Feasibility Studies of Nucleon Structure Observables at PANDA at FAIR

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On behalf of the PANDA collaboration

Dilepton Productions with Meson and Antiproton Beams

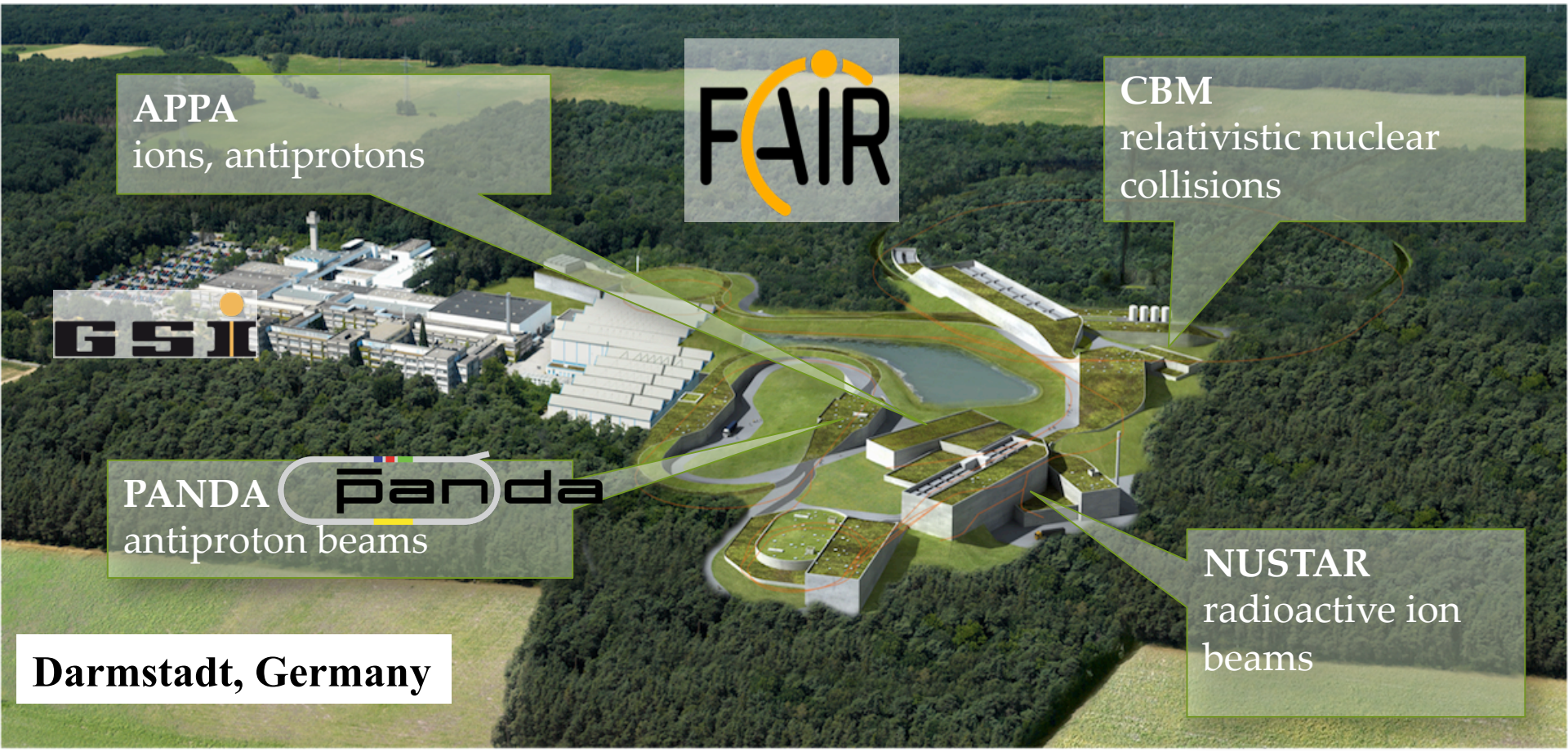
ECT* Trento, 9 November 2017

Helmholtz Institute Mainz
Johannes-Gutenberg University Mainz

Outline

- Facility for Antiproton and Ion Research (FAIR)
- PANDA experiment and physics program
- Study of the nucleon structure at PANDA
  - Electromagnetic form factors FFs
  - Transition distribution amplitudes TDAs
  - Generalized distribution amplitudes GDAs
  - Transverse momentum dependence TMD-PDFs
- PANDA spectrometer and phases

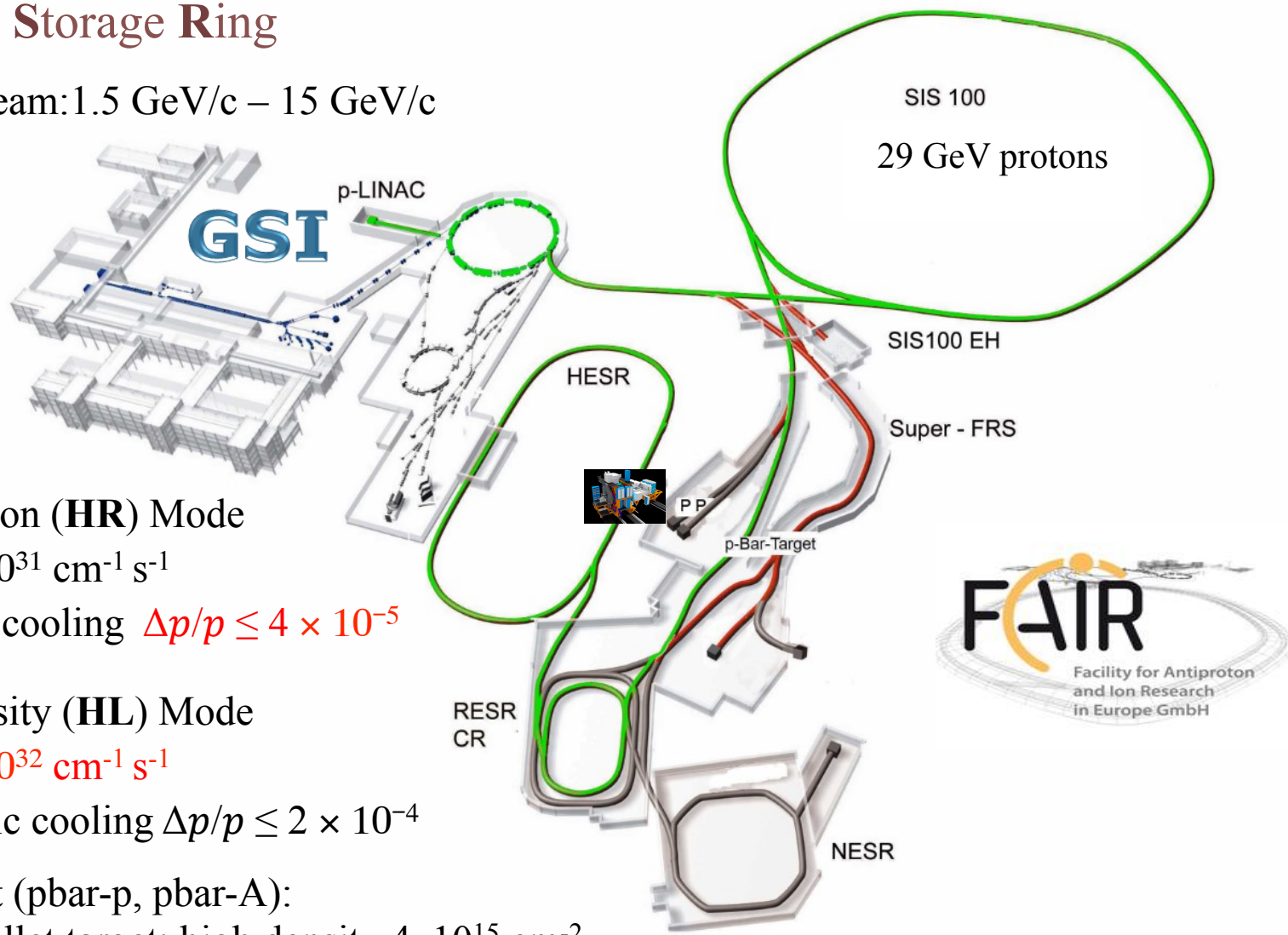
Facility for Antiproton and Ion Research - FAIR (Darmstadt/Germany)



Facility for Antiproton and Ion Research - FAIR

High Energy Storage Ring

- Antiproton beam:1.5 GeV/c – 15 GeV/c

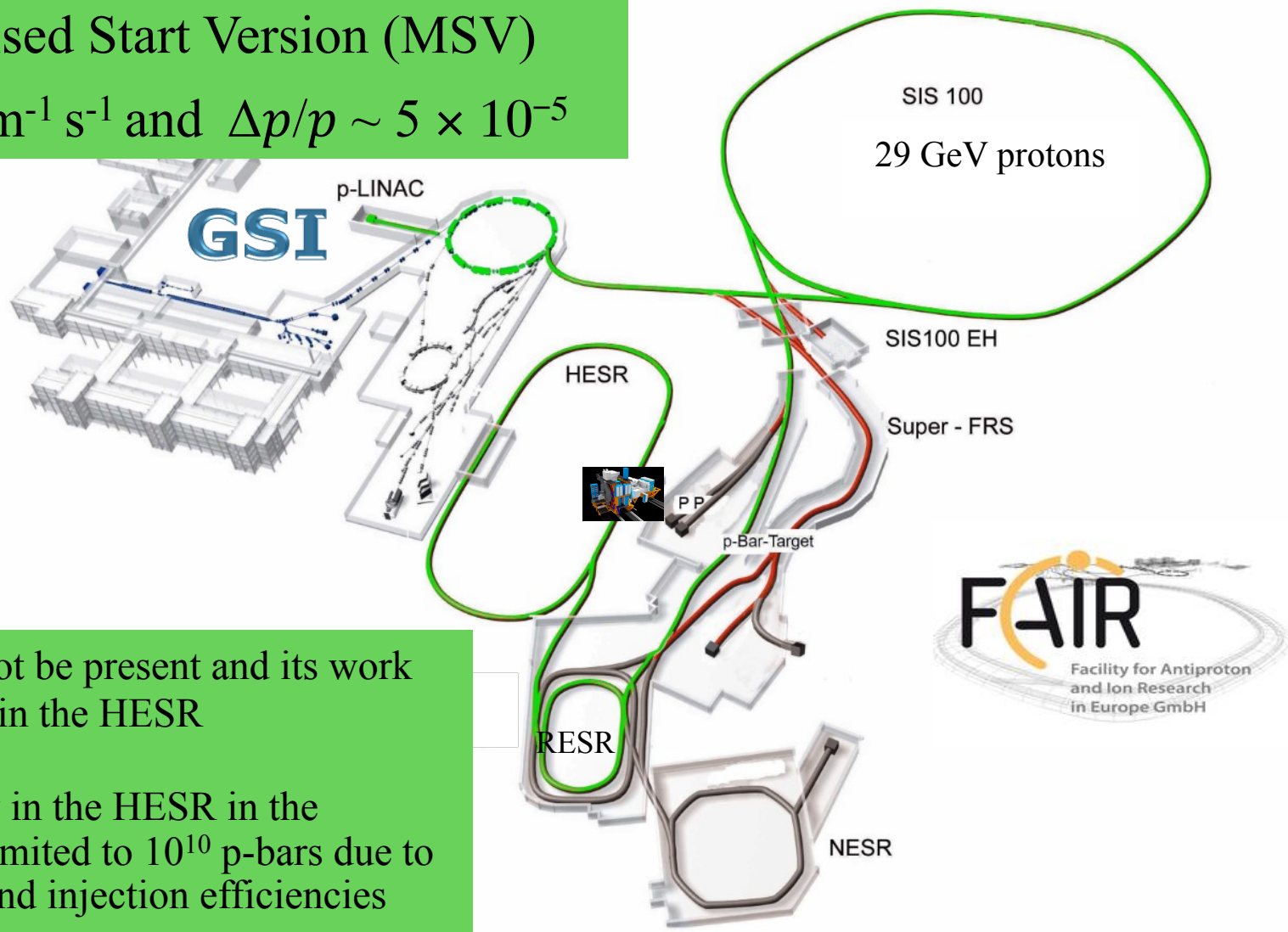


- High Resolution (**HR**) Mode
  - L= 2×10^{31} cm^{-1} s^{-1}
  - Electron cooling $\Delta p/p \leq 4 \times 10^{-5}$
- High Luminosity (**HL**) Mode
  - L= 2×10^{32} cm^{-1} s^{-1}
  - Stochastic cooling $\Delta p/p \leq 2 \times 10^{-4}$
- Internal target (pbar-p, pbar-A):
  cluster jet / pellet target; high density 4×10^{15} cm^{-2}

FAIR-HESR (Start version)

Modularised Start Version (MSV)

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



- 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

The PANDA experiment at FAIR
antiProton ANnihilation at DArmstadt

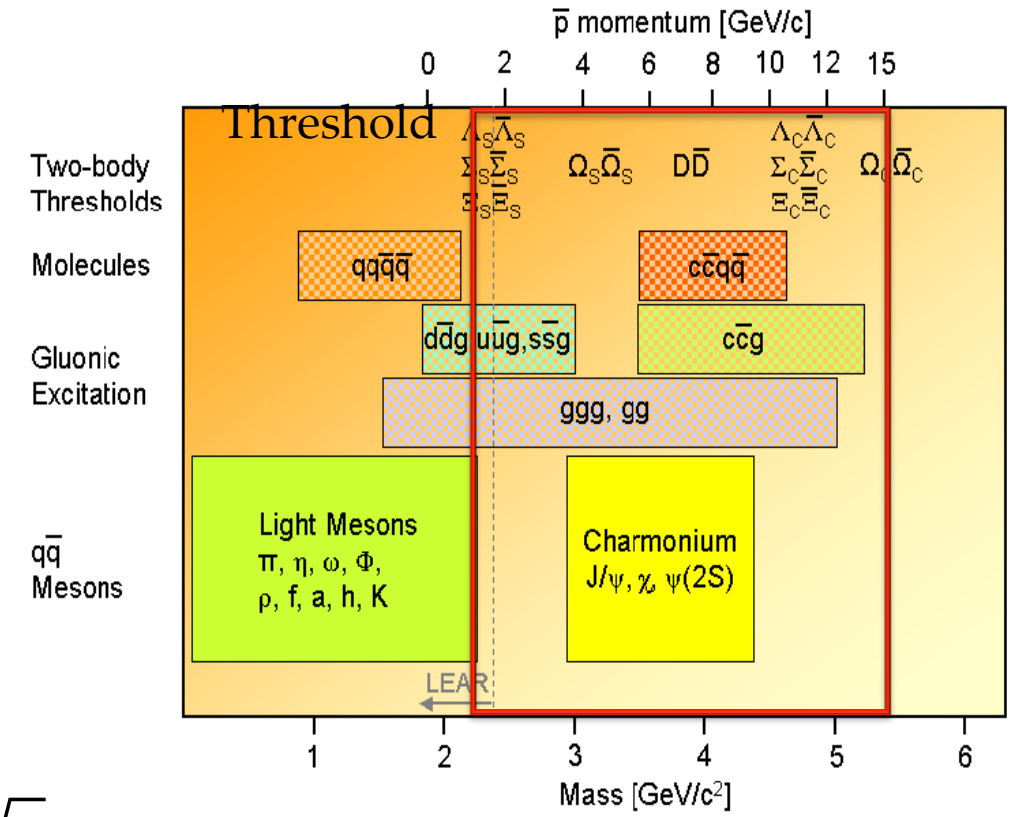
More than 520 physicists from 70 institutions in 19 countries

Hadron Spectroscopy and dynamics
- Charmonium
- Light mesons
- Gluonic exitations
- Open charm
- (Multi) strange baryons

Nucleon structure

Hypernuclear physics

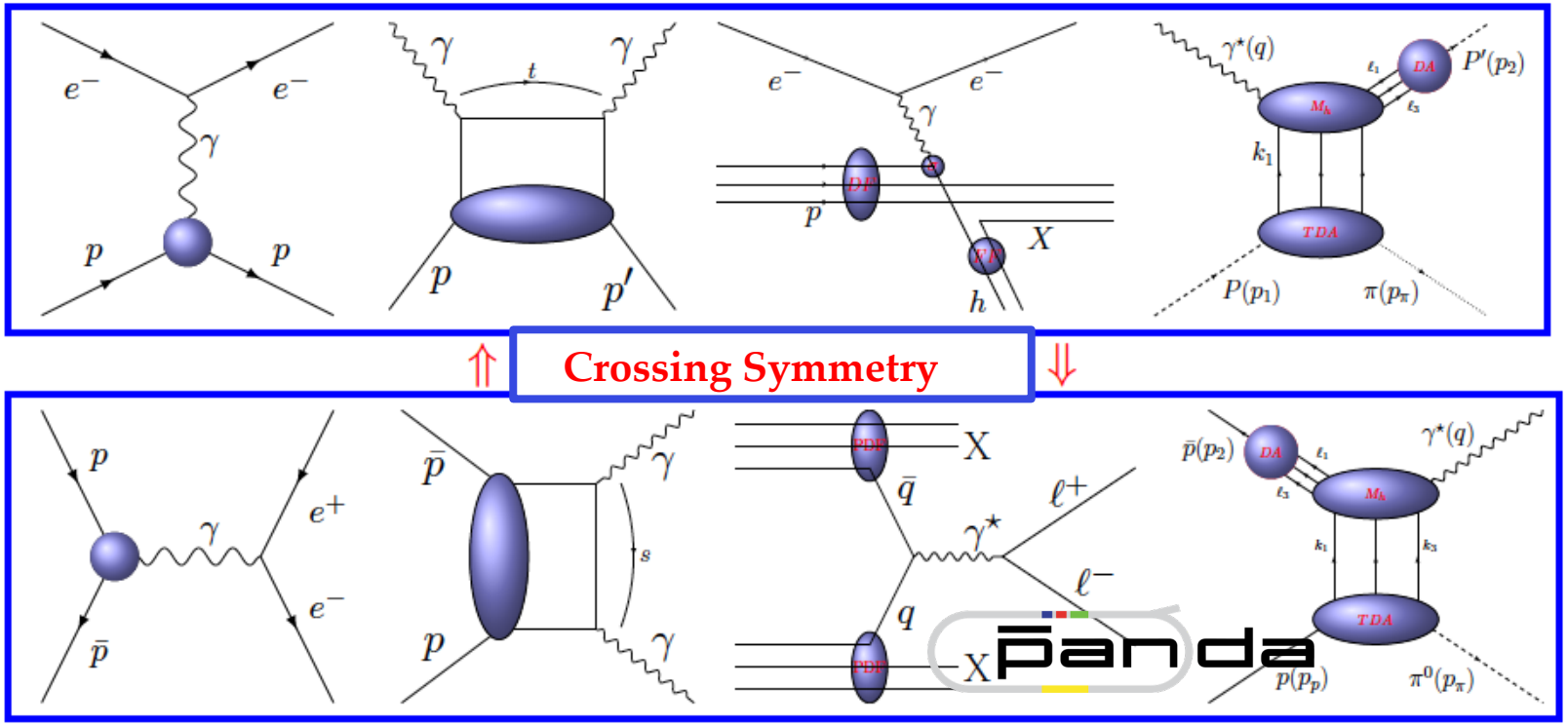
Hadrons in the nuclear medium



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

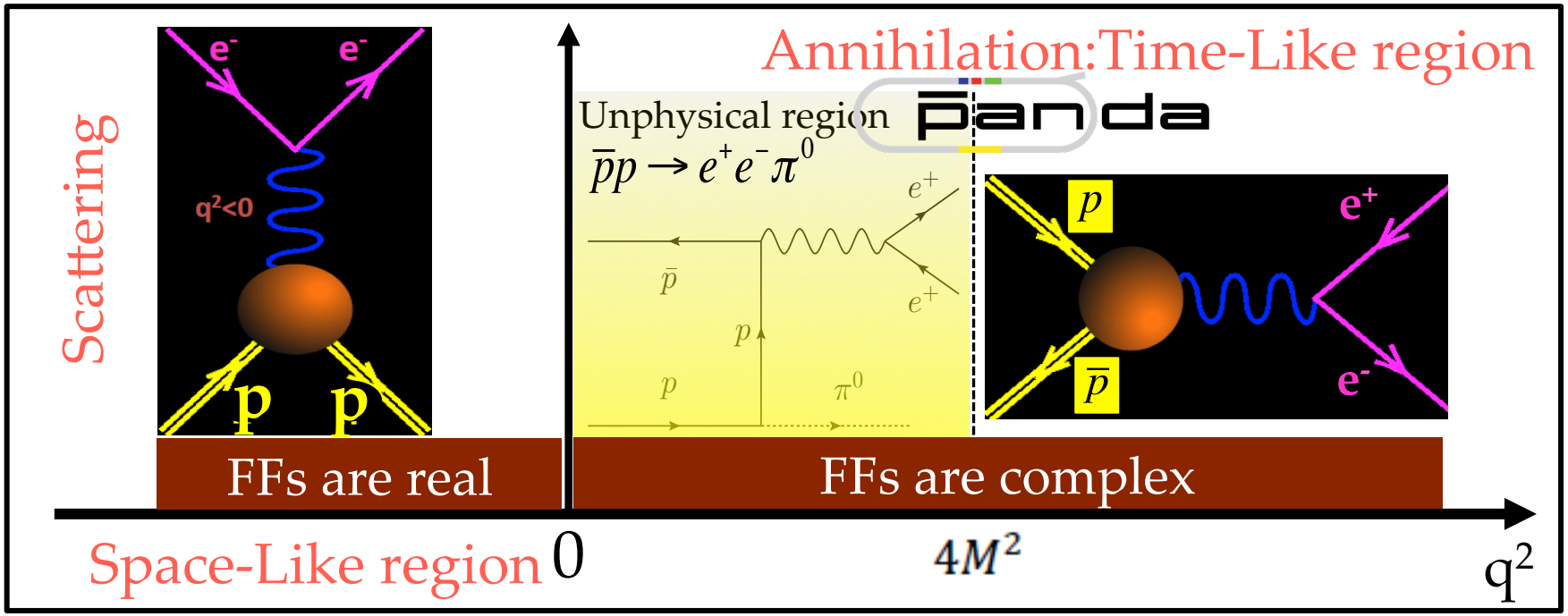
ArXiV:0903.3905

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)

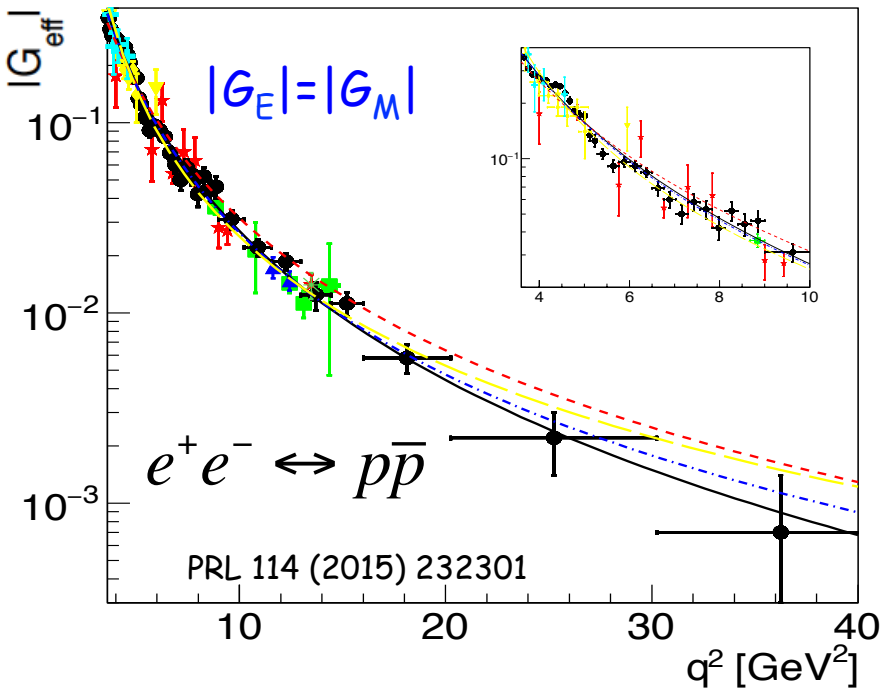
Electromagnetic Form Factors of the Proton



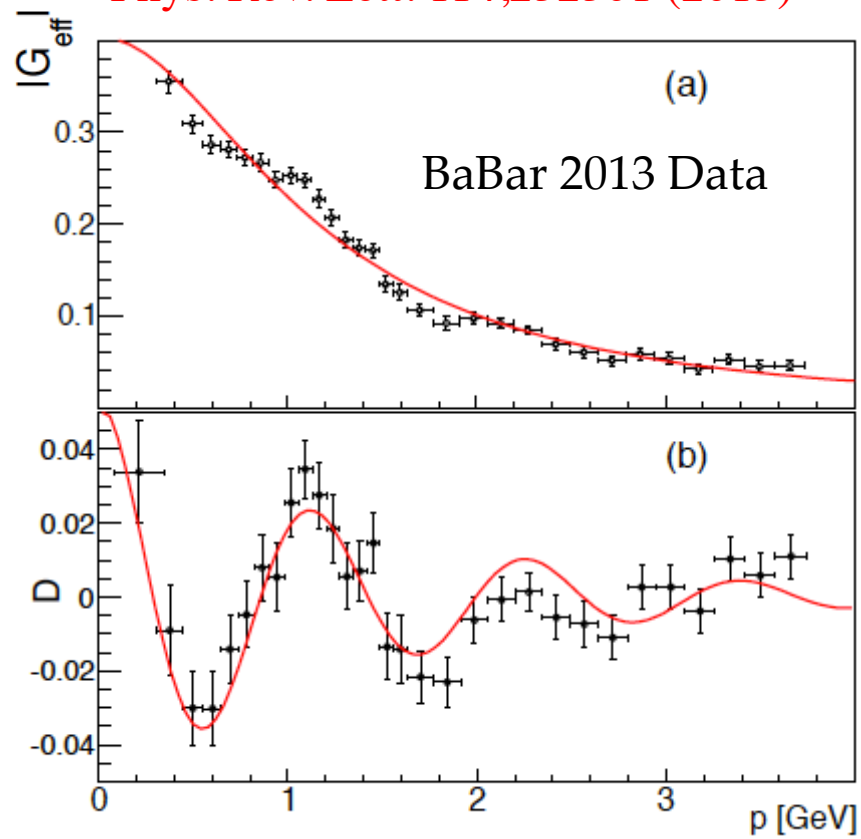
- **Electric G_E and magnetic G_M** proton FFs are analytical functions of the momentum transfer squared q^2

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

Electromagnetic Form Factors of the Proton

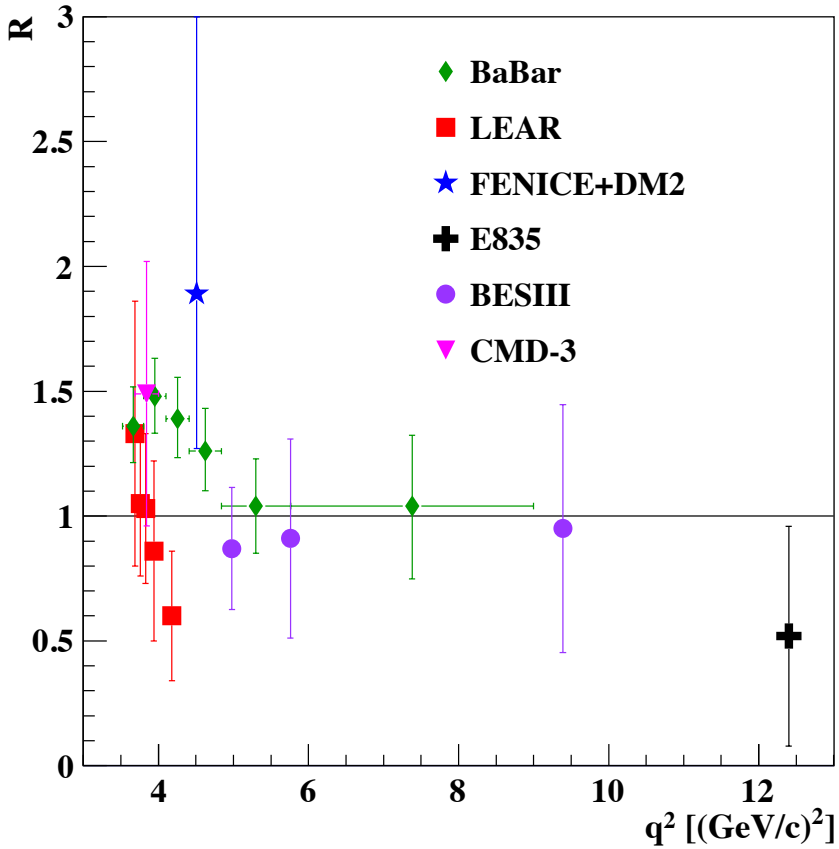


A. Bianconi, E. Tomasi-Gustafsson
Phys. Rev. Lett. 114,232301 (2015)



- No individual determination of G_E and G_M
- Steep behavior of the **effective FF (G_{eff})** at threshold
- Structures appeared in BaBar data (PRD 87 (2013) 092005)?

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

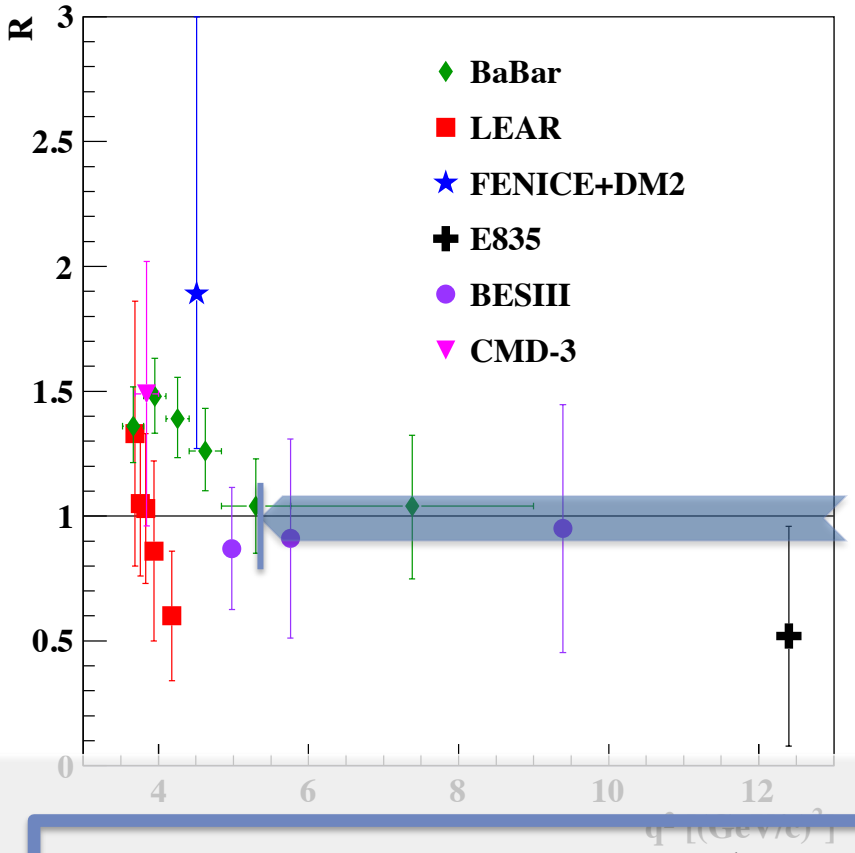
@ BESIII: $e^+e^- \rightarrow \bar{p}p$

- Measurement at different energies
- Uncertainties comparable to previous experiments

@ CMD-3 (VEPP2000 collider, BINP):

- Energy scan $\sqrt{s} = 1-2\ GeV$
- Uncertaincy comparable to the measurement by BaBar

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



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

Test of theoretical models & predictions!

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

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

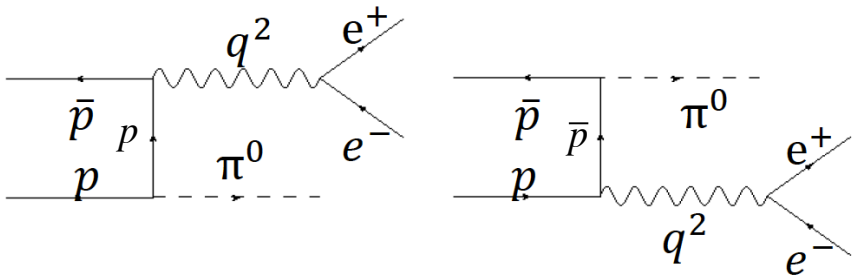
- **A. Z. Dubnickova, S. Dubnicka & M.P. Rekalo Nuovo Cim. A109 (1996) 241-256**

- 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**

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

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

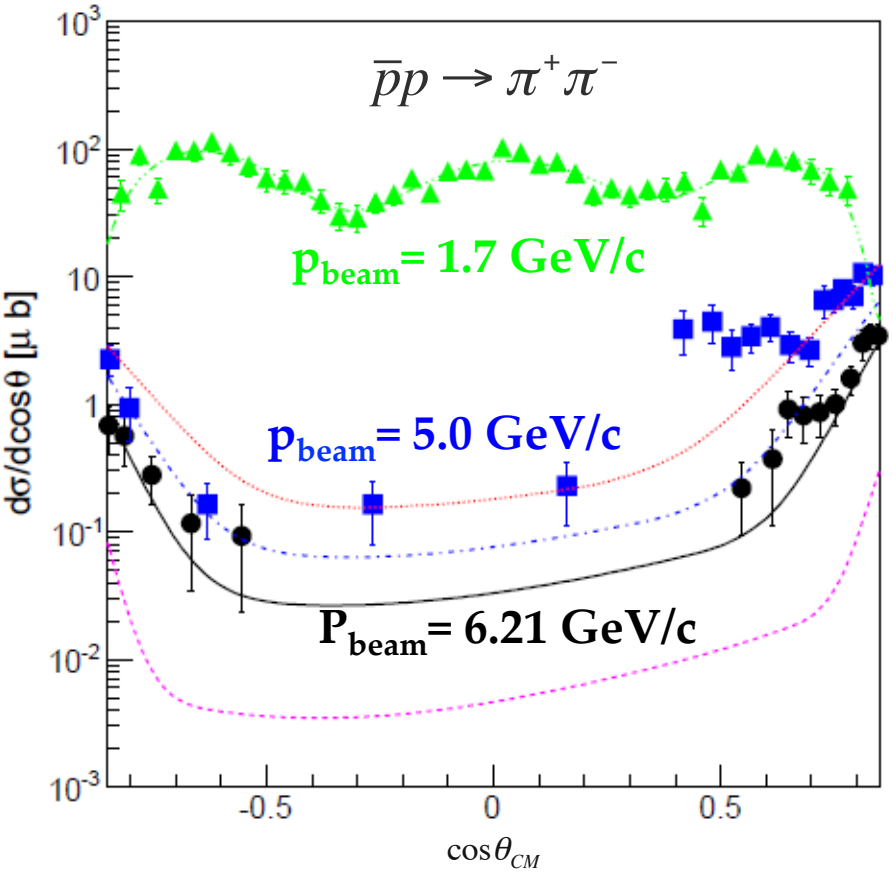
- E.W. Singh et al.: EPJA52, 325 (2016)

Good background rejection necessary → **Feasibility studies needed for both signal channels!**

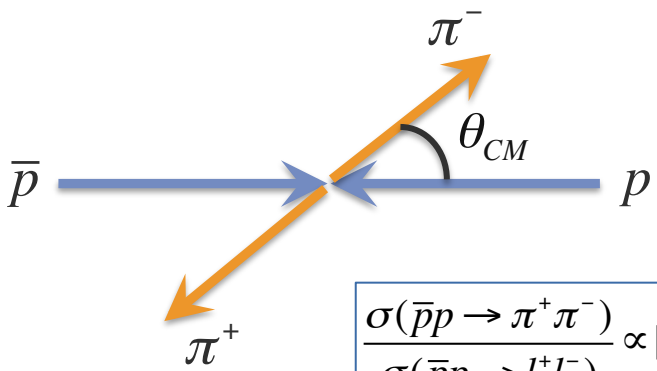
Feasibility studies: time-like proton form factors @ PANDA

Simulation & Analysis: Background studies

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



- **New event generator** developed by Mainz group (M. Zambrana et al.)
- Based on two different parametrizations



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

- **Background rejection ~10^{-8} needed: Pollution < 1%**

- J. Van de Wiele and S. Ong: EPJA46, 291-298 (2010)
- M. Sudol et al.: EPJA44, 373 (2010)
- E.W. Singh et al.: EPJA52, 325 (2016)

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

A) Feasibility studies: time-like proton form factors @ PANDA for

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

- Study of **precision** for $|G_E|$ & $|G_M|$, **the form factor ratio R & effective form factor**

- Study of the **systematic effects** : generator model, fluctuations and fit function

- **Method I**: event generator based on physical cross section & expected events are simulated
- **Method II**: 10^6 events + flat Phase Space (PHSP) event generator + weighting

A) Feasibility studies: time-like proton form factors @ PANDA

Signal efficiency & Background rejection

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

Method I

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

- Zichichi cross section[1] + PHOTOS
- Assuming $R = |G_E|/|G_M| = 1$
- **s [GeV²]: 5.4,** 7.3**, 8.2,** 11.1, 12.9**, 13.9**

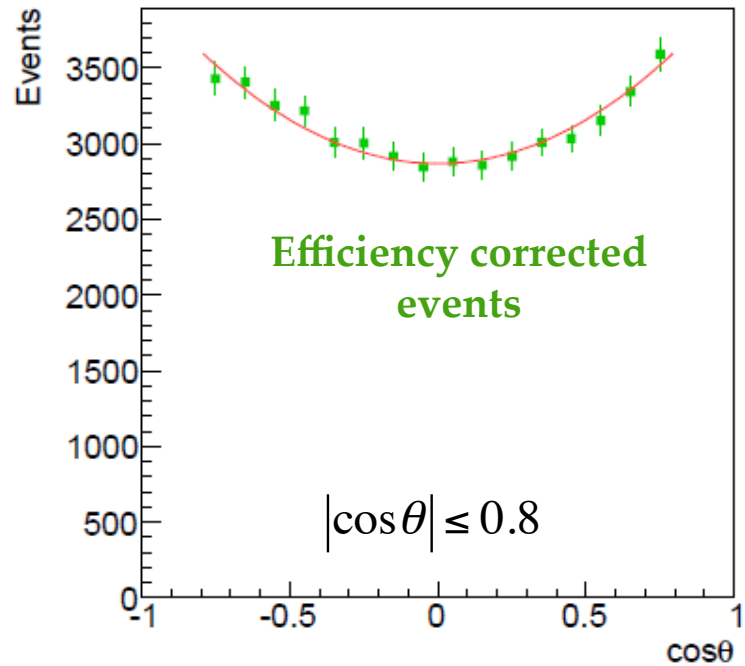
- Additional samples for signal efficiency determination **~10^6 events**

- **High signal efficiencies** between **39%** and **51%**

Background: $\bar{p}p \rightarrow \pi^+\pi^-$

- **New event generator** @ s = 5.4, 8.2, and 13.9 [GeV²]
- **10^8 events at each energy point**

- **Background rejection ~ 10^{-8}**
  Signal pollution < 1%



- **Extraction of FF´s & R±ΔR** from **efficiency corrected signal distribution**

- **Time-integrated cross section of 2 fb^{-1}**

1) A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Nuovo Cim. 24, (1962) 170

A) Feasibility studies: time-like proton form factors @ PANDA

Statistical and total uncertainty on R, $|G_E|$ and $|G_M|$

Results

Statistical relative uncertainty

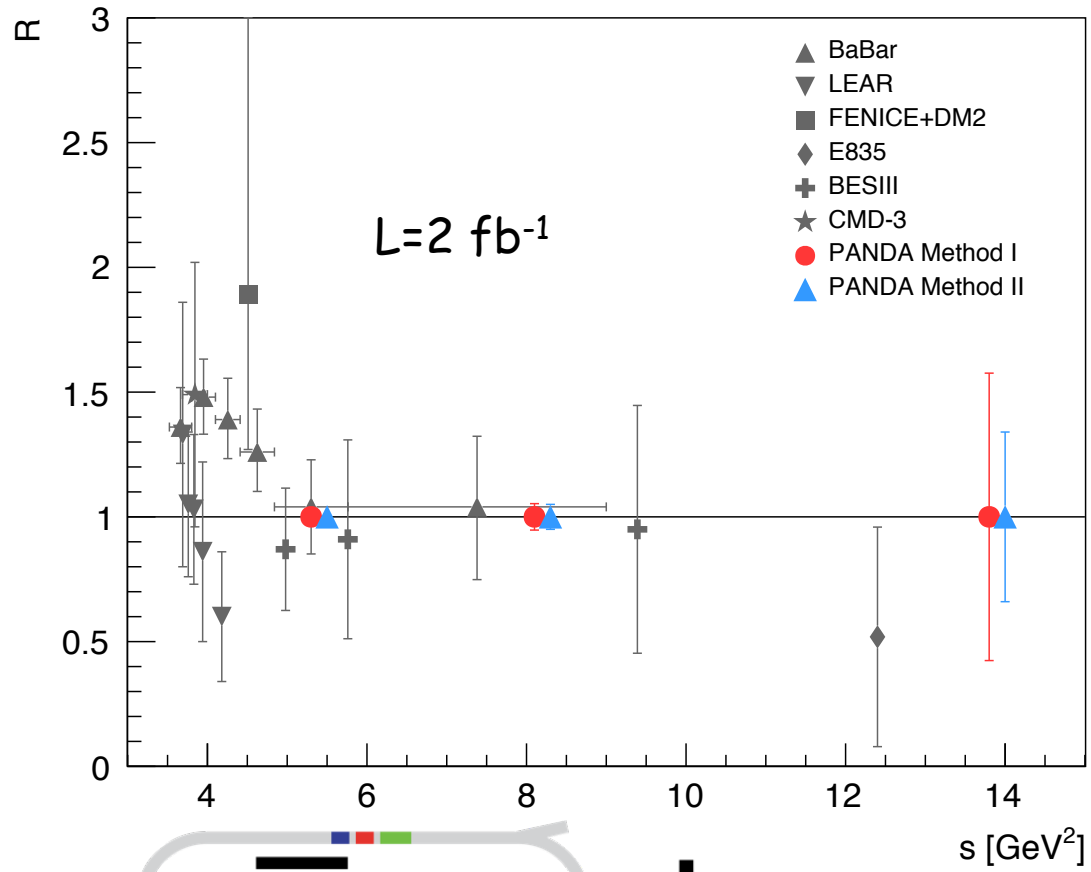
- $\Delta|G_E|/|G_E|$: 0.9% - 48%
- $\Delta|G_M|/|G_M|$: 0.4% - 9.4%
- $\Delta R/R$: 1.3% - 56%

- The **precisions** obtained at **5.4 GeV²** and **8.2 GeV²** are **compatible between Method I & II**
- **Systematic uncertainties** are considered from **luminosity measurement & background contamination.**

Total relative uncertainty

- $\Delta|G_E|/|G_E|$: 2.2% - 48%
- $\Delta|G_M|/|G_M|$: 3.5% - 9.7%
- $\Delta R/R$: 3.3% - 57%

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



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

B) Feasibility studies: time-like proton form factors @ PANDA for

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

Study of the statistical error on R,
$|G_E|$ & $|G_M|$

B) Feasibility studies: time-like proton form factors @ PANDA

Statistical error on $R = |G_E|/|G_M|$

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

Analysis : Boosted Decision Trees & Cuts

$|\cos\theta| \leq 0.8$

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

- Follows physical cross section
- Assuming $R = |G_E|/|G_M| = 1$
- **s [GeV²]: 5.4 (5.1, 6.8, 8.2)**

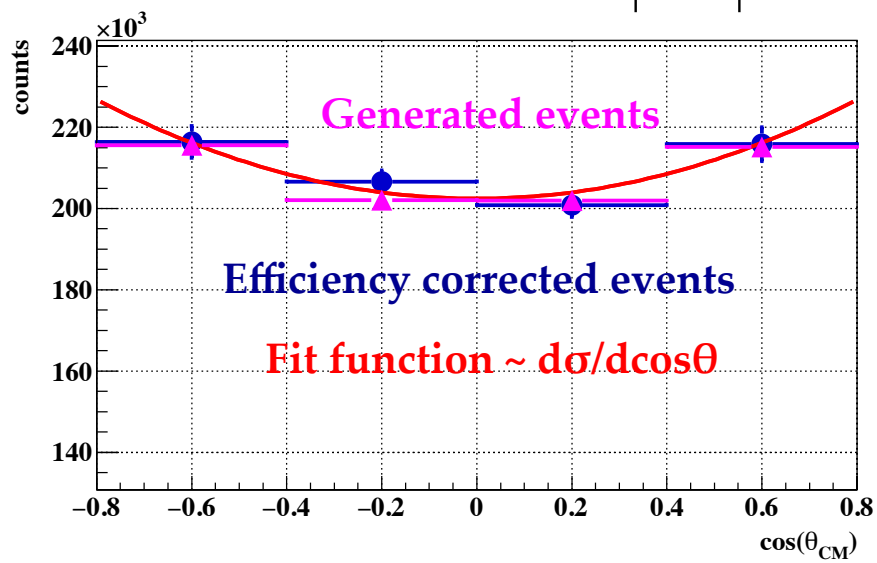
- Additional samples for signal efficiency determination **~10^7 events**

- **Signal efficiency ~ 21%**

Background: $\bar{p}p \rightarrow \pi^+\pi^-$

- **New event generator @ s [GeV²]: 5.4 (5.1, 6.8, 8.2)**

- **Two samples each for studying background rejection and effects of background subtraction, 10^8 events at each energy point**



- **Background rejection factor ~ 10^{-6}**

- Background subtraction removes pion background contamination

- **Extraction of FF´s & R±ΔR** from **efficiency corrected signal distribution**

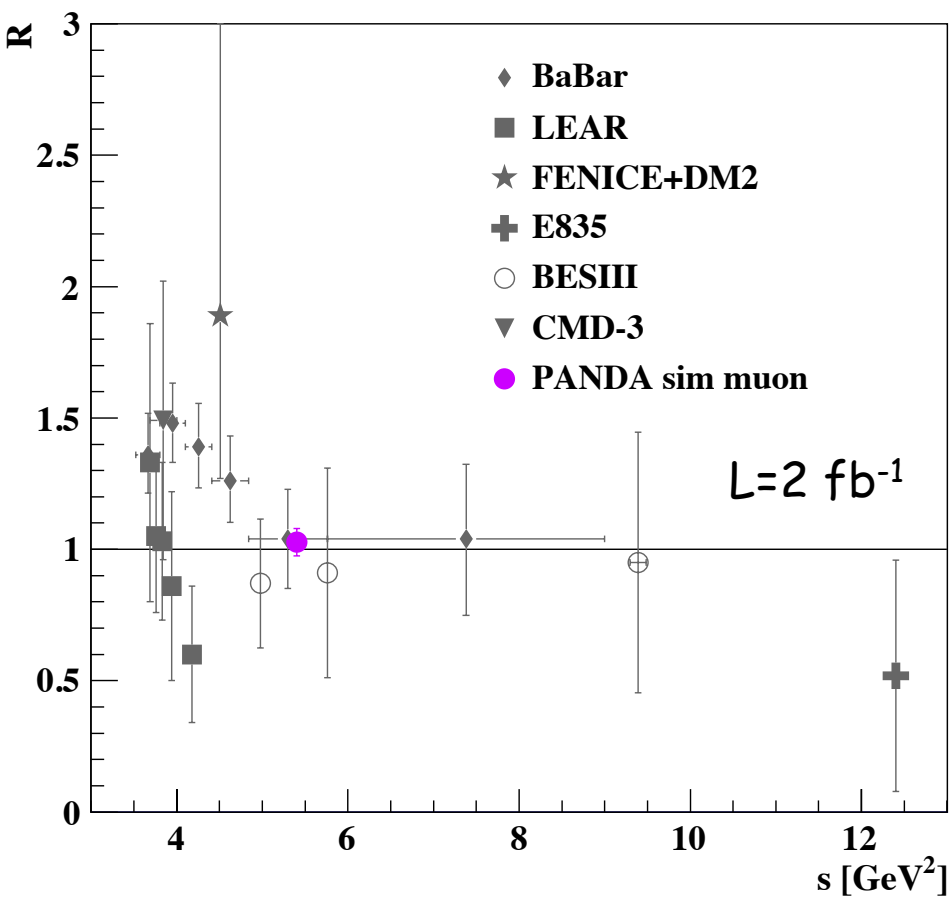
- **Time-integrated cross section of 2 fb^{-1}**

Feasibility studies: time-like proton form factors @ PANDA

Statistical error on R, $|G_E|$ & $|G_M|$

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

World data on R = $|G_E|/|G_M|$



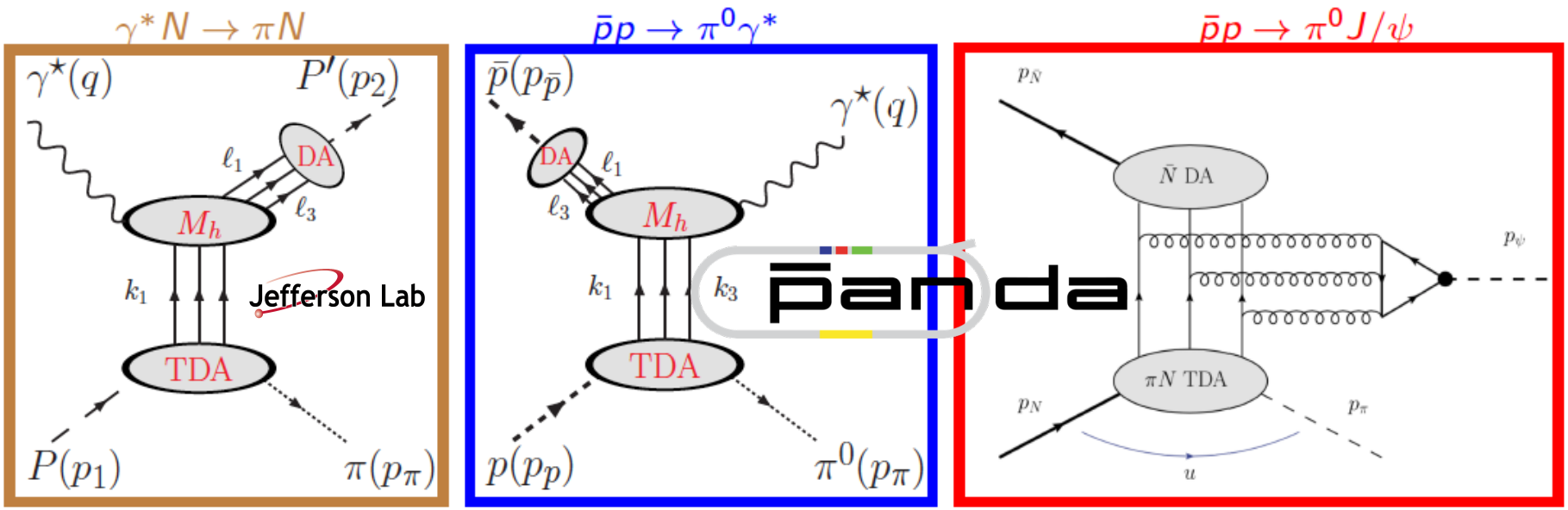
Precision on R, $|G_E|$&$|G_M|$

p [GeV/c]	1.7
$\Delta R/R$	5.1%
$\Delta\|G_E\|/\|G_E\|$	8.6%
$\Delta\|G_M\|/\|G_M\|$	4.1%

-PRELIMINARY-

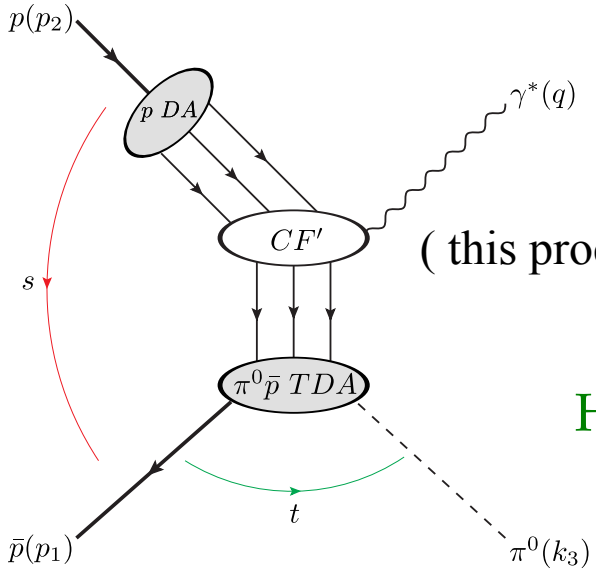
Transition Distribution Amplitudes

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

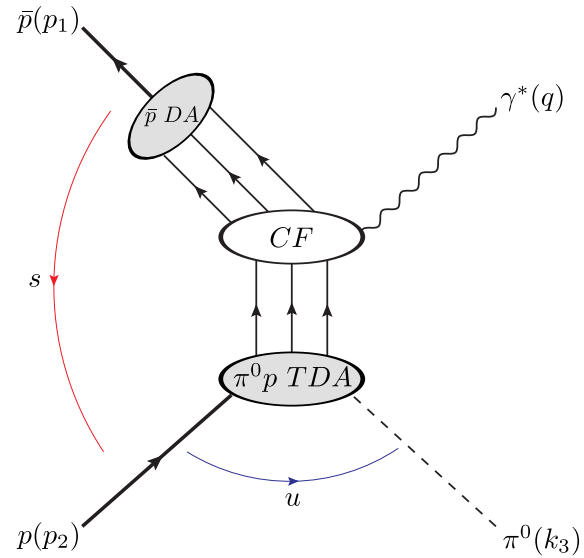
Nucleon to meson TDAs at PANDA



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

(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 $\bar{p}p \rightarrow \gamma^* \pi^0 -> e^+e^-\pi^0$ 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 $\bar{p}p \rightarrow \pi^+\pi^-\pi^0$ [$\sigma(\pi^+\pi^-\pi^0)/\sigma(e^+e^-\pi^0) \sim 10^6$]:

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)

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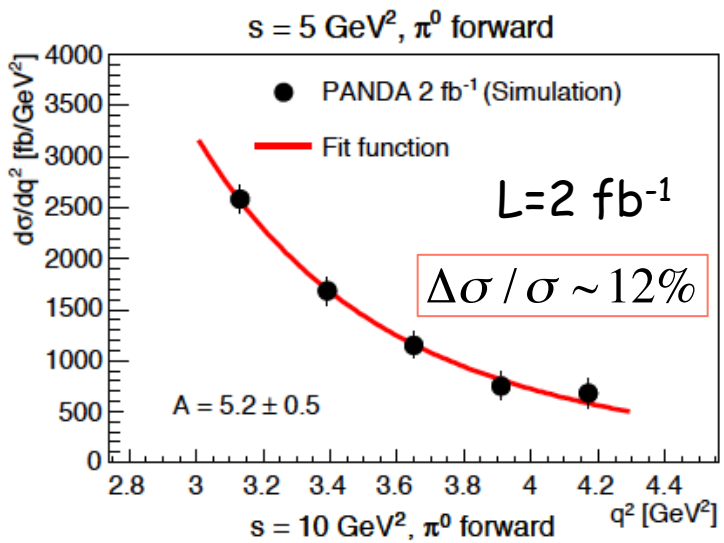
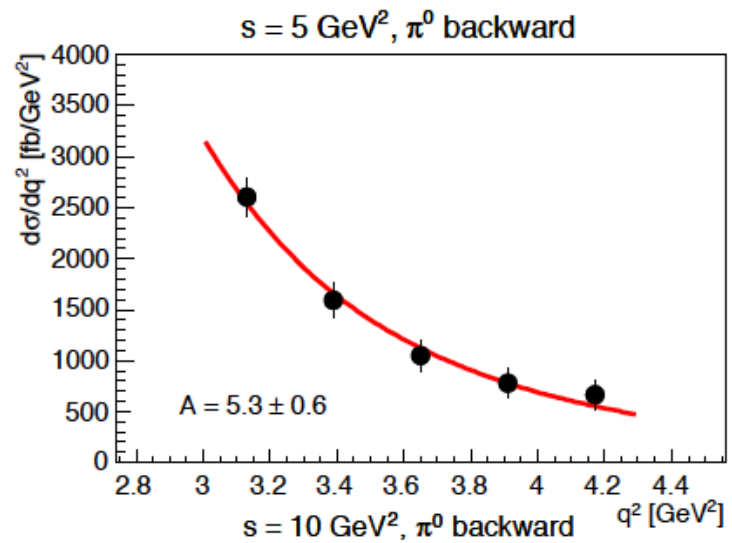
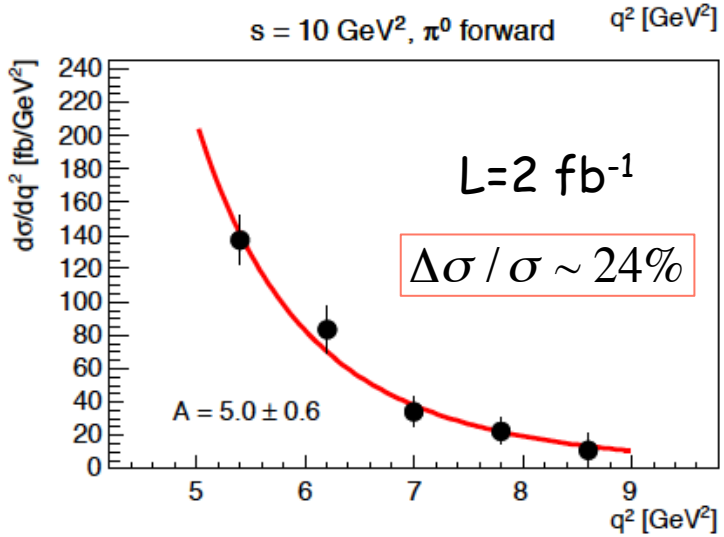
Nucleon to meson TDAs at PANDA

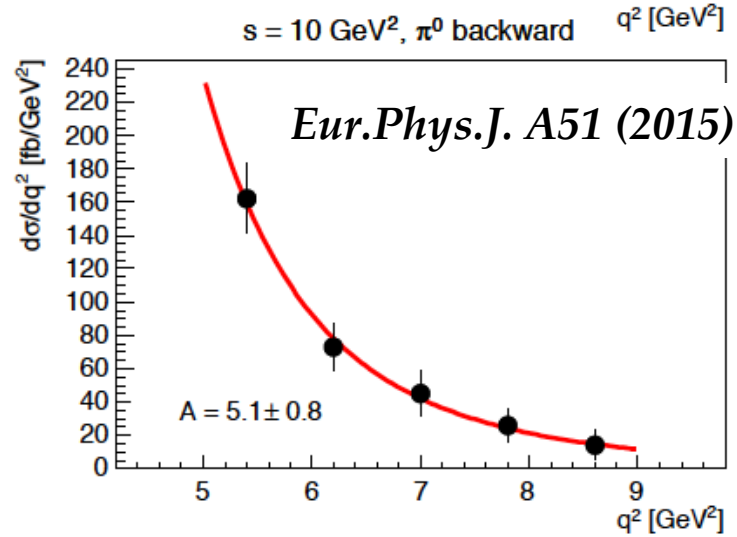
$$\frac{d\sigma}{dq^2} \sim \frac{1}{(q^2)^5}$$

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





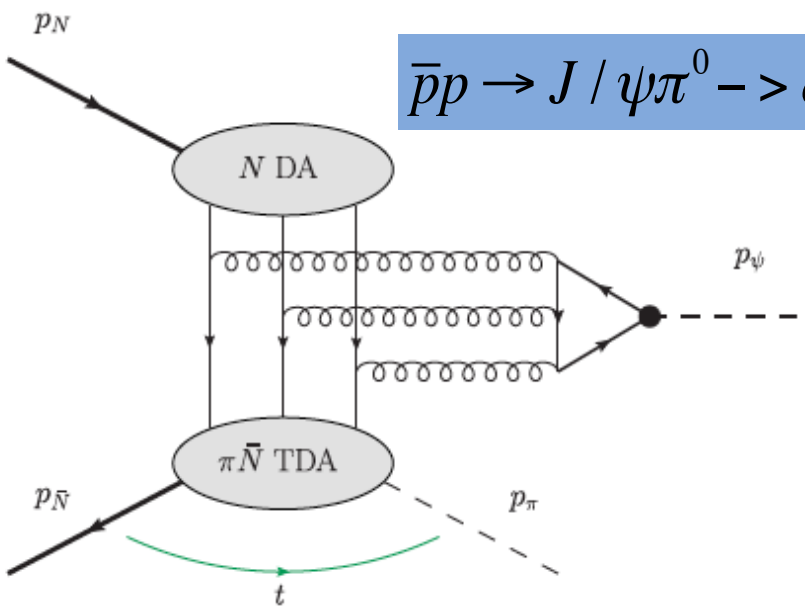


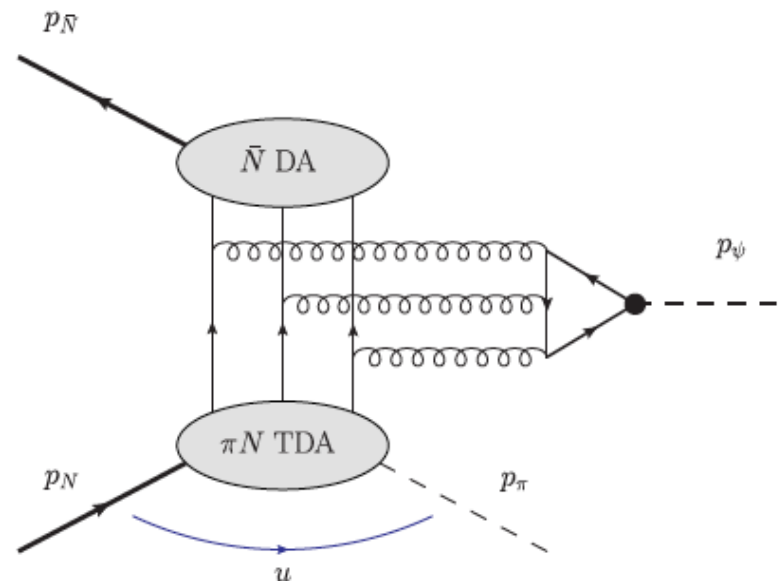


Eur.Phys.J. A51 (2015) 8, 107

Nucleon to meson TDAs at PANDA

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





t is small (forward kinematics)

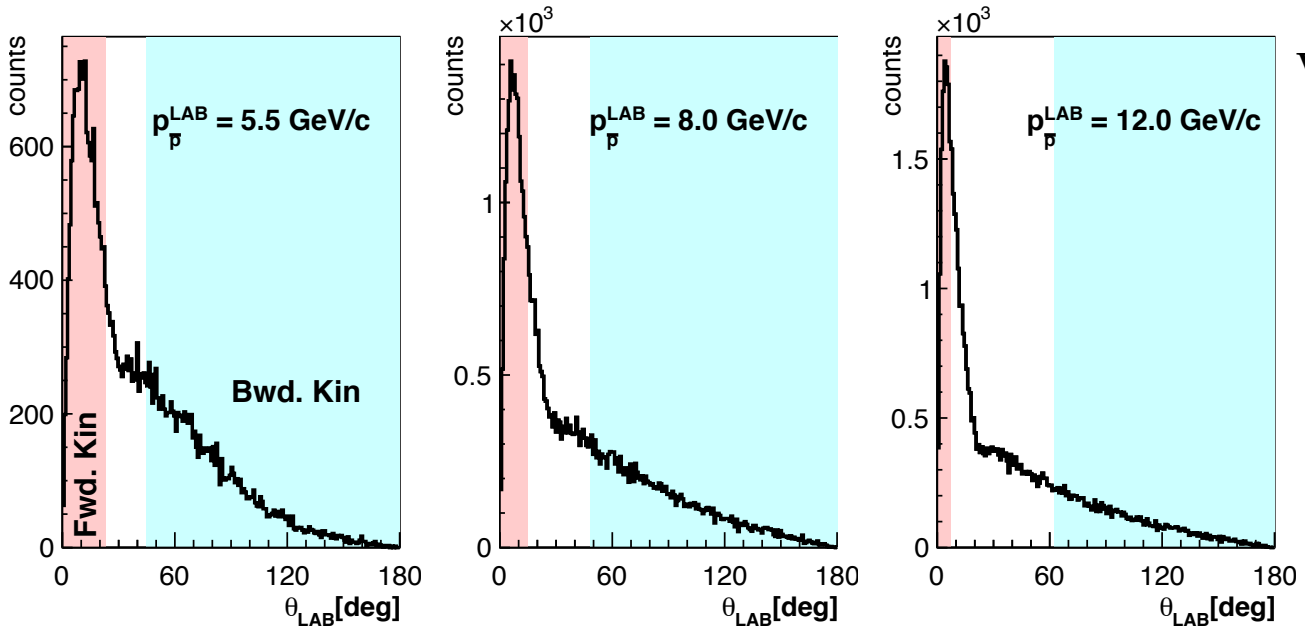
u is small (backward kinematics)

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

- High signal cross section
- Large q^2 fixed to $Q^2 = M^2_{J/\psi} = 9.6 GeV^2$ (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

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



Validity ranges of the TDA model:

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

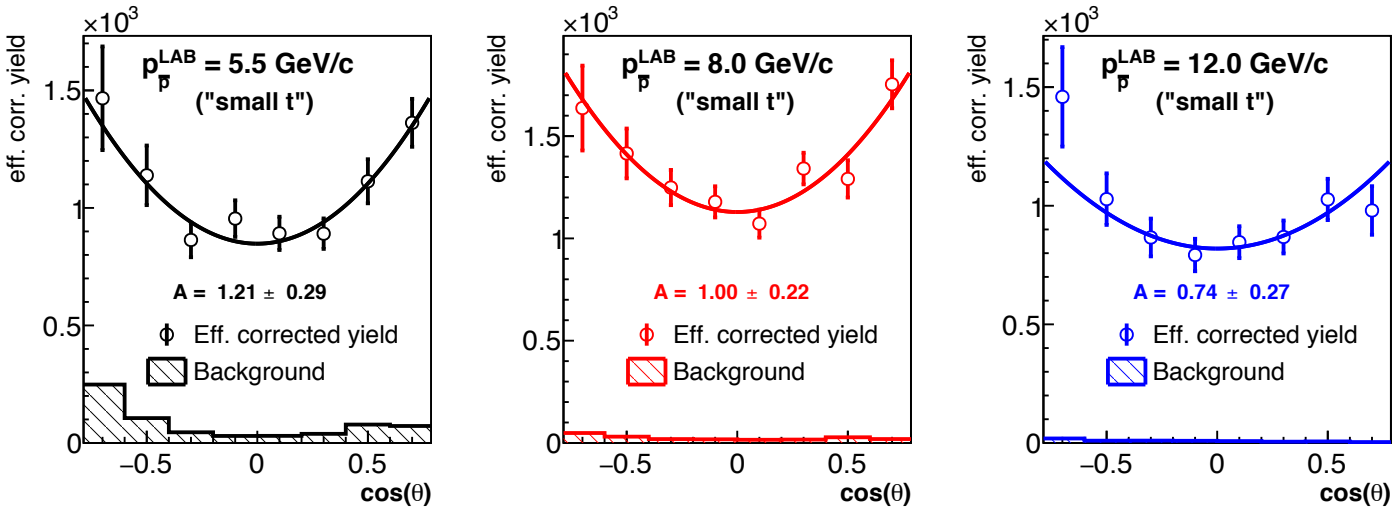
Background final states:

- Three pion production: $\pi^+\pi^-\pi^0$ (B/S~10^5 - 10^6)
- Multipion final states (N>3): $\pi^0\pi^0\pi^+\pi^-$, $\pi^0\pi^+\pi^-\pi^+\pi^-\ \pi^0$ (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)

Nucleon to meson TDAs at PANDA

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

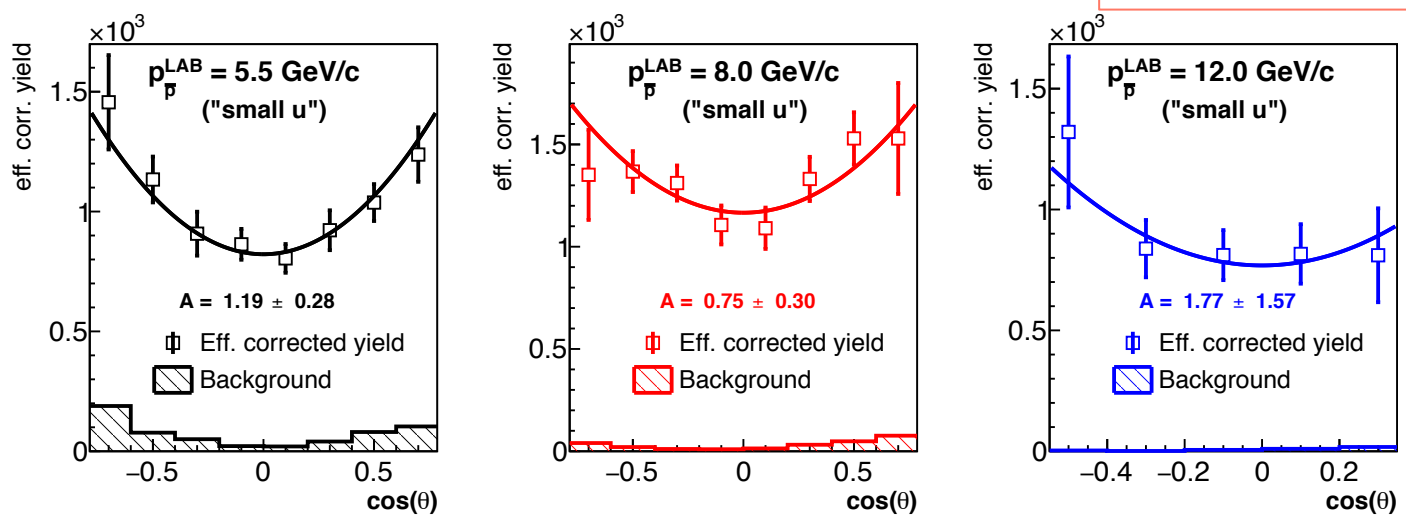


Fit funtion:

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

L=2 fb^{-1}

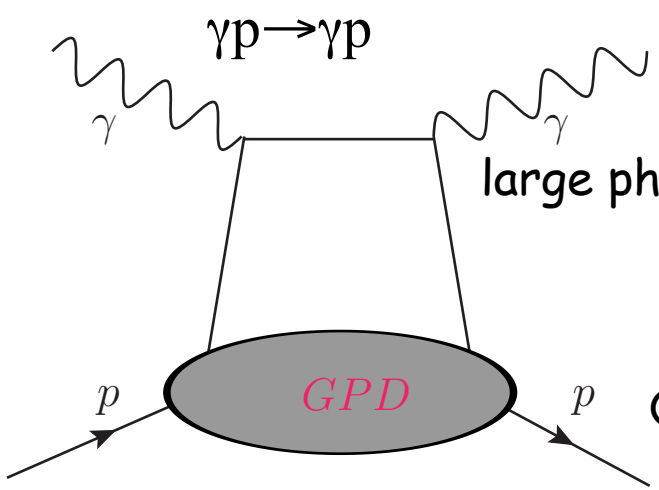
$$\Delta\sigma(t,u)/\sigma(t,u) \sim 5\% - 10\%$$



Phys. Rev. D 95, 032003 (2017)

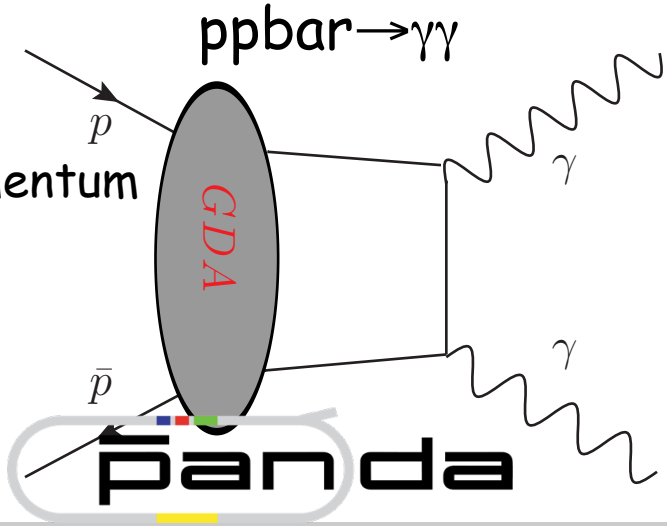
Generalized Distribution Amplitudes

Hard exclusive processes at PANDA-GDAs



large photon transverse momentum
(hard scale)

QCD factorization



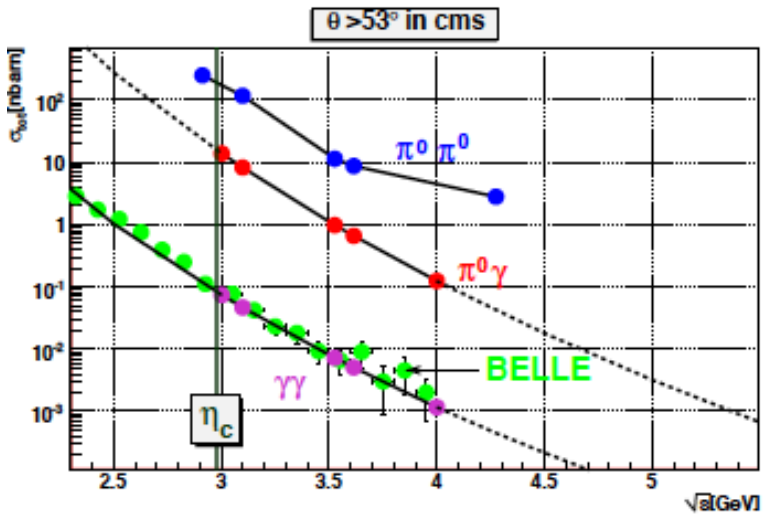
Wide **A**ngle **C**ompton **S**cattering
Generalized Parton Distributions GPDs

Time-Like Wide **A**ngle **C**ompton **S**cattering
Generalized Distribution Amplitudes GPDs

- GDAs can be measured at PANDA with the hard exclusive electromagnetic processes: ppbar→γγ, γM ($M=\pi^0,\eta,\rho^0,\phi$)

- 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



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

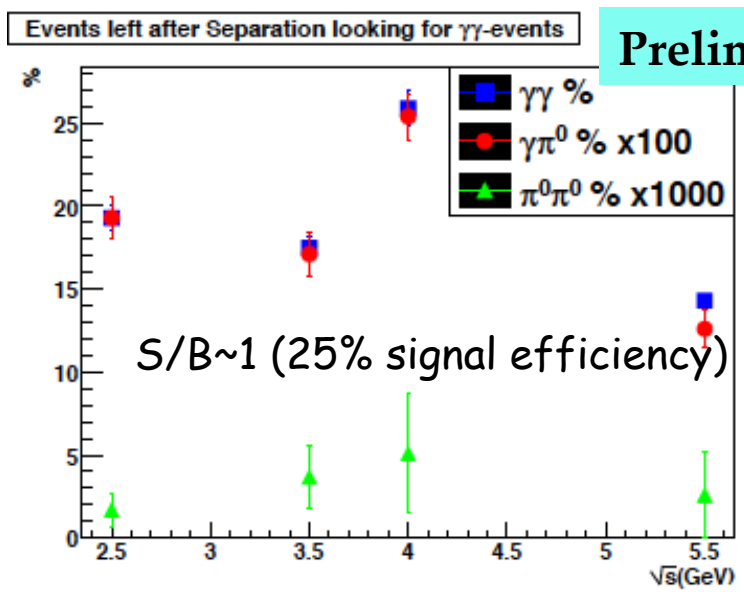
- 4 different CM energies
- Main background channels:

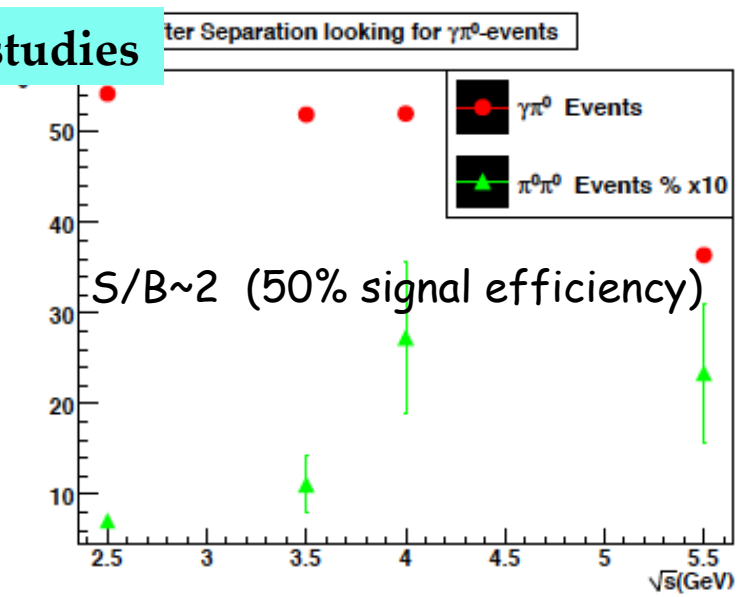
$\bar{p}p \rightarrow \pi^0\pi^0$ (for both signals)

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

PANDA Physics Performance Report
arXiv:0903.3905

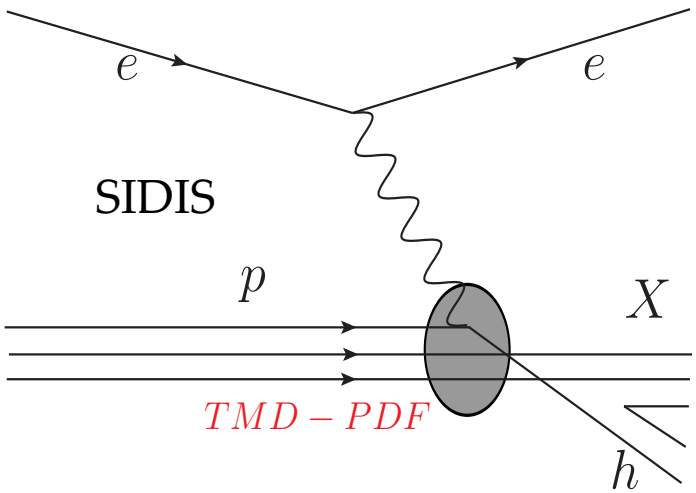
Preliminary studies



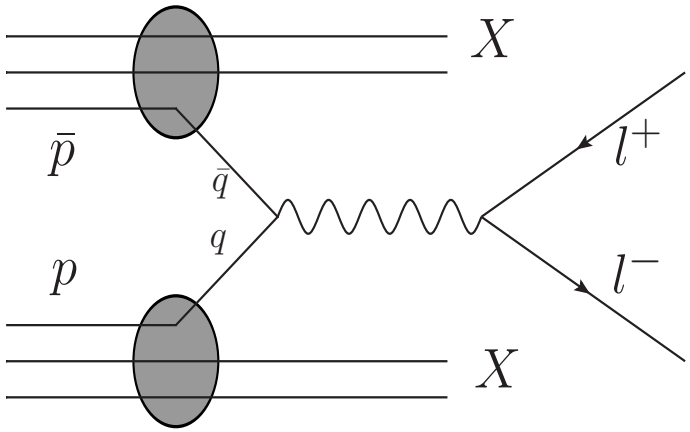


Transverse Momentum dependence - Parton Distribution Functions

Drell-Yan at PANDA



TMD-PDFs are convoluted with the fragmentation functions



Direct access to TMD-PDFs

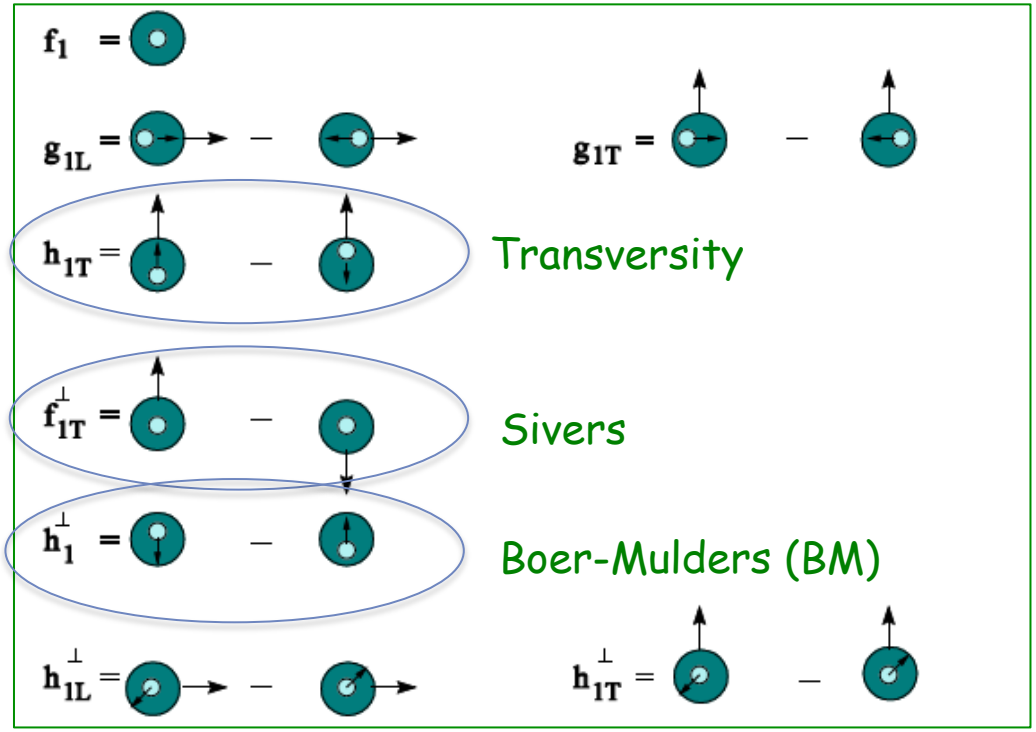
Test of Universality
and the QCD TMD factorization

$$f_{1T}^{\perp}(DY) = -f_{1T}^{\perp}(SIDIS)$$

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

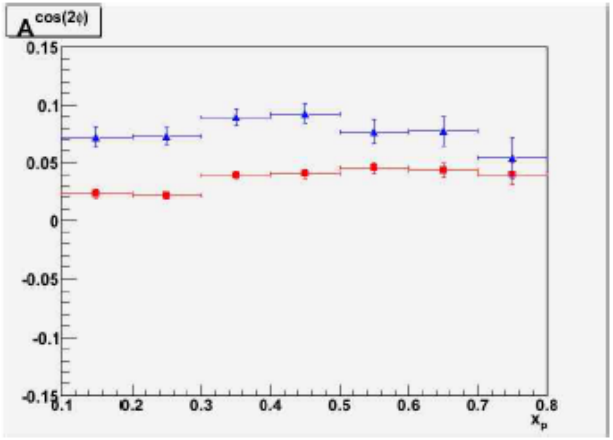
- Main background: $\bar{p}p \rightarrow n(\pi^+\pi^-)X$, required rejection factor ~10^7

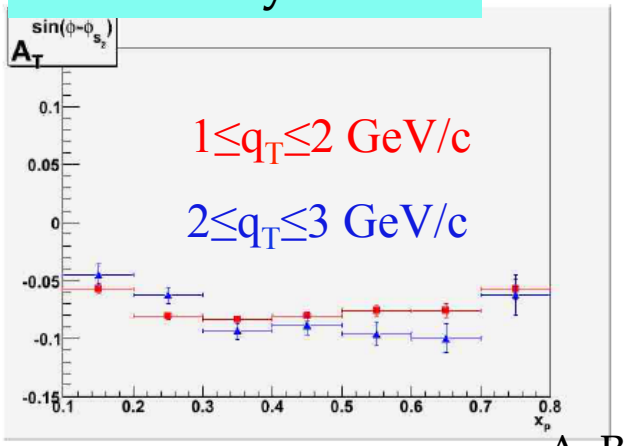
- Simulations @ s=30 GeV^2 and $1.5 \leq M_{\gamma^*} \leq 2.5$ (large cross section)

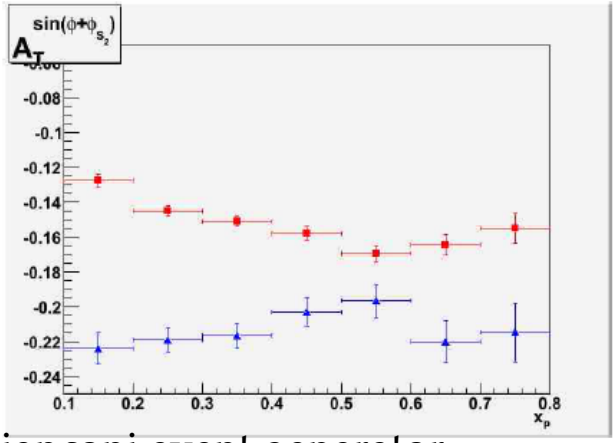
  Number of simulated events N~5 . 10^5

PANDA Physics Performance Report
arXiv:0903.3905

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

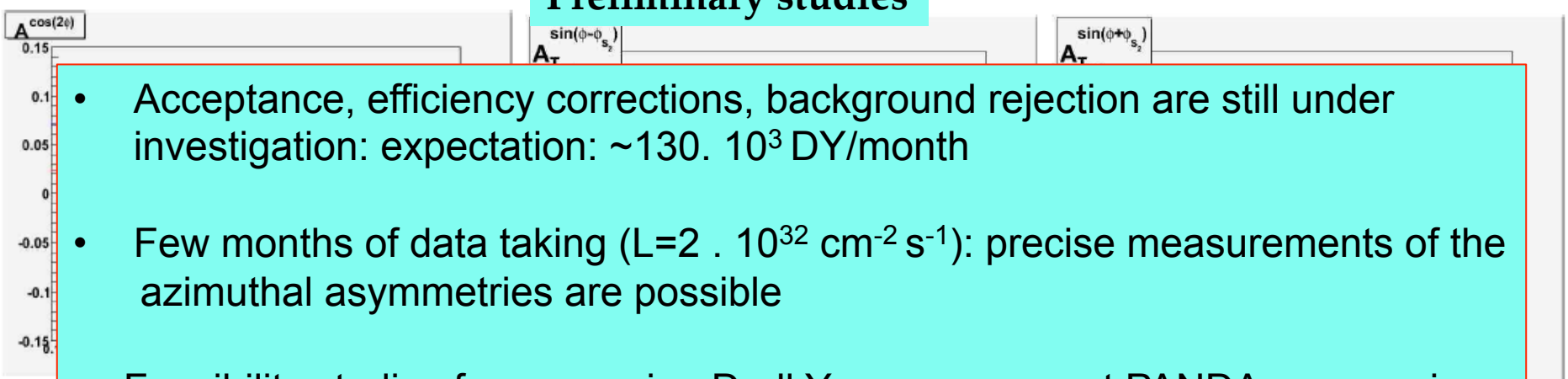
- Main background: $\bar{p}p \rightarrow n(\pi^+\pi^-)X$, required rejection factor ~10^7

- 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



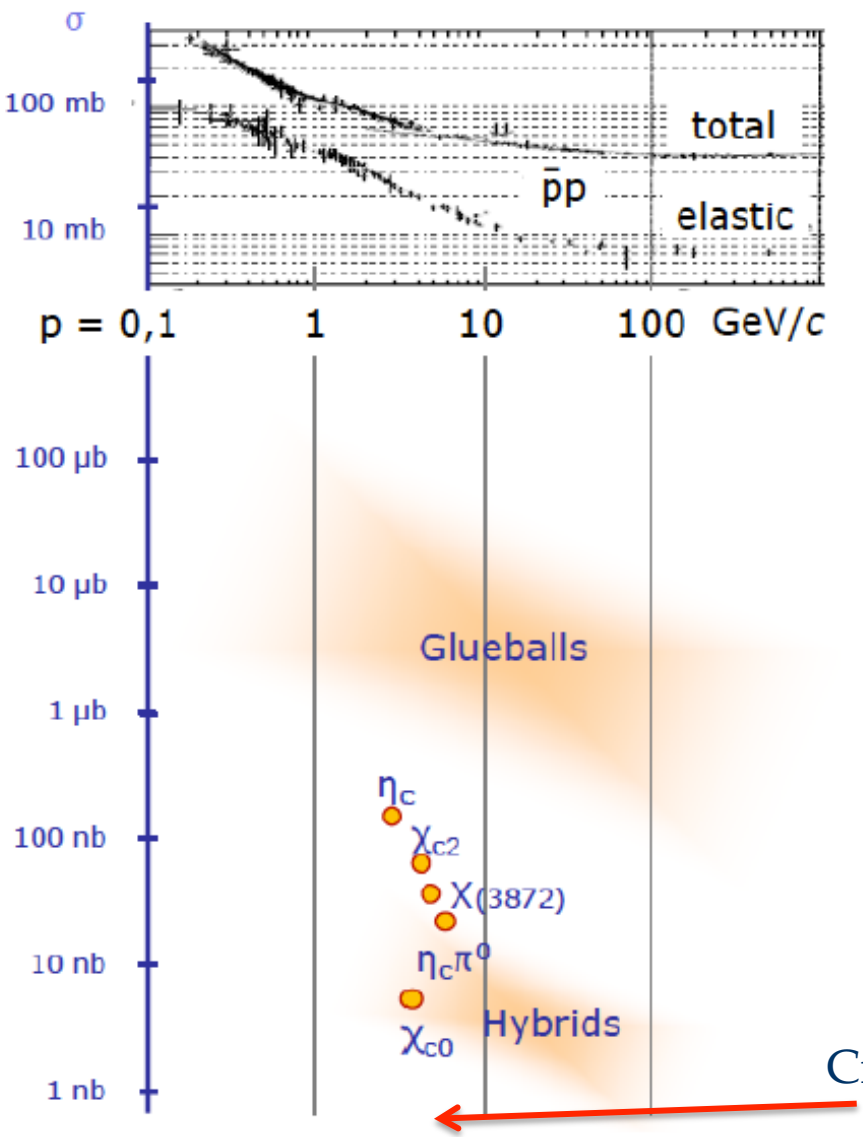
- Acceptance, efficiency corrections, background rejection are still under investigation: expectation: ~130. 10^3 DY/month

- 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

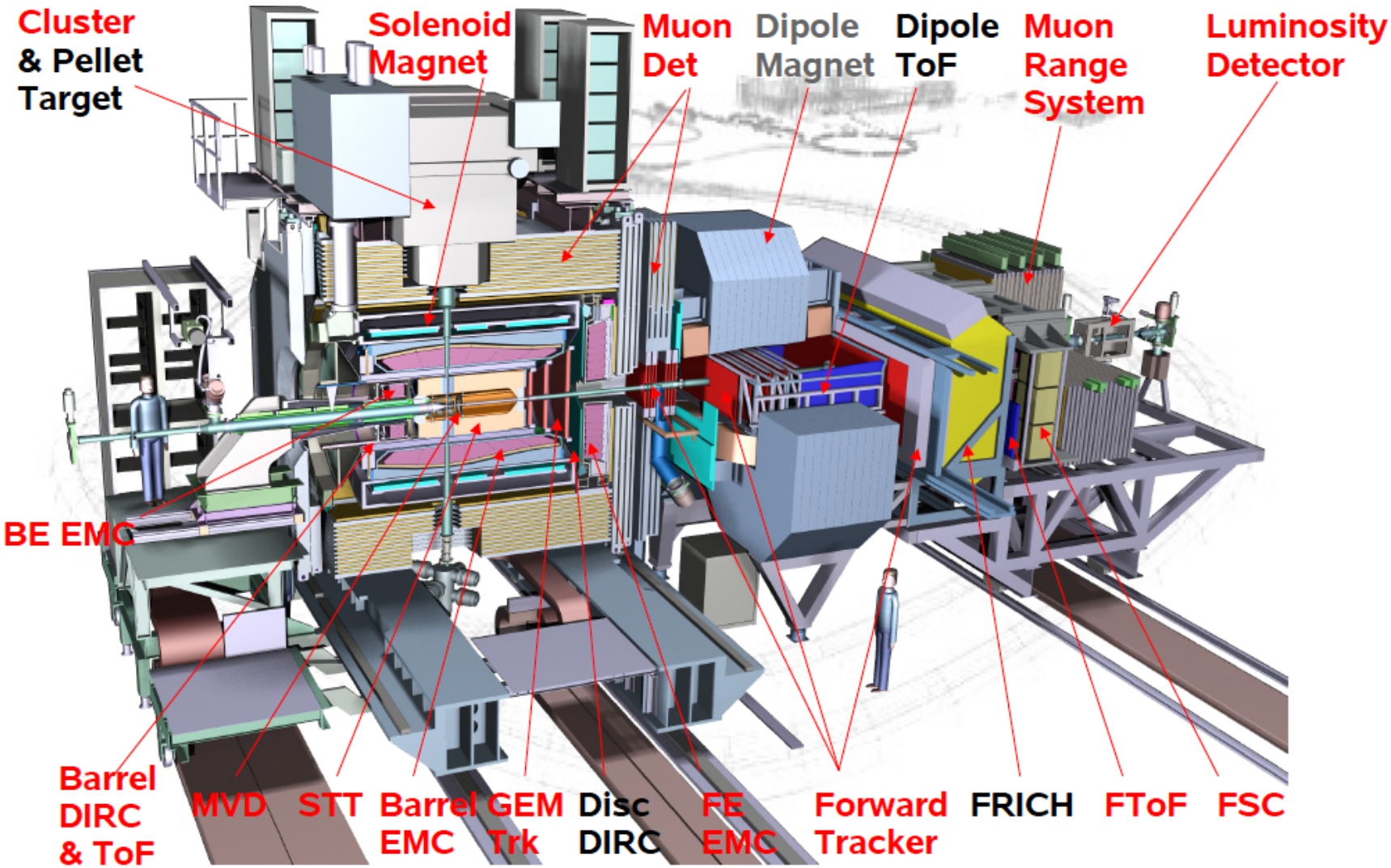
Detector requirements from physics case



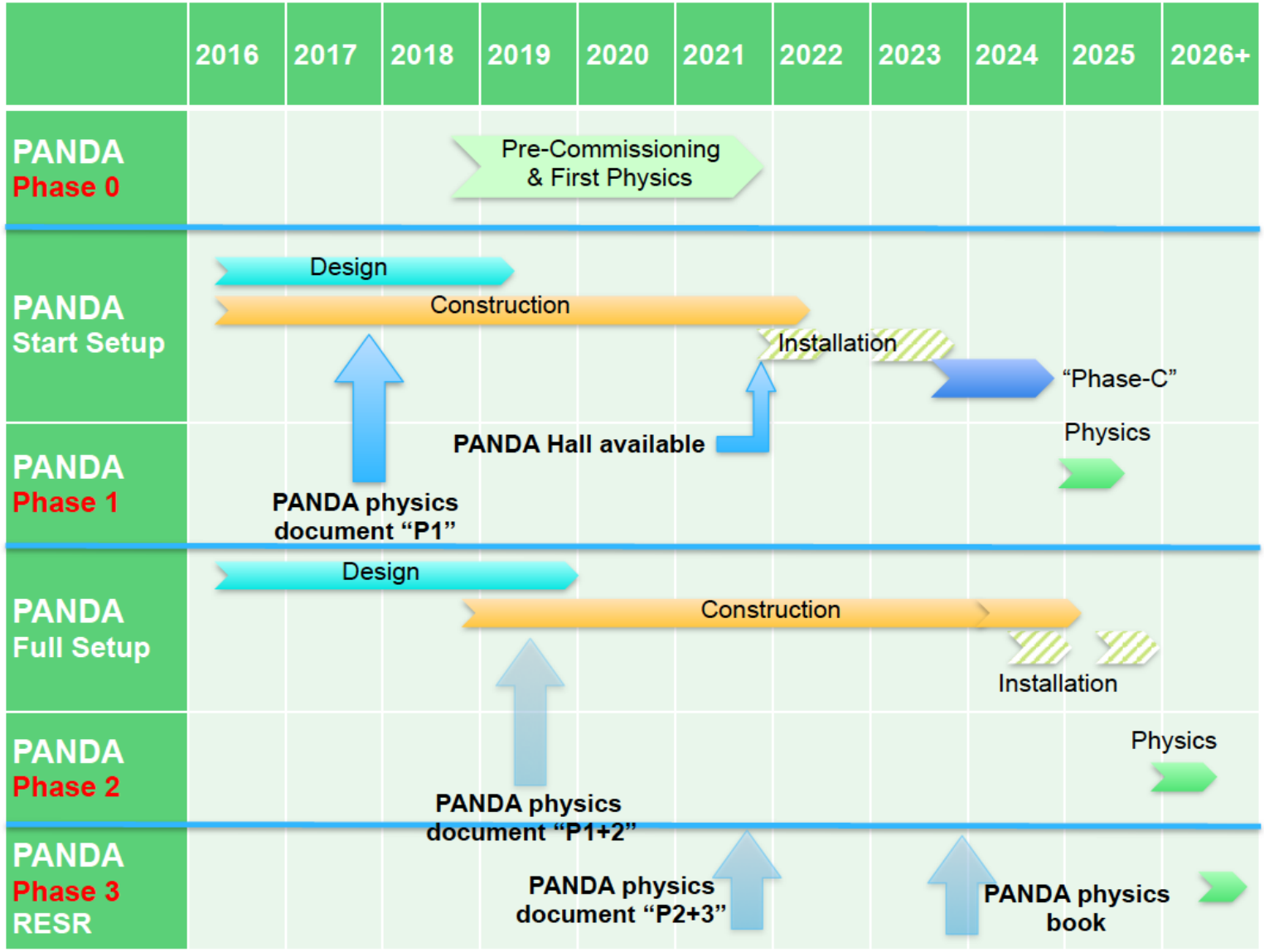
- 4π acceptance
- Momentum resolution: 1%
  central tracker in magnetic field
- Photon detection: 1 MeV - 10 GeV
  high dynamic range
  good energy resolution
- Particle identification: γ, e, μ, π, K, p
  Cherenkov detector
  time of flight, dE/dx, muon counter
- Displaced vertex info
  $c\tau = 317\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

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

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

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

- 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)

Back-up slides

Feasibility studies: time-like proton form factors @ PANDA
Conclusion

B) Feasibility studies for the signal reaction $\bar{p}p \rightarrow \mu^+\mu^-$

- Monte Carlo simulation & analysis for **signal** and main **background** channel

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

  - @ **p = 1.7 GeV/c** a **precision on**
    - **R** of **5.1%,**
    - **$|G_M|$** of **4.1%** & **$|G_E|$** of **8.6%** could be achieved
  - Complete study for the **muonic channel** for beam momenta

of **1.5, 1.7, 2.5** and **3.3 GeV/c currently under review**

  - **Phase-1 simulations** (reduced luminosity & reduced PANDA detector setup) planned

L=2 fb^{-1}

The time-like electromagnetic proton form factors and their ratio R= $|G_E|/|G_M|$ can be measured @ PANDA with unprecedented statistical accuracy

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

- Differential cross section[1] of **signal reaction** $\bar{p}p \rightarrow l^+l^- \quad l = \mu, e$
  → Access to the **time-like, electromagnetic form factors of the proton, $|G_E|$ and $|G_M|$** :

$$\frac{d\sigma}{d\cos\theta_{CM}} \propto \frac{\beta_{l^-}}{\beta_{\bar{p}}} \cdot \frac{|G_M|^2}{s}\left[(1+\frac{4m_{l^-}^2}{s}+\beta_{l^-}^2\cos^2\theta_{CM})+\frac{R^2}{\tau}(1-\beta_{l^-}^2\cos^2\theta_{CM})\right]$$

$$R = \frac{|G_E|}{|G_M|}$$

- High luminosity: **Measurement of signal angular distribution**
  - **Separate determination** of **$|G_E|$, $|G_M|$** over a **large kinematical region in the time-like region**
  - High precision measurement of the **ratio** $R = |G_E|/|G_M|$ at PANDA as well as the **proton effective form factor** $|F_p|^2 \propto \sigma_{tot}$

1) A. Zichichi, S. M. Berman, N. Cabibbo, R. Gatto, Nuovo Cim. 24, (1962) 170

Electromagnetic Form Factors of the Proton

- **Describe the internal structure and dynamics** of the proton
- **Hadronic current** $(q = p' - p)$

$$J^{\mu}_{had} = \langle p(p') | j^{\mu} | p(p) \rangle = e\,\bar{u}(p')\,\Gamma^{\mu}(q)\,u(p)$$

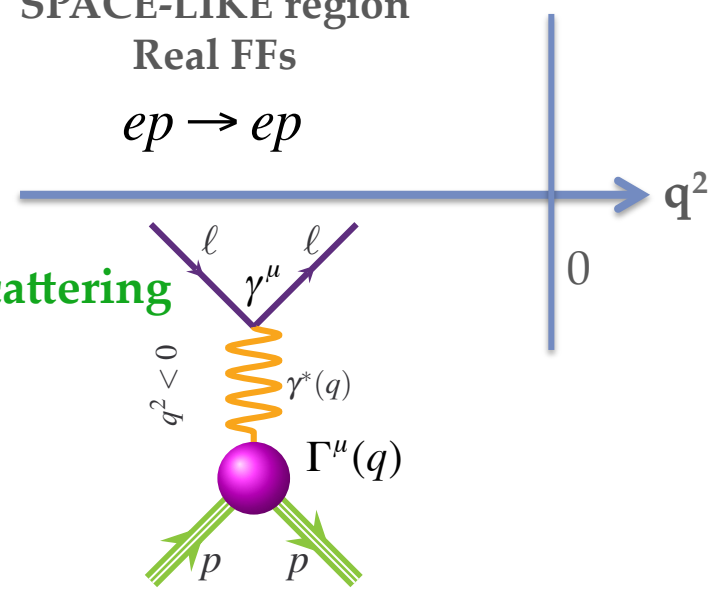
- **Hadronic vertex can be parametrized in terms of Dirac and Pauli Form Factors F_1 & F_2:**

$$\Gamma^{\mu} = F_1(q^2)\,\gamma^{\mu} + \frac{i\sigma^{\mu\nu}q_{\nu}}{2M_p}F_2(q^2)$$

- **F_1 and F_2 are real functions of q^2**

SPACE-LIKE region
Real FFs

$ep \rightarrow ep$



- **Sachs Form Factors**

$$G_E(q^2) = F_1(q^2) + \frac{q^2}{4m_p^2}F_2(q^2), \quad G_E(0) = 1$$
$$G_M(q^2) = F_1(q^2) + F_2(q^2), \quad G_M(0) = \mu_p$$

- In the **Breit frame** q = (0, **q**) and in non relativistic approach, **the FF's** represent the Fourier transforms of electric **charge and magnetization spatial distribution** of the nucleon

Nucleon to meson TDAs at PANDA

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