Helmholtz-Institut Mainz

Study of the nucleon structure with the PANDA experiment at FAIR

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On behalf of the PANDA Collaboration

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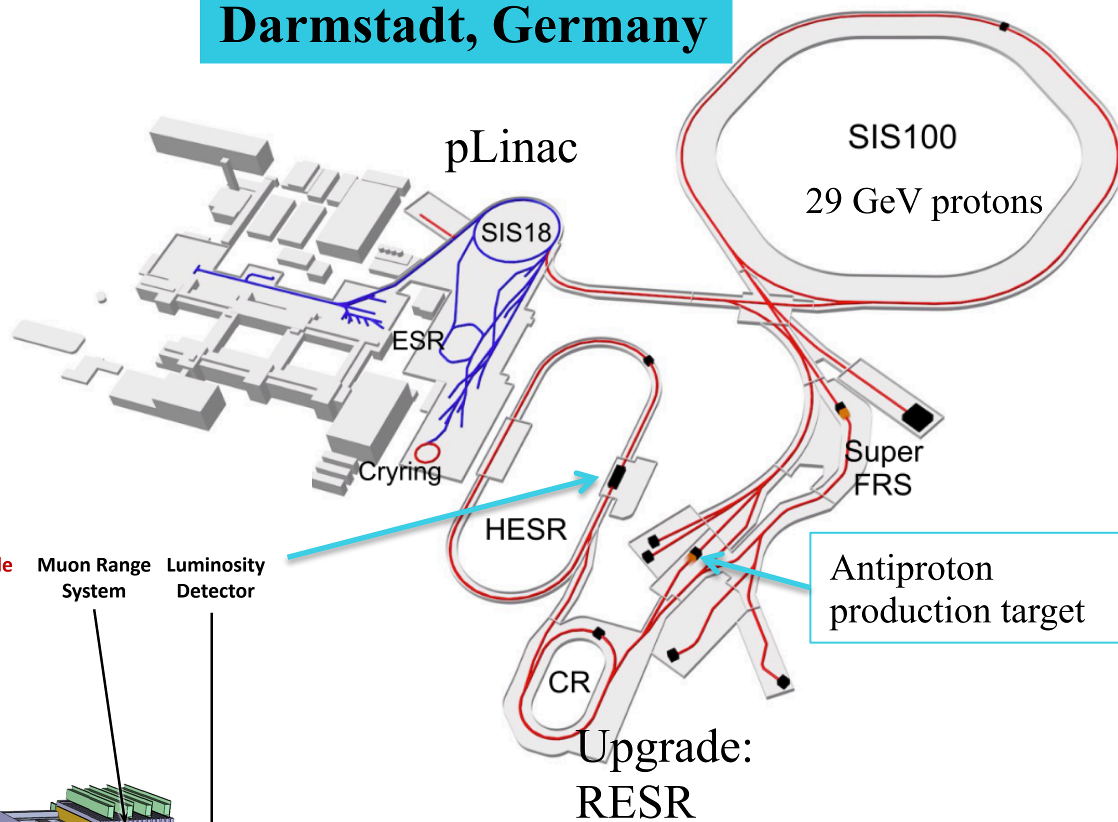
The PANDA experiment at FAIR

Darmstadt, Germany

- Antiproton beams (1.5 – 15 GeV/c)
- Antiproton-proton and antiproton-nucleus interactions

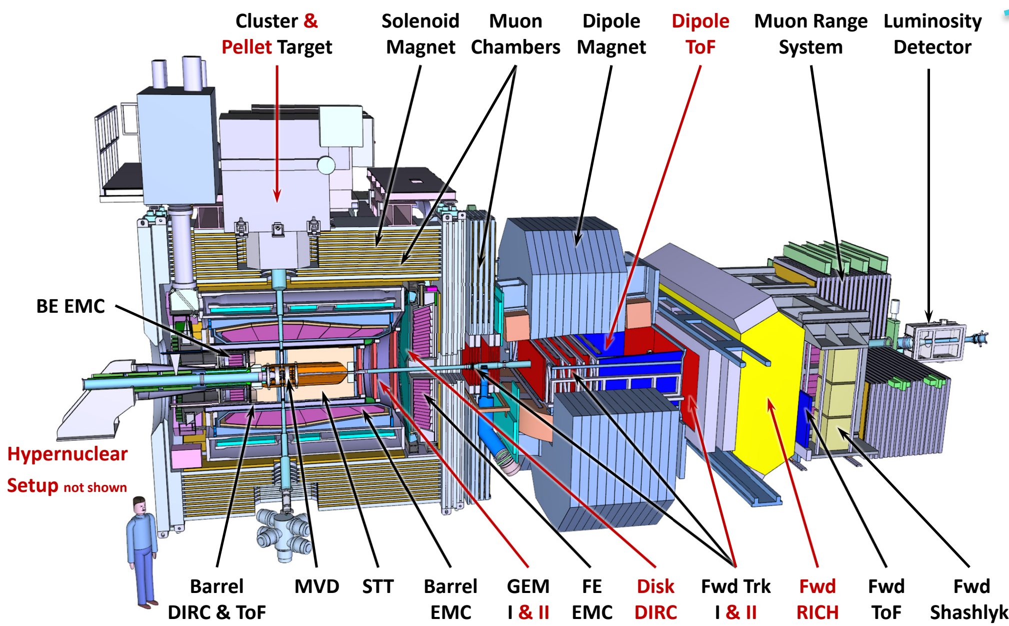
Phase 1+2

- $\Delta p/p \leq 5 \times 10^{-5}$
- $L \sim 10^{31}\ cm^{-2}\ s^{-1}$



Phase 3 (+RESR)

- High Luminosity (**HL**) Mode
  - $L = 2 \times 10^{32}\ cm^{-2}\ s^{-1}$
  - $\Delta p/p \leq 2 \times 10^{-4}$

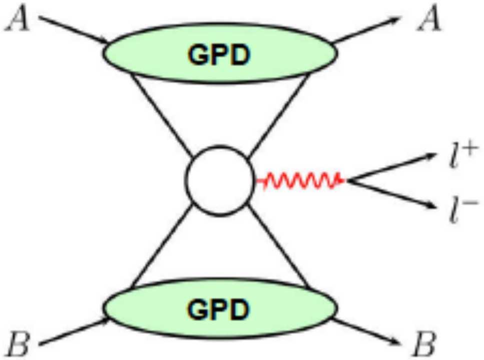


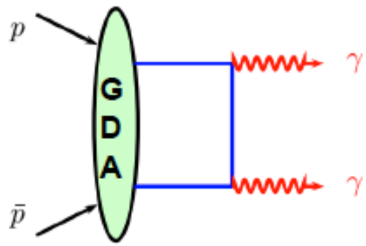
Sub-systems not available in Phase 1

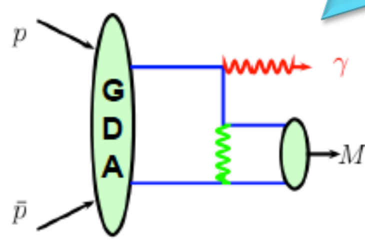
Study of the nucleon structure at PANDA

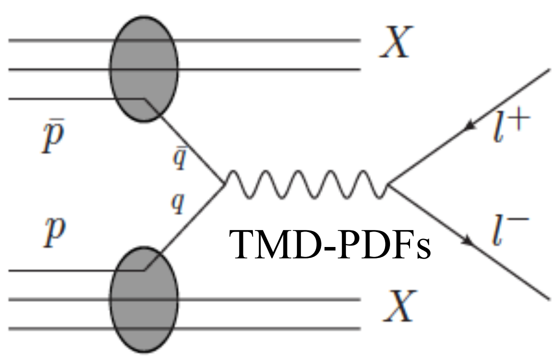
- **Time-like electromagnetic form factors**
- **Transition distribution amplitudes (TDAs)**
- Generalized parton distributions (GPDs)
- Generalized distributions amplitudes (GDAs)
- TMD-parton distribution functions (TMD-PDFs)

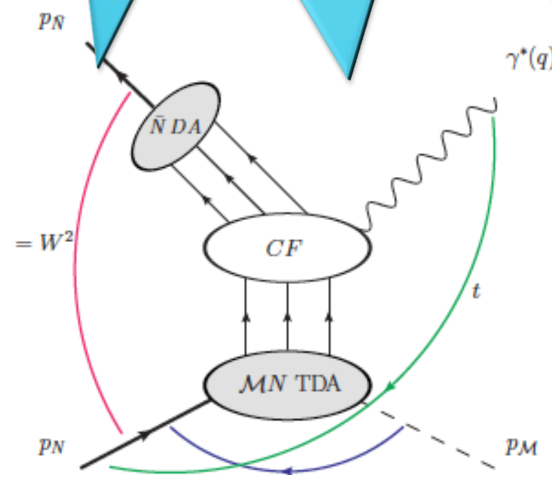
High luminosity
Multi-purpose detector ~ 4pi acceptance
Large center of mass energy range s=[5.1 – 30] GeV²



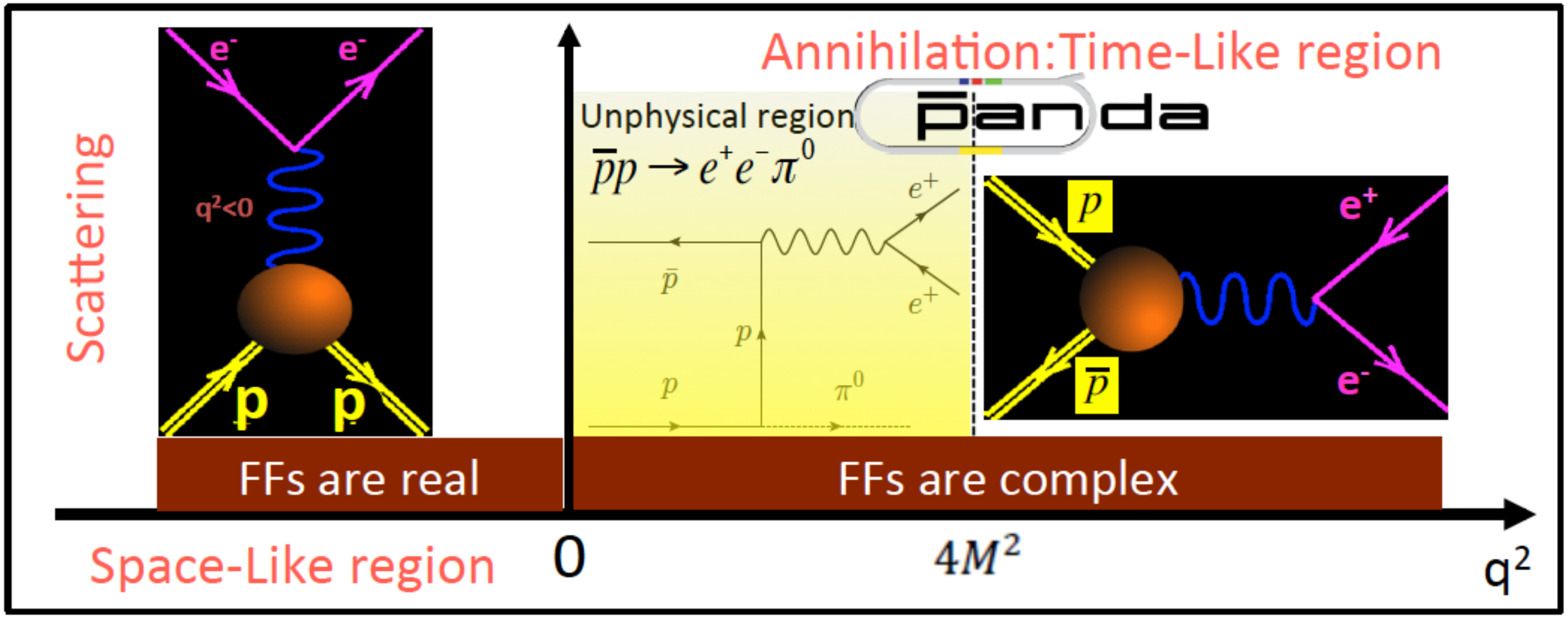








Proton electromagnetic form factors G_E and G_M



- **Precise measurements** of the time-like proton form factors **over large q^2 range**
- **Electron and muon final states**: consistency check of the results and study of systematics (from radiative corrections, event selection,….)
- Study of the proton factors in the **unphysical region** (*M. P. Rekalo, Sov. J. Nucl. Phys. 1 (1965) 760; C. Adamuscin et al. Phys. Rev. C 75, 045205 (2007)*)

Feasibility studies: time-like proton form factors @ PANDA

Simulation & Analysis with PANDARoot

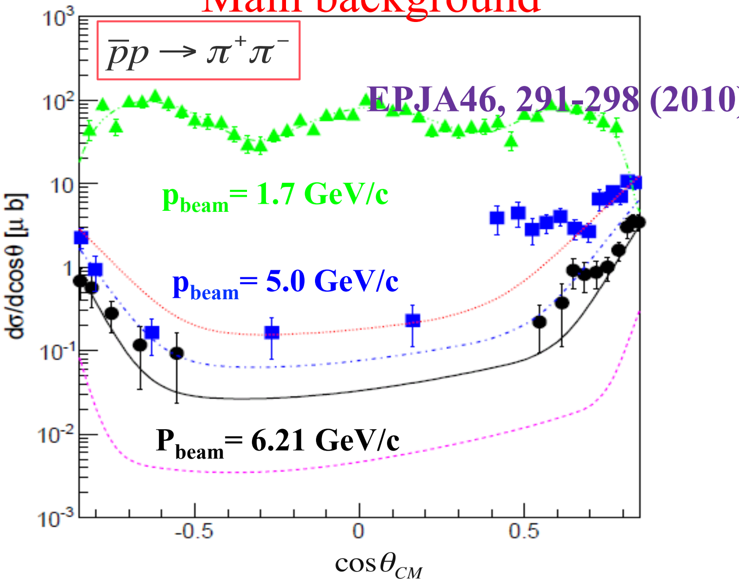
Signal processes $\bar{p}p \to l^+l^- \; (l = e, \mu)$

Event selection:

- **Cuts on kinematical variables**: **Production angles** (back-to-back in CM system), & **Invariant Mass.**
- **Signal/Background separation** based on:
  - For e^+e^- : Different sub-detector information like **EMC**, **STT** etc. contribute to PID
  - For $\mu^+\mu^-$: **Boosted Decision trees** + cuts

Detector information MAINLY from Muon System

Main background



$$\frac{\sigma(\bar{p}p \to \pi^+\pi^-)}{\sigma(\bar{p}p \to l^+l^-)} \propto [10^5 - 10^6]$$

Electron case:

*EPJA **52** (2016) 325*

EPJA 57 (2021) 6, 184

- Pbar between 1.5 and 6.4 GeV/c
- Signal efficiencies between 39% and 51%
- **Background rejection ~10^{-8} achieved: pollution < 1%**

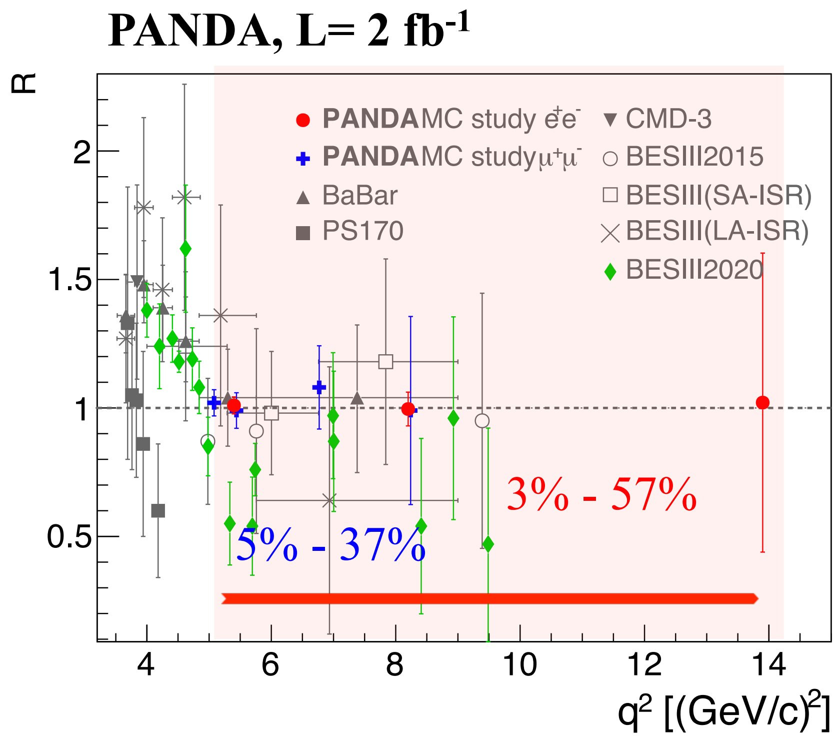
Muon case:

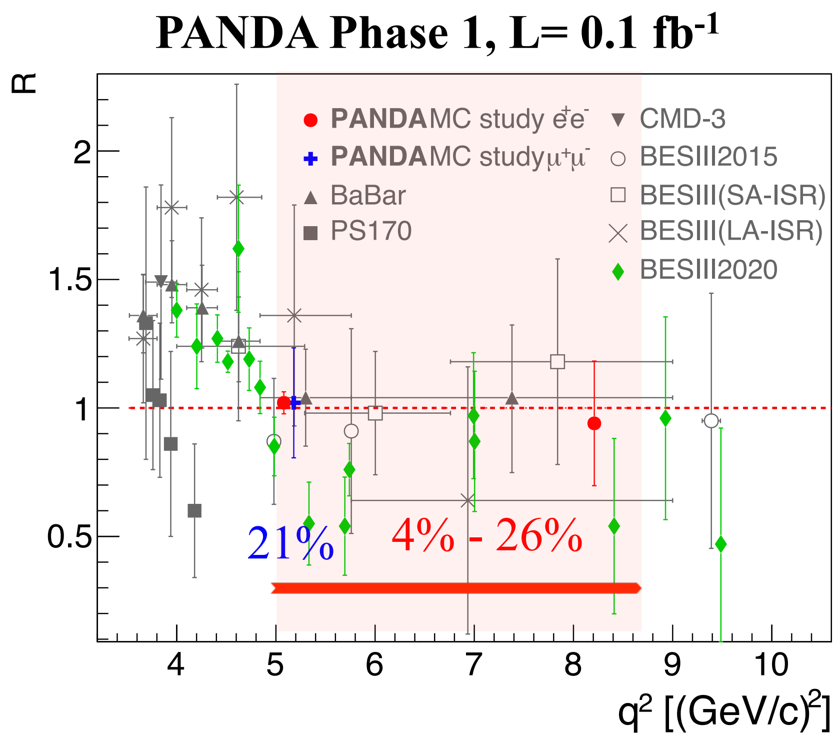
EPJA 57 (2021) 30

- Pbar between 1.5 and 3.3 GeV/c
- Signal efficiency ~ 30%
- **Background rejection ~ 10^{-5}**

Background subtraction removes pion background contamination

Proton electromagnetic form factors at PANDA



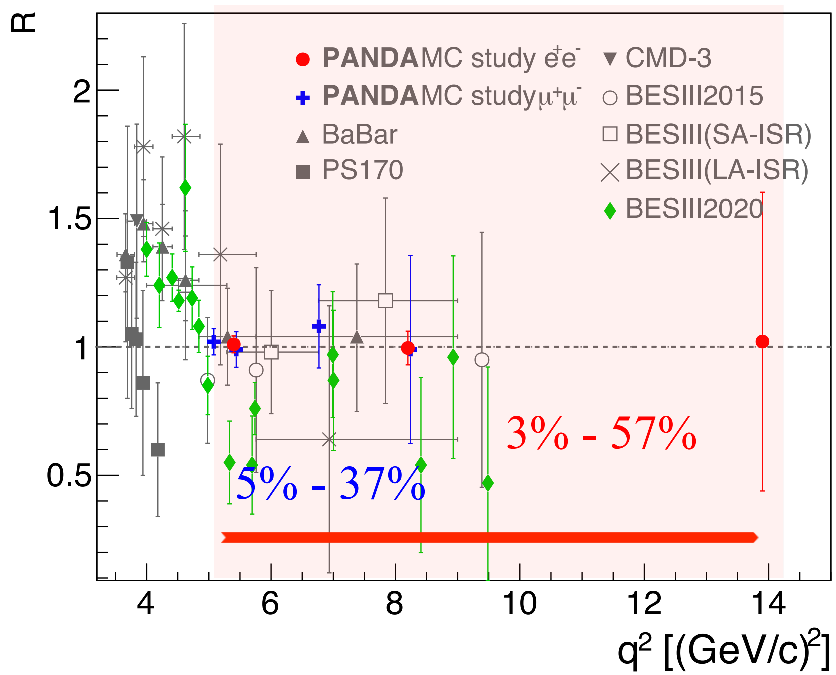


- $|G_E|$, $|G_M|$ and their ratio (R) are determined from the measurement of the angular distributions of the final state proton
- Precise measurements of the lepton angular distribution over a wide range of q^2
- Data with muon channel will be provided by PANDA

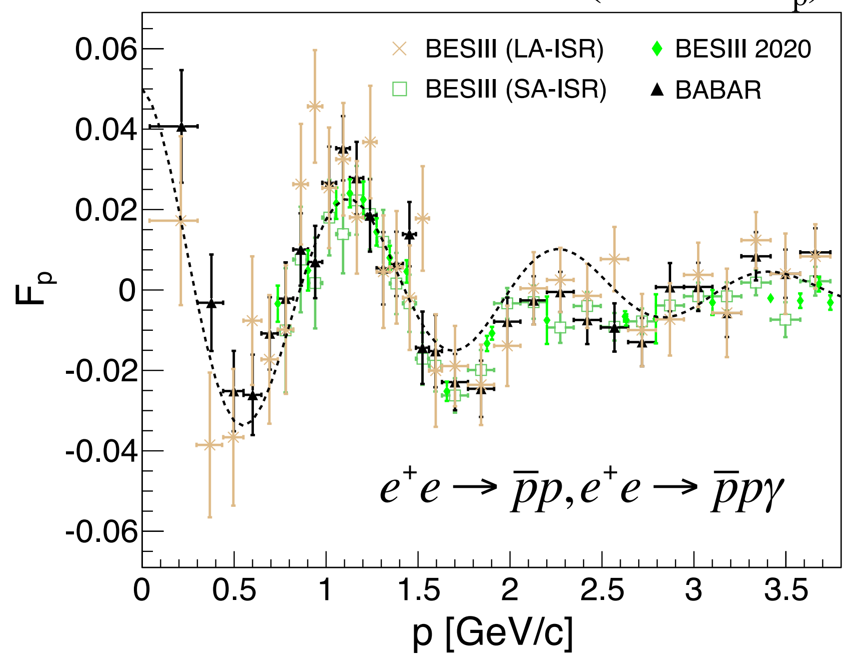
PANDA Collaboration
- *EPJA* ***52*** *(2016) 325*
- *EPJA 57 (2021) 30*
- *EPJA 57 (2021) 184*

Proton electromagnetic form factors at PANDA

PANDA, L= 2 fb^{-1}



Effective form factor (residual F_p)



- **Low statistics data samples**: measurement of the integrated cross section and an effective form factor G_{eff} ($|G_E|=|G_M|$)

Oscillations in proton-antiproton annihilations? *PRC 103 (2021) 3, 035203; PRD 92, 034018 (2015)*

PANDA Collaboration

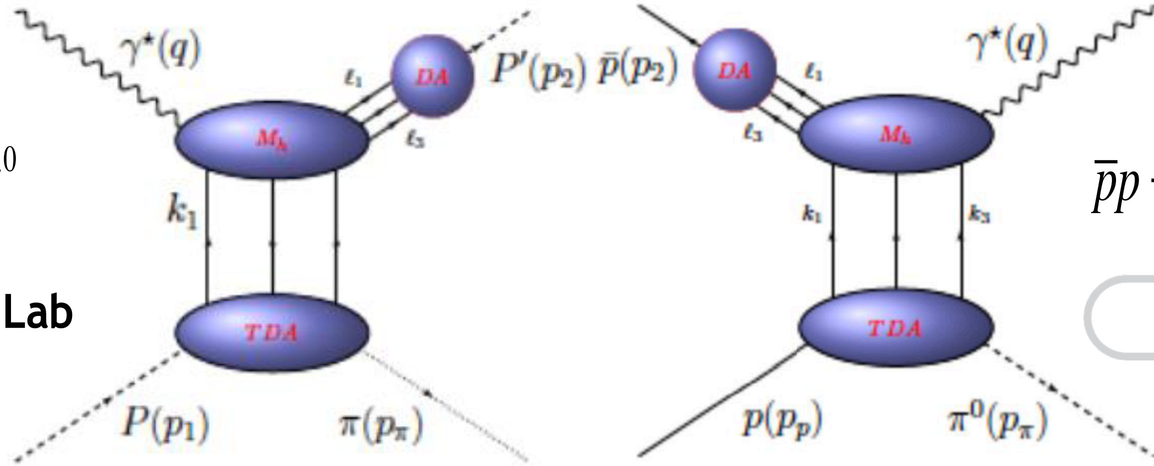
- *EPJA **52** (2016) 325*
- *EPJA 57 (2021) 30*
- *EPJA 57 (2021) 184*

- $\Delta(G_{eff})/G_{eff}$ ~3% at Phase1 (electrons and muons)
- G_{eff} up to ~ 28 (GeV/c)^2 at PANDA Phase 3

Nucleon to meson TDAs

$ep \to e' p' \pi^0$

Jefferson Lab



$\bar{p}p \to \gamma^* \pi^0 -> e^+ e^- \pi^0$

PANDA

J.P. Lansberg et al. (2012), B. Pire, L. Szymanowski, K. Semenov-Tian-Shansky (2013)

- **New class of non-perturbative structure functions**
- **Occur in collinear factorization description of various hard exclusive processes**
- **Are independent of reaction type, s and q^2**

Experimental checks of the collinear factorization regime in hard exclusive reactions:

$\bar{p}p \to \gamma^* \pi^0 -> e^+ e^- \pi^0$

$$\frac{d\sigma}{dt\ dq^2\ d\cos\theta^*_\ell}\bigg|_{\text{Leading twist}} = \frac{K}{s-4M^2}\boxed{\frac{1}{(q^2)^5}}\boxed{(1+\cos^2\theta^*_\ell)}$$

Nucleon to meson TDAs at PANDA

$\bar{p}p \to \gamma^{*}\pi^{0} -> e^{+}e^{-}\pi^{0}$

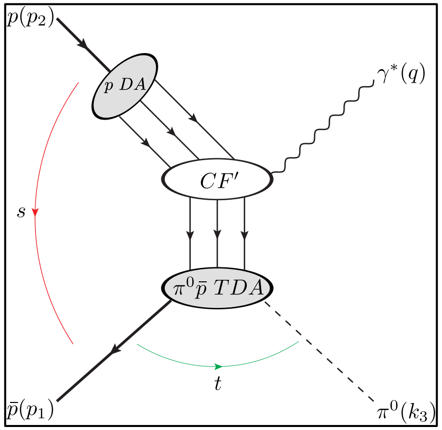
Feasibility studies

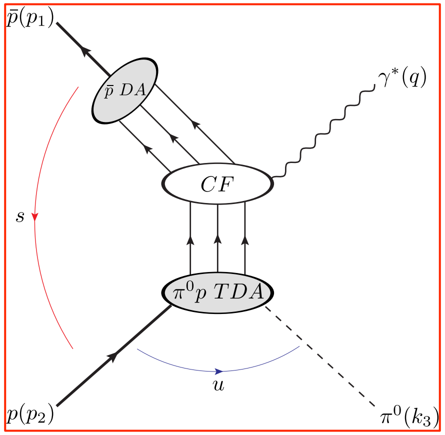
- s=5 GeV^2, q^2=[3, 4.3] GeV^2, $|\cos\theta_{\pi 0}|>0.5$
- s=10 GeV^2, q^2=[5, 9] GeV^2, $|\cos\theta_{\pi 0}|>0.5$
- Main Background: $\sigma(\pi^{+}\pi^{-}\pi^{0})/\sigma(e^{+}e^{-}\pi^{0})\sim 10^{6}$
- Signal reconstruction efficiency ~ 40 %

EPJA 51 (2015) 8, 107

t is small (near forward regime)

u is small (near backward regime)



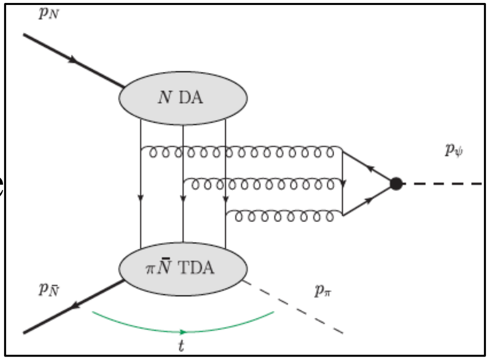


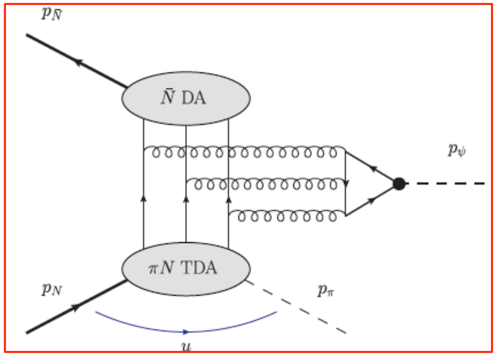
Hard scale: large q^2~s

$\bar{p}p \to J/\psi\pi^{0} -> e^{+}e^{-}\pi^{0}$

- High signal cross section
- Large fixed q^2 ~ 9.6 GeV^2
- Complementary measurements: test of the universality of TDAs
- P=5.5, 8.0, 12.0 GeV/c
- Background studies and subtraction methods
- Signal reconstruction efficiency ~ 7 - 11%

PRD 95, 032003 (2017)





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

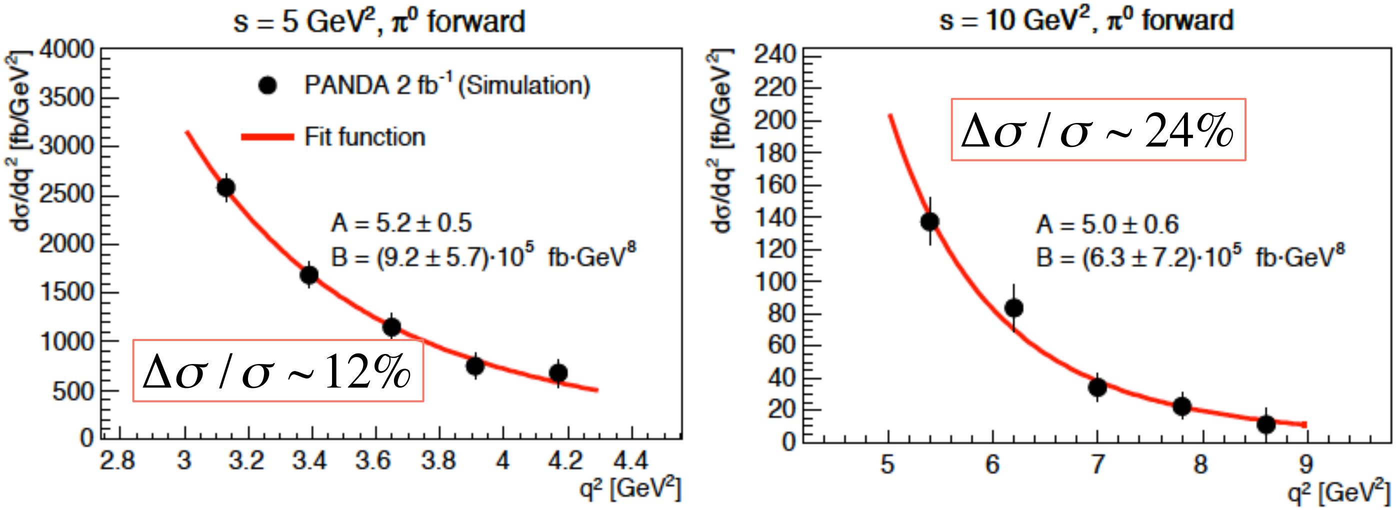
B. Pire et al., Phys. Lett. B. 724 99-107 (2013)

Nucleon to meson TDAs at PANDA

$\bar{p}p \rightarrow \gamma^* \pi^0 -> e^+ e^- \pi^0$

L=2 fb^{-1}

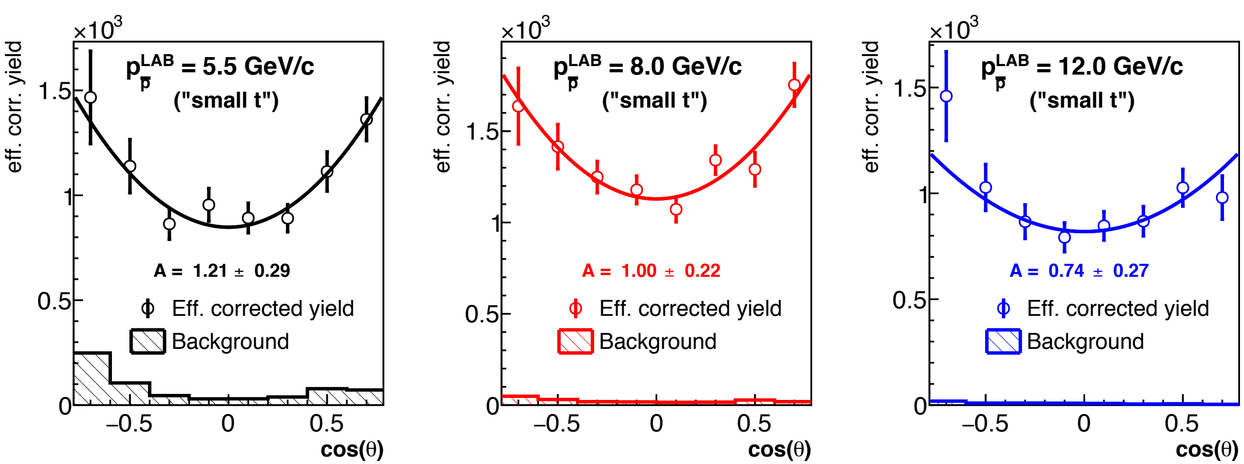
- **Test QCD factorization**



$$\frac{d\sigma}{dq^2} \sim \frac{1}{(q^2)^5}$$

EPJA 51 (2015) 8, 107

$\bar{p}p \rightarrow J/\psi \pi^0 -> e^+ e^- \pi^0$

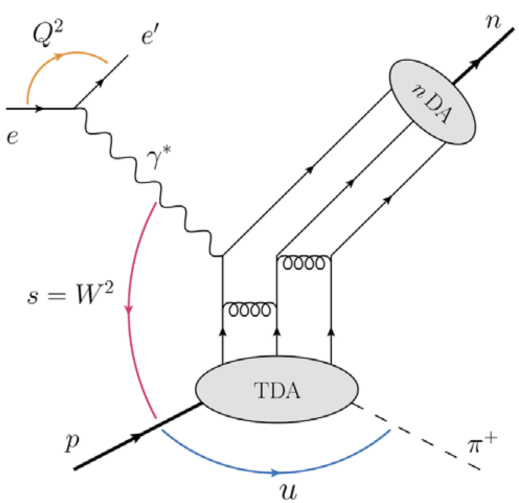


$\Delta\sigma(t,u) / \sigma(t,u) \sim 5\% - 10\%$

Fit function: $B \times (1 + A\cos^2 \theta^{e^+}_{J/\psi})$

PRD 95, 032003 (2017)

TDAs – experimental studies

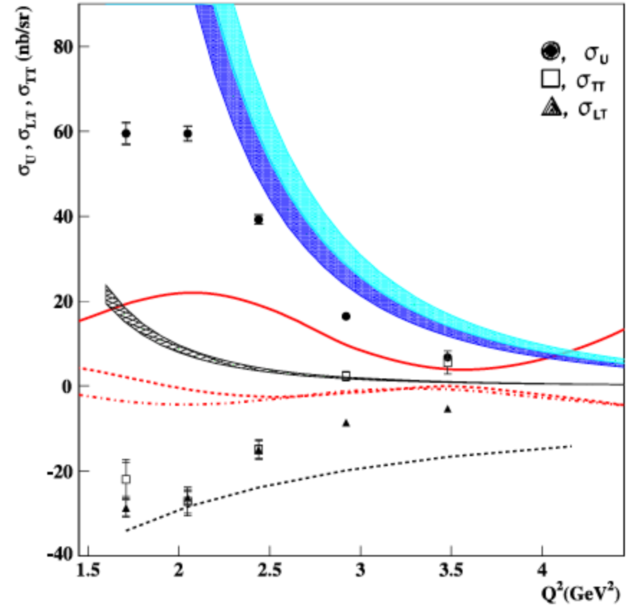


$ep \rightarrow e'n\pi^+$

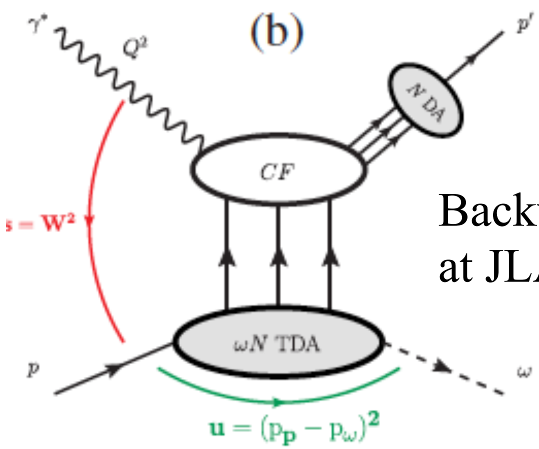
Backward π-production at JLAB –CLAS Collaboration

K. Park et al. PLB 780, 340 (2018)

CLAS Collaboration
PRL 125, 182001 (2020)

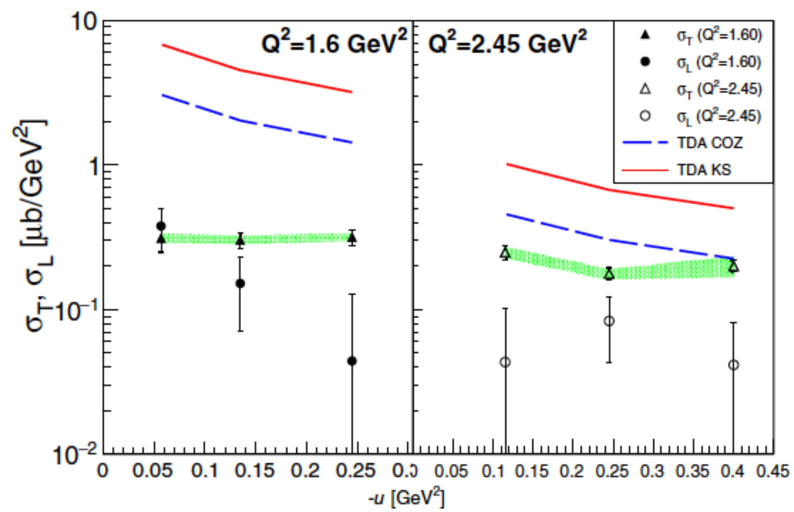


W. B. Li, G. Huber et al.(Jefferson Lab Fπ collaboration)
Phys. Rev. Lett. 123, 182501 (2019)



$ep \rightarrow e'p\omega$

Backward ω-production at JLAB Hall C



TDAs at PANDA

- **Nucleon-to-light meson TDAs:**
  (Vector mesons ρ, ω, ϕ(1020) and Scalar mesons f_0, f_2)

$\bar{p}p \rightarrow \gamma^{*} M -> e^{+}e^{-} M$

$\bar{p}p \rightarrow J/\psi M -> e^{+}e^{-} M$

- Large input for understanding nucleon structure and non perturbative QCD
- Complementary measurements with γ* and *J/ψ*

- **Nucleon-to-photon TDA:**

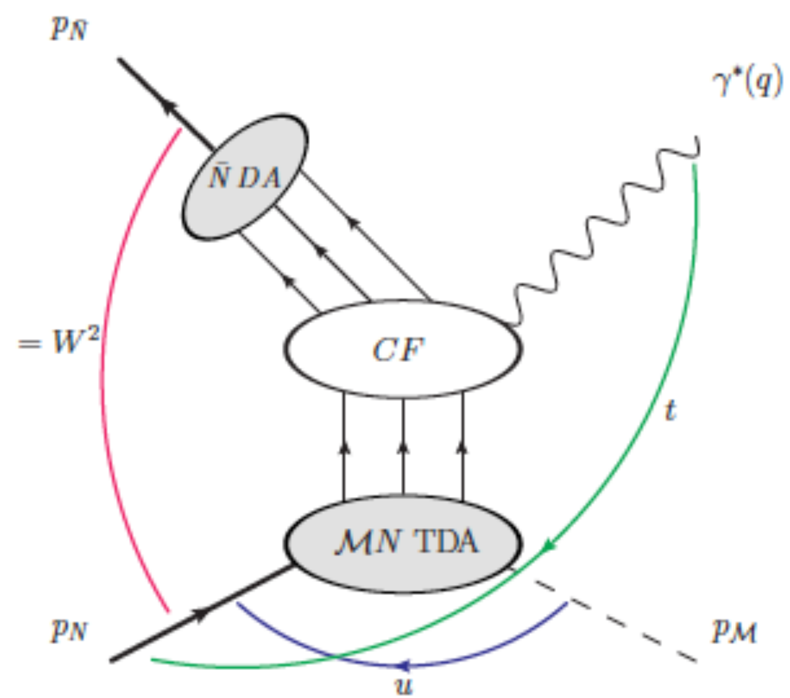
$\bar{p}p \rightarrow \gamma^{*}\gamma -> e^{+}e^{-}\gamma$

$\bar{p}p \rightarrow J/\psi\gamma -> e^{+}e^{-}\gamma$

- **Deuteron-to-baryon TDAs:**

$\bar{p}d \rightarrow \gamma^{*}\Delta^{0}, \bar{p}d \rightarrow J/\Psi\Delta^{0}$

$\bar{p}d \rightarrow \gamma^{*}n, \bar{p}d \rightarrow J/\Psi n$



B. Pire, K. Semenov-Tian-Shansky and L. Szymanowski, [arXiv:2103.01079 [hep-ph]].

Summary

- High precision measurements of the proton time-like form factors are planned at PANDA in large q^2 range
- Electron and muon final states: consistency check of the results and study of systematics (from radiative corrections, event selection,….)

- PANDA is well suited to verify basic characteristics of the TDA models
- Feasibility studies for nucleon-to-pion TDAs have been considered in two channels (virtual photon and J/Psi intermediate states)

- Hard exclusive and inclusive electromagnetic processes can be measured at PANDA and will provide valuable information on the nucleon structure

Thank you for your attention