Experimental observables in $\bar{p}p$ decay into two heavy leptons

Measurements of the electromagnetic form factors of the proton

at

"PANDA Experiment"

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FAIR, Facility for Antiproton and Ion Research Darmstadt, Germany

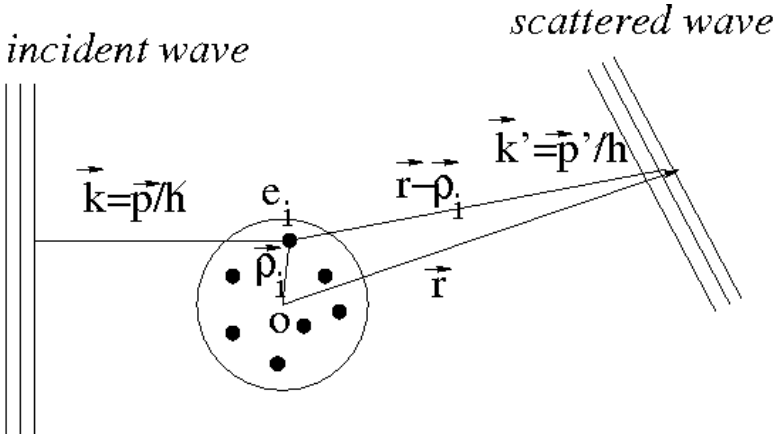
Ion species	Antiprotons
$\bar{p}$ production rate	$2\ 10^7\ s^{-1}$ ($1.2\ 10^{10}$ per 10 min)
Momentum range	1.5 to 15 GeV/c

FAIR: New facility

- heavy ion physics & nuclear structure
- atomic, plasma and applied physics
- higher intensities & energies
- **antiproton physics**

Non-point-like nature of the proton

- 1933 O. Stern observed that the proton magnetic moment is 2.8 times higher than the expected for a point-like particle.
- 1950 Rosenbluth introduced the concept of the form factors for composite targets.



The total scattered amplitude is the sum of the amplitudes on the individual charges ($A = \sum_i A_i$):

$$\frac{d\sigma}{d\Omega} = (\frac{d\sigma}{d\Omega})_{pl}|F(\vec{q})|^2, \quad F(\vec{q}) \sim \sum_i e_i e^{iq\cdot\vec{\rho}_i}$$

$\vec{\rho}_i$: position operators of internal motion in the target.

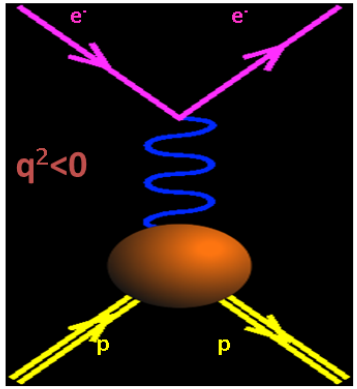
$F(\vec{q})$ is the charge form factor

Electromagnetic Form Factors (FFs)

- Two independent FFs for spin 1/2 particles (2S+1).
- G_M and G_E describe the charge and the magnet distribution of the proton.

Space-like

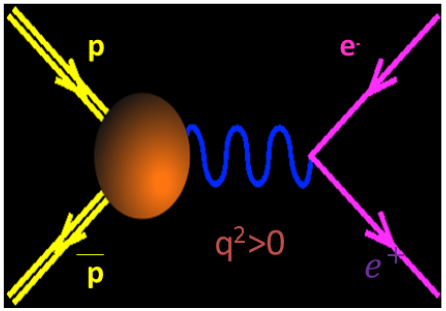
e+p → e+p



FFs are real

Time-like

$\bar{p}$ +p ↔ e⁺+e⁻



FFs are complex

- G_M and G_E parametrize the vertex $pp\gamma$ and $\bar{p}p\gamma$.
- G_M and G_E are complex function of $s = q^2$ only (Born approximation).
- G_M and G_E preserve the symmetries of the theory (real functions in space-like and complex in time-like region).

Time-like Electromagnetic FFs with $\bar{p}p \to e^+e^-$

- **Cross section (Born approximation)**

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

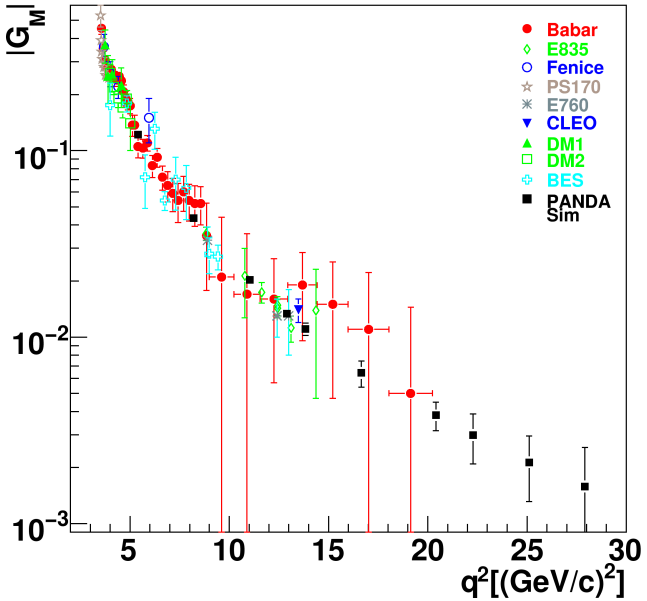


Figure: Experimental data of effective FFs from different experiments at different energies.

- Due to the low statistics in the experiments, FFs are measured under the Hypothesis:

$$|G_M| = |G_E|$$

Generalization to heavy lepton production

Investigation of new electromagnetic channels with PANDA.

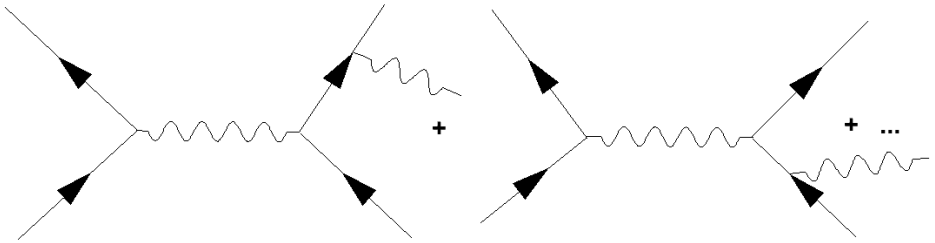
$$\bar{p}p \to e^+e^-, \bar{p}p \to \mu^+\mu^-, \bar{p}p \to \tau^+\tau^-$$

Figure: Proton-antiProton ANnihilation at DArmstadt

- Mass of electron ($m_e = 0.51$ MeV.c^{-2}) can be neglected.
- Mass of muon ($m_\mu = 105.6$ MeV.c^{-2}) can not be neglected at moderate energies (MeV range).
- Mass of tau ($m_\tau = 1777$ MeV.c^{-2}) larger than the mass of proton, can not be neglected at all energies.

Heavy leptons production: advantages

- The radiative corrections are suppressed by the mass of heavy leptons.

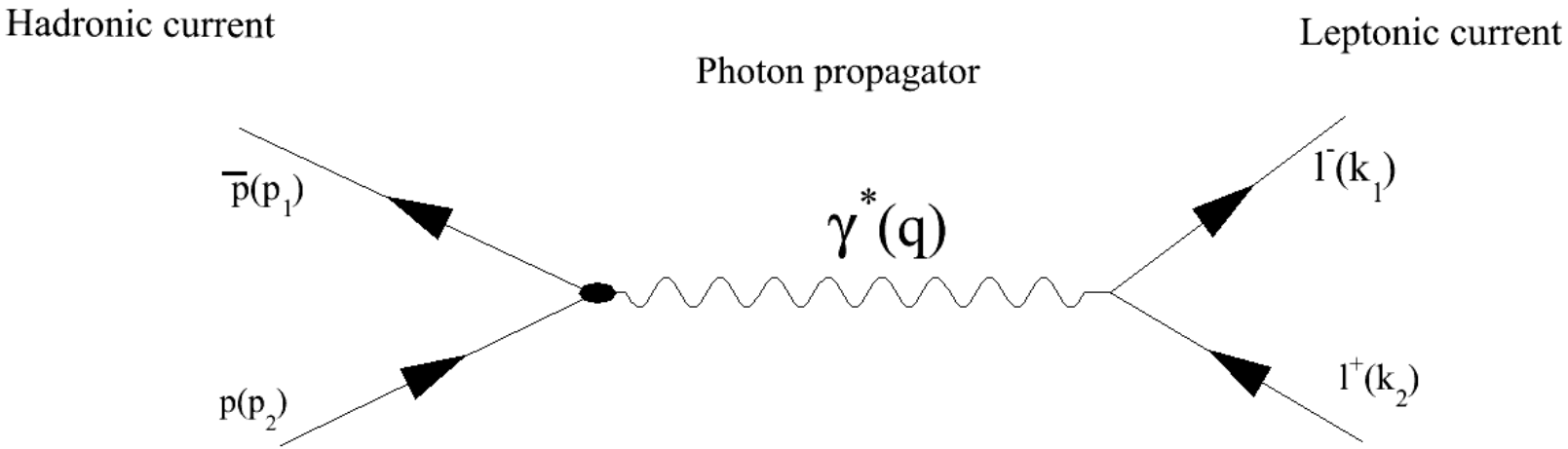


- The polarization of instable particles (μ [2.197×10^{-6}s] and τ [290.6×10^{-15}s]) can be measured through the angular distribution of their (weak) decay products.

- Enhancement of transverse polarization observables.

Starting point: Matrix element

$$\mathcal{M} = -J_\mu \frac{e^2}{q^2} j_\mu$$



$$J_\mu = \bar{v}(p_1)\left[G_M \gamma_\mu + \frac{P_\mu}{M}\frac{G_M - G_E}{1-\eta_p}\right]u(p_2)$$

$$j_\mu = \bar{u}(k_1)\,\gamma_\mu\, v(k_2)$$

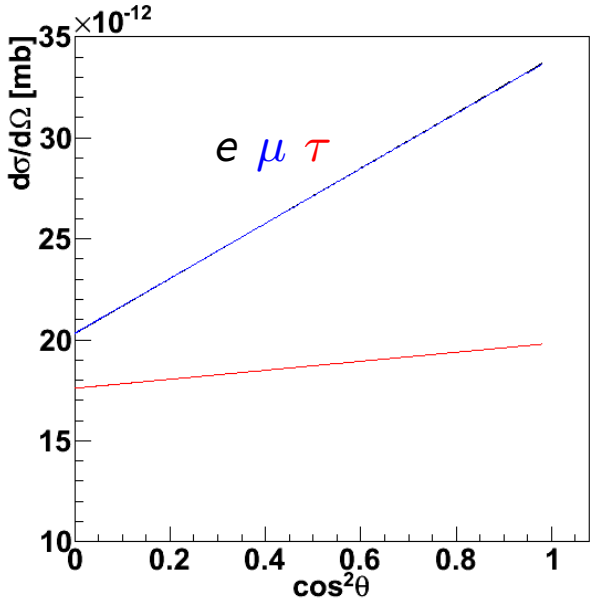
$q = k_1 + k_2 = p_1 + p_2$, $\eta_p = q^2/(4M^2)$, M=mass of proton.

Differential cross section (CM)

Experimental observable to measure the modulus of proton FFs.

$$\frac{d\sigma}{d\cos\theta} = \frac{\overline{|\mathcal{M}|^2}\left|\vec{k}\right|}{32\pi s\,|\vec{p}|} \sim \frac{|G_E|^2}{\eta_p}(1-\beta_\ell^2\cos^2\theta) + |G_M|^2(2-\beta_\ell^2\sin^2\theta)$$

$$d\sigma/d\cos\theta = \sigma_0(1+\mathcal{A}\cos^2\theta),\ \ \sigma_0 \ \textit{and}\ \mathcal{A} = f(|G_M|, |G_E|, m_\ell)$$



- The intercept σ_0 and the slope $\mathcal{A}$ depend on the mass of the leptons.

Total cross section

$$R_\ell = \frac{\sigma(\ell^+\ell^-)}{\sigma(e^+e^-)} = \frac{1}{2}\beta_\ell(3-\beta_\ell^2), \quad \beta_\ell^2 = 1 - 4m_\ell/s;$$

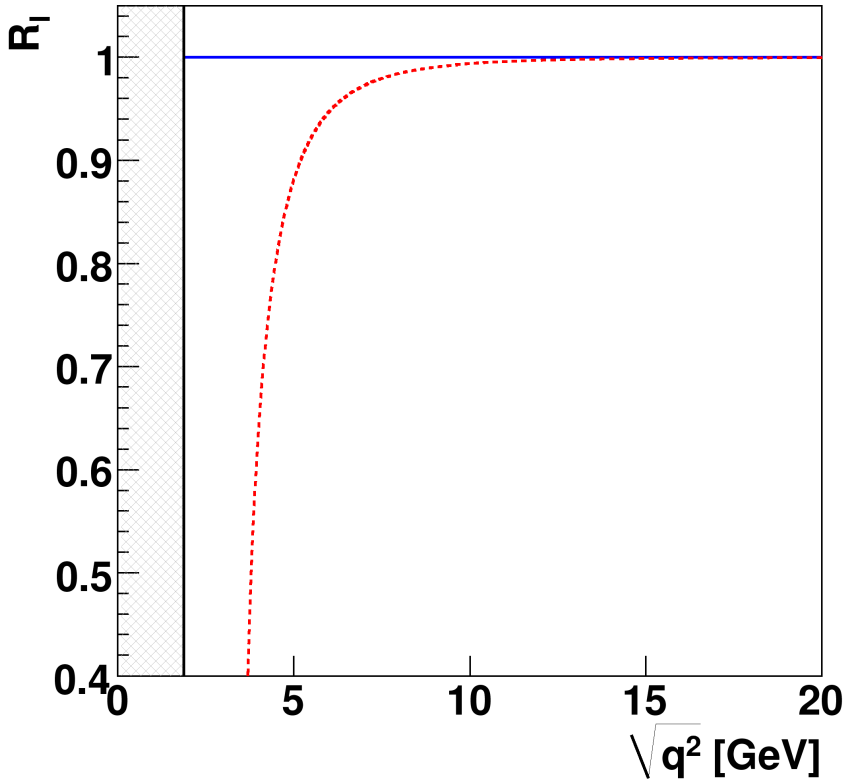


Figure: Cross section ratios $R = \frac{\sigma(\ell^+\ell^-)}{\sigma(e^+e^-)}$, for $\ell = \tau$ (red line) and $\ell = \mu$ (blue line) .

Polarization Phenomena

Polarized cross sections give access to the relative phase of G_M and G_E.

Polarization Phenomena

In the relativistic approach:

$\rho = u(p)\bar{u}(p)$	particle	antiparticle
unpolarized	$\hat{p} + M$	$\hat{p} - M$
polarized	$(\hat{p} + M)\frac{1}{2}(1 - \gamma_5 \hat{s})$	$(\hat{p} - M)\frac{1}{2}(1 - \gamma_5 \hat{s})$

$$s_i^0 = \frac{\vec{p}_i \cdot \vec{\chi}_i}{m_i}, \ \vec{s}_i = \vec{\chi}_i + \frac{\vec{p}_i \cdot \vec{\chi}_i \vec{p}_i}{m_i(E_i + m_i)}$$

$\vec{\chi}_i$ is the direction of the spin particle in its rest frame

General form of hadronic and leptonic tensors:

$$H_{\mu\nu} = J_\mu J_\nu^* = H_{\mu\nu}^{(0)} + H_{\mu\nu}^{(1)}(s_1) + H_{\mu\nu}^{(1)}(s_2) + H_{\mu\nu}^{(2)}(s_1, s_2).$$

$$L_{\mu\nu} = j_\mu j_\nu^* = L_{\mu\nu}^{(0)} + L_{\mu\nu}^{(1)}(s_a) + L_{\mu\nu}^{(1)}(s_b) + L_{\mu\nu}^{(2)}(s_a, s_b).$$

Single Spin observable

Polarized antiproton beam

$$H_{\mu\nu} = H^{(0)}_{\mu\nu} + H^{(1)}_{\mu\nu}(s_1), \quad L_{\mu\nu} = L^{(0)}_{\mu\nu}$$

Polarized cross section:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s^3}\frac{\beta_\ell}{\beta_p}(L_{\mu\nu}(0)H^{(0)}_{\mu\nu} + L^{(0)}_{\mu\nu}H^{(1)}_{\mu\nu}(s_1)) = \frac{d\sigma_{un}}{d\Omega}(1 + A^C_y\chi_{1y})$$

Single spin asymmetry:

$$A^C_y = \frac{2\beta^2_\ell}{\sqrt{\eta_p}\mathcal{D}^C}\cos\theta\sin\theta\, Im G_M G^*_E,$$

$$\mathcal{D}^C = \frac{|G_E|^2}{\eta_p}(1 - \beta^2_\ell\cos^2\theta) + |G_M|^2(2 - \beta^2_\ell\sin^2\theta), \quad \beta^2_\ell = 1 - 4m^2_\ell/q^2.$$

The z-axis is taken along the antiproton beam momentum.

Double & Triple spin observables

- Double spin
  - Polarization transfer coefficients

$$\vec{\bar{p}} + p \to \vec{\ell^-} + \ell^+$$

  - Correlation coefficients

$$\vec{\bar{p}} + \vec{p} \to \ell^- + \ell^+, \quad \bar{p} + p \to \vec{\ell^-} + \vec{\ell^+}$$

- Triple spin
  - Polarized lepton in polarized proton-antiproton annihilation

$$\vec{\bar{p}} + \vec{p} \to \vec{\ell^-} + \ell^+$$

  - Polarized lepton-antilepton with polarized antiproton beam

$$\vec{\bar{p}} + p \to \vec{\ell^-} + \vec{\ell^+}$$

Combination of $|G_M|, |G_E|, ImG_M G_E^*, ReG_M G_E^*$

Full expressions in CM and Lab frame: arXiv:1110.6722 [hep-ph].

Double spin observables: Transfer Coefficient

- Polarized antiproton beam (along x-axis).
- Polarized lepton (transverse polarization).
- Unpolarized proton target and produced antilepton.

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_{un}}{d\Omega}(1 + T_{tx}\chi_t\chi_x)$$

$$T_{tx} = 2\frac{m_\ell}{M}\frac{\cos\theta}{\eta_p\mathcal{D}^{\mathcal{C}}} ReG_M G_E^*,$$

$$\mathcal{D}^{\mathcal{C}} = \frac{|G_E|^2}{\eta_p}(1 - \beta_\ell^2\cos^2\theta) + |G_M|^2(2 - \beta_\ell^2\sin^2\theta)$$

$$\frac{m_e}{M} \sim 0, \frac{m_\mu}{M} = 0.11, \frac{m_\tau}{M} = 1.8$$

x, y, z polarizations of the antiproton along x, y, z-axis respectively.
l, t, n longitudinal ($||k_1$), transverse ($\perp k_1$) and normal ($\perp$ to scattering plane) polarization of lepton.

Double spin observables

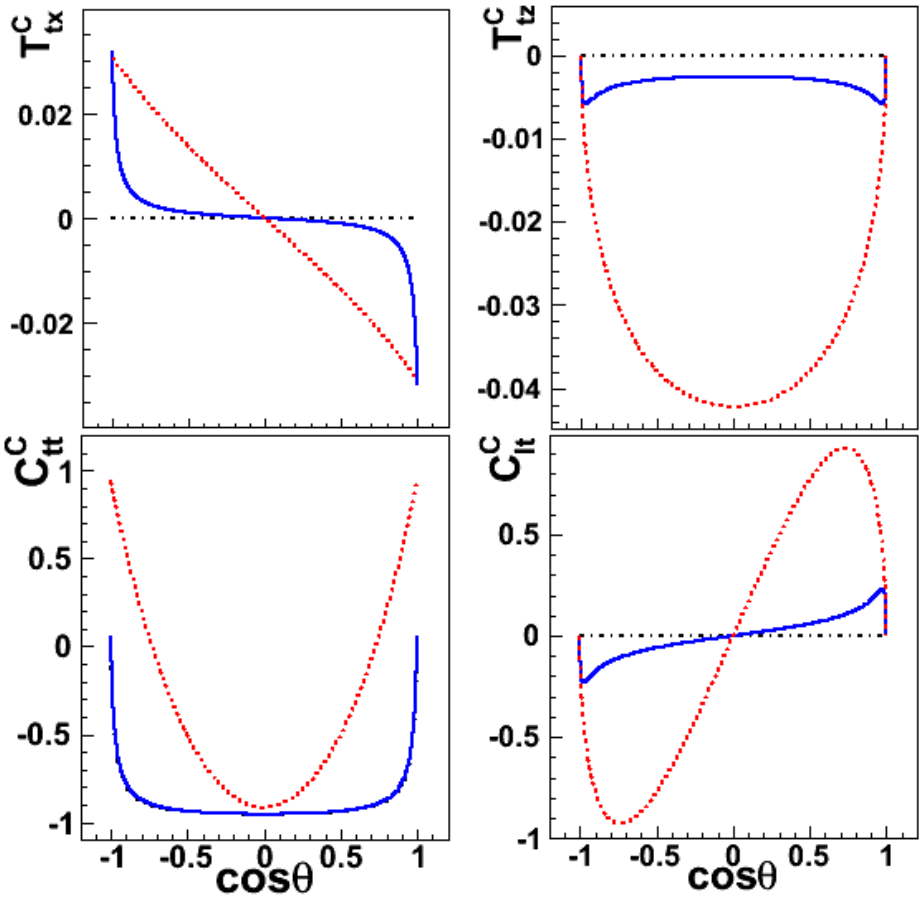


Figure: Polarization observables as function of $\cos\theta$, $\ell = \tau$(red line), $\ell = \mu$ (blue line) and $\ell = e$ (black line), for $q^2 = 15[GeV/c]^2$

Background

Leptonic channels

- Total cross section is in the [nb] level.

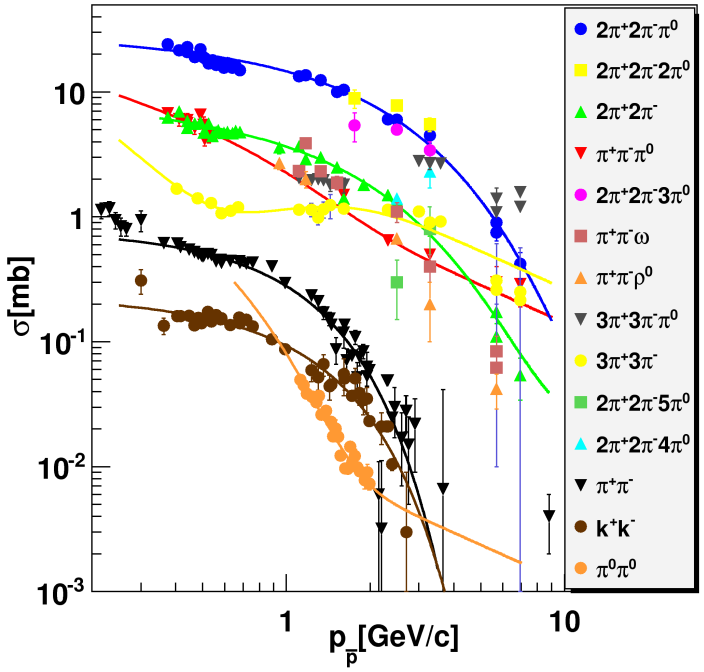


Figure: Pbar p annihilation into mesons

Interested channels:

1) $\bar{p} + p \rightarrow \ell^+\ell^-$
1) $\bar{p} + p \rightarrow \tau^+\tau^- \rightarrow \pi^+\bar{\nu}_\tau\pi^-\nu_\tau$

Main background channels:

1) $\bar{p} + p \rightarrow \pi^+\pi^-$
2) $\bar{p} + p \rightarrow \pi^+\pi^-\pi^0$
3) $\bar{p} + p \rightarrow n\pi^+n\pi^-$
4) $\bar{p} + p \rightarrow n\pi^+n\pi^-n\pi^0$

- The possibility to identify leptons in the proton antiproton annihilation is under study.

Summary

In the present work, we have:

- Studied the Electromagnetic proton form factors with $\bar{p}$ annihilation into heavy leptons.
- Derived model independent expressions of experimental observables in one photon exchange for pbar+p annihilation into heavy leptons.
- Showed the interest of pbar+p annihilation into heavy leptons for the extraction of electromagnetic proton form factors

This work is in progress:

- Calculation of all observables beyond the Born approximation (with 2 photons exchange).
- Full simulation of this reaction in the frame of PANDAroot: elimination of the huge hadronic background.

Thank you for attention

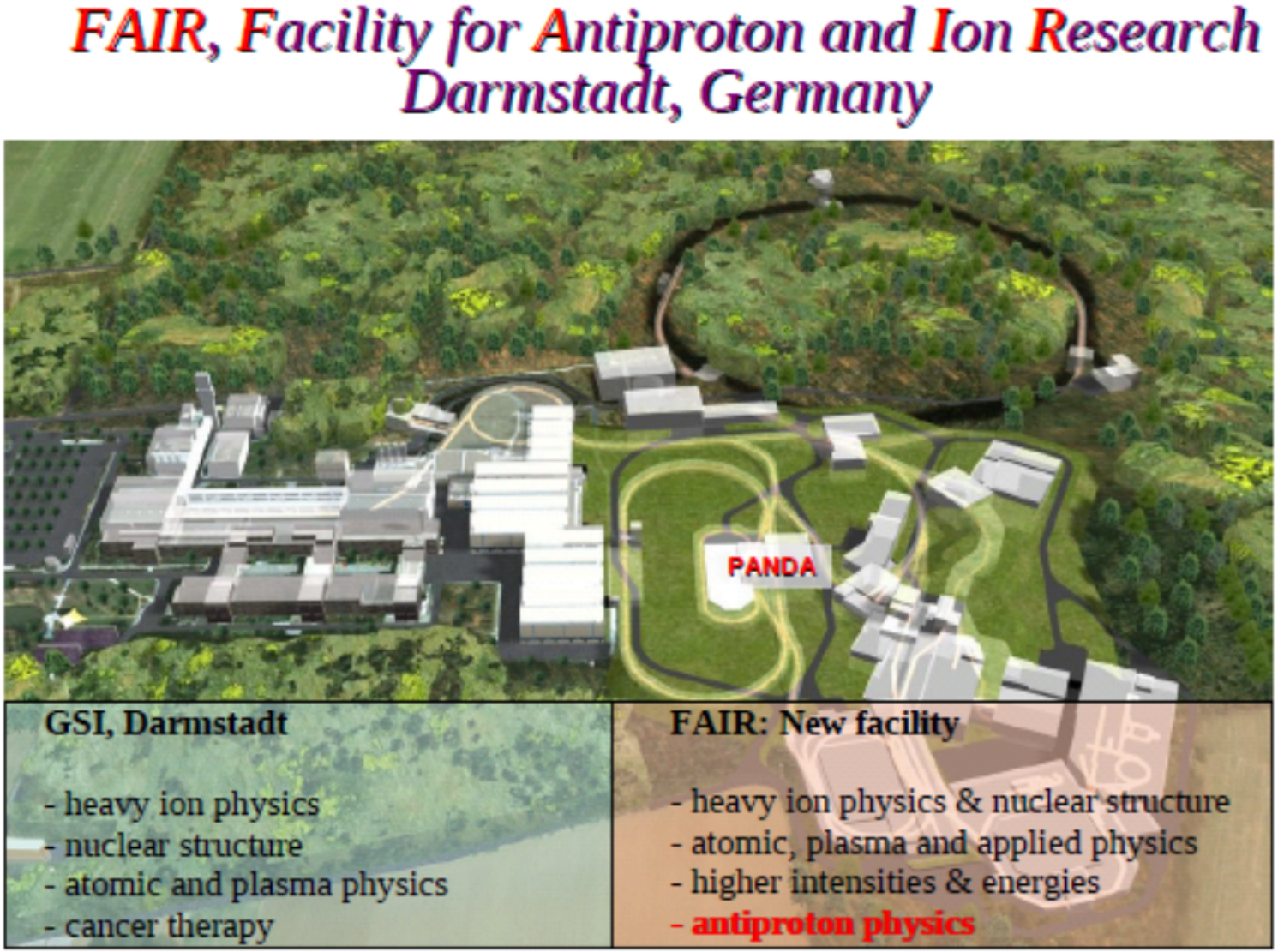
Parametrization of time-like proton FFs

VMD form factors from F. Iachello and Q. Wan, PRC 69, 055204 (2004):

Model of time-like form factors of the nucleon with an intrinsic structure and a meson cloud (Vector Meson Dominance (VMD)).

- Intrinsic part: $g(q^2) = \frac{1}{(1-\gamma e^{i\theta} q^2)^2}$
- Meson cloud parametrized in term of ρ, ω, ϕ

- Fitted to the experimental data.
- Complex functions taking into account the annihilation channels.



• High statistics and large angular coverage in PANDA: First measurement of electric G_E and magnetic G_M Form Factors separately

Dirac formalism

Spin 1/2 particles are described by Dirac spinor:

$$u(p) = \sqrt{E+M}\begin{pmatrix} \Phi \\ \frac{\vec{\sigma}.\vec{p}}{E+M}\Phi \end{pmatrix}$$

- p is the particle 4-momentum.
- $u(p)$ is a four component spinor.
- Φ is two component spinor.

$\rho = u(p)\bar{u}(p)$	particle	antiparticle
unpolarized	$\hat{p} + M$	$\hat{p} - M$
polarized	$(\hat{p} + M)\frac{1}{2}(1 - \gamma_5 \hat{s})$	$(\hat{p} - M)\frac{1}{2}(1 - \gamma_5 \hat{s})$

$$s_i^0 = \frac{\vec{p}_i.\vec{\chi}_i}{m_i}, \ \vec{s}_i = \vec{\chi}_i + \frac{\vec{p}_i.\vec{\chi}_i\vec{p}_i}{m_i(E_i + m_i)}$$

$\vec{\chi}_i$ is the direction of the spin particle in its rest frame

Polarization Phenomena

General form of hadronic (proton-antiproton) and leptonic tensors:

$$J_\mu = \bar{v}(p_1)[G_M\gamma_\mu + \frac{P_\mu}{M}\frac{G_M - G_E}{1-\eta_p}]u(p_2),\ j_\mu = \bar{u}(k_1)\gamma_\mu v(k_2),$$

$$H_{\mu\nu} = J_\mu J_\nu^* = H_{\mu\nu}^{(0)} + H_{\mu\nu}^{(1)}(s_1) + H_{\mu\nu}^{(1)}(s_2) + H_{\mu\nu}^{(2)}(s_1, s_2).$$

$$L_{\mu\nu} = j_\mu j_\nu^* = L_{\mu\nu}^{(0)} + L_{\mu\nu}^{(1)}(s_a) + L_{\mu\nu}^{(1)}(s_b) + L_{\mu\nu}^{(2)}(s_a, s_b).$$

- $H_{\mu\nu}^{(0)}$ Unpolarized antiproton-proton system.
- $H_{\mu\nu}^{(1)}(s_1)$ Polarized antiproton beam.
- $H_{\mu\nu}^{(1)}(s_2)$ Polarized proton target.
- $H_{\mu\nu}^{(2)}(s_1, s_2)$ Polarized antiproton beam and proton target.

Kinematics

- The kinematics of the reaction is derived from the conservation law of energy and momentum.
- Electron is a stable particle, muon is unstable with long life time $[2.197 \times 10^{-6}\text{s}]$: can be detected.
- Tau is unstable with very short life time $[290.6 \times 10^{-15}\text{s}]$: identification with their decay products.

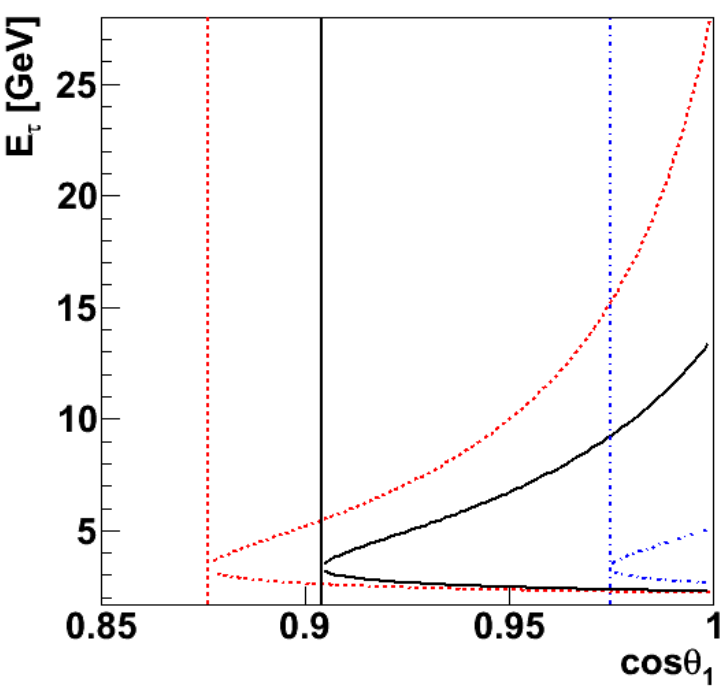
τ^- Decay modes	$\pi^-\nu_\tau$	$\mathbf{K}^-\nu_\tau$	$\mu^-\bar{\nu}_\mu\nu_\tau$
Branching ratio %	10.91 ± 0.07	6.96 ± 0.23	17.36 ± 0.05

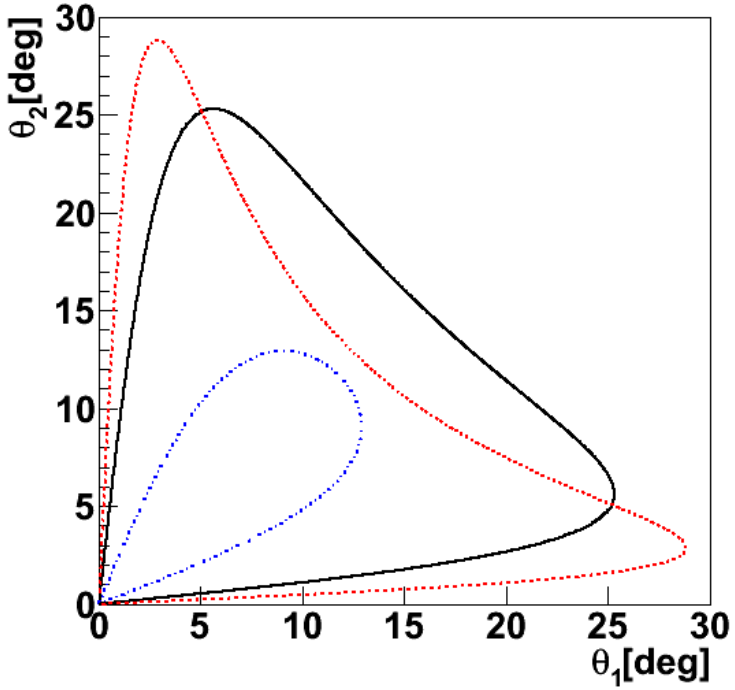
- Special case for τ production : mass of the final state particle (like τ) is larger than initial state particles (proton).

Kinematics of τ in the Lab. frame

- At one scattering angle of τ^-: two solution for the τ^- energy and two possible scattering angles and energies for τ^+.

- Maximum scattering angle depending on the incident energy.





Figures: $E_{\bar{p}} = 6.85$ GeV , $E_{\bar{p}} = 15$ GeV and $E_{\bar{p}} = 30$ GeV.