

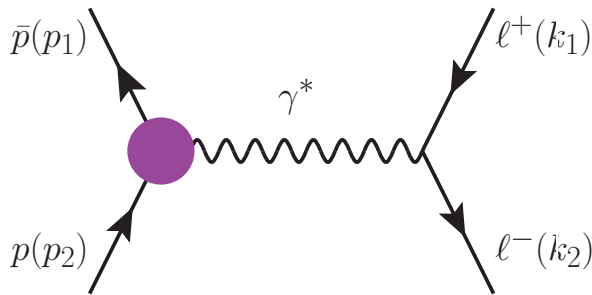
EMP current/planned PANDARoot analyses

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PANDA CM 09.03.2021 (EMP session)

Time-like proton form factors at PANDA



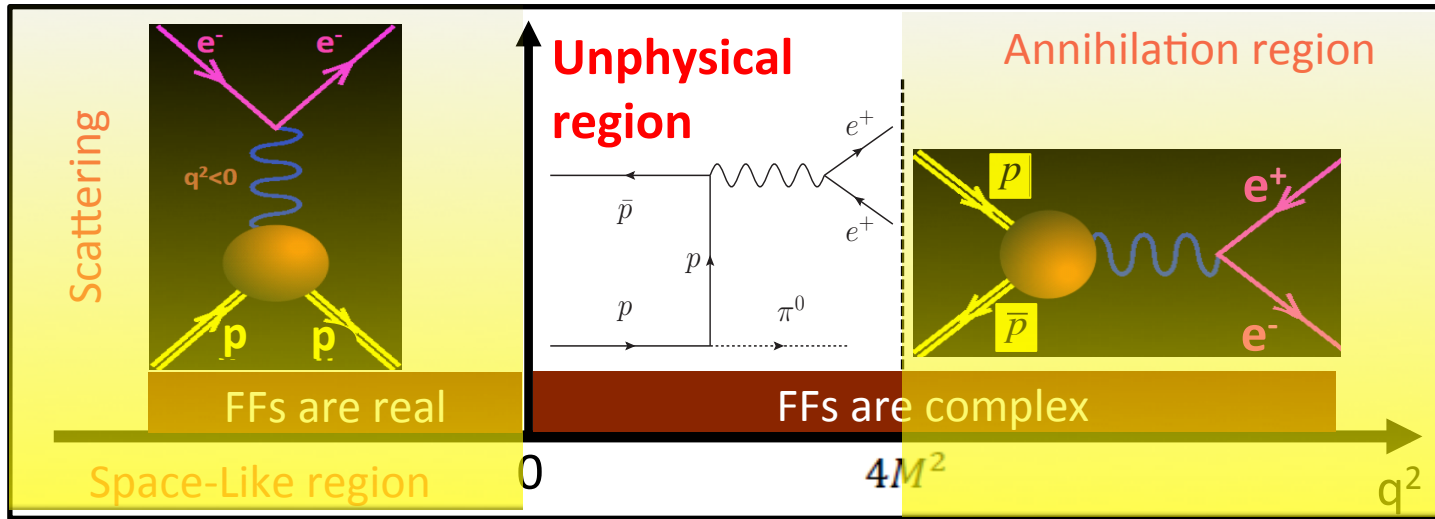
$$\bar{p}p \rightarrow l^+l^- \quad (l = e, \mu)$$

- **High precision measurements in a wide range of q^2 with electron channel**
- **First time measurements with muon channel**

- Monte Carlo event generators for signal and main background processes have been developed; *M. Zambrana et al. Technical reports, HIM Mainz, 2014 (and refs therein)*.
- Feasibility studies for PANDA Phases 1 and 2 (reduced luminosity $0.1 \text{ fb}^{-1}/\text{point}$) and Phase 3 (designed luminosity mode $2 \text{ fb}^{-1}/\text{point}$) completed; *EPJ A 44 (2010) 373-384 (PANDA Phase 3); EPJ A 52 (2016) 10, 325 (PANDA Phase 3); EPJ A 57 (2021) 1, 30 (PANDA Phase 3); PANDA Phase One arXiv:2101.11877 [hep-ex]*
- Monte Carlo event generator for first order radiative corrections (electron case) has been developed; *EPJ A 56 (2020) 2, 58*

- Next steps: - Higher order radiative corrections; polarized target at PANDA and relative phase measurements between proton form factors

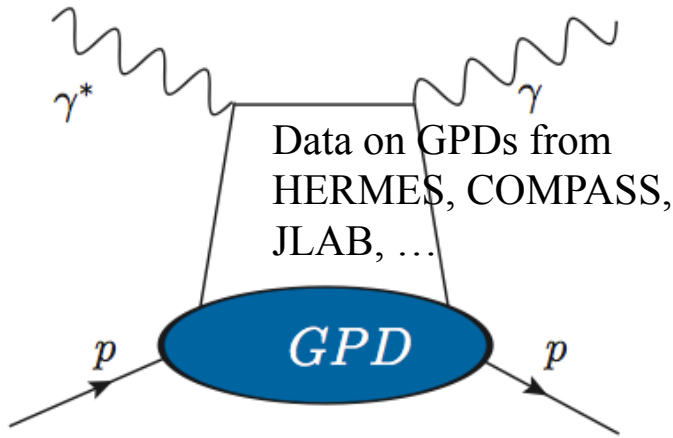
Time-like proton form factors at PANDA



First time measurements below the threshold (unphysical region) with $\bar{p}p \rightarrow e^+ e^- \pi^0$

- Available signal cross section calculations; *M. P. Rekalo, Sov. J. Nucl. Phys. 1 (1965) 760*; *C. Adamuscin et al., Phys. Rev. C 75, 045205 (2007)*; *A.Z. Dubnickova et al, Z. Phys. C 70, 473-481 (1996)*; *G. I. Gakh et al. PRC 83, 025202 (2011)*; *J. Boucher, PhD thesis (BaBar Framework)*; *J. Guttmann, M. Vanderhaeghen, PLB B 719 (2013) 136–142*
- Monte Event generators for signal and background processes based on PHSP angular distributions are sufficient
- **PANDARoot feasibility study for PANDA Phases 1-3 are ongoing at HIM, Mainz (Input for PANDA Phase 2 paper)**

Generalized Distribution Amplitudes (GDAs) at PANDA



DVCS, DVMP and WACS,... in scattering experiments

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

$$\bar{p}p \rightarrow \gamma\gamma$$

$$\bar{p}p \rightarrow \gamma\eta, \bar{p}p \rightarrow \gamma\rho$$

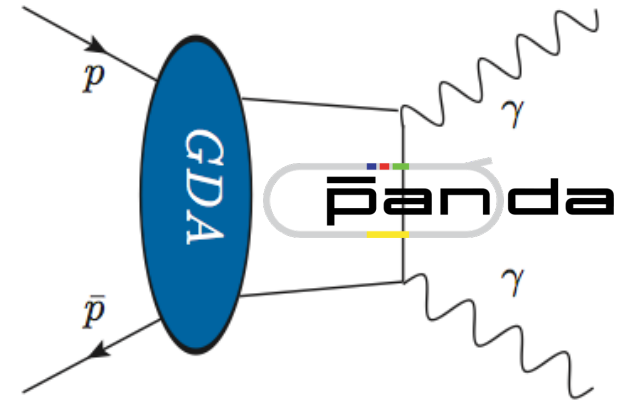
$$\bar{p}p \rightarrow \gamma\omega, \bar{p}p \rightarrow \gamma\eta'$$

$$\bar{p}p \rightarrow \gamma\phi, \bar{p}p \rightarrow \gamma J / \psi$$

t ↔ s channels
GPDs ↔ GDAs



GDAs



- Fermilab $ppbar \rightarrow \gamma\pi^0$ data [8.5 – 13.6] GeV²
- Belle, CLEO,... $\gamma\gamma \rightarrow ppbar$ data below 16 GeV²
- **PANDA can provide more precise data at higher energies and with different processes**

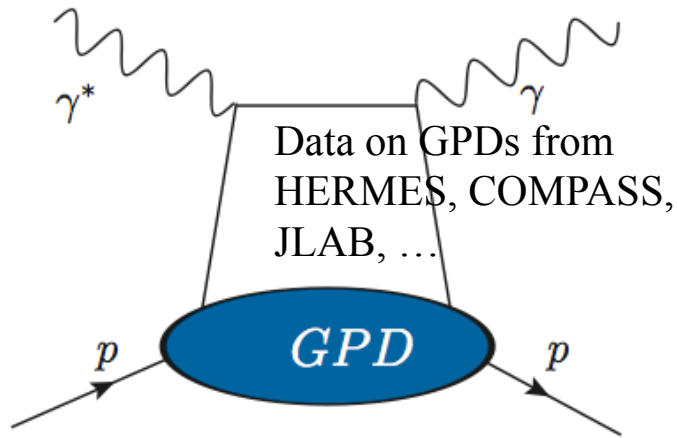
- **In Progress @ Giessen U., available cross section calculations and data from Fermilab at low s (Input for PANDA Phase 2 paper)**

Physical Journal A 26, 89-98 (2005)

European Physical Journal A 50, 1 (2014)

- Initial feasibility study done (S. Diehl), more theoretical inputs and dedicated event generators are needed
- More detailed studies, including background suppression, count rate / beam time estimates are in progress
- GDA program can be extended to charmonium resonances

Generalized Parton Distributions (GPDs) at PANDA



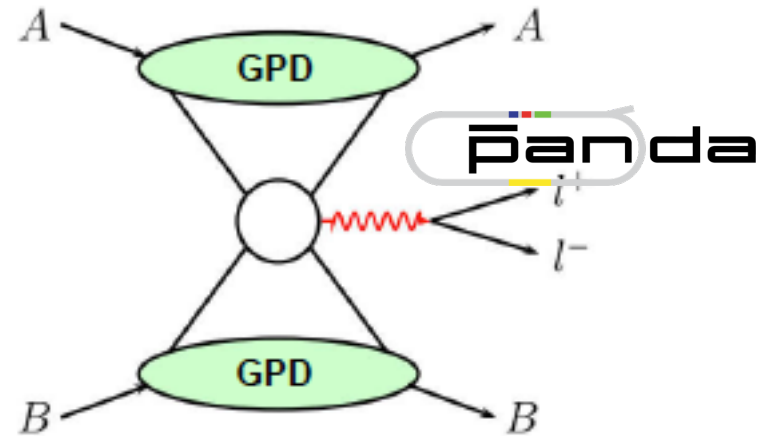
DVCS, DVMP and WACS,... in scattering experiments

$$\bar{p}p \rightarrow \bar{p}pe^+e^-$$

$$\bar{p}p \rightarrow \bar{p}p\mu^+\mu^-$$

$$pp \rightarrow ppl^+l^-$$

Lepton pair production in proton-antiproton collisions

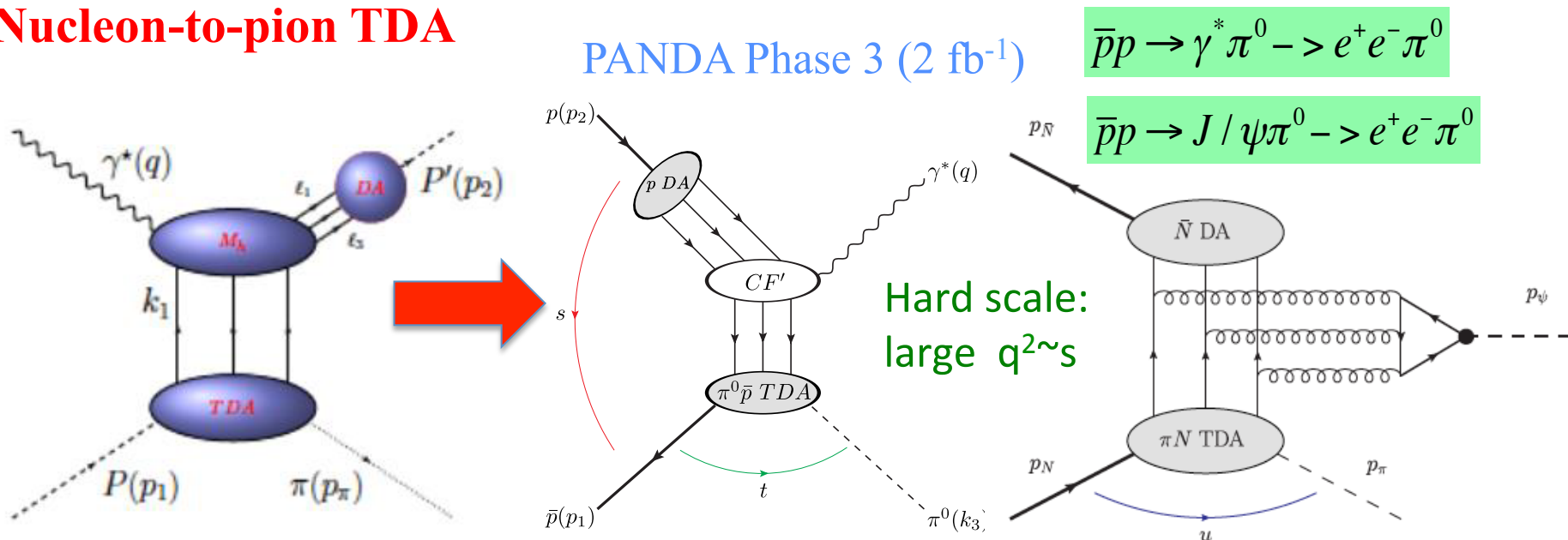


- Initial feasibility study done (S. Diehl),
- Available cross section calculation at large $s=30 \text{ GeV}^2$, more theory calculations are in progress
- Partially integrated measurements are possible during first phases (**Input for PANDA Phase 2 paper ??**)

S. V. Goloskokov, P. Kroll and O. Teryaev [arXiv:2008.13594 [hep-ph]]

Transition distribution amplitudes (TDAs) at PANDA

Nucleon-to-pion TDA



- Complementary measurements in annihilation processes (unique for PANDA) with γ^* and J/ψ – Comparison with Jlab results: test of universality of TDAs
- First measurements from JLAB of $ep \rightarrow en\pi^+$ and backward ω production (TDA regime); *K. Park et al. [CLAS] PLB 780, 340 (2018)*; *S. Diehl et al. [CLAS], PRL 125 (2020) no.18, 182001*; *W. B. Li et al. [Jefferson Lab Fp], PRL 123 (2019) no.18, 18250*
- Feasibility studies for PANDA using dedicated event generators for signal and background process are completed; *EPJ A 51 (2015) no.8, 107*; *Phys. Rev. D 95 (2017) no.3, 032003*

Transition distribution amplitudes (TDAs) at PANDA

Further TDA studies can be addressed at PANDA ...

- **Nucleon-to-light meson TDAs (Vector mesons ρ , ω , $\phi(1020)$ and Scalar mesons f_0 , f_2)**

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

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

- **Nucleon-to-photon TDA**

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

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

- **Deuteron-to-baryon TDAs**

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

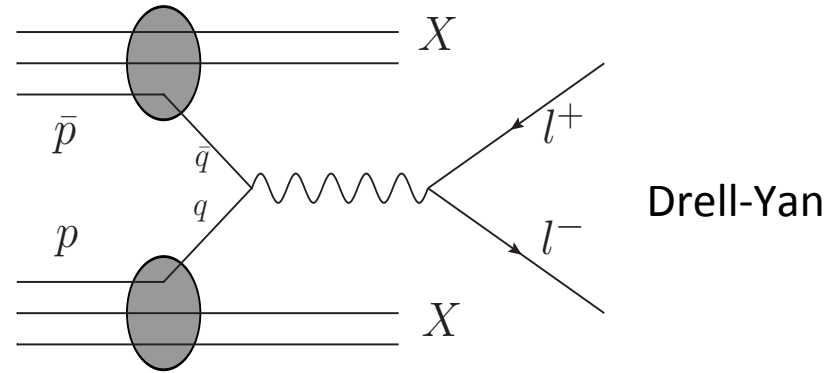
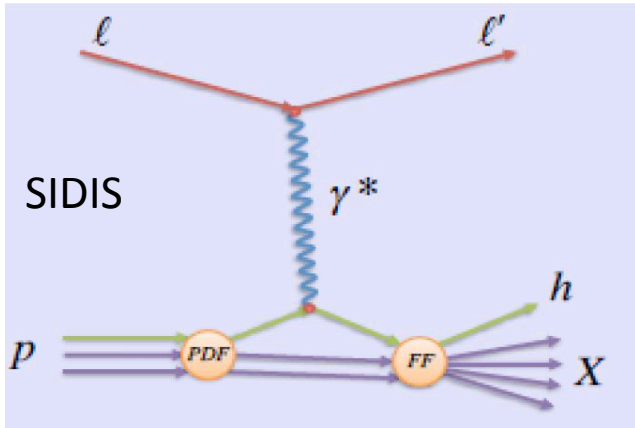
$$\bar{p}d \rightarrow \gamma^* n, \bar{p}d \rightarrow J/\Psi n$$

- Large input for understanding nucleon structure and non pert. QCD
- Processes unique for PANDA: Complementary measurements with γ^* and J/ψ and comparison with Jlab results: test of universality of TDAs

*A Jefferson Lab PAC48 Experiment Proposal [arXiv:2008.10768 [nucl-ex]].
B. Pire et al., PRD 71 (2005) 111501; PRD 91 (2015) no.9, 094006*

- Theoretical calculations of the cross sections and dedicated event generator are needed (TDA experts are interested to provide the theoretical input; *B. Pire, K. Semenov-Tian-Shansky and L. Szymanowski, private communication*)
- Feasibility studies with PANDARoot are not yet started

Transverse Momentum Distributions (TMDs)



Direct access to TMD-PDFs

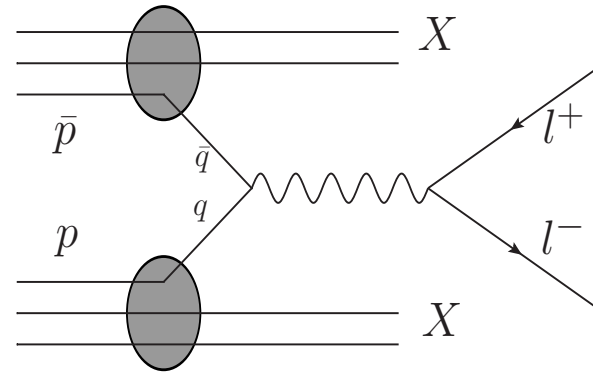
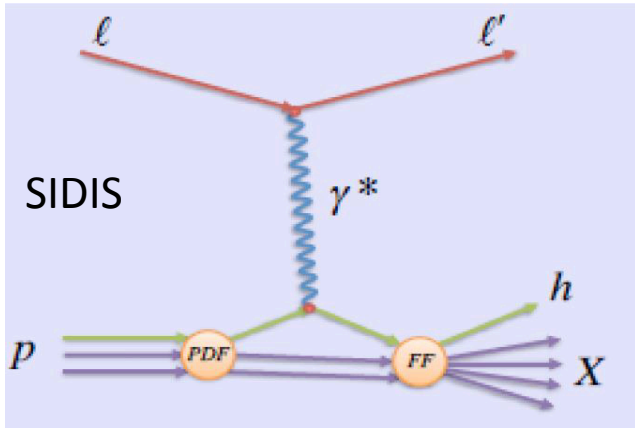
TMD-PDFs are convoluted with the fragmentation functions

Test of Universality and the QCD TMD factorization

- Data on TMDs are from: HERMES, COMPASS, JLab, RHIC, ...: limited kinematical regions and/or precision
- PANDA: Boer-Mulders with unpolarized proton-antiproton experiment; Sivers and Transversity with a polarized target
- PANDA energy range up to $s \sim 30 \text{ GeV}^2$: access to a kinematic region where valence quark effects dominate

| Quark \ Nucleon | U | L | T |
|-----------------|----------------|-------------------------------|------------------------------|
| U | number density | | Boer-Mulders |
| L | | helicity | worm-gear L |
| T | Sivers | Kotzinian-Mulders worm-gear T | transversity pretzelosity |

Transverse Momentum Distributions (TMDs)



Direct access to TMD-PDFs

TMD-PDFs are convoluted with the fragmentation functions

Test of Universality and the QCD TMD factorization

$$\bar{p}p \rightarrow e^+e^-X$$

$$\bar{p}p \rightarrow \mu^+\mu^-X$$

- Analysis ongoing by A. Skachkova (JINR)
- PYTHIA & PANDARoot based simulations: a reasonable background suppression for both processes is not yet reached
- Planned for PANDA Phase 3

| Quark \ Nucleon | U | L | T |
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Backup slides

- **TL Proton Form Factors**

$$\bar{p}p \rightarrow e^+e^-$$

$$\bar{p}p \rightarrow \mu^+\mu^-$$

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

- ✓ Eur. Phys. J. A 44 (2010) 373-384 (PANDA Phase 3)
- ✓ Eur. Phys. J. A 52 (2016) 10, 325 (PANDA Phase 3)
- ✓ Eur. Phys. J. A 57 (2021) 1, 30 (PANDA Phase 3)
- ✓ PANDA Phase One arXiv:2101.11877 [hep-ex]

➤ In Progress @ HIM (Input for PANDA Phase 2 paper)

- **Transition Distributions Amplitudes (TDAs) in hard exclusive processes**

Nucleon-to-pion TDA:

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

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

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• **Parton Distributions Functions (TMD-PDFs) in Drell-Yan**

$$\bar{p}p \rightarrow e^+e^-X$$

$$\bar{p}p \rightarrow \mu^+\mu^-X$$

- Issue of the background suppression is not yet resolved
- Planned for PANDA Phase 3
- Analysis by A. Skachkova (JINR)