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

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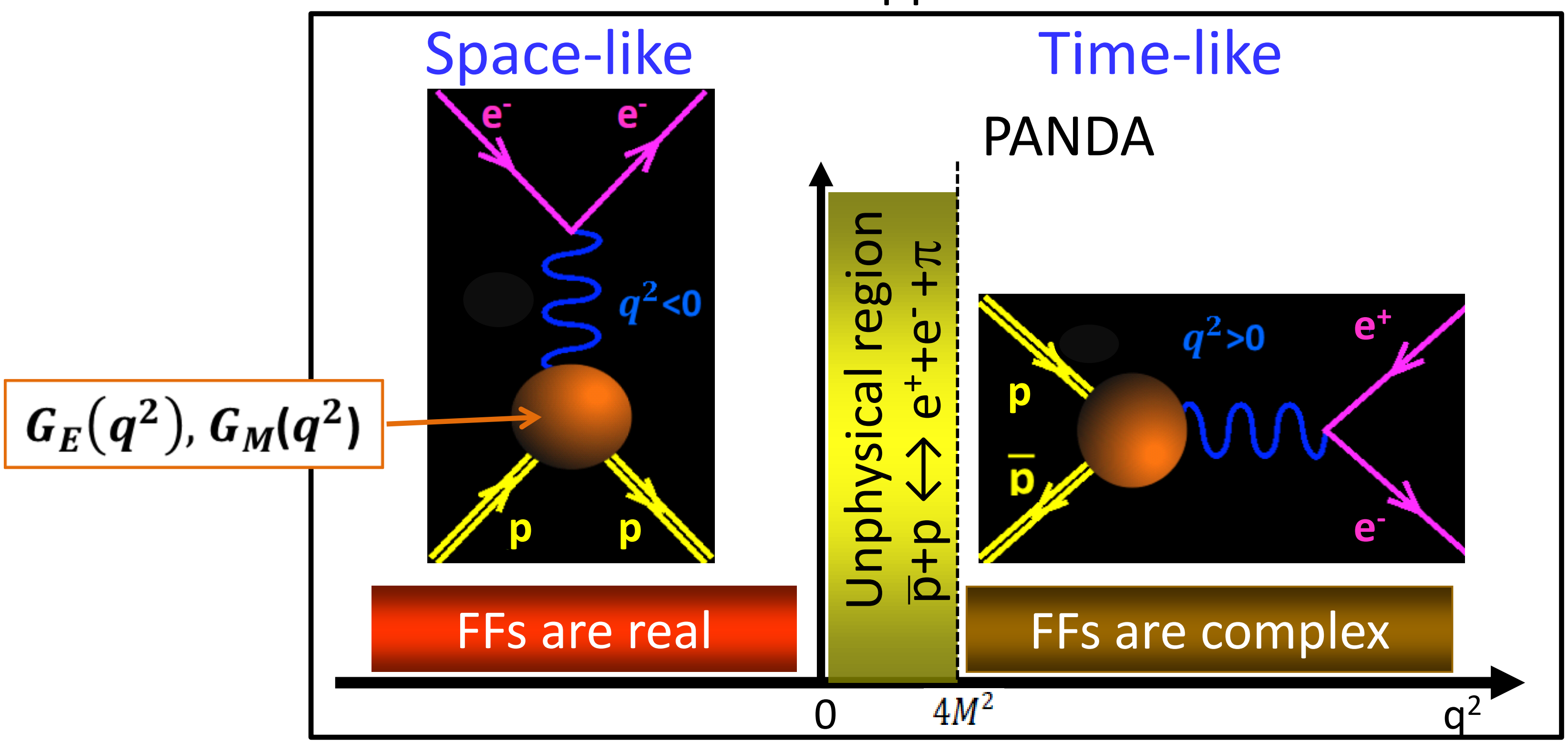
Electromagnetic form factors

- 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



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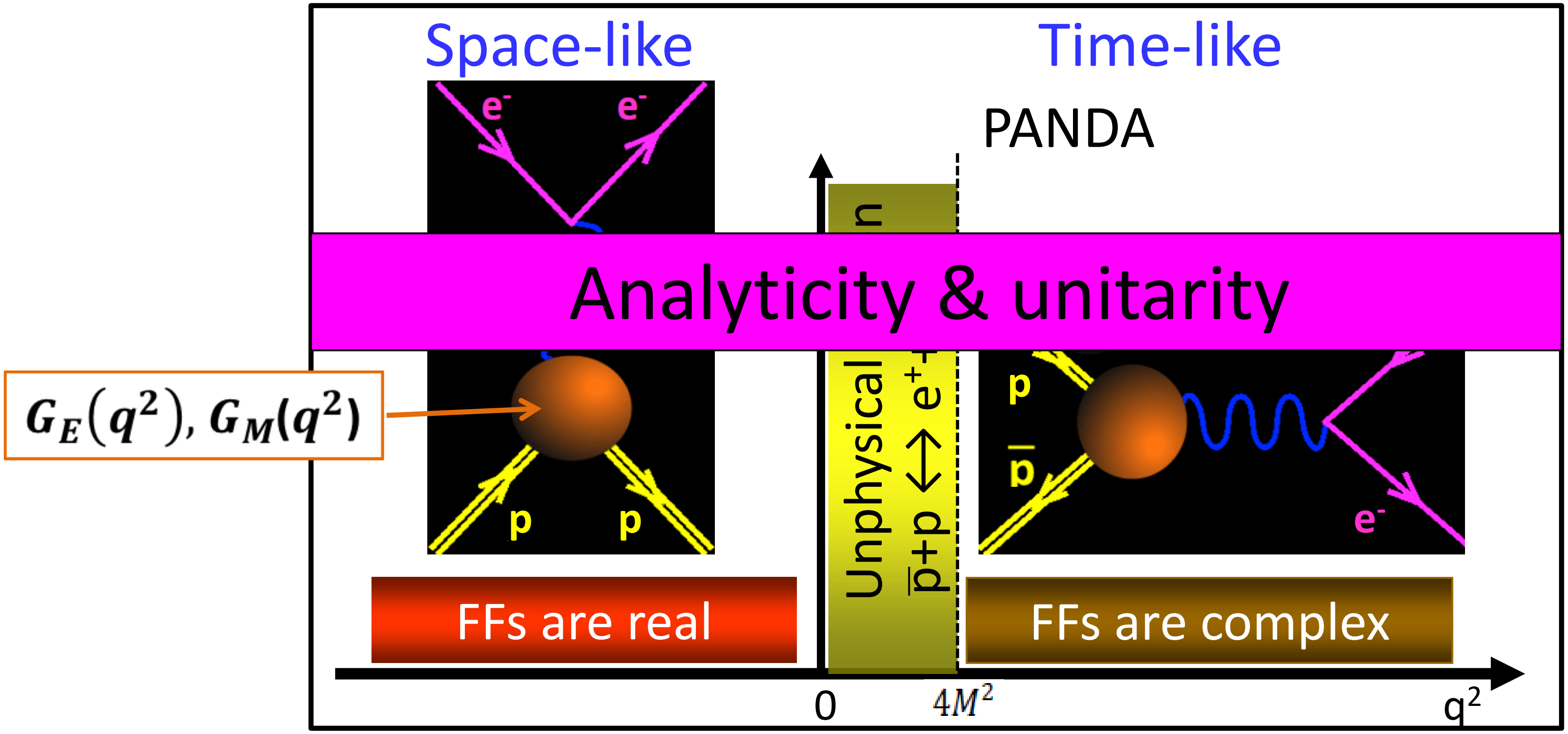
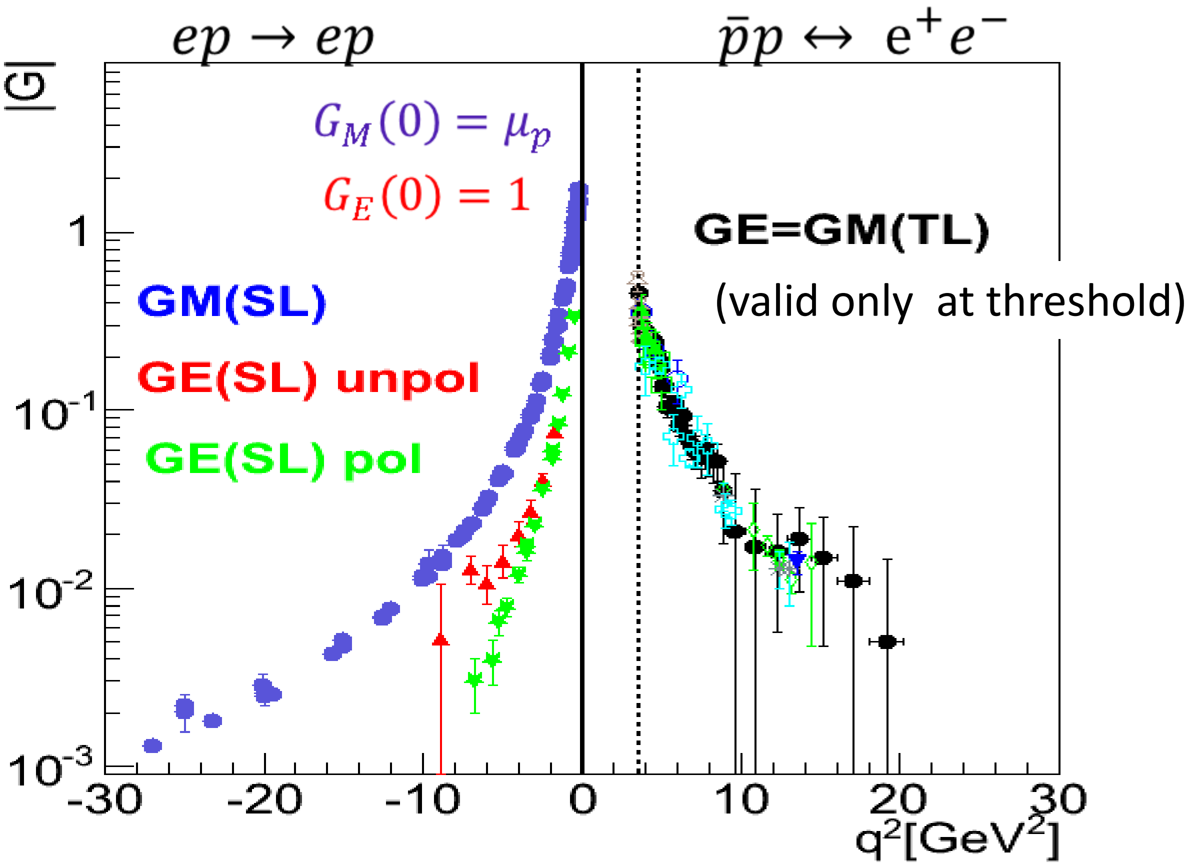


Electromagnetic form factors of the proton



- 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

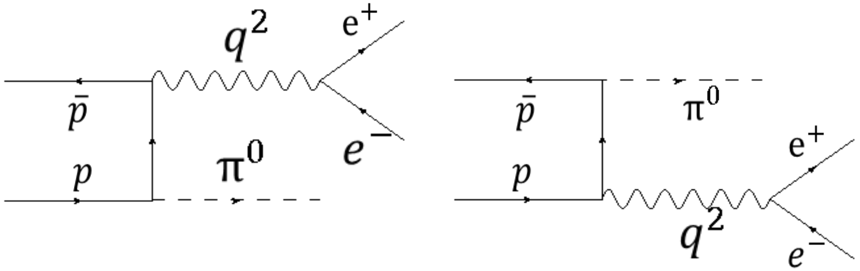
Measurement of TL proton FFs at PANDA: Goals

- 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 $|G_M|$

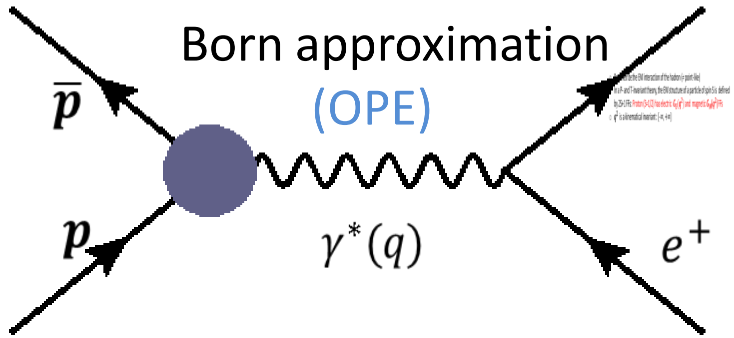
- Possibility to access the relative phase of proton TL FFs
  - $\bar{p}p \rightarrow e^+e^-$ in the **Born approximation:**
    - The unpolarized cross section gives access to $|G_E|$ and $|G_M|$
    - Polarization observables give access to $G_E G_M{}^*$

- 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
C. Adamuscin, E.A. Kuraev, G. I. Gakh, …
Feasibility studies (J. Boucher, M. C. Mora-Espi PhD)

Time-Like proton FF measurements at PANDA



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

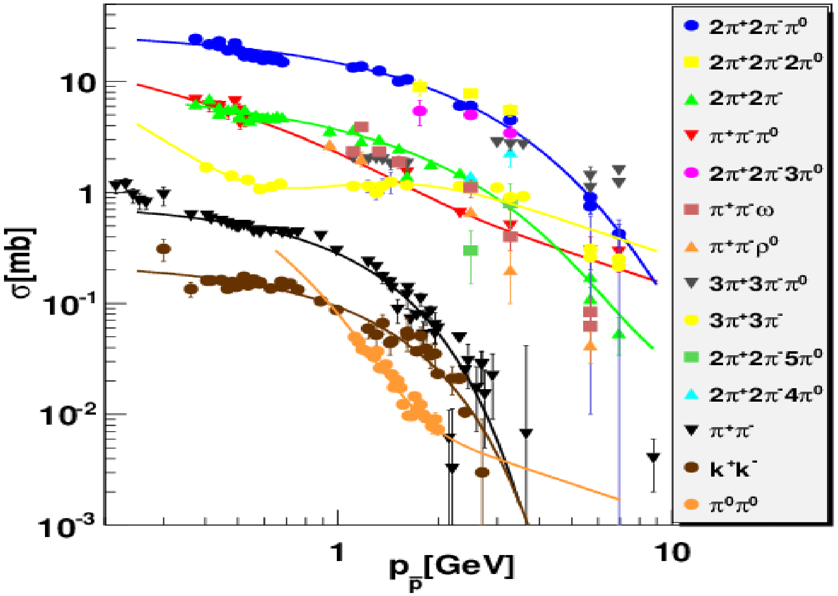
$$= \mathcal{N}|G_M|^2[(1+\cos^2\theta) + \frac{4M^2}{s}\sin^2\theta\ R^2]$$

θ is the electron scattering angle, $R=|G_E|/|G_M|$
and $\mathcal{N}$ is a normalization factor.

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

TL proton FF measurements at PANDA: background study

- Main issue: signal identification from the huge hadronic background
- The signal is $\bar{p}p \rightarrow e^+e^-$ and the main background is $\bar{p}p \rightarrow \pi^+\pi^-$
  - 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 of the order of 10^{-8} is required ***at the simulation level***

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 main **background ($\bar{p}p \rightarrow \pi^{+}\pi^{-}$) 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 GRID of IPNO, PANDA and GSI batch farms. (from April to June 2013)

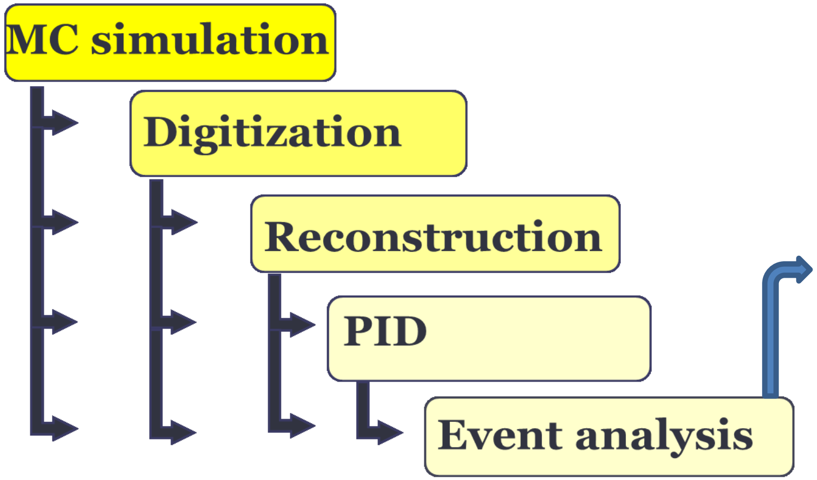
Description of the simulation

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 ($\bar{p}p \rightarrow e^+e^-$)	10^6	10^6	10^6
Events ($\bar{p}p \rightarrow \pi^+\pi^-$)	10^8	10^8	10^8

- PHSP (PHase SPace) model
  - $\bar{p}p \rightarrow e^+e^-$
  - $\bar{p}p \rightarrow \pi^+\pi^-$
- Full range in **θ** and **ϕ** angles

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

PID and kinematical Cuts

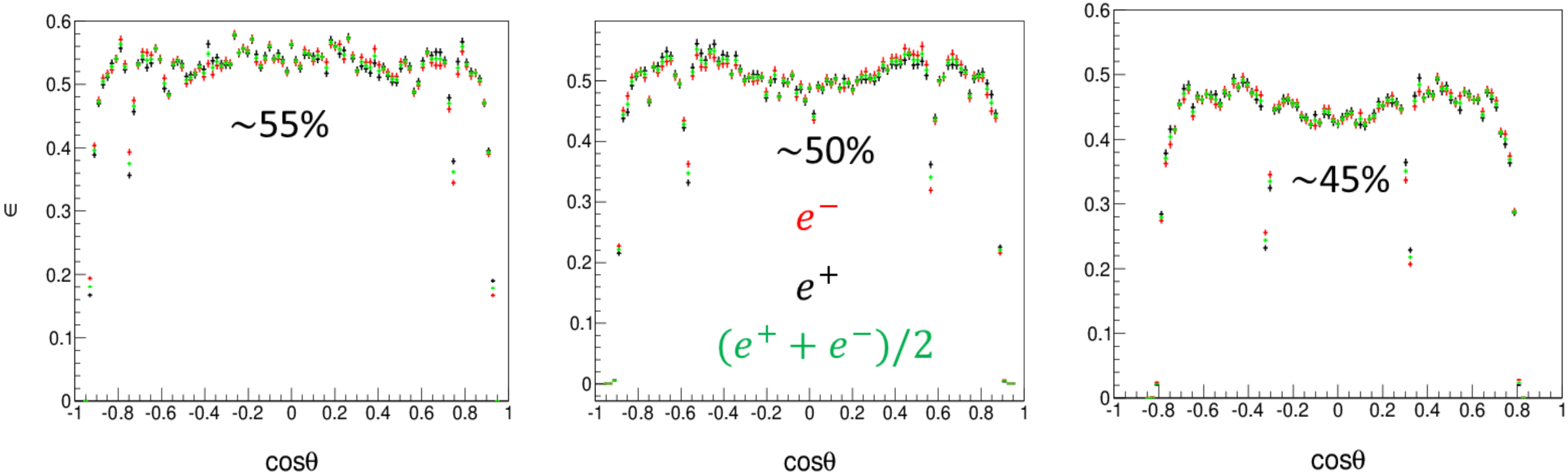
s [GeV^2]	5.4	8.2	13.9
Total PID prob.	>99%	>99%	>99.9%
Individual PID_i prob.	>5%	>5%	>6%
Number of fired crystals in the EMC	>5	>5	>5
$(\theta + \theta')$ [CMS]	[178°-182°]	[178°-182°]	[175°-185°]
$\vert\phi - \phi'\vert$	[178°-182°]	[178°-182°]	[175°-185°]
Invariant mass [GeV]	No cut	> 2.14 GeV	>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

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



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

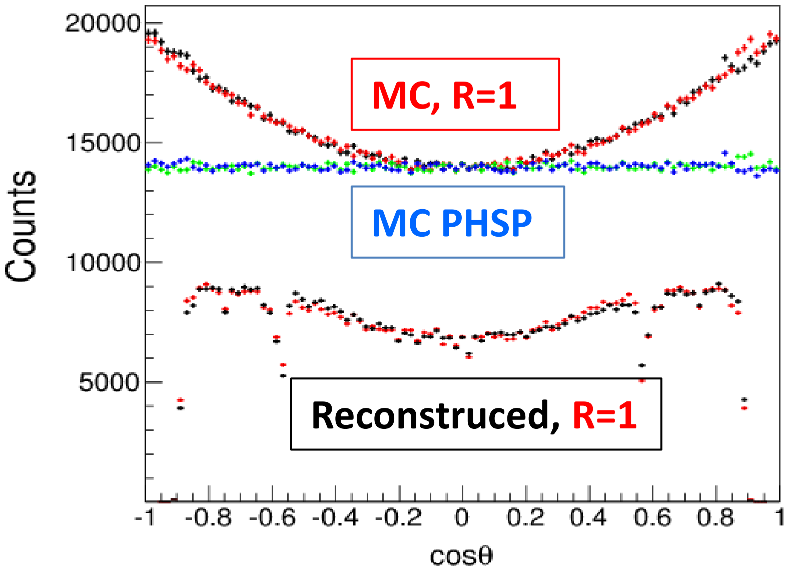
$$\frac{d\sigma}{d\cos\theta} = \sigma_0(1 + \mathcal{A}\cos^2\theta)$$

$$\sigma_0 = \frac{d\sigma}{d\cos\theta}\left(\theta = \frac{\pi}{2}\right)$$

$$\mathcal{A} = \frac{\tau - R^2}{\tau + R^2},\ R = |G_E|/|G_M|,\ \tau = \frac{s}{4M^2}$$

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

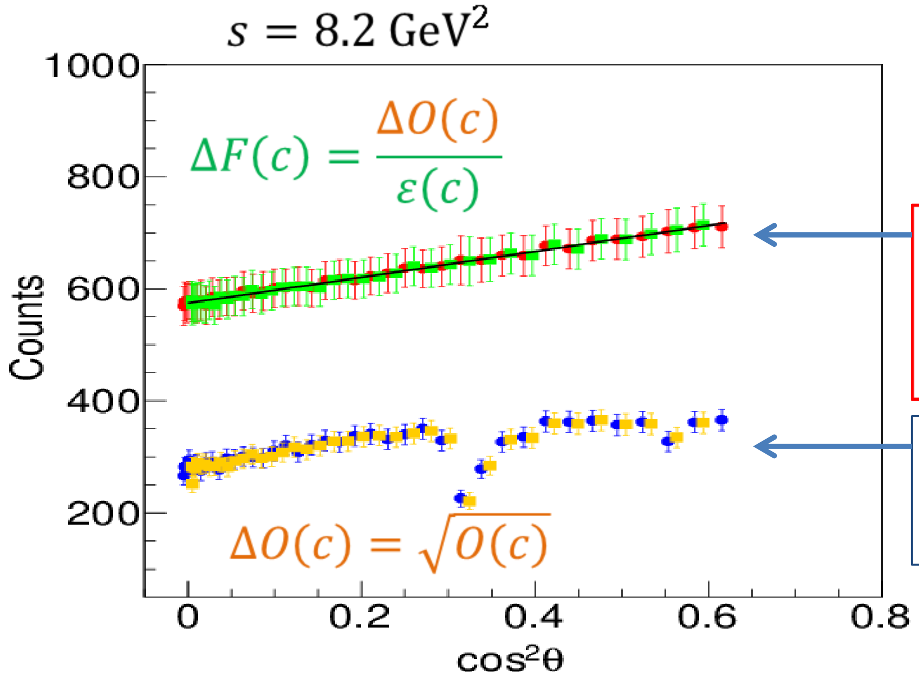
$\times$ Weight: $1 + \mathcal{A}\cos^2\theta$

Physical Monte Carlo events

$\times$ Efficiency $\epsilon(c)$

Physical reconstructed events

Efficiency correction and linear fit



- 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 $\cos^2\theta$

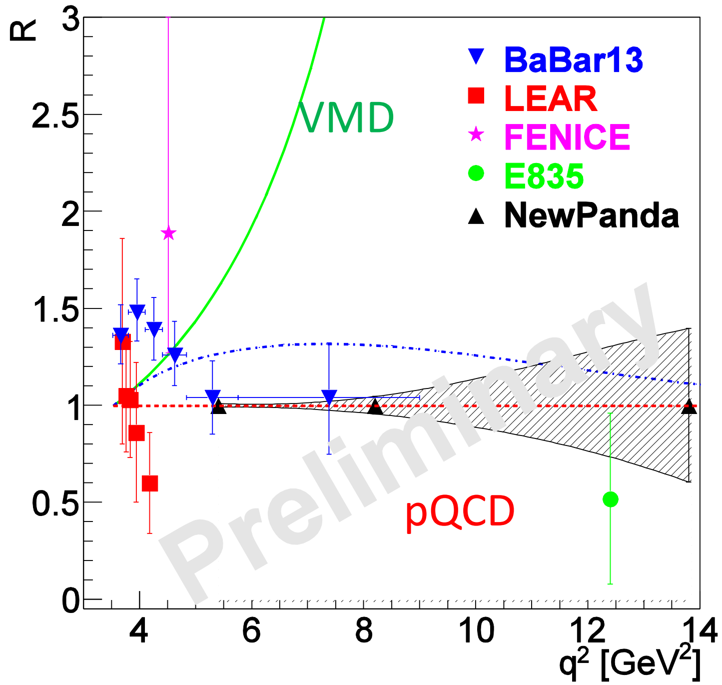
- Fit function: y=$a_0 + a_1 x,\ x = \cos^2\theta$
- The slope a_1 is related to $\mathcal{A}$
- Error on R through: $\mathcal{A} = \frac{\tau - R^2}{\tau + R^2}$

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

Results (R=1)

s [GeV^2]	$\mathcal{A}$	$\mathcal{A} \pm \Delta\mathcal{A}$	R	$R \pm \Delta R$
5.4	0.21	0.218 ± 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



E. Tomasi-Gustafsson et al., INPC 2013

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

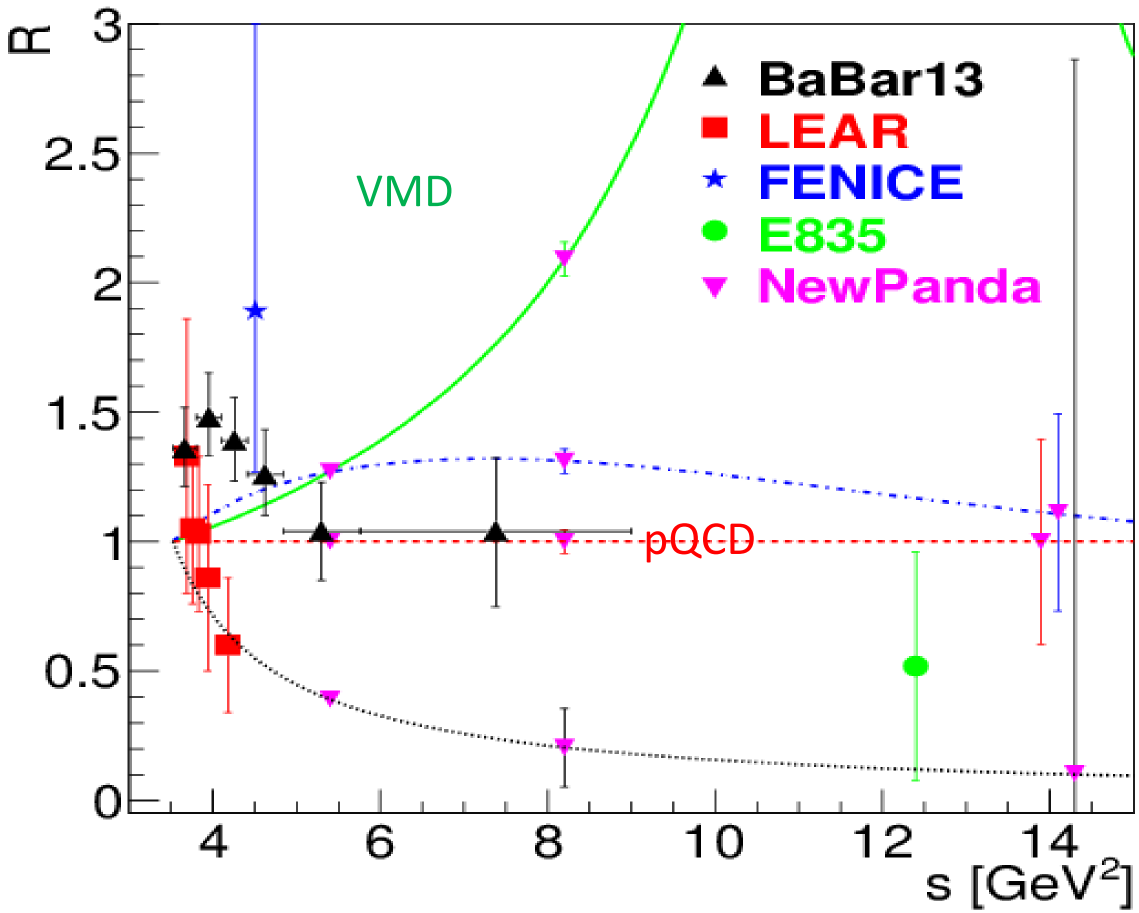
F. Iachello et al., Phys. Rev. C 69 (2004) 055204

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….

Results ($R<1$, $R=1$, $R>1$)



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

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

E. A. Kuraev et al., Phys. Lett. B 712, (2012)

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

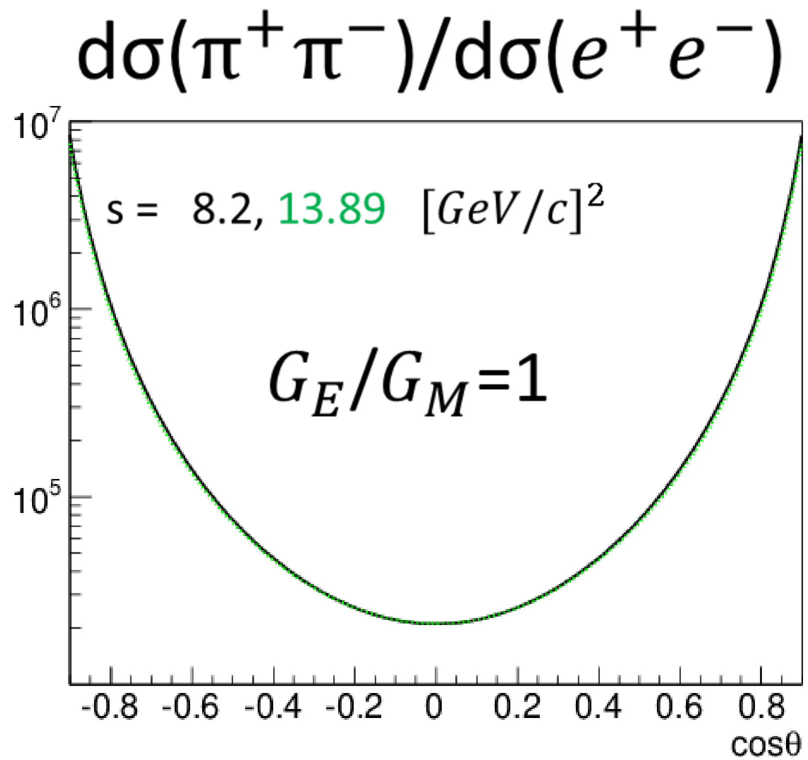
Effect of the angular cut

The rejection power of the background should be effective in each bin of the angular distribution

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

$\cos\Theta = \pm 0.8$

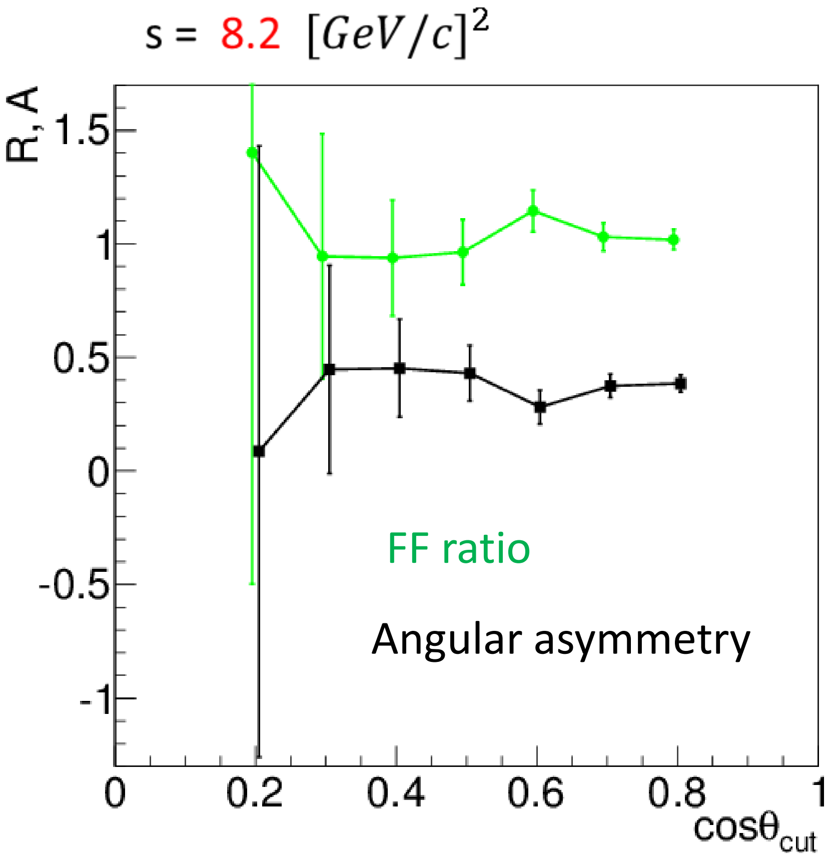
$$\frac{d\sigma(\pi^+\pi^-)}{d\sigma(e^+e^-)} \sim 10^6$$



Differential cross section for the pions

J. Van de Wiele *et al.*, EPJ A46 (2010) 291

Effect of the angular cut



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

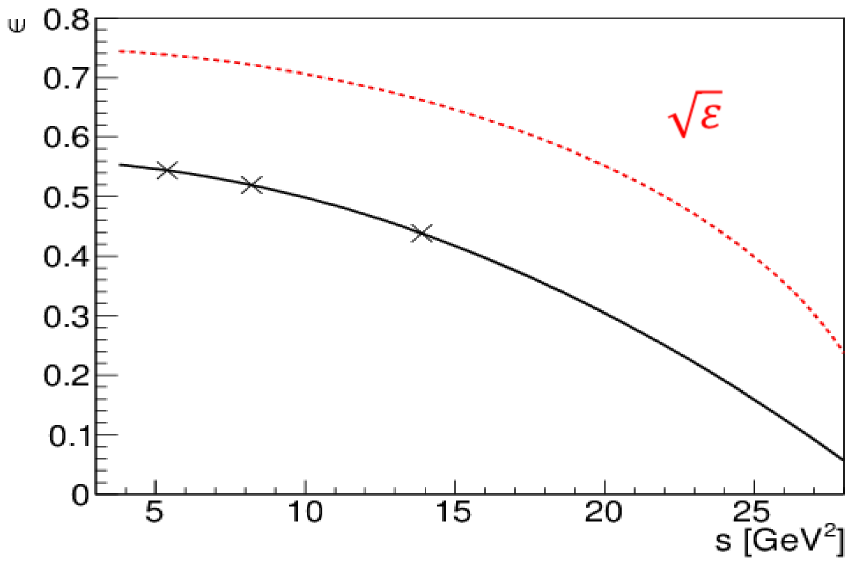
Generalized proton form factor: efficiency extrapolation

- Total cross section for $\bar{p}p \rightarrow e^+e^-$ ($|G_E| = |G_M| = |G_{eff}|$):

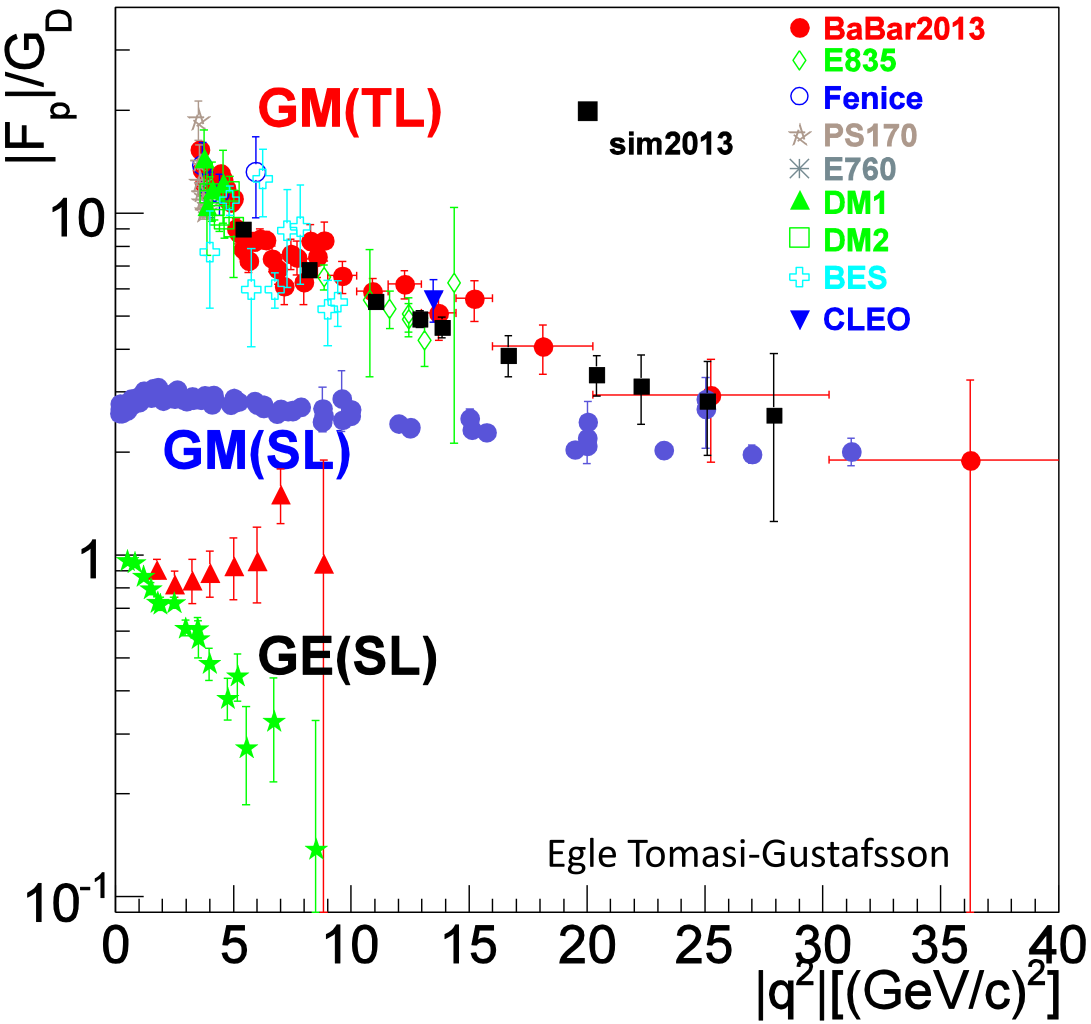
$$\sigma = \frac{\pi(\alpha_{em}\hbar c)^2}{6M_p^2}\frac{(2\tau+1)|G_{eff}|^2}{\tau\sqrt{\tau(\tau-1)}}.$$

- Experimental statistical error $\sim \frac{1}{\sqrt{\varepsilon}}$

- Integrated signal efficiency ($|\cos\Theta| \leq 0.8$):



Generalized time-like proton form factor



Asymptotics:
$q^2 > 30$ GeV^2

Conclusions & perspectives

- Measurement of the proton FF ratio through $\bar{p}p \rightarrow e^+e^-$ 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 extracted at PANDA with unprecedented statistical accuracy

- **Perspectives**

- Feasibility studies for $\bar{p}p \rightarrow \mu^+\mu^-$, $\bar{p}p \rightarrow e^+e^-\pi^0$ measurement at the PANDA experiment including recent model improvement
- Radiative corrections to the annihilation reactions $\boldsymbol{\bar{p}p \rightarrow e^+e^-}$:
  - Event generator for PANDA
  - Simulation and analysis studies:
    effect of radiative correction on the proton form factors

Thank you for your attention