Nucleon structure observables with $\overline{\text{P}}$ANDA

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Outline

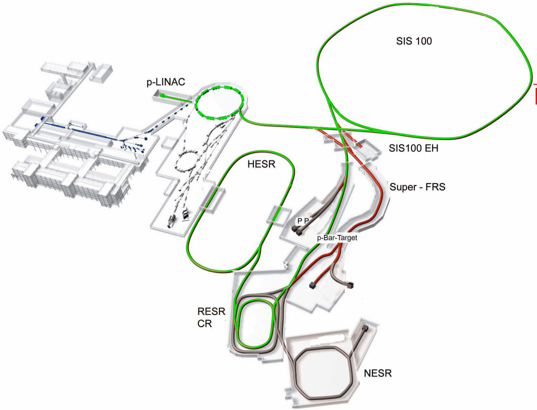
The new FAIR accelerator facility and $\overline{\text{P}}$ANDA

FAIR (Facility for Antiproton and Ion Research)

- 8 storage rings
- 2 linear accelerators

Experiments:

- APPA (Atomic, Plasma Physics and Applications)
- CBM (Compressed Baryonic Matter)
- NUSTAR (NUclear STructure, Astrophysics and Reactions)
- $\overline{\text{P}}$ANDA (AntiProton ANnihilations at DArmstadt)

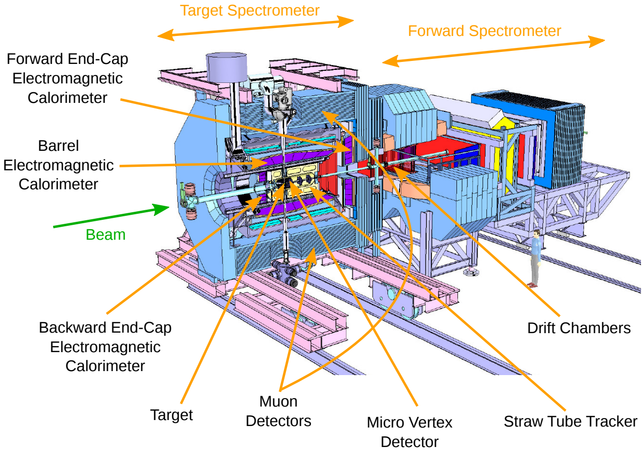


$\overline{\text{P}}$ANDA physics program[1]

- Electromagnetic processes
- QCD bound states
- Non-perturbative QDC dynamics
- Study of hadrons in nuclear matter
- Hypernuclear physics
- Electroweak physics

[1] http://arxiv.org/abs/0903.3905v1

The $\overline{\text{P}}$ANDA detector



$\overline{\text{P}}$ANDA capabilities:

- Particle Identification
- Track Reconstruction
- High Rates
- Radiation hard

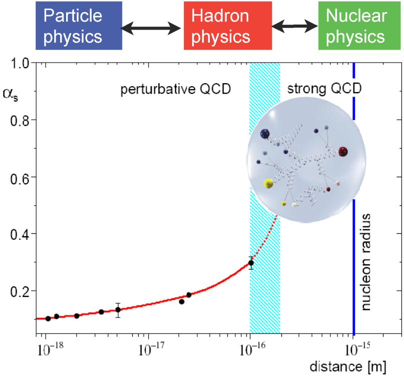
HESR Properties:

$\vec{p}_{\bar{p}} = 1.5\text{-}15\,\text{GeV}/c^2$
$\mathcal{L} = 2 \cdot 10^{32}\text{cm}^{-2}\text{s}^{-1}$

What do we need to test?

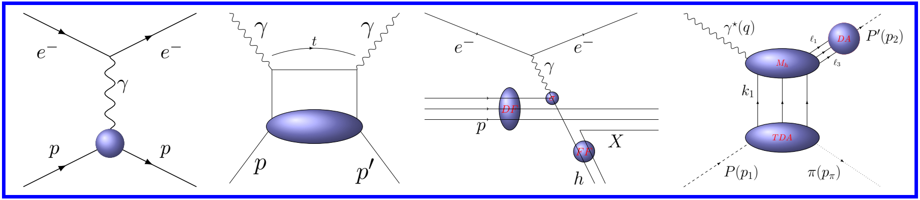
- Hadrons: non-perturbative regime of QCD

- We want to measure nucleon structure functions in this regime

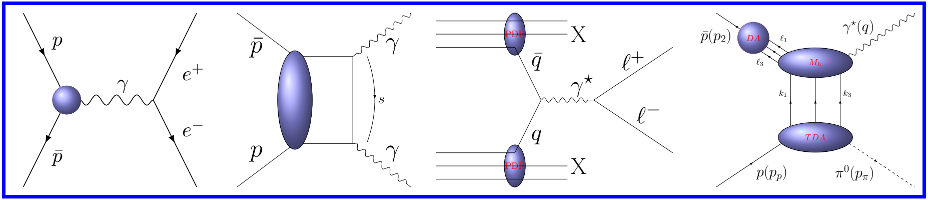


$\overline{\text{P}}$ANDA experiment employing matter and antimatter can determine these functions and test their universality.

Using the Electromagnetic force as a probe



⇑ CROSSED SYMMETRY ⇓

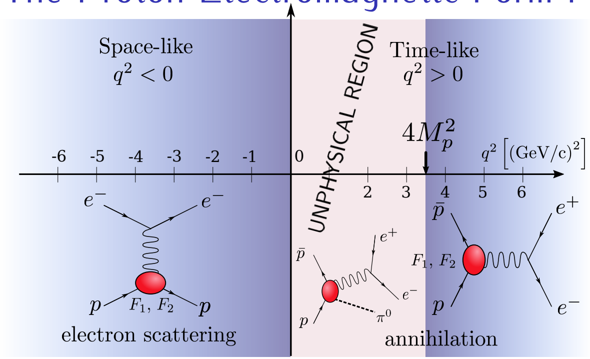


Crossing symmetry:

- Different kinematical regions ⇒
- Observables are counterparts

High quality and high energy $\bar{p}$ beam will be an excellent tool for a complementary study of the nucleon structure with e or γ experiments

The Proton Electromagnetic Form Factors



$$G_{E,M} = f(F_1, F_2)$$

$$G_E = F_1 - \tau F_2 \qquad \tau = \frac{q^2}{4M_p^2}$$
$$G_M = F_1 + F_2$$

$$G_E(0) = 1; \; G_M(0) = \mu_p$$

Parametrize the Hadron Current

- Lepton Current: $\bar{\Psi}\gamma^\mu\Psi$
- Hadron Current: $\bar{\Phi}\Gamma^\mu\Phi$

$$\Gamma^\mu = \left[F_1(q^2)\gamma^\mu + \frac{1}{2M_p} F_2(q^2) i\sigma^{\mu\nu} q_\nu \right]$$

Spacelike Region

Are real functions of q^2

Non-relativistic and $q = (0, \vec{q})$:
G_E and G_M Fourier transform of $\rho_{ch}(\vec{r})$ and $\rho_{mag}(\vec{r})$

World data: high statistics

Timelike Region

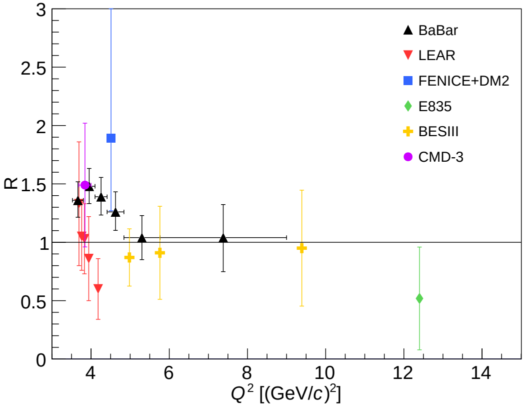
Are complex functions of q^2

G_E and G_M describe the dynamics of the quarks inside the nucleon.

World data: low statistics

Spacelike and the timelike regions are connected by: Dispersion Relations

Data on timelike $R = |G_E|/|G_M|$



BaBar: Phys. Rev. D88 072009
LEAR: Nucl.Phys.J., B411:3-32. 1994
BESIII: arXiv:1504.02680. 2015
CMD-3: arXiv:1507.08013v2 (2015)

@ BaBar (SLAC): $e^+e^- \to \bar{p}p\gamma$

- data collection over wide energy range

@ PS 170 (LEAR): $\bar{p}p \to e^+e^-$

- data collection at low energies

Data from BaBar & LEAR show inconsistencies

@ BESIII: $e^+e^- \to \bar{p}p$

- Measurement at different energies
- Uncertainties comparable to previous experiments

@ CMD-3 (VEPP2000 collider, BINP): $e^+e^- \to \bar{p}p$

- Energy $\sqrt{s} = 1.92 - 2\,\text{GeV}$
- Uncertainty of R in agreement with BaBar data

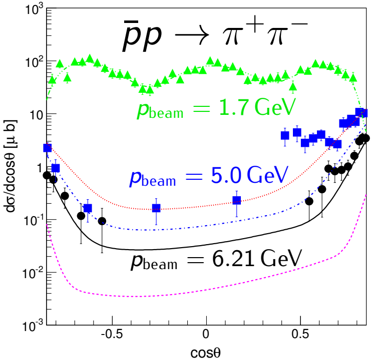
$\overline{\text{P}}$ANDA: TLFF between $s = 5.1$ and $s = 14.0\,\text{GeV}^2$ with remarkable accuracy

Measurement of TL proton FF at $\overline{\text{P}}$ANDA: Prospects

- Measurement of the proton form factors in the timelike region over a large kinematical region through: $p\bar{p} \to e^+e^-$ and $p\bar{p} \to \mu^+\mu^-$.
- Individual measurement of $|G_E|$ and $|G_M|$ and their ratio R.
  - M. Sudol, M.C. Mora Espí et al. EPJ.A44, 373(2010)
  - A. Dbeyssi, D. Khaneft, arXiv:1606.01118[hep-ex]
  - I. Zimmermann (PhD-Thesis)
- Possibility to access the relative phase of proton timelike Form Factors.
  - A. Z. Dubnickova, S. Dubnicka, M.P. Rekalo Nuovo Cim. A109 (1996) 241-256
  - Polarization observables (Born approximation) give access to $G_E \cdot G_M^\star$.
  - Development of a transverse polarized proton target for $\overline{\text{P}}$ANDA in Mainz.
    - Ongoing work B.Fröhlich (PhD-Thesis)
- Measurement of proton FFs in the unphysical region: $\bar{p}p \to e^+e^-\pi^0$.
  - M. P. Rekalo, Sov. J. Nucl. Phys. 1 (1965) 760
  - C. Adamuscin, E.A. Kuraev, E. Tomasi-Gustafsson and F.E. Maas, Phys. Rev. C 75, 045205 (2007)
  - Feasibility studies by J. Boucher (PhD-Thesis)

Feasibility studies: EMFF with $\overline{\text{P}}$ANDA; Background

New $\bar{p}p \to \pi^+\pi^-$ event generator developed at Mainz. M. Zambrana, PANDA internal note, based on J. Van de Wiele and S. Ong, Eur. Phys. J. A 46, 291-298 (2010)



- Low energy: Legendre polynomials
- High energy: Regge-inspired parametrization

- Main challenge: Suppression of the hadronic background, $\bar{p}p \to \pi^+\pi^-$

$$\frac{\sigma(\bar{p}p\to\pi^+\pi^-)}{\sigma(\bar{p}p\to\ell^+\ell^-)} \approx \left[10^5 - 10^6\right]$$

- A background rejection factor of the order 10^{-8} is needed
  $\to$ Pollution $< 1\%$

Results from MC-SIMULATION:

- $\bar{p}p \to e^+e^-$: $\sim 10^{-8}$ bg. suppression
- $\bar{p}p \to \mu^+\mu^-$: $\sim 10^{-6}$ bg. suppression

M. Sudol, M.C. Mora Espí et al., EPJ.A44, 373(2010)
A. Dbeyssi, D. Khaneft, arXiv:1606.01118[hep-ex]
I. Zimmermann, PhD-Thesis, Mainz (in preparation)

Feasibility studies: EMFF with $\overline{\text{P}}$ANDA; $p\bar{p} \to e^+e^-$

METHOD I

- Cross section:
  A. Zichichi, Nuovo Cim. 24, (1962) 170

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

- Assumption: $|G_E|/|G_M| = 1$
- Fit to the $\cos^2\theta$ distribution

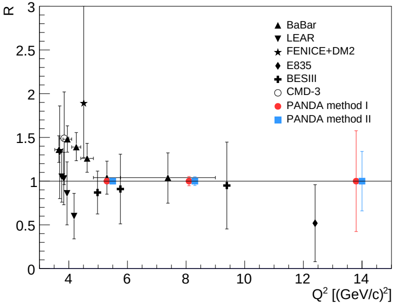
METHOD II

- Flat angular distribution (phase space)
- Scaled to expected statistics and model
- Use of linear fit with:

$$y = \sigma_0 + \sigma_0\mathcal{A}\cos^2\theta$$

$$\sigma_0 = \frac{\pi\alpha^2}{2\beta s}\left(|G_M|^2 + \frac{1}{\tau}|G_E|^2\right) \quad \mathcal{A} = \frac{\tau - R^2}{\tau + R^2}$$

- Additional samples for signal efficiency determination, 10^6 events at each energy



A. Dbeyssi, D. Khaneft, arXiv:1606.01118[hep-ex]

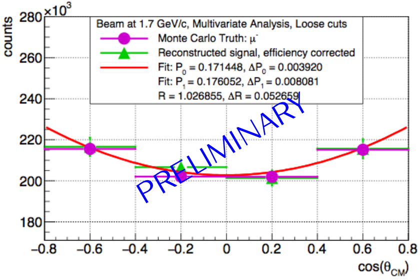
Results from MC-SIMULATION:

- $R = |G_E|/|G_M|$ up to $q^2 \sim 14\,\text{GeV}^2$
- $|G_M|$ up to $q^2 \sim 14\,\text{GeV}^2$ with precision $[2\% - 10\%]$
- $|G_E|$ up to $q^2 \sim 14\,\text{GeV}^2$ with precision $[2\% - 60\%]$
- Effective FF measurable above $q^2 \sim 14\,\text{GeV}^2$

Feasibility studies: EMFF with $\overline{\text{P}}$ANDA; $p\bar{p} \to \mu^+\mu^-$

- Consistency check of FF data with e^+e^-
- Radiative corrections due to final state radiation are neglected due to the heavy m_μ
- Multivariate Analysis is used to improve the Signal-to-Background ratio:
  S/B Cross section ratio : $1 : 10^6$
  S/B ratio after analysis:$1 : 4$

$s = 5.4\,\text{GeV}^2$



PRELIMINARY:
Results from MC-SIMULATION:
I.Zimmermann et al. AIP Conf. Proc. 1735, 080004 (2016);
http://dx.doi.org/10.1063/1.4949457

- $R = 1.027 \pm 0.053$ with
  $\Delta R/R \sim 5.1\%$
- $|G_M| = 0.121 \pm 0.005$ with
  $\Delta|G_M|/|G_M| \sim 4.1\%$
- $|G_E| = 0.124 \pm 0.011$ with
  $\Delta|G_E|/|G_E| \sim 8.6\%$

Transverse Polarized Target

- Polarization observables: Access to relative phase G_E and G_M
- Complex Form Factors: non zero spin assymmetry at the Born level
- Only non-vanishing single spin assymmetry:

$$A_T = \frac{\sin 2\theta \mathcal{I}m\, G_E^{\star} G_M}{D\sqrt{\tau}}$$ (transverse proton polarization)

- Development of a Polarized Target for $\overline{\text{P}}$ANDA in Mainz

Ongoing work (B. Fröhlich, HIM, PhD-Thesis):

- Shielding the longitudinal external field of the $\overline{\text{P}}$ANDA solenoid ($B_{ext} = 2\,\text{T}$)
- Current status: $B_{residual} < 1\,\text{Gauss}$ at $B_{ext} = 1.4\,\text{T}$
  Shielding factor $> 10^4$

$\overline{\text{P}}$ANDA: First time measurement of the relative phase G_E and G_M

Transition Distribution Amplitudes

TDA:

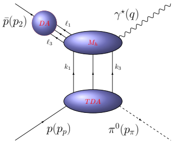
- New non-perturbative objects
- Fourier transform of a Matrix Element of a three-quark light-cone local operator
- Transition between a proton and a pion
- Information about the π-cloud in the proton

In CM of $\overline{\text{P}}$ANDA

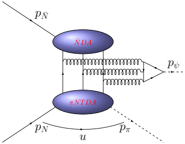
u: π^0 backward $\rightarrow$ emitted by p

t: π^0 forward $\rightarrow$ emmited by $\bar{p}$

- Occur in QCD collinear factorisation at
  - Hard scale: high momentum transfer
  - Low transversal momentum for the π^0
- Independent of reaction type, s and q^2.



$\bar{p}p \rightarrow \pi^0\gamma^\star$



$\bar{p}p \rightarrow \pi^0 J/\psi$

Comparison between $\pi p - TDA$ and $\pi\bar{p} - TDA$

Test of QCD factorization and access to TDAs

$\rightarrow$ kinematically accesible by $\overline{\text{P}}$ANDA

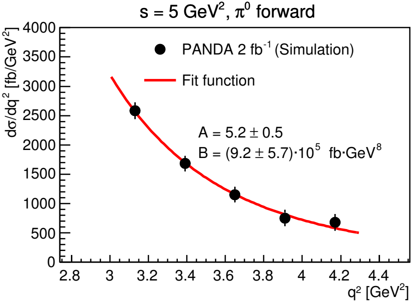
Nucleon to meson TDAs: $\bar{p}p \to \pi^0\gamma^\star$

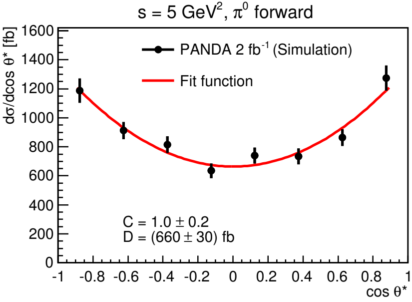
Studies based on: J. P. Lansberg et al., Phys Rev D 76, 111502(R) (2007)

- Feasibility studies of measuring $\bar{p}p \to \gamma^\star\pi^0 \to e^+e^-\pi^0$ at $\overline{\text{P}}$ANDA
  i) $s = 5\,\text{GeV}^2 \quad \to \quad 3.0 < q^2 < 4.3\,\text{GeV}^2, \quad |\cos\theta_{\pi^0}| > 0.5$
  ii) $s = 10\,\text{GeV}^2 \quad \to \quad 5.0 < q^2 < 9.0\,\text{GeV}^2, \quad |\cos\theta_{\pi^0}| > 0.5$
- Background suppression and measurement precision
  $s = 5\,\text{GeV}^2$: $5 \cdot 10^7$ @low q^2 – $1 \cdot 10^7$ @high q^2; $\Delta\sigma/\sigma \sim 12\%$
  $s = 10\,\text{GeV}^2$: $1 \cdot 10^8$ @low q^2 – $6 \cdot 10^6$ @high q^2; $\Delta\sigma/\sigma \sim 24\%$
- Test of QCD factorization and access to the TDAs

$\frac{d\sigma}{dq^2} \approx \frac{1}{(q^2)^5}$; $F(q^2) = B \cdot \frac{1}{(q^2)^A}$

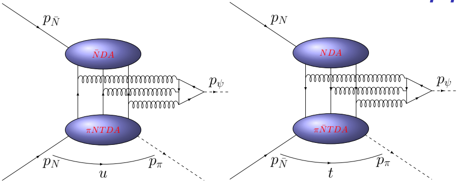
$\frac{d\sigma}{d\cos\theta^\star} \approx 1 + \cos^2\theta$; $F(\cos\theta^\star) = D(1 + C\cos\theta^\star)$





M.C.Mora Espí et al. Eur.Phys.J. A51 (2015) no.8, 107

Nucleon to meson TDAs: $\bar{p}p \to \pi^0 J/\psi$

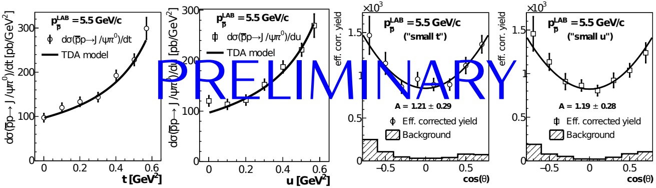


- Background channels:
  - $\bar{p}p \to \pi^0\pi^+\pi^-$
  - $\bar{p}p \to \pi^0\pi^+\pi^+\pi^-\pi^-$,
    $\bar{p}p \to \pi^0\pi^0\pi^+\pi^-$, $\bar{p}p \to \pi^0\pi^0 J/\psi$
  - $\bar{p}p \to \pi^0\gamma^\star \to e^+e^-$

- Cross check for $\bar{p}p \to \pi^0 e^+e^-$
- Feasibility studies for the measurement of $\bar{p}p \to \pi^0 J/\psi$
- Two validity regimes:
  - Small $|t| \to$ Fwd. π^0, $\pi\bar{N}$-TDA
  - Small $|u| \to$ Bwd. π^0, πN-TDA
- Three energies studied:
  $p_{\bar{p}}^{LAB} = 5.5,\ 8.0$ and 12.0 GeV

PRELIMINARY:

Background contamination: $< 2\%$; Signal efficiency: $5 - 10\%$

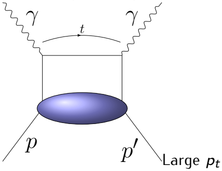


E.Atomssa et al. article in preparation

Generalized Distribution Amplitudes

Spacelike

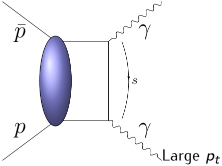
$\gamma p \to \gamma p$:



Generalized Parton Distributions
Wide Angle Compton Scattering

Timelike

$\bar{p}p \to \gamma\gamma$:



Generalized Distribution Amplitudes
Crossed WACS

- The QCD factorization theorem allows us to calculate high energy cross sections separating short-distance process with long-distance non perturbative functions.
- Hard scale is defined by the large transverse momentum of the final state photon.
- WACS process: give access to the GDAs, the counterpart of the GPDs.

Studied in $\overline{\text{P}}$ANDA $\bar{p}p \to \gamma\gamma$ and $\bar{p}p \to \pi^0\gamma$.
Background: $\bar{p}p \to \pi^0\pi^0$ and $\bar{p}p \to \pi^0\gamma$ (only for 1st process).
$S/B \sim 1$ for $\bar{p}p \to \gamma\gamma$ with 25% efficiency,
$S/B \sim 2$ for $\bar{p}p \to \pi^0\gamma$ with 50% efficiency.

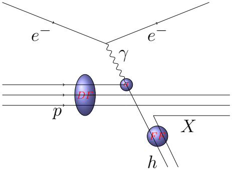
This Processes can be successfully measured in $\overline{\text{P}}$ANDA

http://arxiv.org/abs/0903.3905v1

Transverse Momentum Dependent Parton Distributions Functions

Spacelike

$e^- p \to e^- hX$:



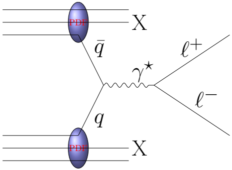
Trasnsverse Momentum Dependent-PDFs

Semi-Inclusive Deep Inelastic Scattering

TMD-PDFs are convoluted with the FF

Timelike

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



Trasnsverse Momentum Dependent-PDFs

Drell-Yan

Direct access to TMD-PDFs through measurement of azimutal asymmetries

Feasibility studies: $\bar{p}p \to \mu^+\mu^- X$ (Unpolarized) and $\bar{p}p^{\uparrow} \to \mu^+\mu^- X$ (Polarized)
Main background: $\bar{p}p \to n(\pi^+\pi^-)X$, 10^7 rejection factor required.
Simulations: $s = 30\,\mathrm{GeV}^2$ and $1.5 \leq M_{\gamma^\star} \leq 2.5$
$\Rightarrow$ Expectation $1.3 \cdot 10^5$ DY/month with a reconstruction efficiency of $\sim 33\%$

Will allow the study of TMD-PDFs with $\overline{\text{P}}$ANDA

http://arxiv.org/abs/0903.3905v1;
EPJ Web of Conferences 73,02012(2014)

Summary

A challenging physics program using electromagnetic processes for the measurement of nucleon structrue observables with $\overline{\text{P}}$ANDA has been presented.

- The Proton Form Factors (effective FF, G_E, G_M, their ratio and their relative phase) can be measured at $\overline{\text{P}}$ANDA over a large momentum range ($\sim 14\,\text{GeV}^2$) with unprecedent accuracy.
- Promising results for accessing nucleon-pion Transition Distribution Amplitudes with $\overline{\text{P}}$ANDA.
- Generalized Distribution Amplitudes can be accessed with $\overline{\text{P}}$ANDA
- Transverse Momentum Dependent PDFs can be measured with Drell-Yan production processes.

With antiproton beams in the GeV energy range,
$\overline{\text{P}}$ANDA will be a unique tool
to study several nucleon structure functions (FFs, GDAs, TMD-PDFs, TDAs, ...)

THANKS FOR LISTENING

PANDA Collaboration

More than 520 physicists from 70 institutions in 19 countries

Aligarh Muslim University
U Basel
IHEP Beijing
U Bochum
Magadh U, Bodh Gaya
BARC Mumbai
IIT Bombay
U Bonn
IFIN-HH Bucharest
U & INFN Brescia
U & INFN Catania
NIT, Chandigarh
AGH UST Cracow
JU Cracow
U Cracow
IFJ PAN Cracow
GSI Darmstadt

Karnatak U, Dharwad
TU Dresden
JINR Dubna
U Edinburgh
U Erlangen
NWU Evanston
U & INFN Ferrara
FIAS Frankfurt
LNF-INFN Frascati
U & INFN Genova
U Glasgow
U Gießen
Birla IT&S, Goa
KVI Groningen
Sadar Patel U, Gujart
Gauhati U, Guwahati
IIT Guwahati
IIT Indore

Jülich CHP
Saha INP, Kolkata
U Katowice
IMP Lanzhou
INFN Legnaro
U Lund
U Mainz
U Minsk
ITEP Moscow
MPEI Moscow
U Münster
BINP Novosibirsk
Novosibirsk State U
IPN Orsay
U & INFN Pavia
Charles U, Prague
Czech TU, Prague
IHEP Protvino

PNPI St. Petersburg
U of Sidney
U of Silesia
U Stockholm
KTH Stockholm
Suranree University
South Gujarat U, Surat
U & INFN Torino
Politecnico di Torino
U & INFN Trieste
U Tübingen
TSL Uppsala
U Uppsala
U Valencia
SMI Vienna
SINS Warsaw
TU Warsaw

The Proton Electromagnetic Form Factors

Spacelike Region

Are real functions of q^2

Non-relativistic and $q = (0, \vec{q})$:
G_E and G_M Fourier transform of $\rho_{ch}(\vec{r})$ and $\rho_{mag}(\vec{r})$

World data: high statistics

Timelike Region

Are complex functions of q^2

G_E and G_M describe the dynamics of the quarks inside the nucleon.

World data: low statistics

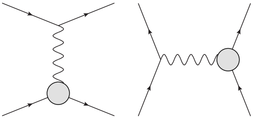
Spacelike and the timelike regions are connected by:
Dispersion Relations

- Based in the Unitarity and Analyticity
- Provide an unified frame for the description of form factors over whole kinematical region
- Provide predicitions for regions without experimental data Phys. Rep. 550 (2015) 1 and references therein
- Asymptotic behaviour E.Tomasi-Gustafsson and M.P.Rekalo, Phys. Lett. B 504, 291 (2001)
  $\lim_{q^2\to-\infty} \left|G^{SL}_{E,M}(q^2)\right| = \lim_{q^2\to\infty} \left|G^{TL}_{E,M}(q^2)\right|$

How can we probe the strong force...

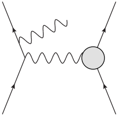
... using Electromagnetic interactions.

- Electron scattering/Annihilation



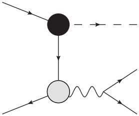
Access to the Form Factors

- Initial State Radiation



Access to the Form Factors

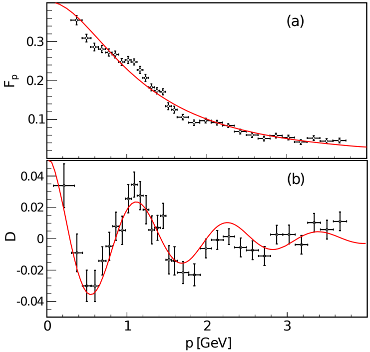
- Meson Production



Access to the Form Factors in Timelike region below the threshold

Oscillations: Regular pattern in p_{lab}

E. Tomasi-Gustafsson et al. Phys.Rev.Lett.114,232301(2015), arXiv:1510.06338[nucl-th], Phys.Lett-B712(2012)240



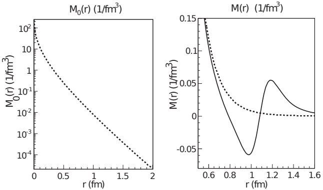
$$F_{osc}(p) \equiv A \exp(-Bp) \cos(Cp + D)$$

A: small perturbation B: damping

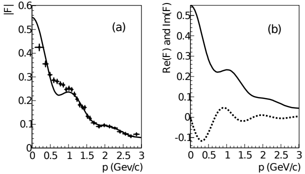
C:$r < 1fm$ $D = 0$: maximum at $p = 0$

Related to the time evolution of the charge density?

Fourier transform

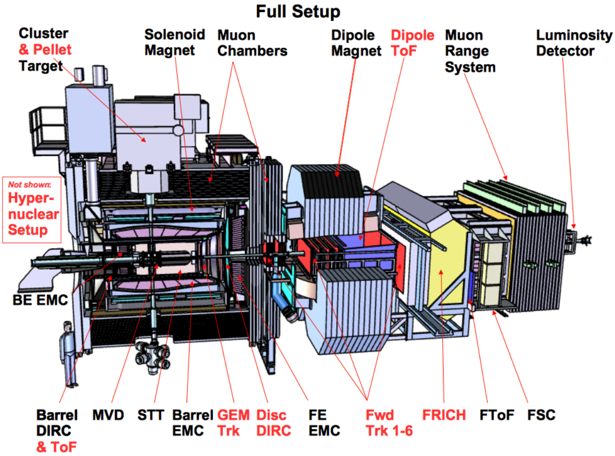


Optical potential analysis: double layer rescattering densities



- feeding at smal r (decay of higher mass states into $\bar{p}p$)
- depletion at larger r (annihilation into mesons)

The $\overline{\text{P}}$ANDA detector



$\overline{\text{P}}$ANDA capabilities:

- Particle Identification
- Track Reconstruction
- High Rates
- Radiation hard

HESR Properties:

$\vec{p}_{\bar{p}} = 1.5\text{–}15\,\text{GeV/c}^2$

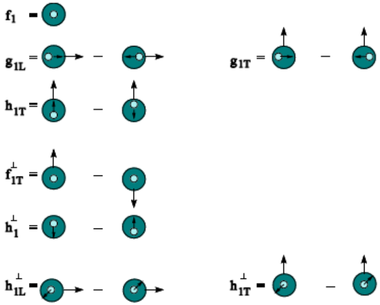
High Resolution Mode:

- $\mathcal{L} = 2 \cdot 10^{31}\text{cm}^{-2}\text{s}^{-1}$
- $\frac{\Delta p}{p} < 2 \cdot 10^{-5}$

High Energy Mode:

- $\mathcal{L} = 2 \cdot 10^{33}\text{cm}^{-2}\text{s}^{-1}$
- $\frac{\Delta p}{p} \sim 10^{-4}$

TMD PDFs



UNPOLARIZED

- Boer-Mulders:
  T-odd chirally odd TMD function. Transverse pol. quarks in unpol. nucleon

SINGLE POLARIZED

- $h_1^{\perp}$
- Transversity
- f_1
- $f_1^{\perp}$ - Sivers:
  Unpol. quark distribution in Transverse pol. hadron.