PANDA collaboration meeting 23/1 (March 2023), Bochum

Overview on possibilities for 3D nucleon structure studies based on proton and antiproton scattering and annihilation

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08.03.2023

Introduction

- Physics options for 3D nucleon structure studies based on proton and antiproton scattering and annihilation
- Proton energies i.e. - 30 / 50 GeV proton beams @ J-PARC
  - up to 30 GeV proton beams from SIS100 @ FAIR
  - 190 GeV hadron beams $(\pi, K, p)^{\pm}$ @ COMPASS
  - …
- Antiproton energies - up to 15 GeV from PANDA @ HESR
  - possible options in a similar region @ J-PARC

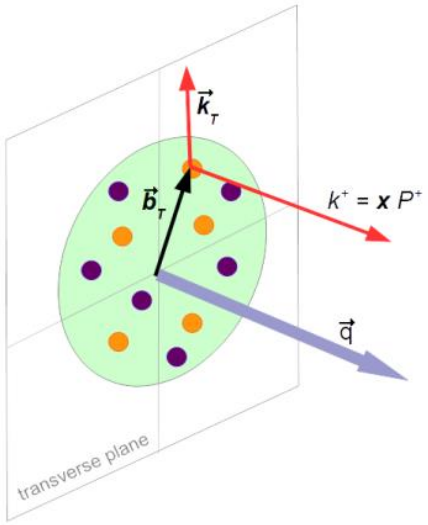
p = 15 GeV/c → s = 30 GeV² → sqrt(s) = 5.5 GeV

p = 30 GeV/c → s = 58 GeV² → sqrt(s) = 7.6 GeV

p = 50 GeV/c → s = 96 GeV² → sqrt(s) = 9.8 GeV

p = 190 GeV/c → s = 358 GeV² → sqrt(s) = 18.9 GeV

Introduction



Wigner distribution $\rho(x, \vec{k}_T, \vec{b}_T)$ — **5D**

$\int d^2k_T$ → **Generalized Parton Distributions (GPDs)**

$\int d^2b_T$ → **Transverse Momentum Distributions (TMDs)** — **3D**

Generalized Parton Distributions (GPDs):

$\int dx$ → **2D** **Form Factors** *eg*: G_E, G_M

$\int d^2b_T$ → **Parton Distribution Functions (PDFs)** — **1D**

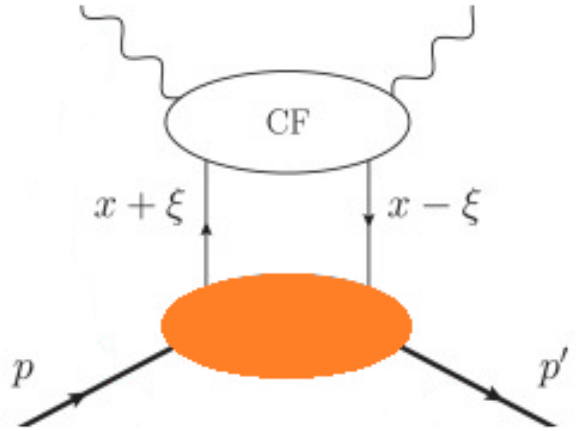
Transverse Momentum Distributions (TMDs):

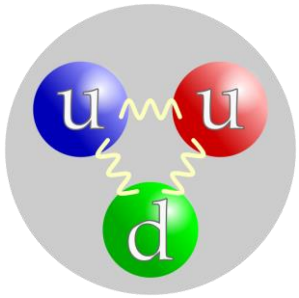
$\int d^2k_T$ → **Parton Distribution Functions (PDFs)** — **1D**

PANDA provides access to the time-like region

Reactions sensitive to

Generalized Parton Distributions (GPDs)





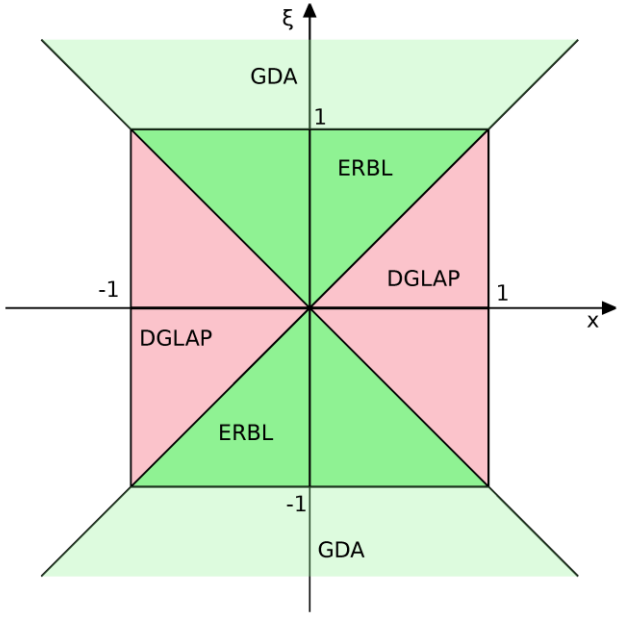


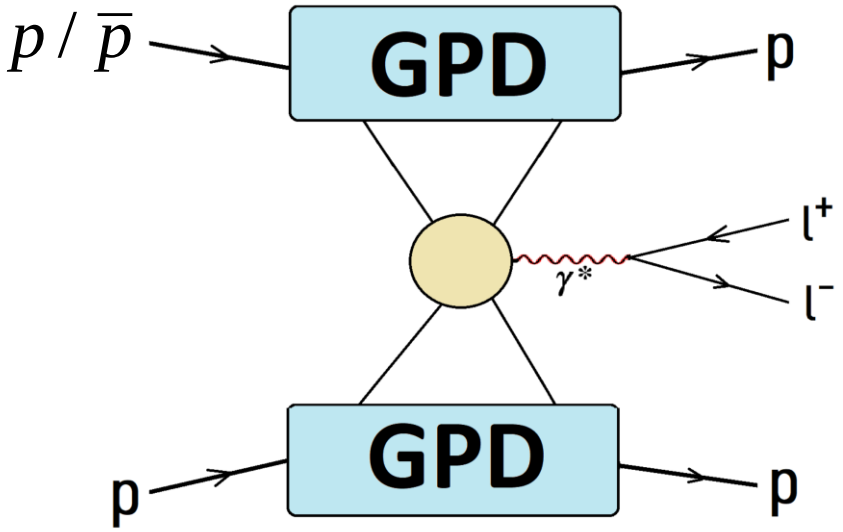
Figure from C. Mezrag, Particles **2023**, *6*(1), 262-296

N\q	U	L	T
U	H		$\bar{E}_T$
L		$\widetilde{H}$	$\widetilde{E}_T$
T	E	$\widetilde{E}$	H_T, $\widetilde{H}_T$

GPDs: space like (lepton / hadron scattering)

GDAs: time like (annihilation)

Lepton pair production in hard exclusive hadron scattering



- **Can be done with protons and antiprotons**
- **Requires an EMC and a full e^- / π separation capability**

Factorization expected for: $t_1/Q'^2 \ll 1 \text{ and } t_2/Q'^2 \ll 1$

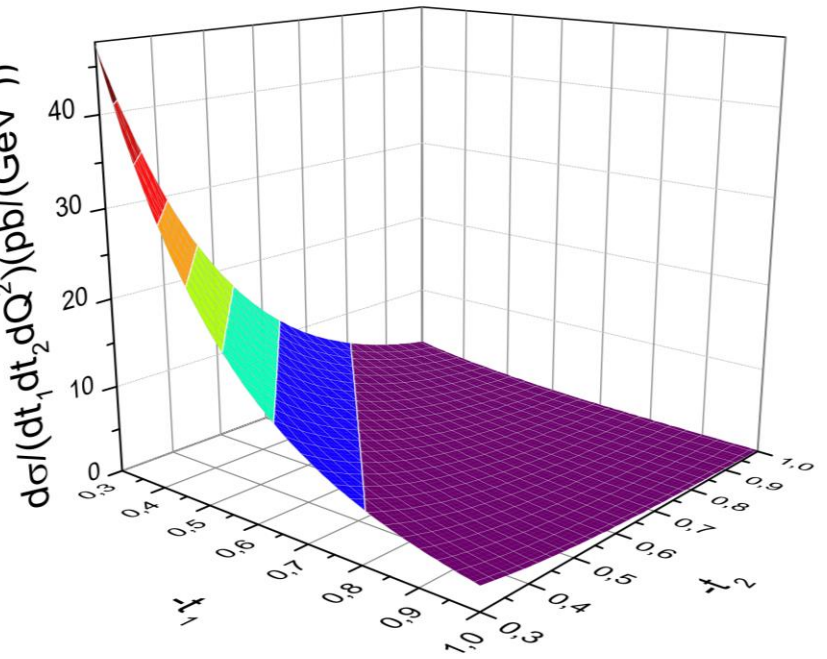
Access to the GPD: $$H_{eff} = H - \frac{\xi^2}{1-\xi^2} E$$

S.V. Goloskokov, P. Kroll, O. Teryaev, https://doi.org/10.48550/arXiv.2008.13594 (2020)

Lepton-pair production in hard exclusive hadron-hadron collisions

arXiv:2008.13594v1
[hep-ph] 31 Aug 2020

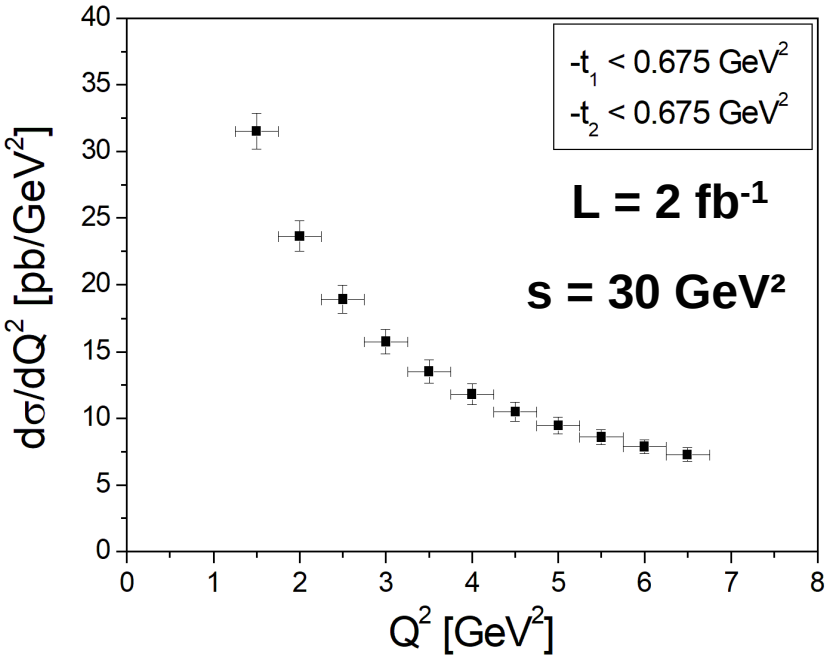
S.V. Goloskokov [§1], P. Kroll [†2] and O. Teryaev [§‡3]

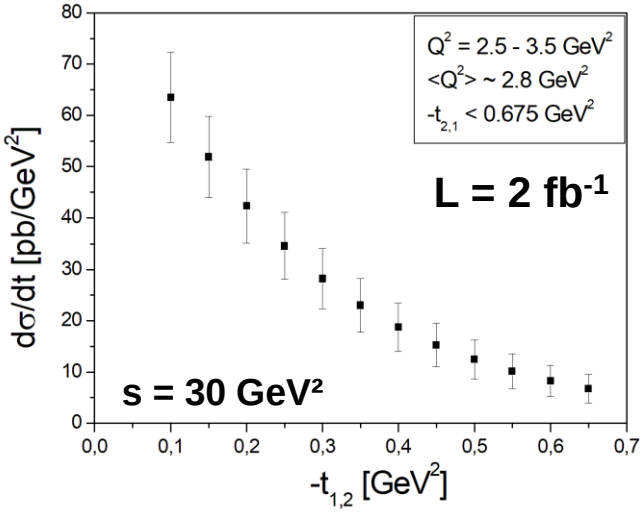


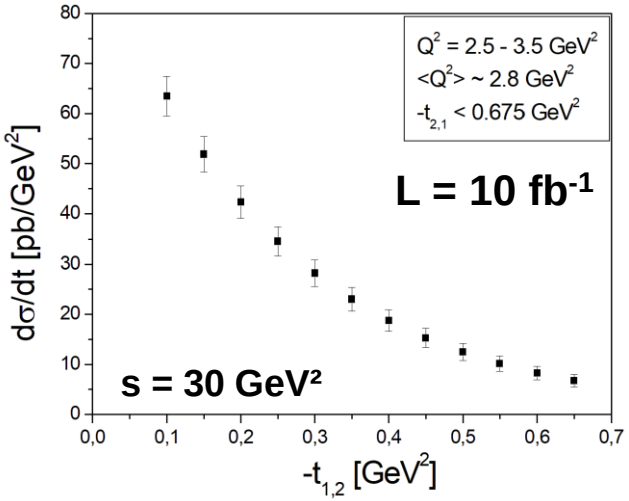
s = 30 GeV² (p = 15 GeV/c) Q² = 3 GeV²

- **Feasibility has been shown for anti-proton scattering with a full PANDA setup for p = 10 - 15 GeV/c at the last CMs**
- **Higher energies will be an advantage!**
- **Feasibility can be 1 to 1 also applied for proton scattering**

Lepton-pair production in hard exclusive hadron-hadron collisions







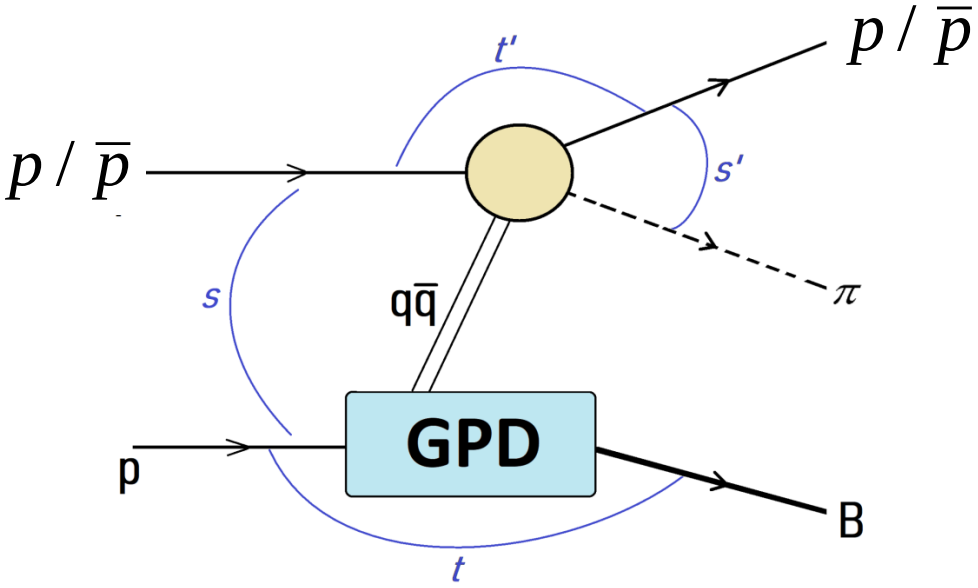
- **L = 2 – 10 fb^{-1} needed (small cs)**

Feasibility: Feasibility study for antiprotons with the full PANDA setup exists (EMC is mandatory), but cross section too low for proton studies @ SIS100

Physics impact of proton / antiproton scattering alone: Medium

Physics impact of proton an antiproton data: High (quark vs antiquark GPDs)

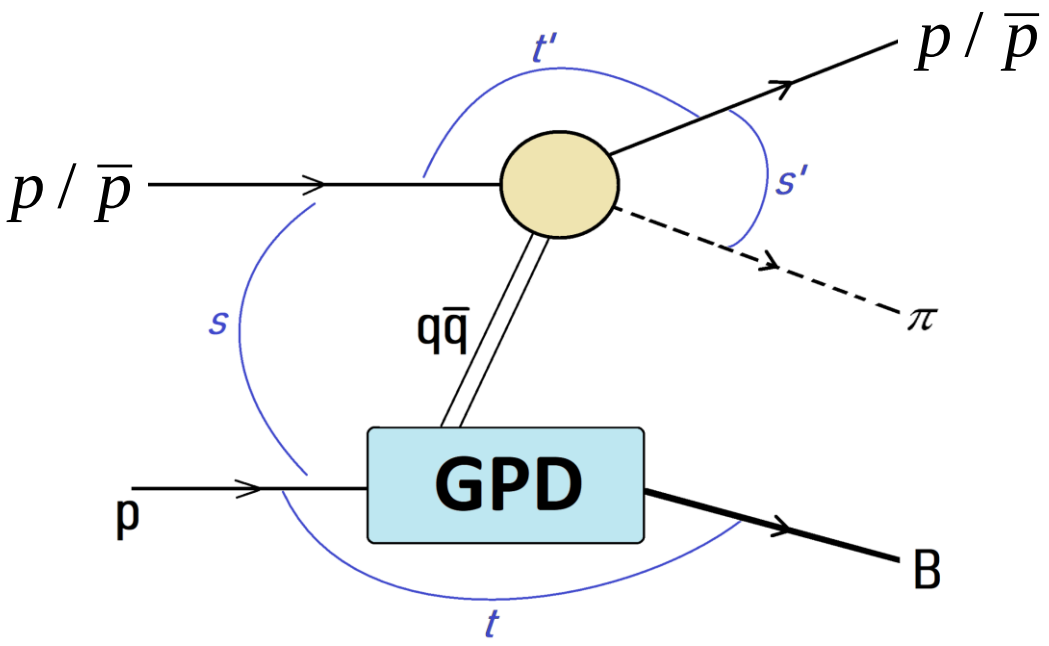
GPDs from the $NN \to N\pi B$ processes



Factorisation for: $|s'|, |t'|, |u'| \gg M_N^2$ with $t'/s' = const.$ and $|t| \ll M_N^2$

- sensitive to the classical twist-2 nucleon GPDs H, E, $\widetilde{H}$ and $\widetilde{E}$
- probe GPDs in the ERBL (Efremov-Radyushkin- Brodsky-Lepage) kinematic regime $(-\xi < x < \xi)$ not accessible in lepton scattering experiments
- baryon resonance in the final state provides sensitivity to the transition GPDs

S. Kumano, M. Strikman, K. Sudoh, Phys. Rev. D 80, 074003 (2009) arXiv:0905.1453



p p → p π^0 p

p p → p π^+ n

p p → p π^- Δ^{++} → p π^- (p π^+)

p p → p π^+ Δ^0 → p π^+ (p π^-)

p p → p π^+ N^{*0} → p π^+ (p π^-)

p p → p K^+ Λ^0 → p K^+ (p π^-) ….

Potential synergy with hyperon physics

+ many options with neutrons and or π^0

S. Kumano, M. Strikman, K. Sudoh, Phys. Rev. D 80, 074003 (2009)

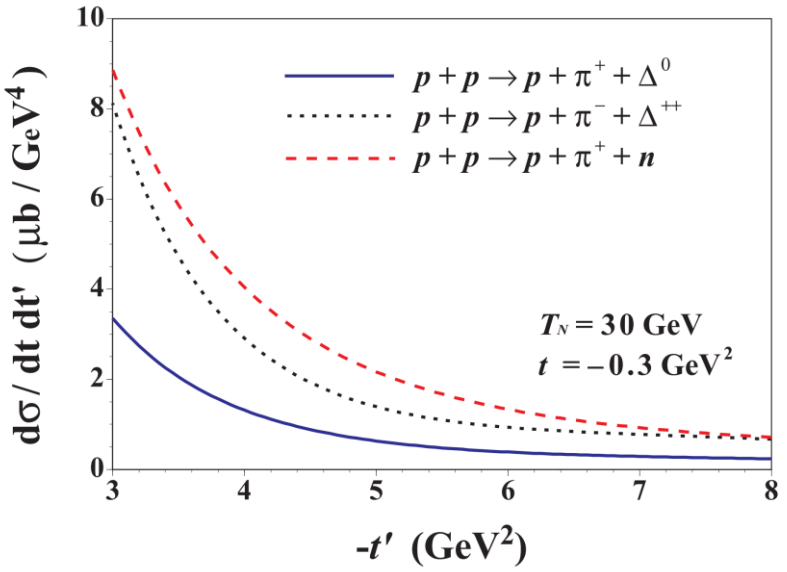


FIG. 11: Differential cross section as a function of t'. The incident proton-beam energy is 30 (50) GeV in the upper (lower) figure, and the momentum transfer is $t = -0.3$ GeV^2.

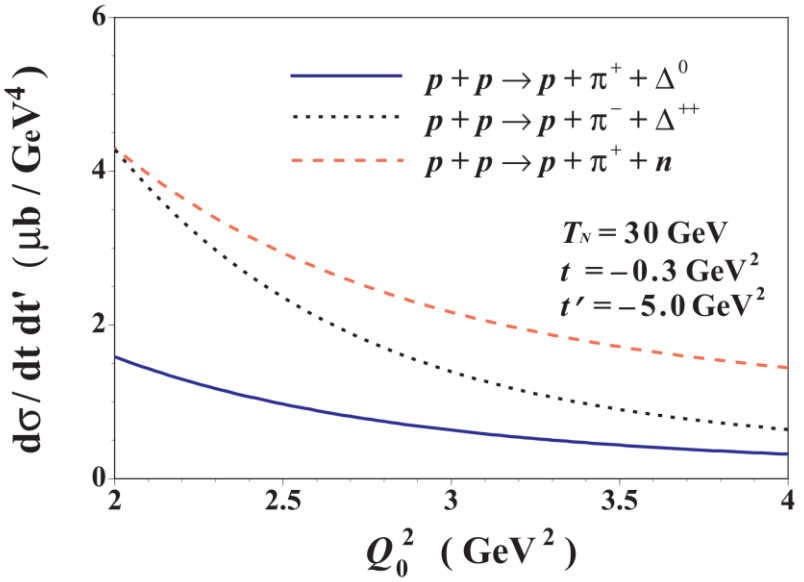


FIG. 13: Cutoff (Q_0^2) dependence of differential cross section. The incident proton-beam energy is 30 GeV, and momentum transfers are fixed at $t = -0.3$ GeV^2 and $t' = -5$ GeV^2.

Feasibility: Likely – Acceptance studies needed / in progress

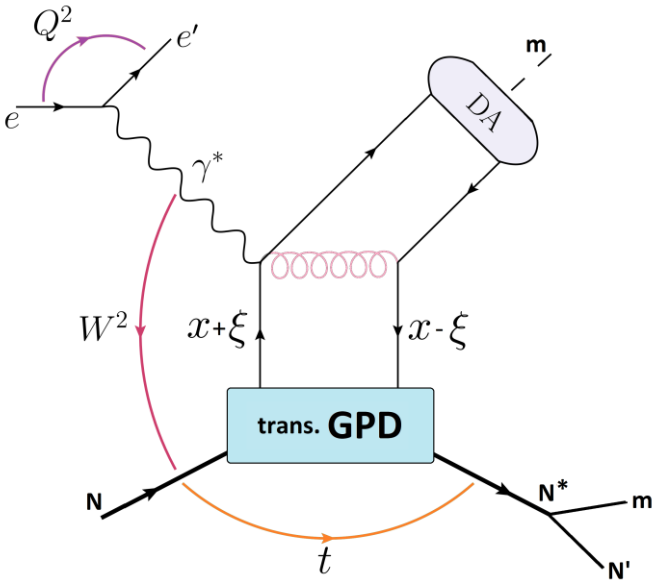
(high cross section, also possible with a partial PANDA setup, depending on the decay)

Theory: Predictions exist and are published for p = 30 GeV/c

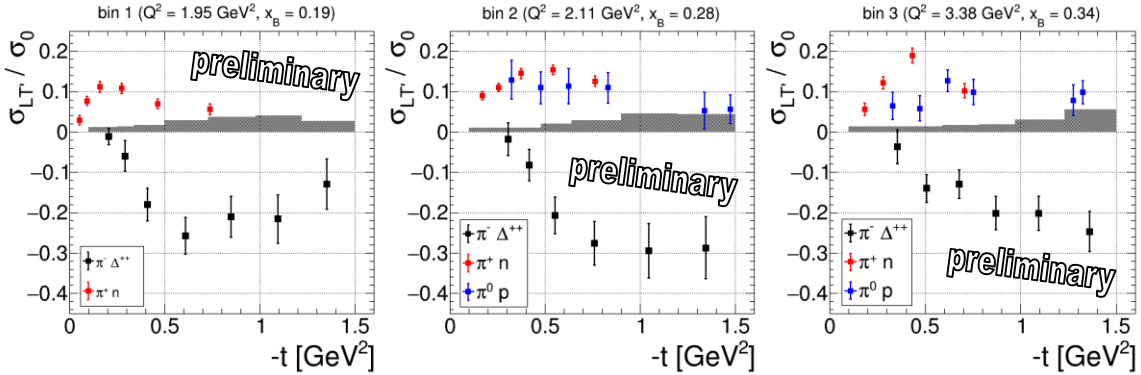
Physics impact from 15 (30) GeV (anti)proton scattering:

High (transition GPDs are nearly unexplored) + quark vs antiquark GPDs

First experimental observable sensitive to transition GPDs from CLAS12



$$BSA = \frac{\sqrt{2\epsilon(1-\epsilon)}\frac{\sigma_{LT'}}{\sigma_0}\sin\phi}{1+\sqrt{2\epsilon(1+\epsilon)}\frac{\sigma_{LT}}{\sigma_0}\cos\phi+\epsilon\frac{\sigma_{TT}}{\sigma_0}\cos 2\phi}$$



$$ep \to e\Delta^{++}\pi^- \to ep\pi^+\pi^-$$

S. Diehl (JLU + UConn)

paper will be submitted to PRL this month

ECT*-APCTP Joint Workshop: Exploring resonance structure with transition GPDs

21 August 2023 — 25 August 2023

ECT* - Villa Tambosi

Strada delle Tabarelle, 286

Trento - Italy

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https://www.ectstar.eu/workshops/ect-apctp-joint-workshop-exploring-resonance-structure-with-transition-gpds/

Conclusion on GPD related processes?

• Both reactions can be studied based on proton **and** antiproton scattering

Assumption: Proton (quark) GPDs are equal to antiproton (antiquark GPDs)

→ „Matter has the same 3D properties as antimatter“

→ Cross sections are expected to be equal!

BUT: Studies of the elastic proton and antiproton scattering show that there is an unexpected difference

→ The cross section for antiprotons is signifiantly smaller, especially in the backward direction ➔ Unsolved „puzzle“

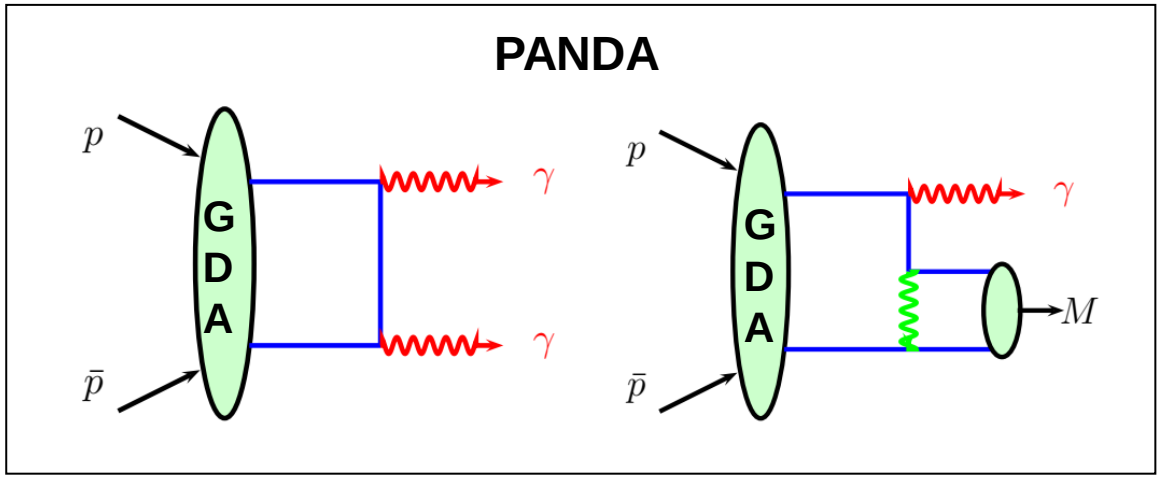
• A measurement of GPDs with protons and with antiprotons can provide a comparison of quark an antiquark GPDs

➔ If there is a difference, this would imply for example a different pressure distribution in protons and antiprotons

➔ Evidence for a matter-antimatter asymmetry!

➔ Understanding of the early universe!

Measurement of GDAs in proton – antiproton annihilation

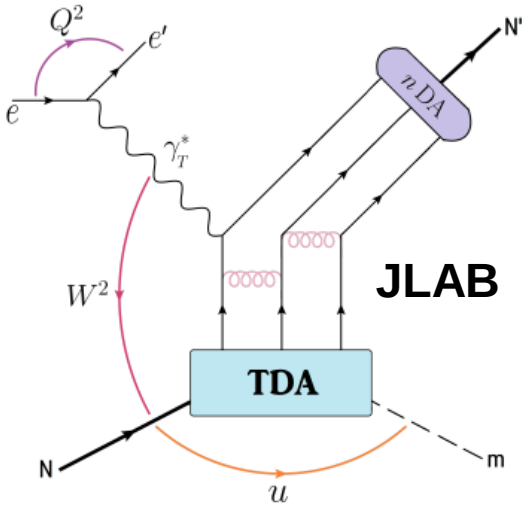


$p\bar{p} \rightarrow \gamma M$ at large Mandelstamm variables $s, -t, -u \gg \Lambda^2$

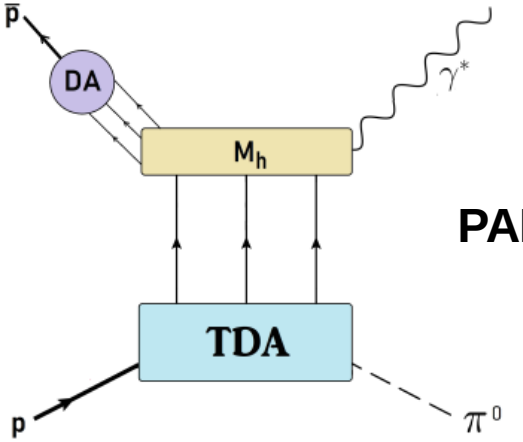
$p\ \bar{p} \rightarrow \gamma\ \gamma$ $\quad$ $p\ \bar{p} \rightarrow \gamma\ \pi^0$

Feasibility: Feasibility study for antiprotons with the full PANDA setup exists / is in progress (EMC is mandatory) → See Faizas talks at the last CMs

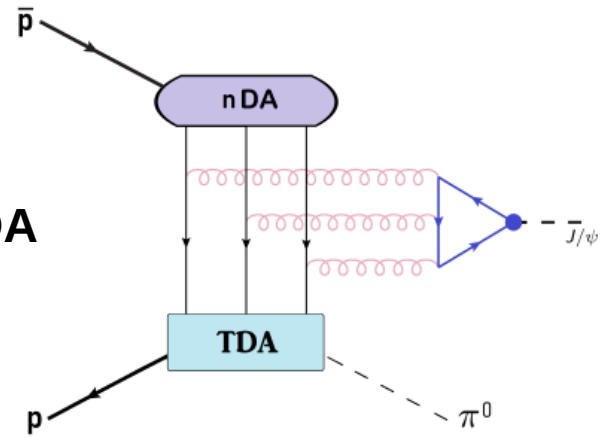
Measurement of TDAs in proton – antiproton annihilation



JLAB



PANDA



Feasibility studies of measuring $\bar{p}p \rightarrow \gamma^* \pi^0 -> e^+e^-\pi^0$ at PANDA

Eur.Phys.J. A51 (2015) 8, 107

Phys. Rev. D 95, 032003 (2017)

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

Feasibility: Feasibility study for antiprotons with the full PANDA setup is published (EMC is mandatory)

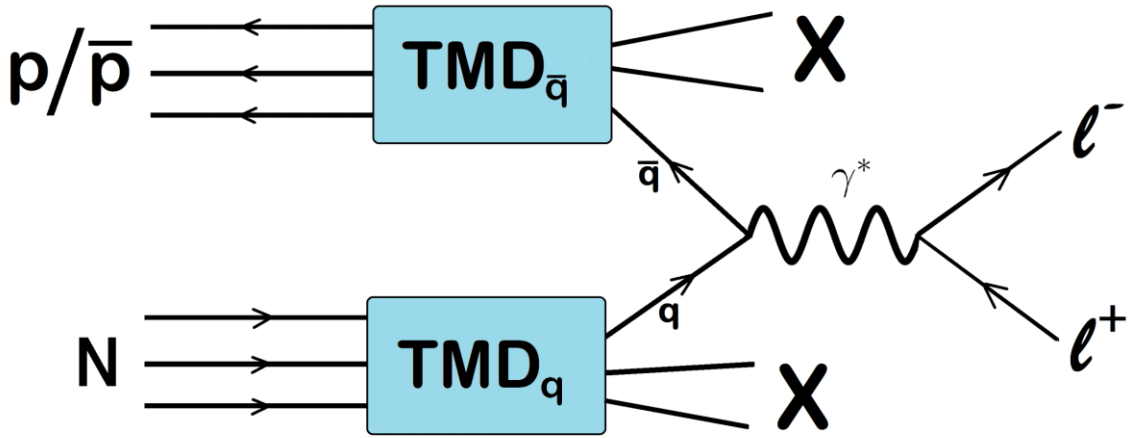
Reactions sensitive to

Transverse momentum dependent distribution functions (TMDs)

3D distributions in momentum space

N\q	U	L	T		twist 3
U	f_1		$h_1^\perp$		$f^\perp, g^\perp, h, e$
L		g_{1L}	$h_{1L}^\perp$		$f_L^\perp, g_L^\perp, h_L, e_L$
T	$f_{1T}^\perp$	g_{1T}	$h_1, h_{1T}^\perp$		$f_T, f_T^\perp, g_T, g_T^\perp, h^\perp, e_T, h_T^\perp, e_T^\perp$

The Drell-Yan process



Unpolarized cross – section:

$$\frac{d\sigma}{d^4q dcos(\theta) d\phi} = \frac{\alpha_{em}^2}{F\ q^2} \times \left\{ \left((1+\cos^2(\theta))\ F_{UU}^1 + (1-\cos^2(\theta))\ F_{UU}^2 + \sin(2\theta)\cos(\phi)\ F_{UU}^{\cos(\phi)} + \sin^2(\theta)\cos(2\phi)\ F_{UU}^{\cos(2\phi)} \right) \right.$$

$$F_{UU}^1 = \zeta \left[f_1 \bar{f}_1 \right],$$

$$F_{UU}^2 = 2F_{UU}^{\cos(2\phi)} = 2\zeta \left[\frac{2(\vec{h}\cdot\vec{k}_{aT})(\vec{h}\cdot\vec{k}_{aT}) - \vec{k}_{aT}\vec{k}_{bT}}{M_a M_b}\ h_1^\perp \bar{h}_1^\perp \right], \quad \text{"Boer-Mulders function"}$$

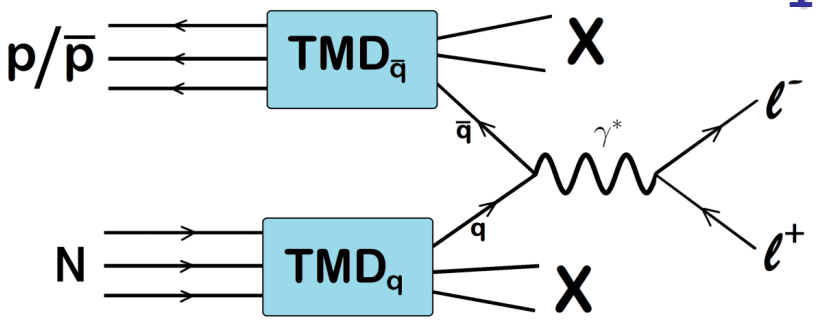
The Drell-Yan process

Unpolarized proton data used in recent global fits:

Experiment	N_{dat}	Observable	$\sqrt{s}$ [GeV]	Q [GeV]
E605	50	$Ed^3\sigma/d^3q$	38.8	7–18
E288 200 GeV	30	$Ed^3\sigma/d^3q$	19.4	4–9
E288 300 GeV	39	$Ed^3\sigma/d^3q$	23.8	4–12
E288 400 GeV	61	$Ed^3\sigma/d^3q$	27.4	5–14
STAR 510	7	$d\sigma/dq_T$	510	73–114
CDF Run I	25	$d\sigma/dq_T$	1800	66–116
CDF Run II	26	$d\sigma/dq_T$	1960	66–116
D0 Run I	12	$d\sigma/dq_T$	1800	75–105
D0 Run II	5	$(1/\sigma)d\sigma/dq_T$	1960	70–110
D0 Run II (μ)	3	$(1/\sigma)d\sigma/dq_T$	1960	65–115

+ LHCb, ATLAS and CMS data in the TeV region

A. Bacchetta et al., JHEP 07, 117 (2020).
https://doi.org/10.1007/JHEP07%282020%29117
[arXiv:1912.07550]



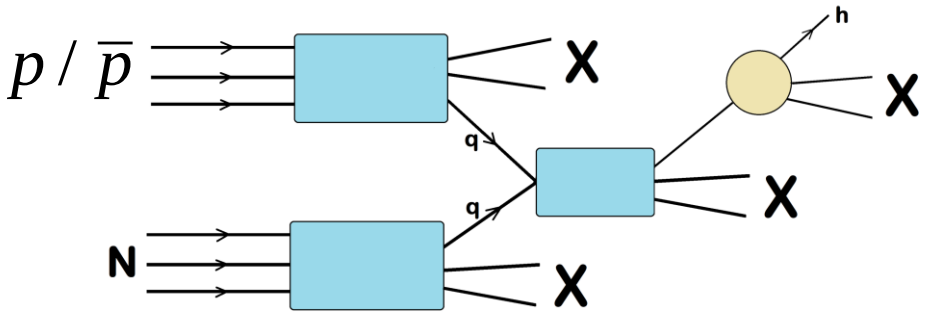
- Recent global fits show, that 15 - 30 GeV proton beams may probably be not sufficient for TMD factorisation
- Antiproton data would be special, since it probes valence quarks while proton data probes sea quarks in the nucleon

Feasibility with 15 – 30 GeV (anti-) protons:

A high background was fond
- Hard to suppress with classcial cuts
- A neural network based event selection may help!

Physics impact:
Low – Medium for protons
Medium – High for antiprotons

Semi-inclusive single and di-hadron production from hadronic interactions



$$pN \to hX$$

$$pN \to h_1 h_2 X$$

Full TMD factorisation needed (questionable for 15 - 30 GeV p / $\bar{p}$)

Theory: Clear connection to TMDs is non-trivial

➔ Study „charm“ PDFs

pp → J/ψ + X

Only twist-2 factorisation needed (15 – 30 GeV may be sufficient)

But: Energy may not be sufficent for a real semi-inclusive di-hadron production
(so far studied at RHIC sqrt(s) = 200 GeV)

Conclusion

- **Measuring GPDs and transition GPDs in a 2 → 3 reaction may be well suited for the scattering of 15 (30 GeV) (anti)protons**

  → It will provide new high impact physics

  → It has high cross sections (few months would be sufficient)

- **Also GPD measurements based on hard exclusive lepton pair production are feasible if the EMC is available.**

  → Low cross section has to be considered

- **Based on antiproton – proton annihilation, GDAs and TDAs will provide access to the time like sector of GPDs and to a different kinematic regime**

- **TMD related measurements are difficult at low (anti)proton enegies and the potential physics value and impact needs further clarification.**

  → The DY process with antiprotons can provide access to anti-valence quarks!

  → Semi-inclusive J/psi production can access the charm PDFs