Update on feasibility studies of Time-Like proton form factors at PANDA

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HIM
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ORSAY

Outline

I. Introduction: Measurements of the proton electromagnetic form factors in the Time-Like (TL) region

II. Feasibility studies of the $\bar{p}p \rightarrow e^+e^-$ reaction measurement at PANDA at 3 values of total energy

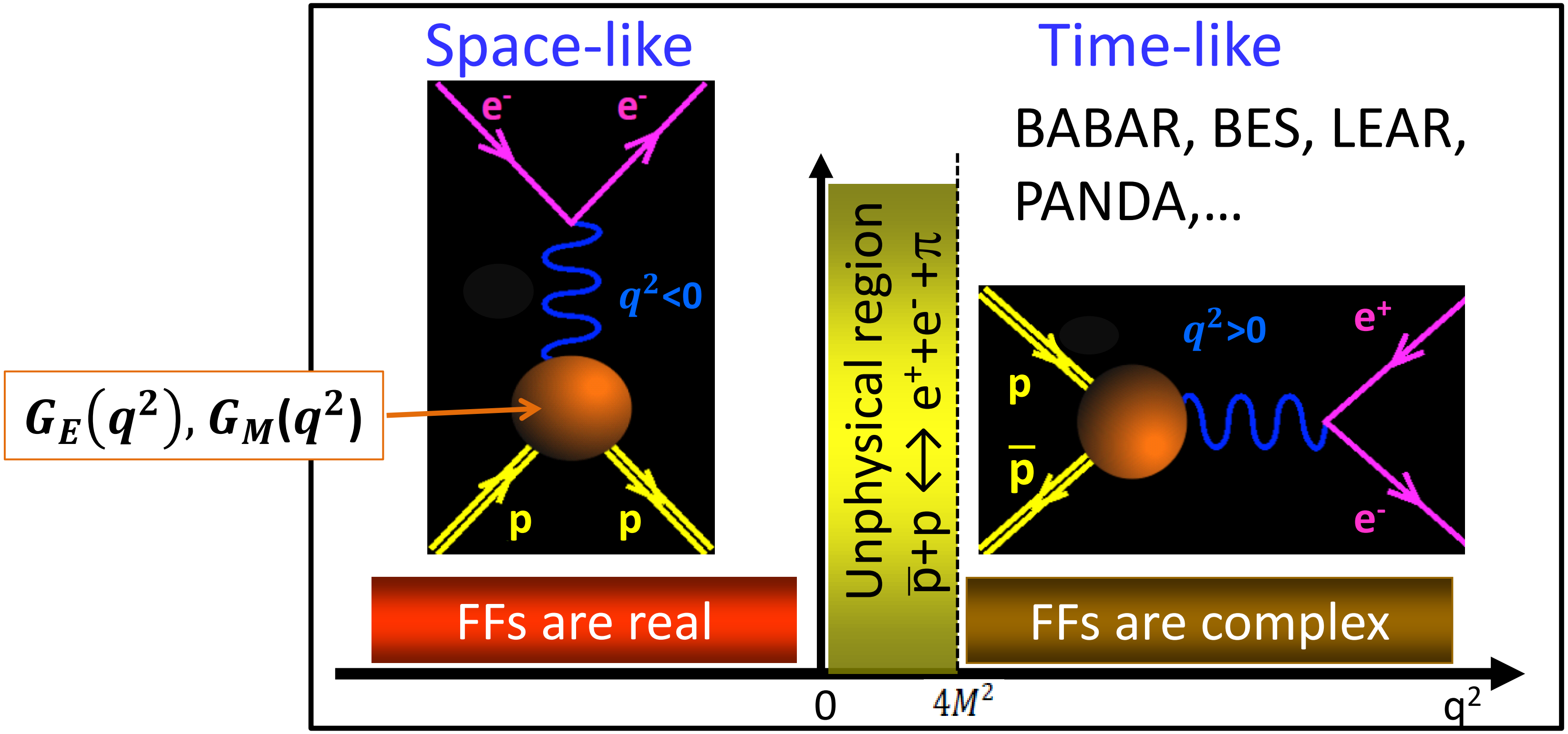
III. Determination of the statistical error on the proton FF ratio

IV. Conclusions

Electromagnetic form factors

- Parametrize the EM interaction of the hadron (≠ point-like)
- In a P- and T-invariant theory, the EM structure of a particle of spin S is defined by 2S+1 FFs: Proton (S=1/2) has electric $G_E(q^2)$ and magnetic $G_M(q^2)$ FFs
- q^2 is a kinematical invariant : [-∞, +∞]

Born approximation



Electromagnetic form factors

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- In a P- and T-invariant theory, the EM structure of a particle of spin S is defined by 2S+1 FFs: Proton (S=1/2) has electric $G_E(q^2)$ and magnetic $G_M(q^2)$ FFs
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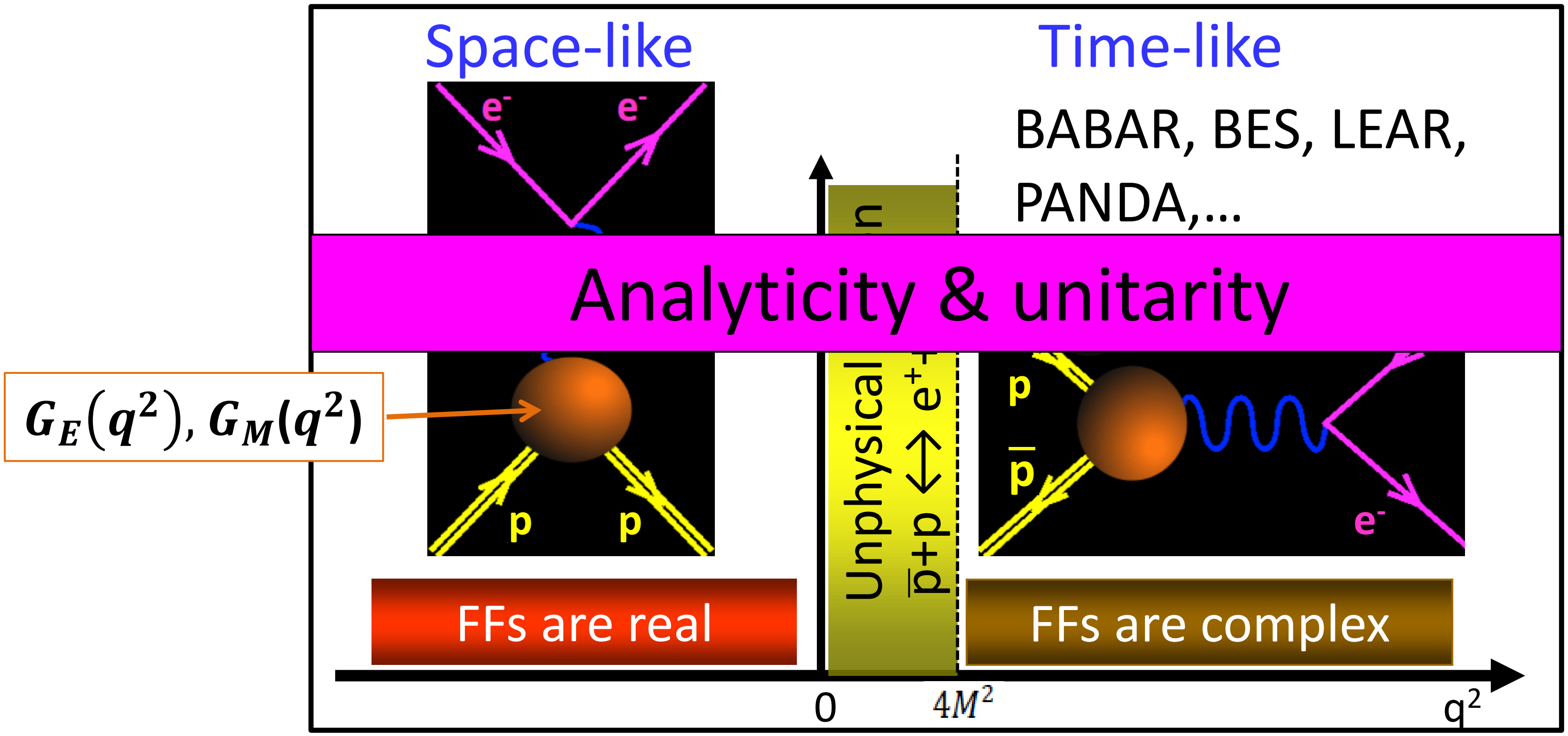
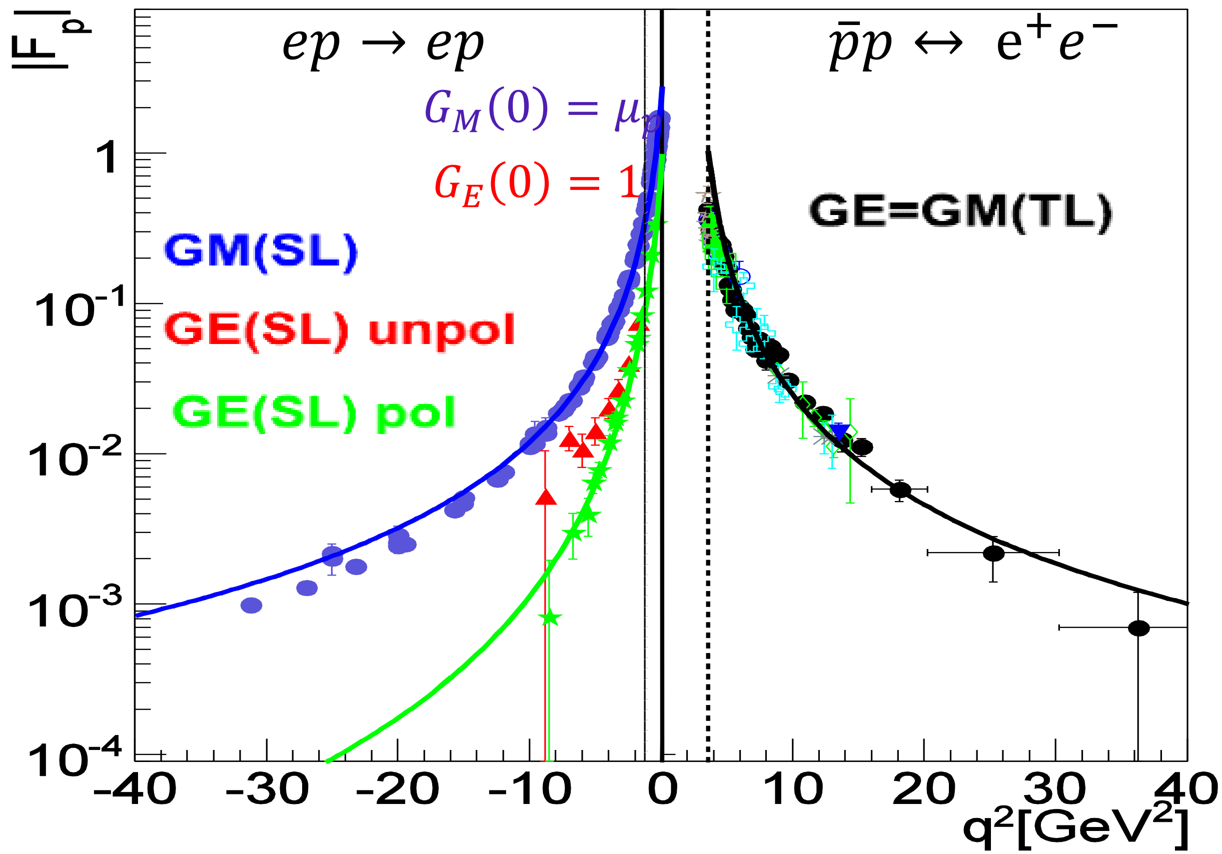
Born approximation



Data on proton electromagnetic form factors

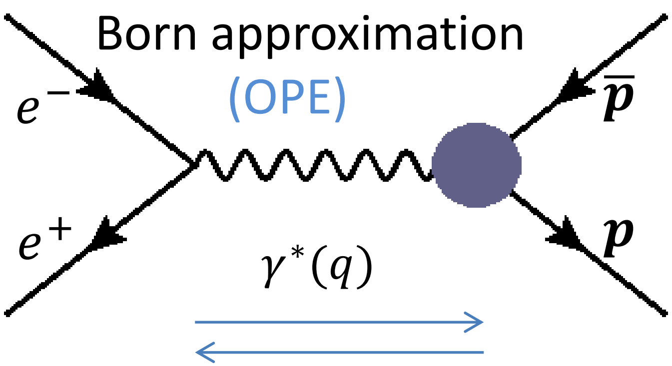


- Space-Like (SL): Discrepancy between the polarized and unpolarized data
- Time-Like (TL): - Individual measurement of $|G_E|$ and $|G_M|$
  - Investigation of the unphysical region

Towards a unified description of FFs in all kinematical regions

proton FF measurements in TL region

❑ Energy scan:



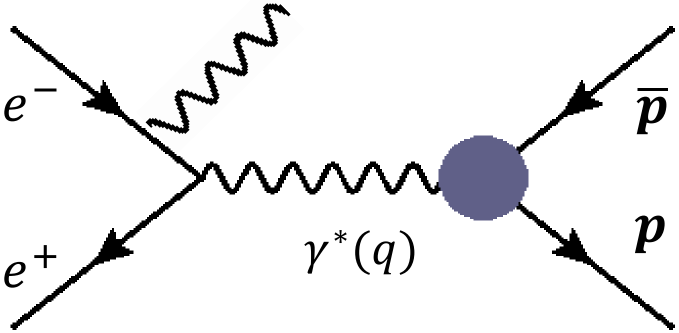
$$\frac{d\sigma}{d\cos\theta} = \mathcal{N}\left[\left(1+\cos^2\theta\right)|G_M|^2 + \frac{4M^2}{s}\sin^2\theta|G_E|^2\right]$$

$$= \mathcal{N}|G_M|^2\left[(1+\cos^2\theta)+\frac{4M^2}{s}\sin^2\theta\ R^2\right]$$

R=$|G_E|/|G_M|$, $\mathcal{N}$ is a normalization factor.

- Angular distribution of the proton (electron) → R=$|G_E|/|G_M|$
- Angular distribution + normalization → $|G_E|$ and $|G_M|$
- Total cross section → effective form factor ($|G_E| = |G_M|$)

❑ Initial State Radiation:

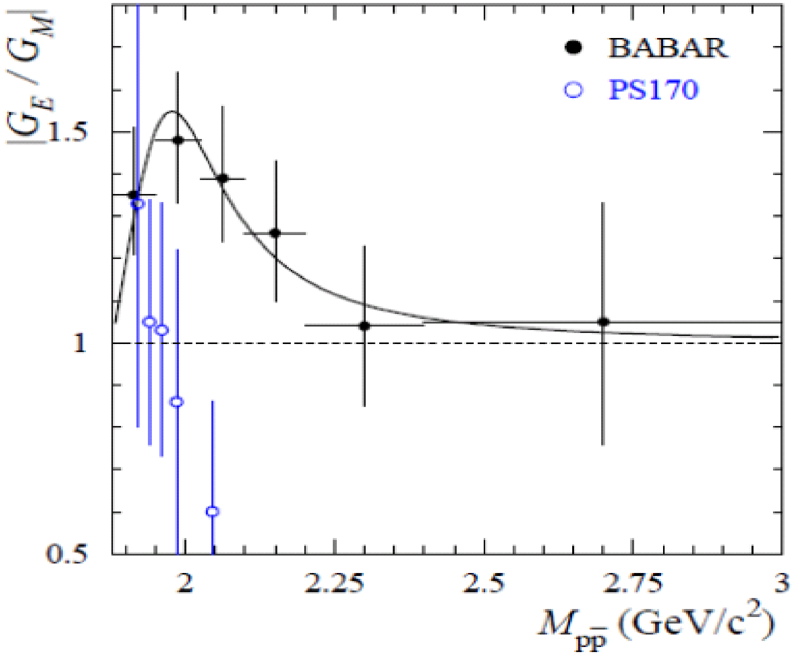


Tagged analysis: proton, antiproton and the photon need to be detected

Untagged analysis: proton and antiproton are detected. 4-momentum of the ISR photon is reconstructed

Data on the ratio of TL proton electromagnetic form factors

- 10%-24% statistical uncertainties
- Inconsistent data between BaBar and PS170
- BaBar: ISR technique [1.877, 3.00] GeV
- PS170 (LEAR): Low energy scan



- Future Data from:

BESIII

- ISR technique (tagged+untagged) : XYZ, J/ψ, ψ′, ψ′′, ψ(4040) data
- Proton FF measurement from 2.0-3.1 GeV energy scan,
  8 energy points, Integrated luminosity= 478 pb^{-1}, R ~10%

- PANDA (2019): Large range of CM energy and high luminosity

FAIR-High quality antiproton beam

Facility	Years	Momentum range [GeV/c]	Luminosity $[cm^{-2}s^{-1}]$	$\Delta p/p$
CERN-LEAR	1983-1996	$0.06 - 1.94$	2×10^{29}	10^{-3}
Fermilab (AA) Low energy experiments	1985-2011	< 8.9	2×10^{31}	10^{-4}
FAIR-PANDA	2018-…	$1.5 - 15$	2×10^{32} (10^{31})	10^{-4} 4×10^{-5}

PANDA will have:

- Larger momentum range of antiproton beam
- Higher luminosity
- Improved beam momentum resolution

Measurement of TL proton FFs at PANDA: Goals

- Measurements of TL proton FFs (effective FF, ratio) over a large kinematical region through: $\bar{p}p \rightarrow e^+e^-$

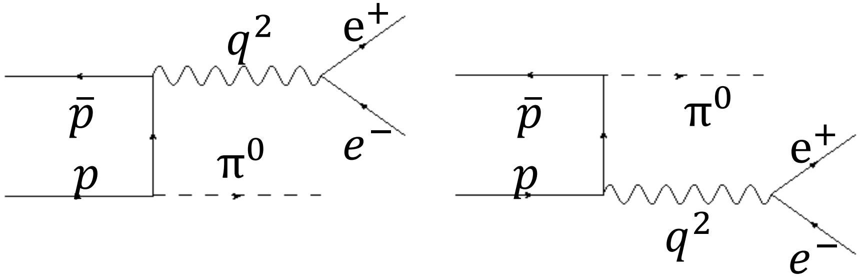
- Individual measurement of $|G_E|$ and $|G_M|$

  "M. Sudol *et al*. EPJ **A44**, 373 (2010)"

- Possibility to access the relative phase of proton TL FFs

  - Polarization observables (**Born approximation**) give access to $G_E G_M^*$
  - Development of a transverse polarized proton target for PANDA in Mainz

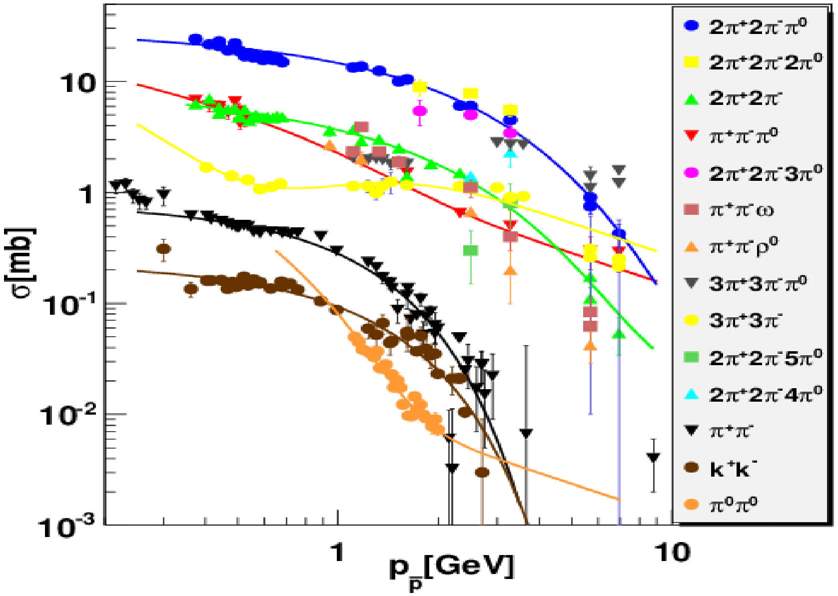
- Measurement of proton FFs in the unphysical region: $\bar{p}p \rightarrow e^+e^-\pi^0$



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

TL proton FF measurements at PANDA: background study

- Main issue: signal identification from the huge hadronic background
- The signal is $\bar{p}p \to e^+e^-$ and the main background is $\bar{p}p \to \pi^+\pi^-$
  - Channels with more than two charged particles in the final state can be rejected using the kinematics (missing mass)
  - The mass of pion is closer to the electron mass than other hadrons (proton and kaon)



A. Dbeyssi and E. Tomasi Gustafsson
Prob. Atomic Sci. Technol. 2012N1, 84 (2012)

$$\frac{\sigma(\pi^+\pi^-)}{\sigma(e^+e^-)} \sim [10^5 - 10^6]$$

A background rejection at the order of 10^{-8} is needed

Outline of the simulation studies

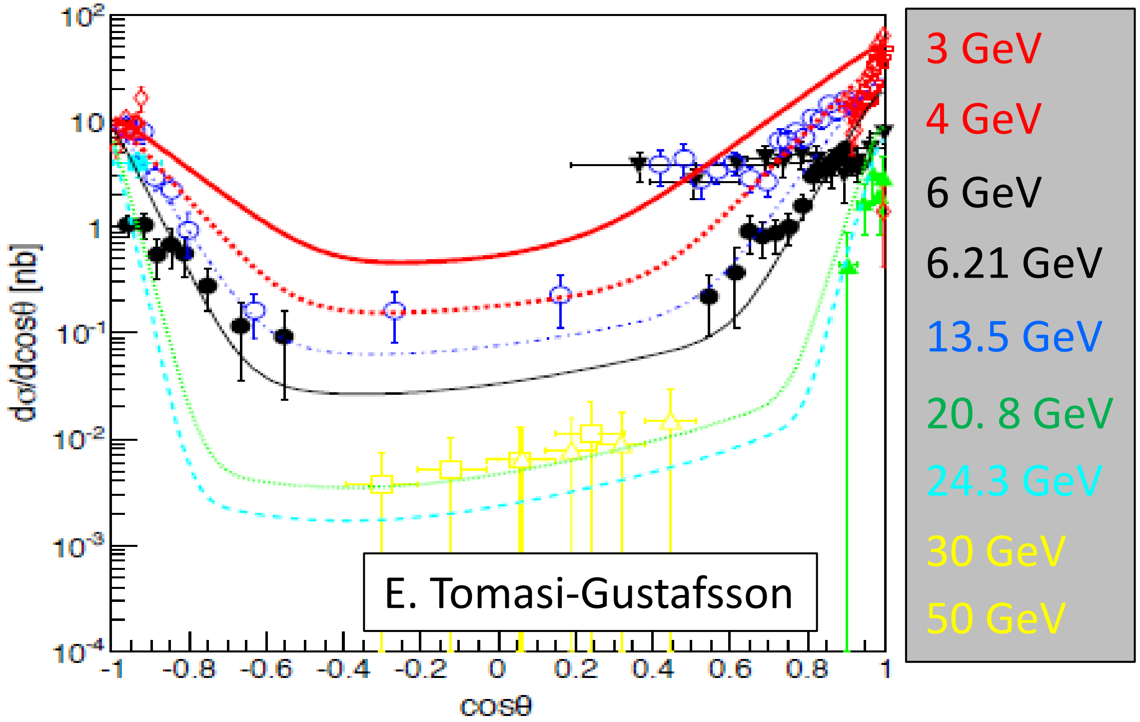
- Feasibility studies of $\bar{p}p \rightarrow e^+e^-$ for the measurement of proton FF ratio at PANDA:

  - Study of the **background suppression** versus the **signal ($\bar{p}p \rightarrow e^+e^-$) efficiency**

  - Determination of the statistical error on the extracted proton FF ratio $R = |G_E|/|G_M|$

Based on realistic Monte Carlo simulation using PANDARoot,
Big amount of data have been handled by the Clusters of HIM

Background angular distribution: Data and modelisation



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

- Reaction mechanism is changing with the energy and the angle

- Data are very scarce not allowing to constrain parameter model

Monte Carlo event generator:

➢ Low energy (p<5 GeV): parameters of Legendre polynomials

➢ High energy (5 GeV≤p<12 GeV) : Regge inspired parametrization

Zambrana et al., " PANDA note - EventGenerators" , HIM Mainz-IPN Orsay, 2011

Description of the simulation

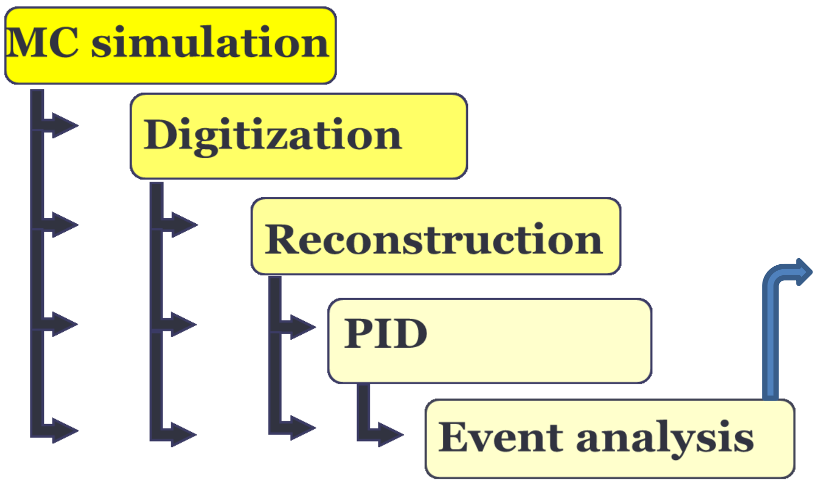
Monte Carlo parameters:

$p_{\bar{p}}$ [GeV]	1.7	3.3	6.4
s=q^2 [GeV^2]	5.4	8.2	13.9
Events ($\bar{p}p \to e^+e^-$)	10^6	10^6	10^6
Events ($\bar{p}p \to \pi^+\pi^-$)	10^8	10^8	10^8

- PHSP (PHase Space, GEANT4)
  - $\bar{p}p \to e^+e^-$
  - *PHOTOS* is switched on
- $\bar{p}p \to \pi^+\pi^-$: cosθ = [-0.8,0.8]

PANDARoot version: 25544 (apr13)

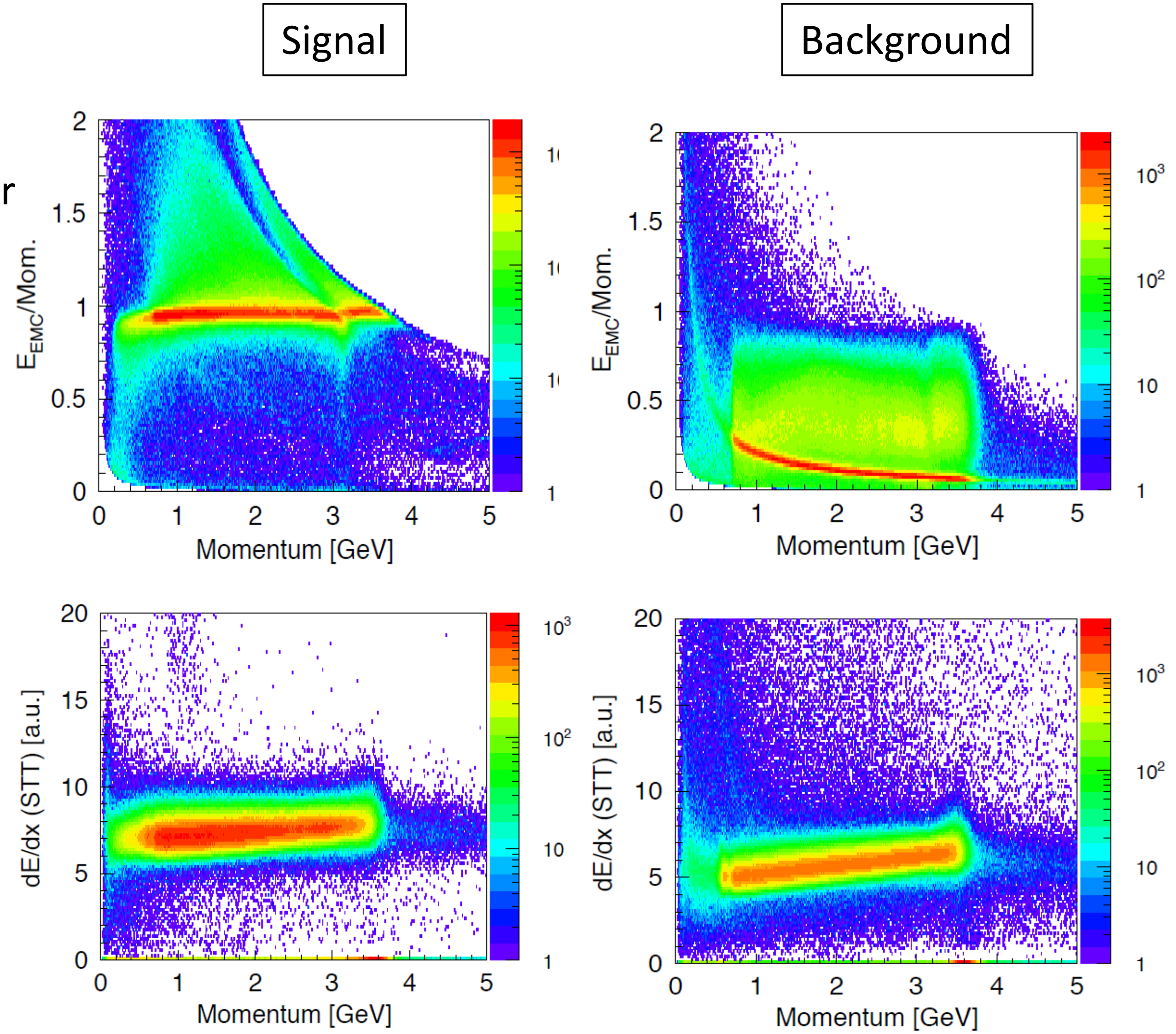
Standard chain of simulation and analysis in PANDARoot:



- One positive and one negative particle per event
- Best back to back pair in the CM is selected among all possible pairs (positive and negative particles) per event
- PID probabilities and kinematics cuts are applied to the selected events

Reconstructed PID variables

- Energy deposit , shower shape, . . . in the ElectroMagnetic Calorimeter
- Energy loss in the Straw Tube Tracker and Micro Vertex Detector
- Cherenkov angles (Cherenkov detectors DIRC)
- Other kinematical an PID variables



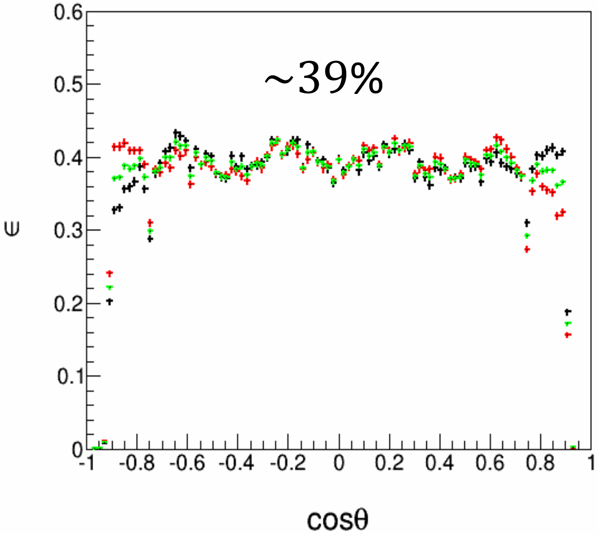
PID and kinematical Cuts

s $[\mathrm{GeV}^2]$	5.4	8.2	13.9
Total PID prob.	>99%	>99%	>99.9%
Individual PID_i prob.	EMC >0.3 STT >0.33 MVD>0.05	EMC >0.63 STT >0.37	EMC >0.06 STT >0.11
$\|\phi - \phi'\|$		[178°-185°]	[175°-185°]
Invariant mass [GeV]	>1.5		> 2.7
Background rejection factor	10^{-8}	10^{-8}	10^{-8}

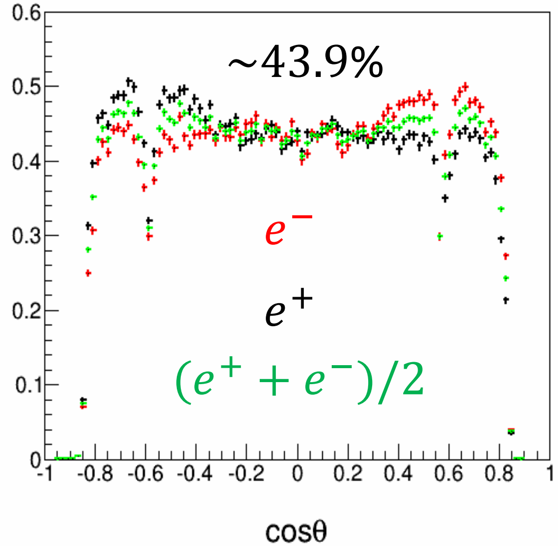
- PID --> probability for the detected particle to be identified as the signal.
- PID information are taken from EMC, STT, DIRC and MVD subdetectors.

ϵ= Selected events (e^+e^-) after the cuts/MC events (e^+e^-)

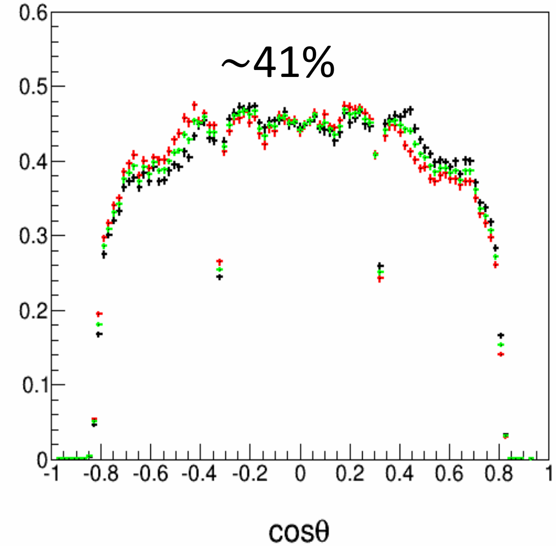
$s = 5.4\ \mathrm{GeV}^2$



$s = 8.2\ \mathrm{GeV}^2$



$s = 13.9\mathrm{GeV}^2$



Analysis for proton FF measurements is limited to the region cosθ = [-0.8,0.8] in the CM

From PHSP to physical angular distributions

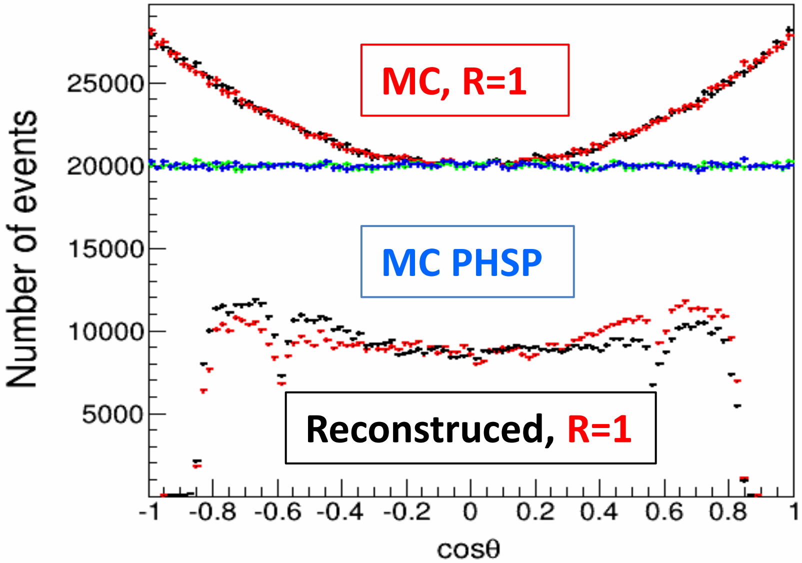
The differential cross section in the CM for $\bar{p}p \to e^+e^-$ is:

$$\frac{d\sigma}{d\cos\theta} = \sigma_0(1 + \mathcal{A}\cos^2\theta)$$

$$\begin{cases} \sigma_0 = \dfrac{d\sigma}{d\cos\theta}\left(\theta = \dfrac{\pi}{2}\right) \\ \mathcal{A} = \dfrac{\tau - R^2}{\tau + R^2}, R = |G_E|/|G_M|, \tau = \dfrac{s}{4M^2} \end{cases}$$

A. Zichichi et al., Nuovo Cim. 24 (1962) 170

E. Tomasi-Gustafsson and M.P. Rekalo, Phys.Lett. B504 (2001) 291-295



Monte Carlo events, PHSP

↓ $\times$ Weight: $1 + \mathcal{A}\cos^2\theta$

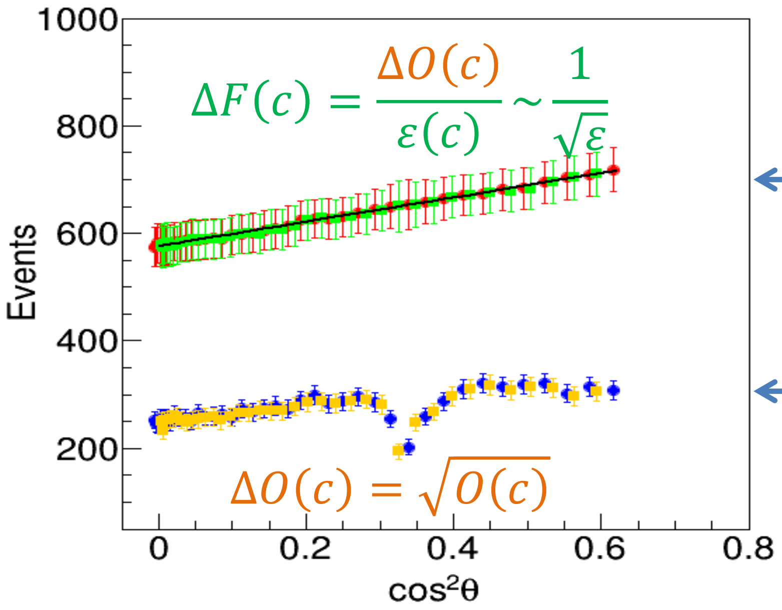
Physical Monte Carlo events

↓ $\times$ Efficiency $\epsilon(c)$

Physical reconstructed events

Efficiency correction and linear fit

$s = 8.2\ \text{GeV}^2$



- The observed events are corrected by the efficiency: $F(c) = \frac{O(c)}{\varepsilon(c)}$
- The events are normalized according to the expected counting rate: O(c)

➢ Linear fit to the signal ($\boldsymbol{e^+e^-}$) events as a function of $\cos^2\theta$

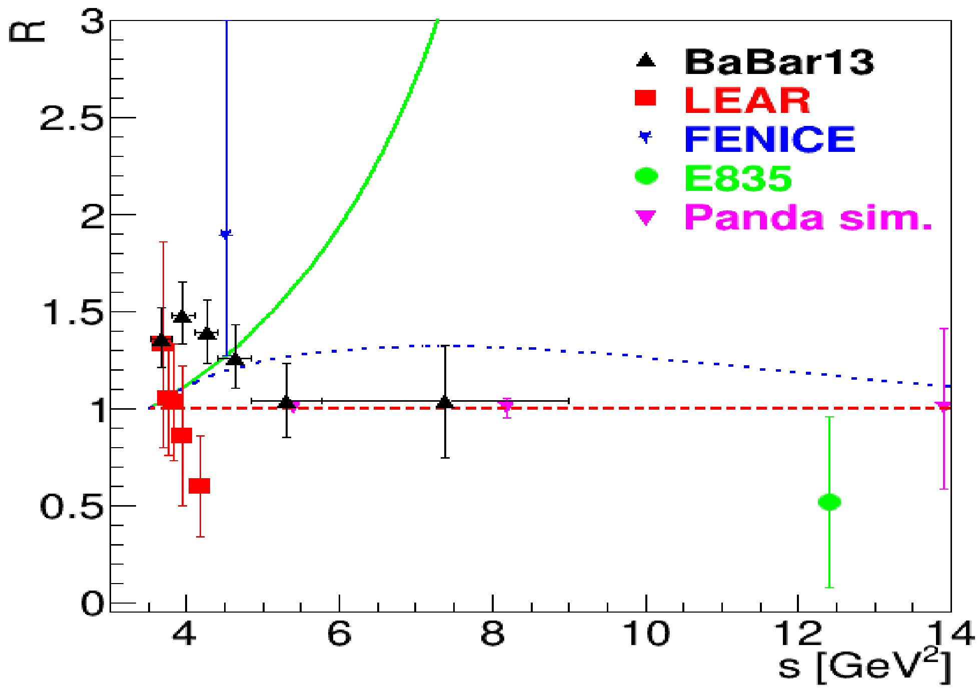
- Fit function: $y = a_0 + a_1 x,\ \ x = \cos^2\theta$
- The slope a_1 is related to $\mathcal{A}$
- Error on R through: $\mathcal{A} = \frac{\tau - R^2}{\tau + R^2} \rightarrow \Delta R = \frac{1}{R}\frac{\tau}{(1+\mathcal{A})^2}\Delta\mathcal{A}$

$$\frac{d\sigma}{d\cos\theta} = \sigma_0(1 + \mathcal{A}\cos^2\theta)$$

Results (R=1)

s [GeV^2]	$\mathcal{A}$	$\mathcal{A} \pm \Delta\mathcal{A}$	R	$R \pm \Delta R$
5.4	**0.21**	**0.217 ± 0.011**	**1**	**0.993 ± 0.011**
8.2	**0.4**	**0.393 ± 0.041**	**1**	**1.007 ± 0.049**
13.9	**0.59**	**0.588 ± 0.268**	**1**	**1.01 ± 0.415**

The **extracted values** are compatible with the **Monte Carlo input**



F. Iachello et al., Phys. Rev. C 69 (2004) 055204

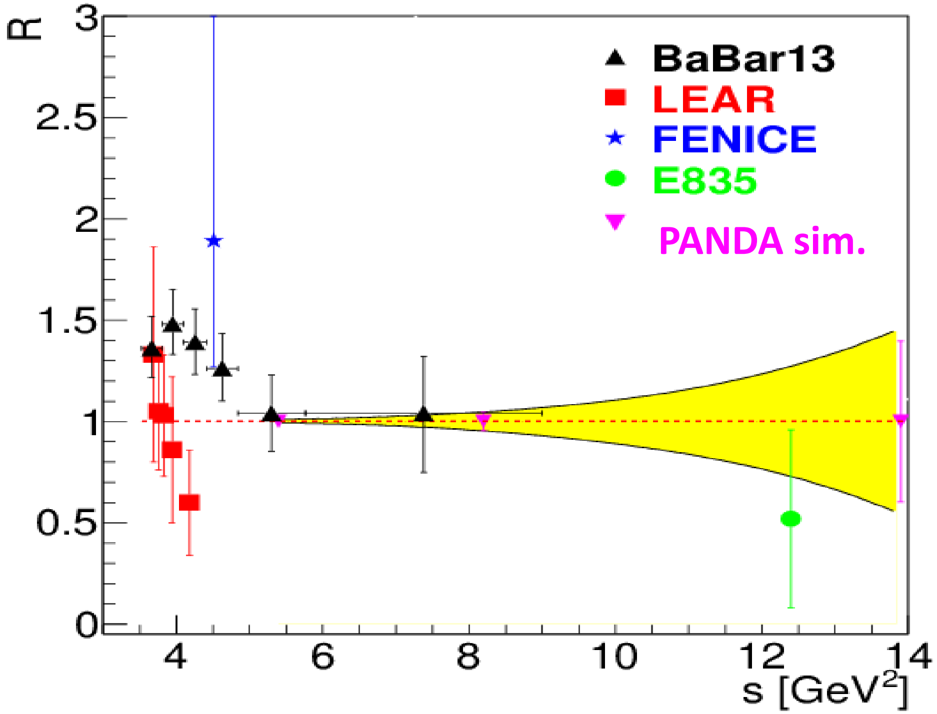
E. L. Lomon, Phys. Rev. C 66 (2002) 045501

E. Tomasi-Gustafsson et al., Eur. Phys. J. A 24, 419 (2005)

V. A. Matveev, S. J. Brodsky , D. V. Shirkov….

Comparison with previous simulations

s [GeV^2]	$R \pm \Delta R$	$R \pm \Delta R$ (new simulation)
5.4	**0.992 ± 0.009**	**0.993 ± 0.011**
8.2	**0.997 ± 0.045**	**1.007 ± 0.049**
13.9	**1 ± 0.396**	**1.01 ± 0.415**



- New version of PANDARoot
- More background events have been generated

Expected statistical precision using the **BaBar** framework for R=1.
[M. Sudol *et al*. EPJ A44, 373 (2010)]

Points under investigation

- Determination of the statistical errors on the individual proton form factors
- Efficiency extrapolation and effective form factor determination at large energies
- Second analysis done by Dmitry khaneft (HIM Mainz) :
  - Different event generator for the signal
  - Different PID and kinematical cuts
  - Different fit functions (study of the correlation matrix elements)
- Radiative corrections to the annihilation reactions $\boldsymbol{\bar{p}p} \rightarrow \boldsymbol{e^+e^-}$
  - Event generator for PANDA
  - Simulation and analysis studies:
    effect of radiative correction on the proton form factors

Conclusions

- Feasibility studies (PANDARoot) for measuring proton TL EM FFs at PANDA:
  - Three values of the momentum transfer squared are considered q^2 = s = **5.4**, **8.2** and **13.9** GeV^2
  - The suppression of the main background at the order of $\mathbf{10^{-8}}$ is achieved keeping sufficient signal efficiency
  - The proton FF ratio can be measured at PANDA with unprecedented statistical accuracy

Thank you for your attention

PID and kinematical Cuts

Previous simulations

s $[\mathrm{GeV}^2]$	5.4	8.2	13.9
Total PID prob.	>99%	>99%	>99.9%
Individual PID_i prob.	>5%	>5%	>6%
Number of fired crystals in the EMC	>5	>5	>5
$(\theta + \theta')$ [CMS]	[178°-182°]	[178°-182°]	[175°-185°]
$\lvert\phi - \phi'\rvert$	[178°-182°]	[178°-182°]	[175°-185°]
Invariant mass [GeV]	No cut	> 2.14 GeV	> 2.5 GeV
Background [Events]	0	0	0

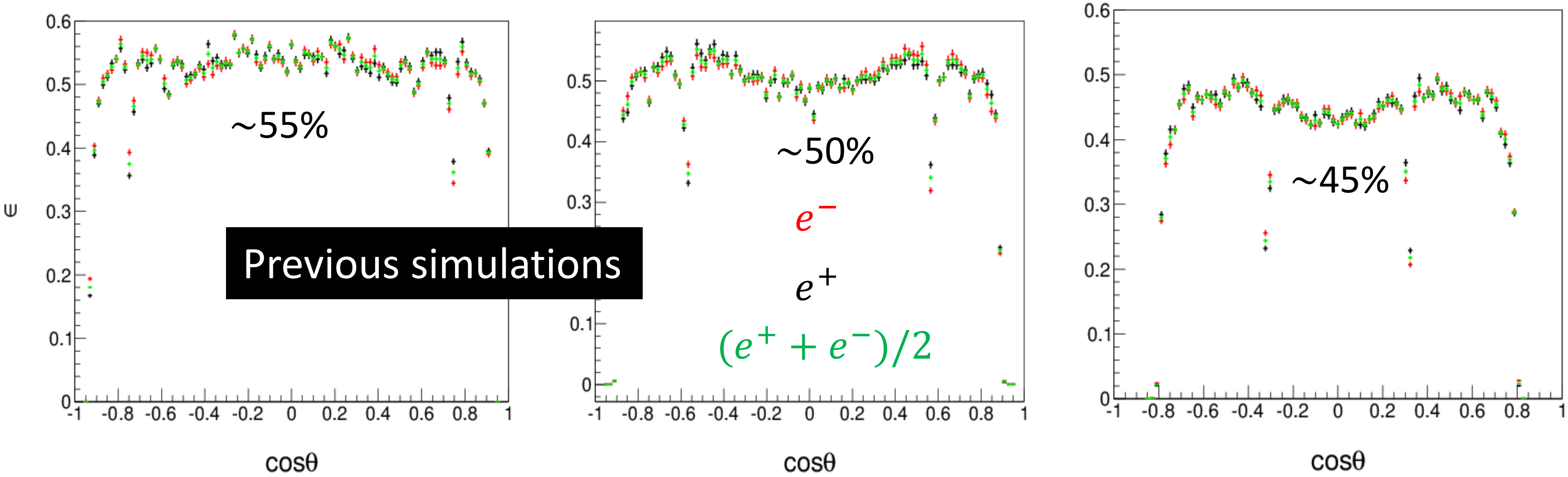
- PID --> probability for the detected particle to be identified as the signal.
- PID information are taken from EMC, STT, DIRC and MVD subdetectors.

Signal efficiency after background suppression

ϵ= Selected events (e^+e^-) after the cuts/MC events (e^+e^-)

Previous simulations

$s = 5.4\ \text{GeV}^2$ $s = 8.2\ \text{GeV}^2$ $s = 13.9\text{GeV}^2$

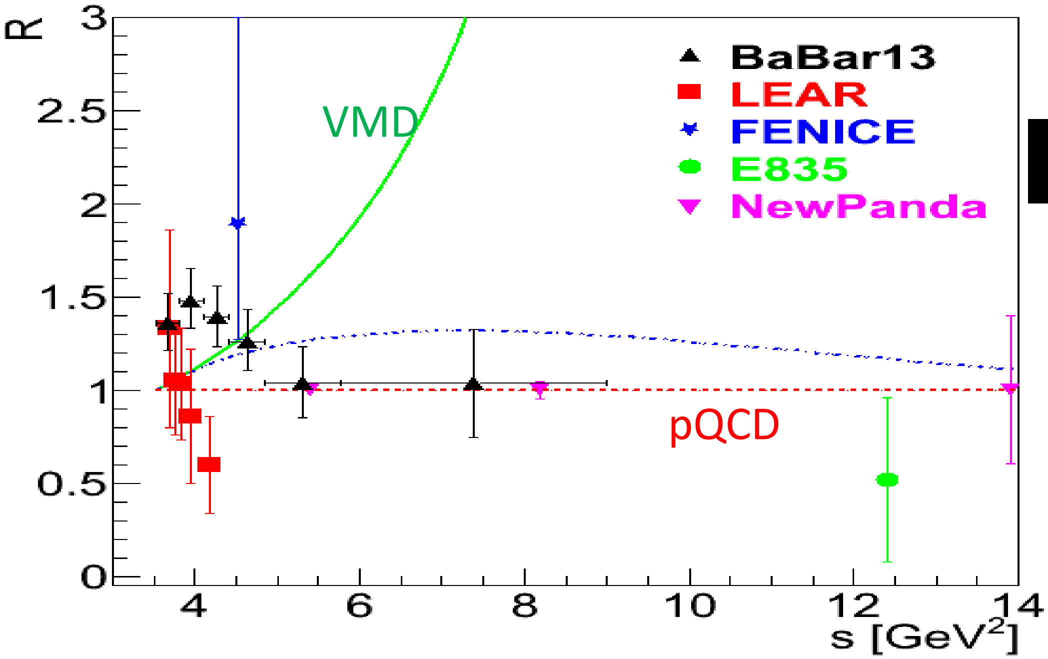


Analysis for proton FF measurements is limited to the region cosθ = [-0.8,0.8] in the CM

Results:

s [GeV^2]	$\mathcal{A}$	$\mathcal{A} \pm \Delta\mathcal{A}$	R	$R \pm \Delta R$
5.4	0.21	0.218 ± 0.009	1	0.992 ± 0.009
8.2	0.4	0.401 ± 0.038	1	0.997 ± 0.045
13.9	0.59	0.595 ± 0.255	1	1 ± 0.396

The extracted values are compatible with the Monte Carlo input



Previous simulations

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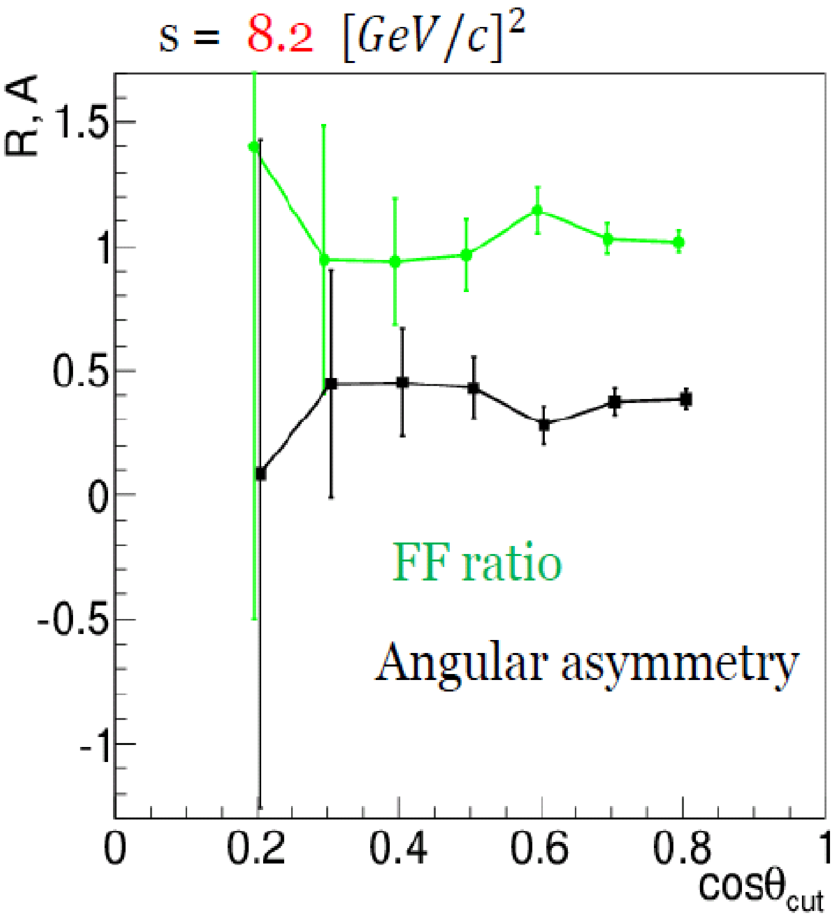
Effect of the angular cut

Previous simulations



Experimental data on **R** have been extracted in the region of $|\cos\theta|<0.8$:

Small effect of the angular cut

M. Ambrogiani et al., PRD 60 (1999)
Bardin NPB 411 (1994)

$\cos\theta_{cut}$	0.8	0.6
ΔR	0.045	0.092