
- Choice of histogram bin width

Time-like electromagnetic proton form factors can be measured with high precision @ PANDA using the muon channel

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

Other relevant background channels

Estimation of rejection factors for other relevant background channels

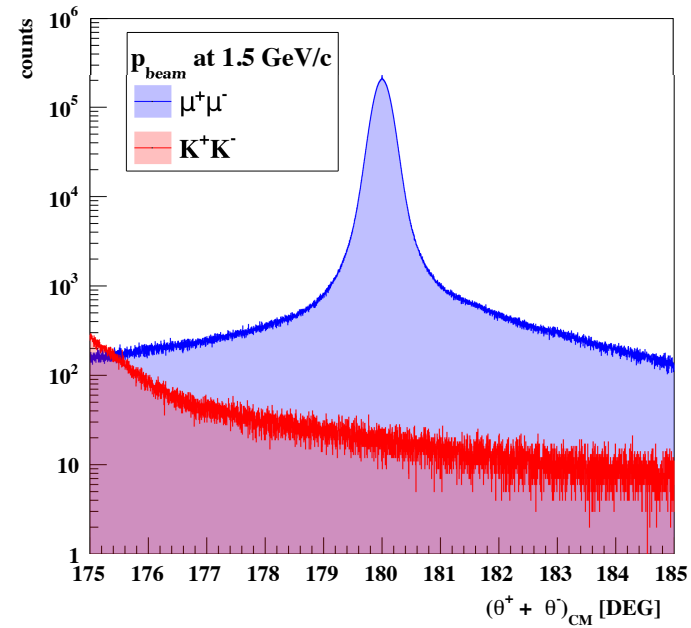
Monte-Carlo simulation with PHSP & Analysis at **q^2 = 5.1 GeV^2 & 8.2 GeV^2** for

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

Calculation of expected statistics and rejection factor

Estimation of upper limit @ CL 95% : **sufficient suppression achieved -> signal pollution < 1%**

After event preselection



New investigations on **light meson (charged and neutral) channels** can be found in

- Phys. Rev., 2017, C95 (4), pp.045202
- Phys. Rev. C 96 025204

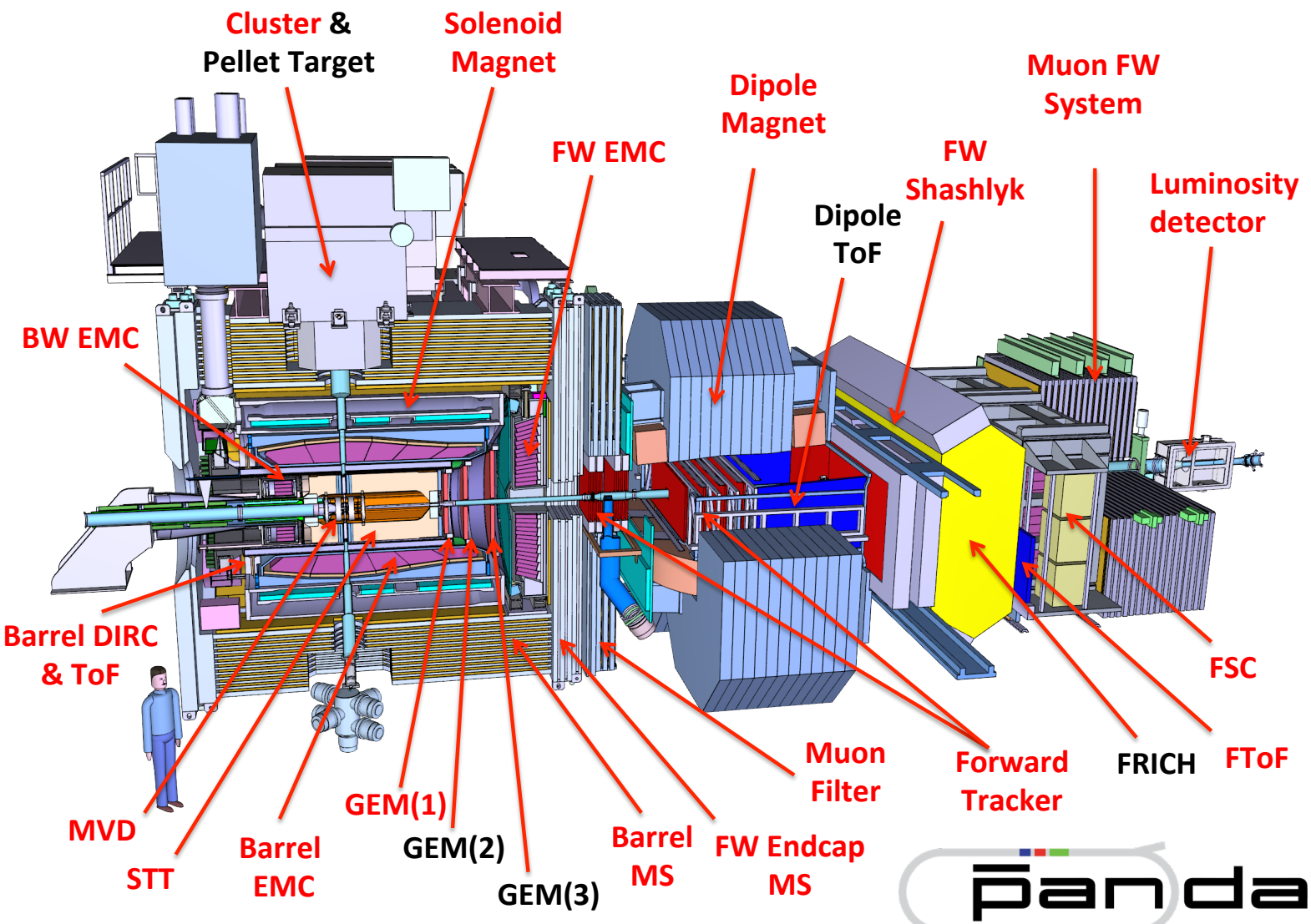
C) Feasibility studies: time-like proton form factors for PANDA PHASE-1

$$\bar{p}p \rightarrow \ell^+\ell^- \ (\ell = e, \mu)$$

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

The PANDA detector (start/full setup)

PANDA Phase-1: first data taking phase with reduced luminosity and **reduced detector setup**



Proton form factor measurements at PANDA-PHASE1

Relative statistical (total) uncertainty

L = 0.1 fb^{-1}

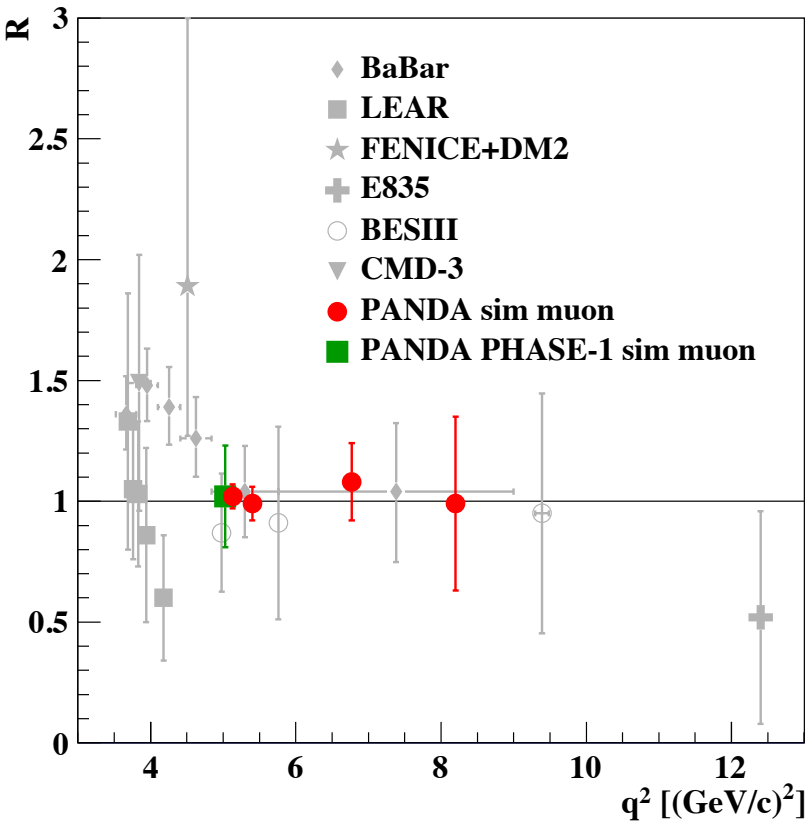
$\bar{p}p \rightarrow \mu^+\mu^-$ **Results**

Statistical (total) relative uncertainty

p_{beam} = 1.5 GeV/c

- $\Delta|G_E|/|G_E|$: 13.8% (14.3%)
- $\Delta|G_M|/|G_M|$: 6.5% (6.9%)
- $\Delta R/R$: 20.0% (21%)

- $\Delta|F_p|/|F_p|$: 1.5% (2.5%)
- $\Delta\sigma/\sigma$: 3.0% (5.0%)



Summary & Outlook

- **Measurements of the proton form factors in the TL region over a large kinematical region using electron and muon channels:** $\bar{p}p \rightarrow \ell^+\ell^- \ (\ell = e, \mu)$
  - Feasibility studies show that the TL proton form factors will be measured @ PANDA with high precision for both signal channels
  - For PANDA-Phase-1 (reduced luminosity), the measurement is also possible with both channels

  - Publication for electron channel 2016: **E.W. Singh et al.: EPJA52, 325 (2016)**
  - Publication for muon channel in preparation
  - Development of an event generator including **next-to leading order** QED radiative corrections is in progress
- **Measurement of proton FFs in the unphysical region:** $\bar{p}p \rightarrow e^+e^-\pi^0$
  - Feasibility studies with PANDARoot are needed

- **Possibility to access the relative phase of proton TL FFs**
  - Polarization observables give access to $G_E G_M{}^*$
  - Development of a transverse polarized proton target for PANDA in Mainz

Backup slides

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

Statistical & total relative uncertainty

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

Results

Statistical relative uncertainty (MII)

- $\Delta|G_E|/|G_E|$: 3.1% - 27%
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Total relative uncertainty (MII)

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- $\Delta|G_M|/|G_M|$: 2.5% - 9.9%
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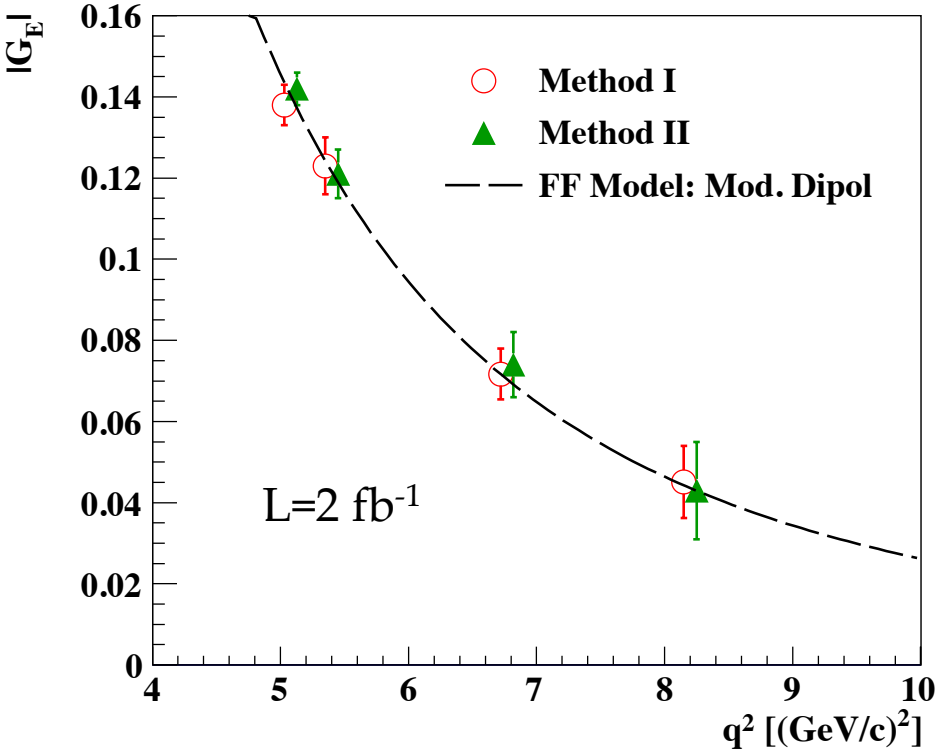
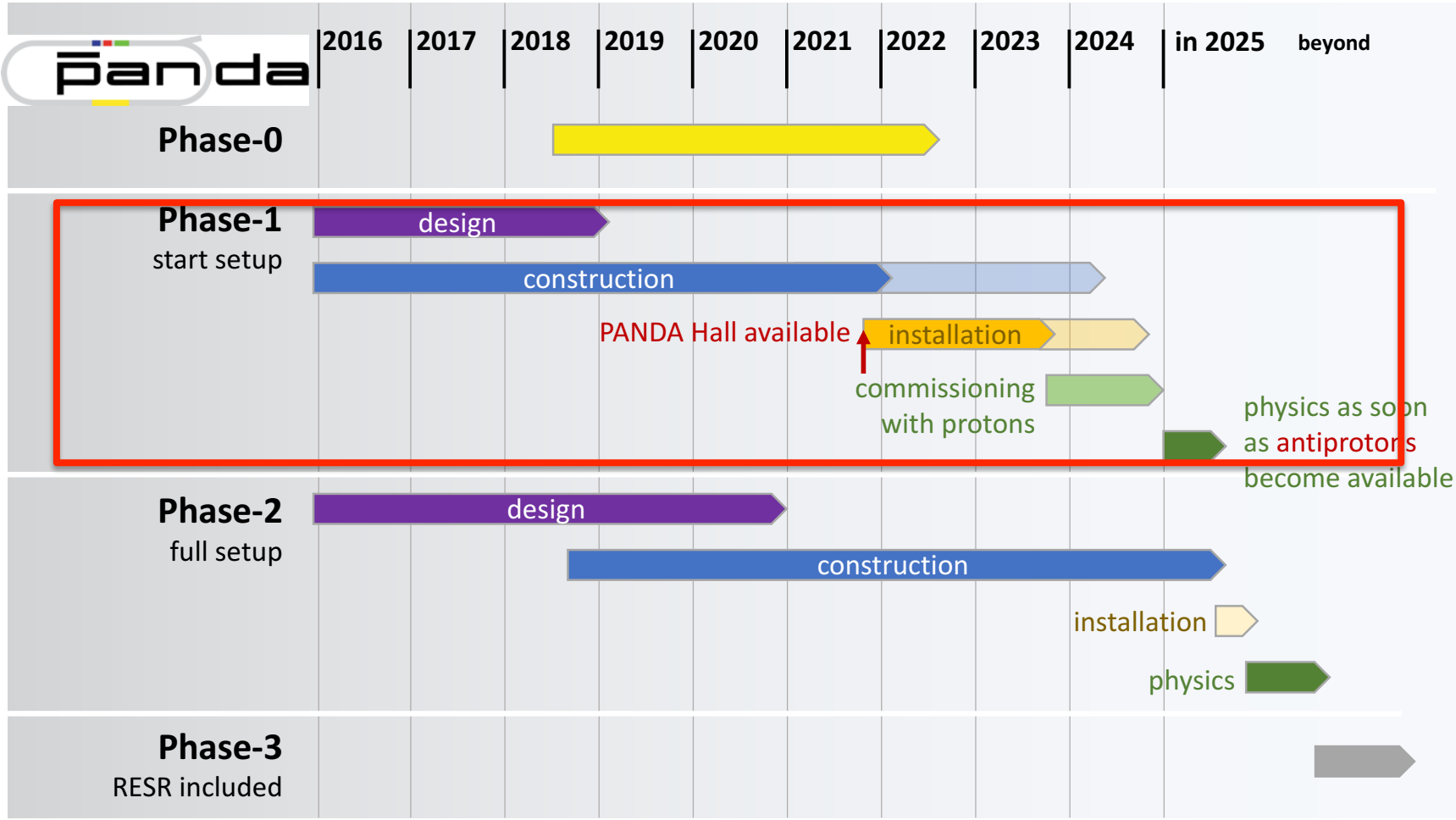


PANDA: Phases of data taking

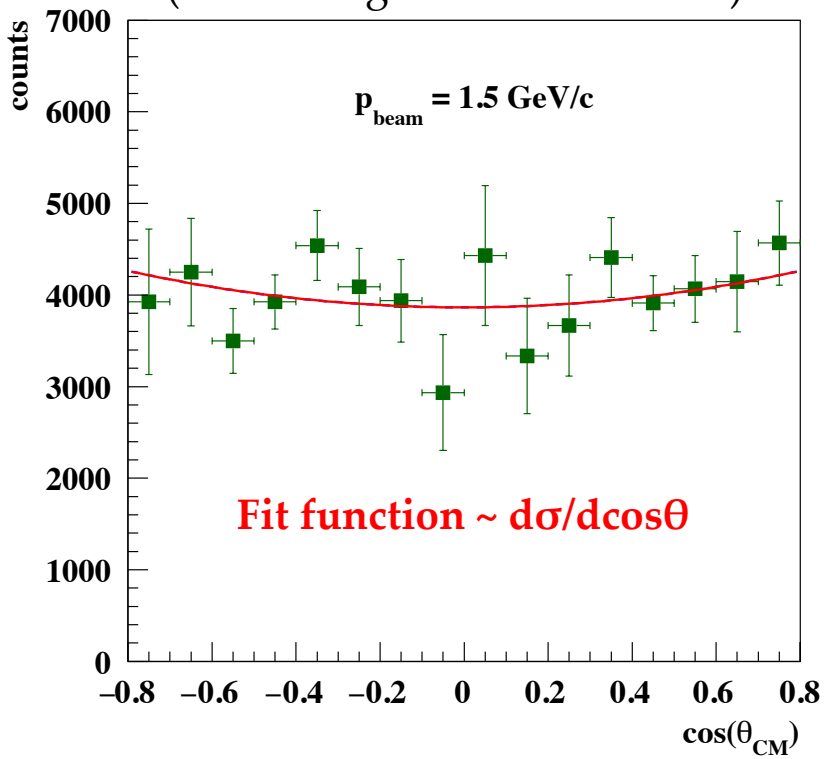


Proton form factor measurements at PANDA-PHASE1

Relative statistical uncertainty

$L = 0.1\ fb^{-1}$

Efficiency corrected signal distribution
(after background subtraction)



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

Results

Statistical (total) relative uncertainty

p_{beam} = 1.5 GeV/c

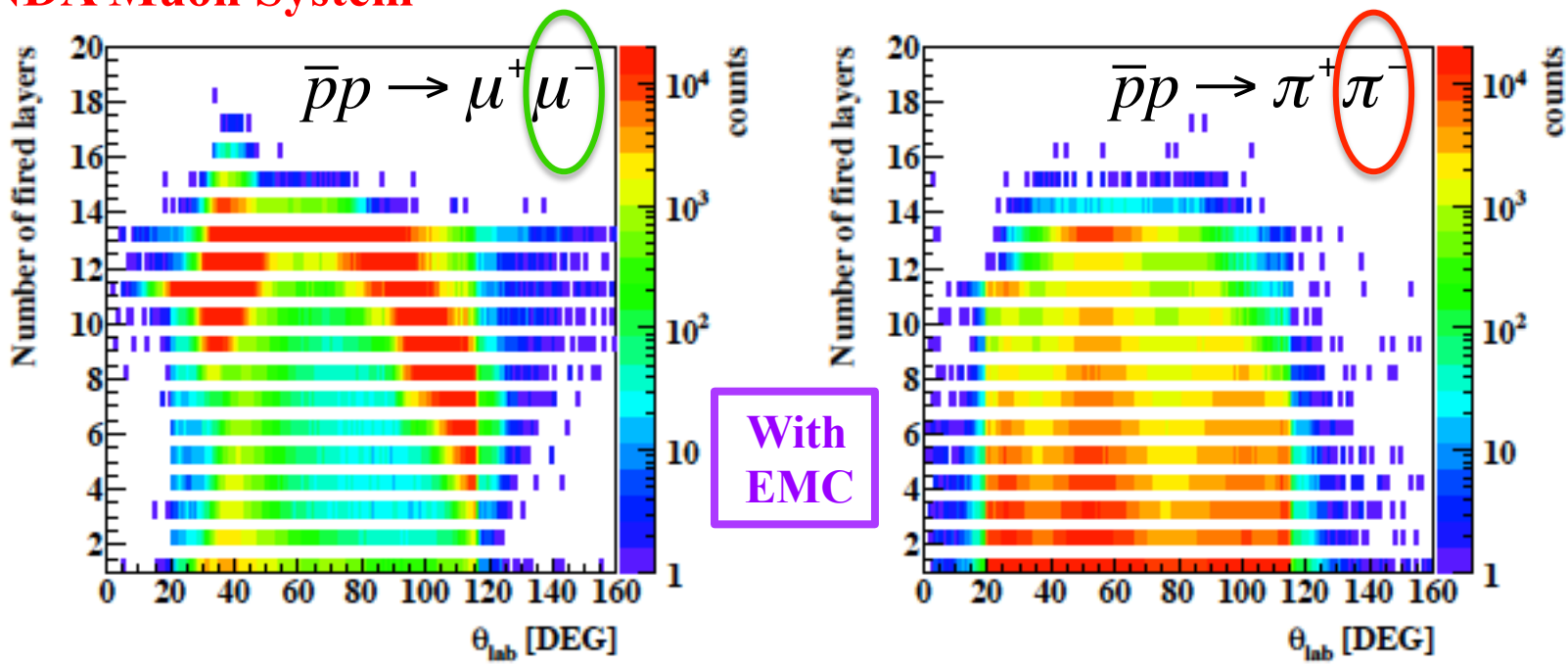
- $\Delta|G_E|/|G_E|$: 13.8% (14.3%)
- $\Delta|G_M|/|G_M|$: 6.5% (6.9%)
- $\Delta R/R$: 20.0% (21%)

- $\Delta|F_p|/|F_p|$: 1.5% (2.5%)
- $\Delta\sigma/\sigma$: 3.0% (5.0%)

Proton form factor measurements at PANDA-Phase1

Importance of the EMC

PANDA Muon System



EMC material in front of Muon System -> most of pions are stopped inside the first layers of the Muon System -> EMC material acts as muon filter

p_{beam}= 1.5 GeV/c	Total signal efficiency	Total background efficiency	S/B ratio	ΔR/R (stat.)
With EMC	32 %	$1.2 * 10^{-5}$	1/8	**20%**
Without EMC	36 %	$1.7 * 10^{-4}$	1/100	**60%**

Feasibility studies: time-like proton form factors @ PANDA

Background studies

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

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

	Low energy	Transistion region	High energy
	2.43		5.00
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)

p_{beam} (GeV/c)