Feasibility studies for the measurement of the time-like electromagnetic form factors of the proton at PANDA (Nucleon structure studies)

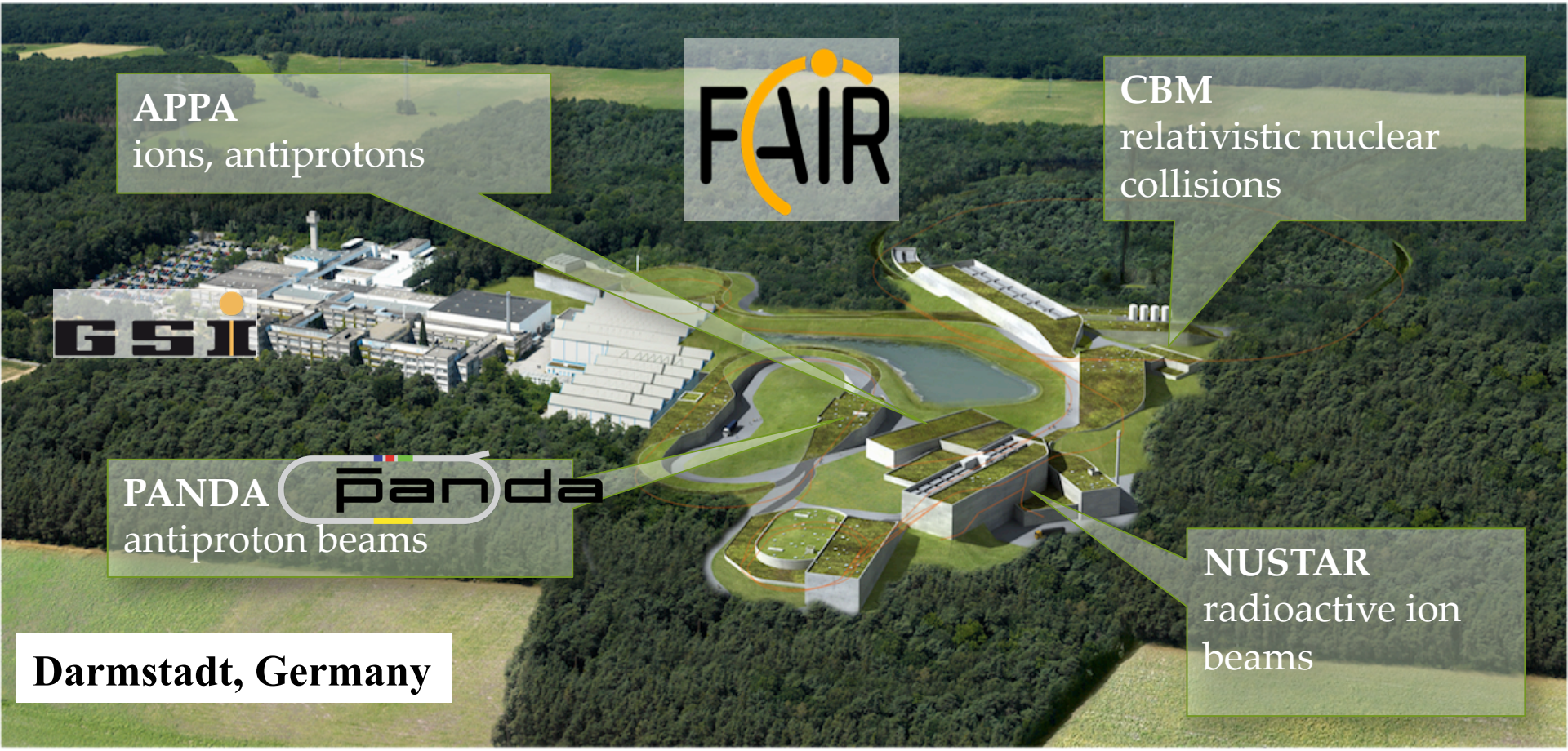
Alaa Dbeyssi

On behalf of the PANDA collaboration

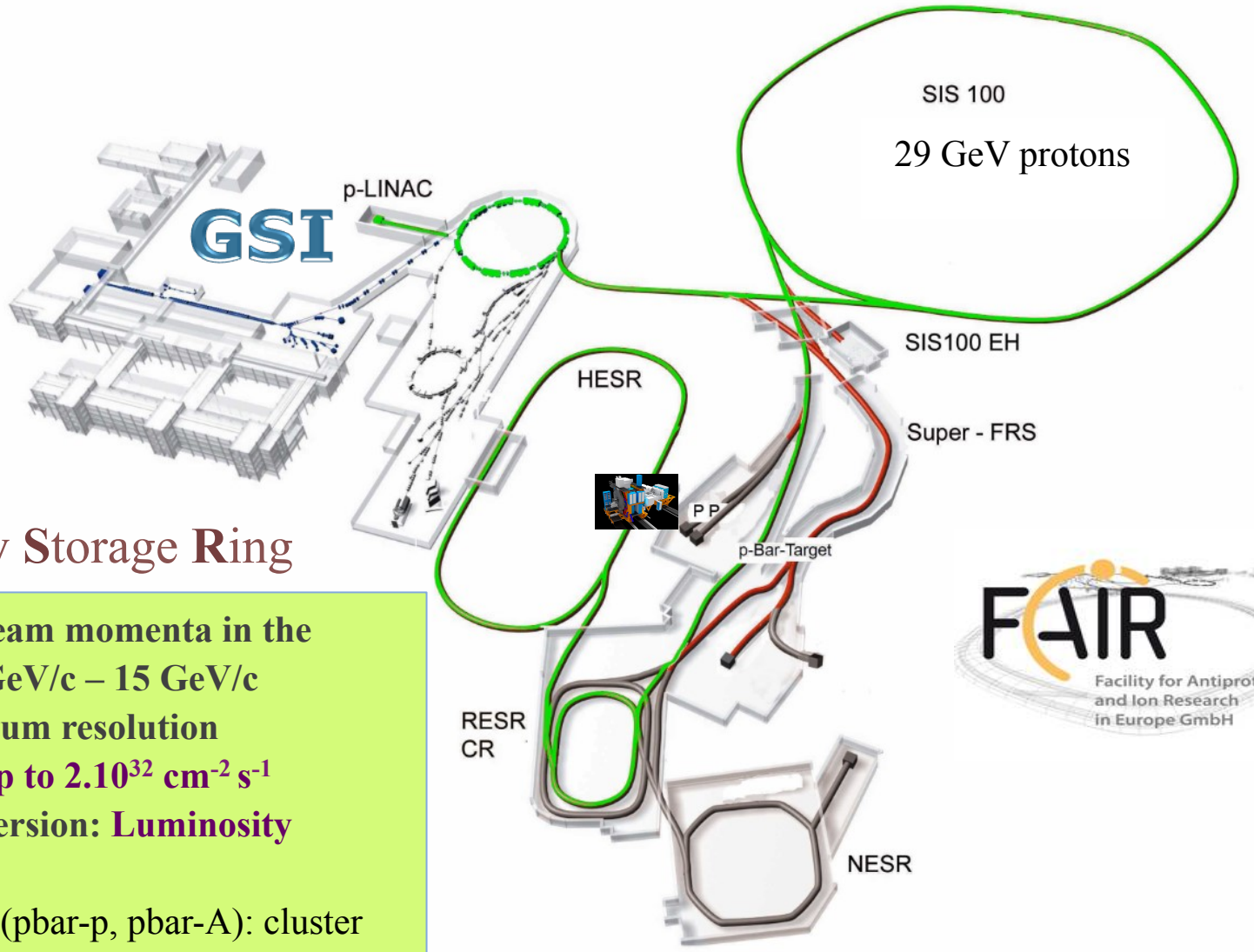
Electromagnetic Structure of Strange Baryons
GSI, 24 October 2018

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

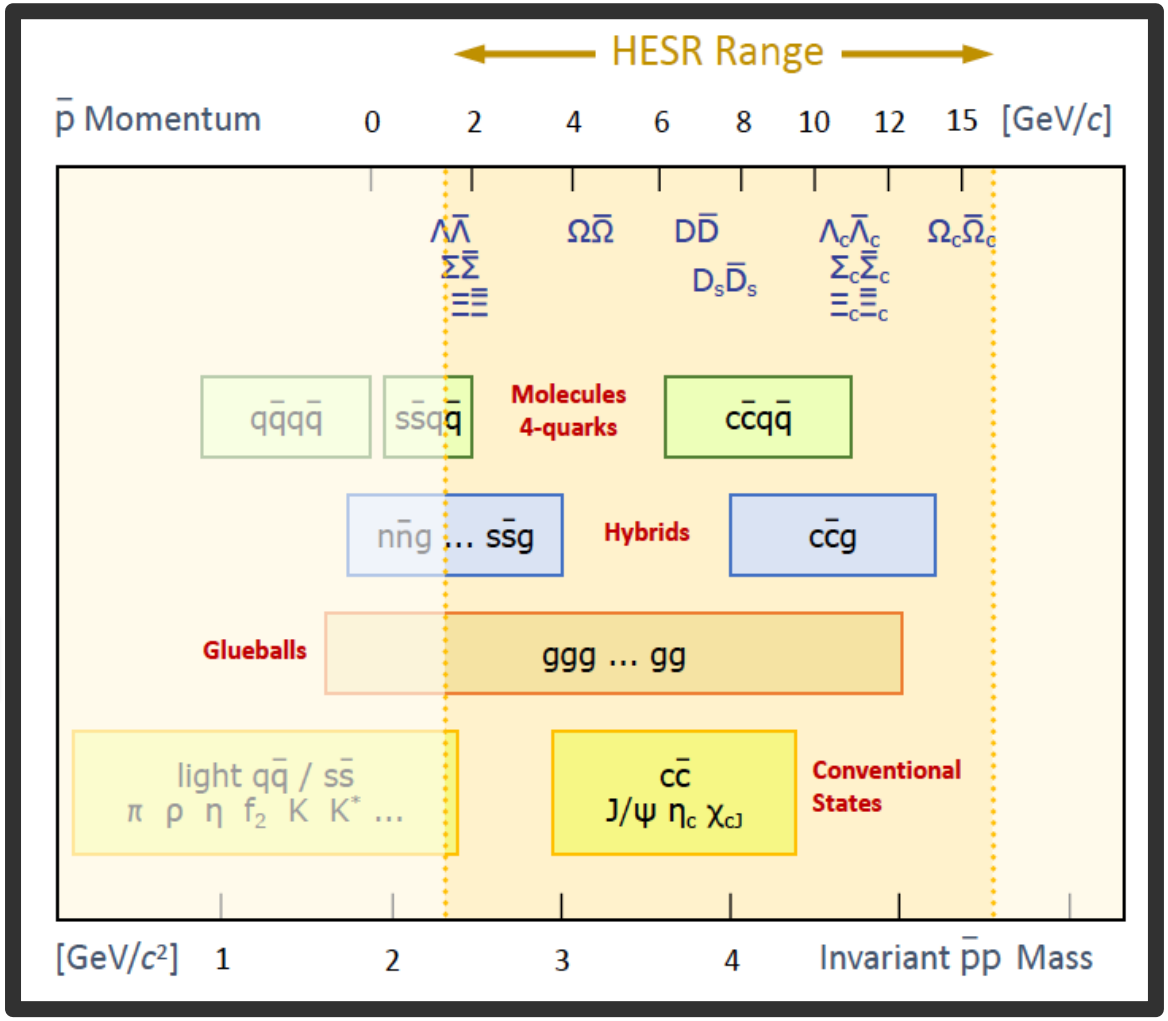
$$\sqrt{s} = [2.25 - 5.56]\ \text{GeV}$$

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

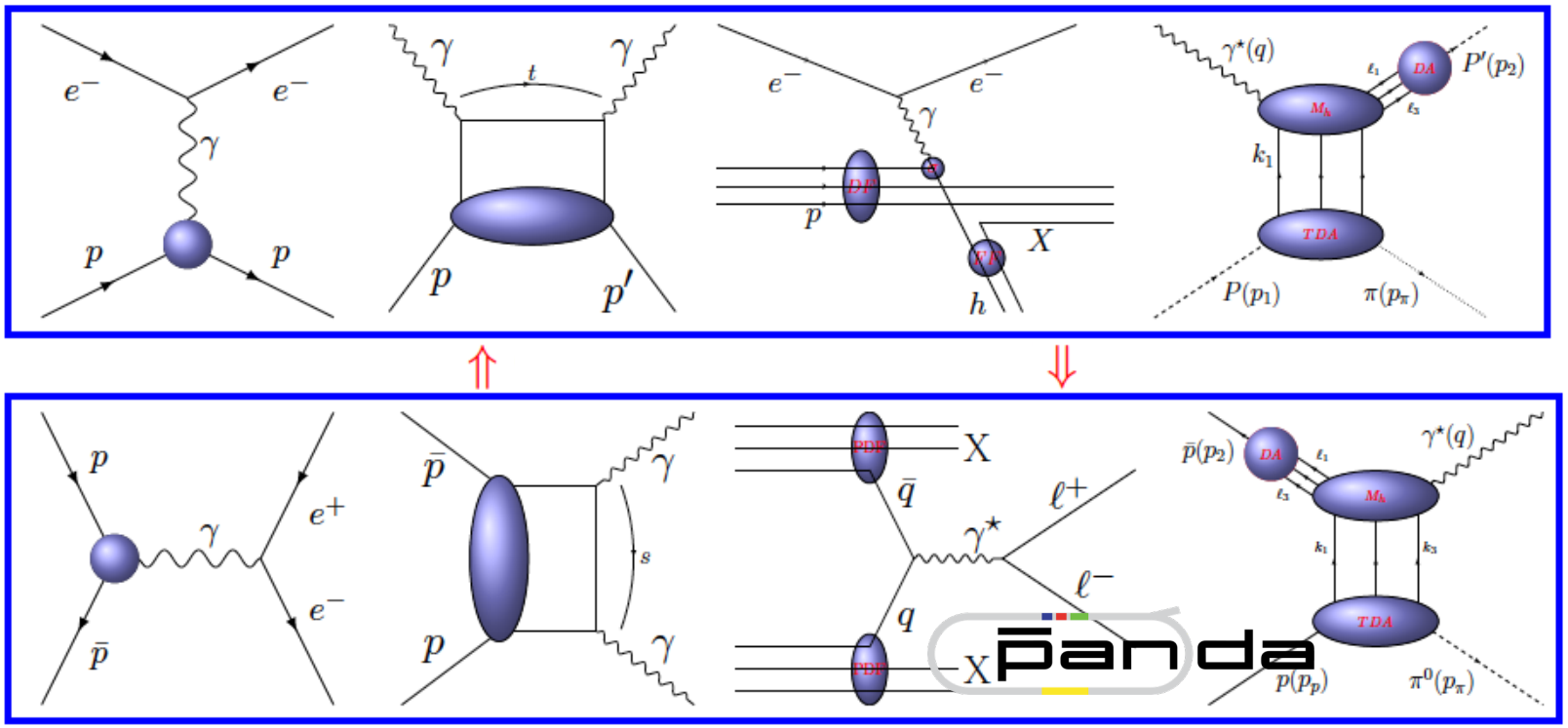
Hypernuclear physics

Hadrons in the nuclear medium

Nucleon structure

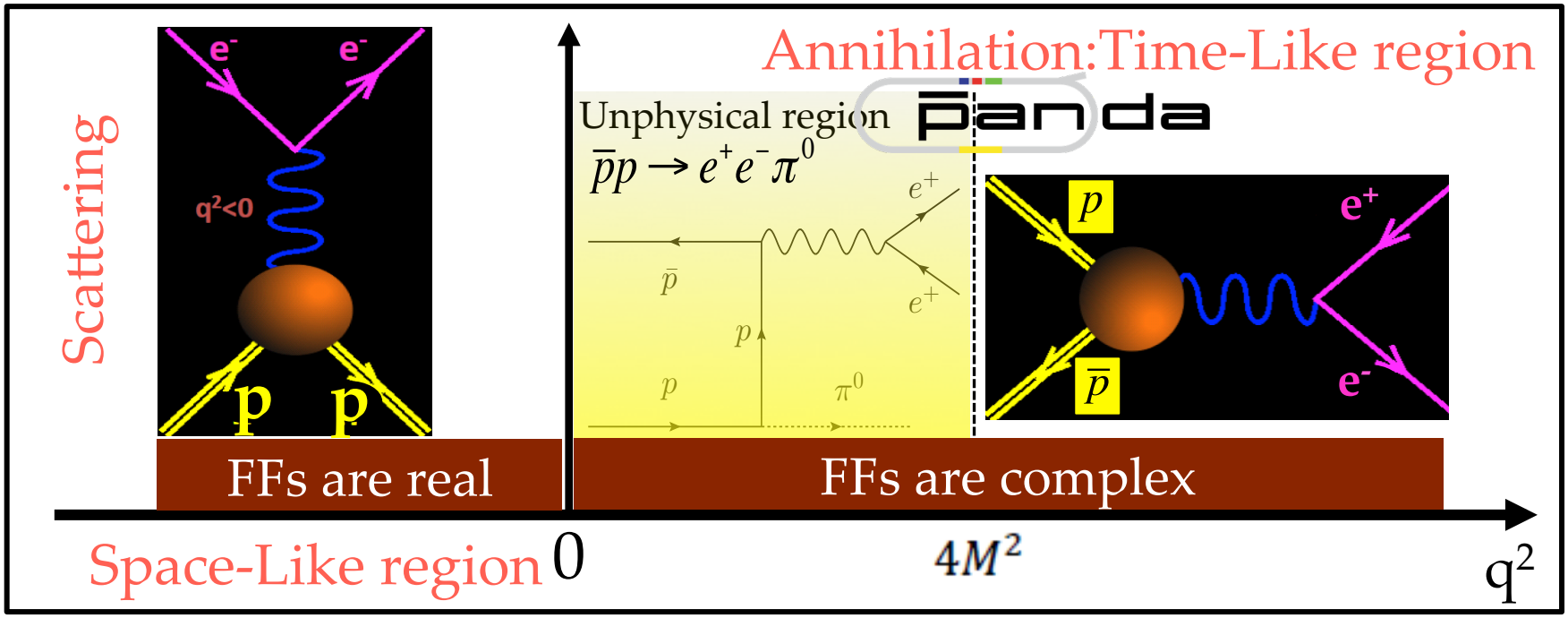


Study of the Nucleon Structure at PANDA



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

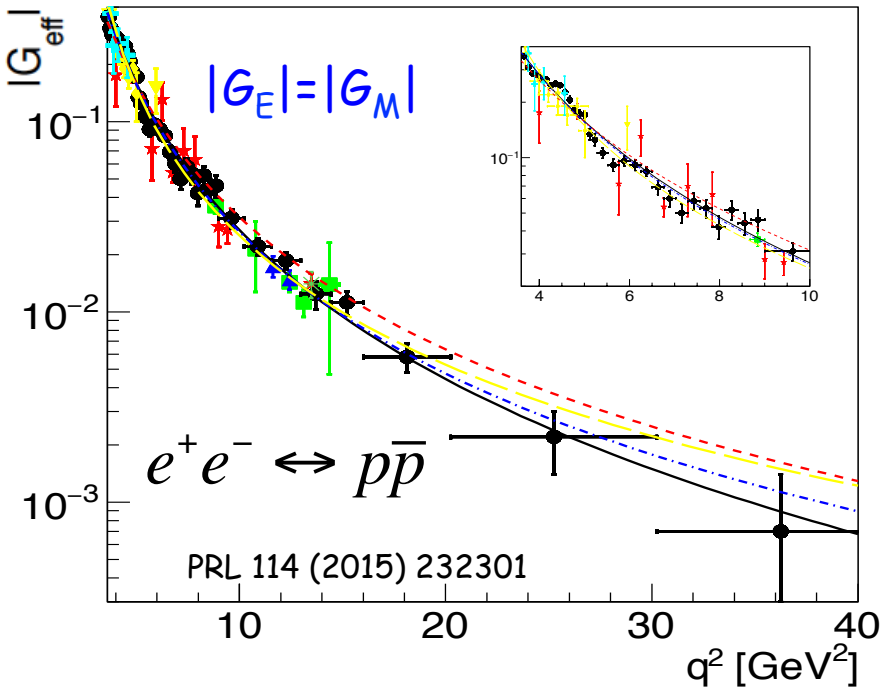
Electromagnetic Form Factors of the Proton



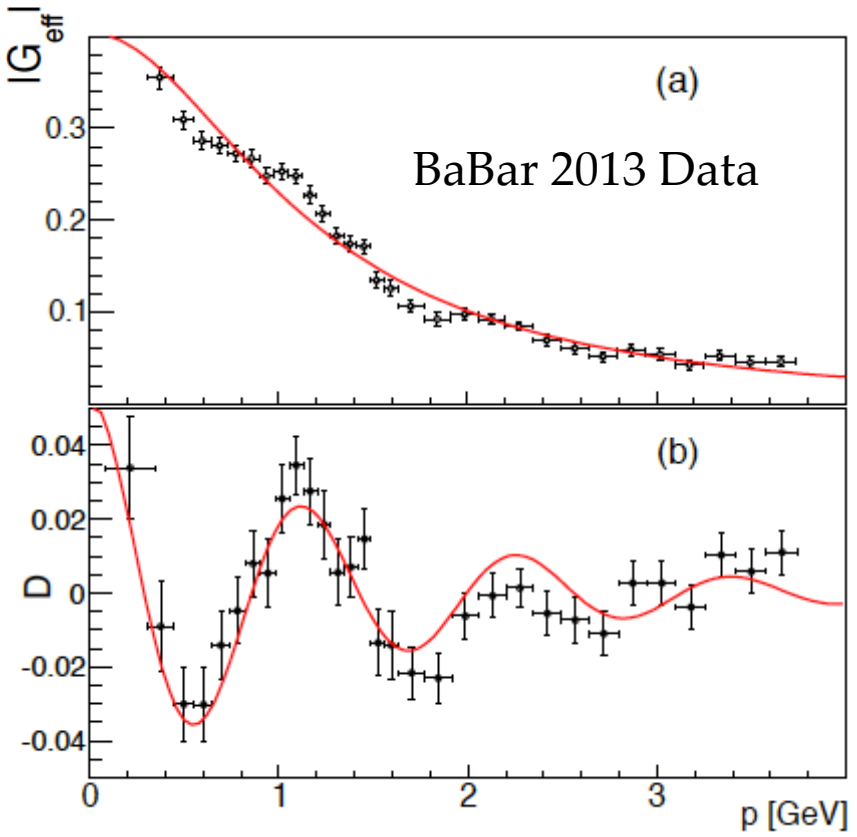
- **Electric G_E and magnetic G_M** proton FFs are analytical functions of the momentum transfer squared q^2

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

World data on the time-like (effective) proton form factor



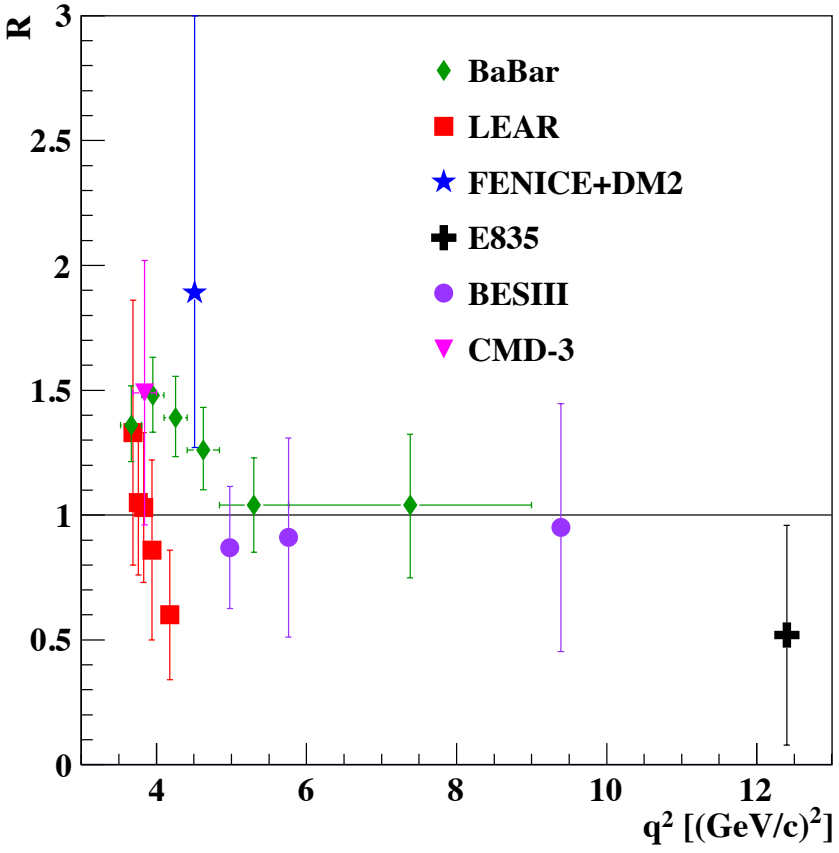
Phys. Rev. Lett. 114,232301 (2015)



Structures seen in BaBar data

- Interference effect from rescattering processes in the final states.
  Phys. Rev. Lett. 114,232301 (2015)
- Independent resonant structures
  Phys. Rev. D 92, 034018 (2015)

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

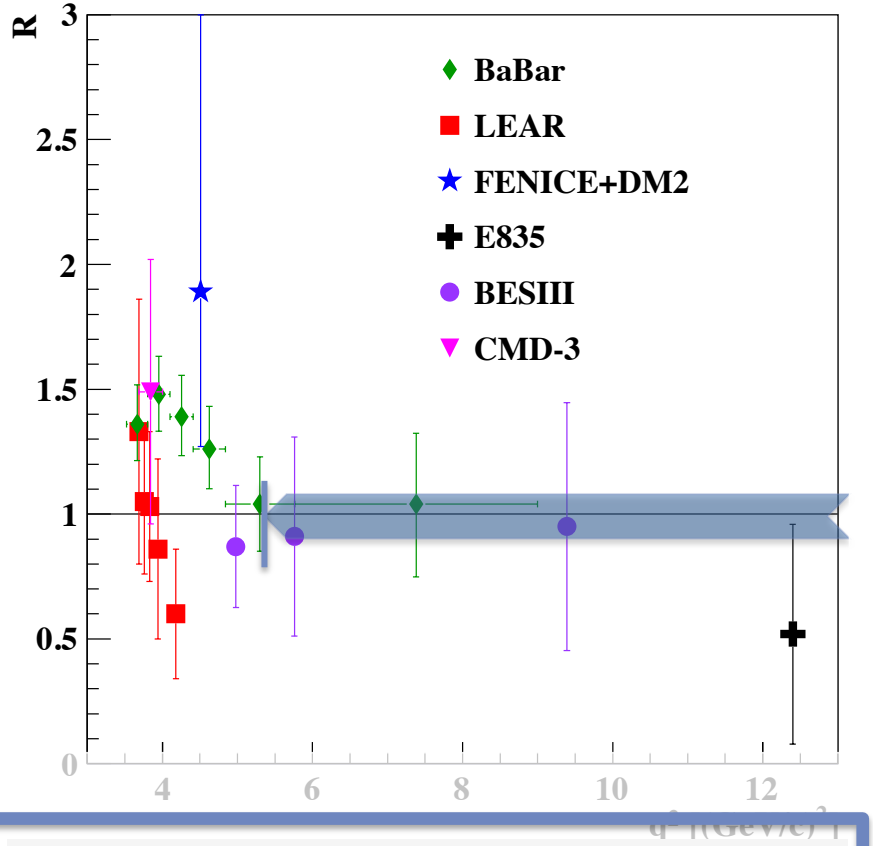
@ PS 170 (LEAR): $\bar{p}p \rightarrow e^+e^-$
- data collection at low energies

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

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

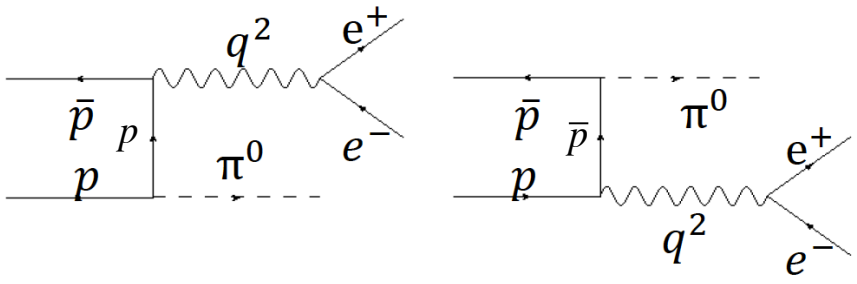
- **A. Z. Dubnickova, S. Dubnicka & M.P. Rekalo Nuovo Cim. A109 (1996) 241-256**

- 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)

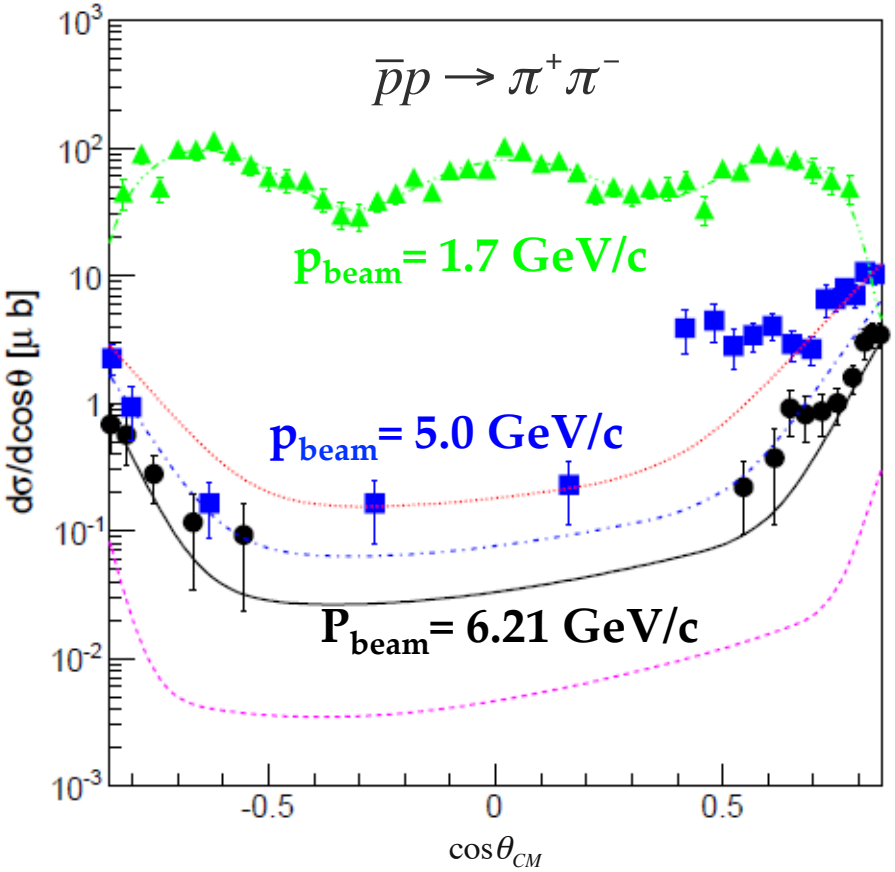
Good background rejection (~10^{-8}) necessary

Feasibility studies needed for both signal channels!

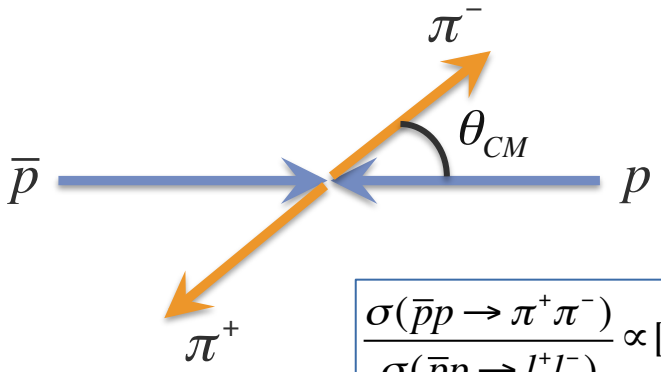
Feasibility studies: time-like proton form factors @ PANDA

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



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

- **10^8 events generated at each energy point**

- 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)

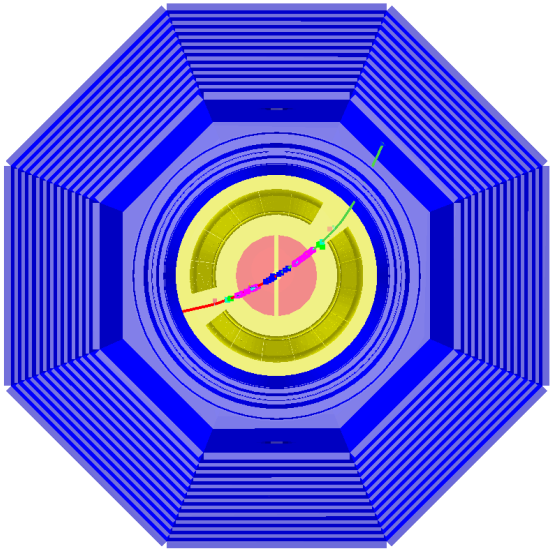
Feasibility studies: time-like proton form factors @ PANDA

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



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

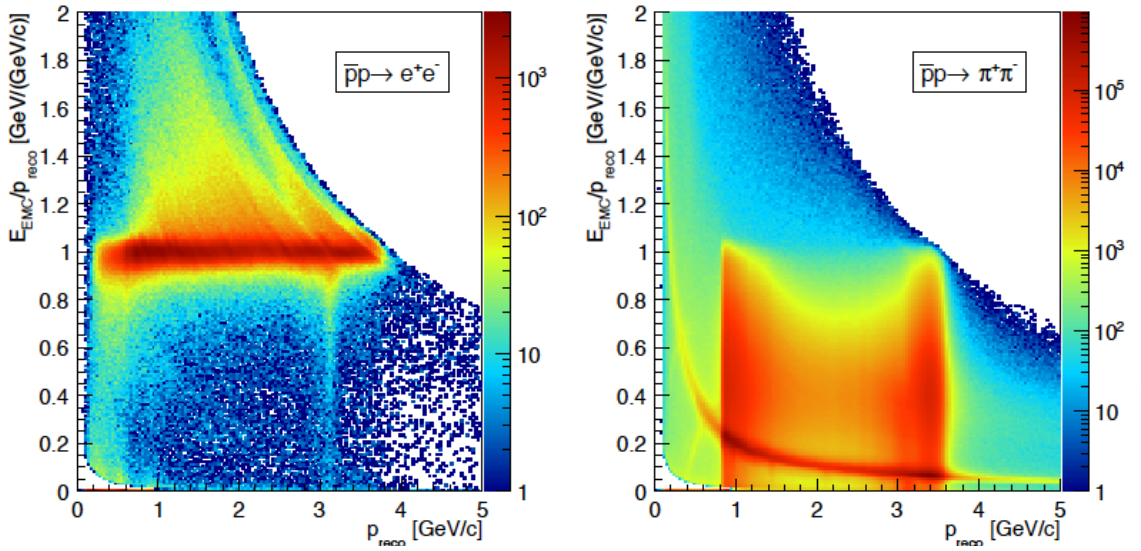
  Detector information MAINLY from Muon **R**ange **S**ystem

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

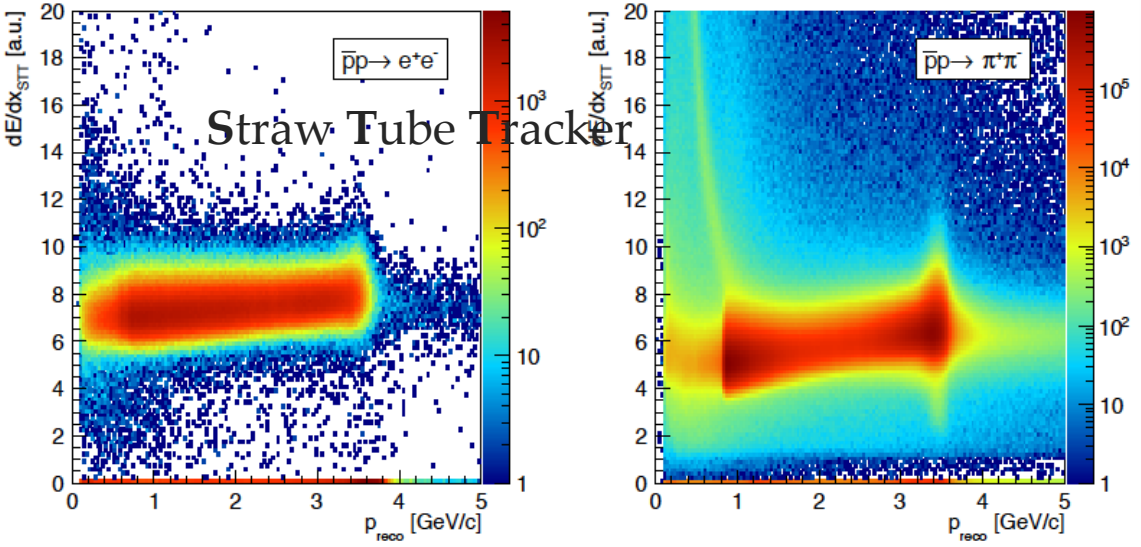
Signal efficiency & Background rejection

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

Electromagnetic Calorimeter



Straw Tube Tracker



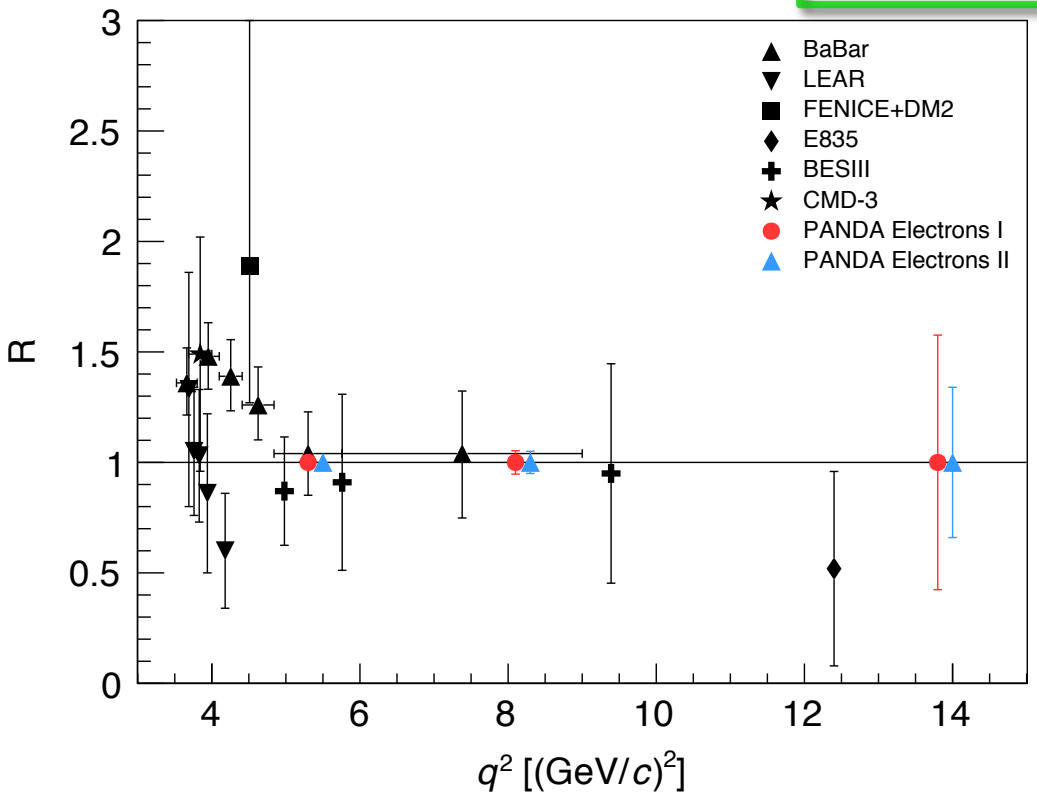
PID variables from the EMC, STT, DIRC, MVD → PID probability $PID_e > 0.99$

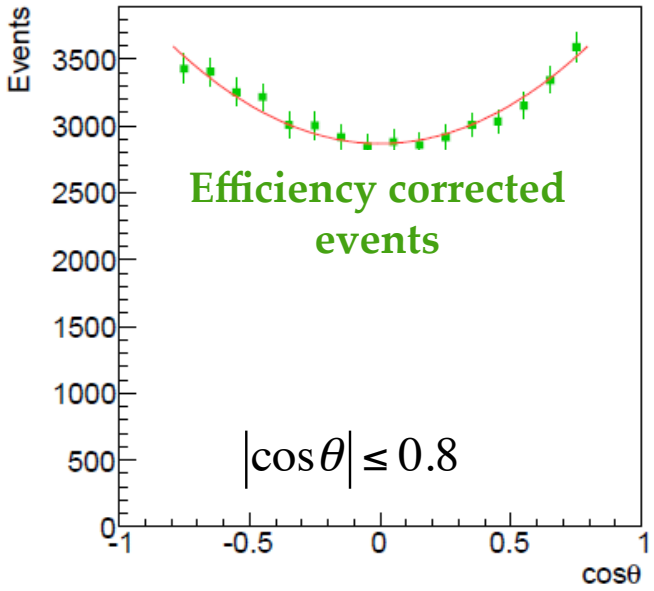
- **Signal efficiencies** between **39%** and **51%**
- **Background rejection ~ 10^{-8}**
  Signal pollution < 1%

Feasibility studies: time-like proton form factors @ PANDA

The results

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





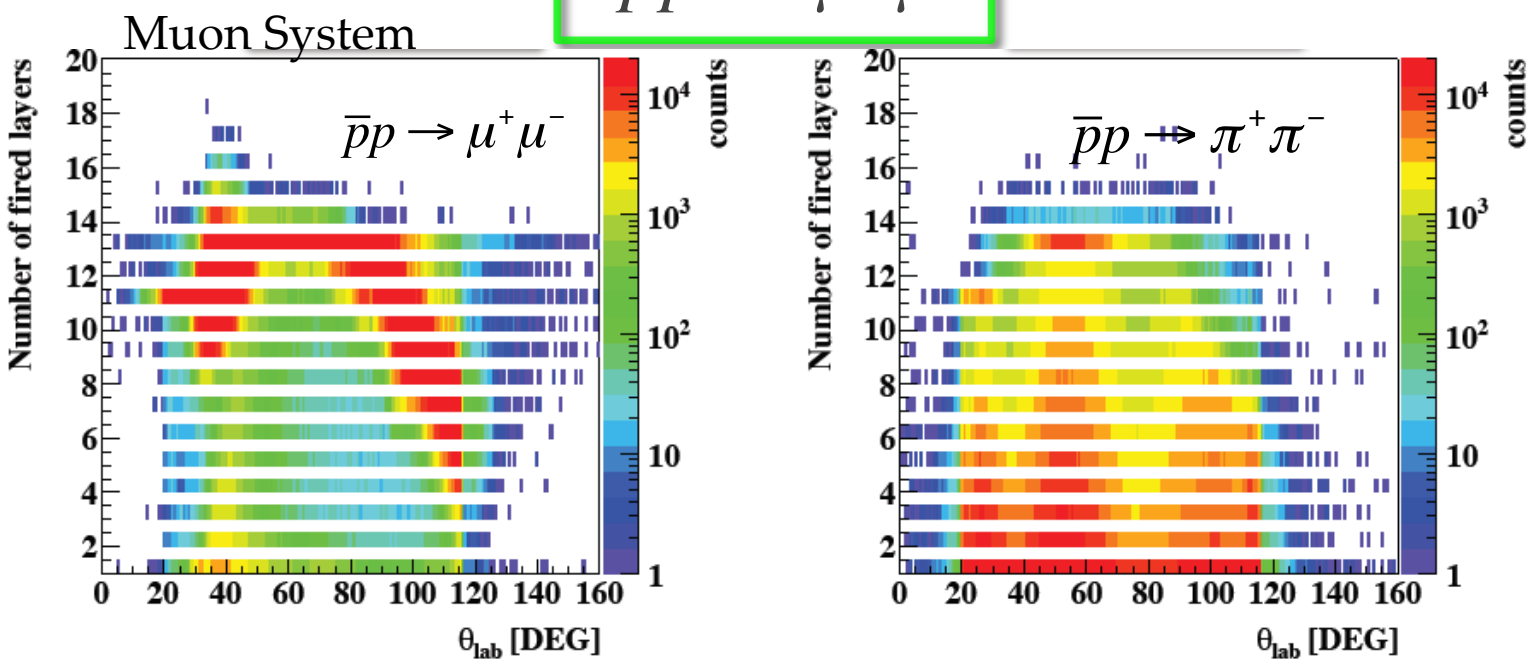
p_{beam} [GeV/c]	1.7	3.3	6.4
q2 [(GeV/c)^2]	5.4	8.2	13.9

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

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

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

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



- Only Muon System provides powerful variables
- Signal/Background separation using simple cuts, typically expected S:B ratio too small: 1:50 – 1:70

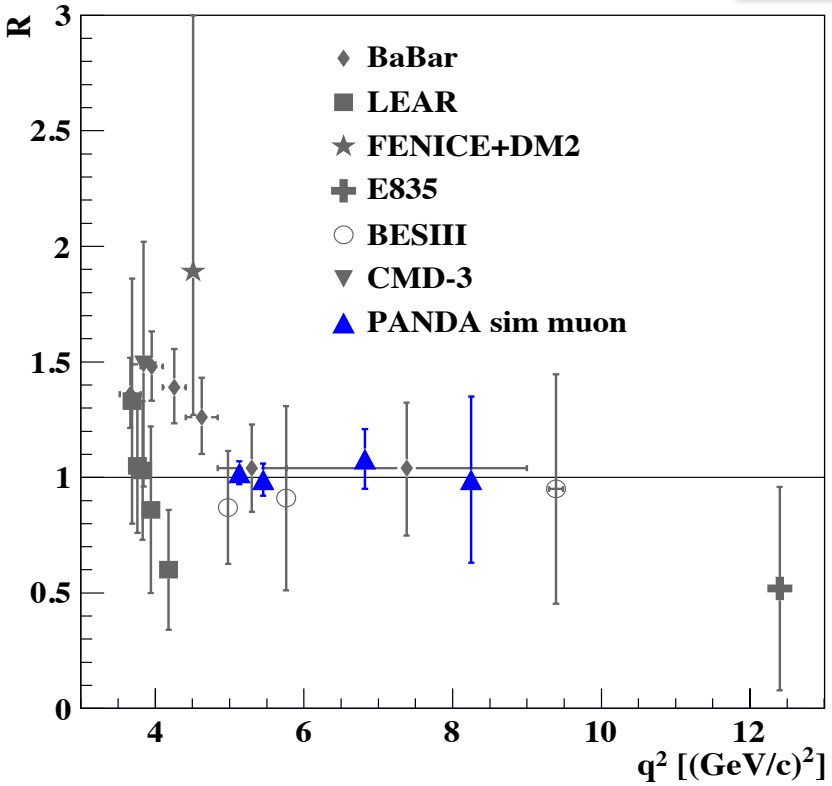
  Enhanced data classification needed

  ➢ **Analysis based on Boosted Decision Trees & Cuts**

Feasibility studies: time-like proton form factors @ PANDA

The results

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



p_{beam} [GeV/c]	Total signal efficiency ε	Background rejection [10^{-5}]	Expected S-B ratio
1.5	0.315	1.22	1:8
1.7	0.274	1.12	1:10
2.5	0.334	1.75	1:13
3.3	0.295	1.30	1:5

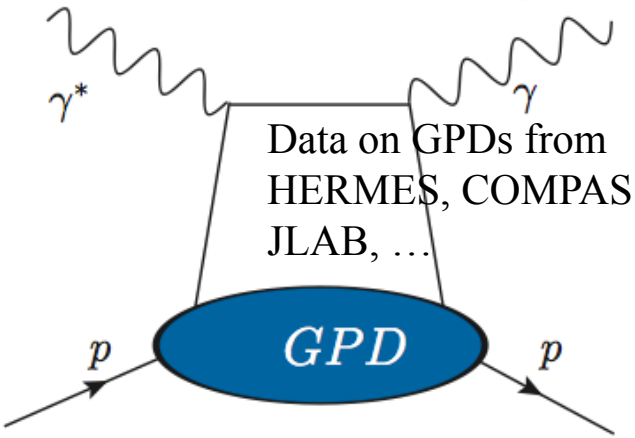
Precision on R=1, L= 2 fb^{-1}

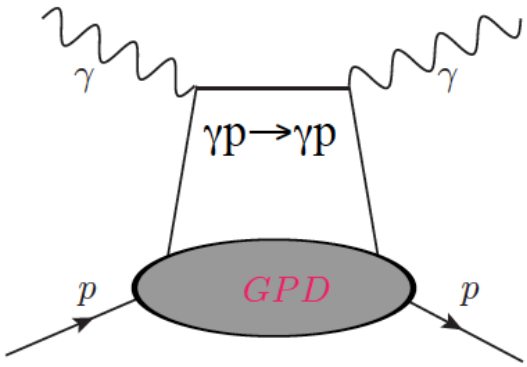
q^2 [(GeV/c)^2]	5.1 – 8.2
ΔR/R	5.0 % - 37%

$\Delta\sigma/\sigma$: 4.05% - 4.87%
$\Delta|G_{eff}|/|G_{eff}|$: 2.03% - 2.44%

Hard exclusive processes at PANDA

From GPDs to GDAs and TDAs

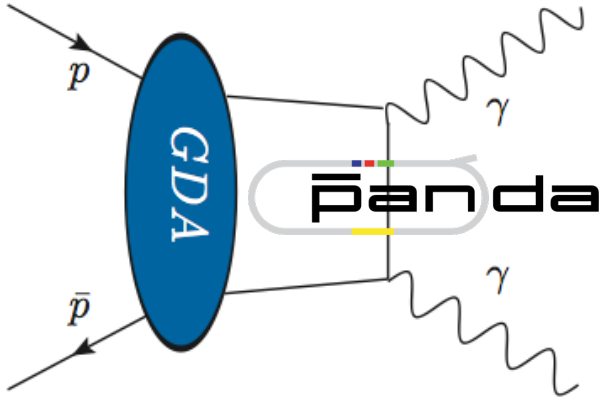




Wide Angle Compton Scattering
Generalized Parton Distributions GPDs

t <-> s channels
GPDs <-> GDAs

GDAs



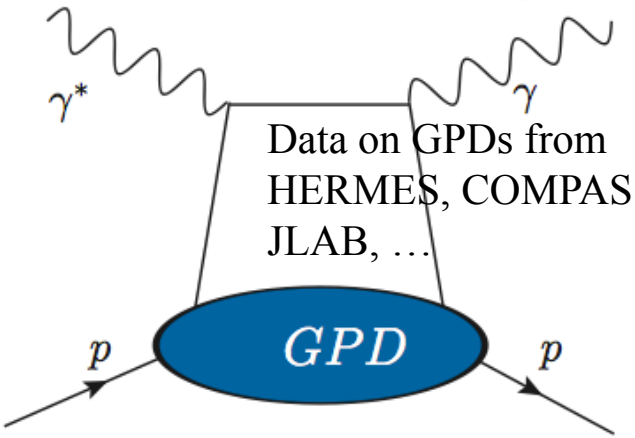
- Fermilab ppbar→γπ^0 data [8.5 – 13.6] GeV^2
- Belle, CLEO,… γγ→ppbar data below 16 GeV^2

➢ Precise data at higher energies and with different processes are needed

PANDA: ppbar→γγ, γM (M=π^0,η,ρ^0,ϕ)

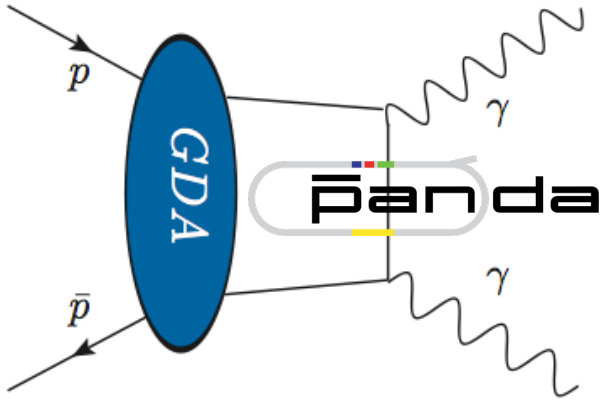
Time-Like Wide Angle Compton Scattering
Generalized Distribution Amplitudes GPDs

From GPDs to GDAs and TDAs



t <-> s channels
GPDs <-> GDAs

GDAs



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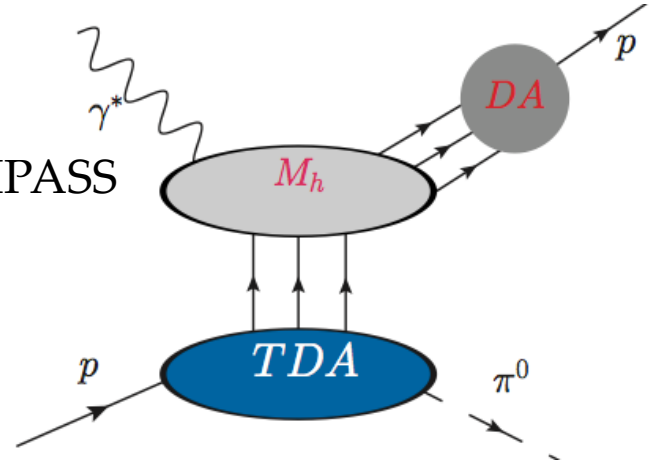
➢ Precise data at higher energies and with different processes are needed

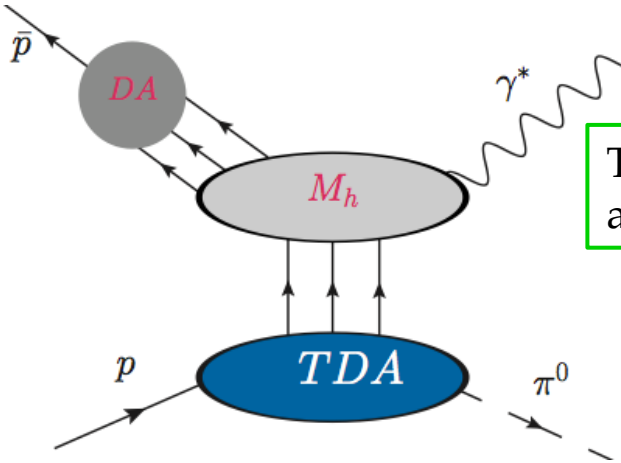
PANDA: ppbar→γγ, γM (M=π^0,η,ρ^0,ϕ)

TDAs

No data yet on TDAs !
Test of TDA universality with different process is needed

JLAB
COMPASS
EIC





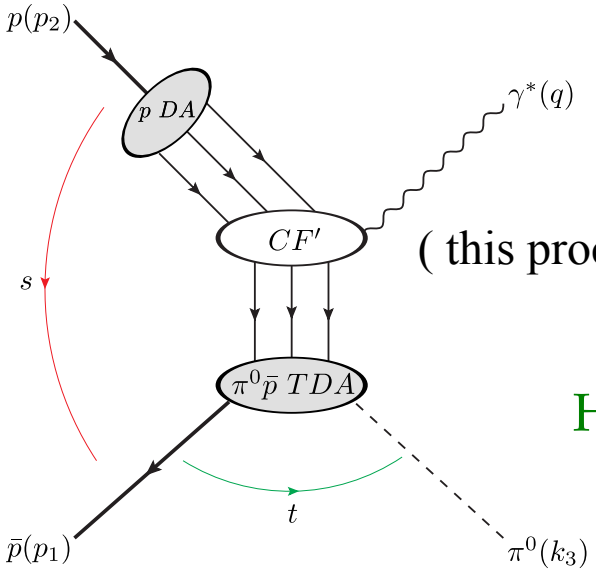
panda

TDAs for proton and antiproton !

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

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

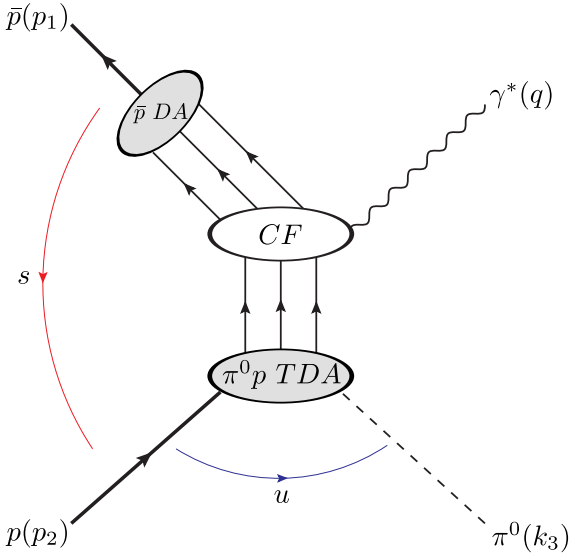
Nucleon to meson TDAs at PANDA



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

(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)

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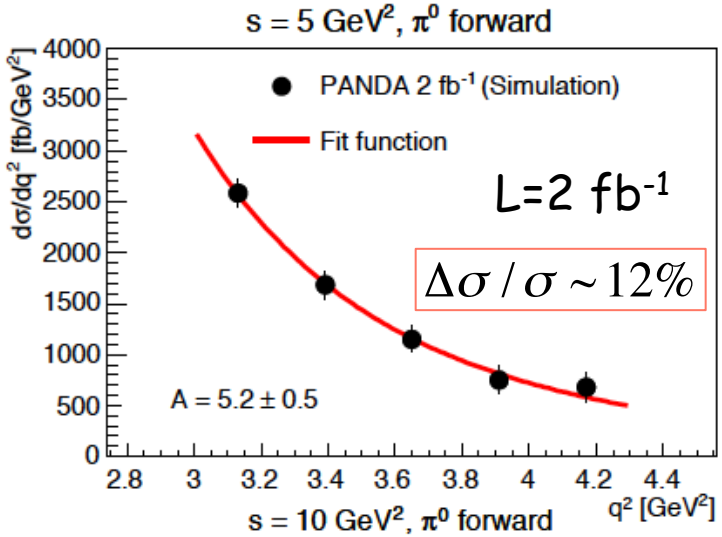
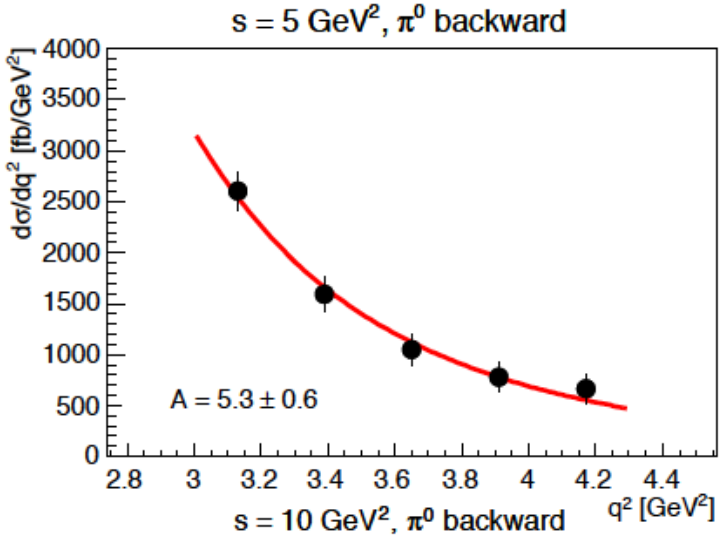
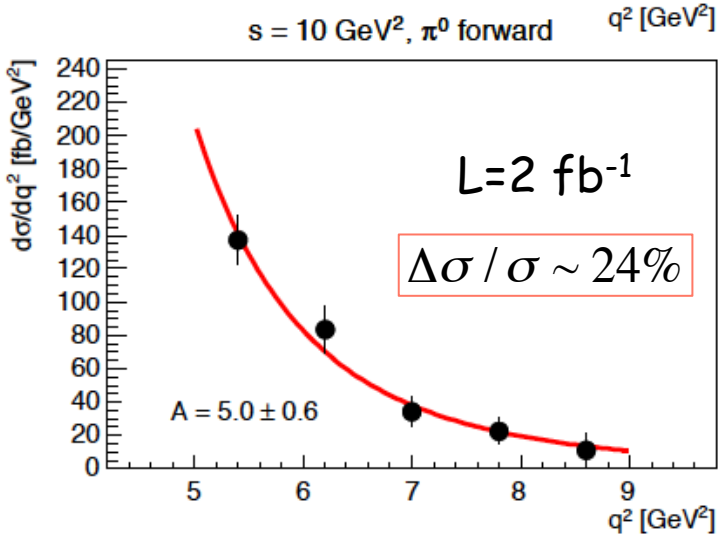
Nucleon to meson TDAs at PANDA

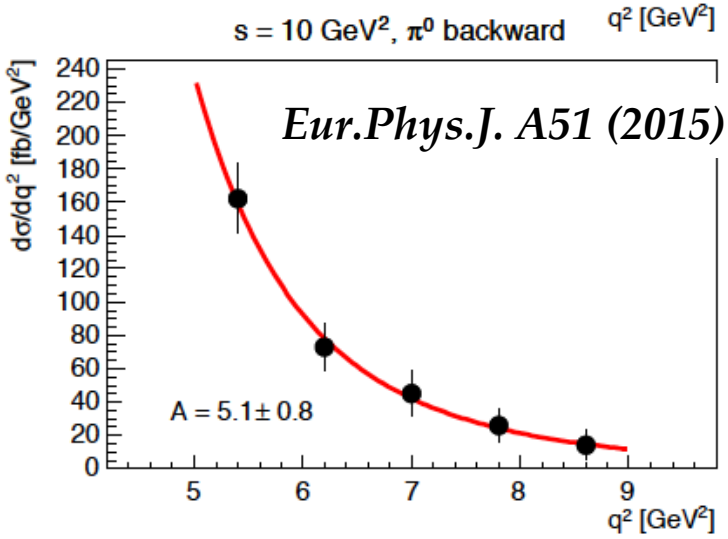
$$\frac{d\sigma}{dq^2} \sim \frac{1}{(q^2)^5}$$

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





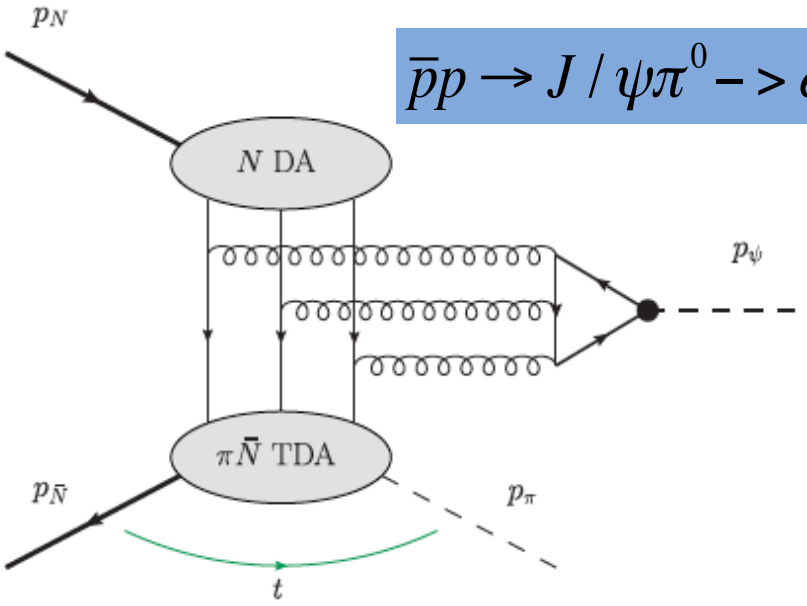


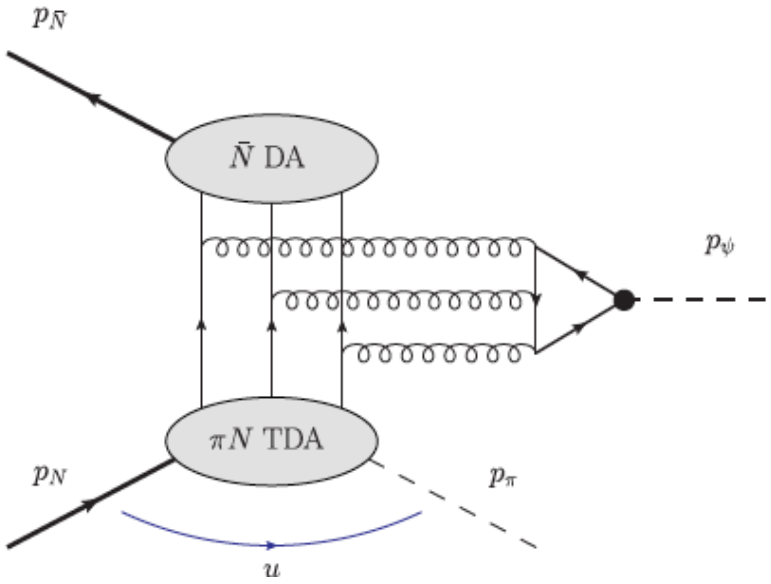


Eur.Phys.J. A51 (2015) 8, 107

Nucleon to meson TDAs at PANDA

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





t is small (forward kinematics)

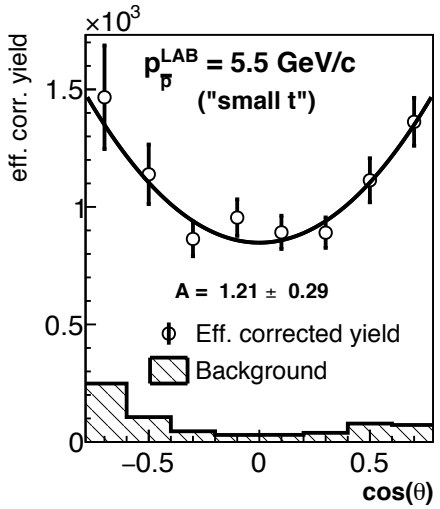
u is small (backward kinematics)

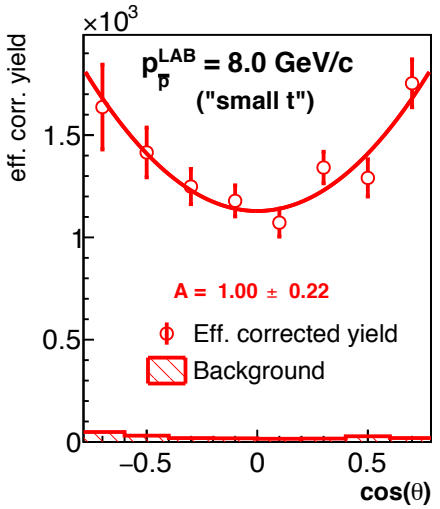
B. Pire et al., Phys. Lett. B. 724 99-107 (2013)

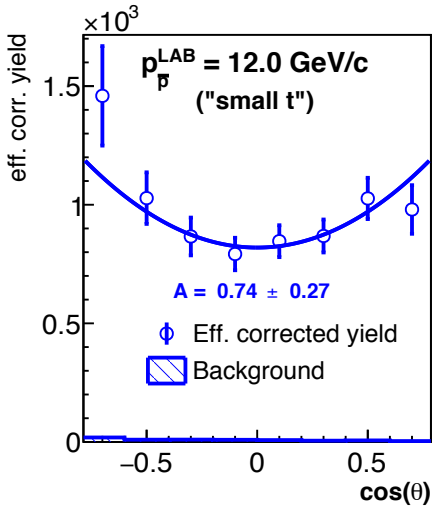
- High signal cross section
- Large q^2 fixed to $Q^2 = M^2_{J/\psi} = 9.6GeV^2$ (factorization theorem is likely reached)
- Reduces uncertainty on DAs by using the data on the $J/\psi -> pp$ partial decay modes
- Complementary measurements: test of universality of TDAs by comparing to $\bar{p}p \rightarrow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

Nucleon to meson TDAs at PANDA

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





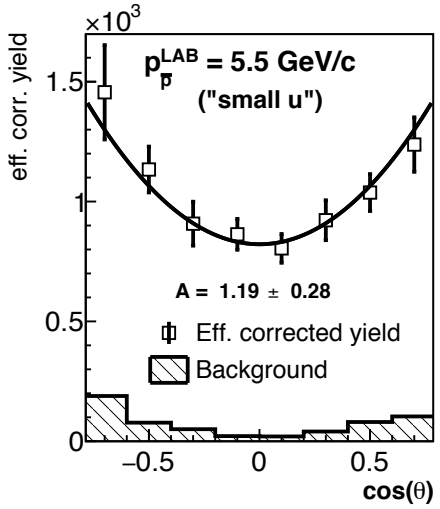


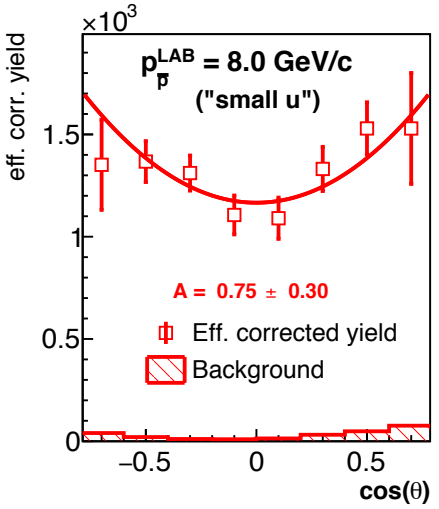
Fit funtion:

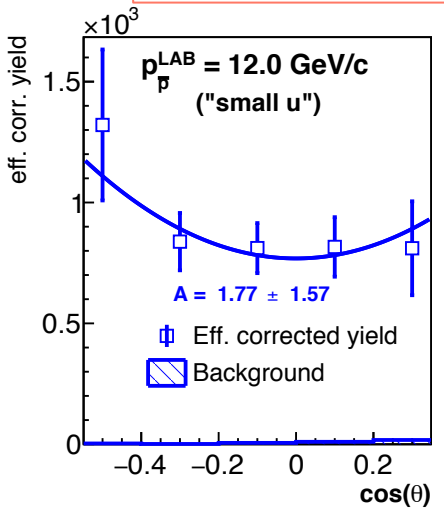
$$B \times (1 + A\cos^2\theta^{e^+}_{J/\psi})$$

L=2 fb^{-1}

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



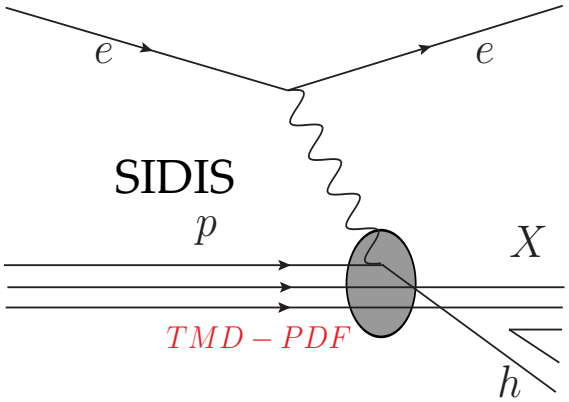


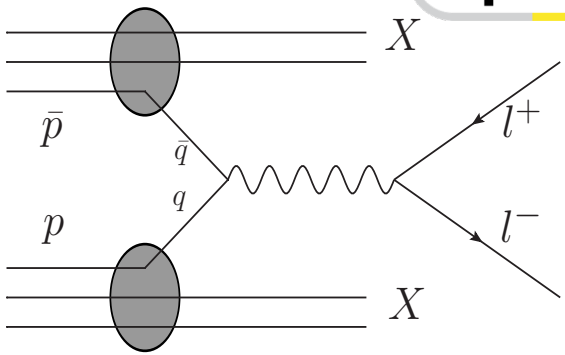


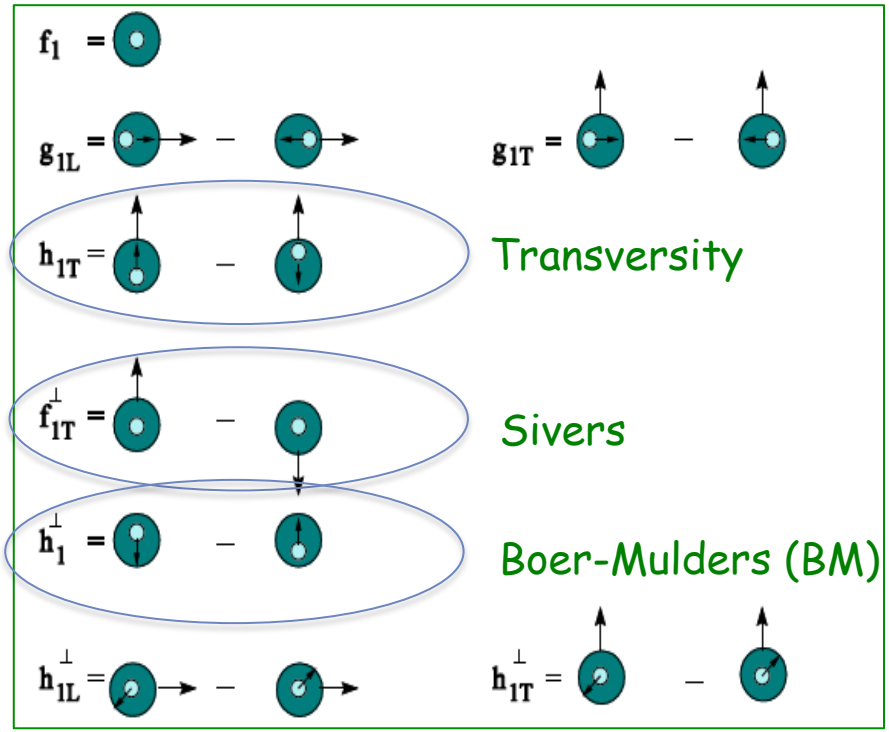
Phys. Rev. D 95, 032003 (2017)

Drell-Yan at PANDA

Drell-Yan at PANDA: TMD-PDFs

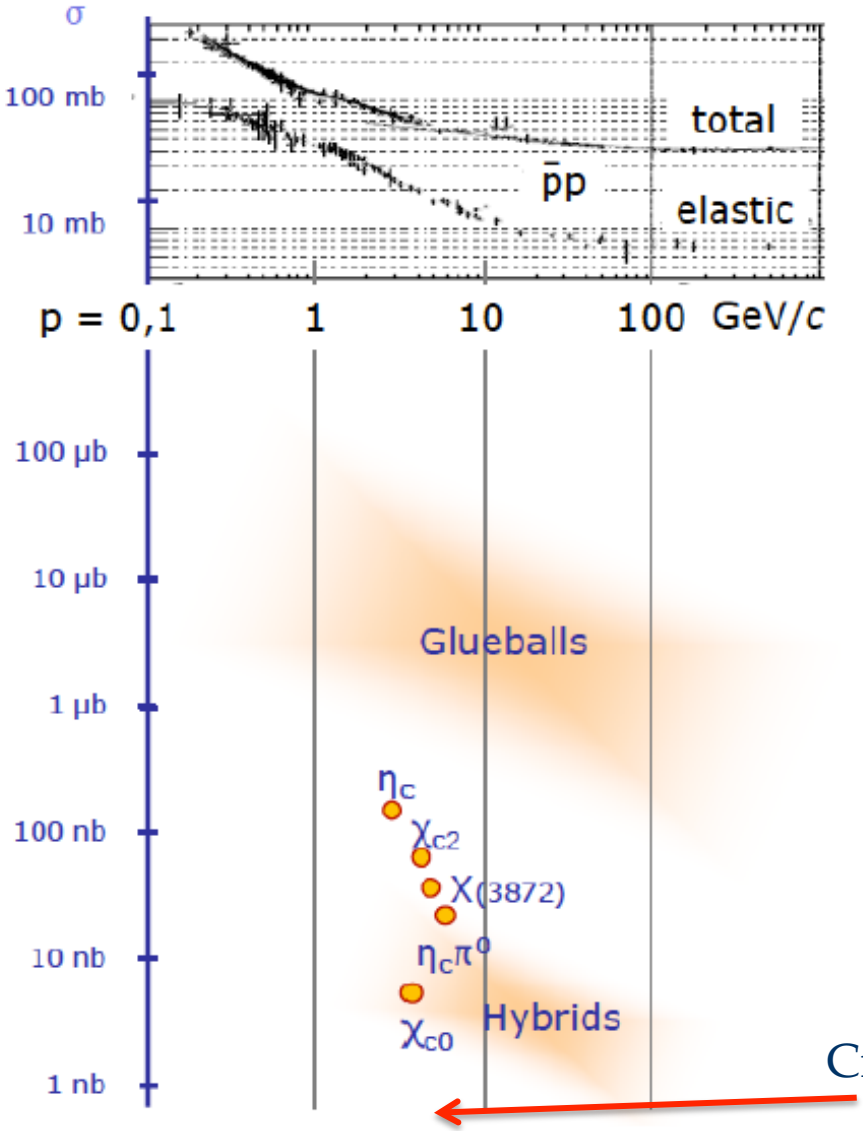






- Data on TMDs are from: HERMES, COMPASS, JLab, RHIC, …: limited kinematical regions and/or precision
- TMD measurements requires High luminosity, polarized beams and targets, and large acceptance detectors
- PANDA: Boer-Mulders with unpolarized proton-antiproton experiment; Sivers and Transversity with a polarized target

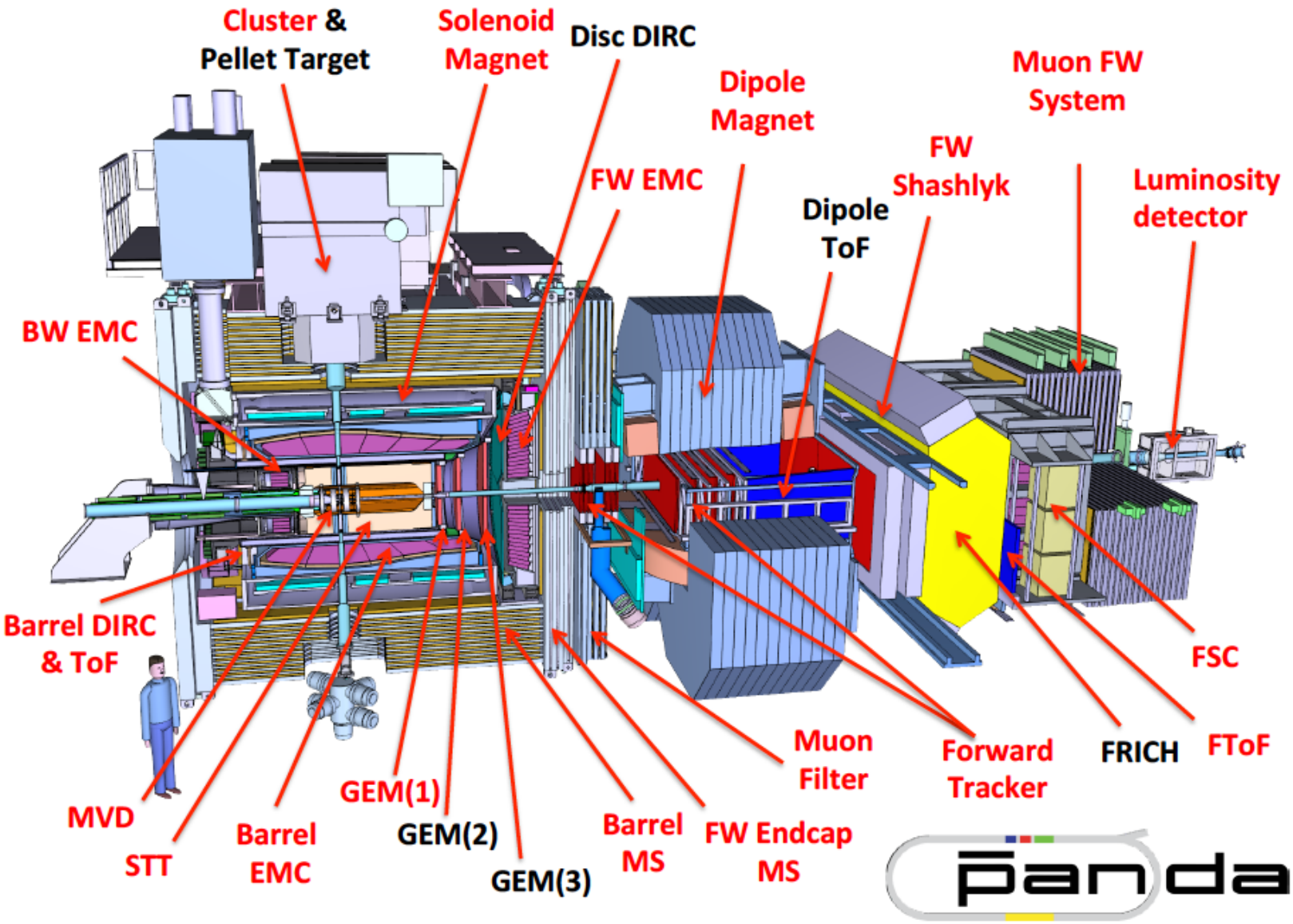
Detector requirements from physics case



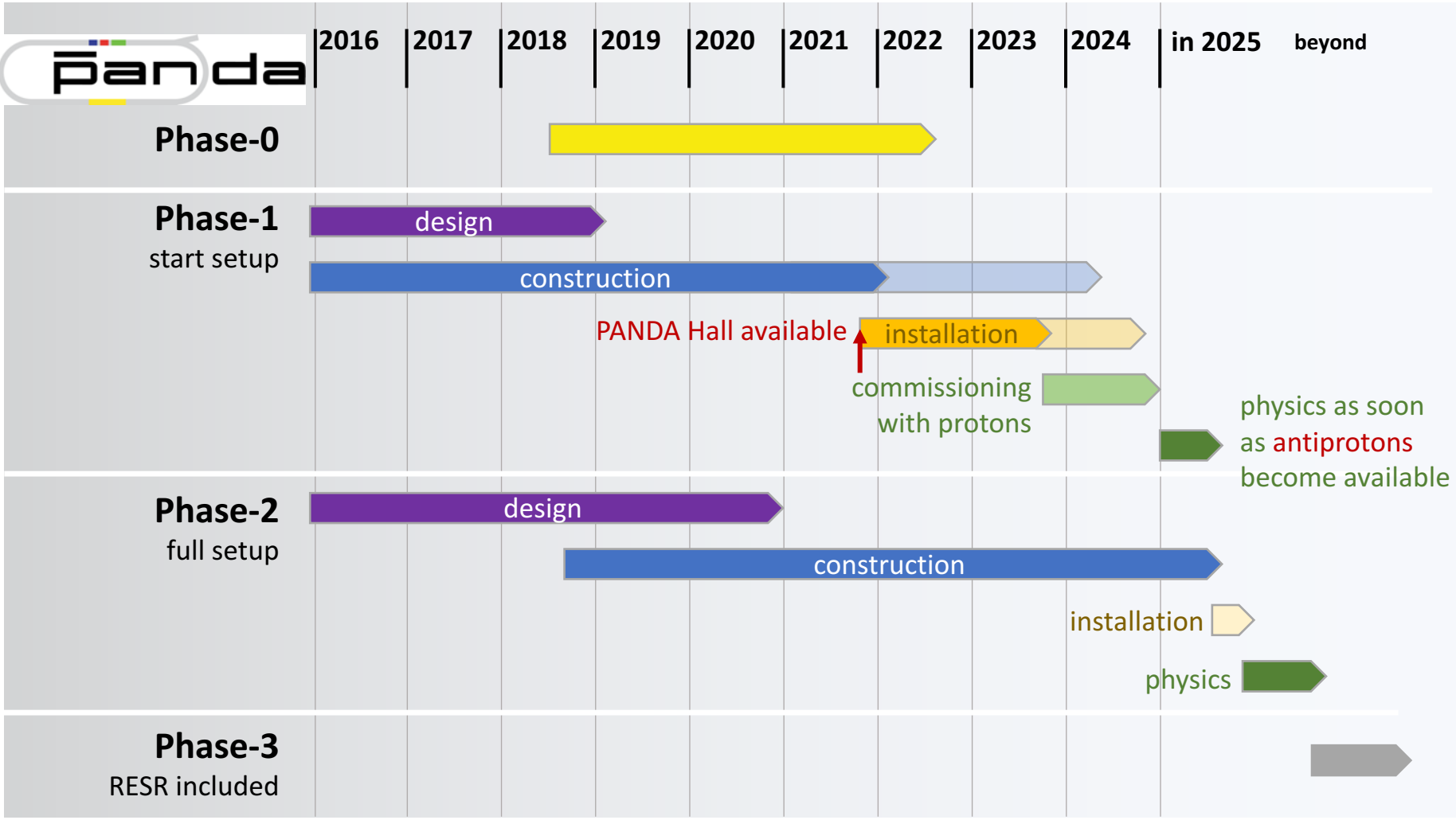
- ~ 4π acceptance
- Momentum resolution: 1%
  central tracker in magnetic field
- Photon detection: 1 MeV - 10 GeV
  high dynamic range
  good energy resolution
- Particle identification: γ, e, μ, π, K, p
  Cherenkov detector
  time of flight, dE/dx, muon counter
- Displaced vertex info
  $c\tau = 317\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

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

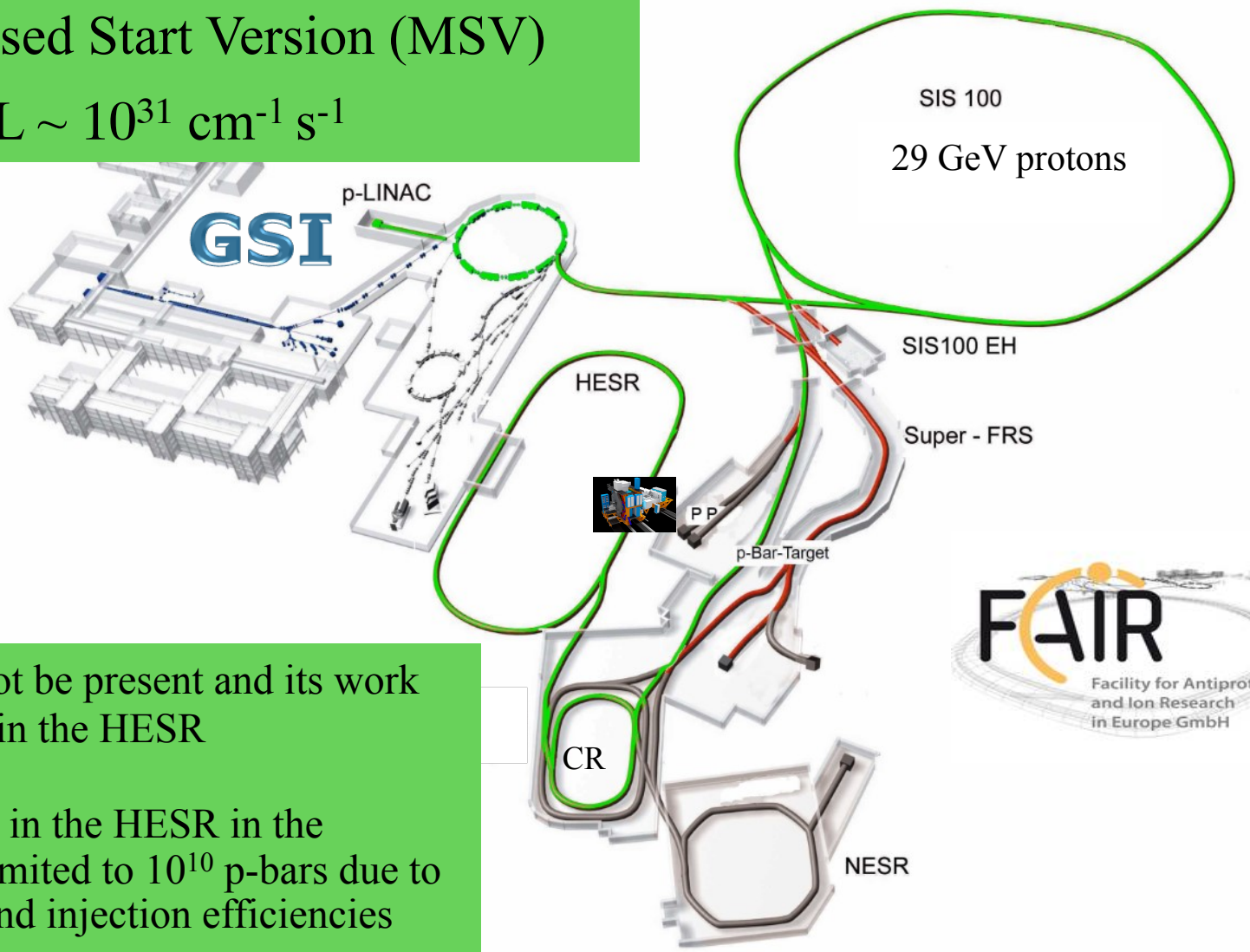
- PANDA experiment will provide a **complementary** study of the nucleon structure with the hard inclusive and exclusive processes: Generalized Distribution Amplitudes (GDAs), (TMD) Parton Distribution Functions, and Transition Distribution Amplitudes (TDAs)

- **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)

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

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

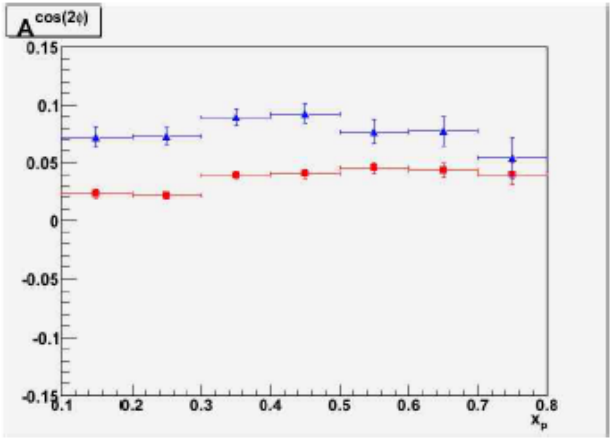
- Main background: $\bar{p}p \rightarrow n(\pi^+\pi^-)X$, required rejection factor ~10^7

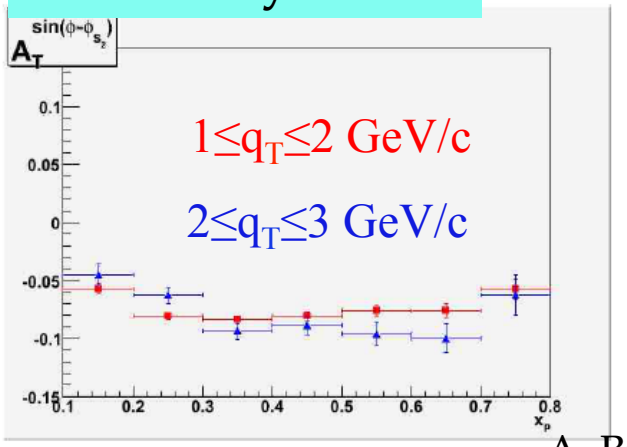
- Simulations @ s=30 GeV^2 and $1.5 \leq M_{\gamma^*} \leq 2.5$ (large cross section)

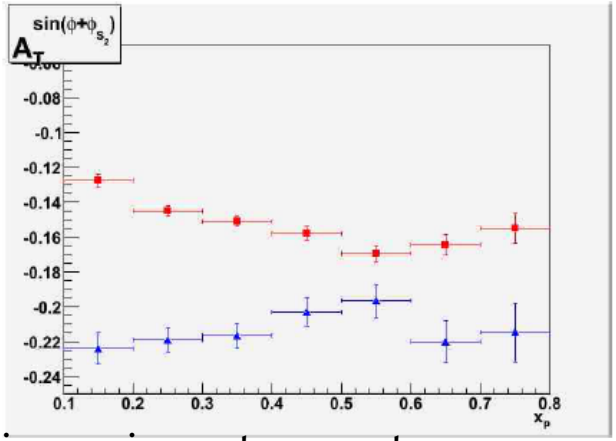
  Number of simulated events N~5 . 10^5

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

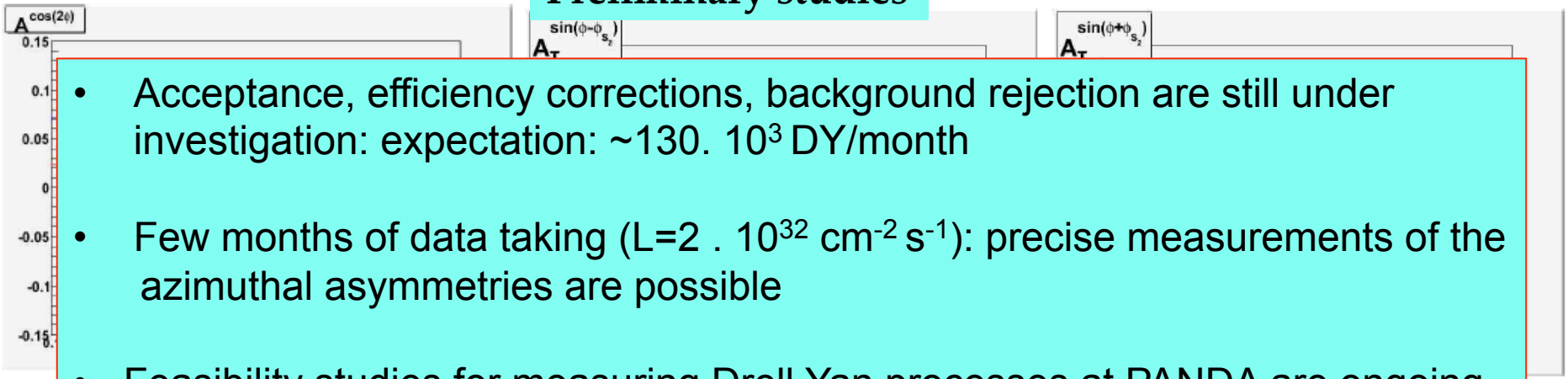
- Main background: $\bar{p}p \rightarrow n(\pi^+\pi^-)X$, required rejection factor ~10^7

- 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

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

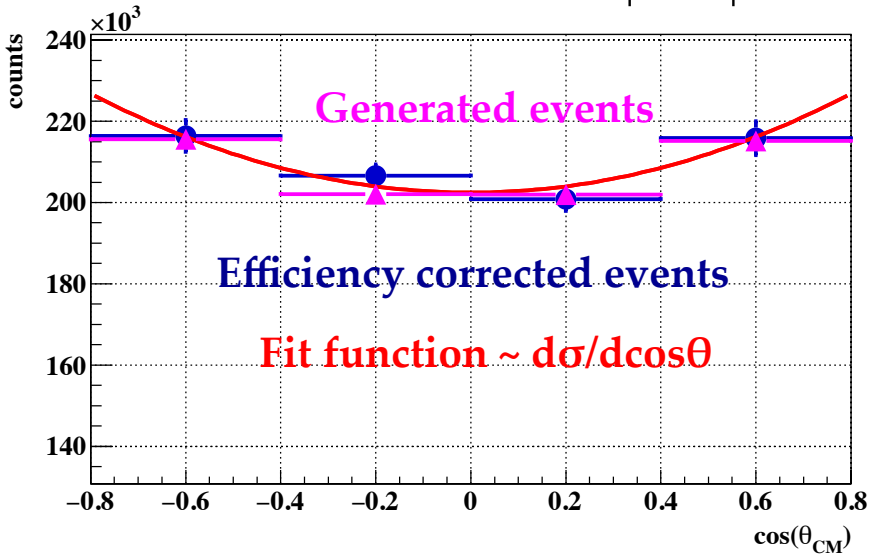
$|\cos\theta| \leq 0.8$

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**

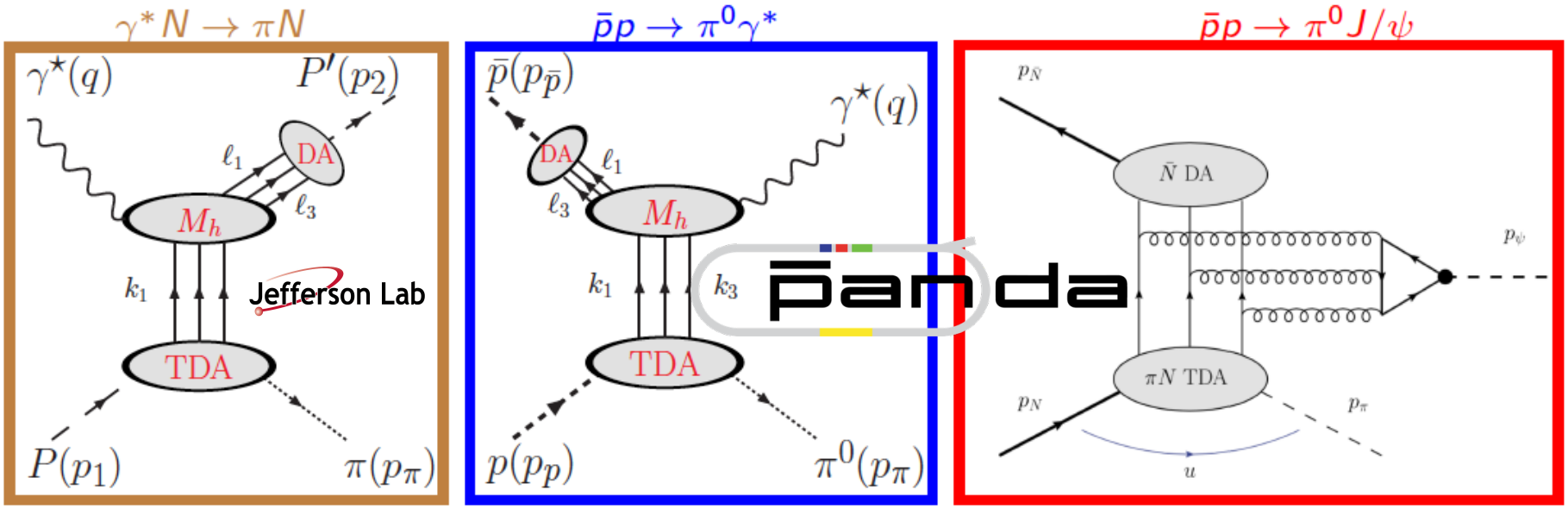
- **Background rejection factor ~ 10^{-6}**

- 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}**

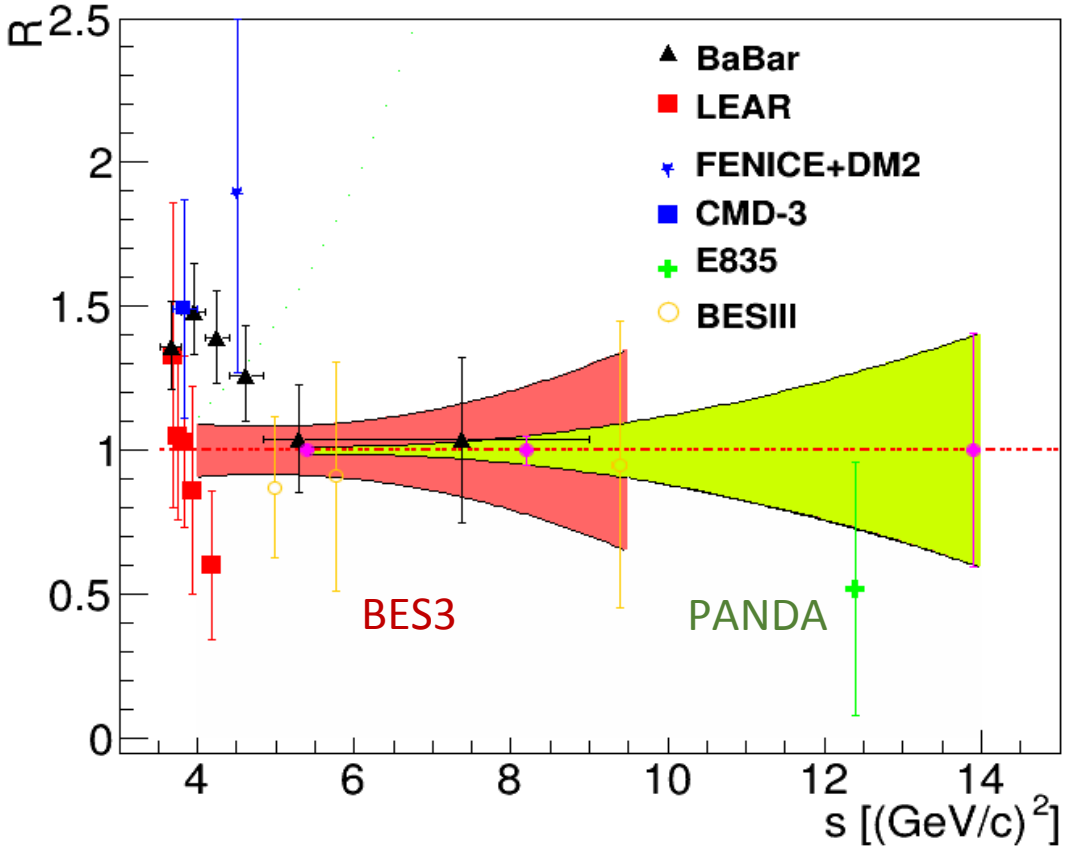
Nucleon to meson TDAs



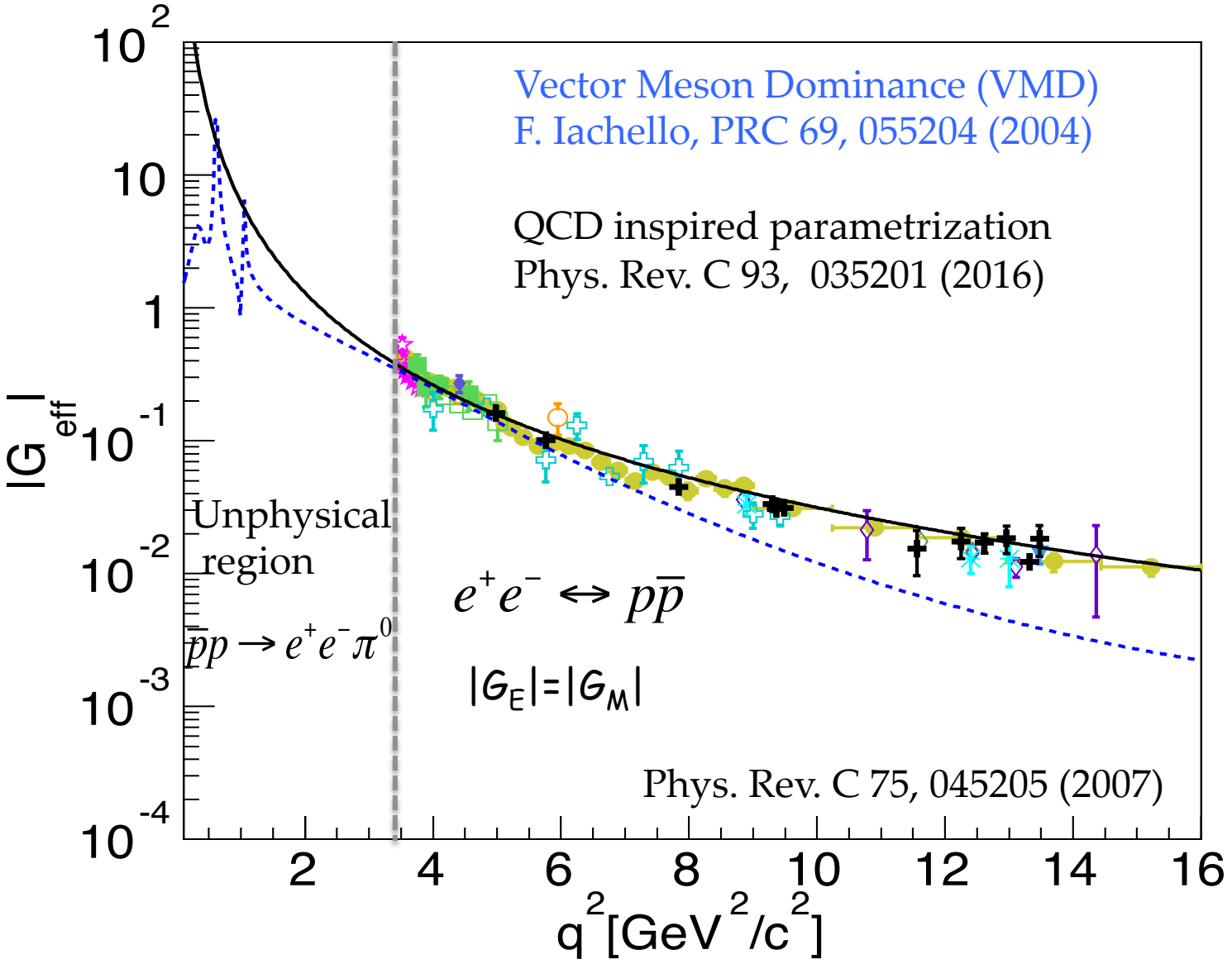
- New class of non-perturbative structure functions
- Occur in collinear factorization description of various hard exclusive processes
- Are independent of reaction type, s and q^2
- Give information on pionic components of the nucleon wave-function

Time-like electromagnetic proton form factors @ PANDA

Eur.Phys.J. A52 (2016) no.10, 325



Electromagnetic form factors of the proton (Time-Like region)

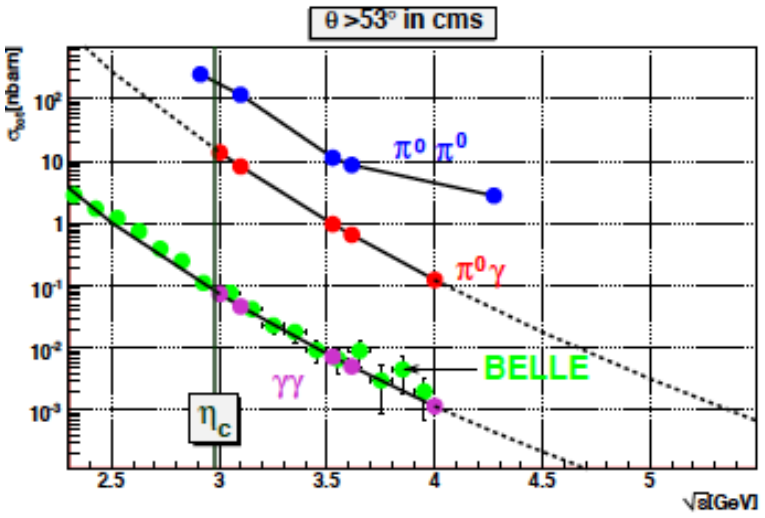


A) Feasibility studies: time-like proton form factors @ PANDA for

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

- 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

Feasibility studies for GDAs measurement at PANDA



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

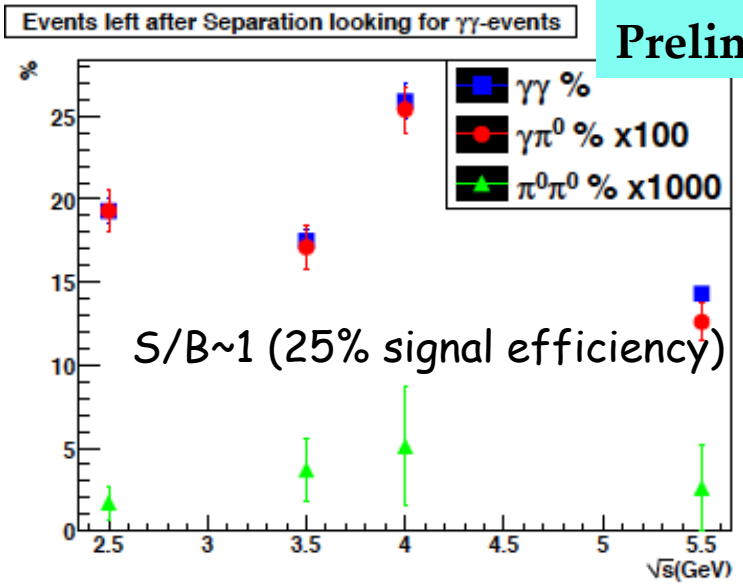
- 4 different CM energies
- Main background channels:

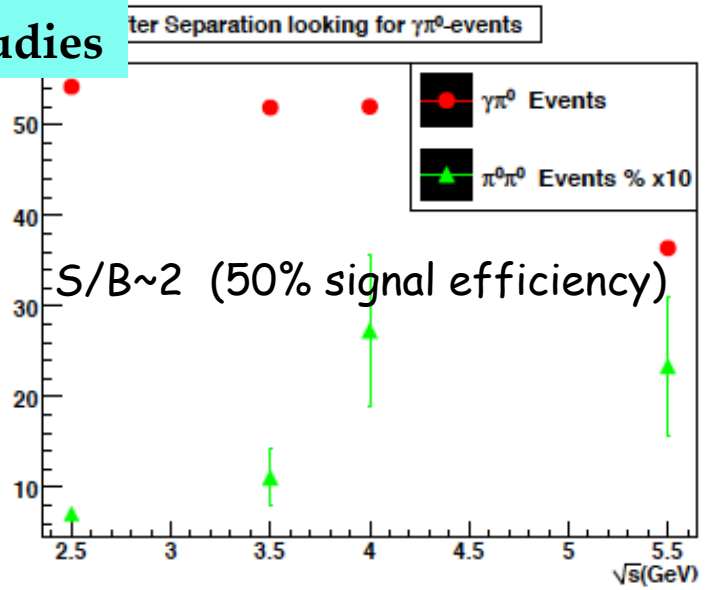
$\bar{p}p \to \pi^0\pi^0$ (for both signals)

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

PANDA Physics Performance Report
arXiv:0903.3905

Preliminary studies





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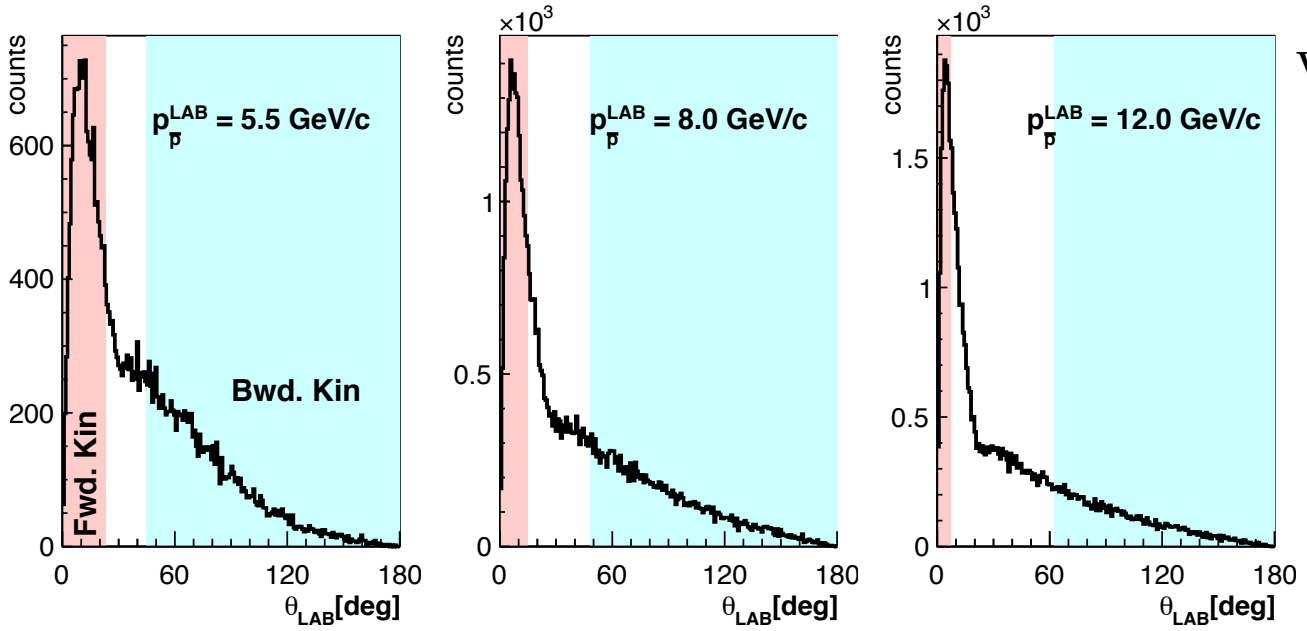
$$\bar{p}p \rightarrow J/\psi\pi^0 -> e^+e^-\pi^0$$



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)