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Electromagnetic Processes in PANDA

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OUTLINE

- **electromagnetic form factors in the timelike region**

- **electromagnetic probe opportunities with PANDA, Transition Distribution Amplitudes**

- **summary and conclusions**

Electromagnetic structure of hadrons

- **hadrons: particle states in an interacting QFT of quarks and gluons: QCD**
- **quarks: electric charge $\Rightarrow j^\mu(x)$ observable $\Rightarrow$ electromagnetic structure**

$$\langle \bar{N}(p') \,|\, q_u \bar{u}\gamma_\mu u + q_d \bar{d}\gamma_\mu d + \cdots \,|\, N(p) \,\rangle =$$

$$\bar{u}(p')\left\{ F_1(q^2)\gamma_\mu \;+\; F_2(q^2)\frac{1}{4M}[\hat{q},\gamma_\mu]\right\}u(p), \qquad \hat{q} \equiv q_\nu\gamma_\nu$$

Dirac (F_1) — Pauli (F_2)

$$\mathrm{G_E} = \mathrm{F_1} + \tau \mathrm{F_2}$$
$$\mathrm{G_M} = \mathrm{F_1} + \mathrm{F_2}$$

$\longrightarrow$ **encode all hadron electromagnetic structure brought by strong interaction**

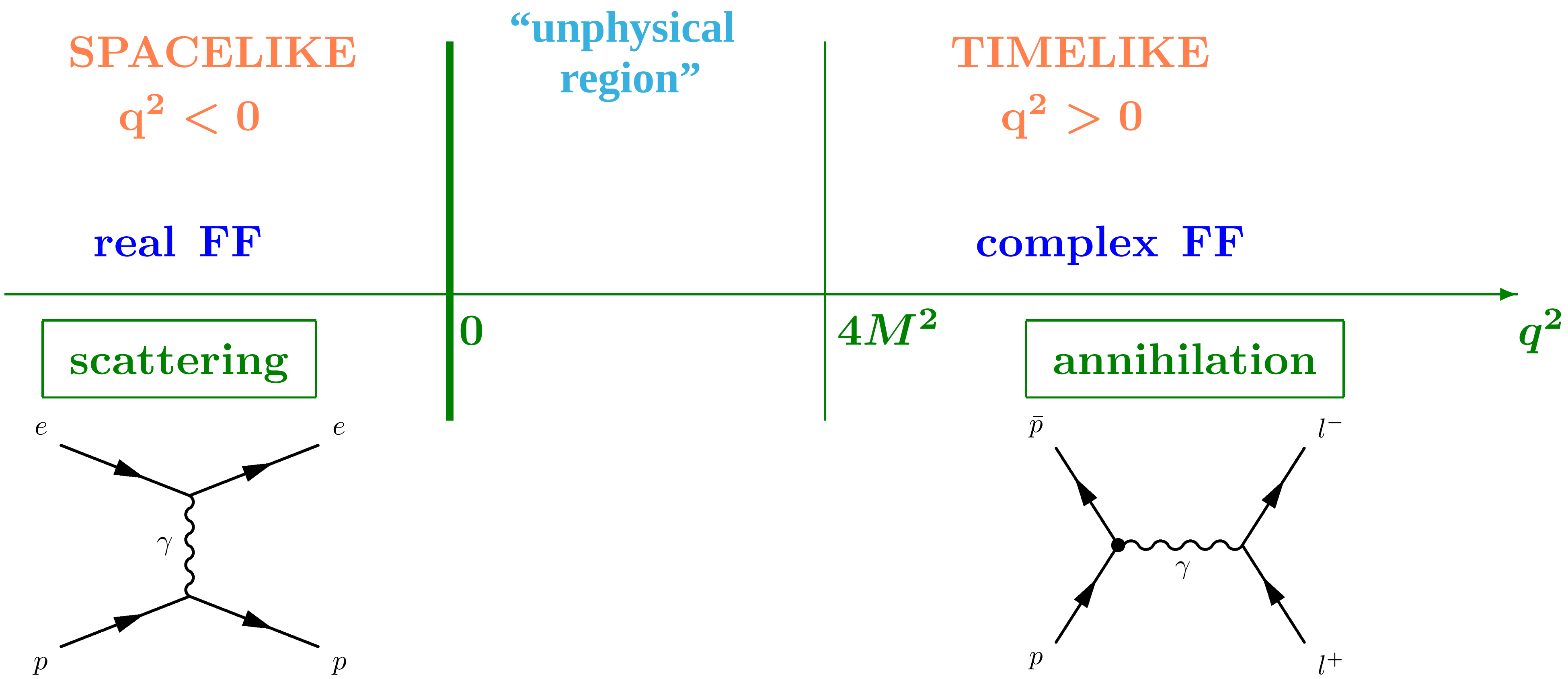
$\longrightarrow$ G_E, G_M **charge and magnetisation spatial distribution (Breit frame)**

measurement of FF (via EM processes, subject to radiative corrections)

i) **observation of hadron EM structure**

ii) **test of non-perturbative QCD predictions (lattice QCD, ChPT), constraints for model building**

Electromagnetic proton form factors



cross section (Rosenbluth)
~~single~~/double spin observables

cross section (angular distribution)
single/double spin observables

- **same matrix element: highly explored in spacelike region, almost unknown in timelike**
- **early investigations in the fifties, still a hot topic in hadron physics: many open questions**

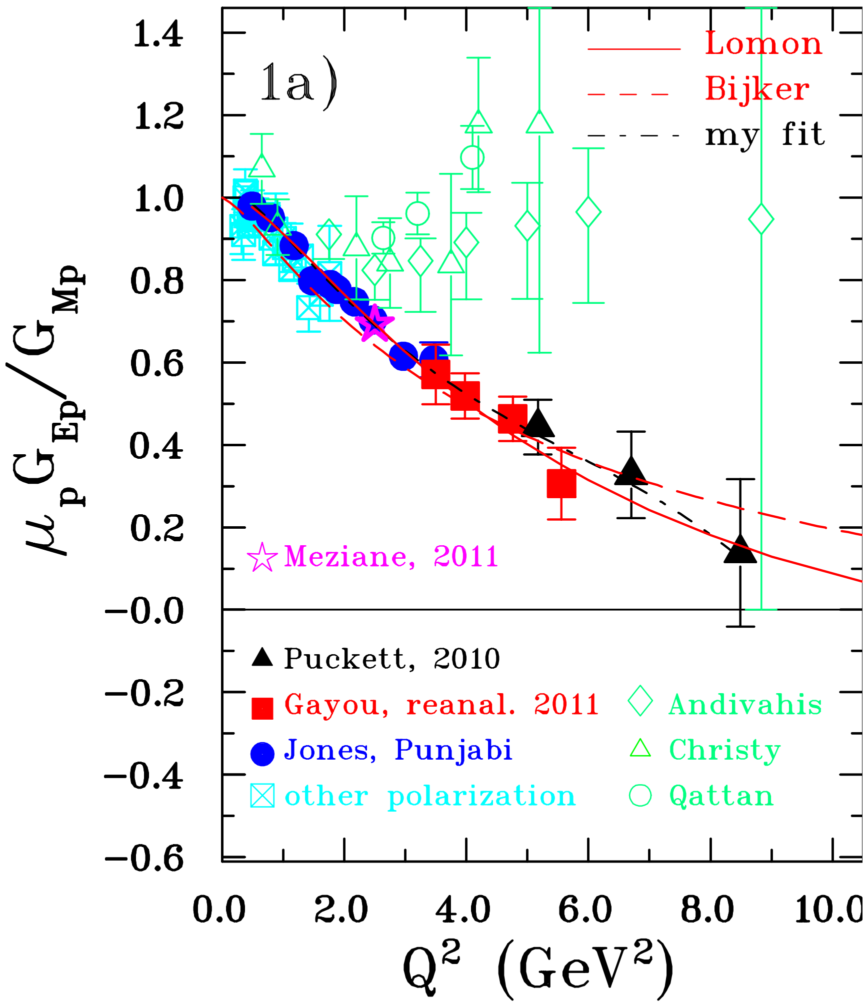
  $\rightarrow$ **charge radius of the proton**
  $\rightarrow$ **incompatibility of Rosenbluth and polarisation data in spacelike**
  $\rightarrow$ **structure of the unphysical region: resonance content, implications in dispersive analysis**

Electromagnetic proton form factors

SPACELIKE ($q^2 < 0$)

many high precision measurements

Rosenbluth separation / polarization transfer



Rosenbluth: $\mu G_E/G_M \sim 1$

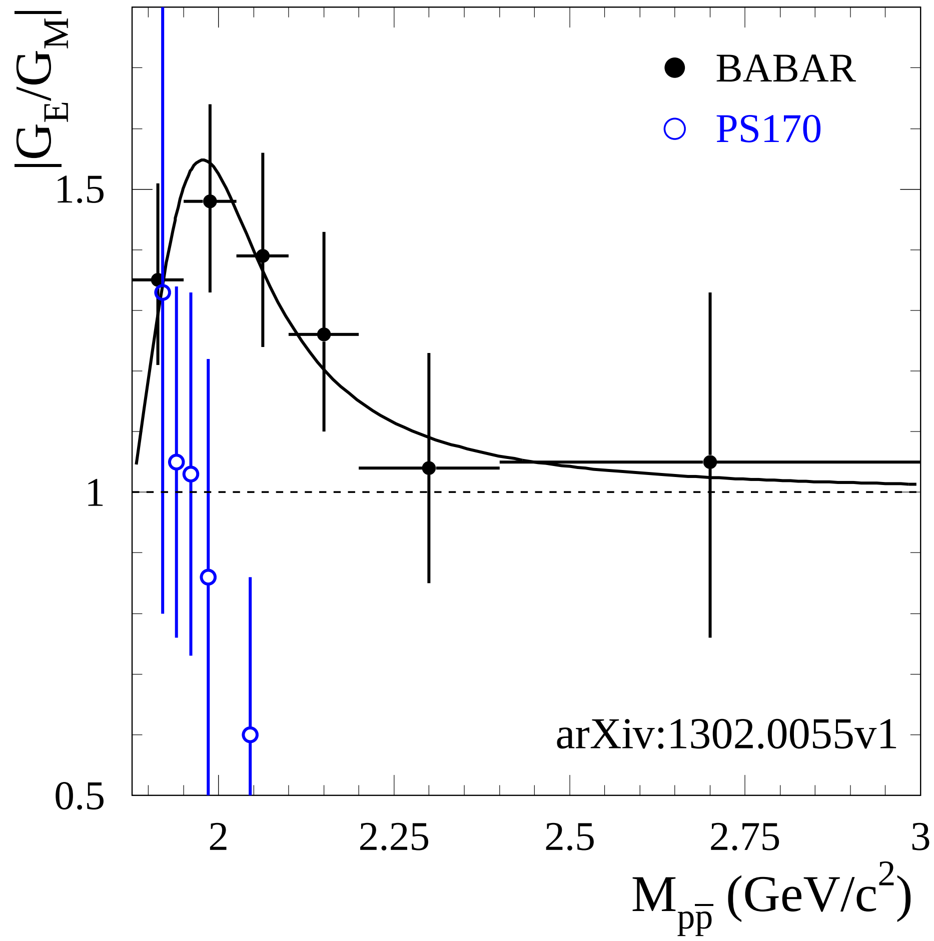
polarisation: $G_E/G_M \sim a + bq^2$

radiative corrections ?

TIMELIKE ($q^2 > 0$)

few low precision measurements

cross section (angular distribution)



PANDA

Timelike EM form factor : $\bar{p}p \to e^+e^-$, cross section

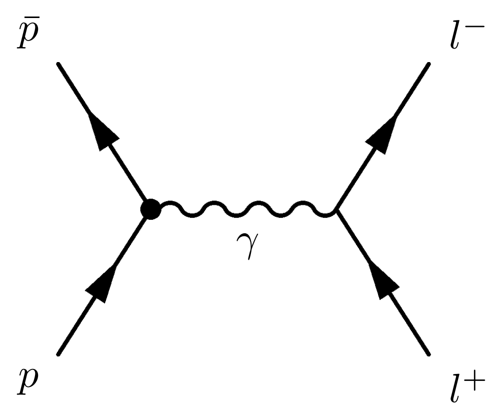
- **at the lowest order (one-photon exchange approximation):**

A.Zichichi et al., Nuovo Cimento XXIV, 170 (1962)

$$\frac{d\sigma}{d\cos\theta^*} = \frac{\pi\alpha^2}{2s}\frac{1}{\beta}\left\{(1+\cos^2\theta^*)\,|G_M|^2 + \frac{1}{\tau}(1-\cos^2\theta^*)|G_E|^2\right\}$$

$$= \frac{\pi\alpha^2}{2s\tau}\frac{1}{\beta}|G_M|^2\left\{\tau\,(1+\cos^2\theta^*) + (1-\cos^2\theta^*)\frac{|G_E|^2}{|G_M|^2}\right\}$$

$$\tau = q^2/4M^2$$

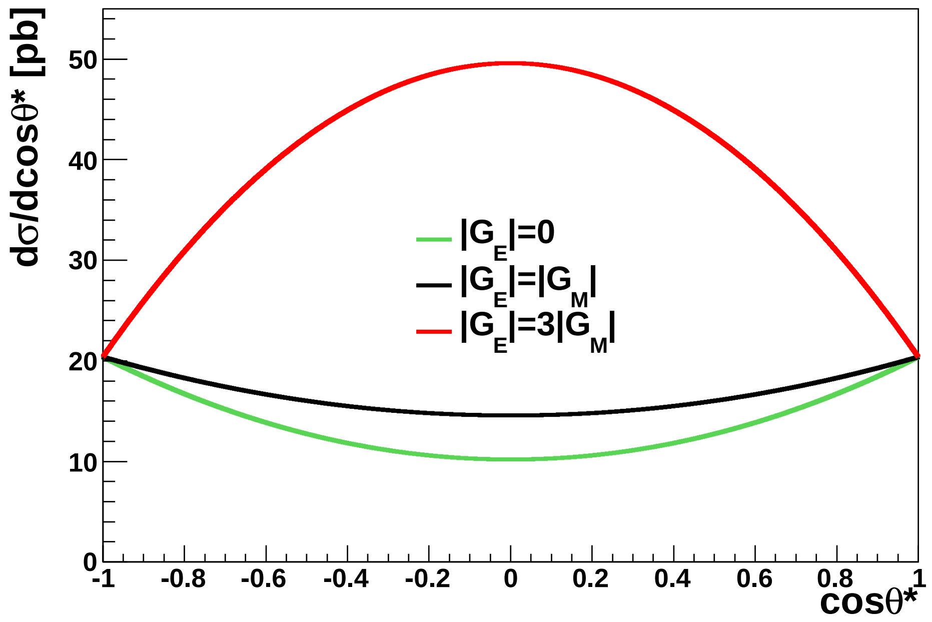


$\to$ **extract $|G_E|$ and $|G_M|$: with luminosity measurement, low q^2 (no $|G_E|$ suppression)**

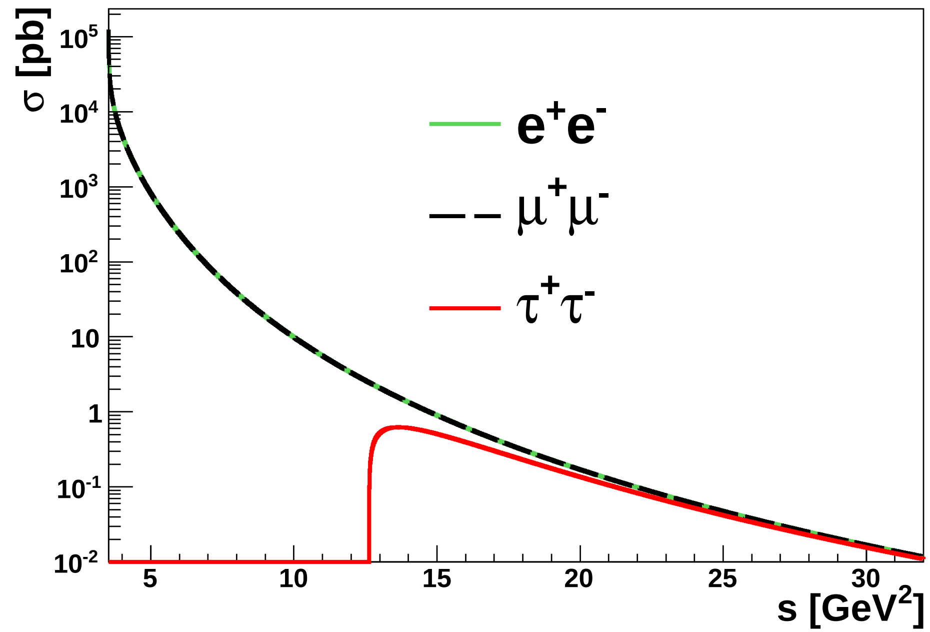
$\to$ **extract $|G_E|/|G_M|$**

- **integrated cross section:** $\sigma = \frac{4}{3}\frac{\pi\alpha^2}{\beta s}\left[|G_M|^2 + \frac{1}{2\tau}|G_E|^2\right]$ $\Rightarrow$ **effective FF, assume** $\frac{|G_E|}{|G_M|}$

differential cross section



integrated cross section

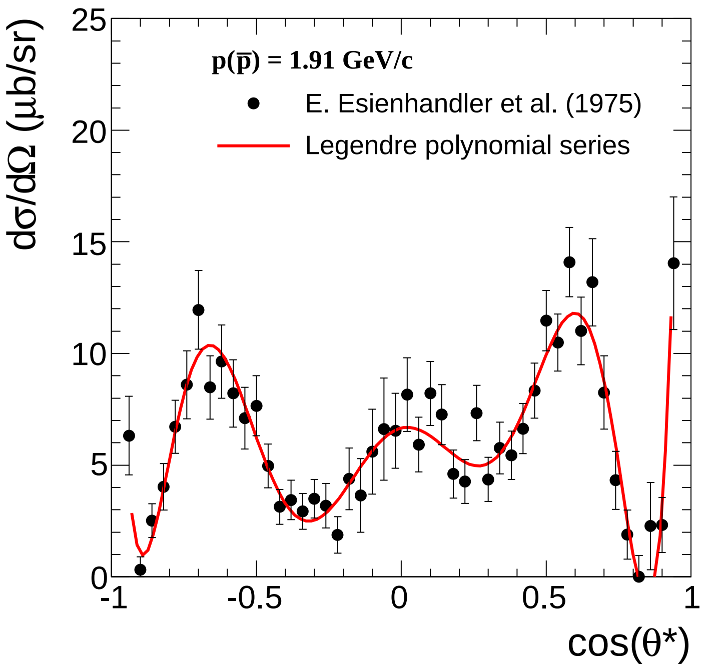


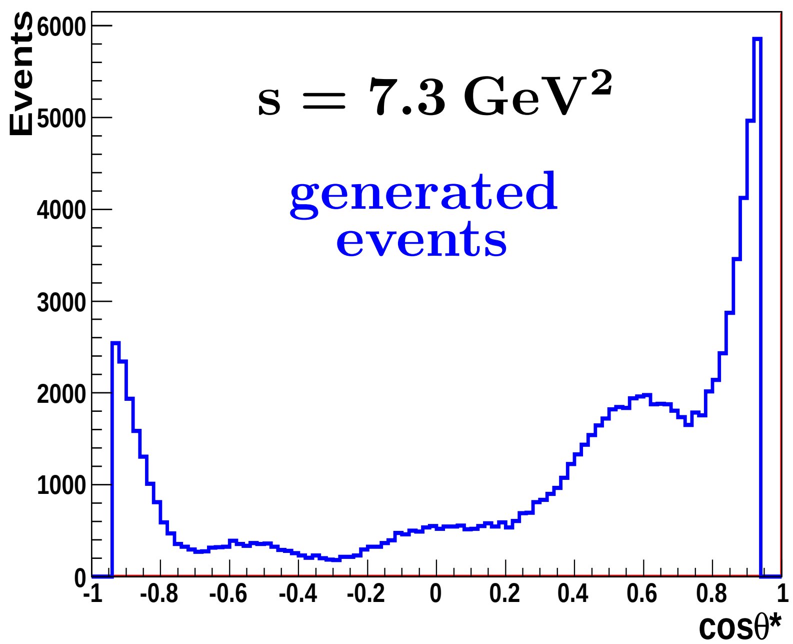
Timelike EM form factor : $\bar{p}p \to e^+e^-$, pion background

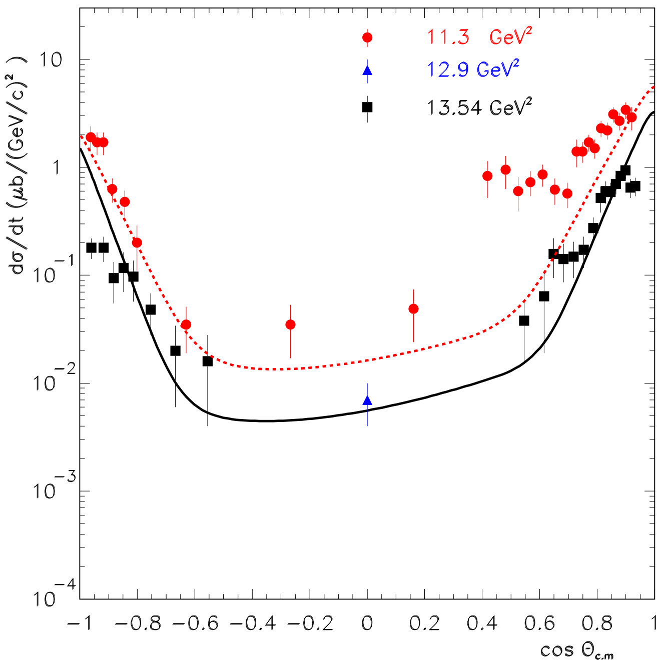
- **difficulty in $\bar{p}p \to e^+e^-$ reconstruction: suppression of $\bar{p}p \to \pi^+\pi^-$ background:**
  $\sigma(\pi^+\pi^-)/\sigma(e^+e^-) \sim 10^6 \Rightarrow$ suppression factor of 10^8 needed for 1% pion pollution

	low energy		transition region		high energy
		~ 6		9	s(GeV²)
data :	Eisenhandler et al. NP B 96 (1975)				A. Eide et al. NP B 60 (1973) T. Buran et al. NP B 116 (1976) C. White et al. PR D 49 (1994)
model :	**Legendre polynomial fit**		← interpolation →		**Regge Theory** J. Van de Wiele and S. Ong, EPJ A46 (2010)

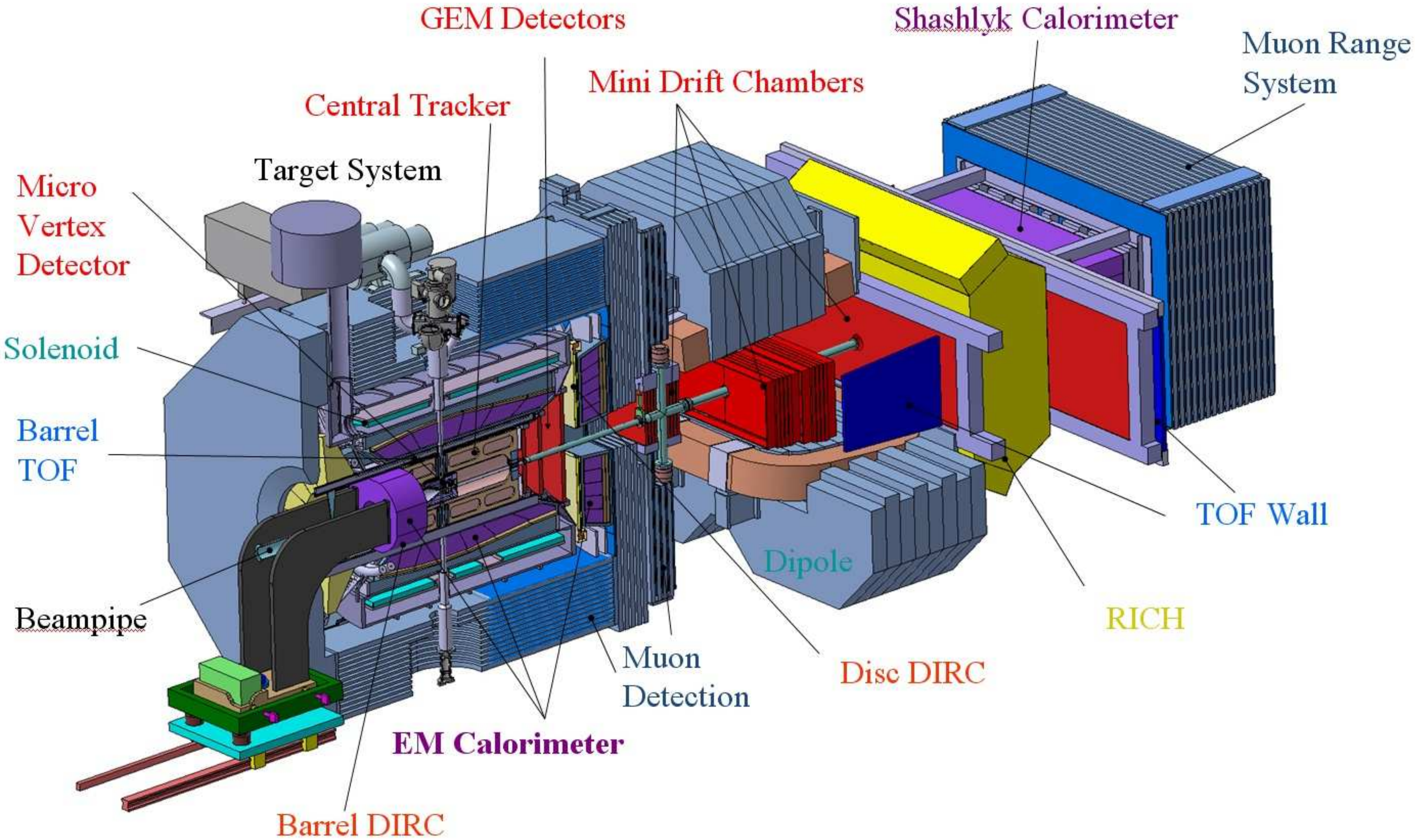
⇒ event generator developed in Mainz
`http://panda-wiki.gsi.de/cgi-bin/view/PANDAMainz/EventGenerators` **(PANDA report)**







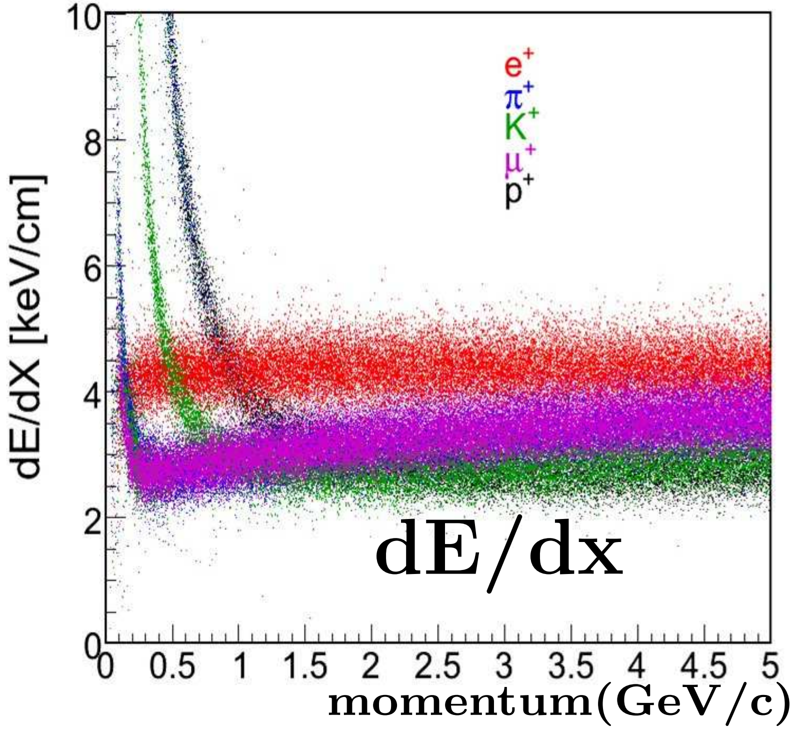
The PANDA Experiment



- $\bar{p}p$ **fixed target experiment at the FAIR facility (GSI, Darmstadt)** $1.5 < \mathrm{P} < 15$ GeV (P : antiproton momentum), **data taking programmed for 2018**
- **high performance: high luminosity** $\mathrm{L} = 2 \cdot 10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$**, good tracking/PID**
- **wide physics program: hadron spectroscopy (up to c-sector, exotics), hadron structure (time-like form factors, TPD), non-perturbative dynamics (TDA, spin), hypernuclei, etc.**

Particle identification capability in PANDA

$\sigma(\pi^+\pi^-)/\sigma(e^+e^-) \sim 10^6 \Rightarrow$ suppression factor of 10^8 for 1% pion pollution $\Rightarrow$ **PID crucial**

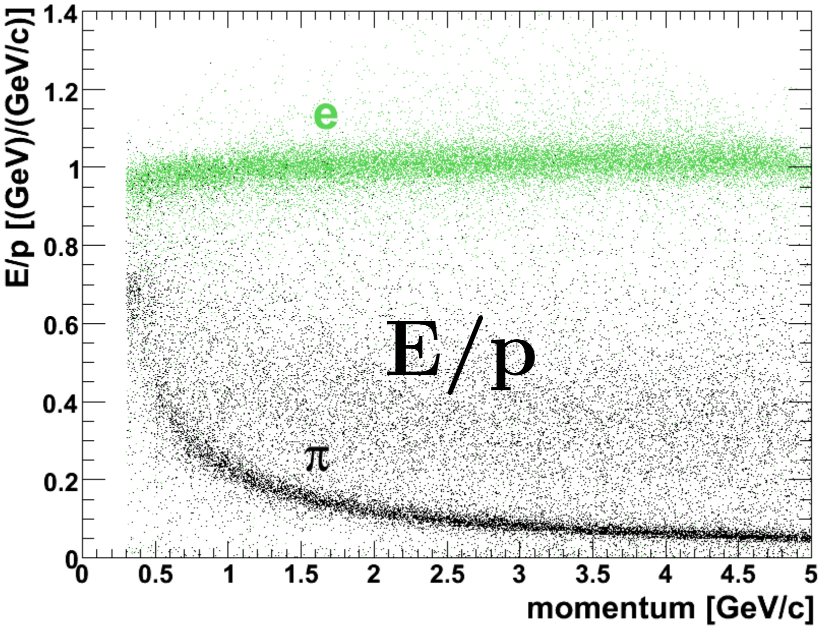


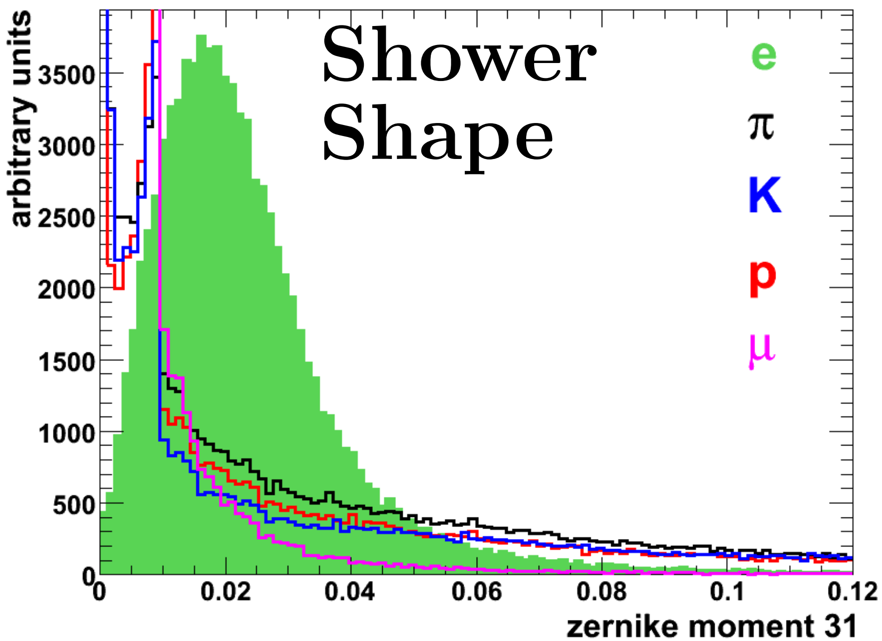
poweful PID capabilities with PANDA

$i)$ **individual detector PID:**
probability under e, μ, π, K, p hypothesis

$ii)$ **global PID: info from $i)$ + standard likelihood**

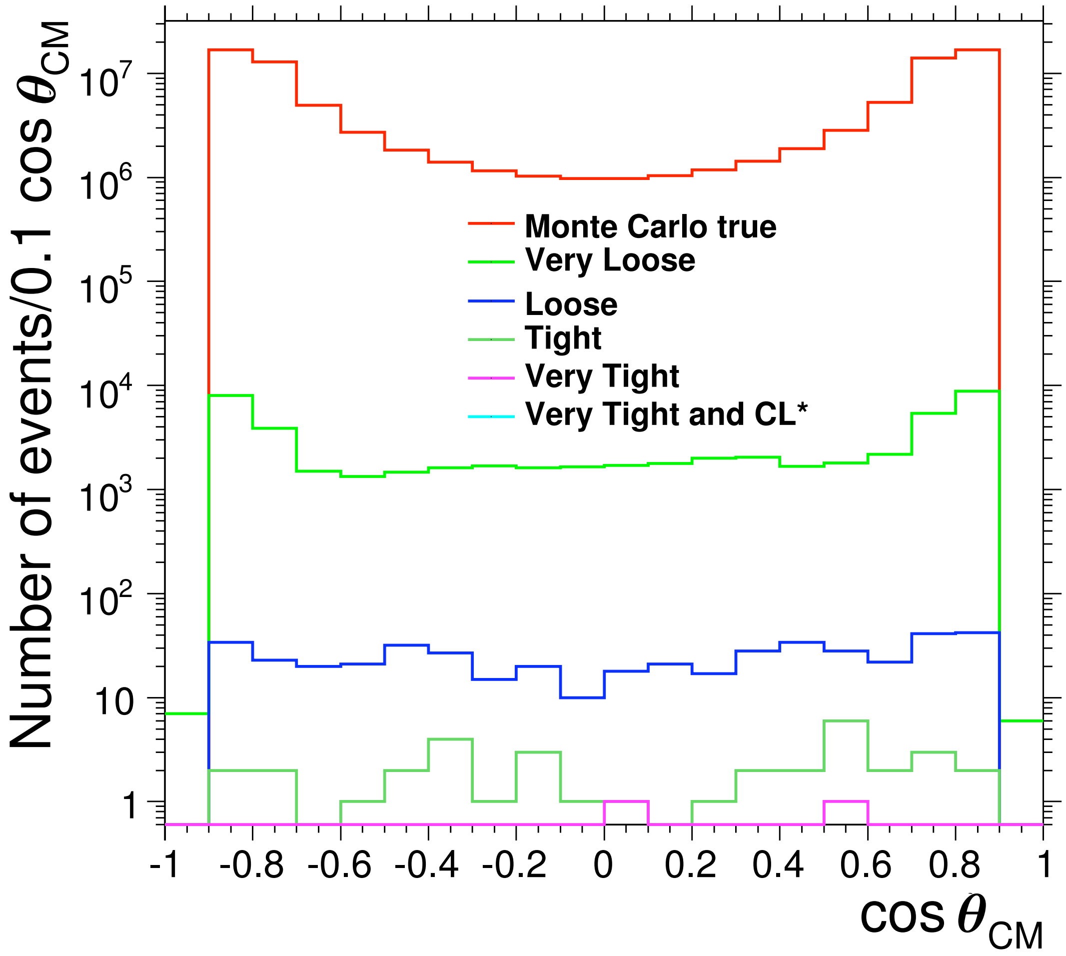
- **energy loss dE/dx at MVD, central tracking spectrometer detector**
- **EMC: efficient and clean e identification with E/p, cluster shower shapes (Zernike moments, etc.)**



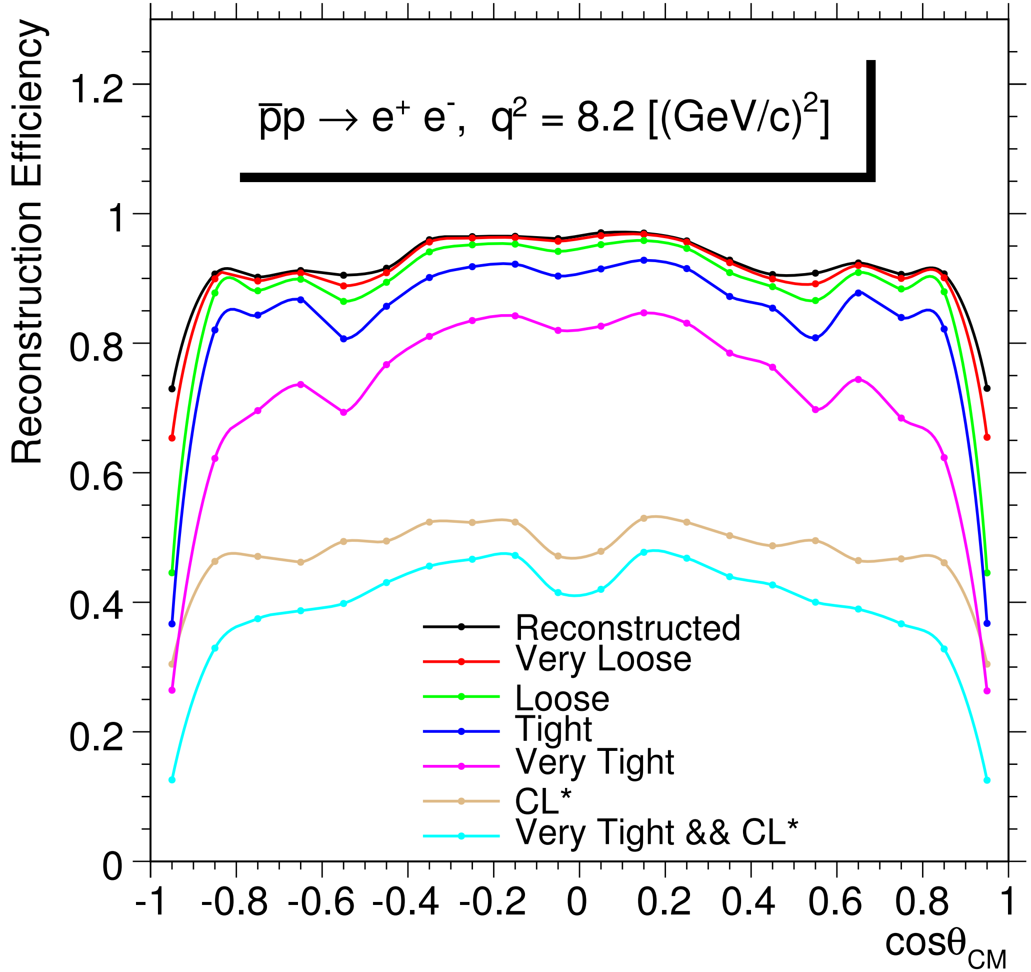


Background suppression and signal efficiency

suppression of $\bar{p}p \to \pi^+\pi^-$



reconstruction of $\bar{p}p \to e^+e^-$



PANDA Collab., "Physics Performance Report for PANDA", arXiv:0903.3905v1

a suppresion factor $> 10^8$ is achieved

$\Rightarrow$ a pion pollution in signal sample $< 1\%$

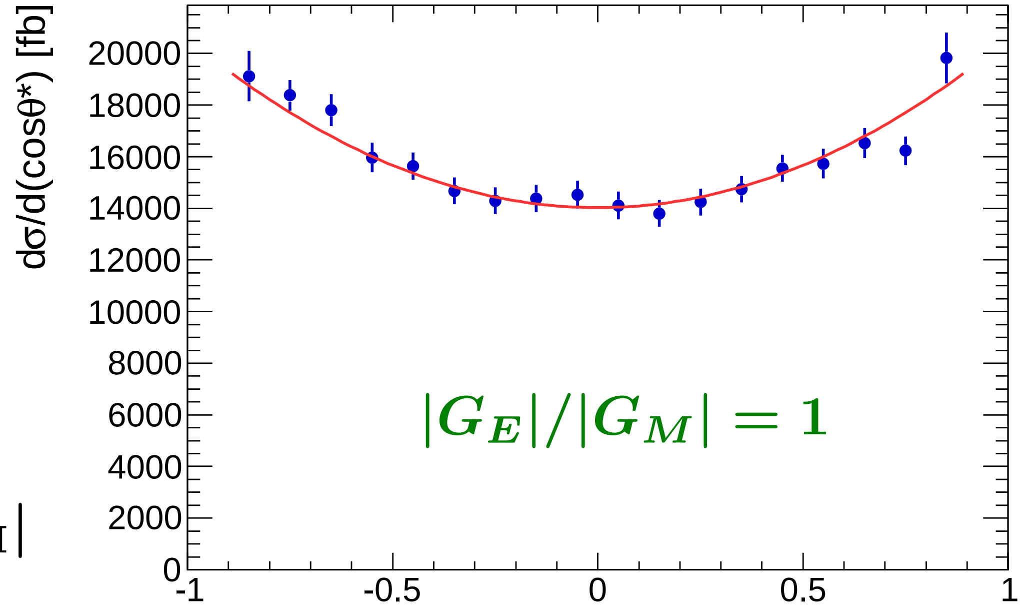
signal efficiency is about 40%

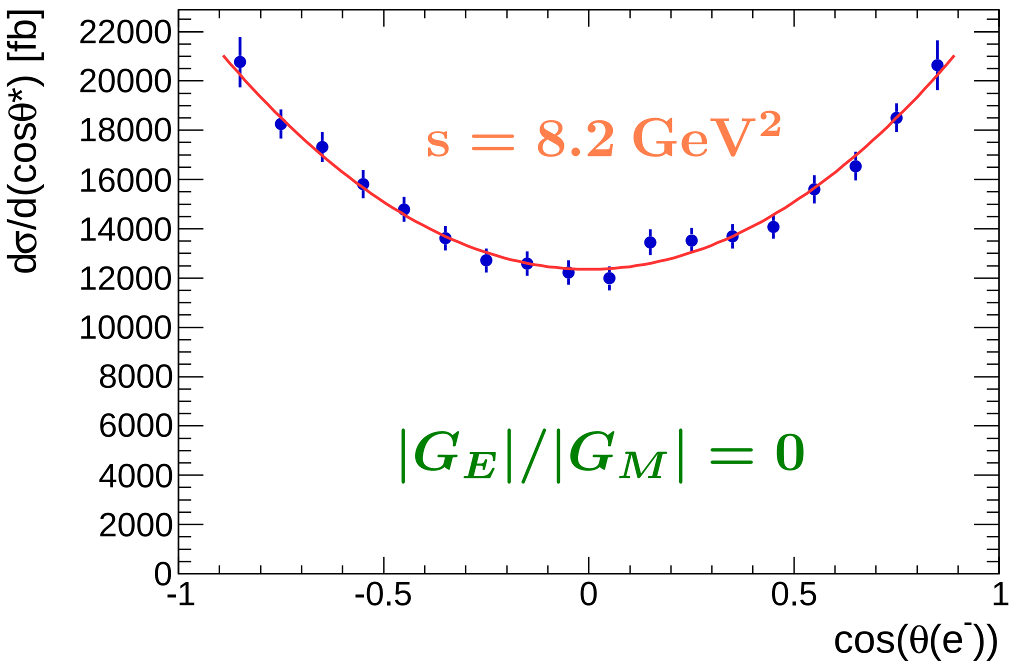
Signal reconstruction, cross section measurement, FF extraction

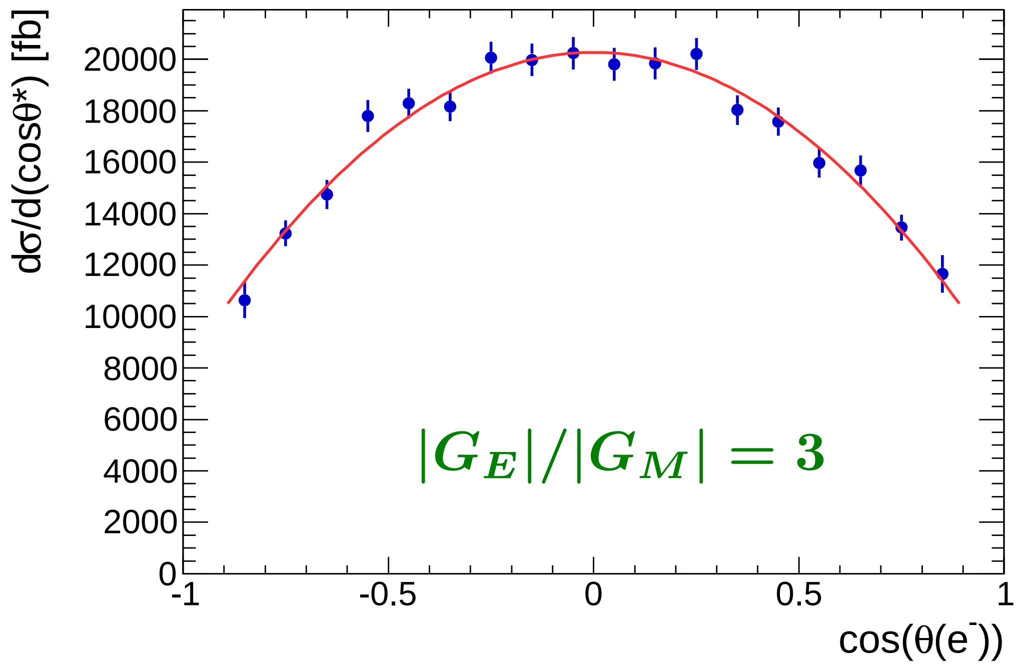
- simulations with $\mathrm{L} = 2\ \mathrm{fb}^{-1}$, several s, $|\mathrm{G_E}|/|\mathrm{G_M}| = 0, 1, 3$
- signal corrected by efficiency ϵ_i
- measure cross section:

$$\sigma_i = \frac{N_i}{\epsilon_i\, L}$$

- fit distribution and extract $|\mathrm{G_E}|$ and $|\mathrm{G_M}|$ or ratio $|\mathrm{G_E}|/|\mathrm{G_M}|$

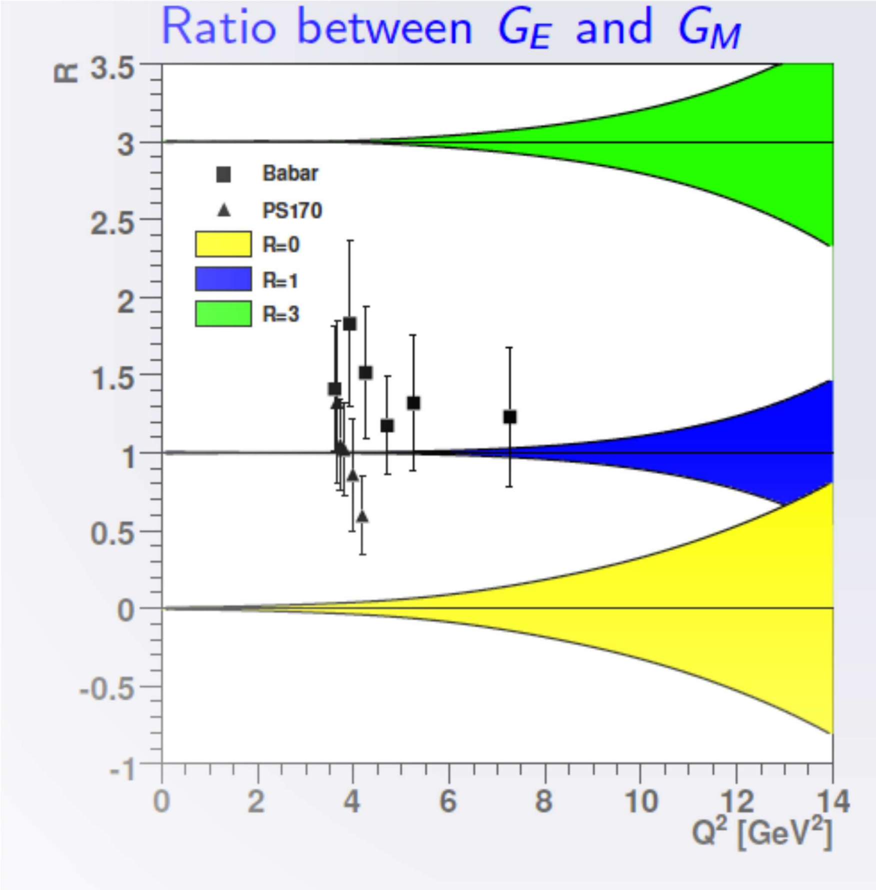




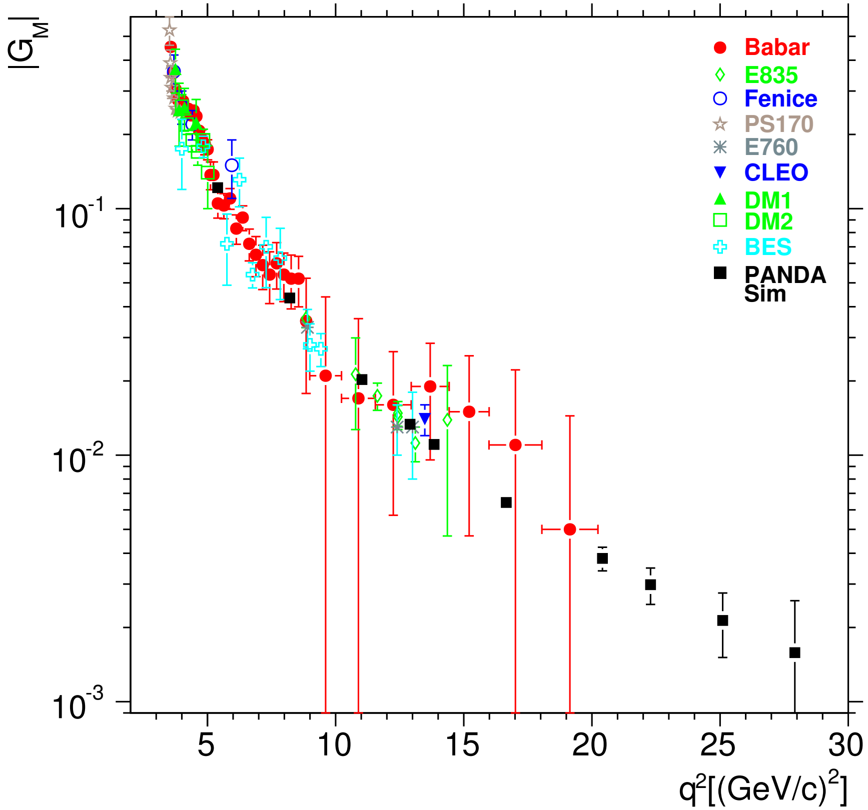


Electromagnetic proton form factor measurement

from angular distribution



from total cross section assumption : $|G_E| = |G_M|$



M. Sudol et al., Eur. Phys. J. A 44, 373-384 (2010)
M.C. Mora Espí, PhD thesis (2012)

⇒ unprecedent precision in PANDA measurements : 50% → 3 − 5%

recent work:

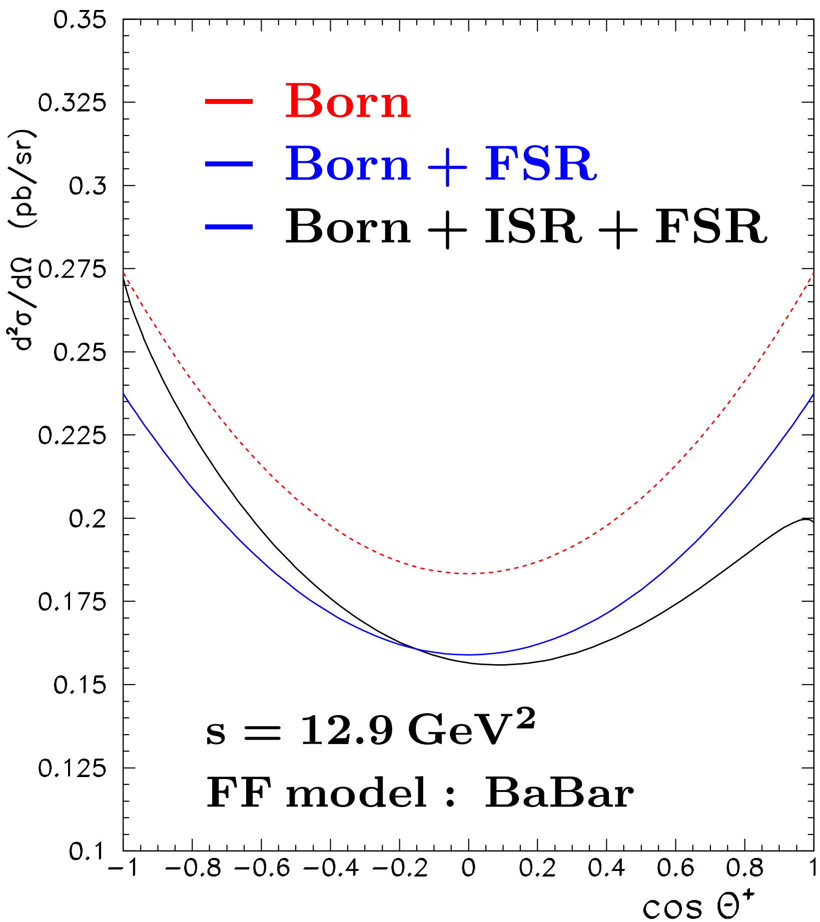
- **new simulations with PandaRoot framework on channel $\bar{p}p \to e^+e^-$ (D. Khaneft)**
- **extension to $\bar{p}p \to \mu^+\mu^-$ (I. Zimmermann)**
- **polarised target in PANDA (B. Feher)**
- **development of event generators (M. Zambrana)**

Electromagnetic radiative corrections

- **measured cross sections subject to radiative effects: correction to bring them to Born level**
- **so far, interference effects of initial state radiation (ISR) and final state radiation (FSR) were neglected**
- **complete $o(\alpha)$ corrections (real: ISR, FSR, virtual, interference) recently calculated**

J. Van de Wiele and S. Ong, Eur.Phys.J. A49 (2013) 18

see also: A.I. Ahmadov et al. Phys. Rev. D 82, 094016 (2010) and G.I. Gakh et al. Phys. Rev. C 83, 0452012 (2011)



interference :
$\Rightarrow$ asymmetry in $\cos\theta^*$ distribution

event generator in preparation

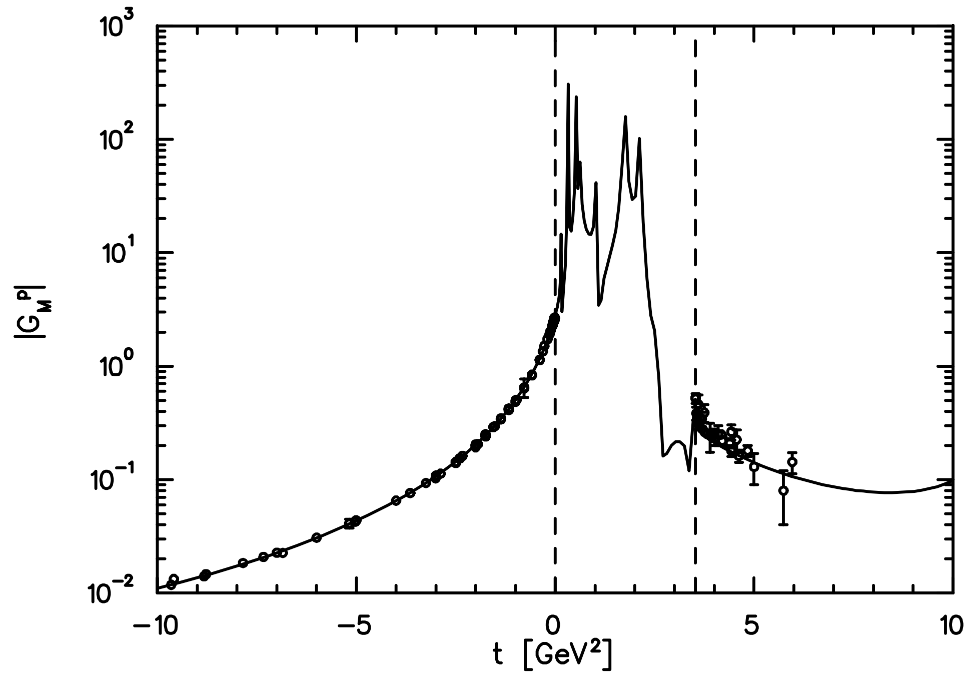
$\bar{p}p \to e^+e^-\pi^0$: form factors below threshold

- **unphysical region $0 < q^2 < 4M^2$ is important:**

  contribution of resonances (e.g. vector mesons) has fundamental implications:

  - **$\to$ dispersion relations**
  - **$\to$ asymptotic behaviour of the form factors**
  - **$\to$ proton radius, etc.**

  $\Rightarrow$ but not accesible by process $\bar{p}p \to e^+e^-$



U. Meissner Nucl.Phys. A666 (2000) 51-60

- **idea: consider $\bar{p}p \to \pi^0\,\gamma^* \to \pi^0\,e^+e^-$**

  A. Z. Dubnickova et al. Z. Phys. C 70, 473 (1996)

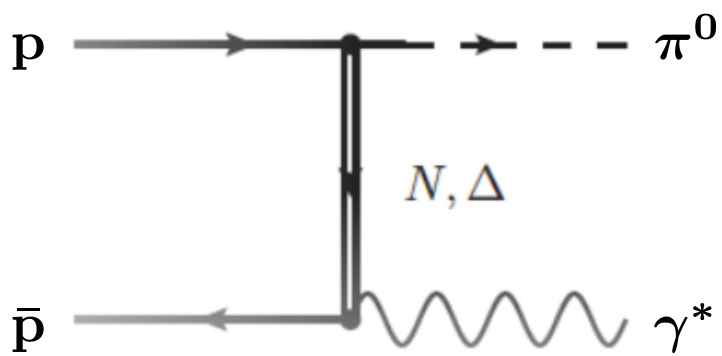
  Adamuscin et al., Phys. Review C 75, 045205 (2007)

part of the initial 4-mom transferred to π^0

$$\Rightarrow 4m_e^2 < q^2 < q^2_{max}; \;\; q^2_{max} = (\sqrt{s} - m_\pi)^2$$

$\Rightarrow$ region $4m_e^2 < q^2 < 4M^2$ accesible

J. Boucher, PhD Thesis (2011)



- **theory issues: model dependence, off-shell FF... best we have now**

$\bar{p}p \to e^+e^-\pi^0$: results in the Regge framework

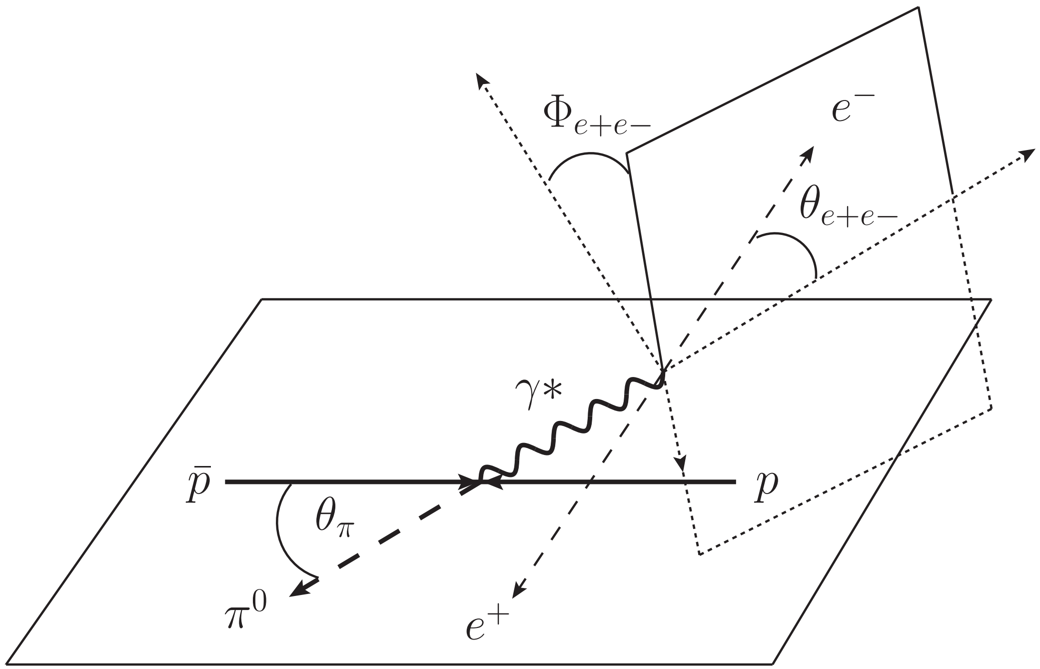
cross section: $d\sigma/dt\, dq^2\, d\Omega_{e^+e^-}$ J. Guttmann and M. Vanderhaeghen, PL B 719 (2013) 136-142

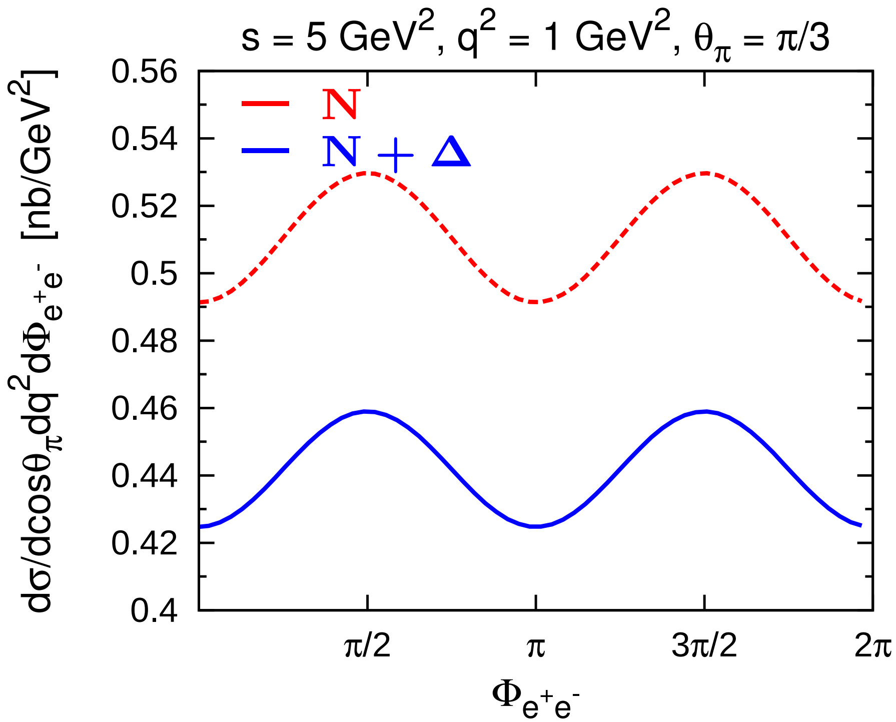
lepton phase space $d\Omega_{e^+e^-} = d(\cos_{e^+e^-})d\Phi_{e^+e^-},\ \Phi_{e^+e^-} = \angle(\text{leptonic plane, hadronic plane})$

$\Phi_{e^+e^-}$ **modulation $\Rightarrow$ access to FF phase difference through interference terms $G_E G_M$ (without polarised target)**

model reproduces real photoproduction data $\bar{p}p \to \pi^0\gamma$,

E760 Collab. (Fermilab), PR D 56 (1997) 2509





$\bar{p}p \to e^+e^-\pi^0$: Transition Distribution Amplitudes

- **new analysis topic in Mainz PANDA group introduced to us by Bernard Pire**
- $\bar{p}p \to e^+e^-\pi^0$ **admits QCD collinear factorisation at high $M(e^+e^-)$ and low $p_T(\pi_0)$ in terms of Distribution Amplitudes (DAs) and Transition Distribution Amplitudes (TDAs)**

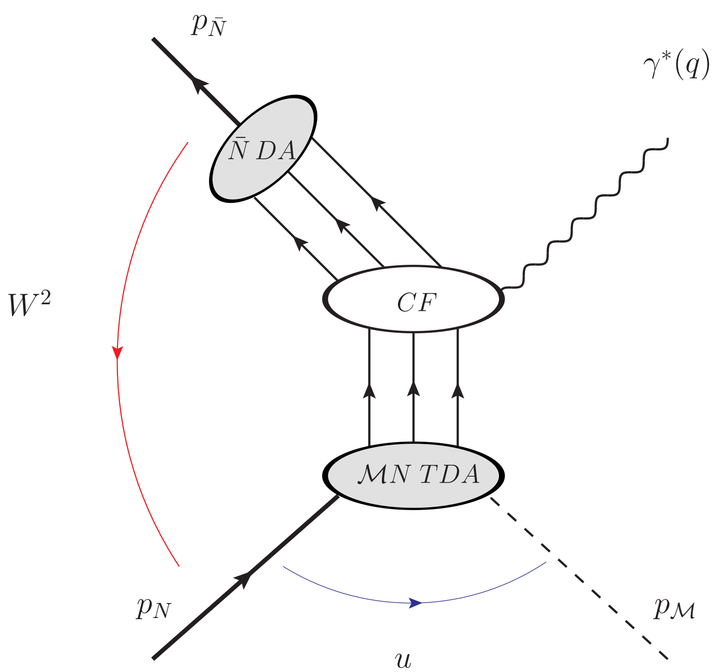
  $\to$ **non-perturbative objects (models)**

J.P. Lansberg et al., PR D 76, 111502 (2007)
J.P. Lansberg et al., PR D 86, 114033 (2012)

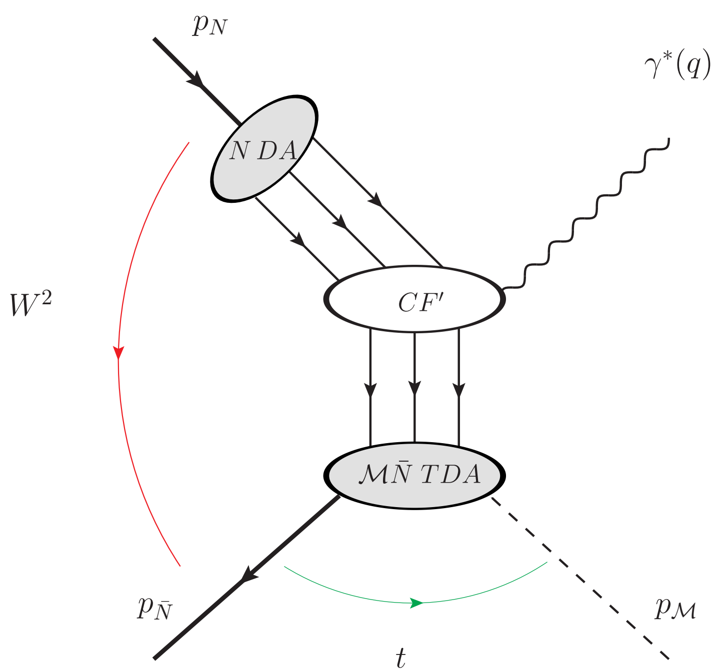
kinematics accesible by PANDA:

cross section measurement $\Rightarrow$ test of QCD factorisation and access to TDAs

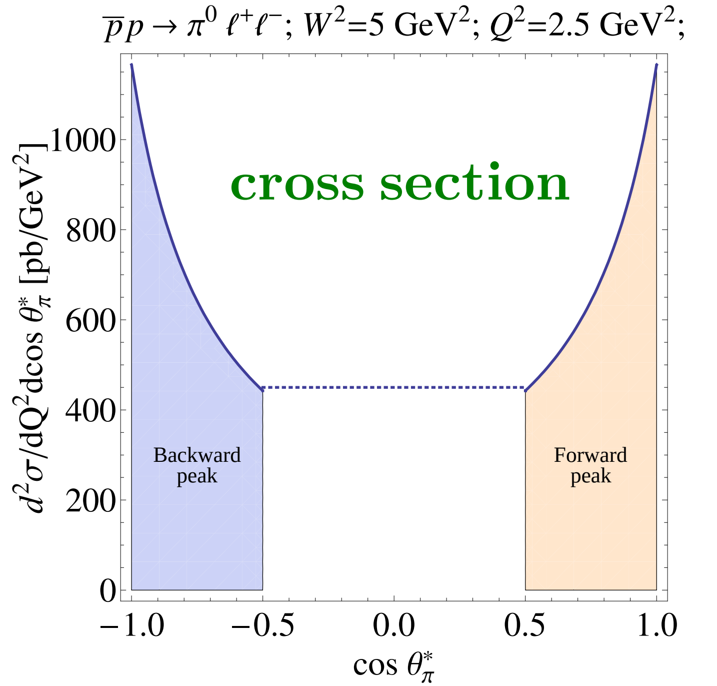
π^0 backwards



π^0 forward

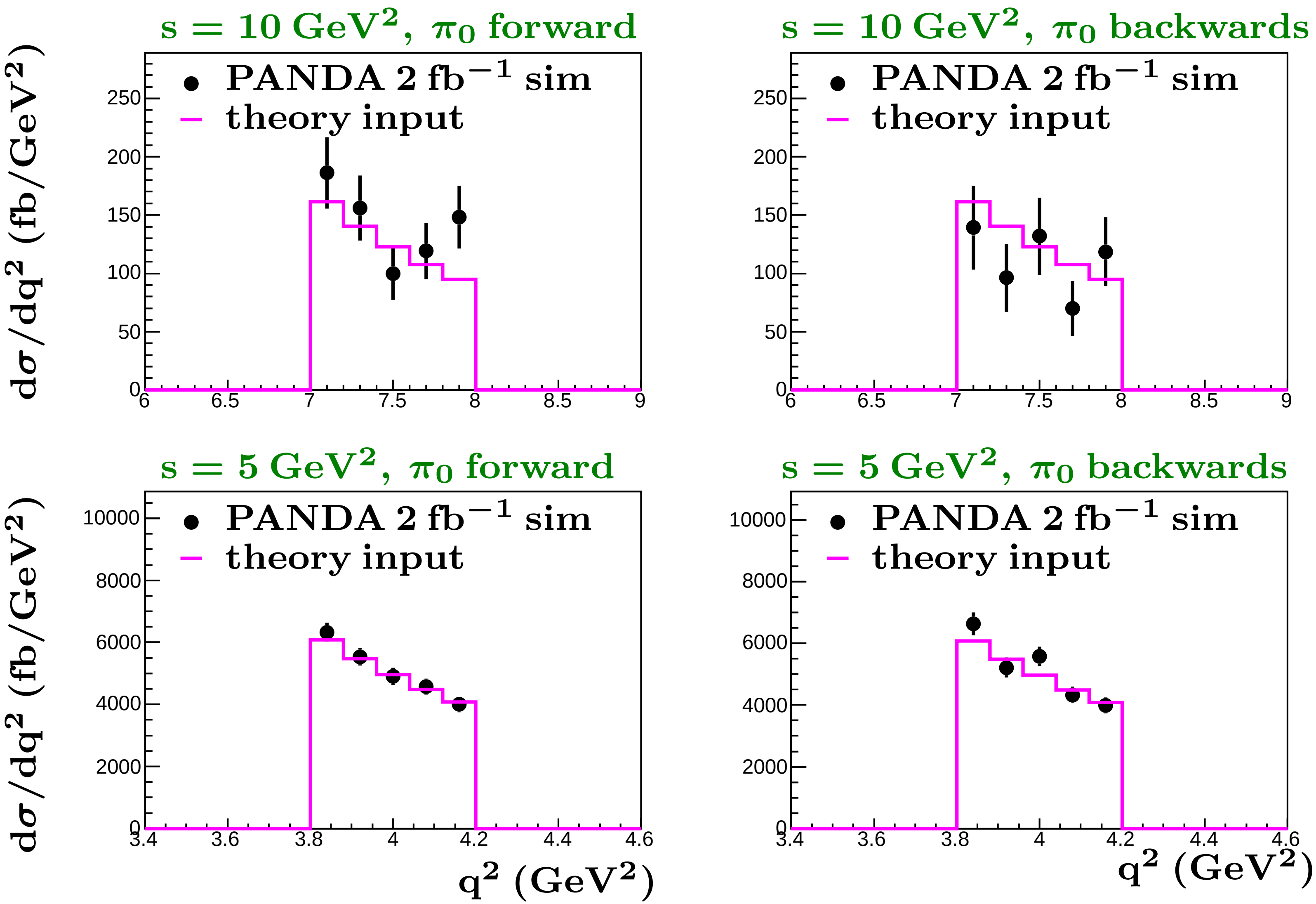


π^0 forward/backward peak



$\bar{p}p \to e^+e^-\pi^0$: simulations with TDAs cross sections

- **simulations done with $p_T(\pi_0) = 0$, cross section extrapolated up to $|\cos(\theta_{\pi_0})| > 0.85$**
- **$\bar{p}p \to \pi^+\pi^-\pi^0$ background assumed to be 10^6 higher than $\bar{p}p \to e^+e^-\pi^0$, with identical angular distributions** $\Rightarrow$ suppression factor of 10^8 achieved



M.C. Mora Espí
PhD Thesis (2012)

$\Rightarrow$ measurement at $s = 5$ GeV^2 and $s = 10$ GeV^2 feasible

Summary and conclusions

- **electromagnetic nucleon form factors with PANDA: unprecedent precision (from 50% to 5 − 3%)** $\bar{p}p \to e^+e^-$

- **hadron cross sections 10^6 larger than signal: suppression factor of 10^8 achieved (⇒ background pollution $< 1\%$) due to PANDA PID capabilities and kinematical fit**

- **polarised target and/or beam in PANDA: access to form factors imaginary part**

- **active theory: model building for time-like form factors, radiative corrections (ISR, FSR, two photon exchange), Regge, TDAs physics**

- **PANDA Mainz group current activities:**

  → **new simulations with PandaRoot framework on channel $\bar{p}p \to e^+e^-$ (D. Khaneft)**
  → **extension to $\bar{p}p \to \mu^+\mu^-$ (I. Zimmermann)**
  → **polarised target in PANDA (B. Feher)**
  → **simulations with TDAs cross sections (M.C. Mora Espí)**
  → **development of event generators (M. Zambrana)**

rich nucleon structure program with PANDA,

exciting times for nucleon electromagnetic form factors

Backup Slides

$\bar{p}p \rightarrow e^+e^-$ with polarisation : single/double spin asymmetry

$\bar{p}p \rightarrow e^+e^-$ with transversely polarized target $\Rightarrow$ single/double spin asymmetry

E. Tomasi-Gustafsson et al. Eur. Phys. J. A 24, 419-430 (2005)

$\Rightarrow$ access to form factors imaginary part

angular asymmetry and polarization observables

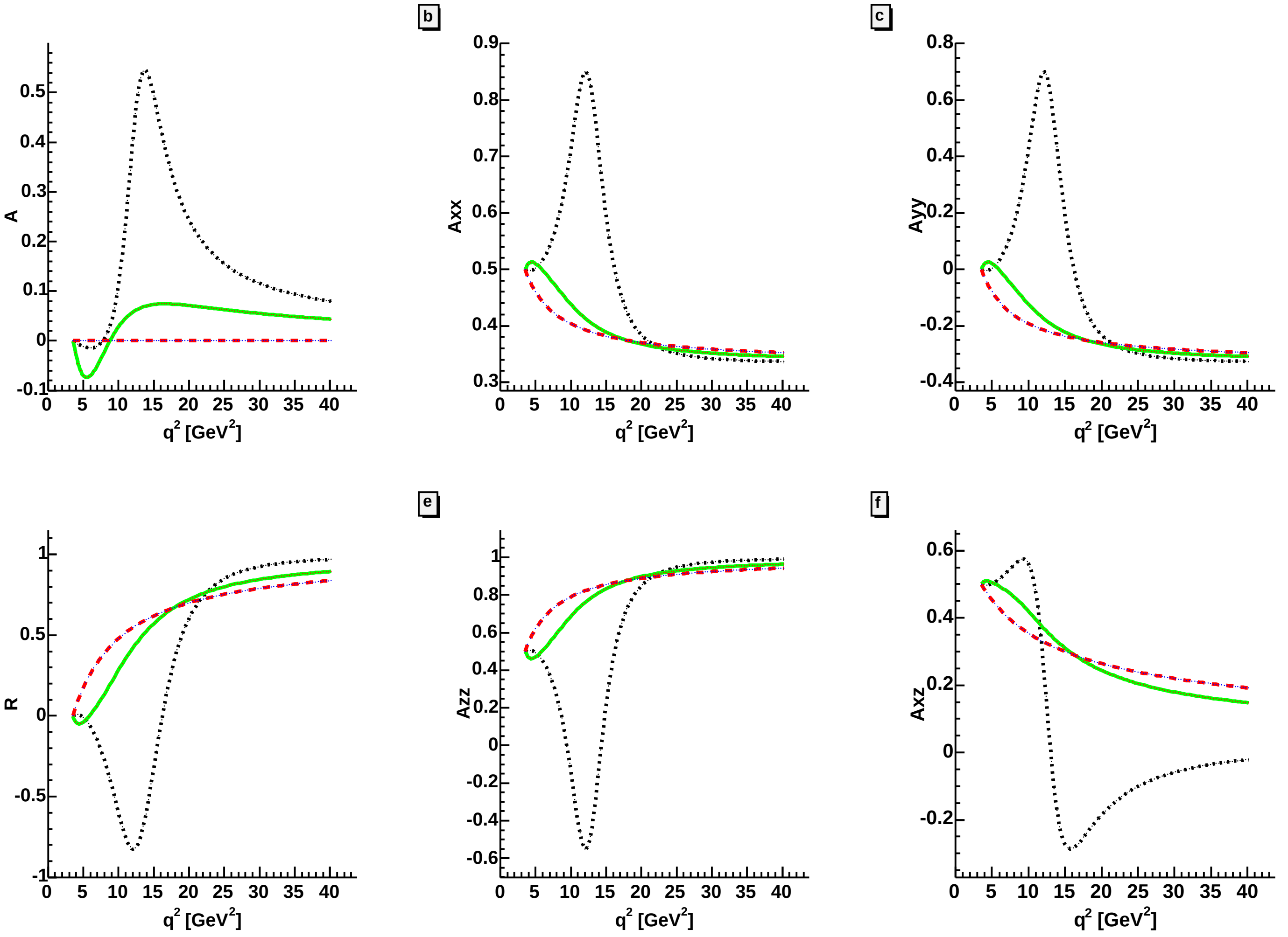
$$\left(\frac{d\sigma}{d\Omega}\right) = \underbrace{\left(\frac{d\sigma}{d\Omega}\right)_0}_{\text{born}} + \left(\frac{d\sigma}{d\Omega}\right)_1$$

$$\left(\frac{d\sigma}{d\Omega}\right)_1 = \frac{\alpha^2}{4s\beta}\frac{1}{\tau^{1/2}} \times S_y \ \sin 2\theta \ \mathrm{Im}(G_M G_E^*)$$

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_y S_y = \left(\frac{d\sigma}{d\Omega}\right)_1$$

$$\vec{S} = (S_x, S_y) = (\cos\phi, \sin\phi)$$

spin vector



$\bar{p}p \rightarrow e^+e^-\pi^0$ with polarisation : single/double spin asymmetry

$\bar{p}p \rightarrow e^+e^-\pi^0$ when target and/or beam polarized: single/double spin asymmetries

G.I. Gakh et al., Physical Review C 86, 025204 (2012)

$\Rightarrow$ access to form factors imaginary part

transversely polarised target in PANDA

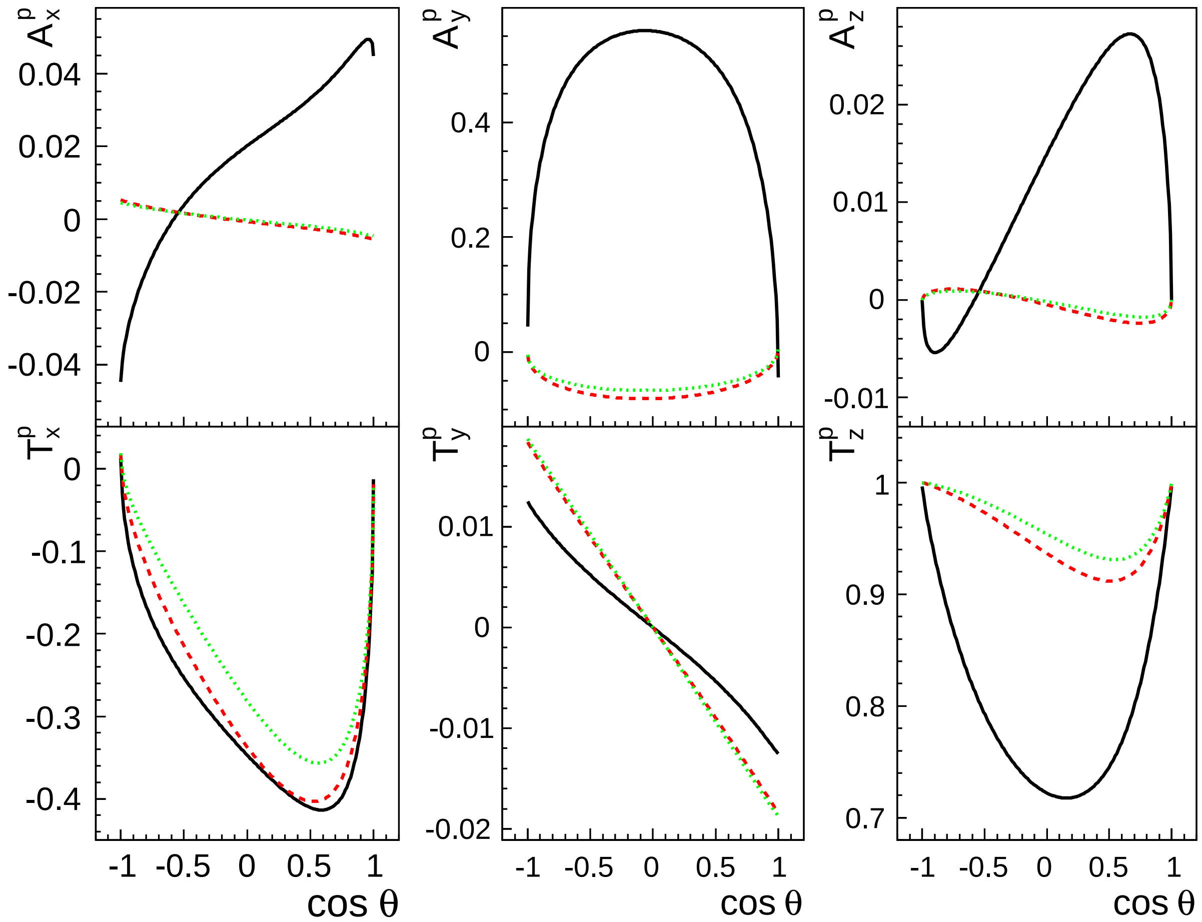
$s = 5.5\ \mathrm{GeV}^2$

black (solid) : $q^2 = 0.5\ \mathrm{GeV}^2$

red (dashed) : $q^2 = 2\ \mathrm{GeV}^2$

green (dotted) : $q^2 = 4\ \mathrm{GeV}^2$

analyzing powers (asymmetries)



coefficients of polarisation transfer $\bar{p} \rightarrow e^-$