Study of the internal structure of the proton with the PANDA experiment at FAIR

PANDA PhD prize

Alaa Dbeyssi

September 10th, 2014

IPNO-France

UNIVERSITÉ PARIS SUD

INSTITUT DE PHYSIQUE NUCLÉAIRE ORSAY

*new address: Helmholtz-Institut Mainz

This work was ….

- done at the "Institut de Physique Nucléaire Orsay"
- financed by the Lebanese CNRS
- supervised by E. Tomasi-Gustafsson & D. Marchand
- defended on September 27th 2013 in front of the jury:

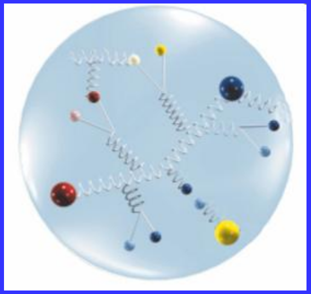
T. Suomoijarvi, P. Gianotti, M. Guidal, D. Marchand, J. Ritman,
E. Tomasi-Gustafsson, E. Voutier. and H. Zaraket

PANDA-IPNO

Main interest of the IPN group : The nucleon structure;
towards a unified understanding of the nucleon structure

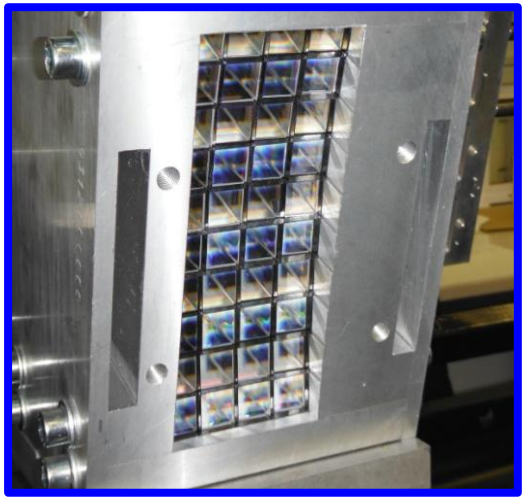
Studied through the annihilation reactions:

1. ***pbar p → e+ e- (access to Time-Like Form Factors)***
2. ***pbar p → e+ e- X (TDA/pion content of the proton, GDA, PDF)***



Phenomenological and simulation activities

- **Feasibility demonstration of Time-Like FF measurements**
- **Software development for advanced PID and filtering methods**
- **Electron tracking with Bremsstrahlung**
- **Radiative corrections**
- **Development of phenomenological models and generators (EM and hadronic channels)**



Technical (R&D) activities

- ✓ **Mechanical design of the calorimeter**
- ✓ **Cooling at -25°C**
- ✓ **Prototype building and tests**

Outline

- **Personal contributions:** Measurements of Time-Like proton form factors through the **electromagnetic processes** at PANDA

  I. Feasibility studies of the $\bar{p}p \rightarrow e^+e^-$ reaction measurement at PANDA

  II. Tests of optical glues for the PANDA electromagnetic calorimeter (EMC)

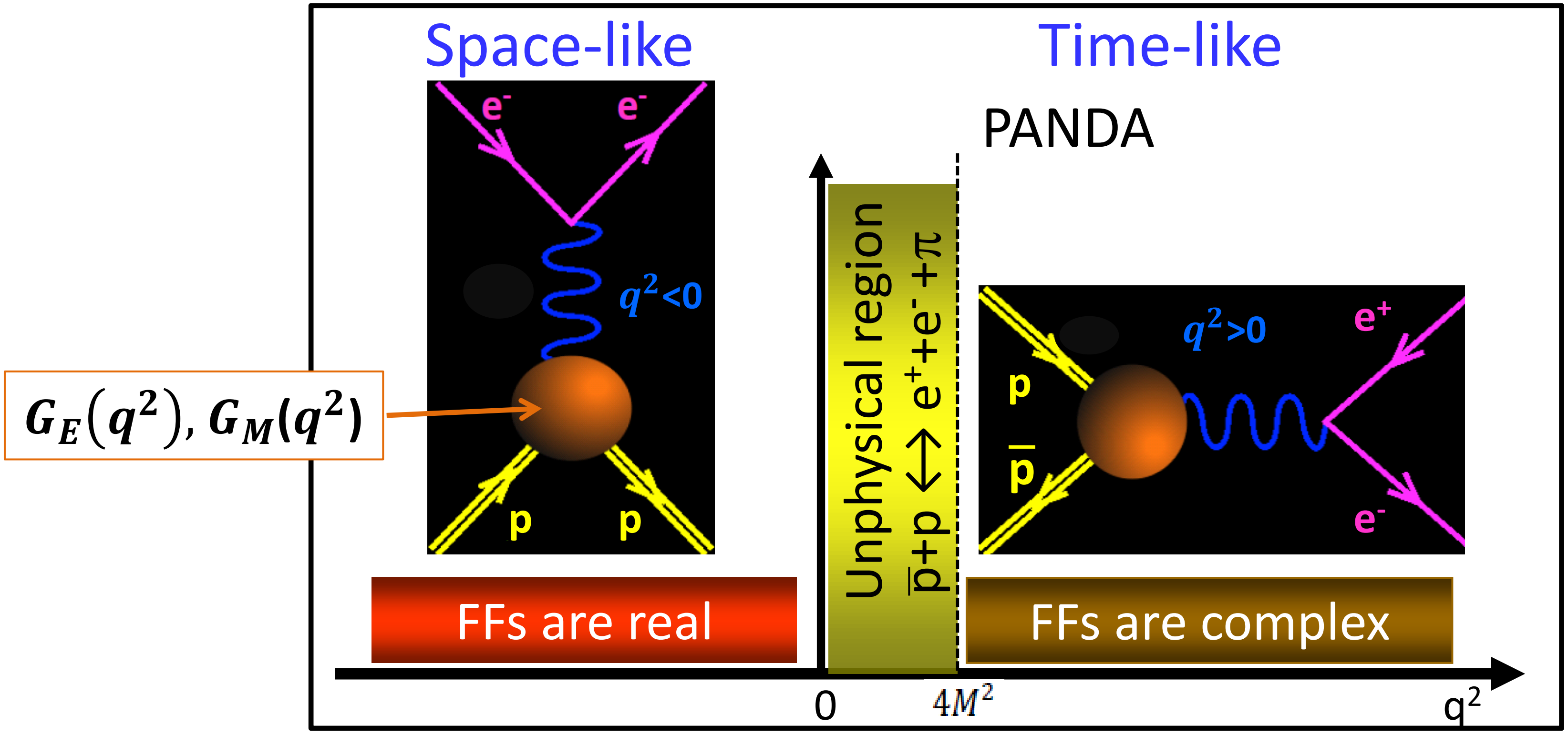
  III. Generalization of a model independent formalism for *electron proton* interaction *taking into account the lepton mass*
  - heavy lepton production $\bar{p}p \rightarrow \mu^+\mu^-, \tau^+\tau^-$
  - antiproton polarization with proton electron scattering (inverse kinematics)

- **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 $\boldsymbol{G_M(q^2)}$ FFs
- $\boldsymbol{q^2}$ is a kinematical invariant : [-∞, +∞]

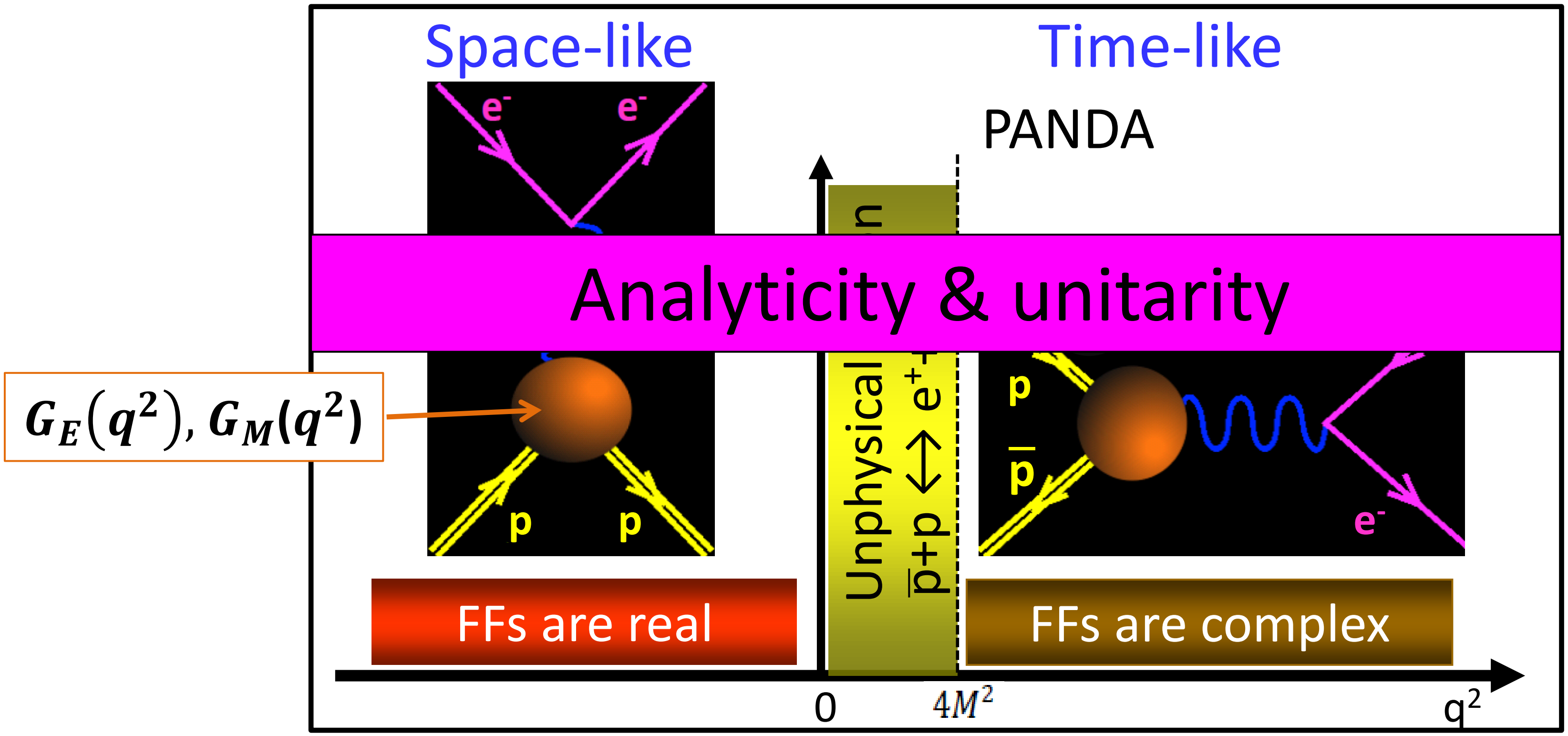
Born approximation



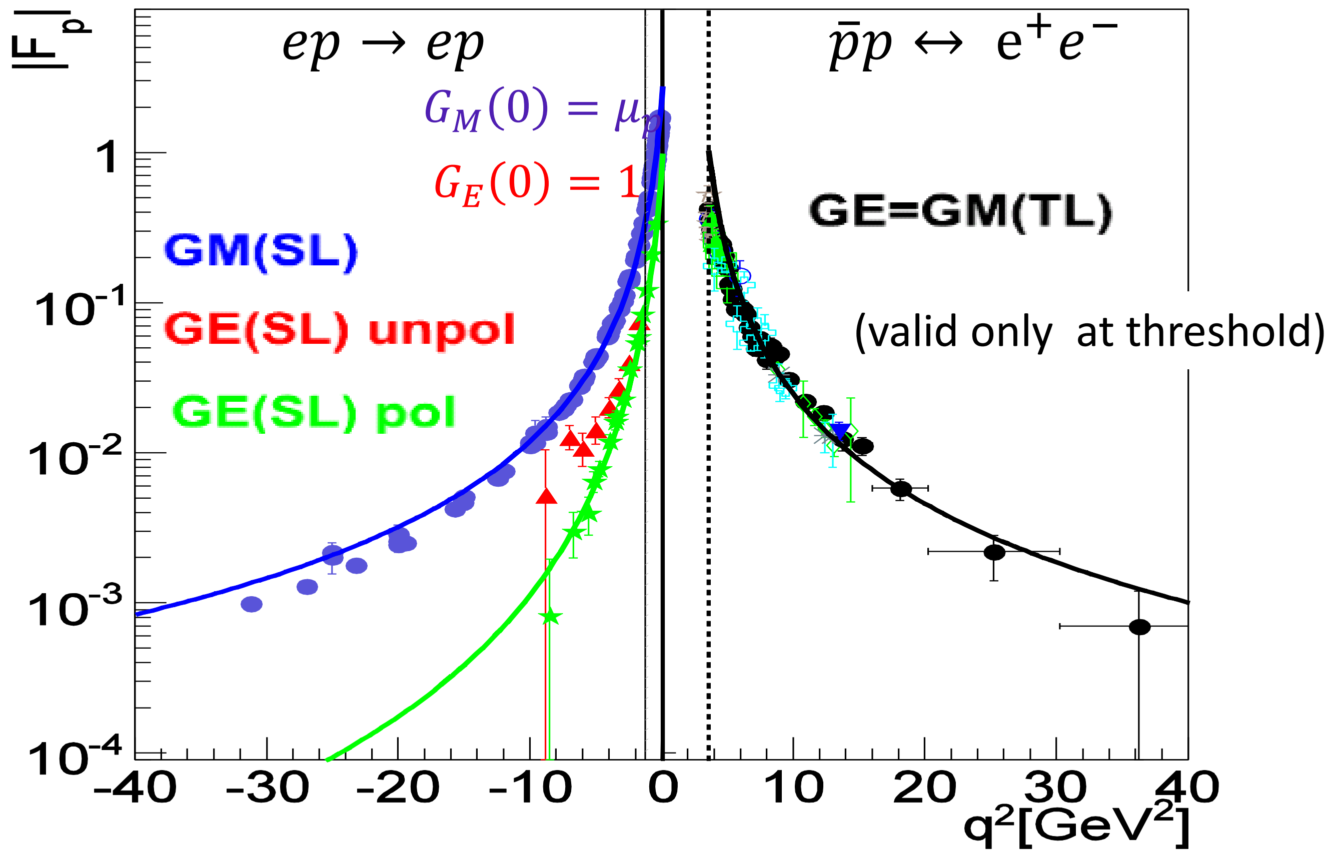
Electromagnetic form factors

- 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 $\boldsymbol{G_M(q^2)}$ FFs
- $\boldsymbol{q^2}$ is a kinematical invariant : [-∞, +∞]

Born approximation



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

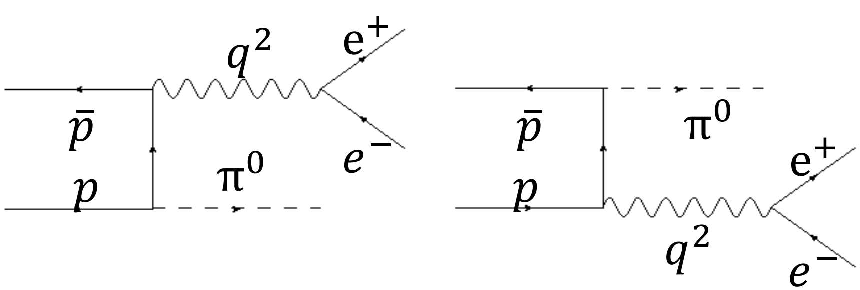
Measurement of TL proton FFs at PANDA: Goals

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

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

- Possibility to access the relative phase of proton TL FFs
  - $\bar{p}p \to e^+e^-$ 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: $\bar{p}p \to e^+e^-\pi^0$



- 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)

Outline of the simulation studies

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

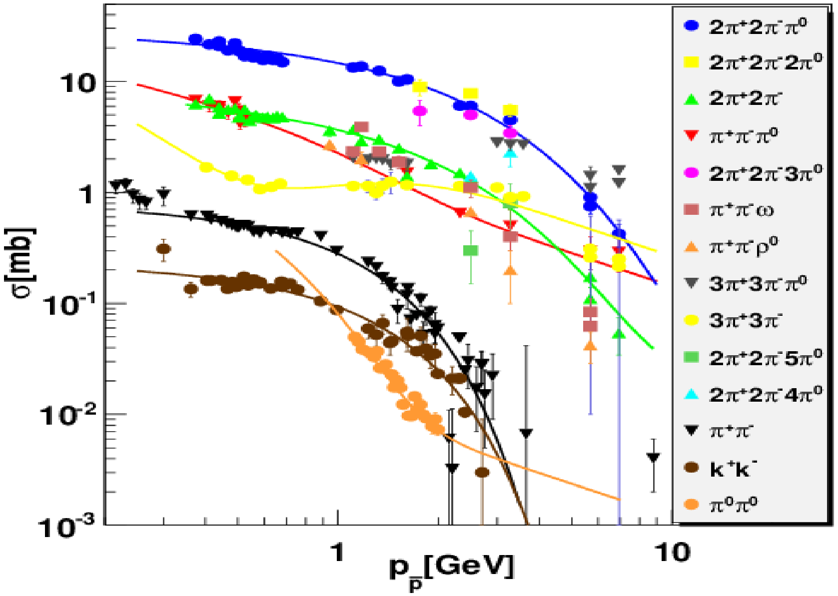
- Study of the **background suppression** versus the **signal ($\bar{p}p \rightarrow e^+e^-$) efficiency**

- 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 GRID of IPNO,
PANDA and GSI batch farms. (from April to June 2013)

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)

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

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

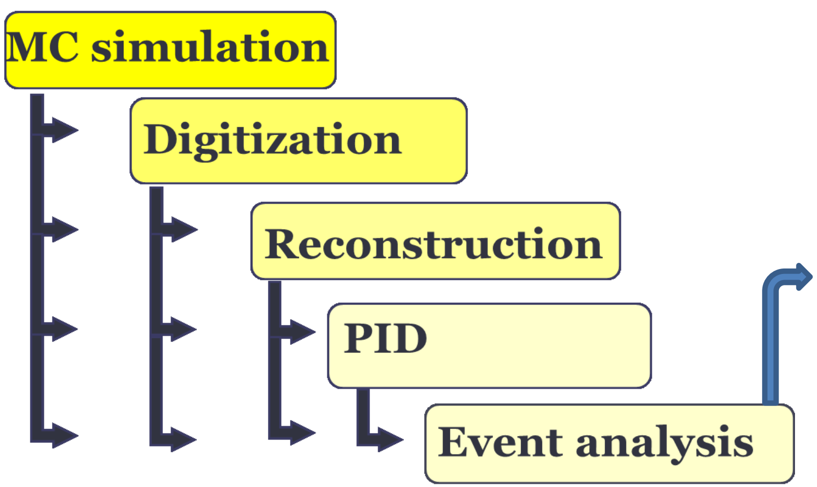
Description of the simulation

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

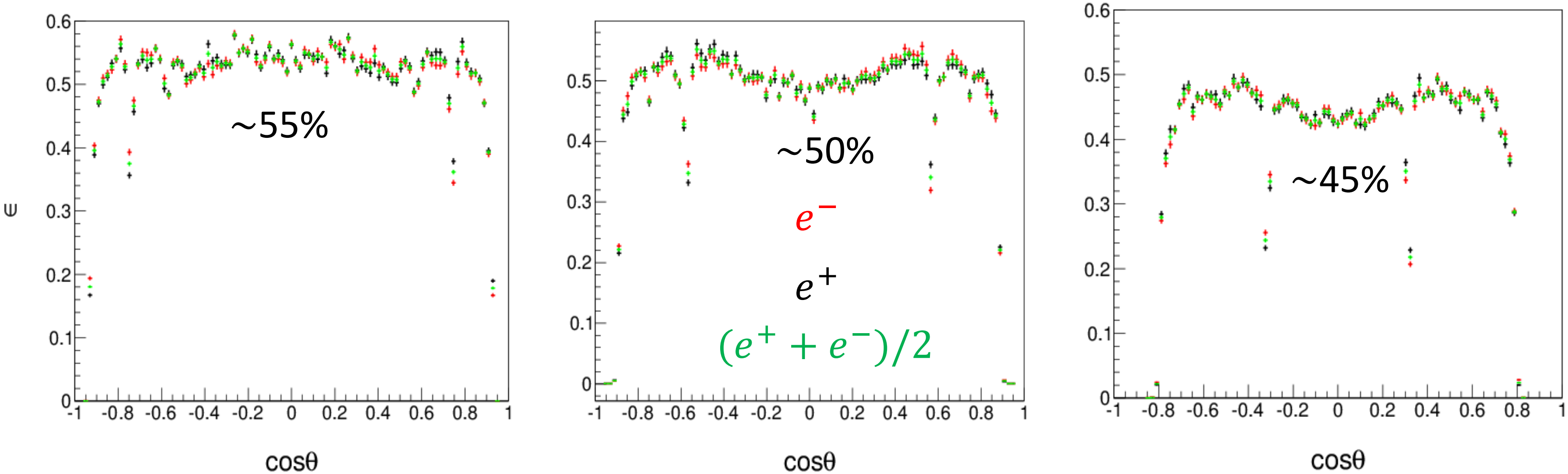
s $[\mathrm{GeV}^2]$	5.4	8.2	13.9
Total PID prob.	>99%	>99%	>99.9%
Individual PID_i prob.	>5%	>5%	>6%
Number of fired crystals in the EMC	>5	>5	>5
$(\theta + \theta')$ [CMS]	[178°-182°]	[178°-182°]	[175°-185°]
$\|\phi - \phi'\|$	[178°-182°]	[178°-182°]	[175°-185°]
Invariant mass [GeV]	No cut	> 2.14 GeV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

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



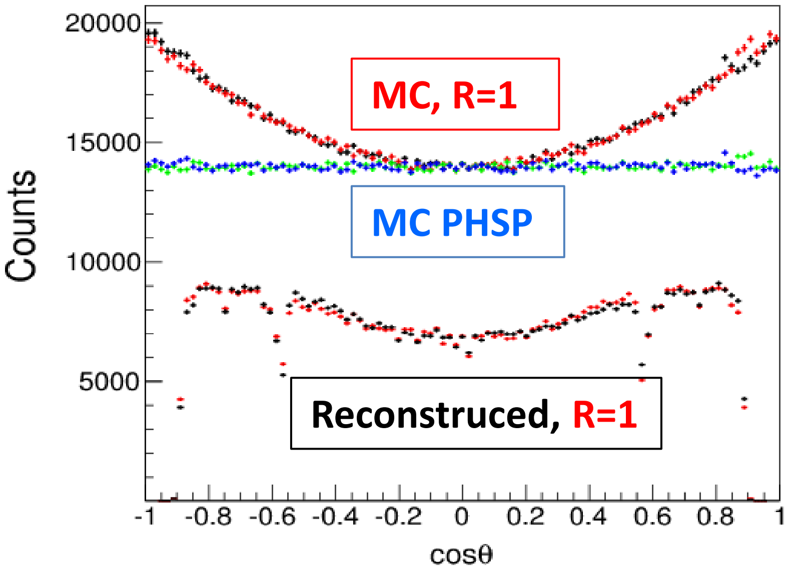
Analysis for proton FF measurements is limited to the region
cosθ = [-0.8,0.8] in the CM

From PHSP to physical angular distributions

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

$$\frac{d\sigma}{d\cos\theta} = \sigma_0(1 + \mathcal{A}\cos^2\theta) \quad \begin{cases} \sigma_0 = \frac{d\sigma}{d\cos\theta}\left(\theta = \frac{\pi}{2}\right) \\ \mathcal{A} = \frac{\tau - R^2}{\tau + R^2}, R = |G_E|/|G_M|, \tau = \frac{s}{4M^2} \end{cases}$$

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

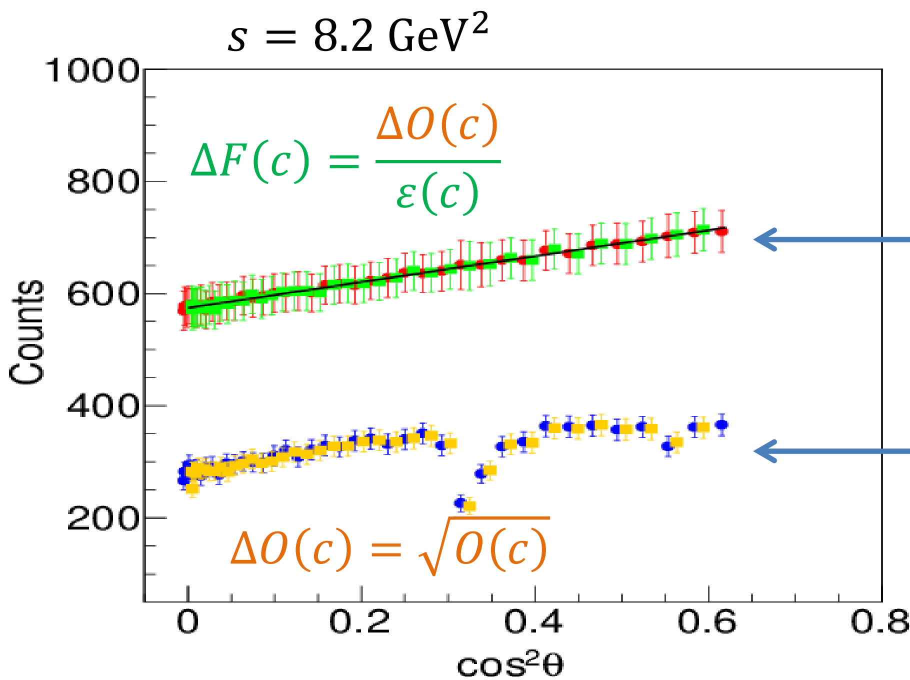
$\times$ Weight: $1 + \mathcal{A}\cos^2\theta$

Physical Monte Carlo events

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

Physical reconstructed events

Efficiency correction and linear fit



- 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 $\cos^2\theta$

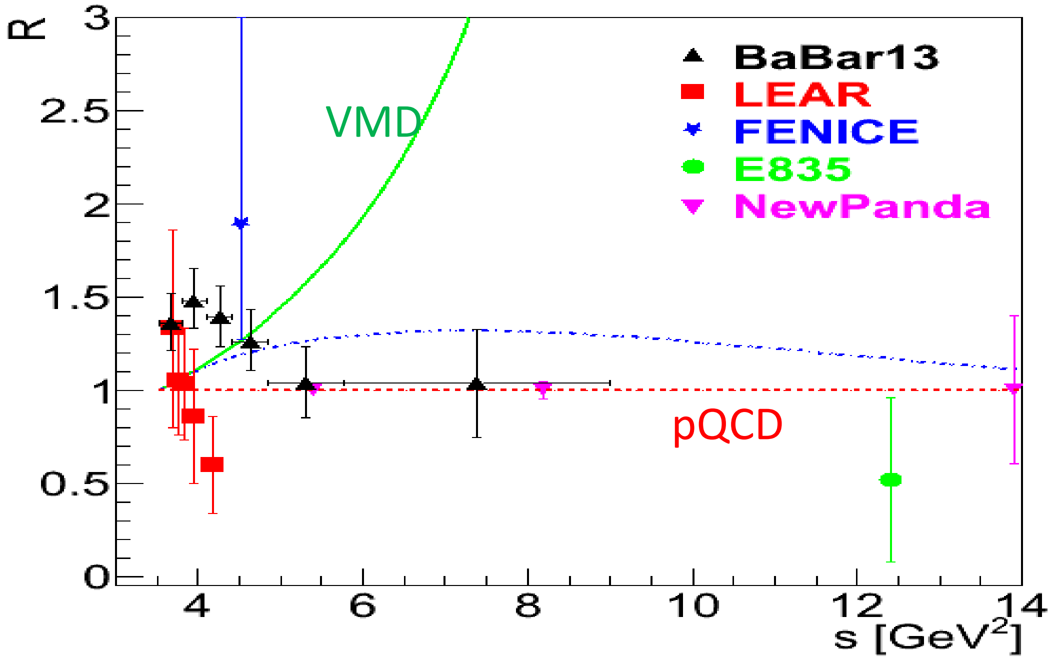
- Fit function: y=$a_0 + a_1 x,\ x = \cos^2\theta$
- The slope a_1 is related to $\mathcal{A}$
- Error on R through: $\mathcal{A} = \frac{\tau - R^2}{\tau + R^2}$

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

Results:

s $[\mathrm{GeV}^2]$	$\mathcal{A}$	$\mathcal{A} \pm \Delta\mathcal{A}$	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



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)

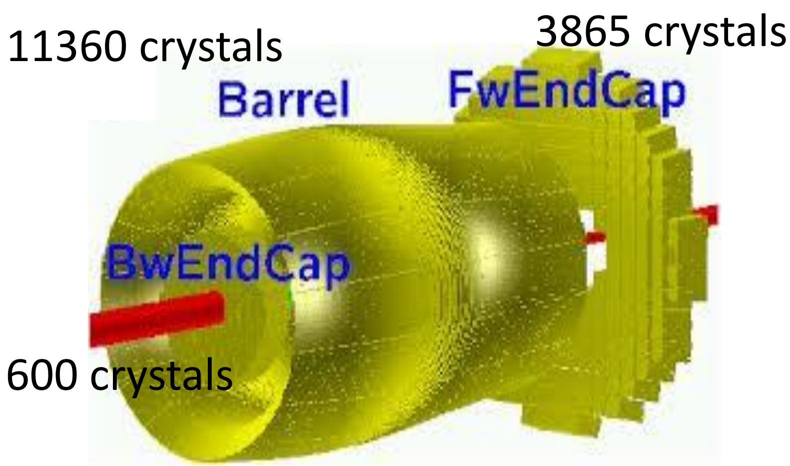
V. A. Matveev, S. J. Brodsky , D. V. Shirkov….

Personal contributions

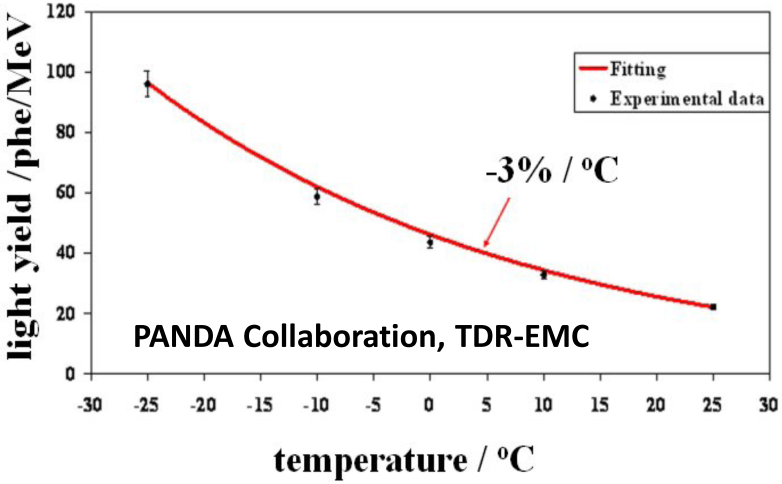
II. Tests of optical glues for the PANDA electromagnetic calorimeter (EMC)

A. Dbeyssi *at al.* NIM A, 722 (2013) 82-86

The PANDA electromagnetic calorimeter



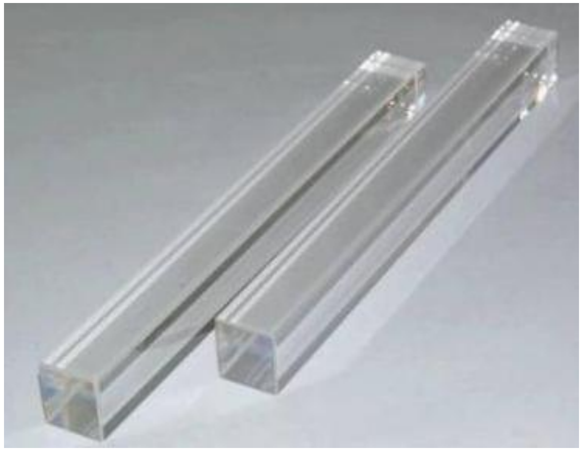
- γ detection : 10 MeV- 12 GeV

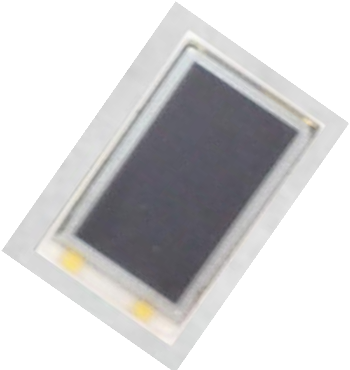


Scintillator material : $PbWO_4$ (PWO)

Photo sensors (Barrel): LAAPDs

EMC will be operated at -25°C





$14\times 7\ \mathrm{mm}^2$

Optical coupling PWO – LAAPD:

1. Easy to handle
2. Resistant to thermal variation and mechanical forces
3. Transparent at **T**=-25°C for scintillation light [λ =300-600 nm]
4. Resistant to radiation damage

Tests of optical glues for the PANDA EMC

- Tests of thermal and mechanical properties
- Measurements of optical transmittance :
  - Low temperatures effects
  - Radiation hardness

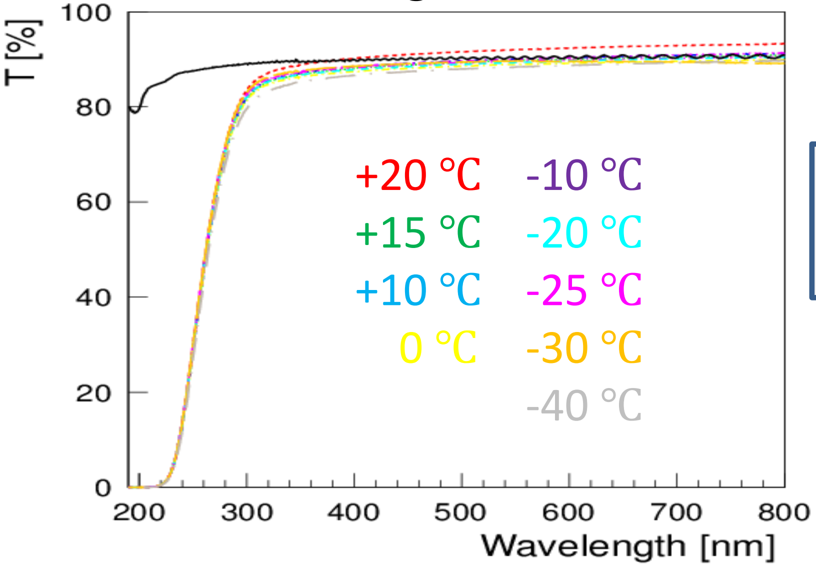
- **Glue candidates (silicone):**

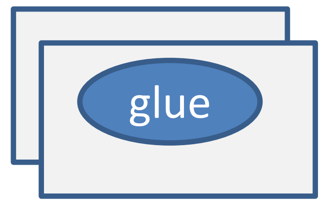
- Dow Corning (3145 RTV MIL-A-46146)
- ELASTOSIL® RT 601 A/B

Measurements of the optical transmittance

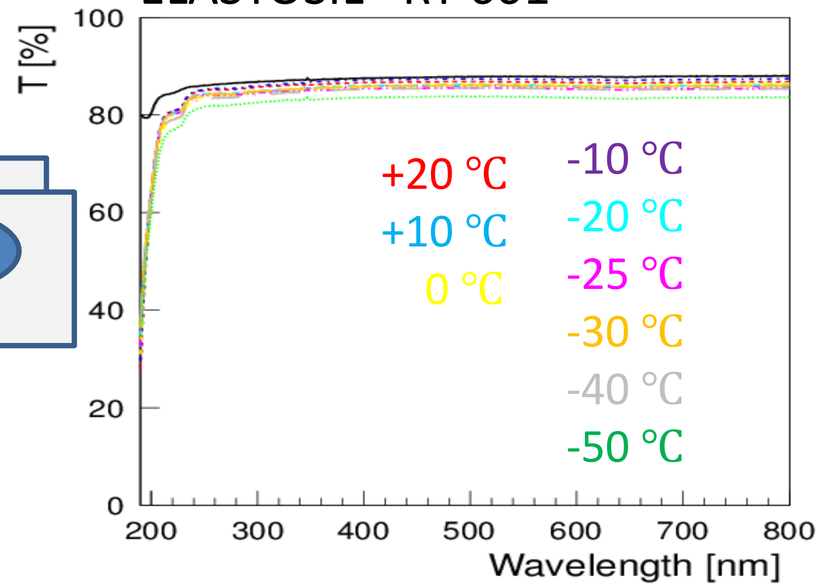
- **Low temperature tests:**
  (Varian spectrophotometer @ ICMMO, Université Paris Sud)

Dow Corning 3145





ELASTOSIL® RT 601



- **Gamma irradiation tests** : 100 Gy -> 1000 Gy ($^{60}\mathrm{CO}$ $-$source)
- **Proton irradiation tests**: $10^{12}\ p/\mathrm{cm}^2$ and $1.8\ \times 10^{13} p/\mathrm{cm}^2$

(Radiation Center of the University of Giessen)

Part II: summary

Dow Corning 3145	ELASTOSIL® RT 601
Easy to handle	Mixing of 2 components
High mechanical strength, can be unbonded with ethyl alcohol	Low mechanical strength, can be easily unbonded
Used by CMS collaboration	
Withstands the temperature variation	Withstands the temperature variation
Transparent at -25° C [300-600 nm]	Transparent at -25° C [300-600 nm]
Radiation (gamma, proton) hard	Radiation (gamma) hard

Dow Corning 3145 Has been chosen for the optical coupling between the LAAPDs and PWO crystals for the electromagnetic calorimeter

III. Extension of a model independent formalism for electron proton interaction

- Proton antiproton annihilation into heavy leptons:

$$\bar{p}p \to \mu^+\mu^- \text{ and } \bar{p}p \to \tau^+\tau^-$$

- Polarization of high energy (anti)proton beam using proton electron scattering (inverse kinematics)

The mass of the lepton cannot be neglected

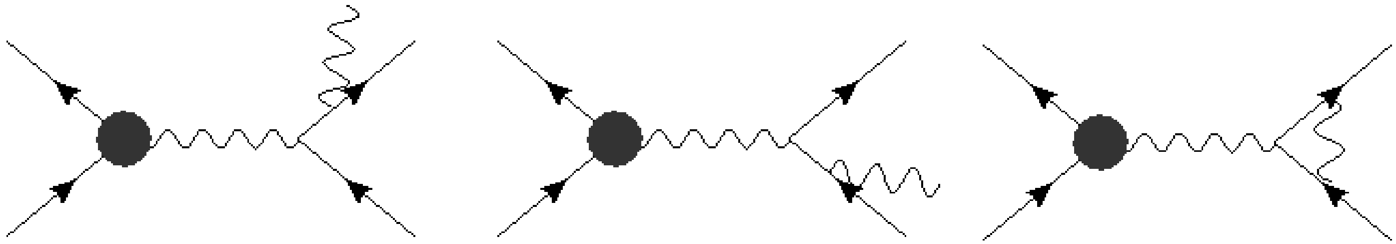
A. Dbeyssi *et al.* Nucl. Phys. A 894 (2012) 20

G. I. Gakh *et al.* , Phys. Rev. C 84 (2011) 015212

Heavy leptons production at PANDA: advantages

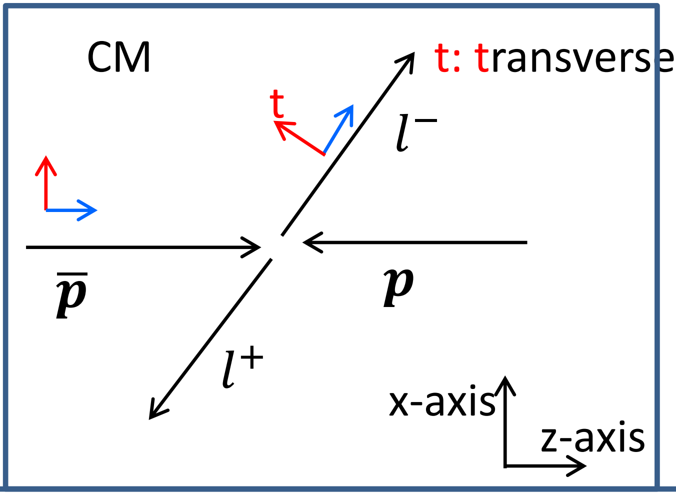
- Consistency check of proton FF data with electron pair

- Radiative corrections due to the final state radiation are suppressed by the mass of heavy leptons:



- The polarization observables give access to the relative phase of the proton FFs:
  the polarization of unstable particles can be measured, in principle, through the angular distribution of their (weak) decay products

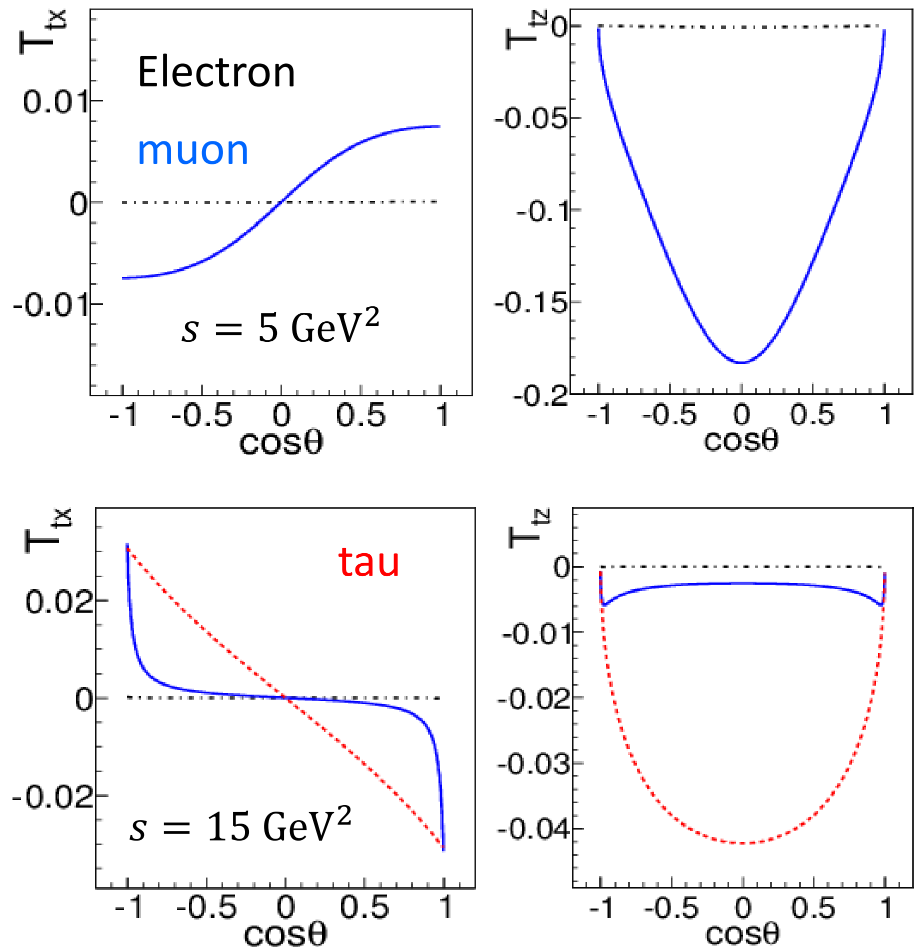
Polarization transfer coefficients



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

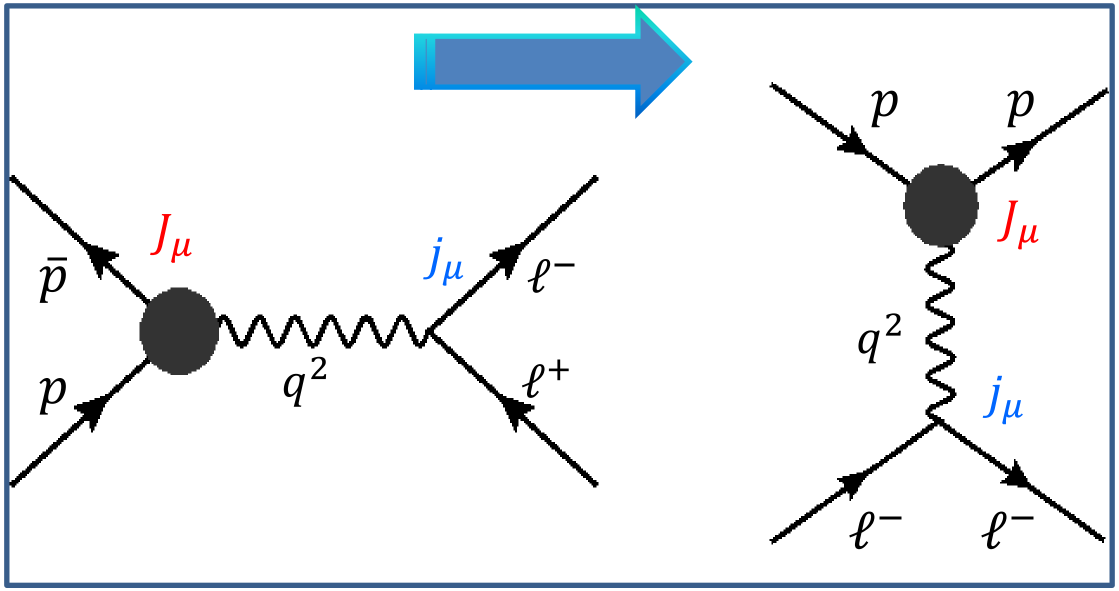
$$T_{tz} = -2\frac{m_\ell}{M}\frac{\sin\theta}{\sqrt{\eta_p}\mathcal{D}^C}|G_M|^2$$

Transverse polarization observables are enhanced with heavy lepton production (antiproton beam is polarized)



How to polarize anti(proton) beam ?

From TL to SL region: model independent formalism



Proton vertex:

$$J_\mu = G_M \gamma_\mu + \frac{P_\mu}{M} \frac{G_M - G_E}{1 - \eta_p}$$

Lepton vertex: $j_\mu = ie\gamma_\mu$

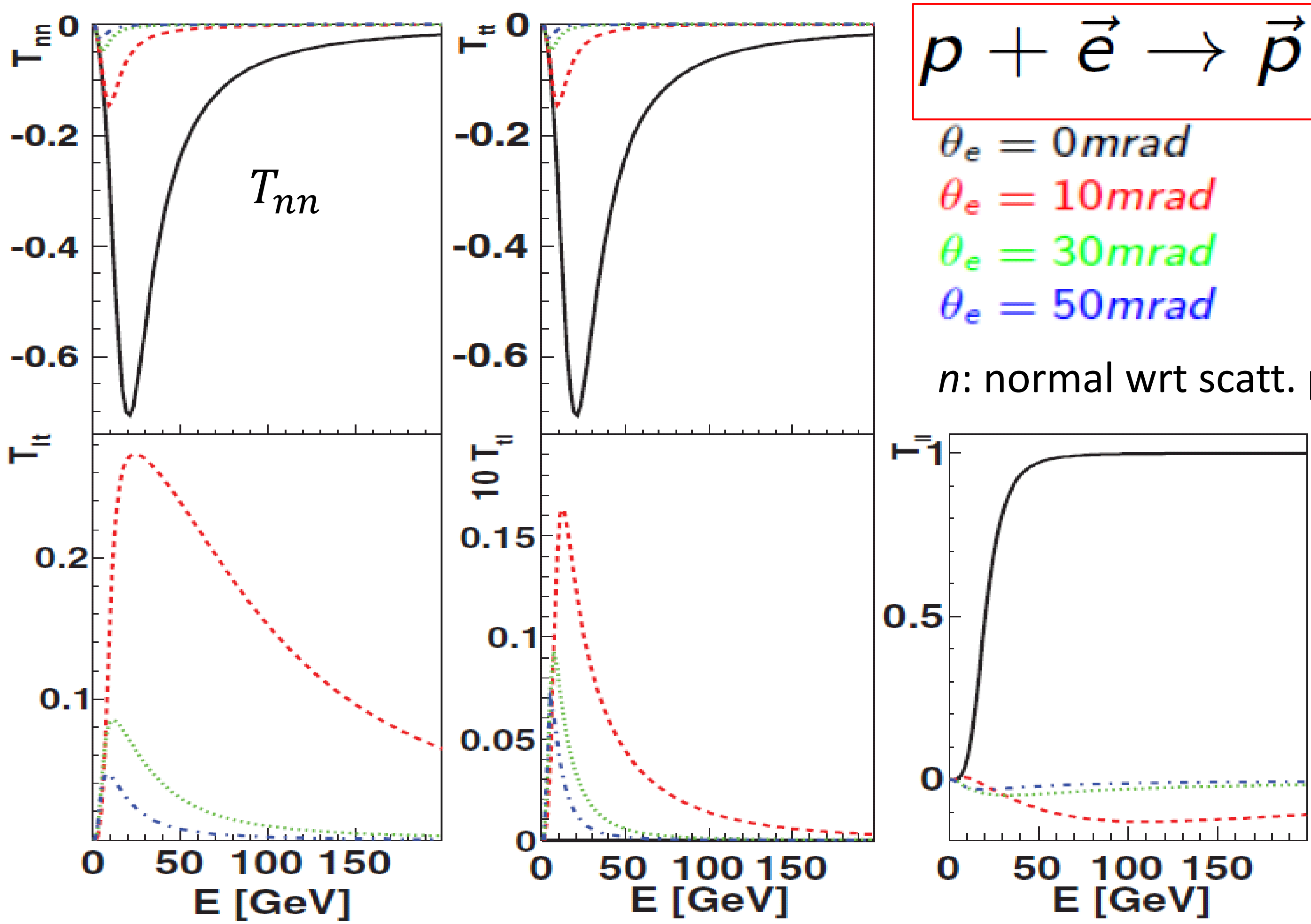
Photon propagator $\propto \dfrac{1}{q^2}$

Elastic scattering of proton beam on electron target at rest (inverse kinematics): the lepton mass can not be neglected

Applications:

1) Polarization of high energy (anti)proton beam: $\mathrm{p} + \vec{e} \rightarrow \vec{p} + e$
2) Polarimetry (Phys. Rev. C 84 (2011) 015212)
3) Measurement of proton charge radius (Phys. Part. Nucl. Lett. 10 (2013) 393)

Polarization transfer coefficients in pe scattering



$$p + \vec{e} \rightarrow \vec{p} + e$$

$\theta_e = 0mrad$

$\theta_e = 10mrad$

$\theta_e = 30mrad$

$\theta_e = 50mrad$

n: normal wrt scatt. plane

Large polarization effects appear at large energies between 10 & 50 GeV

Antiproton polarization at high energy

$$p + \vec{e} \rightarrow \vec{p} + e$$

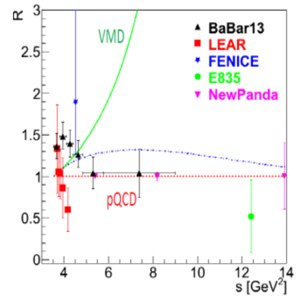
C-invariance

$$\bar{p} + \vec{e}^{\,+} \rightarrow \vec{\bar{p}} + e^{+}$$

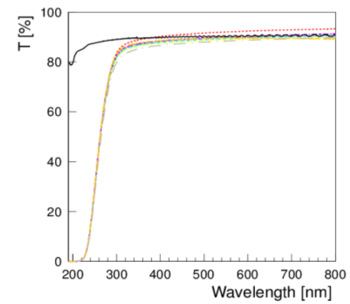
Feasibility studies need to be performed taking into account experimental conditions

Conclusions

- **Simulation:**
  Feasibility studies (PANDARoot) for measuring proton TL EM FFs at PANDA: proton FF ratio can be measured at PANDA experiment with unprecedented statistical accuracy

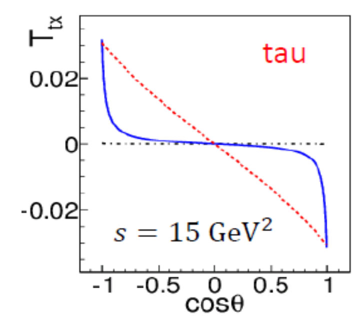


- **Experimental studies:**
  Mechanical, thermal, optical properties and radiation hardness of two glues have been studied in view of their use for optical coupling in the PANDA EMC which will be operated at -25°C: the Dow Corning 3145 has been chosen



- **Phenomenology:** model independent formalism
  - $pe \rightarrow pe$ ***(inverse kinematics) :***
  - $\bar{p}p \rightarrow \mu^+\mu^-, \tau^+\tau^-$

<u>*including the lepton mass*</u>



Collaboration: Dubna, Kharkov (JINR-IN2P3 grant, PICS), ….
PANDA collaboration, Orsay group
IPNO/Division Instrumentation et Informatique

Prof. Eduard A. Kuraev
17/10/1940-4/3/2014

Collaboration: Dubna, Kharkov (JINR-IN2P3 grant, PICS), ….
PANDA collaboration, Orsay group
IPNO/Division Instrumentation et Informatique

Thank you for your attention

Perspectives

- **Phenomenology (dependance on lepton mass)**
  - $\mu p \rightarrow \mu p$: measurement of the proton radius *(MUSE collaboration arXiv:1303.2160)*
  - $\bar{p}p \rightarrow \mu^+\mu^-$ beyond the Born approximation (2γ $exchange$)

Gakh et al. , arXiv:1408.2723 [nuvl-th],2014

- **Experimental studies**
  - Feasibility studies for polarization measurements : the possibility of
    - a transverse polarized proton target for PANDA in Mainz.
    - a polarized antiproton beam at CERN and COSY
- **Simulation**
  - 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 $\bar{p}p \rightarrow e^+e^-$
    - Event generator for PANDA
    - Simulation and analysis studies: effect of radiative correction on the proton form factors

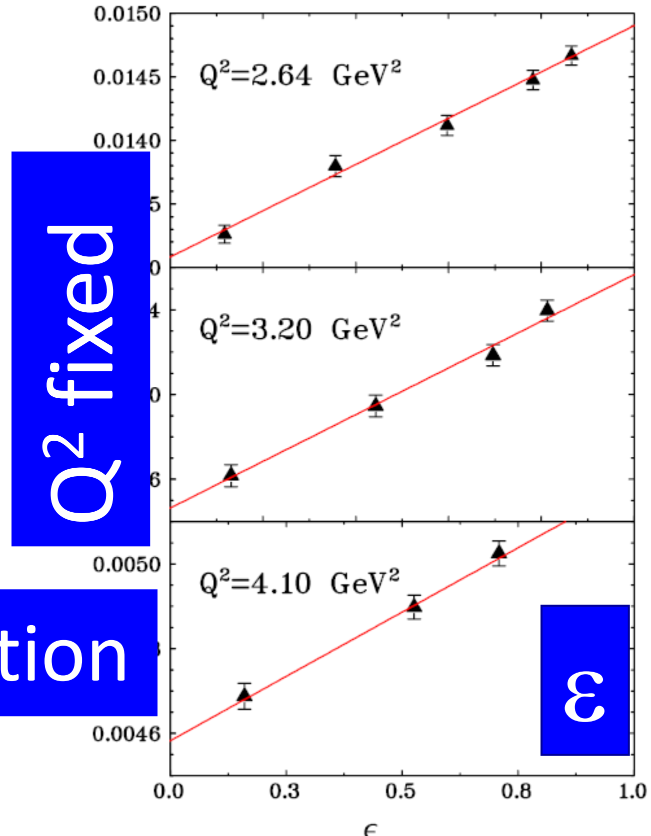
Helmholtz PostDoc Programe 2014-2017

The Rosenbluth separation

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_{Mott} \frac{1}{(1+\tau)}\left(G_E^2(Q^2) + \frac{\tau}{\varepsilon} G_M^2(Q^2)\right)$$

$$\varepsilon = \left[1 + 2(1+\tau)\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1}, \quad \tau = \frac{Q^2}{4M^2}$$

$$\sigma_R = \varepsilon G_E^2 + \tau G_M^2$$



PRL 94, 142301 (2005)

Linearity of the reduced cross section

→ $\tan^2\theta_e$ dependence

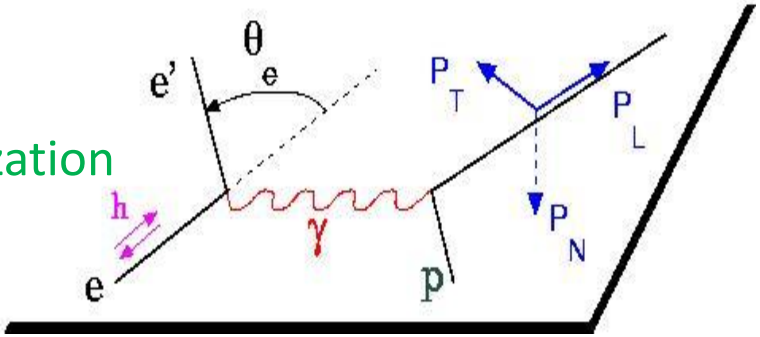
→ Holds for 1γ exchange only

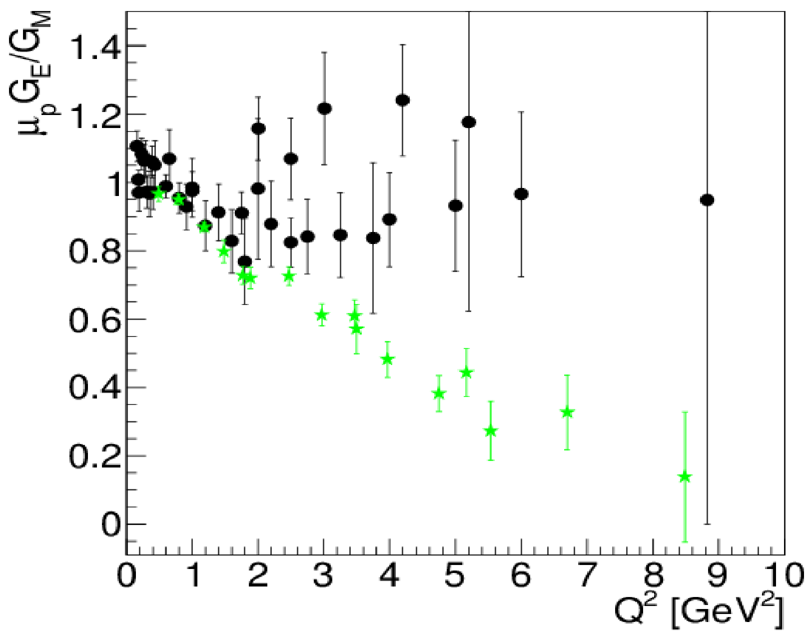
Polarization phenomena in *ep* elastic scattering

A. I. Akhiezer and M.P Rekalo, Sov. Phys. Dokl. 13 (1968)

The polarization induces a term in the cross section proportional to $G_E G_M$

GE_p collaboration-Jefferson laboratory:
polarized electron beam and recoil proton polarization

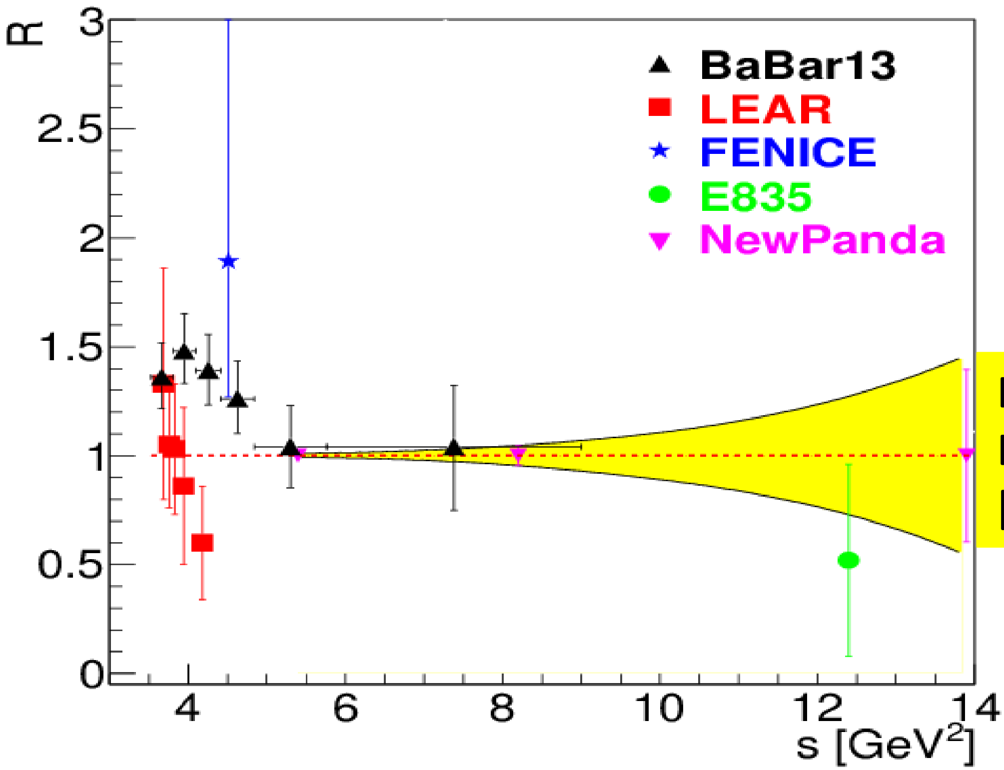




contradiction between polarized and unpolarized measurements

Results:

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



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

Effect of the angular cut

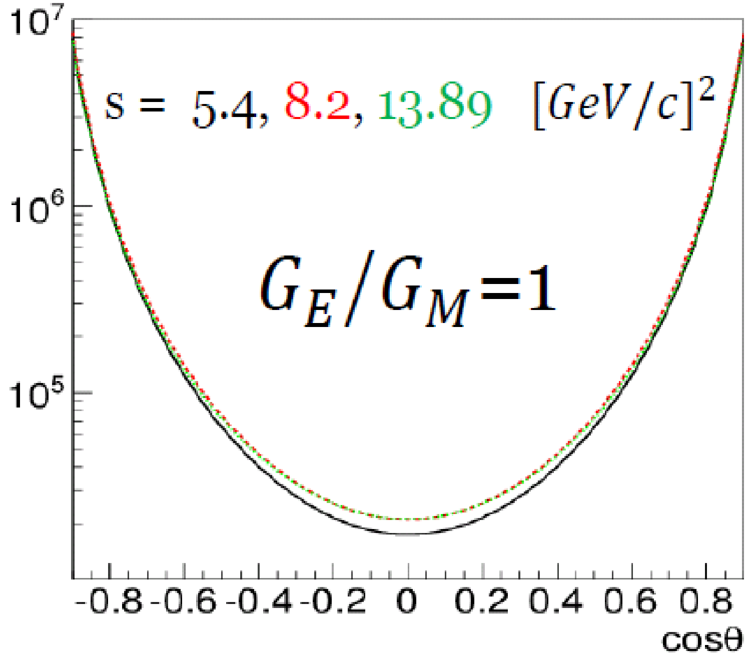
Rejection power should be effective in each bin of the angular distribution

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

$\cos\theta = \pm 0.8$

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

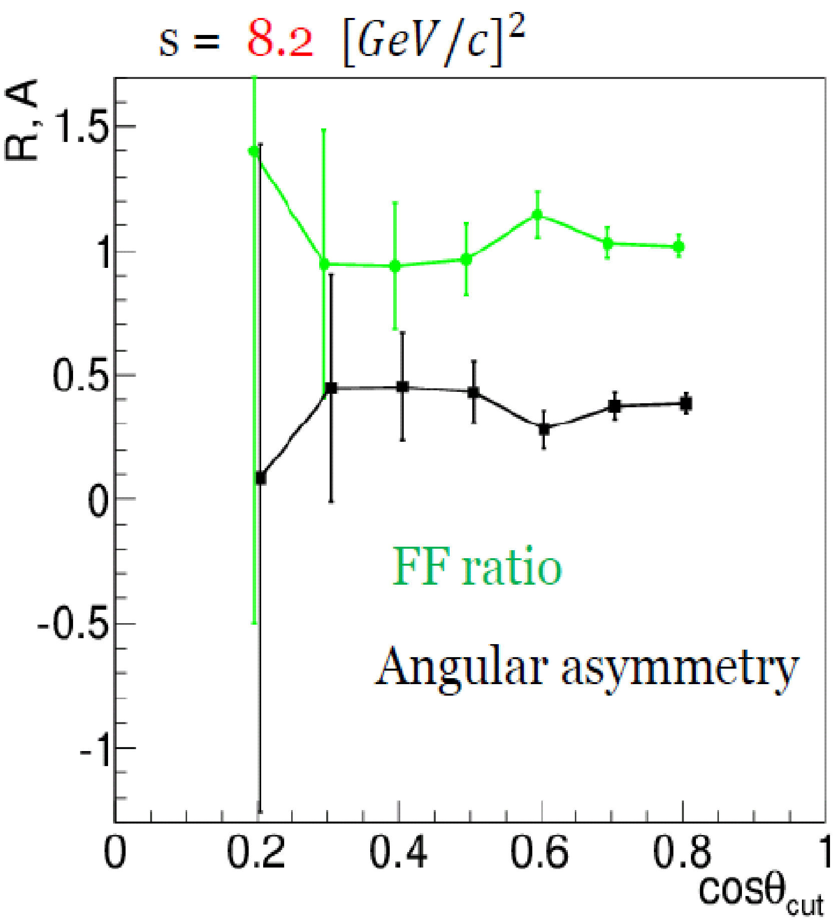
$d\sigma(\pi^+\pi^-)/d\sigma(e^+e^-)$



Differential cross section for the pions

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

Effect of the angular cut



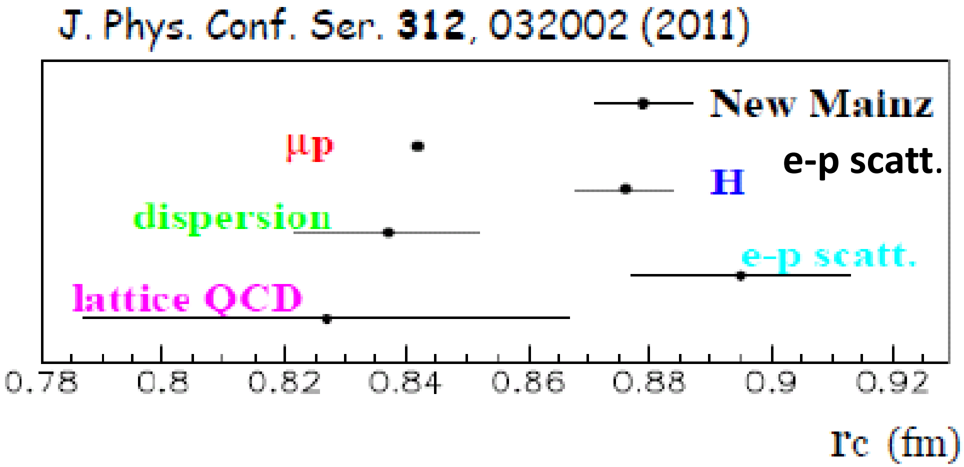
Experimental data on **R** have been extracted in the region of $|\cos\theta|<0.8$:

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

Proton radius puzzle



$r_c = 0.879(8)$

$r_c = 0.84184(67)$

$r_c = 0.8768(69)$

$r_c = 0.895(18)$

Elastic electron proton scattering:

- For small value of momentum transfer squared Q^2:

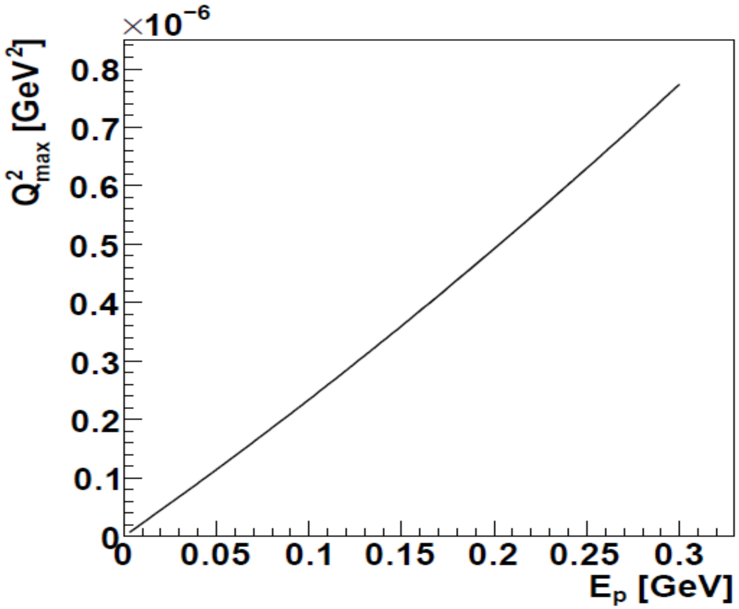
$$G_E(Q^2) = 1 - \frac{1}{6} Q^2 < r_c{}^2 > + O(Q^2) \Longrightarrow < r_c{}^2 > = -6 \frac{dG_E(Q^2)}{dQ^2} \Big|_{Q^2=0}$$

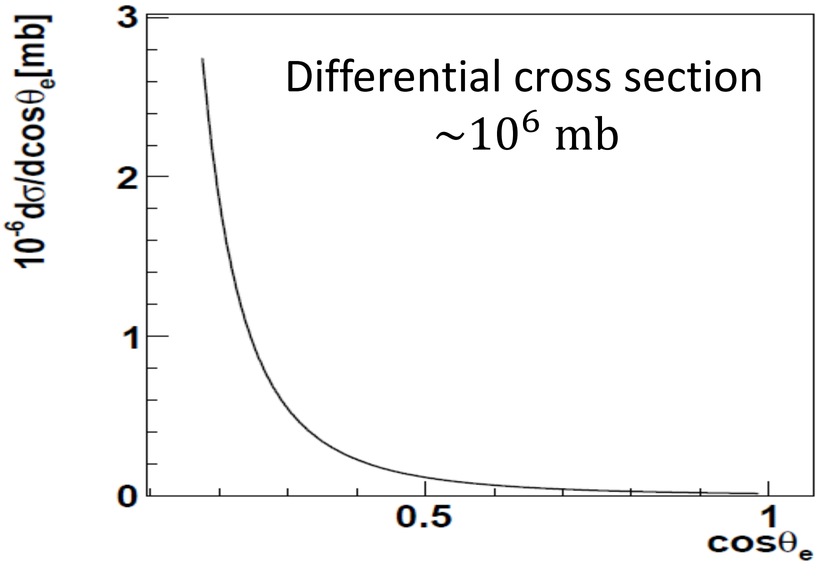
- Precison on the measurement is strongly depend on the fit function of G_E at $Q^2 = 0$:

Minimum value of Q^2 achieved by the experiment is 0.004 GeV^2

J. C. Bernauer et al., Phys. Rev. Lett. 105, 242001 (2010)

Proton radius measurement with *pe* elastic scattering





Q^2: 10^{-3} (ep) → 10^{-7} (pe)

Possibility to accessing low Q^2 value s with high statistics in pe elastic scattering provide precise measurement of proton charge radius

Third application: polarimeters for high energy proton beams.

(I. V. Glavanakov *et al.*, Nucl. Instrum. Methodes Phys. Res. A 381, 275 (1996))

$$\boxed{Angular\ asymmetry = C_{ij} P_i^{targ.} P_j^{beam}}$$

Analyzing power reaction requirements:

1- Smallest theoretical uncertainties as possible at the level of process amplitude.

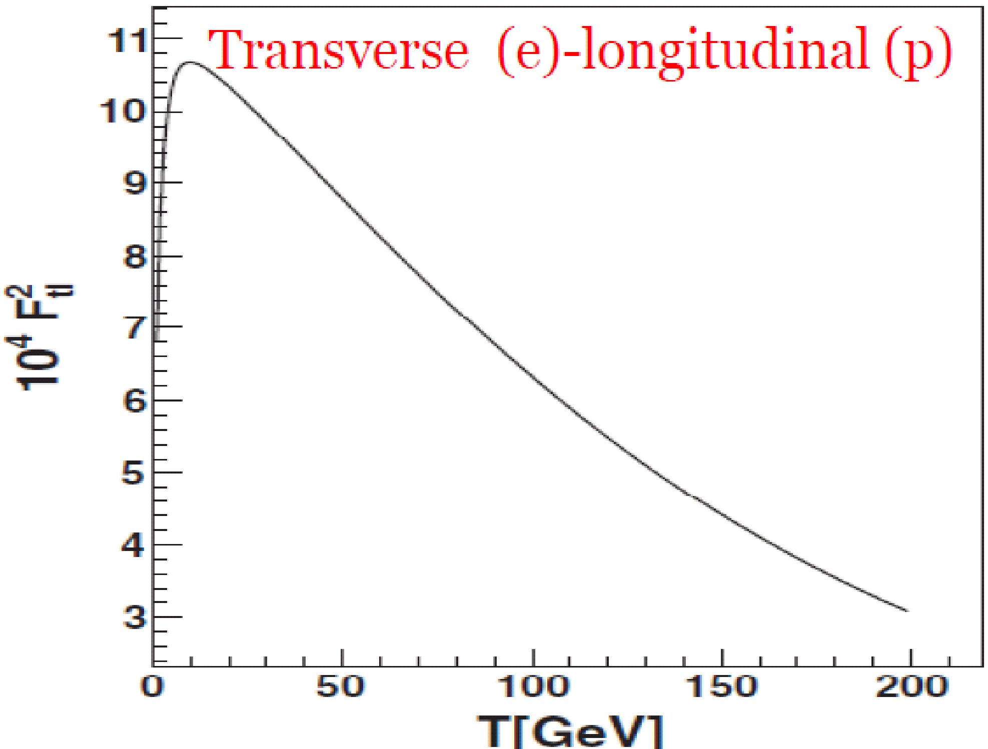
2- Large analyzing power C_{ij}.

$\vec{p}\vec{e}$ elastic scattering fulfills these requirements

The figure of merit

$$\left(\frac{\Delta P}{P}\right)^2 = \frac{2}{\mathcal{L} t_m d\sigma/d\Omega d\Omega C_{ij}^2 P^2}$$

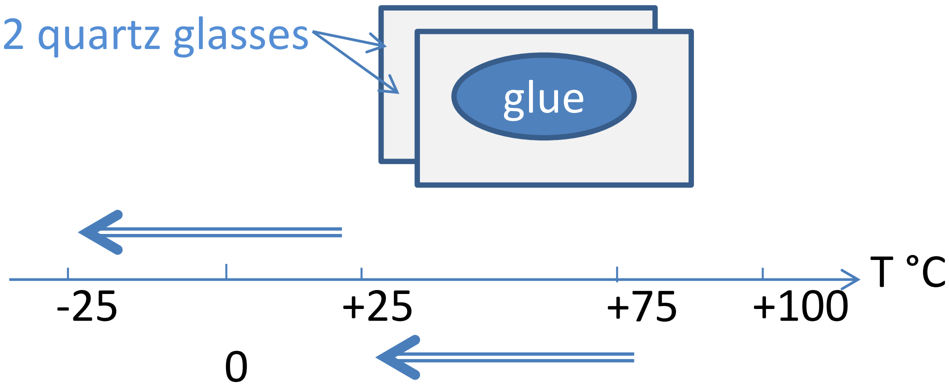
$$\boxed{F_{ij}^2 = \int \frac{d\sigma}{d\Omega} C_{ij}^2 d\Omega}$$



At E~10 GeV,
$\mathcal{L}$ =10^{32} cm^{-2}s^{-1}
Δp=1% in t_m=3min

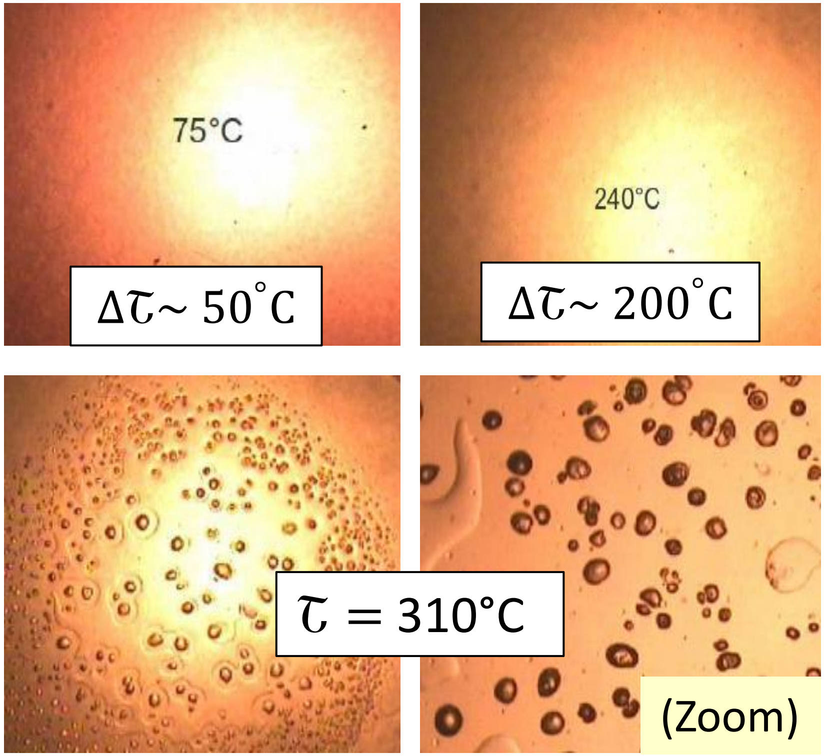
Thermal properties of the glues

Cooling process: $\Delta\tau\ (+25° \rightarrow -25°):\ 50^{\circ}\mathrm{C}$



The Dow Corning glue withstands a temperature variation $\gg 50^{\circ}$ C

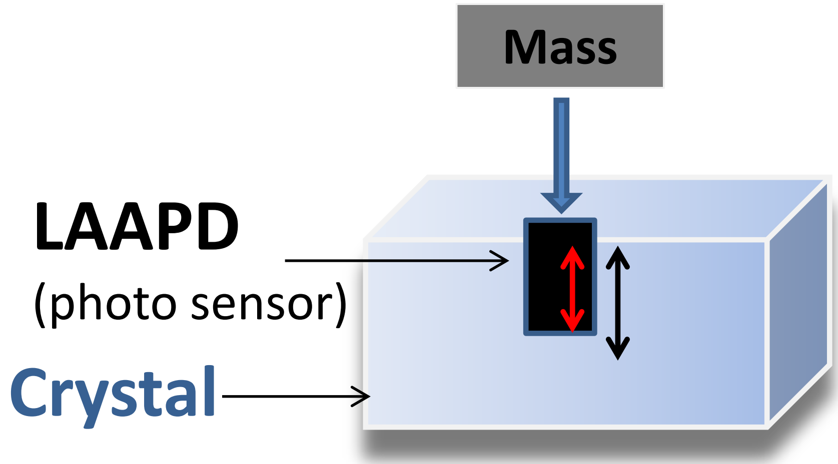
Dow Corning 3145



The **ELASTOSIL® RT 601** was cycled in a climate chamber from +40°C down to -40°C (PANDA collaboration, Bochum group)

Mechanical properties of the glues

The difference ($\Delta\lambda$) of the thermal expansion coefficients between LAAPDs and PWO will induce during the cooling operation mechanical force on the glue : $F \propto \Delta\tau \times \Delta\lambda$~0.5 kg



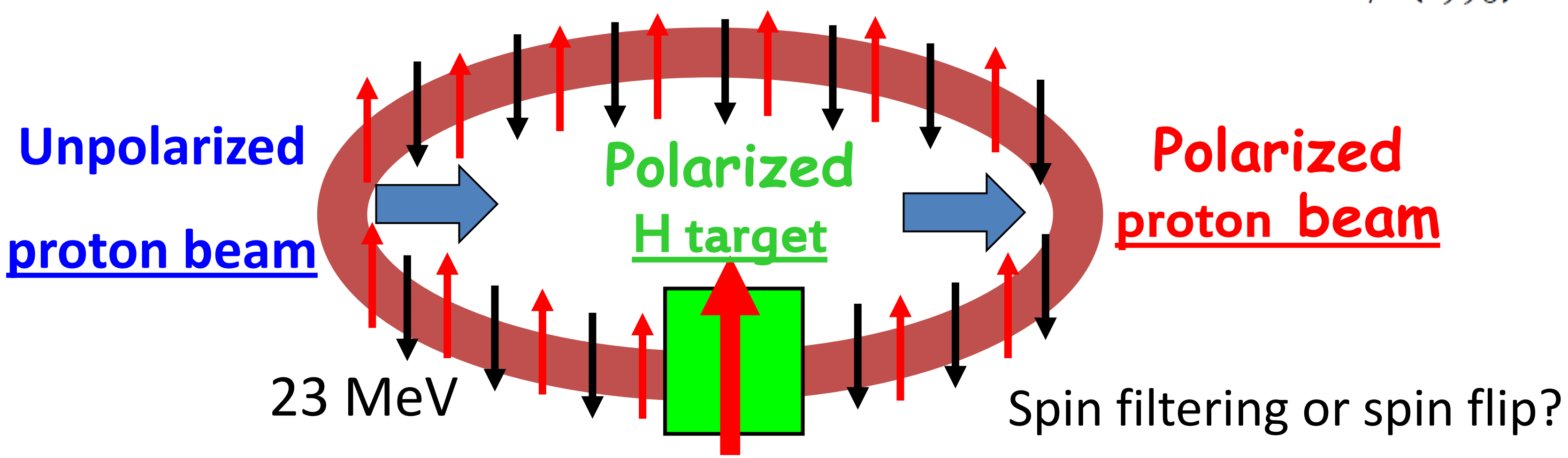
Dow Corning 3145 releases over 50kg.

ELASTOSIL® RT 601 releases over 0.86 kg.

Polarized protons

- **FILTEX** collaboration (1992):
  the proton beam get polarized when passing through hydrogen target (proton-proton and proton-electron scattering)

Rathmann PRL 71 (1993)



- Recent experiment studies at COSY show that:
  the polarization transfer from electron target at **low energy** can not polarize the proton beam

D. Oellers, Phys. Lett. B **674** (2009) 269-275

- Polarization transfer in *pe* elastic scattering at high energy ?