Nucleon structure studies with the PANDA experiment at FAIR

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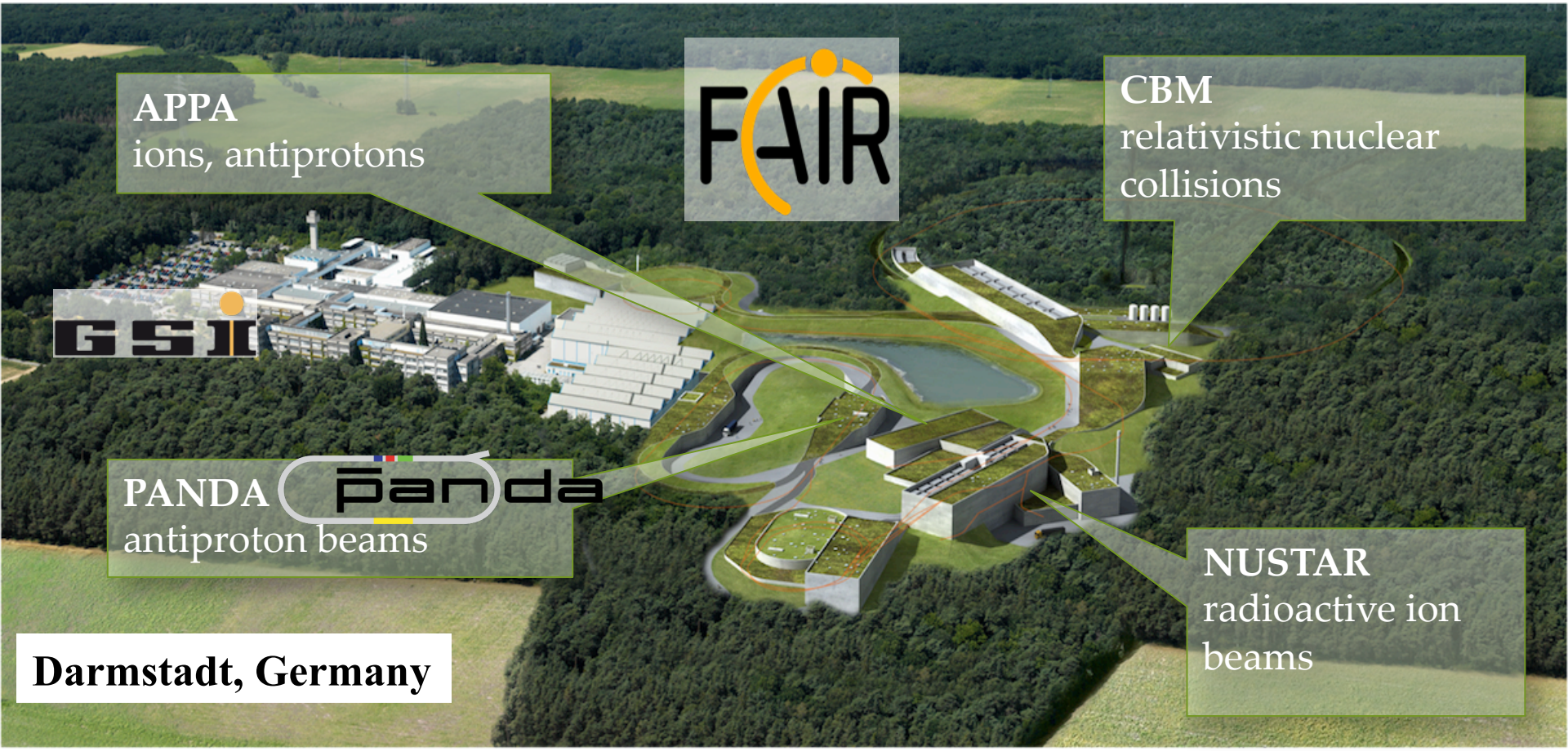
On behalf of the PANDA collaboration

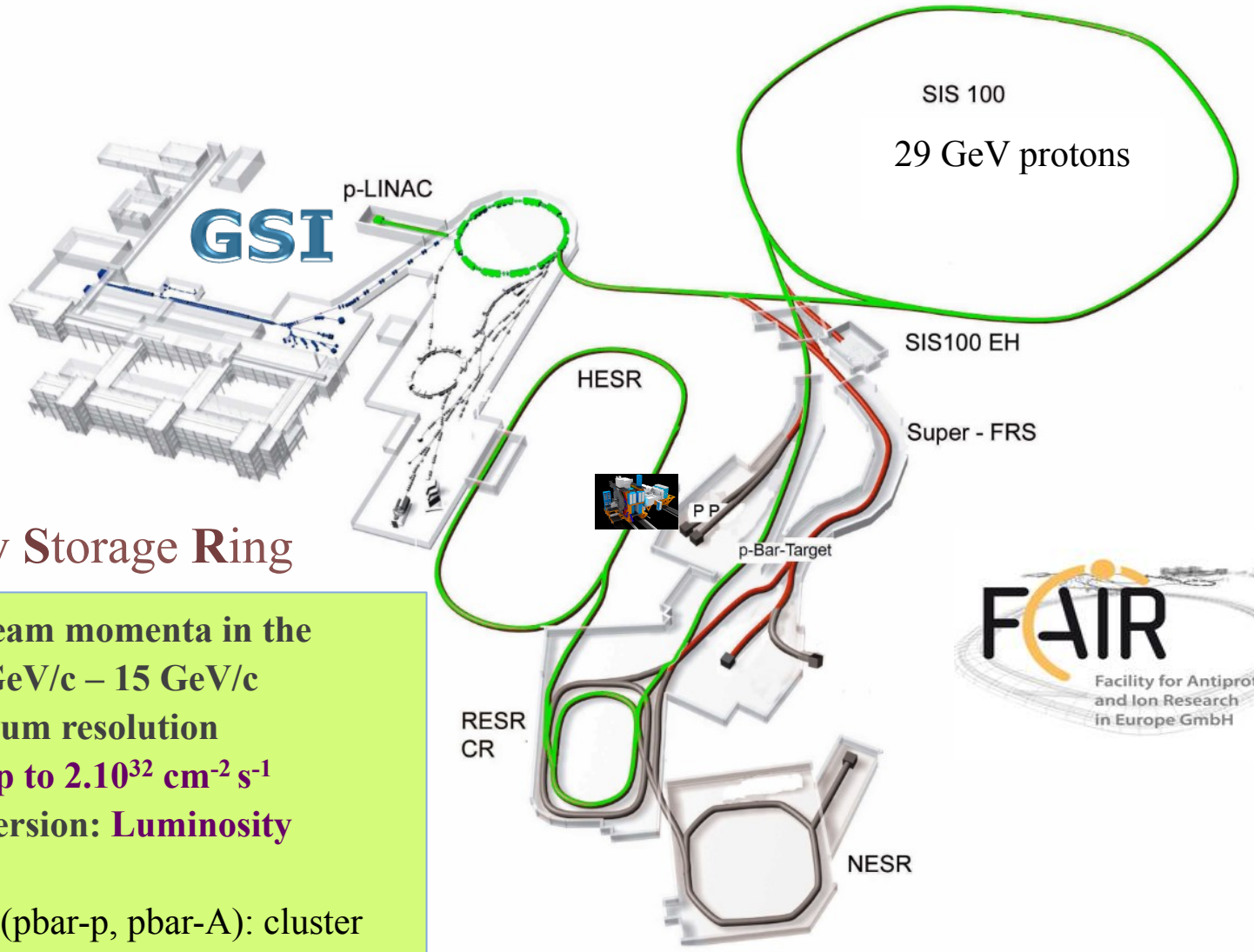
Baldin ISHEPP XXIV
JINR Dubna, 18 September 2018

Helmholtz Institute Mainz
Johannes-Gutenberg University Mainz

Facility for Antiproton and Ion Research - FAIR (Darmstadt/Germany)



Facility for Antiproton and Ion Research - FAIR



High Energy Storage Ring

- **Antiproton beam momenta in the range of 1.5 GeV/c – 15 GeV/c**
- **High momentum resolution**
- **Luminosity up to 2.10^{32} cm^{-2} s^{-1}**
- **FAIR Start Version: Luminosity $10^{31} cm^{-2} s^{-1}$**
- Internal target (pbar-p, pbar-A): cluster jet / pellet target; high density $4x10^{15}$ cm^{-2}

The PANDA experiment at FAIR

Collaboration

UniVPM Ancona
U Basel
IHEP Beijing
U Bochum
Abant Izzet Baysal
U Golkoy, Bolu
U Bonn
U Brescia
IFIN-HH Bucharest
AGH UST Cracow
IFJ PAN Cracow
JU Cracow
U Cracow
FAIR Darmstadt
GSI Darmstadt
JINR Dubna
U Edinburgh
U Erlangen
NWU Evanston
U & INFN Ferrara
FIAS Frankfurt
U Frankfurt
LNF-INFN Frascati
U & INFN Genova
U Gießen
U Glasgow
BITS Pilani KKBGC, Goa
KVI Groningen
Sadar Patel U, Gujart
Gauhati U, Guwahati
USTC Hefei
URZ Heidelberg
FH Iserlohn
Doğuş U, Istanbul
FZ Jülich
IMP Lanzhou
INFN Legnaro
U Lund
HI Mainz
U Mainz
INP Minsk
ITEP Moscow
MPEI Moscow
BARC Mumbai
U Münster
Nankai U, Tianjin
BINP Novosibirsk
Novosibirsk State U
IPN Orsay
U Wisconsin, Oshkosh
U & INFN Pavia
Charles U, Prague
Czech TU, Prague
IHEP Protvino
Irfu Saclay
U of Sidney
PNPI St. Petersburg
West Bohemian U, Pilzen
KTH Stockholm
U Stockholm
SUT, Nakhon Ratchasima
SVNIT Surat-Gujarat
S Gujarat U, Surat-Gujarat
FSU Tallahassee
U & INFN Torino
Politecnico di Torino
U & INFN Trieste
U Uppsala
U Valencia
SMI Vienna
U Visva-Bharati
NCBJ Warsaw

more than 460 physicists from
from more than 75 institutions in 20 countries

The PANDA experiment at FAIR

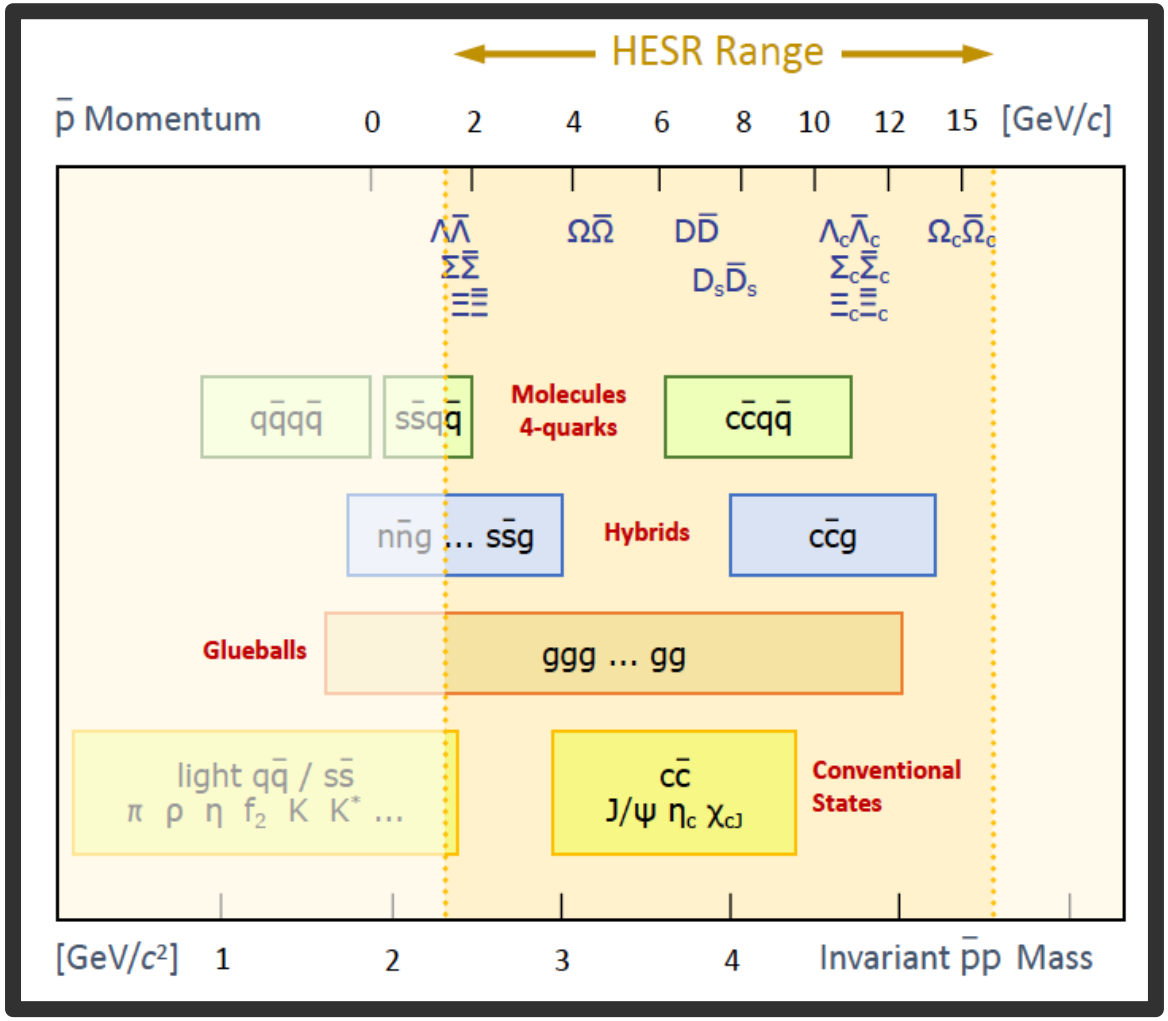
$$\sqrt{s} = [2.25 - 5.56]\ \text{GeV}$$

Hadron Spectroscopy
– Charmonium
– Light mesons, baryons
– Open charm
– QCD exotics: glueballs, hybrid states, X,Y,Z-states,…

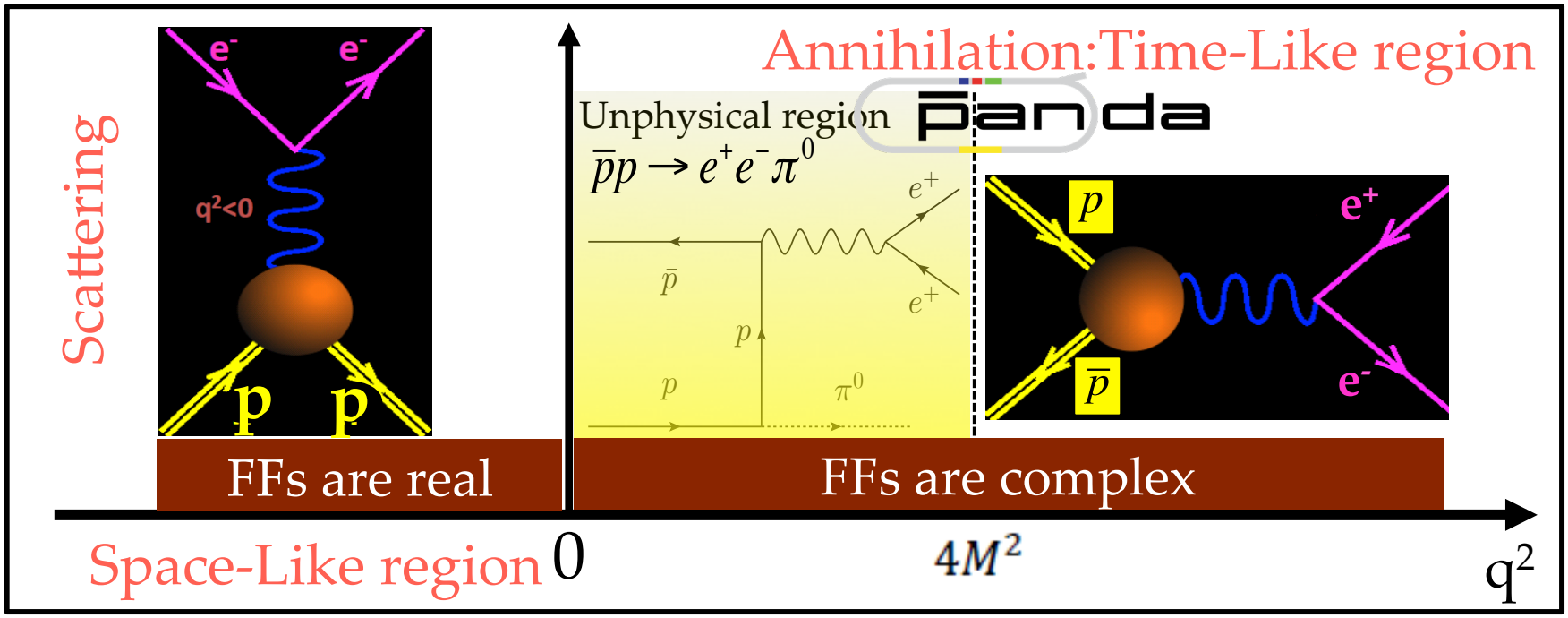
Hypernuclear physics

Hadrons in the nuclear medium

Nucleon structure



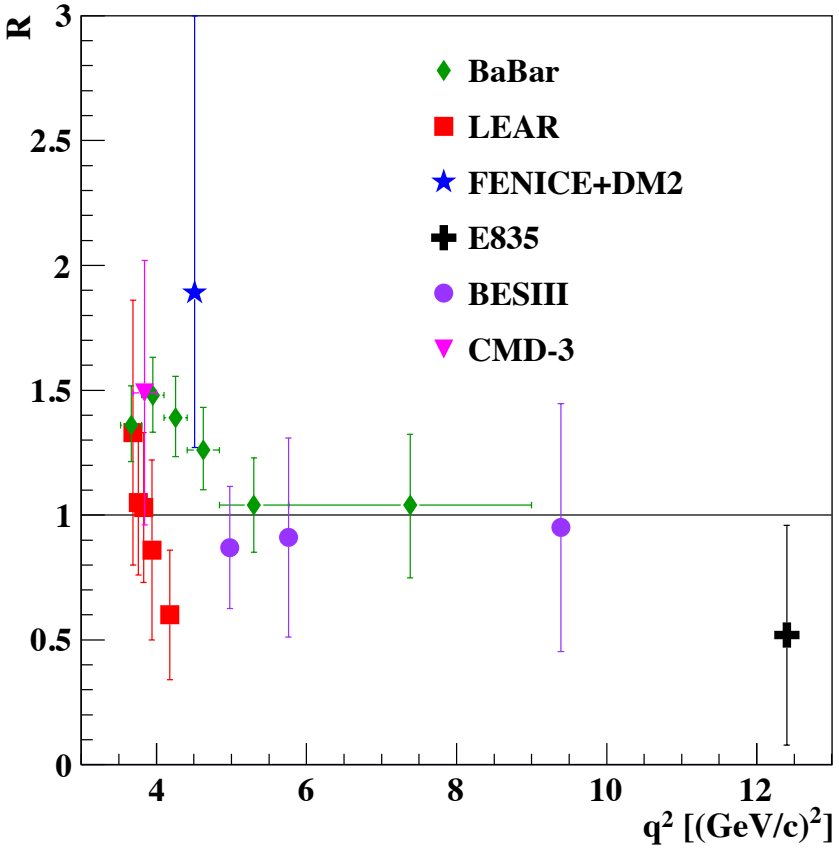
Electromagnetic Form Factors of the Proton



- **Electric G_E and magnetic G_M** proton FFs are analytical functions of the momentum transfer squared q^2

- Playground for theory and experiment:
  - at low q^2, probe the size of the nucleus,
  - at high q^2, test QCD scaling

World data on the time-like proton form factor ratio $R=|G_E|/|G_M|$



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): $e^+e^- \rightarrow \bar{p}p\gamma$
- data collection over wide energy range

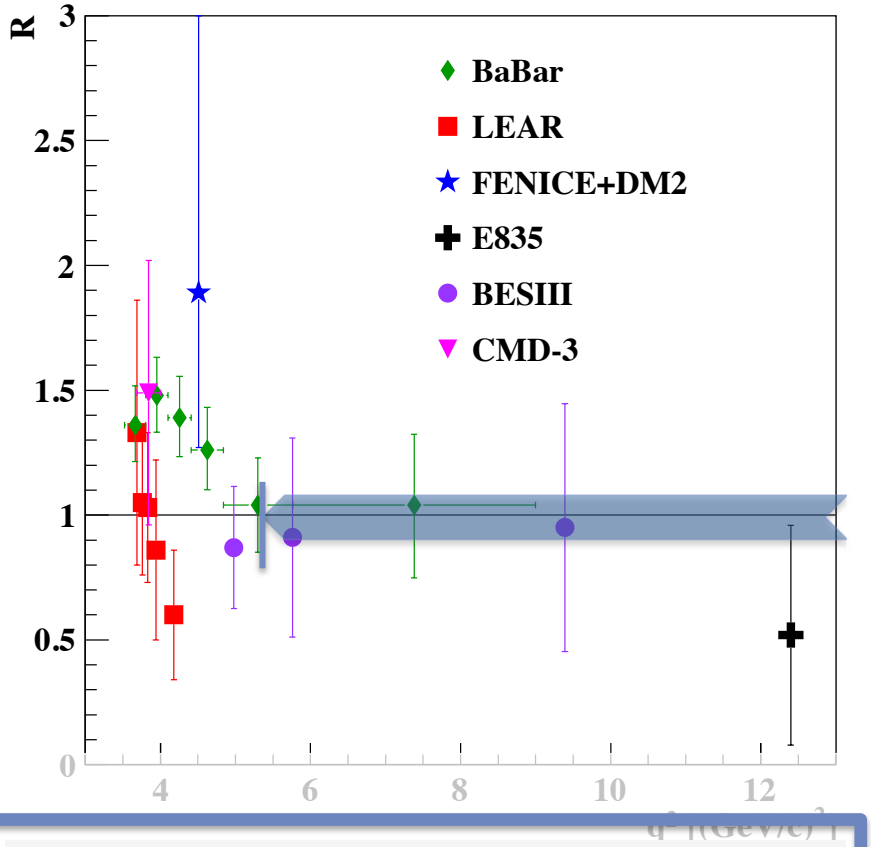
@ PS 170 (LEAR): $\bar{p}p \rightarrow e^+e^-$
- data collection at low energies

Data from BaBar & LEAR show different trends

@ BESIII: $e^+e^- \rightarrow \bar{p}p$
- Measurement at different energies
- Uncertainties comparable to previous experiments

@ CMD-3 (VEPP2000 collider, BINP):
- Energy scan $\sqrt{s} = 1-2\ GeV$
- Uncertainty comparable to the existing data

World data on the time-like proton form factor ratio $R=|G_E|/|G_M|$



PANDA: Measurement over wide range of q^2 with high precision

More data needed with high precision!

- **Test of the theory, also at high q^2**
- **Data with high statistics increase the precision of Form Factors**
- **Existing data were obtained with electron channels**

Time-like electromagnetic proton form factors @ PANDA: The goals

- Form factor measurements different final states: $\bar{p}p \rightarrow l^+l^- \ (l = \mu, e)$
  - **First time** measurement with **muons in final state**
  - **Study of radiative corrections**
  - **Consistency check** of proton form factor data
- Possibility to access the **relative phase** of proton time-like form factors:

  $\bar{p}p \rightarrow l^+l^-$ **in the Born approximation:**
  - **Unpolarized cross section -> access to $|G_E|$ & $|G_M|$**
  - **Polarization observables -> access to relative phase $G_E G_M^*$:**

Single spin polarization observable

$$\left(\frac{d\sigma}{d\Omega}\right)_0 A_{l,y} \propto \sin 2\Theta \, \mathrm{Im}\left(G_M G_E^*\right)$$

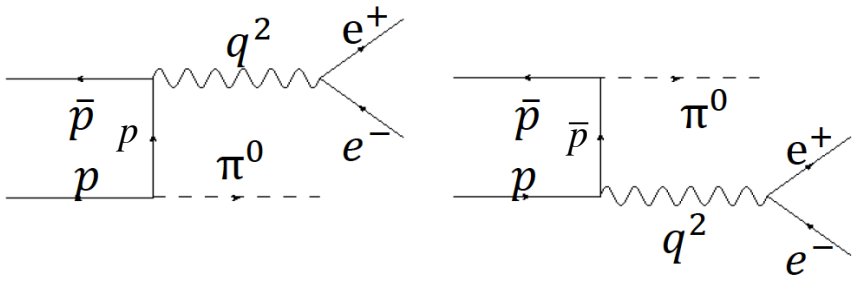
- **A. Z. Dubnickova, S. Dubnicka & M.P. Rekalo Nuovo Cim. A109 (1996) 241-256**

- Development of a **transverse polarized target for PANDA** in **Mainz**

Time-like electromagnetic proton form factors @ PANDA: The goals

- Access the **unphysical region** (R=$|G_E|/|G_M|$ and **relative phase** between G_E and G_M) :

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



- 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, M. C. Mora-Espi; PhD thesis

- **Measurement of time-like proton form factors over wide range of q^2 @ PANDA**
  - **Study the asymptotic behavior of the form factors**

Phys.Rev. C95 (2017) no.4, 045202
Phys.Rev. C96 (2017) no.2, 025204

- **Strong hadronic background**, mainly $\bar{p}p \rightarrow \pi^+\pi^-$, $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$

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

- E.W. Singh et al.: EPJA52, 325 (2016)

Good background rejection (~10^{-8}) necessary

Feasibility studies needed for both signal channels!

Feasibility studies: time-like proton form factors @ PANDA

Monte Carlo Simulation Studies

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

Standard chain
Simulation & Analysis
with **PANDARoot**:

- Event generation
- Digitization
- Reconstruction
- Particle Identification
- Event Analysis

p_{beam} [GeV/c]	1.7	3.3	6.4
s [GeV]^2	5.4	8.2	13.9

Event selection:

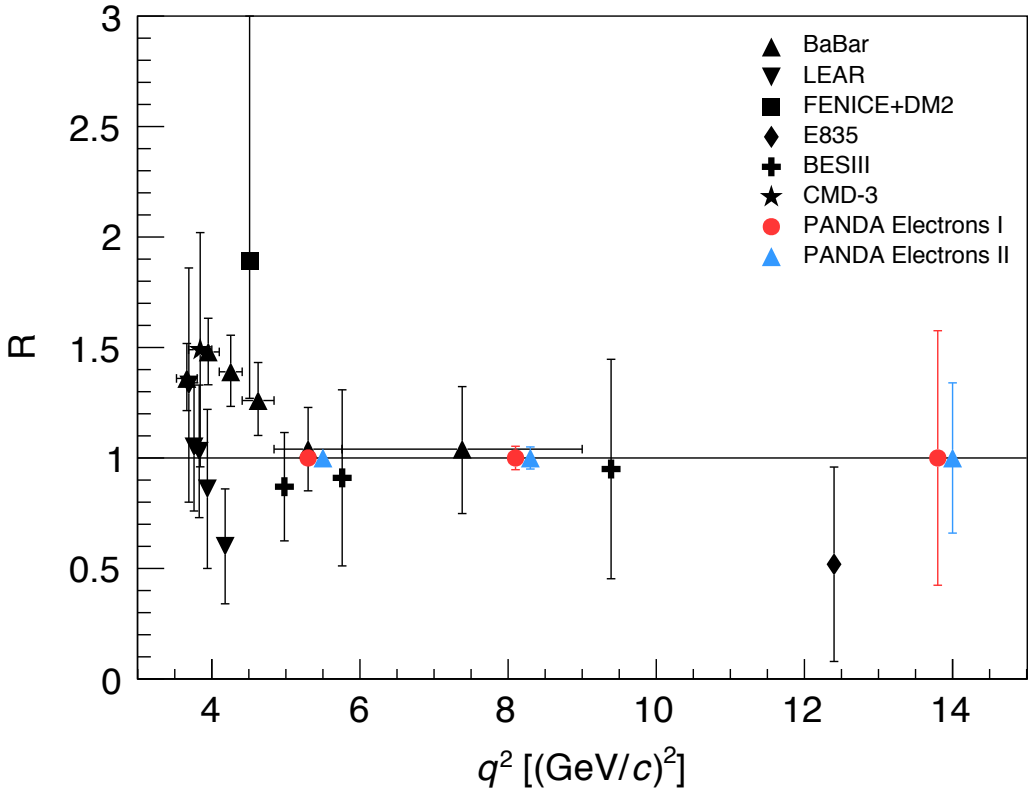
- **Preselection: One positive** and **one negative particle** per event
- **Cuts on kinematical variables**: **Production angles** (back-to-back in center-of-mass system), & **Invariant Mass.**
- **Signal/Background separation** based on:
  - For e^+e^- : Different subdetector information like **E**lectro**m**agnetic **C**alorimeter, **S**traw **T**ube **T**racker etc. contribute to particle identification
  - For $\mu^+\mu^-$: **Boosted Decision trees** + cuts

  Detector information MAINLY from Muon Range System

Feasibility studies: time-like proton form factors @ PANDA

The results

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



- **Signal efficiencies** between **39%** and **51%**
- **Background rejection ~ 10^{-8}**
  Signal pollution < 1%

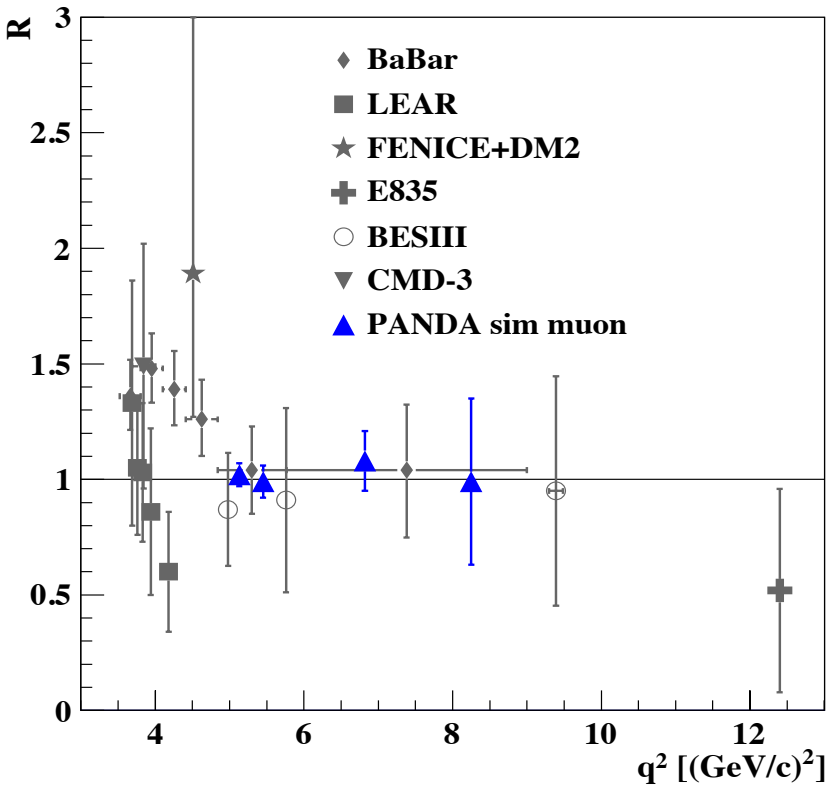
Precision on R=1, L= 2 fb^{-1}

q^2 [(GeV/c)^2]	5.4 – 14
ΔR/R	3.3 % - 57%

Feasibility studies: time-like proton form factors @ PANDA

The results

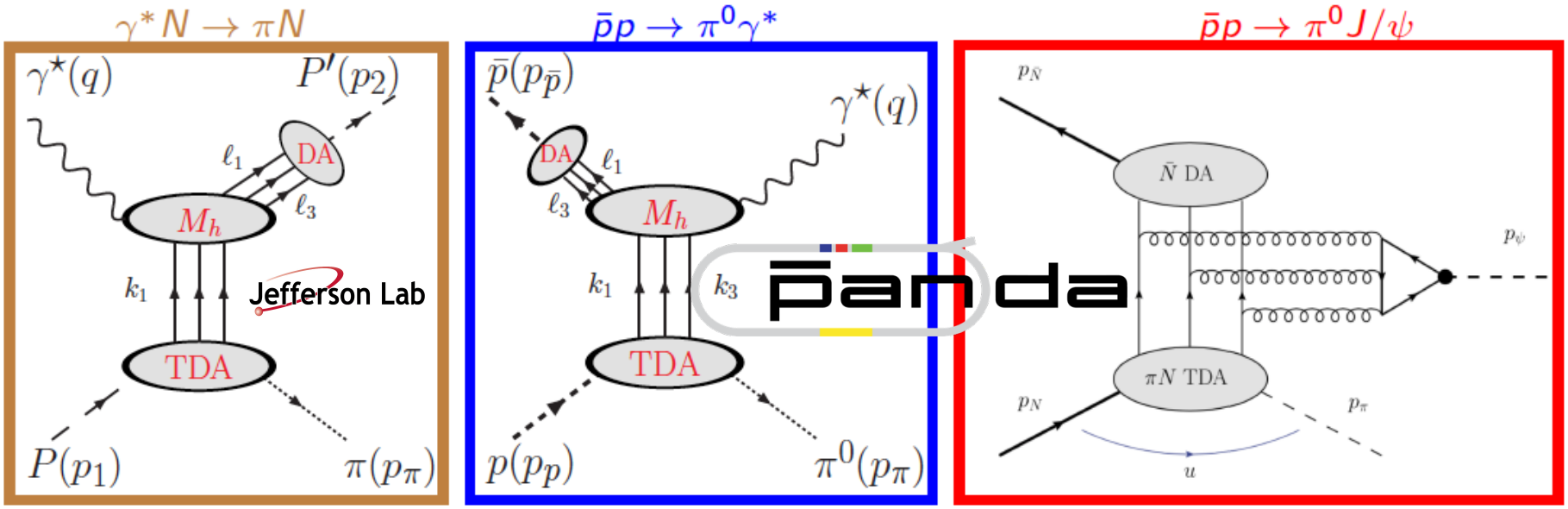
$$\bar{p}p \rightarrow \mu^+\mu^-$$



- Signal efficiencies ~ 21%
- Background rejection ~ 10^{-6}
  Background subtraction is possible

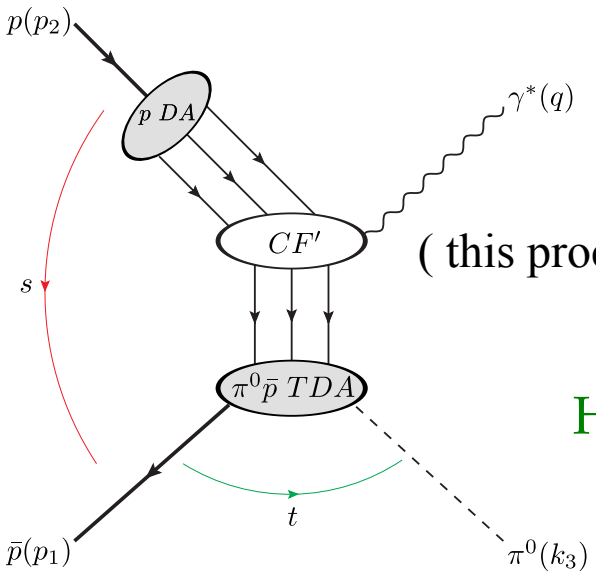
Precision on R=1, L= 2 fb^{-1}	
q^2 [(GeV/c)²]	5.1 – 8.2
ΔR/R	5.0 % - 37%

Nucleon to meson TDAs



- 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
- Give information on pionic components of the nucleon wave-function

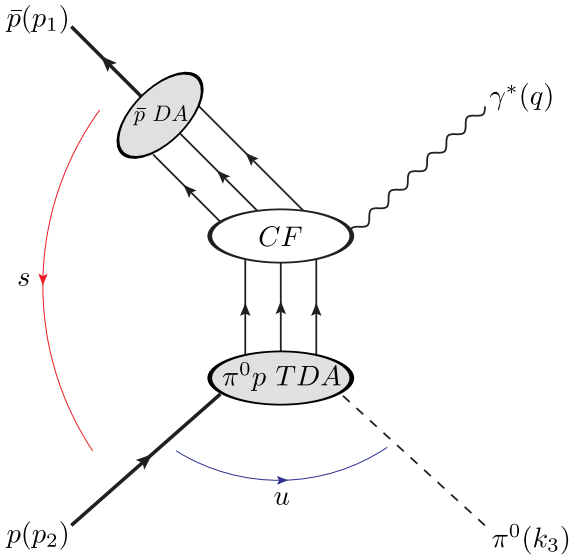
Nucleon to meson TDAs at PANDA



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

(this process never been measured)

Hard scale: large q^2~s



t is small (forward kinematics)

u is small (backward kinematics)

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

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

Luminosity= 2 fb^{-1}

i) $s = 5\ \mathrm{GeV}^2 \rightarrow 3.0 < q^2 < 4.3\ \mathrm{GeV}^2, \quad |\cos\theta_{\pi^0}| > 0.5$

ii) $s = 10\ \mathrm{GeV}^2 \rightarrow 5 < q^2 < 9\ \mathrm{GeV}^2, \quad |\cos\theta_{\pi^0}| > 0.5$

- Background suppression of the $\bar{p}p \to \pi^+\pi^-\pi^0$ [$\sigma(\pi^+\pi^-\pi^0)/\sigma(e^+e^-\pi^0) \sim 10^6$]:

s = 5 GeV^2: 5 . 10^7 at low q^2 (1 . 10^7 at high q^2)

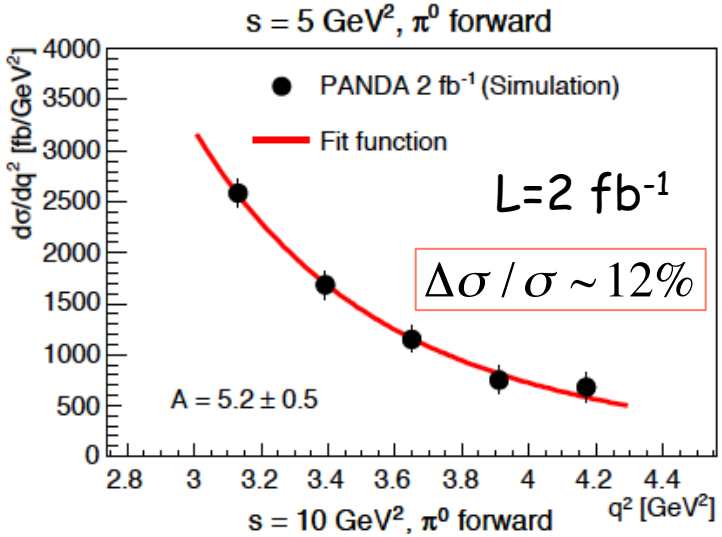
s = 10 GeV^2: 1 . 10^8 at low q^2 (6 . 10^6 at high q^2)

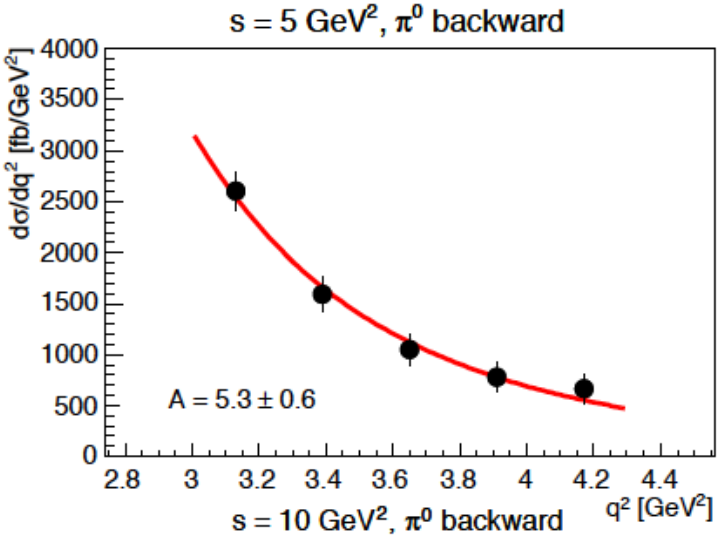
Eur.Phys.J. A51 (2015) 8, 107

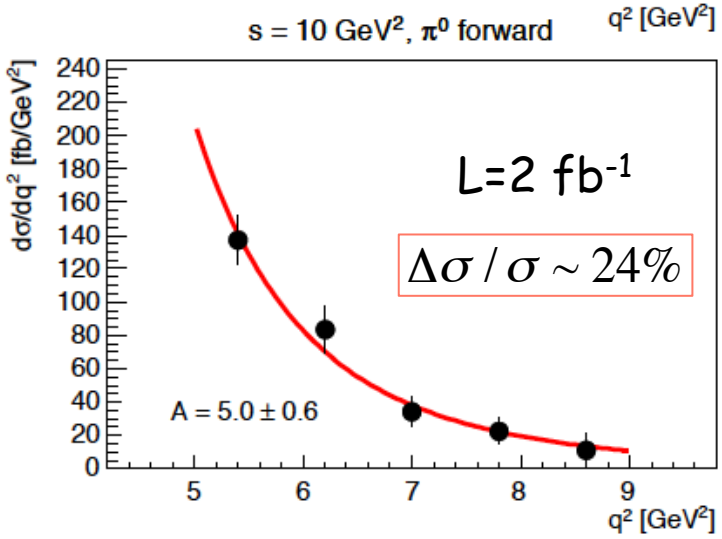
Nucleon to meson TDAs at PANDA

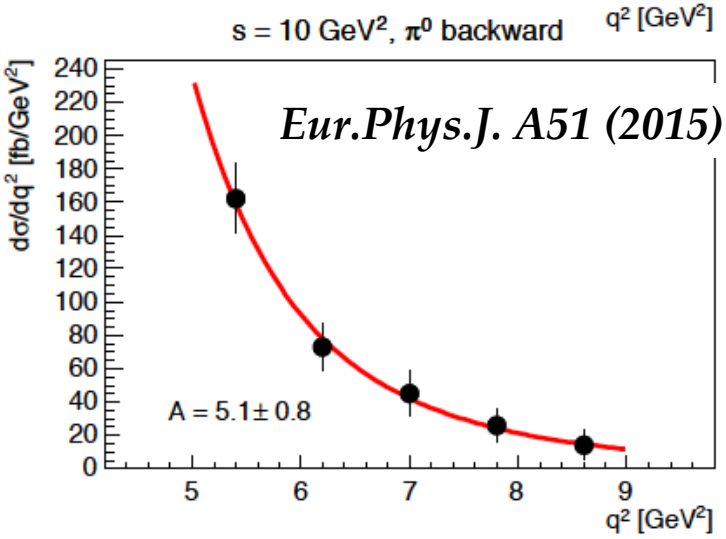
$$\frac{d\sigma}{dq^2} \sim \frac{1}{(q^2)^5}$$

Fit measured cross section and measure scaling component A (A=5)
→**Test QCD factorization**





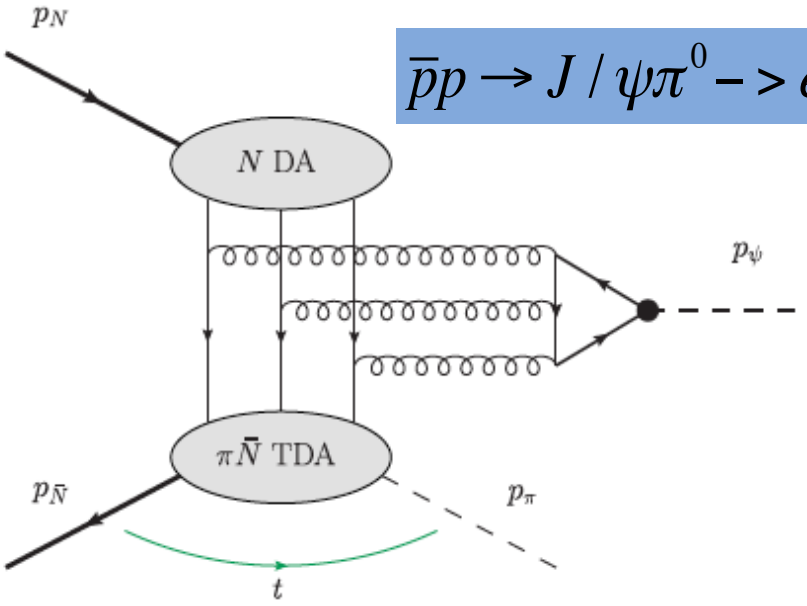


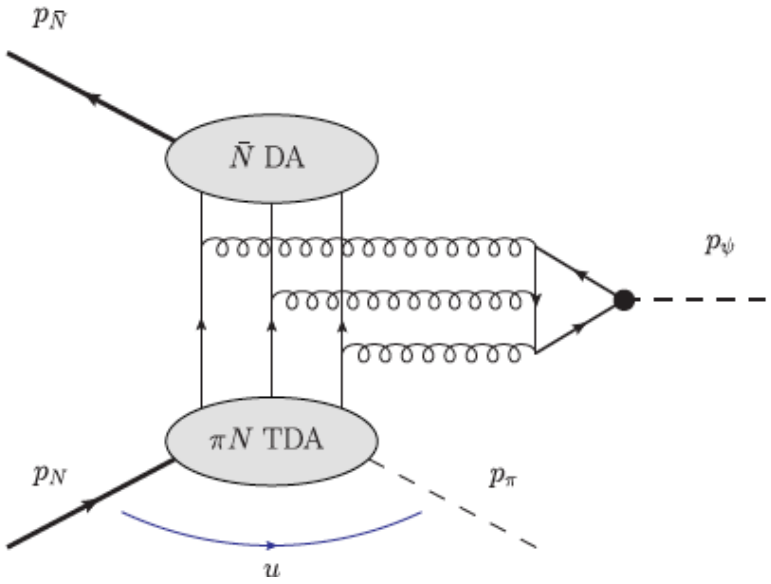


Eur.Phys.J. A51 (2015) 8, 107

Nucleon to meson TDAs at PANDA

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





t is small (forward kinematics)

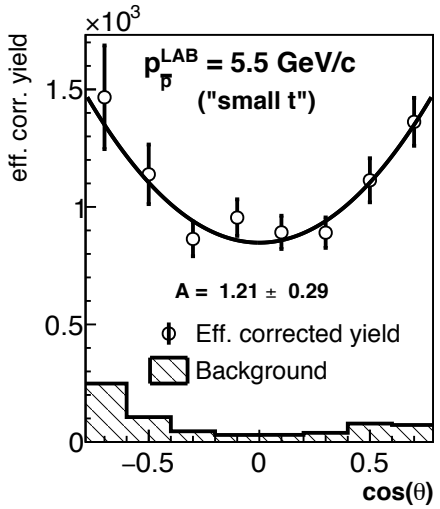
u is small (backward kinematics)

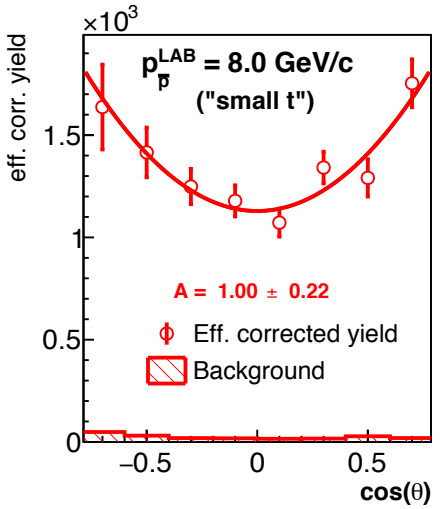
B. Pire et al., Phys. Lett. B. 724 99-107 (2013)

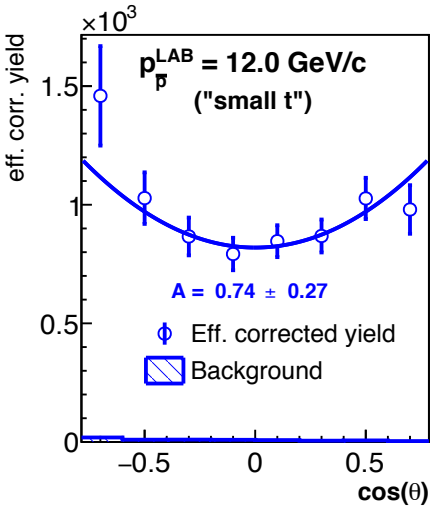
- High signal cross section
- Large q^2 fixed to $Q^2 = M^2_{J/\psi} = 9.6GeV^2$ (factorization theorem is likely reached)
- Reduces uncertainty on DAs by using the data on the $J/\psi -> pp$ partial decay modes
- Complementary measurements: test of universality of TDAs by comparing to $\bar{p}p \rightarrow \gamma^*\pi^0 -> e^+e^-\pi^0$ at different q^2

Nucleon to meson TDAs at PANDA

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





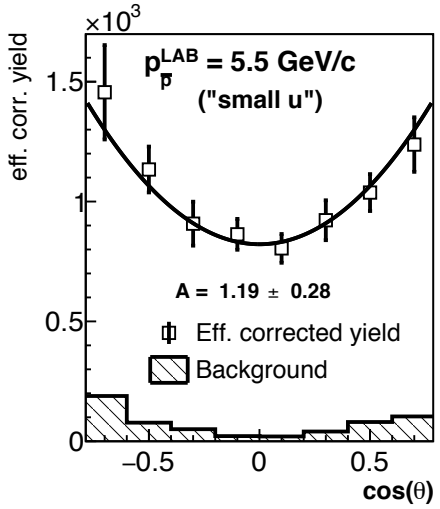


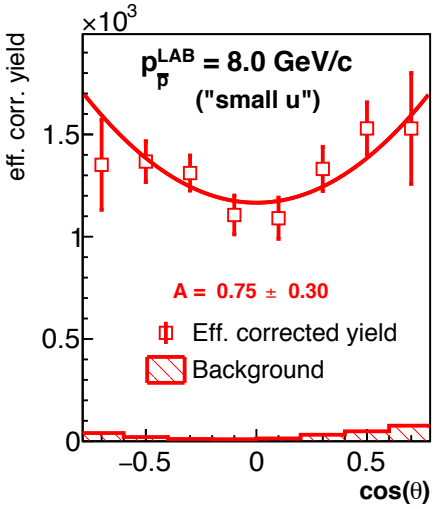
Fit funtion:

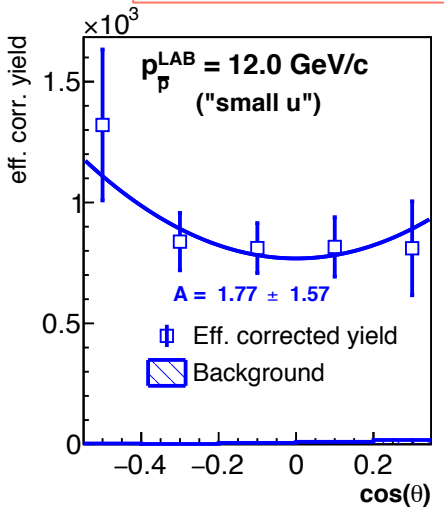
$$B \times (1 + A\cos^2\theta^{e^+}_{J/\psi})$$

L=2 fb^{-1}

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

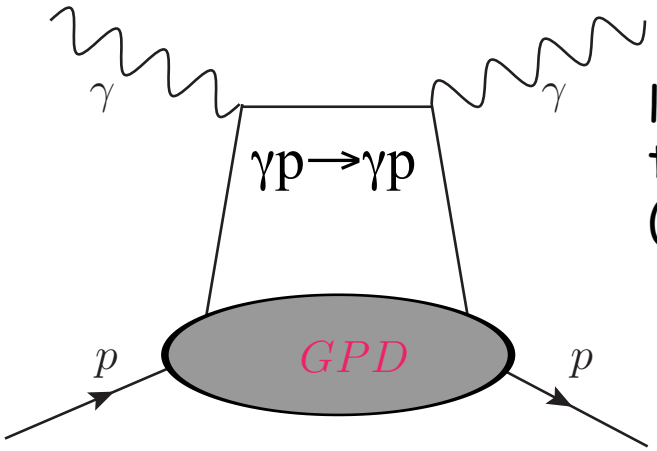




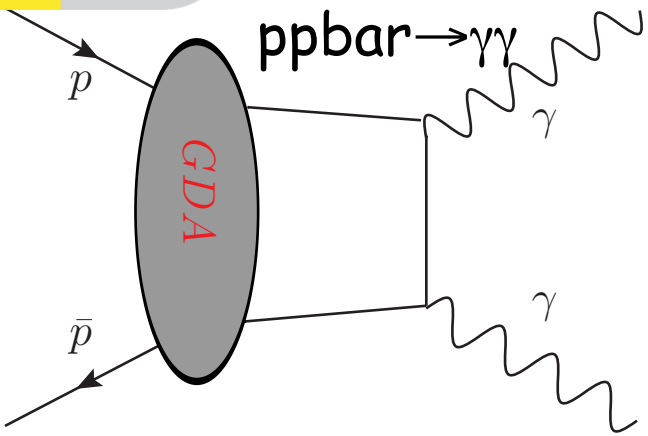


Phys. Rev. D 95, 032003 (2017)

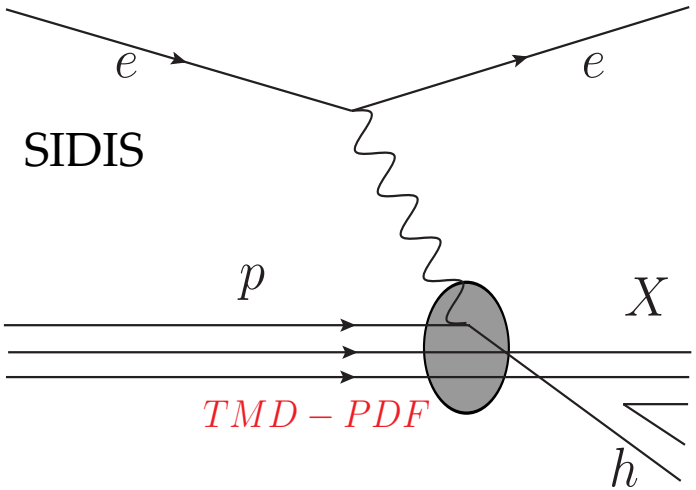
Hard exclusive and inclusive processes at PANDA

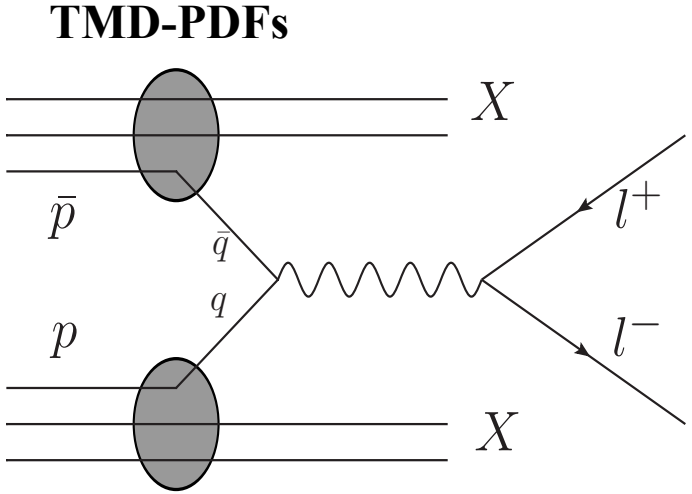


large photon
transverse momentum
(hard scale)

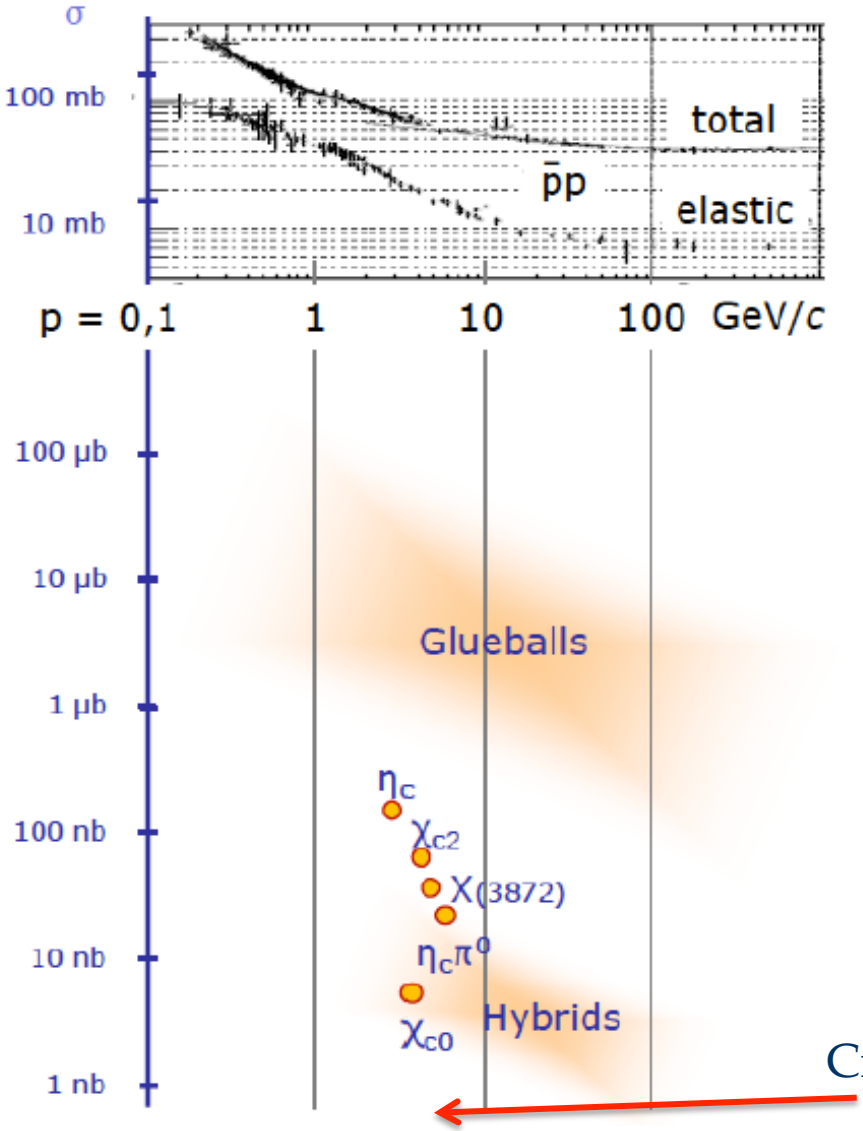


Drell-Yan at PANDA





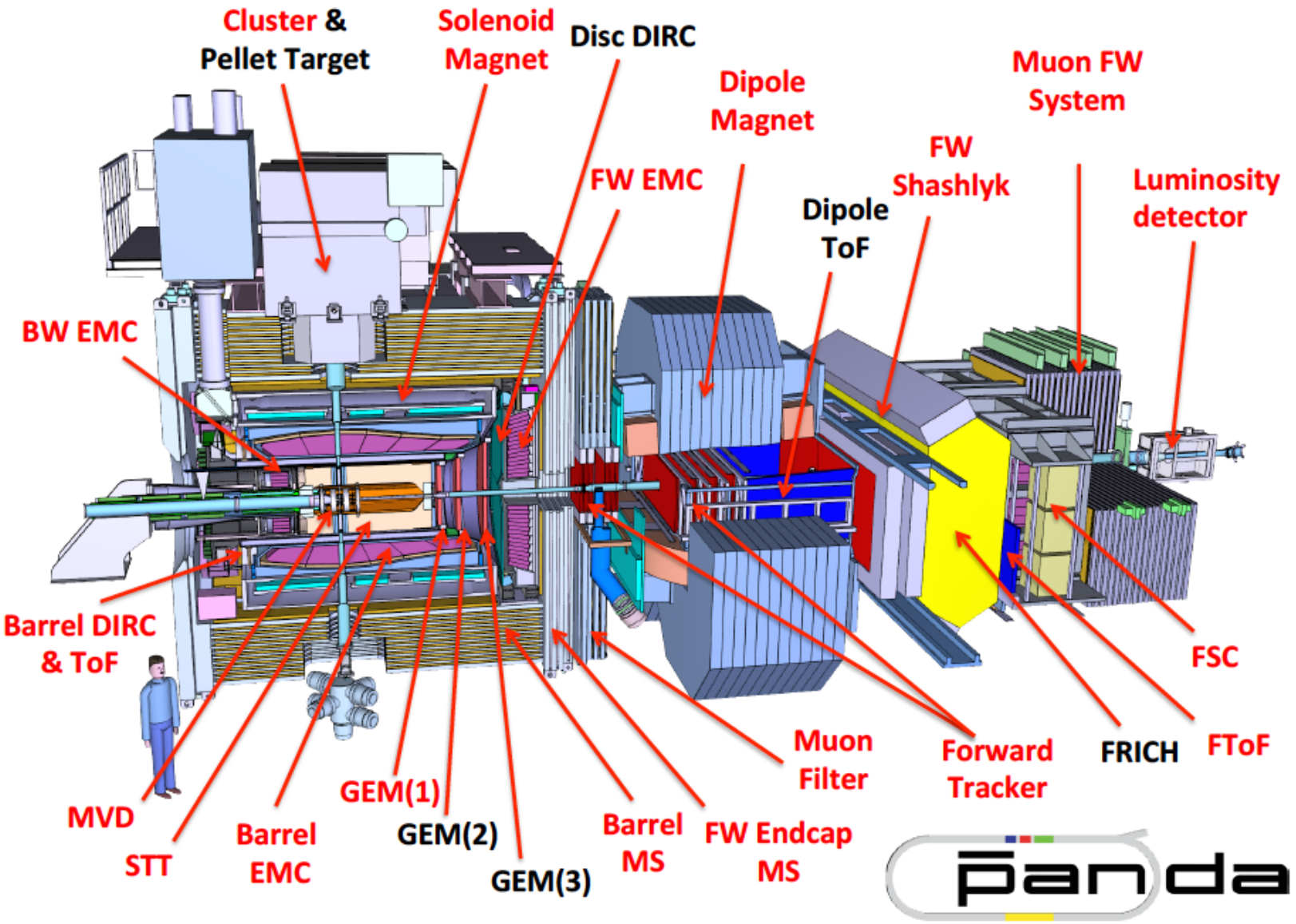
Detector requirements from physics case



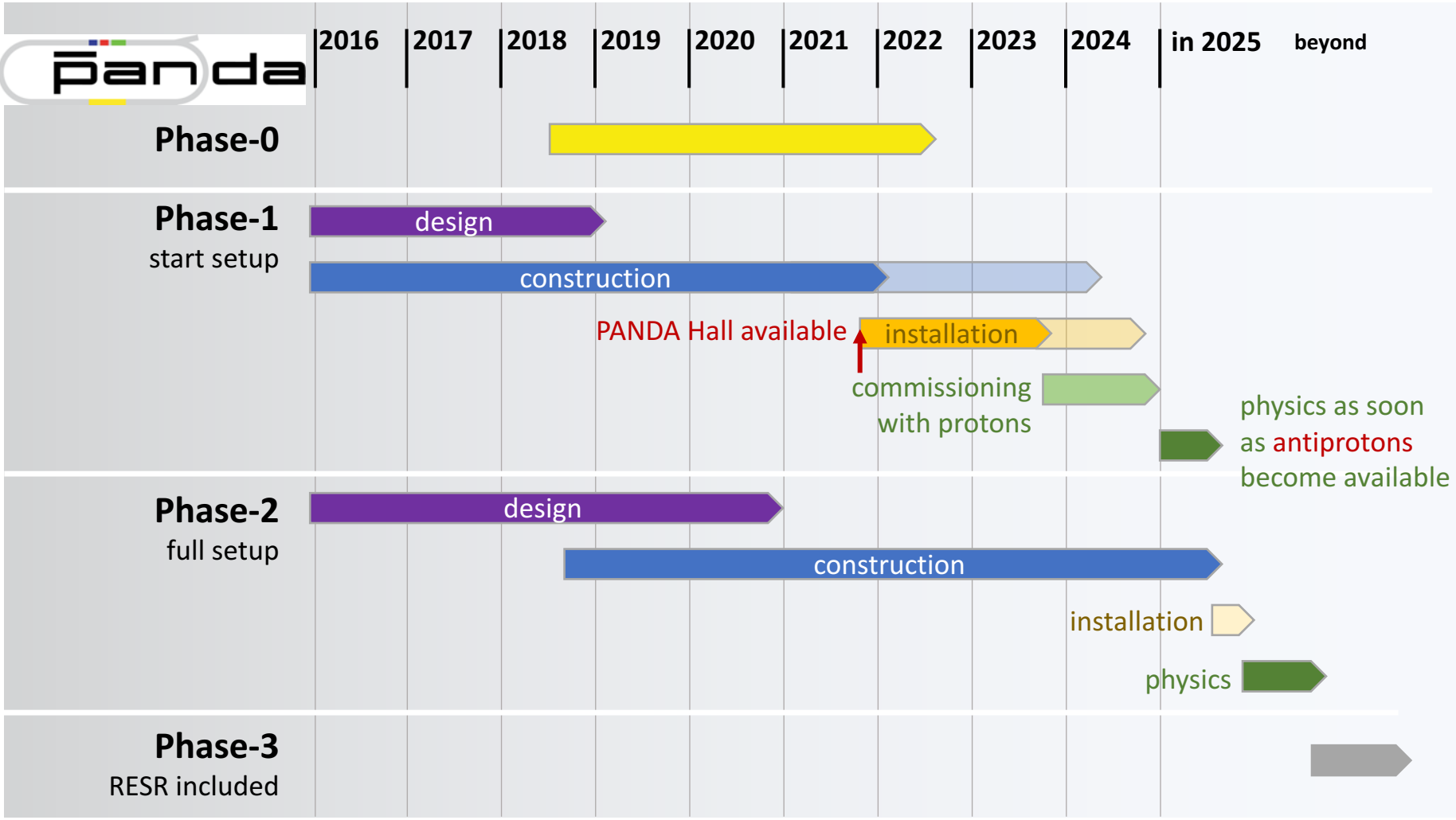
- ~ 4π acceptance
- Momentum resolution: 1%
  central tracker in magnetic field
- Photon detection: 1 MeV - 10 GeV
  high dynamic range
  good energy resolution
- Particle identification: γ, e, μ, π, K, p
  Cherenkov detector
  time of flight, dE/dx, muon counter
- Displaced vertex info
  $c\tau = 317\ \mu m$ for $D^{\pm}$
  $\gamma\beta \approx 2$

Cross section for electromagnetic Processes

The PANDA detector (start/full setup)



The PANDA phases



Summary

- Proton form factors can be measured at PANDA in the time-like region and over a large kinematical region through:

$$\bar{p}p \to e^+e^- \qquad \bar{p}p \to \mu^+\mu^- \qquad \bar{p}p \to e^+e^-\pi^0$$

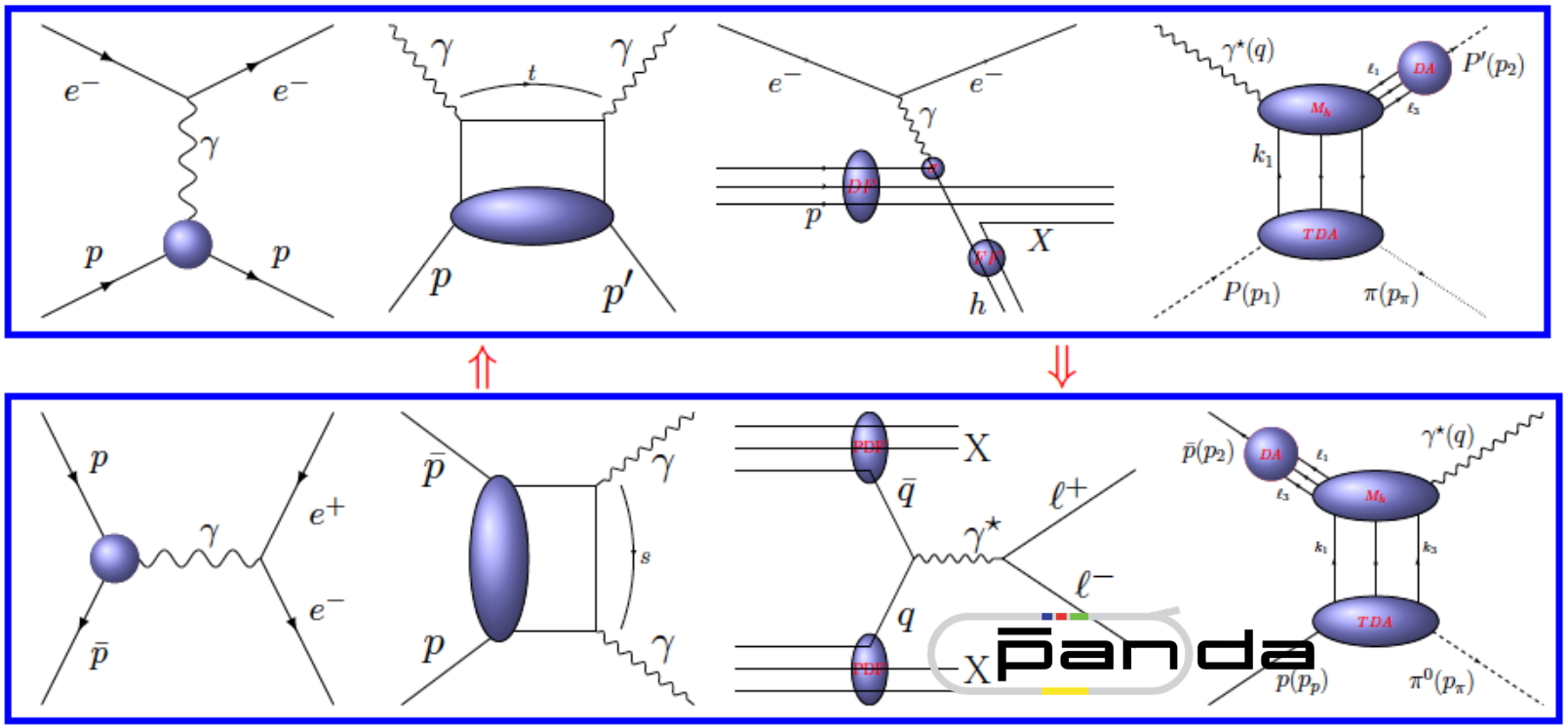
- PANDA will provide valuable measurements for the test of universality of TDAs through:

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

- PANDA experiment will provide a **complementary** study of the nucleon structure with the hard inclusive and exclusive processes: Generalized Distribution Amplitudes (GDAs), (TMD) Parton Distribution Functions, and Transition Distribution Amplitudes (TDAs)

- **Physics Performance Report for PANDA: Strong Interaction Studies with Antiprotons, arXiv:0903.3905**
- [PANDA Collaboration], Phys. Rev. D 95, 032003 (2017)
- [PANDA Collaboration], Eur. Phys. J. A 52, 325 (2016)
- [PANDA Collaboration], Eur. Phys. J. A 51, 107 (2015)

Study of the Nucleon Structure at PANDA

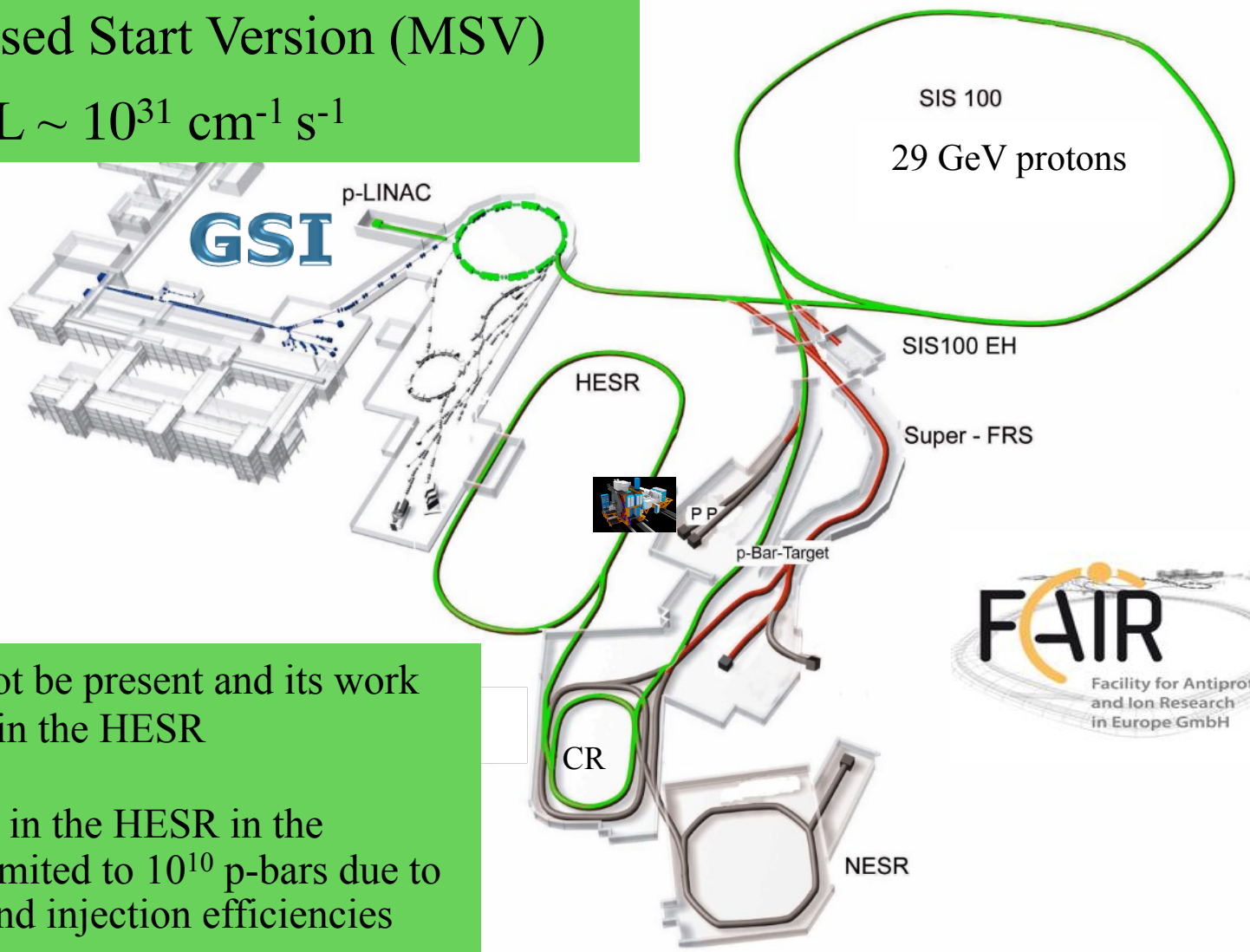


- Proton Electromagnetic Form Factors (FFs)
- Generalized Distribution Amplitudes (GDAs)
- Transverse Momentum Dependent Parton Distribution Functions (TMD-PDFs)
- Transition Distribution Amplitudes (TDAs)

FAIR-HESR (Start version)

Modularised Start Version (MSV)

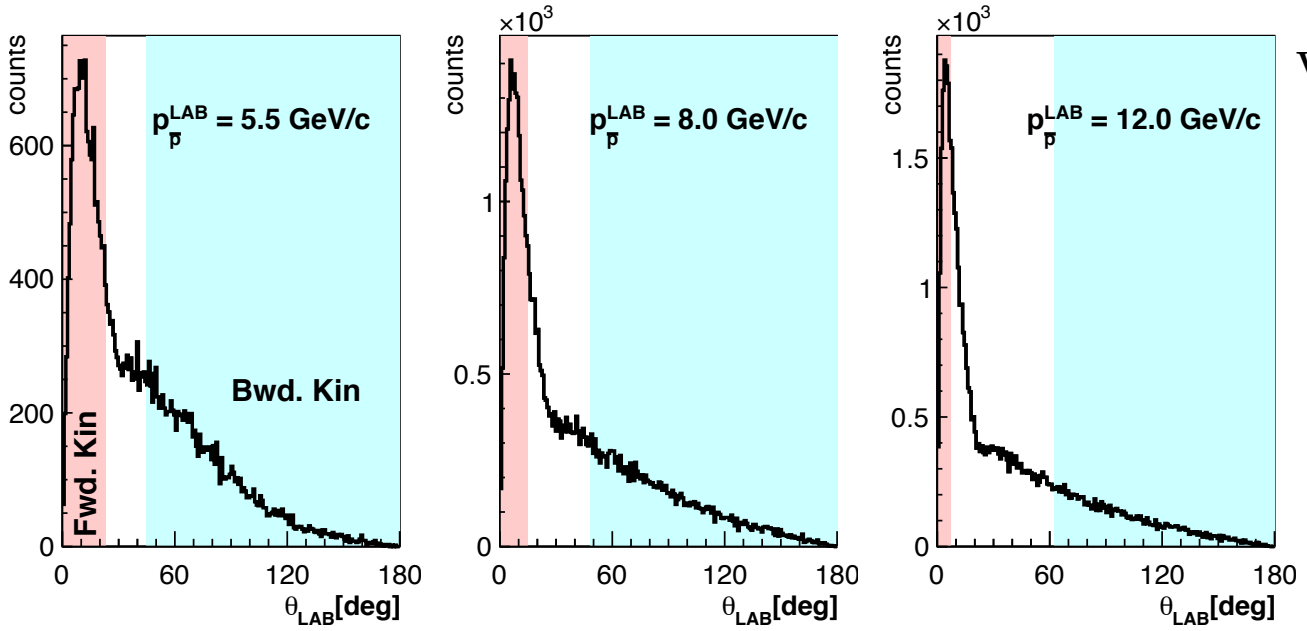
$L \sim 10^{31}\ cm^{-1}\ s^{-1}$



- RESR will not be present and its work will be done in the HESR
- The intensity in the HESR in the MSV0-3 is limited to 10^{10} p-bars due to the cooling and injection efficiencies

Nucleon to meson TDAs at PANDA

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



Validity ranges of the TDA model:

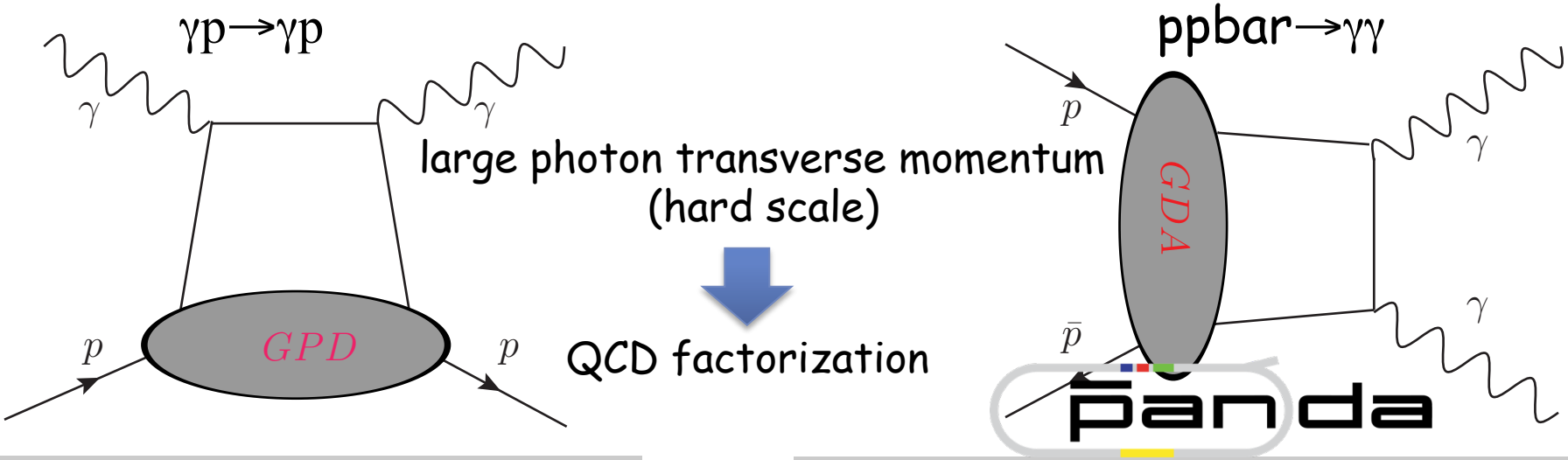
- *t* is small (forward kin.)
- *u* is small (backward kin.)

Background final states:

- Three pion production: $\pi^+\pi^-\pi^0$ (B/S~10^5 - 10^6)
- Multipion final states (N>3): $\pi^0\pi^0\pi^+\pi^-$, $\pi^0\pi^+\pi^-\pi^+\pi^-$ π^0 (B/S~3-15)
- Dielectron continuum :$\gamma^*\pi^0$ ->$e^+e^-\pi^0$
- Annihilation into $\pi^0\pi^0 J/\psi$
- Hadronic decays of J/ψ

Phys. Rev. D 95, 032003 (2017)

Hard exclusive processes at PANDA-GDAs



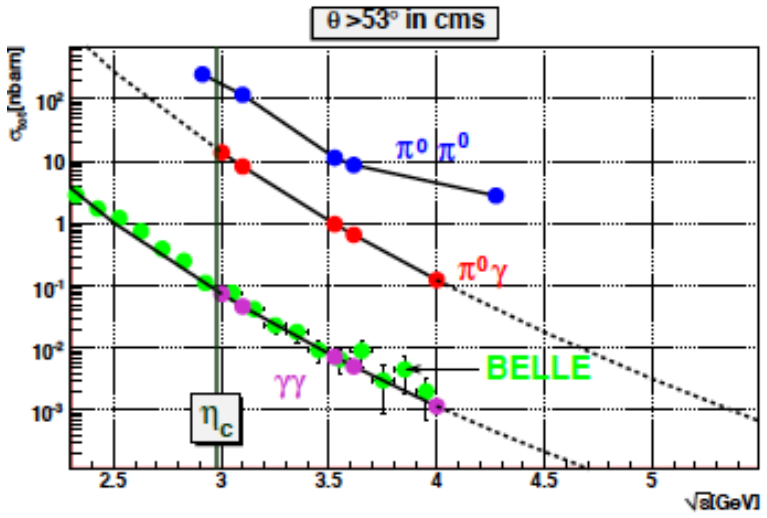
Wide Angle Compton Scattering
Generalized Parton Distributions GPDs

Time-Like Wide Angle Compton Scattering
Generalized Distribution Amplitudes GDAs

- GDAs can be measured at PANDA with the hard exclusive electromagnetic processes: ppbar→γγ, γM (M=π^0,η,ρ^0,ϕ)

- PANDA measurements are complementary to the results from the deeply virtual Compton scattering (**DVCS**), the deeply virtual meson production (**DVMP**), the time-like Compton scattering using real photon beams, and lepton-pair production with meson beams.

Feasibility studies for GDAs measurement at PANDA



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

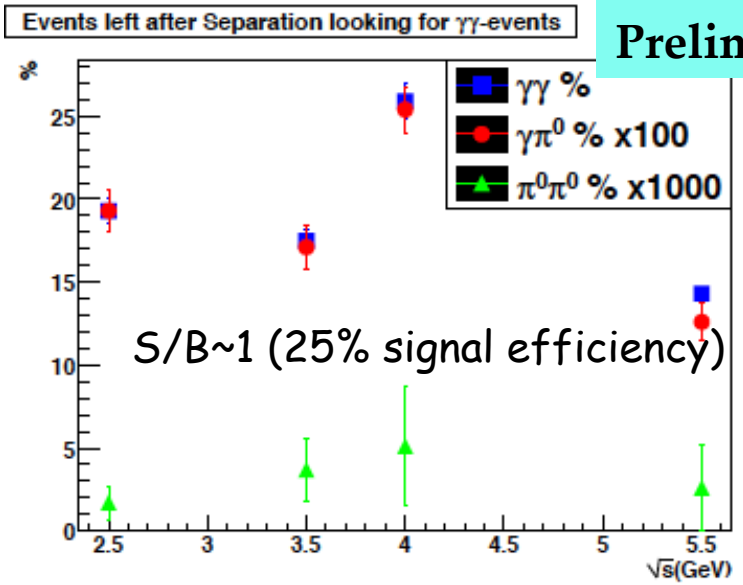
- 4 different CM energies
- Main background channels:

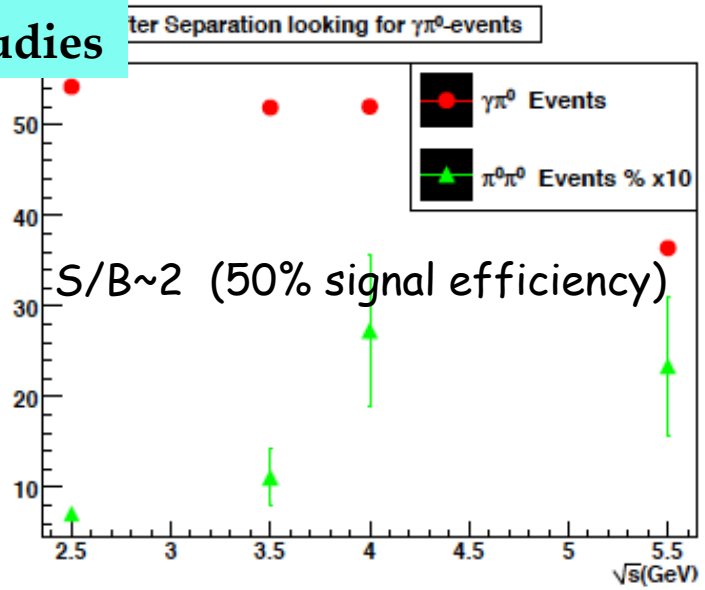
$\bar{p}p \to \pi^0\pi^0$ (for both signals)

$\bar{p}p \to \pi^0\gamma$ (for signal1: $\bar{p}p \to \gamma\gamma$)

PANDA Physics Performance Report
arXiv:0903.3905

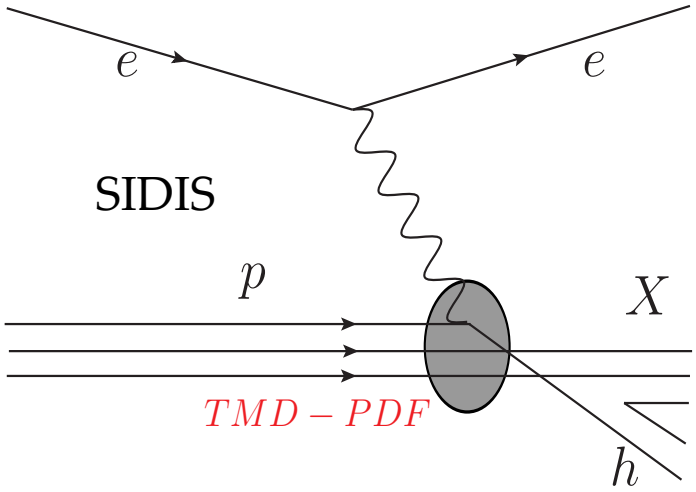
Preliminary studies



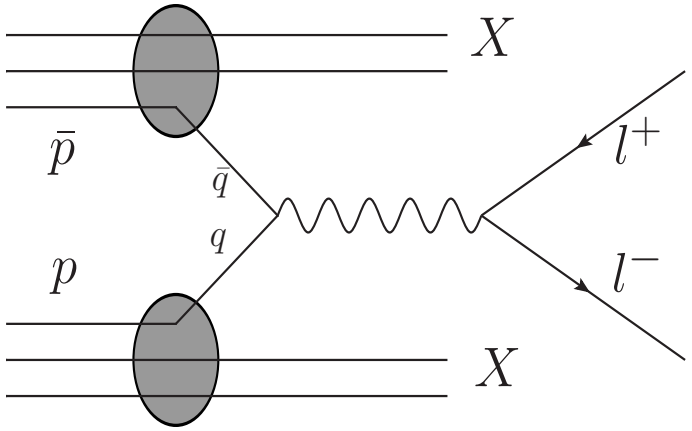


Transverse Momentum dependence - Parton Distribution Functions

Drell-Yan at PANDA



TMD-PDFs are convoluted with the fragmentation functions



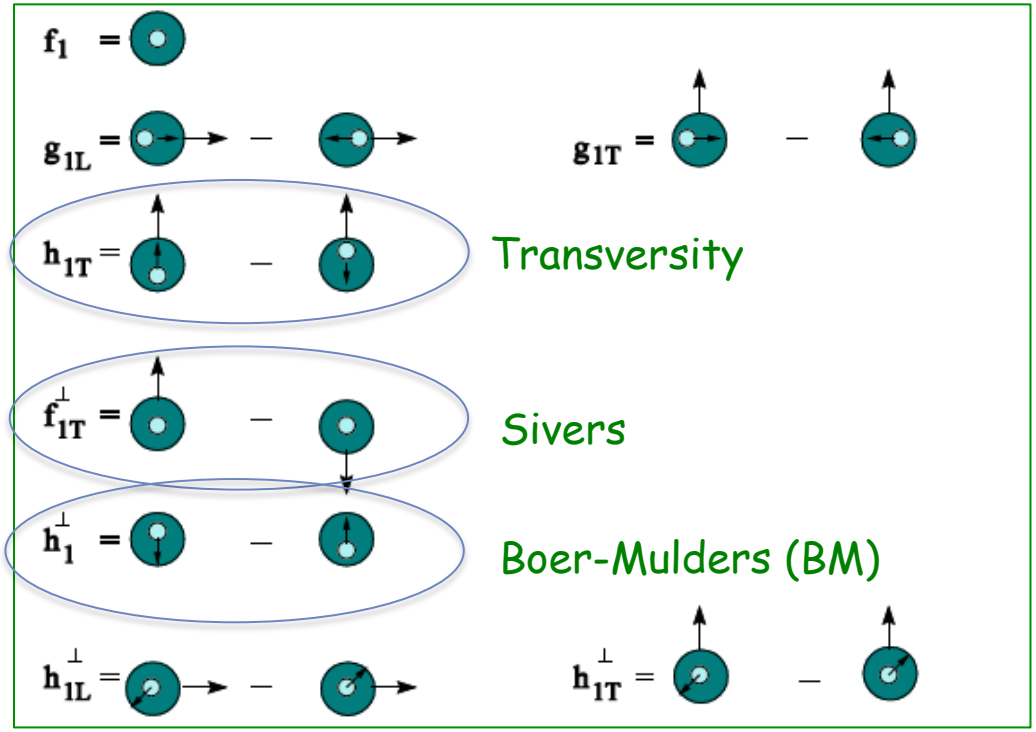
Direct access to TMD-PDFs

Test of Universality
and the QCD TMD factorization

Drell-Yan at PANDA: TMD-PDFs

@ PANDA energy range up to s~30 GeV^2:

- access to a unique kinematic region where valence quark effects dominate
- In ppbar annihilation each valence quark can contribute to the DY diagram



Asymmetry measurements:

Unpolarized Drell Yan

$$A^{\cos 2\varphi} \rightarrow h_1^{\perp}$$

Single-polarized Drell Yan

$$A^{\sin(\varphi \pm \varphi s2)} \rightarrow h_1^{\perp}, h_{1T}, f_{1T}^{\perp}$$

φ : angle between hadron and lepton planes

φ_{s2}: angle between hadron spin and lepton plane

Feasibility measurement of Drell Yan processes at PANDA

Monte-Carlo simulations:

- Signal: $\bar{p}p \rightarrow \mu^+\mu^- X$ Unpolarized DY
  $\bar{p}p^{\uparrow} \rightarrow \mu^+\mu^- X$ Single-polarized DY
- Main background: $\bar{p}p \rightarrow n(\pi^+\pi^-)X$, required rejection factor ~10^7
- Simulations @ s=30 GeV^2 and $1.5 \leq M_{\gamma^*} \leq 2.5$ (large cross section)

  Number of simulated events N~5 . 10^5

PANDA Physics Performance Report
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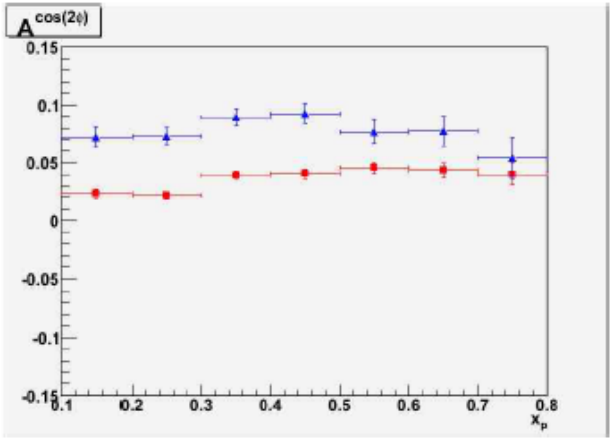
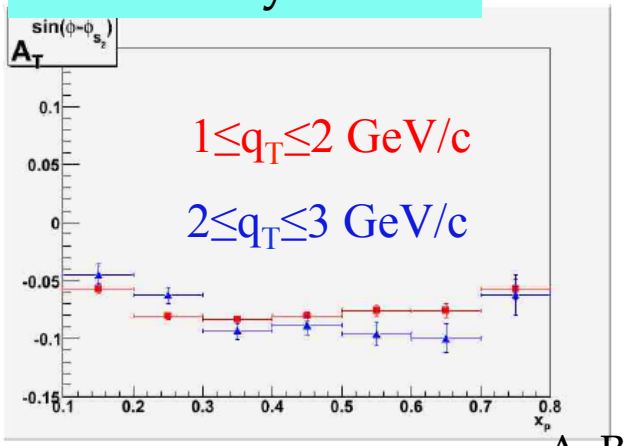
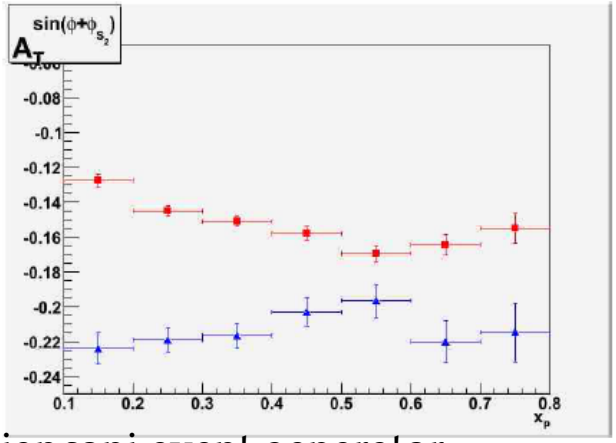
Preliminary studies







x_p: the longitudinal momentum of the hadronic probe
q_T: transverse momentum of the muon pair

A. Bianconi event generator
Phys. Rev. D 71, 074014 (2005)

Feasibility measurement of Drell Yan processes at PANDA

Monte-Carlo simulations:

- Signal: $\bar{p}p \rightarrow \mu^+\mu^- X$ Unpolarized DY
  $\bar{p}p^{\uparrow} \rightarrow \mu^+\mu^- X$ Single-polarized DY

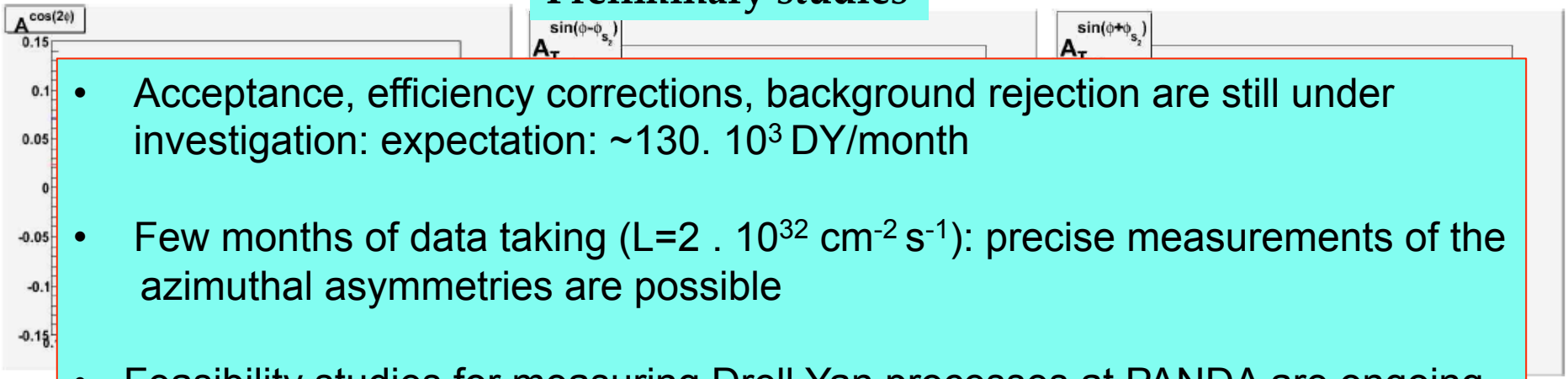
- Main background: $\bar{p}p \rightarrow n(\pi^+\pi^-)X$, required rejection factor ~10^7

- Simulations @ s=30 GeV^2 and $1.5 \leq M_{\gamma^*} \leq 2.5$ (non resonance region, large cross section)

  Number of simulated events N~5 . 10^5

PANDA Physics Performance Report
arXiv:0903.3905

Preliminary studies



- Acceptance, efficiency corrections, background rejection are still under investigation: expectation: ~130. 10^3 DY/month
- Few months of data taking (L=2 . 10^{32} cm^{-2} s^{-1}): precise measurements of the azimuthal asymmetries are possible
- Feasibility studies for measuring Drell Yan processes at PANDA are ongoing

q_T: transverse momentum of the muon pair